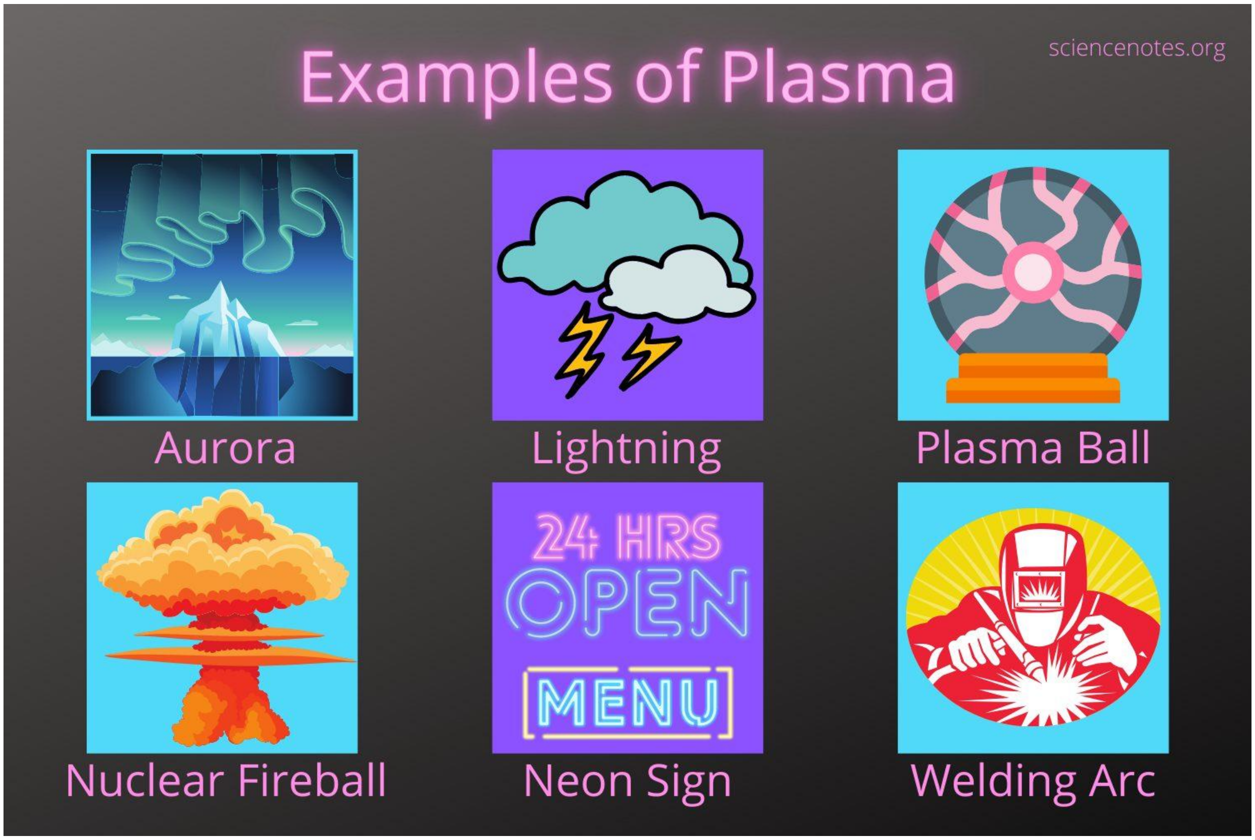
PLASMA PHYSICS



What is Plasma?

Plasma is superheated matter – so hot that the electrons are ripped away from the atoms forming an ionized gas. It comprises over 99% of the visible universe. In the night sky, plasma glows in the form of stars, nebulas, and even the auroras that sometimes ripple above the north and south poles. That branch of lightning that cracks the sky is plasma, so are the neon signs along our city streets. And so is our sun, the star that makes life on earth possible.

Plasma is often called "the fourth state of matter," along with solid, liquid and gas. Just as a liquid will boil, changing into a gas when energy is added, heating a gas will form a plasma – a soup of positively charged particles (ions) and negatively charged particles (electrons).

Because so much of the universe is made of plasma, its behavior and properties are of intense interest to scientists in many disciplines. Importantly, at the temperatures required for the goal of practical fusion energy, all matter is in the form of plasma. Researchers have used the properties of plasma as a charged gas to confine it with magnetic fields and to heat it to temperatures hotter than the core of the sun. Other researchers pursue plasmas for making computer chips, rocket propulsion, cleaning the environment, destroying biological hazards, healing wounds and other exciting applications.

The Future of Fusion

The fundamental features of fusion – inexhaustible fuel and large power density – would allow it to provide carbon-free energy at a scale needed to address climate change. Making clean, safe and economical fusion energy available to our society is a grand challenge of 21st century science and engineering. There is no known science stopping us from developing fusion energy; in fact the fundamental conditions needed to make fusion, such as achieving temperatures of 100 million degrees, have mostly been achieved, including in laboratories at MIT. Nonetheless many people wonder if fusion will be available in a timely manner since it has been long promised, but slow to become reality. Fusion has been delayed because its science was more complex than first imagined, and due to the large sizes of experimental facilities needed to explore fusion.

However, exploiting newly available technologies and science can accelerate the development of fusion energy. A host of new technologies, such as high-temperature superconductors and 3-D printing, provide exciting new opportunities to build small fusion devices, while fundamental understanding of the fusion science through advanced computing and measurement is providing greater confidence in the performance of fusion power plants. Bringing together these new opportunities in an integrated manner, all while training a new generation of fusion scientists, lies at the heart of our fusion energy mission at the PSFC.

Glossary

ADX

The “Advanced Divertor eXperiment”, a proposed new experiment at MIT that would develop solutions for taming the interface between the extremely hot plasma and ordinary matter — a key challenge for the development of practical fusion energy. The experiment would also explore advanced techniques for steady-state plasma sustainment by driving currents using RF waves.

Alcator C-Mod

MIT's recent tokamak fusion experiment. The third in a series of compact high-magnetic-field devices at MIT, Alcator C-Mod holds the record for the highest plasma pressure achieved in any tokamak.

ARC

A conceptual fusion pilot power plant design from MIT using demountable, high-field, high-temperature superconducting magnets. The design concept includes innovative features like a molten salt blanket and an advanced, long-legged divertor.

B

The symbol used to denote the strength of the magnetic field, typically given in units of “Tesla”. The Earth's magnetic field is 0.00005 Tesla. Fusion experiments at MIT have had fields in the range of 8-12 Tesla, the world’s highest.

Blanket

In a fusion power plant, the plasma will be surrounded by a blanket which serves three crucial functions — breeding tritium fuel, extracting heat from the fusion reactions and shielding the magnet and other components from fusion neutrons.

Breakeven

To be useful for energy production, a plasma must produce more fusion power output than the power required to heat it to fusion-relevant temperatures. This condition is termed “Breakeven” and has been the goal of research since 1955, when John Lawson derived a simple formula that translated the goal into quantitative requirements for plasma density, temperature and confinement.

Confinement

Fusion reactions only occur at tens or hundreds of millions of degrees, a state of matter called a plasma. Since these temperatures are inconsistent with ordinary states of matter, the plasma must be well insulated — that is confined or isolated from any material apparatus that surrounds it. While the plasma in stars is confined gravitationally by their enormous mass, on earth strong magnetic fields are the most successful method.The transport of heat across magnetic fields by collisions and turbulence in the plasma was one of the most important and most challenging scientific problems facing practical fusion.

Cryogenics

Cryogenics is the production and study of very low temperatures. Exploitation of cryogenic materials, often in the form of liquefied gases, is a key technology for fusion experiments and fusion power.

Current Drive

The mechanism by which electrical currents are maintained in a magnetically confined plasma. Because the tokamak concept requires a substantial current to function, current drive mechanisms are a subject of intense study. The most promising approach uses microwave RF waves.

Cyclotron Motion

The spiraling motion of charged particles in a magnetic field. Also called gyration or gyro-motion. Cyclotron motion is the basis for magnetic confinement, particle accelerators and methods for heating plasmas.

Deuterium/Tritium

Deuterium and tritium are the two forms of hydrogen which are used as fusion fuel. While the nucleus of ordinary hydrogen is a single proton, deuterium nuclei contain a neutron as well and tritium nuclei contain a proton and two neutrons. The deuterium-tritium reaction is the easiest fusion reaction to use for energy production. Deuterium occurs naturally and is plentiful as a fuel for fusion. Tritium does not occur naturally and must be produced in the blanket surrounding a fusion plasma.

Divertor

The magnetic “exhaust pipe” of a tokamak. The interaction between the hot plasma and ordinary matter is controlled by the divertor.

Electrons

The light, negatively charged particles in a plasma. At ordinary temperatures, electrons are tightly bound into atoms and molecules, but at fusion-relevant temperatures, the atoms are pulled apart into their constituents.

FLiBe

Heated to its melting point, a salt called FLiBe is a promising blanket material, containing the elements Fluorine (F), Lithium (Li), and Beryllium (Be). FLiBe becomes a liquid at 459°C and remains liquid up to 1427°C.

Fusion Reaction

Fusion is the process that powers the sun and the stars and produces all of the elements of the periodic table. In a fusion reaction, two light nuclei combine to make heavier nuclei. For practical fusion, we fuse deuterium and tritium in a plasma, forming helium and a neutron. The difference in mass is released in the form of energy as a result of $E=mc^2$.

HEDP (High Energy Density Physics)

High-Energy-Density Physics (HEDP) is the study of matter under extreme states of pressure, typically one million to one trillion times the atmospheric pressure on the surface of the Earth. At these pressures, which occur naturally in the core of stars and planets, matter exhibits new properties. HEDP is studied in the lab in Inertial-Confinement-Fusion (ICF) implosions providing better understanding of how stars form and how elements are made

High Temperature Superconductors (HTS)

These are materials that can become superconducting at temperatures significantly above absolute zero The most promising HTS materials for fusion are made of YBCO – Yttrium Barium Copper Oxide, which will remain superconducting even at the temperatures of liquid nitrogen temperature at 77 °K (equal to -196 °C).

Inertial Confinement Fusion (ICF)

ICF is a method of inducing fusion by extreme compression of matter. In the lab, ICF is typically driven by powerful lasers, which are focused on tiny fuel capsules. NIF and OMEGA are two large ICF facilities in the U.S.

Ions

The heavy, positively charged particles in a plasma. Ions are created when electrons are stripped away from atoms in hot plasmas.

ITER

A very large tokamak experiment under construction in France by a consortium of nations including the European Union, China, India, Japan, Korea, Russia and the U.S. The ITER magnets are made with conventional superconductors (LTS), providing a moderate magnetic field and necessitating its very large size. ITER is expected to begin research operations in 2030.

Lithium

Lithium, the third lightest element in the periodic table, and deuterium will provide the fuel for fusion power plants. While the burning plasma is made of deuterium and tritium, the tritium is recycled through a breeding process in the blanket. The net reaction is lithium and deuterium combining to make helium. Enough lithium exists on earth for millions of years of fusion energy.

Low Temperature Superconductors (LTS)

LTS is an older generation of superconductors that require cooling to extremely low temperatures, often using liquefied helium at 4 °K. A tokamak made with LTS cannot achieve a magnetic field in the plasma any higher than 6 Tesla. (With HTS, 15 Tesla should be possible.)

Magnet Coil

An electromagnet in which a loop of electrical current produces a magnetic field. The strength of the magnetic field is set by the amount of electrical current in the loop and its geometry as defined by Ampere's law.

Magnetic Confinement

The property of magnetic fields, imbedded in hot plasmas, which slows the transport of heat. Magnetic confinement is critical to insulate the plasma, at temperatures up to 200,000,000 °C from ordinary matter.

Magnetic Field

A fundamental field in nature, produced by moving electrical charges, i.e. electrical currents. Magnetic fields have a magnitude and direction, leading to the concept of the magnetic field line, which is aligned with the local direction of the field. Magnetic fields exert a force on charged particles that causes them to spiral around the magnetic field lines in what is called cyclotron or gyro-motion. Since it is composed of electrically charged particles, magnetic fields have very strong effects on plasmas on earth and in space.

Major Radius

Denotes half the distance – the long way - across a toroid, usually referred to with the symbol R. A related quantity is the minor radius, a, which is half the distance the short way. For illustration a car tire and a bicycle tire (both toroids) have roughly the same major radius, but the car tire has a much larger minor radius. Fusion experiments have been built with major radii from about 0.5 to 5.5 meters.

Megawatt (MW)

A unit of power, useful to describe how much electricity a power plant can produce, with one MW equal to a million watts. For comparison, the average microwave oven uses 1,000 watts, or 0.001 MW. Each MW of electrical power produced serves approximately 160 American households (a figure which includes their use at home and their share of commercial and industrial electrical consumption). A compact fusion power plant, based on HTS technology, might produce 100-500 MW.

MHD (Magnetohydrodynamics)

MHD is a theory of plasma dynamics in which the plasma is treated as a fluid. While not a complete description, it is extremely useful in establishing the basic equilibrium and stability of magnetically confined plasmas.

NIF (National Ignition Facility)

An ICF facility sited at the Lawrence Livermore National Laboratory (LLNL) in California, which houses the most powerful laser system on Earth. The lasers produce almost 2 million Joules of ultraviolet light in a pulse lasting less than 10 nanoseconds. While constructed for national security missions, NIF is also used to push the frontiers of HEDP science.

OMEGA

An ICF facility sited at the University of Rochester in New York. Capable of producing 30 thousand Joules per pulse, OMEGA is one of the largest laser systems in the world and by far the largest on a university campus. As such, it has a major role in basic HEDP, laser and optics research and in the training of students.

Particle Accelerators

Machines used to raise the energy of elementary particles to enormous levels. The largest, such as the LHC at CERN, are used for fundamental studies of matter, but smaller particle accelerators have found a broad range of applications in materials research, industry and medicine. Because the physics in accelerators involve the interactions of charged particles with electrical and magnetic fields, it has always had a close relation to the field of plasma physics.

Plasma

A gas which is so hot that electrons have been stripped from its constituent atoms. Almost all of the visible universe is made of plasmas — that is all of the stars and galaxies that we can see in the sky. On earth, lightning and the auroras are examples of naturally formed plasmas. Plasma can rightfully be called the “fourth state of matter” along with solid, liquid and gas. It is formed when ordinary matter is heated above 10,000 to 20,000°C

Plasma Acceleration

A technique for accelerating charged particles to very high velocities utilizing the electric fields created in plasma waves. Plasma acceleration has the potential to shrink the size of particle accelerators.

Plasma Current

As an excellent conductor of electricity, large currents can be driven in plasmas, creating, at the same time, an embedded magnetic field. Plasma current is a key element in the operation of tokamaks, the most common magnetic confinement configuration.

Plasma Density

The number of plasma particles in a given volume (per cubic meter in standard units). Normal air has a molecular density of $2x10^{25}m^{-3}$ while the density of a fusion plasma is $2x10^{20}m^{-3}$, 100,000 times less. This is one of the reasons why fusion is so safe—there is an extremely low amount of fuel in the core at any one time. Since the fusion rate in a plasma is proportional to the square of its density, it is a critical parameter for power generation.

Plasma Heating

Significant amounts of heat must be added to a plasma for it to attain the range of temperatures required for fusion. A number of methods have been tested in experiments over the years, but two have emerged as the most effective – that is injection of high energy neutral beams and application of RF waves at frequencies where they resonate with gyrating plasma ions. In a burning deuterium-tritium plasma most of this “extra” heating can be turned off and the plasma is heated instead by the energetic helium ions produced by fusion.

Plasma-Materials Interactions (PMI)

The interface between the hot plasma and ordinary matter presents one of the greatest challenges for fusion energy. The power load on the wall of a fusion device can rival what is found in a rocket nozzle — but the wall of a fusion device must survive for years, not minutes. The solution requires both innovation in engineering and plasma physics.

Plasma Pressure

Like the pressure of ordinary gases, plasma pressure is proportional to the product of temperature times density. It is also a measure of the plasma energy density, the energy contained per unit volume. At fusion relevant temperatures, the fusion rate is proportional to the pressure squared while plasma stability limits the pressure by a factor proportional to the magnetic field squared. Thus all other things being equal, fusion power density increases as the fourth power of the magnetic field.

Plasma Temperature

The average energy of the plasma's particles. Compared to air, which has a typical temperature of 20 °C, plasmas occur when temperatures exceed 10,000 °C and fusion energy requires temperatures well above 50,000,000 °C.

Plasma Waves

Just as an ordinary fluid medium like air carries sound waves, plasmas support a rich array of waves. These plasma waves have a distinct and complicated set of properties owing to the low density and high temperature of the medium, the influence of electric and magnetic field on plasma motion and because the plasma motion itself can generate electric and magnetic fields. Plasma waves can be used to heat plasmas, drive current or to make measurements.

RF (Radio Frequency)

Many of the plasma waves of interest are in parts of the frequency spectrum designated as radio frequencies — roughly 20 kHz to around 300 GHz. As a result, electromagnetic waves in this frequency range are useful for heating, driving current or making measurements of the plasma.

Simulation

In many fields such as plasma physics and materials science, the underlying equations are known, but calculating the solutions is far beyond what can be done with pencil and paper. For these problems, computers can be used to derive approximate solutions — a process called simulation. Fusion research has always been a leader in simulation, using the most advanced computers available at any given time. Its requirements drove the founding of the first non-classified supercomputer center in 1974.

SPARC

A proposed high-field, compact fusion experiment which will burn deuterium-tritium fuel and is aiming to be the first to exceed energy breakeven. Using the new high-temperature superconductors (HTS), SPARC would have a magnetic field at the plasma center of 12 Tesla and a major radius, R, of about 1.6 meters. It is predicted that this device would produce 50-100 MW of fusion power.

Stellarator

A toroidal magnetic confinement device where the magnetic field lines are twisted through the use of coils with three-dimensional shapes. Though more complicated to build, stellarators unlike tokamaks, do not require any external means to sustain their equilibrium.

Superconductor

A material that can conduct electricity without any resistance. Many materials have been identified that become superconducting when very cold, typically a few degrees above absolute zero (defined as 0 °K = -273 °C). Only a handful of these have any practical or commercial use however, but those that do have become essential in many applications. In recent years, so-called high temperature superconductors have been developed which can operate up to about 90 °K.

Tokamak

A toroidal magnetic confinement device where an essential part of the magnetic configuration is generated by a large current flowing in the plasma itself. For this reason, steady-state operation requires an external means of driving the current — for example through the application of microwaves. Tokamaks have demonstrated the highest performance levels of any controlled fusion approach.

Torus/Toroid

An object with a hole in the middle like a doughnut or inner tube. Because magnetic fields only confine plasma in the direction perpendicular to a magnetic field and not in the direction parallel to the field, a successful magnetic confinement concept must have field lines without beginnings or ends. This is accomplished by wrapping the field around on themselves, covering the surface of a torus.

Plasma

state of matter

plasma, in physics, an electrically conducting medium in which there are roughly equal numbers of positively and negatively charged particles, produced when the atoms in a gas become ionized. It is sometimes referred to as the fourth state of matter, distinct from the solid, liquid, and gaseous states.

The negative charge is usually carried by electrons, each of which has one unit of negative charge. The positive charge is typically carried by atoms or molecules that are missing those same electrons. In some rare but interesting cases, electrons missing from one type of atom or molecule become attached to another component, resulting in a plasma containing both positive and negative ions. The most extreme case of this type occurs when small but macroscopic dust particles become charged in a state referred to as a dusty plasma. The uniqueness of the plasma state is due to the importance of electric and magnetic forces that act on a plasma in addition to such forces as gravity that affect all forms of matter. Since these electromagnetic forces can act at large distances, a plasma will act collectively much like a fluid even when the particles seldom collide with one another.

Nearly all the visible matter in the universe exists in the plasma state, occurring predominantly in this form in the Sun and stars and in interplanetary and interstellar space. Auroras, lightning, and welding arcs are also plasmas; plasmas exist in neon and fluorescent tubes, in the crystal structure of metallic solids, and in many other phenomena and objects. The Earth itself is immersed in a tenuous plasma called the solar wind and is surrounded by a dense plasma called the ionosphere.

A plasma may be produced in the laboratory by heating a gas to an extremely high temperature, which causes such vigorous collisions between its atoms and molecules that electrons are ripped free, yielding the requisite electrons and ions. A similar process occurs inside stars. In space the dominant plasma formation process is photoionization, wherein photons from sunlight or starlight are absorbed by an existing gas, causing electrons to be emitted. Since the Sun and stars shine continuously, virtually all the matter becomes ionized in such cases, and the plasma is said to be fully ionized. This need not be the case, however, for a plasma may be only partially ionized. A completely ionized hydrogen plasma, consisting solely of electrons and protons (hydrogen nuclei), is the most elementary plasma.

The development of plasma physics

The modern concept of the plasma state is of recent origin, dating back only to the early 1950s. Its history is interwoven with many disciplines. Three basic fields of study made unique early contributions to the development of plasma physics as a discipline: electric discharges, magnetohydrodynamics (in which a conducting fluid such as mercury is studied), and kinetic theory.

Interest in electric-discharge phenomena may be traced back to the beginning of the 18th century, with three English physicists—Michael Faraday in the 1830s and Joseph John Thomson and John Sealy Edward Townsend at the turn of the 19th century—laying the foundations of the present understanding of the phenomena. Irving Langmuir introduced the term plasma in 1923 while investigating electric discharges. In 1929 he and Lewi Tonks, another physicist working in the United States, used the term to designate those regions of a discharge in which certain periodic variations of the negatively charged electrons could occur. They called these oscillations plasma oscillations, their behaviour suggesting that of a jellylike substance. Not until 1952, however, when two other American physicists, David Bohm and David Pines, first considered the collective behaviour of electrons in metals as distinct from that in ionized gases, was the general applicability of the concept of a plasma fully appreciated.

The collective behaviour of charged particles in magnetic fields and the concept of a conducting fluid are implicit in magnetohydrodynamic studies, the foundations of which were laid in the early and middle 1800s by Faraday and André-Marie Ampère of France. Not until the 1930s, however, when new solar and geophysical phenomena were being discovered, were many of the basic problems of the mutual interaction between ionized gases and magnetic fields considered. In 1942 Hannes Alfvén, a Swedish physicist, introduced the concept of magnetohydrodynamic waves. This contribution, along with his further studies of space plasmas, led to Alfvén's receipt of the Nobel Prize for Physics in 1970.

How scientists use lasers to learn about the universeLearn about the PHELIX (Petawatt High-Energy Laser for Heavy Ion Experiments) laser at the GSI Helmholtz Centre for Heavy Ion Research in Darmstadt, Germany. PHELIX is used for plasma and atomic physics research.(more)
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These two separate approaches—the study of electric discharges and the study of the behaviour of conducting fluids in magnetic fields—were unified by the introduction of the kinetic theory of the plasma state. This theory states that plasma, like gas, consists of particles in random motion, whose interactions can be through long-range electromagnetic forces as well as via collisions. In 1905 the Dutch physicist Hendrik Antoon Lorentz applied the kinetic equation for atoms (the formulation by the Austrian physicist Ludwig Eduard Boltzmann) to the behaviour of electrons in metals. Various physicists and mathematicians in the 1930s and ’40s further developed the plasma kinetic theory to a high degree of sophistication. Since the early 1950s interest has increasingly focused on the plasma state itself. Space exploration, the development of electronic devices, a growing awareness of the importance of magnetic fields in astrophysical phenomena, and the quest for controlled thermonuclear (nuclear fusion) power reactors all have stimulated such interest. Many problems remain unsolved in space plasma physics research, owing to the complexity of the phenomena. For example, descriptions of the solar wind must include not only equations dealing with the effects of gravity, temperature, and pressure as needed in atmospheric science but also the equations of the Scottish physicist James Clerk Maxwell, which are needed to describe the electromagnetic field.

Plasma oscillations and parameters

Just as a lightweight cork in water will bob up and down about its rest position, any general displacement of light electrons as a group with respect to the positive ions in a plasma leads to the oscillation of the electrons as a whole about an equilibrium state. In the case of the cork, the restoring force is provided by gravity; in plasma oscillations, it is provided by the electric force. These movements are the plasma oscillations that were studied by Langmuir and Tonks. Analogously, just as buoyancy effects guide water waves, plasma oscillations are related to waves in the electron component of the plasma called Langmuir waves. Wavelike phenomena play a critical role in the behaviour of plasmas.

The time τ required for an oscillation of this type is the most important temporal parameter in a plasma. The main spatial parameter is the Debye length, h, which is the distance traveled by the average thermal electron in time $\tau/2\pi$. A plasma can be defined in terms of these parameters as a partially or fully ionized gas that satisfies the following criteria: (1) a constituent electron may complete many plasma oscillations before it collides with either an ion or one of the other heavy constituents, (2) inside each sphere with a radius equal to the Debye length, there are many particles, and (3) the plasma itself is much larger than the Debye length in every dimension.

Another important temporal parameter is the time between collisions of particles. In any gas, separate collision frequencies are defined for collisions between all different particle types. The total collision frequency for a particular species is the weighted sum of all the separate frequencies. Two basic types of collision may occur: elastic and inelastic. In an elastic collision, the total kinetic energy of all the particles participating in the collision is the same before and after the event. In an inelastic collision, a fraction of the kinetic energy is transferred to the internal energy of the colliding particles. In an atom, for example, the electrons have certain allowed (discrete) energies and are said to be bound. During a collision, a bound electron may be excited—that is, raised from a low to a high energy state. This can occur, however, only by the expenditure of kinetic energy and only if the kinetic energy exceeds the difference between the two energy states. If the energy is sufficient, a bound electron may be excited to such a high level that it becomes a free electron, and the atom is said to be ionized; the minimum, or threshold, energy required to free an electron is called the ionization energy. Inelastic collisions may also occur with positive ions unless all the electrons have been stripped away. In general, only collisions of electrons and photons (quanta of electromagnetic radiation) with atoms and ions are significant in these inelastic collisions; ionization by a photon is called photoionization.

A molecule has additional discrete energy states, which may be excited by particle or photon collisions. At sufficiently high energies of interaction, the molecule can dissociate into atoms or into atoms and atomic ions. As in the case of atoms, collision of electrons and photons with molecules may cause ionization, producing molecular ions. In general, the reaction rate for inelastic collisions is similar to that of chemical reactions. At sufficiently high temperatures, the atoms are stripped of all electrons and become bare atomic nuclei. Finally, at temperatures of about 1,000,000 K or greater, nuclear reactions can occur—another form of inelastic collisions. When such reactions lead to the formation of heavier elements, the process is called thermonuclear fusion; mass is transmuted, and kinetic energy is gained instead of lost.

All sources of energy now existing on the Earth can be traced in one way or another to the nuclear fusion reactions inside the Sun or some long-extinct star. In such energy sources, gravity controls and confines the fusion process. The high temperatures required for the nuclear fusion reactions that take place in a hydrogen, or thermonuclear, bomb are attained by first igniting an atomic bomb, which produces a fission chain reaction. One of the great challenges of humankind is to create these high temperatures in a controlled manner and to harness the energy of nuclear fusion. This is the great practical goal of plasma physics—to produce nuclear fusion on the Earth. Confinement schemes devised by scientists use magnetic fields or the inertia of an implosion to guide and control the hot plasma.

Basic plasma physics

Plasma formation

Apart from solid-state plasmas, such as those in metallic crystals, plasmas do not usually occur naturally at the surface of the Earth. For laboratory experiments and technological applications, plasmas therefore must be produced artificially. Because the atoms of such alkalies as potassium, sodium, and cesium possess low ionization energies, plasmas may be produced from these by the direct application of heat at temperatures of about 3,000 K. In most gases, however, before any significant degree of ionization is achieved, temperatures in the neighbourhood of 10,000 K are required. A convenient unit for measuring temperature in the study of plasmas is the electron volt (eV), which is the energy gained by an electron in vacuum when it is accelerated across one volt of electric potential. The temperature, W, measured in electron volts is given by $W = T/12{,}000$ when T is expressed in kelvins. The temperatures required for self-ionization thus range from 2.5 to 8 electron volts, since such values are typical of the energy needed to remove one electron from an atom or molecule.

Because all substances melt at temperatures far below that level, no container yet built can withstand an external application of the heat necessary to form a plasma; therefore, any heating must be supplied internally. One technique is to apply an electric field to the gas to accelerate and scatter any free electrons, thereby heating the plasma. This type of ohmic heating is similar to the method in which free electrons in the heating element of an electric oven heat the coil. Because of their small energy loss in elastic collisions, electrons can be raised to much higher temperatures than other particles. For plasma formation a sufficiently high electric field must be applied, its exact value depending on geometry and the gas pressure. The electric field may be set up via electrodes or by transformer action, in which the electric field is induced by a changing magnetic field. Laboratory temperatures of about 10,000,000 K, or 8 kiloelectron volts (keV), with electron densities of about 10^{19} per cubic metre have been achieved by the transformer method. The temperature is eventually limited by energy losses to the outside environment. Extremely high temperatures, but relatively low-density plasmas, have been produced by the separate injection of ions and electrons into a mirror system (a plasma device using a particular arrangement of magnetic fields for containment). Other methods have used the high temperatures that develop behind a wave that is moving much faster than sound to produce what is called a shock front; lasers have also been employed.

Natural plasma heating and ionization occur in analogous ways. In a lightning-induced plasma, the electric current carried by the stroke heats the atmosphere in the same manner as in the ohmic heating technique described above. In solar and stellar plasmas the heating is internal and caused by nuclear fusion reactions. In the solar corona, the heating occurs because of waves that propagate from the surface into the Sun's atmosphere, heating the plasma much like shock-wave heating in laboratory plasmas. In the ionosphere, ionization is accomplished not through heating of the plasma but rather by the flux of energetic photons from the Sun. Far-ultraviolet rays and X rays from the Sun have enough energy to ionize atoms in the Earth's atmosphere. Some of the energy also goes into heating the gas, with the result that the upper atmosphere, called the thermosphere, is quite hot. These processes protect the Earth from energetic photons much as the ozone layer protects terrestrial life-forms from lower-energy ultraviolet light. The typical temperature 300 kilometres above the Earth's surface is 1,200 K, or about 0.1 eV. Although it is quite warm compared with the surface of the Earth, this temperature is too low to create self-ionization. When the Sun sets with respect to the ionosphere, the source of ionization ceases, and the lower portion of the ionosphere reverts to its nonplasma state. Some ions, in particular singly charged oxygen (O^+), live long enough that some plasma remains until the next sunrise. In the case of an aurora, a plasma is created in the nighttime or daytime atmosphere when beams of electrons are accelerated to hundreds or thousands of electron volts and smash into the atmosphere.

Methods of describing plasma phenomena

The behaviour of a plasma may be described at different levels. If collisions are relatively infrequent, it is useful to consider the motions of individual particles. In most plasmas of interest, a magnetic field exerts a force on a charged particle only if the particle is moving, the force being at right angles to both the direction of the field and the direction of particle motion. In a uniform magnetic field (B), a charged particle gyrates about a line of force. The centre of the orbit is called the guiding centre. The particle may also have a component of velocity parallel to the magnetic field and so traces out a helix in a uniform magnetic field. If a uniform electric field (E) is applied at right angles to the direction of the magnetic field, the guiding centre drifts with a uniform velocity of magnitude equal to the ratio of the electric to the magnetic field (E/B), at right angles to both the electric and magnetic fields. A particle starting from rest in such fields follows the same cycloidal path a dot on the rim of a rolling wheel follows. Although the "wheel" radius and its sense of rotation vary for different particles, the guiding centre moves at the same E/B velocity, independent of the particle's charge and mass. Should the electric field change with time, the problem would become even more complex. If, however, such an alternating electric field varies at the same frequency as the cyclotron frequency (i.e., the rate of gyration), the guiding centre will remain stationary, and the particle will be forced to travel in an ever-expanding orbit. This phenomenon is called cyclotron resonance and is the basis of the cyclotron particle accelerator.

The motion of a particle about its guiding centre constitutes a circular current. As such, the motion produces a dipole magnetic field not unlike that produced by a simple bar magnet. Thus, a moving charge not only interacts with magnetic fields but also produces them. The direction of the magnetic field produced by a moving particle, however, depends both on whether the particle is positively or negatively charged and on the direction of its motion. If the motion of the charged particles is completely random, the net associated magnetic field is zero. On the other hand, if charges of different sign have an average relative velocity (i.e., if an electric current flows), then a net magnetic field over and above any externally applied field exists. The magnetic interaction between charged particles is therefore of a collective, rather than of an individual, particle nature.

At a higher level of description than that of the single particle, kinetic equations of the Boltzmann type are used. Such equations essentially describe the behaviour of those particles about a point in a small-volume element, the particle velocities lying within a small range about a given value. The interactions with all other velocity groups, volume elements, and any externally applied electric and magnetic fields are taken into account. In many cases, equations of a fluid type may be derived from the kinetic equations; they express the conservation of mass, momentum, and energy per unit volume, with one such set of equations for each particle type.

Determination of plasma variables

The basic variables useful in the study of plasma are number densities, temperatures, electric and magnetic field strengths, and particle velocities. In the laboratory and in space, both electrostatic (charged) and magnetic types of sensory devices called probes help determine the magnitudes of such variables. With the electrostatic probe, ion densities, electron and ion temperatures, and electrostatic potential differences can be determined. Small search coils and other types of magnetic probes yield values for the magnetic field; and from Maxwell's electromagnetic equations the current and charge densities and the induced component of the electric field may be found. Interplanetary spacecraft have carried such probes to nearly every planet in the solar system, revealing to scientists such plasma phenomena as lightning on Jupiter and the sounds of Saturn's rings and radiation belts. In the early 1990s, signals were being relayed to the Earth from several spacecraft approaching the edge of the plasma boundary to the solar system, the heliopause.

In the laboratory the absorption, scattering, and excitation of neutral and high-energy ion beams are helpful in determining electron temperatures and densities; in general, the refraction, reflection, absorption, scattering, and interference of electromagnetic waves also provide ways to determine these same variables. This technique has also been employed to remotely measure the properties of the plasmas in the near-space regions of the Earth using the incoherent scatter radar method. The method works by bouncing radio waves from small irregularities in the electron gas that occur owing to random thermal motions of the particles. The returning signal is shifted slightly from the transmitted one—because of the Doppler-shift effect—and the velocity of the plasma can be determined in a manner similar to the way in which the police detect a speeding car. Using this method, the wind speed in space can be found, along with the temperature, density, electric field, and even the types of ions present. In geospace the appropriate radar frequencies are in the range of 50 to 1,000 megahertz (MHz), while in the laboratory, where the plasma densities and plasma frequencies are higher, microwaves and lasers must be used.

Aside from the above methods, much can be learned from the radiation generated and emitted by the plasma itself; in fact, this is the only means of studying cosmic plasma beyond the solar system. The various spectroscopic techniques covering the entire continuous radiation spectrum determine temperatures and identify such nonthermal sources as those pulses producing synchrotron radiations.

Waves in plasmas

The waves most familiar to people are the buoyancy waves that propagate on the surfaces of lakes and oceans and break onto the world's beaches. Equally familiar, although not necessarily recognized as waves, are the disturbances in the atmosphere that create what is referred to as the weather. Wave phenomena are particularly important in the behaviour of plasmas. In fact, one of the three criteria for the existence of a plasma is that the particle-particle collision rate be less than the plasma-oscillation frequency. This in turn implies that the collective interactions that control the plasma gas depend on the electric and magnetic field effects as much as, or more so than, simple collisions. Since waves are able to propagate, the possibility exists for force fields to act at large distances from the point where they originated.

Ordinary fluids can support the propagation of sound (acoustic) waves, which involve pressure, temperature, and velocity variations. Electromagnetic waves can propagate even in a vacuum but are slowed down in most cases by the interaction of the electric fields in the waves with the charged particles bound in the atoms or molecules of the gas. Although it is important for a complete description of electromagnetic waves, such an interaction is not very strong. In a plasma, however, the particles react in concert with any electromagnetic field (e.g., as in an electromagnetic wave) as well as with any pressure or velocity field (e.g., as in a sound wave). In fact, in a plasma sound wave the electrons and ions become slightly separated owing to their difference in mass, and an electric field builds up to bring them back together. The result is called an ion acoustic wave. This is just one of the many types of waves that can exist in a plasma. The brief discussion that follows touches on the main types in order of increasing wave-oscillation frequency.

Low-frequency waves

At the lowest frequency are Alfvén waves, which require the presence of a magnetic field to exist. In fact, except for ion acoustic waves, the existence of a background magnetic field is required for any wave with a frequency less than the plasma frequency to occur in a plasma. Most natural plasmas are threaded by a magnetic field, and laboratory plasmas often use a magnetic field for confinement, so this requirement is usually met, and all types of waves can occur.

Alfvén waves are analogous to the waves that occur on the stretched string of a guitar. In this case, the string represents a magnetic field line. When a small magnetic field disturbance takes place, the field is bent slightly, and the disturbance propagates in the direction of the magnetic field. Since any changing magnetic field creates an electric field, an electromagnetic wave results. Such waves are the slowest and have the lowest frequencies of any known electromagnetic waves. For example, the solar wind streams out from the Sun with a speed greater than either electromagnetic (Alfvén) or sound waves. This means that, when the solar wind hits the Earth's outermost magnetic field lines, a shock wave results to "inform" the incoming plasma that an obstacle exists, much like the shock wave associated with a supersonic airplane. The shock wave travels toward the Sun at the same speed but in the opposite direction as the solar wind, so it appears to stand still with respect to the Earth. Because there are almost no particle-particle collisions, this type of collisionless shock wave is of great interest to space plasma physicists who postulate that similar shocks occur around supernovas and in other astrophysical plasmas. On the Earth's side of the shock wave, the heated and slowed solar wind interacts with the Earth's atmosphere via Alfvén waves propagating along the magnetic field lines.

The turbulent surface of the Sun radiates large-amplitude Alfvén waves, which are thought to be responsible for heating the corona to 1,000,000 K. Such waves can also produce fluctuations in the solar wind, and, as they propagate through it to the Earth, they seem to control the occurrence of magnetic storms and auroras that are capable of disrupting communication systems and power grids on the planet.

Two fundamental types of wave motion can occur: longitudinal, like a sound or ion acoustic wave, in which particle oscillation is in a direction parallel to the direction of wave propagation; and transverse, like a surface water wave, in which particle oscillation is in a plane perpendicular to the direction of wave propagation. In all cases, a wave may be characterized by a speed of propagation (u), a wavelength (λ), and a frequency (ν) related by an expression in which the velocity is equal to the product of the wavelength and frequency, namely, $u = \lambda\nu$. The Alfvén wave is a transverse wave and propagates with a velocity that depends on the particle density and the magnetic field strength. The velocity is equal to the magnetic flux density (B) divided by the square root of the mass density (ρ) times the permeability of free space (μ_o)—that is to say, B/Square root of$\sqrt{\mu_o\rho}$. The ion acoustic wave is a longitudinal wave and also propagates parallel to the magnetic field at a speed roughly equal to the average thermal velocity of the ions. Perpendicular to the magnetic field a different type of longitudinal wave called a magnetosonic wave can occur.

Higher frequency waves

In these waves the plasma behaves as a whole, and the velocity is independent of wave frequency. At higher frequencies, however, the separate behaviour of ions and electrons causes the wave velocities to vary with direction and frequency. The Alfvén wave splits into two components, referred to as the fast and slow Alfvén waves, which propagate at different frequency-dependent speeds. At still higher frequencies these two waves (called the electron cyclotron and ion cyclotron waves, respectively) cause electron and cyclotron resonances (synchronization) at the appropriate resonance frequencies. Beyond these resonances, transverse wave propagation does not occur at all until frequencies comparable to and above the plasma frequency are reached.

At frequencies between the ion and electron gyrofrequencies lies a wave mode called a whistler. This name comes from the study of plasma waves generated by lightning. When early researchers listened to natural radio waves by attaching an antenna to an audio amplifier, they heard a strange whistling sound. The whistle occurs when the electrical signal from lightning in one hemisphere travels along the Earth's magnetic field lines to the other hemisphere. The trip is so long that some waves (those at higher frequencies) arrive first, resulting in the generation of a whistlelike sound. These natural waves were used to probe the region of space around the Earth before spacecraft became available. Such a frequency-dependent wave velocity is called wave dispersion because the various frequencies disperse with distance.

The speed of an ion acoustic wave also becomes dispersive at high frequencies, and a resonance similar to electron plasma oscillations occurs at a frequency determined by electrostatic oscillations of the ions. Beyond this frequency no sonic wave propagates parallel to a magnetic field until the frequency reaches the plasma frequency, above which electroacoustic waves occur. The wavelength of these waves at the critical frequency (ω_p) is infinite, the electron behaviour at this frequency taking the form of the plasma oscillations of Langmuir and Tonks. Even without particle collisions, waves shorter than the Debye length are heavily damped—i.e., their amplitude decreases rapidly with time. This phenomenon, called Landau damping, arises because some electrons have the same velocity as the wave. As they move with the wave, they are accelerated much like a surfer on a water wave and thus extract energy from the wave, damping it in the process.

Containment

Magnetic fields are used to contain high-density, high-temperature plasmas because such fields exert pressures and tensile forces on the plasma.
An equilibrium configuration is reached only when at all points in the plasma these pressures and tensions exactly balance the pressure from the motion of the particles. A well-known example of this is the pinch effect observed in specially designed equipment. If an external electric current is imposed on a cylindrically shaped plasma and flows parallel to the plasma axis, the magnetic forces act inward and cause the plasma to constrict, or pinch. An equilibrium condition is reached in which the temperature is proportional to the square of the electric current. This result suggests that any temperature may be achieved by making the electric current sufficiently large, the heating resulting from currents and compression. In practice, however, since no plasma can be infinitely long, serious energy losses occur at the ends of the cylinder; also, major instabilities develop in such a simple configuration. Suppression of such instabilities has been one of the major efforts in laboratory plasma physics and in the quest to control the nuclear fusion reaction.

A useful way of describing the confinement of a plasma by a magnetic field is by measuring containment time (τ_c), or the average time for a charged particle to diffuse out of the plasma; this time is different for each type of configuration. Various types of instabilities can occur in plasma. These lead to a loss of plasma and a catastrophic decrease in containment time. The most important of these is called magnetohydrodynamic instability. Although an equilibrium state may exist, it may not correspond to the lowest possible energy. The plasma, therefore, seeks a state of lower potential energy, just as a ball at rest on top of a hill (representing an equilibrium state) rolls down to the bottom if perturbed; the lower energy state of the plasma corresponds to a ball at the bottom of a valley. In seeking the lower energy state, turbulence develops, leading to enhanced diffusion, increased electrical resistivity, and large heat losses. In toroidal geometry, circular plasma currents must be kept below a critical value called the Kruskal-Shafranov limit, otherwise a particularly violent instability consisting of a series of kinks may occur. Although a completely stable system appears to be virtually impossible, considerable progress has been made in devising systems that eliminate the major instabilities. Temperatures on the order of 10,000,000 K at densities of 10^{19} particles per cubic metre and containment times as high as 1/50 of a second have been achieved.

Applications of plasmas

The most important practical applications of plasmas lie in the future, largely in the field of power production. The major method of generating electric power has been to use heat sources to convert water to steam, which drives turbogenerators. Such heat sources depend on the combustion of fossil fuels, such as coal, oil, and natural gas, and fission processes in nuclear reactors. A potential source of heat might be supplied by a fusion reactor, with a basic element of deuterium-tritium plasma; nuclear fusion collisions between those isotopes of hydrogen would release large amounts of energy to the kinetic energy of the reaction products (the neutrons and the nuclei of hydrogen and helium atoms). By absorbing those products in a surrounding medium, a powerful heat source could be created. To realize a net power output from such a generating station—allowing for plasma radiation and particle losses and for the somewhat inefficient conversion of heat to electricity—plasma temperatures of about 100,000,000 K and a product of particle density times containment time of about 10^{20} seconds per cubic metre are necessary. For example, at a density of 10^{20} particles per metre cubed, the containment time must be one second. Such figures are yet to be reached, although there has been much progress.

In general, there are two basic methods of eliminating or minimizing end losses from an artificially created plasma: the production of toroidal plasmas and the use of magnetic mirrors (see nuclear fusion). A toroidal plasma is essentially one in which a plasma of cylindrical cross section is bent in a circle so as to close on itself. For such plasmas to be in equilibrium and stable, however, special magnetic fields are required, the largest component of which is a circular field parallel to the axis of the plasma. In addition, a number of turbulent plasma processes must be controlled to keep the system stable. In 1991 a machine called the JET (Joint European Torus) was able to generate 1.7 million watts of fusion power for almost 2 seconds after researchers injected titrium into the JET's magnetically confined plasma. It was the first successful controlled production of fusion power in such a confined medium.

Besides generating power, a fusion reactor might desalinate seawater. Approximately two-thirds of the world's land surface is uninhabited, with one-half of this area being arid. The use of both giant fission and fusion reactors in the large-scale evaporation of seawater could make irrigation of such areas economically feasible. Another possibility in power production is the elimination of the heat–steam–mechanical energy chain. One suggestion depends on the dynamo effect. If a plasma moves perpendicular to a magnetic field, an electromotive force, according to Faraday's law, is generated in a direction perpendicular to both the direction of flow of the plasma and the magnetic field. This dynamo effect can drive a current in an external circuit connected to electrodes in the plasma, and thus electric power may be produced without the need for steam-driven rotating machinery. This process is referred to as magnetohydrodynamic (MHD) power generation and has been proposed as a method of extracting power from certain types of fission reactors. Such a generator powers the auroras as the Earth's magnetic field lines tap electrical current from the MHD generator in the solar wind.

The inverse of the dynamo effect, called the motor effect, may be used to accelerate plasma. By pulsing cusp-shaped magnetic fields in a plasma, for example, it is possible to achieve thrusts proportional to the square of the magnetic field. Motors based on such a technique have been proposed for the propulsion of craft in deep space. They have the advantage of being capable of achieving large exhaust velocities, thus minimizing the amount of fuel carried.

A practical application of plasma involves the glow discharge that occurs between two electrodes at pressures of one-thousandth of an atmosphere or thereabouts. Such glow discharges are responsible for the light given off by neon tubes and such other light sources as fluorescent lamps, which operate by virtue of the plasmas they produce in electric discharge. The degree of ionization in such plasmas is usually low, but electron densities of 10^{16} to 10^{18} electrons per cubic metre can be achieved with an electron temperature of 100,000 K. The electrons responsible for current flow are produced by ionization in a region near the cathode, with most of the potential difference between the two electrodes occurring there. This region does not contain a plasma, but the region between it and the anode (i.e., the positive electrode) does.

Other applications of the glow discharge include electronic switching devices; it and similar plasmas produced by radio-frequency techniques can be used to provide ions for particle accelerators and act as generators of laser beams. As the current is increased through a glow discharge, a stage is reached when the energy generated at the cathode is sufficient to provide all the conduction electrons directly from the cathode surface, rather than from gas between the electrodes. Under this condition the large cathode potential difference disappears, and the plasma column contracts. This new state of electric discharge is called an arc. Compared with the glow discharge, it is a high-density plasma and will operate over a large range of pressures. Arcs are used as light sources for welding, in electronic switching, for rectification of alternating currents, and in high-temperature chemistry. Running an arc between concentric electrodes and injecting gas into such a region causes a hot, high-density plasma mixture called a plasma jet to be ejected. It has many chemical and metallurgical applications.

Natural plasmas

Extraterrestrial forms

It has been suggested that the universe originated as a violent explosion about 13.8 billion years ago and initially consisted of a fireball of completely ionized hydrogen plasma. Irrespective of the truth of this, there is little matter in the universe now that does not exist in the plasma state. The observed stars are composed of plasmas, as are interstellar and interplanetary media and the outer atmospheres of planets. Scientific knowledge of the universe has come primarily from studies of electromagnetic radiation emitted by plasmas and transmitted through them and, since the 1960s, from space probes within the solar system.

In a star the plasma is bound together by gravitational forces, and the enormous energy it emits originates in thermonuclear fusion reactions within the interior. Heat is transferred from the interior to the exterior by radiation in the outer layers, where convection is of greater importance. In the vicinity of a hot star, the interstellar medium consists almost entirely of completely ionized hydrogen, ionized by the star’s ultraviolet radiation. Such regions are referred to as H II regions. The greater proportion by far of interstellar medium, however, exists in the form of neutral hydrogen clouds referred to as H I regions. Because the heavy atoms in such clouds are ionized by ultraviolet radiation (or photoionized), they also are considered to be plasmas, although the degree of ionization is probably only one part in 10,000. Other components of the interstellar medium are grains of dust and cosmic rays, the latter consisting of very high-energy atomic nuclei completely stripped of electrons. The almost isotropic velocity distribution of the cosmic rays may stem from interactions with waves of the background plasma.

Throughout this universe of plasma there are magnetic fields. In interstellar space magnetic fields are about 5×10^{-6} gauss (a unit of magnetic field strength) and in interplanetary space 5×10^{-5} gauss, whereas in intergalactic space they could be as low as 10^{-9} gauss. These values are exceedingly small compared with the Earth's surface field of about 5×10^{-1} gauss. Although small in an absolute sense, these fields are nevertheless gigantic, considering the scales involved. For example, to simulate interstellar phenomena in the laboratory, fields of about 10^{15} gauss would be necessary. Thus, these fields play a major role in nearly all astrophysical phenomena. On the Sun the average surface field is in the vicinity of 1 to 2 gauss, but magnetic disturbances arise, such as sunspots, in which fields of between 10 and 1,000 gauss occur. Many other stars are also known to have magnetic fields. Field strengths of 10^{-3} gauss are associated with various extragalactic nebulae from which synchrotron radiation has been observed.

Solar-terrestrial forms

Regions of the Sun

The visible region of the Sun is the photosphere, with its radiation being about the same as the continuum radiation from a 5,800 K blackbody. Lying above the photosphere is the chromosphere, which is observed by the emission of line radiation from various atoms and ions. Outside the chromosphere, the corona expands into the ever-blowing solar wind (see below), which on passing through the planetary system eventually encounters the interstellar medium. The corona can be seen in spectacular fashion when the Moon eclipses the bright photosphere. During the times in which sunspots are greatest in number (called the sunspot maximum), the corona is very extended and the solar wind is fierce. Sunspot activity waxes and wanes with roughly an 11-year cycle. During the mid-1600s and early 1700s, sunspots virtually disappeared for a period known as the Maunder minimum. This time coincided with the Little Ice Age in Europe, and much conjecture has arisen about the possible effect of sunspots on climate. Periodic variations similar to that of sunspots have been observed in tree rings and lake-bed sedimentation. If real, such an effect is important because it implies that the Earth's climate is fragile.

In 1958 the American astrophysicist Eugene Parker showed that the equations describing the flow of plasma in the Sun's gravitational field had one solution that allowed the gas to become supersonic and to escape the Sun's pull. The solution was much like the description of a rocket nozzle in which the constriction in the flow is analogous to the effect of gravity. Parker predicted the Sun's atmosphere would behave just as this particular solar-wind solution predicts rather than according to the solar-breeze solutions suggested by others. The interplanetary satellite probes of the 1960s proved his solution to be correct.

Interaction of the solar wind and the magnetosphere

The solar wind is a collisionless plasma made up primarily of electrons and protons and carries an outflow of matter moving at supersonic and super-Alfvénic speed. The wind takes with it an extension of the Sun's magnetic field, which is frozen into the highly conducting fluid. In the region of the Earth, the wind has an average speed of 400 kilometres per second; and, when it encounters the planet's magnetic field, a shock front develops, the pressures acting to compress the field on the side toward the Sun and elongate it on the nightside (in the Earth's lee away from the Sun). The Earth's magnetic field is therefore confined to a cavity called the magnetosphere, into which the direct entry of the solar wind is prohibited. This cavity extends for about 10 Earth radii on the Sun's side and about 1,000 Earth radii on the nightside.

Inside this vast magnetic field a region of circulating plasma is driven by the transfer of momentum from the solar wind. Plasma flows parallel to the solar wind on the edges of this region and back toward the Earth in its interior. The resulting system acts as a secondary magnetohydrodynamic generator (the primary one being the solar wind itself). Both generators produce potential on the order of 100,000 volts. The solar-wind potential appears across the polar caps of the Earth, while the magnetospheric potential appears across the auroral oval. The latter is the region of the Earth where energetic electrons and ions precipitate into the planet's atmosphere, creating a spectacular light show. This particle flux is energetic enough to act as a new source of plasmas even when the Sun is no longer shining. The auroral oval becomes a good conductor; and large electric currents flow along it, driven by the potential difference across the system. These currents commonly are on the order of 1,000,000 amperes.

The plasma inside the magnetosphere is extremely hot (1–10 million K) and very tenuous (1–10 particles per cubic centimetre). The particles are heated by a number of interesting plasma effects, the most curious of which is the auroral acceleration process itself. A particle accelerator that may be the prototype for cosmic accelerators throughout the universe is located roughly one Earth radius above the auroral oval and linked to it by all-important magnetic field lines. In this region the auroral electrons are boosted by a potential difference on the order of three to six kilovolts, most likely created by an electric field parallel to the magnetic field lines and directed away from the Earth. Such a field is difficult to explain because magnetic field lines usually act like nearly perfect conductors. The auroras occur on magnetic field lines that—if it were not for the distortion of the Earth's dipole field—would cross the equatorial plane at a distance of 6–10 Earth radii.

Closer to the Earth, within about 4 Earth radii, the planet wrests control of the system away from the solar wind. Inside this region the plasma rotates with the Earth, just as its atmosphere rotates with it. This system can also be thought of as a magnetohydrodynamic generator in which the rotation of the atmosphere and the ionospheric plasma in it create an electric field that puts the inner magnetosphere in rotation about the Earth's axis. Since this inner region is in contact with the dayside of the Earth where the Sun creates copious amounts of plasma in the ionosphere, the inner zone fills up with dense, cool plasma to form the plasmasphere. On a planet such as Jupiter, which has both a larger magnetic field and a higher rotation rate than the Earth, planetary control extends much farther from the surface.

The ionosphere and upper atmosphere

At altitudes below about 2,000 kilometres, the plasma is referred to as the ionosphere. Thousands of rocket probes have helped chart the vertical structure of this region of the atmosphere, and numerous satellites have provided latitudinal and longitudinal information. The ionosphere was discovered in the early 1900s when radio waves were found to propagate "over the horizon." If radio waves have frequencies near or below the plasma frequency, they cannot propagate throughout the plasma of the ionosphere and thus do not escape into space; they are instead either reflected or absorbed. At night the absorption is low since little plasma exists at the height of roughly 100 kilometres where absorption is greatest. Thus, the ionosphere acts as an effective mirror, as does the Earth's surface, and waves can be reflected around the entire planet much as in a waveguide. A great communications revolution was initiated by the wireless, which relied on radio waves to transmit audio signals. Development continues to this day with satellite systems that must propagate through the ionospheric plasma. In this case, the wave frequency must be higher than the highest plasma frequency in the ionosphere so that the waves will not be reflected away from the Earth.

The dominant ion in the upper atmosphere is atomic oxygen, while below about 200 kilometres molecular oxygen and nitric oxide are most prevalent. Meteor showers also provide large numbers of metallic atoms of elements such as iron, silicon, and magnesium, which become ionized in sunlight and last for long periods of time. These form vast ion clouds, which are responsible for much of the fading in and out of radio stations at night.

The lower atmosphere and surface of the Earth

A more normal type of cloud forms at the base of the Earth's plasma blanket in the summer polar mesosphere regions. Located at an altitude of 85 kilometres, such a cloud is the highest on Earth and can be seen only when darkness has just set in on the planet. Hence, clouds of this kind have been called noctilucent clouds. They are thought to be composed of charged and possibly dusty ice crystals that form in the coldest portion of the atmosphere at a temperature of 120 K. This unusual medium has much in common with dusty plasmas in planetary rings and other cosmic systems. Noctilucent clouds have been increasing in frequency throughout the 20th century and may be a forerunner of global change.

High-energy particles also exist in the magnetosphere. At about 1.5 and 3.5 Earth radii from the centre of the planet, two regions contain high-energy particles. These regions are the Van Allen radiation belts, named after the American scientist James Van Allen, who discovered them using radiation detectors aboard early spacecraft. The charged particles in the belts are trapped in the mirror system formed by the Earth's magnetic dipole field.

Plasma can exist briefly in the lowest regions of the Earth's atmosphere. In a lightning stroke an oxygen-nitrogen plasma is heated at approximately 20,000 K with an ionization of about 20 percent, similar to that of a laboratory arc. Although the stroke is only a few centimetres thick and lasts only a fraction of a second, tremendous energies are dissipated. A lightning flash between the ground and a cloud, on the average, consists of four such strokes in rapid succession. At all times, lightning is occurring somewhere on the Earth, charging the surface negatively with respect to the ionosphere by roughly 200,000 volts, even far from the nearest thunderstorm. If lightning ceased everywhere for even one hour, the Earth would discharge. An associated phenomenon is ball lightning. There are authenticated reports of glowing, floating, stable balls of light several tens of centimetres in diameter occurring at times of intense electrical activity in the atmosphere. On contact with an object, these balls release large amounts of energy. Although lightning balls are probably plasmas, so far no adequate explanation of them has been given.

Considering the origins of plasma physics and the fact that the universe is little more than a vast sea of plasma, it is ironic that the only naturally occurring plasmas at the surface of the Earth besides lightning are those to be found in ordinary matter. The free electrons responsible for electrical conduction in a metal constitute a plasma. Ions are fixed in position at lattice points, and so plasma behaviour in metals is limited to such phenomena as plasma oscillations and electron cyclotron waves (called helicon waves) in which the electron component behaves separately from the ion component. In semiconductors, on the other hand, the current carriers are electrons and positive holes, the latter behaving in the material as free positive charges of finite mass. By proper preparation, the number of electrons and holes can be made approximately equal so that the full range of plasma behaviour can be observed.

Magnetic fields

The importance of magnetic fields in astrophysical phenomena has already been noted. It is believed that these fields are produced by self-generating dynamos, although the exact details are still not fully understood. In the case of the Earth, differential rotation in its liquid conducting core causes the external magnetic dipole field (manifest as the North and South poles). Cyclonic turbulence in the liquid, generated by heat conduction and Coriolis forces (apparent forces accompanying all rotating systems, including the heavenly bodies), generates the dipole field from these loops.
Over geologic time, the Earth's field occasionally becomes small and then changes direction, the North Pole becoming the South Pole and vice versa. During the times in which the magnetic field is small, cosmic rays can more easily reach the Earth's surface and may affect life forms by increasing the rate at which genetic mutations occur.

Similar magnetic-field generation processes are believed to occur in both the Sun and the Milky Way Galaxy. In the Sun the circular internal magnetic field is made observable by lines of force apparently breaking the solar surface to form exposed loops; entry and departure points are what are observed as sunspots. Although the exterior magnetic field of the Earth is that of a dipole, this is further modified by currents in both the ionosphere and magnetosphere. Lunar and solar tides in the ionosphere lead to motions across the Earth's field that produce currents, like a dynamo, that modify the initial field. The auroral oval current systems discussed earlier create even larger magnetic-field fluctuations. The intensity of these currents is modulated by the intensity of the solar wind, which also induces or produces other currents in the magnetosphere. Such currents taken together constitute the essence of a magnetic storm.

Ionization

ionization, in chemistry and physics, any process by which electrically neutral atoms or molecules are converted to electrically charged atoms or molecules (ions) through gaining or losing electrons. Ionization is one of the principal ways that radiation, such as charged particles and X rays, transfers its energy to matter.

In chemistry, ionization often occurs in a liquid solution. For example, neutral molecules of hydrogen chloride gas, HCl, react with similarly polar water molecules, H_2O, to produce positive hydronium ions, H_3O^+, and negative chloride ions, Cl^-. At the surface of a piece of metallic zinc in contact with an acidic solution, zinc atoms, Zn, lose electrons to hydrogen ions and become colourless zinc ions, Zn^{2+}.

Ionization by collision occurs in gases at low pressures when an electric current is passed through them. If the electrons constituting the current have sufficient energy (the ionization energy is different for each substance), they force other electrons out of the neutral gas molecules, producing ion pairs that individually consist of the resultant positive ion and detached negative electron. Negative ions are also formed as some of the electrons attach themselves to neutral gas molecules. Gases may also be ionized by intermolecular collisions at high temperatures.

Ionization, in general, occurs whenever sufficiently energetic charged particles or radiant energy travel through gases, liquids, or solids. Charged particles, such as alpha particles and electrons from radioactive materials, cause extensive ionization along their paths. Energetic neutral particles, such as neutrons and neutrinos, are more penetrating and cause almost no ionization. Pulses of radiant energy, such as X-ray and gamma-ray photons, can eject electrons from atoms by the photoelectric effect to cause ionization. The energetic electrons resulting from the absorption of radiant energy and the passage of charged particles in turn may cause further ionization, called secondary ionization. A certain minimal level of ionization is present in Earth's atmosphere because of continuous absorption of cosmic rays from space and ultraviolet radiation from the Sun.

Gas

state of matter

gas, one of the three fundamental states of matter, with distinctly different properties from the liquid and solid states.

Structure

The remarkable feature of gases is that they appear to have no structure at all. They have neither a definite size nor shape, whereas ordinary solids have both a definite size and a definite shape, and liquids have a definite size, or volume, even though they adapt their shape to that of the container in which they are placed. Gases will completely fill any closed container; their properties depend on the volume of a container but not on its shape.

Kinetic-molecular picture

Gases nevertheless do have a structure of sorts on a molecular scale. They consist of a vast number of molecules moving chaotically in all directions and colliding with one another and with the walls of their container. Beyond this, there is no structure—the molecules are distributed essentially randomly in space, traveling in arbitrary directions at speeds that are distributed randomly about an average determined by the gas temperature. The pressure exerted by a gas is the result of the innumerable impacts of the molecules on the container walls and appears steady to human senses because so many collisions occur each second on all sections of the walls. More subtle properties such as heat conductivity, viscosity (resistance to flow), and diffusion are attributed to the molecules themselves carrying the mechanical quantities of energy, momentum, and mass, respectively. These are called transport properties, and the rate of transport is dominated by the collisions between molecules, which force their trajectories into tortuous shapes. The molecular collisions are in turn controlled by the forces between the molecules and are described by the laws of mechanics.

Thus, gases are treated as a large collection of tiny particles subject to the laws of physics. Their properties are attributed primarily to the motion of the molecules and can be explained by the kinetic theory of gases. It is not obvious that this should be the case, and for many years a static picture of gases was instead espoused, in which the pressure, for instance, was attributed to repulsive forces between essentially stationary particles pushing on the container walls. How the kinetic-molecular picture finally came to be universally accepted is a fascinating piece of scientific history and is discussed briefly below in the section Kinetic theory of gases. Any theory of gas behaviour based on this kinetic model must also be a statistical one because of the enormous numbers of particles involved. The kinetic theory of gases is now a classical part of statistical physics and is indeed a sort of miniature display case for many of the fundamental concepts and methods of science. Such important modern concepts as distribution functions, cross sections, microscopic reversibility, and time-reversal invariance have their historical roots in kinetic theory, as does the entire atomistic view of matter.

Numerical magnitudes

When considering various physical phenomena, it is helpful for one to have some idea of the numerical magnitudes involved. In particular, there are several characteristics whose values should be known, at least within an order of magnitude (a factor of 10), in order for one to obtain a clear idea of the nature of gaseous molecules. These features include the size, average speed, and intermolecular separation at ordinary temperatures and pressures. In addition, other important considerations are how many collisions a typical molecule makes in one second under these conditions and how far such a typical molecule travels before colliding with another molecule. It has been established that molecules have sizes on the order of a few angstrom units (1 Å = 10^{-8} centimetre [cm]) and that there are about 6 × 10^{23} molecules in one mole, which is defined as the amount of a substance whose mass in grams is equal to its molecular weight (e.g., 1 mole of water, H_2O, is 18.0152 grams). With this knowledge, one could calculate at least some of the gas values. It is interesting to see how the answers could be estimated from simple observations and then to compare the results to the accepted values that are based on more precise measurements and theories.

Intermolecular separation and average speed

One of the easiest properties to work out is the average distance between molecules compared to their diameter; water will be used here for this purpose. Consider 1 gram of H_2O at 100° C and atmospheric pressure, which are the normal boiling point conditions. The liquid occupies a volume of 1.04 cubic centimetres (cm^3); once converted to steam it occupies a volume of 1.67 × 10^3 cm^3. Thus, the average volume occupied by one molecule in the gas is larger than the corresponding volume occupied in the liquid by a factor of 1.67 × 10^3/1.04, or about 1,600. Since volume varies as the cube of distance, the ratio of the mean separation distance in the gas to that in the liquid is roughly equal to the cube root of 1,600, or about 12. If the molecules in the liquid are considered to be touching each other, the ratio of the intermolecular separation to the molecular diameter in ordinary gases is on the order of 10 under ordinary conditions. It should be noted that the actual separation and diameter cannot be determined in this way; only their ratio can be calculated.

It is also relatively simple to estimate the average speed of gas molecules. Consider a sound wave in a gas, which is just the propagation of a small pressure disturbance. If pressure is attributed to molecular impacts on a test surface, then surely a pressure disturbance cannot travel faster than the molecules themselves. In other words, the average molecular speed in a gas should be somewhat greater than the speed of sound in the gas. The speed of sound in air at ordinary temperatures is about 330 metres per second (m/s), so the molecular speed will be estimated here to be somewhat greater, say, about 5 × 10^4 centimetres per second (cm/s). This value depends on the particular gas and the temperature, but it will be sufficient for the kind of estimates sought here.

Mean-free path and collision rate

The average molecular speed, along with an observed rate of the diffusion of gases, can be used to estimate the length and tortuosity of the path traveled by a typical molecule. If a bottle of ammonia is opened in a closed room, at least a few minutes pass before the ammonia can be detected at a distance of just one metre. (Ammonia, NH_3, is a gas; the familiar bottle of "ammonia" typically seen is actually a solution of the gas in water.) Yet, if the ammonia molecules traveled directly to an observer at a speed somewhat faster than that of sound, the odour should be detectable in only a few milliseconds. The explanation for the discrepancy is that the ammonia molecules collide with many air molecules, and their paths are greatly distorted as a result. For a quantitative estimate of the diffusion time, a more controlled system must be considered, because even gentle stray air currents in a closed room greatly speed up the spreading of the ammonia. To eliminate the effect of such air currents, a closed tube—say, a glass tube one centimetre in diameter and one metre in length—can be used. A small amount of ammonia gas is released at one end, and both ends are then closed. In order to measure how long it takes for the ammonia to travel to the other end, a piece of moist red litmus paper might be used as a detector; it will turn blue when the ammonia reaches it. This process takes quite a long time—about several hours—because diffusion occurs at such a slow rate. In this case, the time will be taken to be approximately 3 hours, or roughly 10^4 seconds (s). During this time interval, a typical ammonia molecule actually travels a distance of $(5 \times 10^4 \text{ cm/s})(10^4 \text{ s}) = 5 \times 10^8$ cm = 5,000 kilometres (km), roughly the distance across the United States. In other words, such a molecule travels a total distance of five million metres in order to progress a net distance of only one metre.

The solution to a basic statistical problem can be used to estimate the number of collisions such a typical diffusing molecule experienced (N) and the average distance traveled between collisions (l), called the mean free path. The product of N and l must equal the total distance traveled—i.e., $Nl = 5 \times 10^8$ cm. This distance can be thought of as a chain 5,000 km long, made up of N links, each of length l. The statistical question then is as follows: If such a chain is randomly jumbled, how far apart will its ends be on the average? This end-to-end distance corresponds to the length of the diffusion tube (one metre). This is a venerable statistical problem that recurs in many applications. One of the more vivid ways of illustrating the concept is known as the “drunkard’s walk.” In this scenario a drunkard takes steps of length l but, because of inebriation, takes them in random directions. After N steps, how far will he be from his starting point? The answer is that his progress is proportional not to N but to $N^{1/2}$. For example, if the drunkard takes four steps, each of length l, he will end up at a distance of $2l$ from his starting point. Gas molecules move in three dimensions, whereas the drunkard moves in two dimensions; however, the result is the same. Thus, the square root of N multiplied by the length of the mean free path equals the length of the diffusion tube: $N^{1/2}l = 10^2$ cm. From the equations for Nl and $N^{1/2}l$, it can readily be calculated that $N = 2.5 \times 10^{13}$ collisions and $l = 2.0 \times 10^{-5}$ cm. The mean time between collisions, τ, is found by dividing the time of the diffusion experiment by the number of collisions during that time: $\tau = (10^4)/(2.5 \times 10^{13}) = 4 \times 10^{-10}$ seconds between collisions, corresponding to a collision frequency of 2.5×10^9 collisions per second. It is thus understandable that gases appear to be continuous fluids on ordinary scales of time and distance.

Molecular sizes

Molecular sizes can be estimated from the foregoing information on the intermolecular separation, speed, mean free path, and collision rate of gas molecules. It would seem logical that large molecules should have a better chance of colliding than do small molecules. The collision frequency and mean free path must therefore be related to molecular size. To find this relationship, consider a single molecule in motion; during a time interval t it will sweep out a certain volume, hitting any other molecules present in this so-called collision volume. If molecules are located by their centres and each molecule has a diameter d, then the collision volume will be a long cylinder of cross-sectional area πd^2. The cylinder must be sufficiently long to include enough molecules so that good statistics on the number of collisions are obtained, but otherwise the length does not matter. If the molecule is observed for a time t, then the length of the collision cylinder will be $\bar{v}t$, where $\bar{v}$ is the average speed of the molecule, and the volume of the cylinder will be $(\pi d^2)(\bar{v}t)$, the product of its cross-sectional area and its length. Every molecule in the cylinder will be struck within time t, so the number of molecules in the collision cylinder will equal the number of collisions that occur in time t. Each collision will put a kink in the cylinder, but this will not affect the results as long as the number of collisions is not too large. If the gas is uniform, the number of molecules per volume will be consistent throughout the entire gas. Suppose that there are N molecules in volume V; then there will be $(N/V)(\pi d^2)(\bar{v}t)$ molecules in the collision volume; this is the number of collisions in time t. The mean free path is equal to the total length of the collision cylinder divided by the number of collisions that occur in it:

$$l = \frac{(\bar{v}t)}{(N/V)(\pi d^2)(\bar{v}t)} = \frac{1}{(N/V)(\pi d^2)}.$$

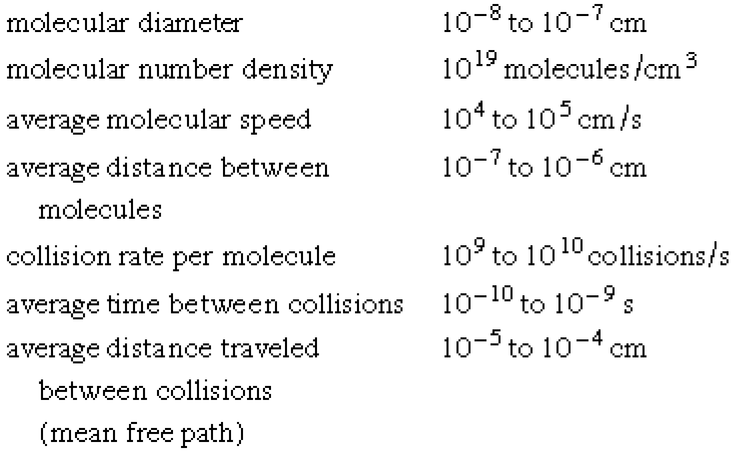
Since l has been shown to be roughly 2.0×10^{-5} cm, d could be calculated if N/V was known.

It is relatively easy to find $(N/V)d^3$, from which both d and N/V can be determined. Recall that the volume of one gram of steam is about 1,600 times larger than the volume of one gram of liquid water. In other words, there are roughly 1,600 N molecules in a volume V of liquid, and, if the molecules are just touching (i.e., the separation distance between their centres is one molecular diameter), the volume V of the liquid is 1,600 Nd^3. When this equation for volume is combined with the above expression for l, the following values are obtained: $d = \pi(2.0 \times 10^{-5})/1{,}600 = 3.9 \times 10^{-8}$ cm = 3.9 Å, and $N/V = 1/\pi d^2 l = 1.0 \times 10^{19}$ molecules per cubic centimetre. Thus, a typical molecule is exceedingly small, and there is an impressively large number of them in one cubic centimetre of gas.

Between collisions, a gas molecule travels a distance of about $l/d = (2.0 \times 10^{-5})/(3.9 \times 10^{-8}) = 500$ times its diameter. Since it was calculated above that the average separation between molecules is about 10 times the molecular diameter, the mean free path is approximately 50 times greater than the mean molecular separation. Accordingly, a typical molecule passes roughly 50 other molecules before it hits one.

Summary of numerical magnitudes

The following is a summary of the above estimates of molecular quantities in a gas, with a little spread in the numbers to allow for molecules both smaller and larger than the typical ones used here—which are H_2O, NH_3, and the nitrogen (N_2) plus oxygen (O_2) mixture that is air—and to allow for the fact that some of these quantities depend on temperature and pressure. It is important to note that these estimates and calculations are rather simplified, although fundamentally correct, and that there may well be missing factors such as 3π/8 or Square root of$\sqrt{2}$. The numerical estimates for gases at ordinary pressure and temperature are:



molecular diameter	10^{-8} to 10^{-7} cm
molecular number density	10^{19} molecules/cm^3
average molecular speed	10^{4} to 10^{5} cm/s
average distance between molecules	10^{-7} to 10^{-6} cm
collision rate per molecule	10^{9} to 10^{10} collisions/s
average time between collisions	10^{-10} to 10^{-9} s
average distance traveled between collisions (mean free path)	10^{-5} to 10^{-4} cm

The general impression of gas molecules given by these numbers is that they are exceedingly small, that there are enormous numbers of them in even one cubic centimetre, that they are moving very fast, and that they collide many times in one second. Two other facts are especially important. The first is that the lengths involved, especially the mean free path, are minute compared with ordinary lengths, even with the diameter of a capillary tube. This means that gas behaviour and properties are dominated by collisions between molecules and that collisions with walls play only a secondary (though important) role. The second is that the mean free path is much larger than the molecular diameter. Thus, collisions between pairs of molecules are of paramount importance in determining ordinary gas behaviour, while collisions that involve three or more molecules at the same time can basically be ignored.

A cautious reader might feel a bit uneasy about the glibness of the preceding estimates, so a simple check will be made here by calculating the number of molecules in one mole of gas, a quantity known as Avogadro’s number. The number density of a gas was approximated to be about 1.0 × 10^{19} molecules per cubic centimetre, and from experiment it is known that 1 mole of gas occupies a volume of about 25 litres (2.5 × 10^{4} cubic centimetres) under ordinary conditions. Using these values, an estimate of Avogadro’s number is (1.0 × 10^{19})(2.5 × 10^{4}) = 2.5 × 10^{23} molecules per mole. This deviates somewhat from the accepted value of 6.022 × 10^{23} molecules per mole, but the order of magnitude is certainly correct. In point of historical fact, a value for Avogadro’s number as good as this estimate was not obtained until 1865, when Josef Loschmidt in Vienna made a calculation similar to the one here but based on gas viscosity rather than on gas diffusion. In the older German scientific literature, Avogadro’s number is often referred to as Loschmidt’s number for this reason. In current English-language scientific literature, Loschmidt’s number is usually taken to mean the number of gas molecules in one cubic centimetre at 0° C and one atmosphere pressure (2.687 × 10^{19} molecules per cubic centimetre).

There are other ways by which molecular sizes and Avogadro’s number could have been estimated, such as from the spreading of a surface oil film on water or from the surface tension and the energy of evaporation of a liquid, but they will not be discussed here.

The foregoing picture of a gas as a collection of molecules dominated by binary molecular collisions is in reality only a limited view. Two limitations of the model are briefly discussed below.

Free-molecule gas

The mean free path in a gas may easily be increased by decreasing the pressure. If the pressure is halved, the mean free path doubles in length. Thus, at low enough pressures the mean free path can become sufficiently large that collisions of the gas molecules with surfaces become more important than collisions with other gas molecules. In such a case, the molecules can be envisioned as moving freely through space until they encounter some solid surface; hence, they are termed free-molecule gases. Such gases are sometimes called Knudsen gases, after the Danish physicist Martin Knudsen, who studied them experimentally. Many of their properties are strikingly different from those of ordinary gases (also known as continuum gases). A radiometer is a four-vaned mill that depends essentially on free-molecule effects. A temperature difference in the free-molecule gas causes a thermomolecular pressure difference that drives the vanes. The radiometer will stop spinning if enough air leaks into its glass envelope. (It will also stop spinning if all the air is removed from the envelope.) The flight of objects at high altitudes, where the mean free path is very long, is also subject to free-molecule effects. Such effects can even occur at ordinary pressures if a significant physical dimension becomes small enough. Important examples are found in many chemical process industries, where reactions are forced by catalysts to proceed at reasonable speeds. Many of these catalysts are porous materials whose pore sizes are smaller than molecular mean free paths. The speed of the desired chemical reaction may be controlled by how fast the reactant gases diffuse into the porous catalyst and by how fast the product gases can diffuse out so more reactants can enter the pores.

There is a large transition region between free-molecule behaviour and continuum behaviour, where both molecule-molecule and molecule-surface collisions are significant. This region is rather difficult to describe theoretically and remains an active field of research.

Continuity of gaseous and liquid states

It may be somewhat surprising to learn that there is no fundamental distinction between a gas and a liquid. It was noted above that a gas occupies a volume about 1,600 times greater than that of an equal weight of liquid. The question arises as to the behaviour of a gas that has been compressed to 1/1,600 of its volume by application of sufficiently high pressure. If this compression is carried out above a specific temperature called the critical temperature, which is different for each gas, no phase change occurs, and the resulting substance is a gas that is just as dense as a liquid. If the compression is carried out at a fixed temperature below the critical temperature, an astonishing phenomenon occurs—at a particular pressure liquid suddenly forms. Attempts to compress the gas further simply increase the amount of liquid present and decrease the amount of gas, with the pressure remaining constant until all the gas has been converted to liquid. The applied pressure must subsequently rise a great deal to reduce the volume further, since liquids are much less compressible than gases.

The abrupt condensation of a gas to a liquid usually does not seem astonishing because it is so commonplace—nearly everyone has boiled water, for example, which is the reverse process. From the standpoint of the kinetic-molecular theory of gases, however, it is something of a mystery. Why does it occur so abruptly and only at temperatures below a critical temperature? Equations have been written down that describe condensation, but an explanation is still lacking in the sense that no one has been able to show that it must occur, given only the forces between the molecules and the fact that their motion is described by ordinary mechanics. Condensation, which is an example of a first-order phase transition, remains one of the outstanding unsolved problems of statistical physics.

The critical temperature marks the separation between an abrupt change and a continuous change. Other peculiar phenomena occur near the critical temperature. The densities of the coexisting liquid and gas (which is usually called a vapour in this case) become closer as the critical temperature is approached from below, and at the critical temperature they are identical. There is a unique point for every fluid, called the critical point. It is described by a critical temperature, a critical volume, and a critical pressure, at which liquid and vapour become identical. Above that temperature there is no distinction between gas and liquid; there is only a single fluid. Moreover, it is possible to pass continuously from an apparently definite gas or vapour to an apparently definite liquid with no abrupt condensation occurring. This can be accomplished by heating the vapour above the critical temperature while keeping the volume constant, then compressing it to a high density characteristic of a liquid, and finally cooling it at constant volume to its original temperature, where it is now clearly a liquid.

In short, gases and liquids are just the extreme stages of a fluid, with no fundamental distinction between the two. For this reason, an arbitrary decision has been made for the present discussion to define what is meant by the gaseous state. The definition will be based on the number density (i.e., molecules per unit volume): the number density of the fluid must be low enough that only collisions between two molecules at a time need to be considered. More specifically, the mean free path must be much larger than the molecular diameter. Such a fluid shall be termed a dilute gas.

A few brief historical remarks are in order before leaving the subject of the continuity of the gaseous and liquid states. The first extensive experimental study that clearly demonstrated the phenomena involved was performed on carbon dioxide, CO_2. (Carbon dioxide, whose solid form is called dry ice, has a critical temperature of 31° C.) The experiment was conducted by Thomas Andrews at what is now the Queen's University of Belfast in Northern Ireland, and its results were summarized in 1869 in a Bakerian lecture to the Royal Society of London entitled "On the Continuity of the Gaseous and Liquid States of Matter." In 1873 a Dutch thesis was presented to the University of

Leiden by Johannes D. van der Waals with virtually the same title (but in Dutch) as Andrews' lecture. In his study van der Waals used some ingenious approximations to obtain a simple equation relating the pressure, temperature, and molar volume of a fluid, based on a model that considered molecules as hard spheres with weak long-range attractive forces between them. This equation can be used to locate the critical point of a system, and it is also consistent with the occurrence of condensation when supplemented with a thermodynamic condition. This is possibly one of the most-quoted but little-read theses in science. Nevertheless, van der Waals started a scientific trend that continues to the present. His pressure-volume-temperature relation, called an equation of state, is the standard equation of state for real gases in physical chemistry, and at least one new equation of state is proposed every year in an attempt to improve on its quantitative accuracy (which is not very good). It furnished the impetus for the development of theories of liquids and of solutions. The equation is compatible with a unifying idea called the principle of corresponding states. This principle states that, if the pressure (p), volume (V), and temperature (T) of a gas are replaced, respectively, with the corresponding reduced variables—i.e., the pressure divided by the critical pressure (p/p_c), the volume divided by the critical volume (V/V_c), and the temperature divided by the critical temperature (T/T_c)—all gases will behave in essentially the same manner.

The critical point has itself proved to be a rich and deep subject. The gas-liquid critical point turns out to be only one of many types of critical points, including those of a magnetic variety, with the common feature that long-range correlations develop regardless of the molecular details of the system. That is, any small part of a system near its critical point seems to "know" what quite distant parts are doing. The mathematical description of the behaviour of a system near its critical point also becomes rather unusual.

Behaviour and properties

The enormous number of molecules in even a small volume of a dilute gas produces not complication, as might be expected, but rather simplification. The reason is that ordinarily only statistical averages are observed in the study of the behaviour and properties of gases, and statistical methods are quite accurate when large numbers are involved. Compared to the numbers of molecules involved, there are only a few properties of gases that warrant attention here, namely, pressure, density, temperature, internal energy, viscosity, heat conductivity, and diffusivity. (More subtle properties can be brought into view by the application of electric and magnetic fields, but they are of minor interest.)

It is a remarkable fact that these properties are not independent. If two are known, the rest can be determined from them. That is to say, for a given gas, the specification of only two properties—usually chosen to be temperature and density or temperature and pressure—fixes all the others. Thus, if the temperature and density of carbon dioxide are specified, the gas can have only one possible pressure, one internal energy, one viscosity, and so on. In order to determine the values of these other properties, they must either be measured or calculated from the known properties of the molecules themselves. Such calculations are the ultimate goal of statistical mechanics and kinetic theory, and dilute gases constitute the case for which the most progress toward that goal has been made.

In discussing the behaviour of gases, it is useful to separate the equilibrium properties and the nonequilibrium transport properties. By definition, a system in equilibrium can undergo no net change unless some external action is performed on it (e.g., pushing in a piston or adding heat). Its behaviour is steady with time, and no changes appear to be occurring, even though the molecules are in ceaseless motion. In contrast, the nonequilibrium properties describe how a system responds to some external action, such as the imposition of a temperature or pressure difference. Equilibrium behaviour is much easier to analyze, because any change that occurs on the molecular level must be compensated by some other change or changes on the molecular level in order for the system to remain in equilibrium.

Equilibrium properties

Ideal gas equation of state

Among the most obvious properties of a dilute gas, other than its low density compared with liquids and solids, are its great elasticity or compressibility and its large volume expansion on heating. These properties are nearly the same for all dilute gases, and virtually all such gases can be described quite accurately by the following universal equation of state: $pv = RT.$ (15)

This expression is called the ideal, or perfect, gas equation of state, since all real gases show small deviations from it, although these deviations become less significant as the density is decreased. Here *p* is the pressure, *v* is the volume per mole, or molar volume, *R* is the universal gas constant, and *T* is the absolute thermodynamic temperature. To a rough degree, the expression is accurate within a few percent if the volume is more than 10 times the critical volume; the accuracy improves as the volume increases. The expression eventually fails at both high and low temperatures, owing to ionization at high temperatures and to condensation to a liquid or solid at low temperatures.

The ideal gas equation of state is an amalgamation of three ideal gas laws that were formulated independently. The first is Boyle's law, which refers to the elastic properties of the gas; it was described by the Anglo-Irish scientist Robert Boyle in 1662 in his famous " . . . Experiments . . . Touching the Spring of the Air . . . ." It states that the volume of a gas at constant temperature is inversely proportional to the pressure; i.e., if the pressure on a gas is doubled, for example, its volume decreases by one-half. The second, usually called Charles's law, is concerned with the thermal expansion of the gas. It is named in honour of the French experimental physicist Jacques-Alexandre-César Charles for the work he carried out in about 1787. The law states that the volume of a gas at constant pressure is directly proportional to the absolute temperature; i.e., an increase of temperature of 1° C at room temperature causes the volume to increase by about 1 part in 300, or 0.3 percent. The third law embodied in equation (15) is based on the 1811 hypothesis of the Italian scientist Amedeo Avogadro—namely, that equal volumes of gases at the same temperature and pressure contain equal numbers of particles. The number of particles (or molecules) is proportional to the number of moles n, the constant of proportionality being Avogadro's number, N_0. Thus, at constant temperature and pressure the volume of a gas is proportional to the number of moles. If the total volume V contains n moles of gas, then only $v = V/n$ appears in the equation of state. By measuring the quantity of gas in moles rather than grams, the constant R is made universal; if mass were measured in grams (and hence v in volume per gram), then R would have a different value for each gas.

The ideal gas law is easily extended to mixtures by letting n represent the total number of moles of all species present in volume V. That is, if there are n_1 moles of species 1, n_2 moles of species 2, etc., in the mixture, then $n = n_1 + n_2 + \cdots$ and $v = V/n$ as before. This result can also be rewritten and reinterpreted in terms of the partial pressures of the different species, such that $p_1 = n_1RT/V$ is the partial pressure of species 1 and so on. The total pressure is then given as $p = p_1 + p_2 + \cdots$. This rule is known as Dalton's law of partial pressures in honour of the British chemist and physicist John Dalton, who formulated it about 1801.

A brief aside on units and temperature scales is in order. The (metric) unit of pressure in the scientific international system of units (known as the SI system) is newton per square metre (N/m^2), where one newton (N) is the force that gives a mass of one kilogram an acceleration of 1 m/s^2. The unit N/m^2 is given the name pascal (Pa), where one standard atmosphere is exactly 101,325 Pa (approximately 14.7 pounds per square inch). The unit of volume in the SI system is the cubic metre (1 m^3 = 10^6 cm^3), and the unit of temperature is the kelvin (K). The Kelvin thermodynamic temperature scale is defined through the laws of thermodynamics so as to be absolute or universal, in the sense that its definition does not depend on the specific properties of any particular kind of matter. Its numerical values, however, are assigned by defining the triple point of water—i.e., the unique temperature at which ice, liquid water, and water vapour are all in equilibrium—to be exactly 273.16 K. The freezing point of water under one atmosphere of air then turns out to be (by measurement) 273.1500 K. The freezing point is 0° on the Celsius scale (or 32° on the Fahrenheit scale), by definition. The precise thermodynamic definition of the Kelvin scale and the rather peculiar number chosen to define its numerical values (i.e., 273.16) are historical choices made so that the ideal gas equation of state will have the simple mathematical form given by the right-hand side of equation (15).

The gas constant R is determined by measurement. The best value so far obtained is that of the U.S. National Institute of Standards and Technology—namely, 8.3144621 J/mol · K. Here the unit J is one of work or energy, one joule (J) being equal to one newton-metre.

Internal energy

Once the equation of state is known for an ideal gas, only its internal energy, *E*, needs to be determined in order for all other equilibrium properties to be deducible from the laws of thermodynamics. That is to say, if the equation of state and the internal energy of a fluid are known, then all the other thermodynamic properties (e.g., enthalpy, entropy, and free energy) are fixed by the condition that it must be impossible to construct perpetual motion machines from the fluid. Proofs of such statements are usually rather subtle and involved and constitute a large part of the subject of thermodynamics, but conclusions based on thermodynamic principles are among the most reliable results of science.

A thermodynamic result of relevance here is that the ideal gas equation of state requires that the internal energy depend on temperature alone, not on pressure or density. The actual relationship between *E* and *T* must be measured or calculated from known molecular properties by means of statistical mechanics. The internal energy is not directly measurable, but its behaviour can be determined from measurements of the molar heat capacity (i.e., the specific heat) of the gas. The molar heat capacity is the amount of energy required to raise the temperature of one mole of a substance by one degree; its units in the SI system are J/mol · K. A system with many kinds of motion on a molecular scale absorbs more energy than one with only a few kinds of motion. The interpretation of the temperature dependence of *E* is particularly simple for dilute gases, as is shown in the discussion of the kinetic theory of gases below. The following highlights only the major aspects.

Every gas molecule moves in three-dimensional space, and this translational motion contributes (3/2)*RT* (per mole) to the internal energy *E*. For monatomic gases, such as helium, neon, argon, krypton, and xenon, this is the sole energy contribution. Gases that contain two or more atoms per molecule also contribute additional terms because of their internal motions: $E\ (\text{per mole}) = \frac{3}{2}RT + E_{int},\qquad (16)$ where E_{int} may include contributions from molecular rotations and internal vibrations and occasionally from internal electronic excitations. Some of these internal motions may not contribute at ordinary temperatures because of special conditions imposed by quantum mechanics, however, so that the temperature dependence of E_{int} can be rather complex.

The extension to gas mixtures is straightforward—the total internal energy *E* (per mole) is the weighted sum of the internal energies of each of the species: $nE = n_1E_1 + n_2E_2 + \cdots$, where $n = n_1 + n_2 + \cdots$.

It is the task of the kinetic theory of gases to account for these results concerning the equation of state and the internal energy of dilute gases.

Transport properties

The following is a summary of the three main transport properties: viscosity, heat conductivity, and diffusivity. These properties correspond to the transfer of momentum, energy, and matter, respectively.

Viscosity

All ordinary fluids exhibit viscosity, which is a type of internal friction. A continuous application of force is needed to keep a fluid flowing, just as a continuous force is needed to keep a solid body moving in the presence of friction. Consider the case of a fluid slowly flowing through a long capillary tube. A pressure difference of Δp must be maintained across the ends to keep the fluid flowing, and the resulting flow rate is proportional to Δp. The rate is inversely proportional to the viscosity (η) since the friction that opposes the flow increases as η increases. It also depends on the geometry of the tube, but this effect will not be considered here. The SI units of η are N · s/m² or Pa · s. An older unit of the centimetre-gram-second version of the metric system that is still often used is the poise (1 Pa · s = 10 poise). At 20° C the viscosity of water is 1.0×10^{-3} Pa · s and that of air is 1.8×10^{-5} Pa · s. To a rough approximation, liquids are about 100 times more viscous than gases.

There are three important properties of the viscosity of dilute gases that seem to defy common sense. All can be explained, however, by the kinetic theory (see below Kinetic theory of gases). The first property is the lack of a dependence on pressure or density. Intuition suggests that gas viscosity should increase with increasing density, inasmuch as liquids are much more viscous than gases, but gas viscosity is actually independent of density. This result can be illustrated by a pendulum swinging on a solid support. It eventually slows down owing to the viscous friction of the air. If a bell jar is placed over the pendulum and half the air is pumped out, the air remaining in the jar damps the pendulum just as fast as a full jar of air would have done. Robert Boyle noted this peculiar phenomenon in 1660, but his results were largely either ignored or forgotten. The Scottish chemist Thomas Graham studied the flow of gases through long capillaries, which he called transpiration, in 1846 and 1849, but it was not until 1877 that the German physicist O.E. Meyer pointed out that Graham's measurements had shown the independence of viscosity on density. Prior to Meyer's investigations, the kinetic theory had suggested the result, so he was looking for experimental proof to support the prediction. When James Clerk Maxwell discovered (in 1865) that his kinetic theory suggested this result, he found it difficult to believe and attempted to check it experimentally. He designed an oscillating disk apparatus (which is still much copied) to verify the prediction.

The second unusual property of viscosity is its relationship with temperature. One might expect the viscosity of a fluid to increase as the temperature is lowered, as suggested by the phrase "as slow as molasses in January." The viscosity of a dilute gas behaves in exactly the opposite way: the viscosity increases as the temperature is raised. The rate of increase varies approximately as T^s, where s is between 1/2 and 1, and depends on the particular gas. This behaviour was clearly established in 1849 by Graham.

The third property pertains to the viscosity of mixtures. A viscous syrup, for example, can be made less so by the addition of a liquid with a lower viscosity, such as water. By analogy, one would expect that a mixture of carbon dioxide, which is fairly viscous, with a gas like hydrogen, which is much less viscous, would have a viscosity intermediate to that of carbon dioxide and hydrogen. Surprisingly, the viscosity of the mixture is even greater than that of carbon dioxide. This phenomenon was also observed by Graham in 1849.

Finally, there is no obvious correlation of gas viscosity with molecular weight. Heavy gases are often more viscous than light gases, but there are many exceptions, and no simple pattern is apparent.

Heat conduction

If a temperature difference is maintained across a fluid, a flow of energy through the fluid will result. The energy flow is proportional to the temperature difference according to Fourier's law, where the constant of proportionality (aside from the geometric factors of the apparatus) is called the heat conductivity or thermal conductivity of the fluid, λ. Mechanisms other than conduction can transport energy, in particular convection and radiation; here it is assumed that these can be eliminated or adjusted for. The SI units for λ are J/m · s · K or watt per metre degree (W/m · K), but sometimes calories are used for the energy term instead of joules (one calorie = 4.184 J). At 20° C the thermal conductivity of water is 0.60 W/m · K, and that of many organic liquids is roughly only one-third as large. The thermal conductivity of air at 20° C is only about 2.5×10^{-2} W/m · K. To a rough approximation, liquids conduct heat about 10 times better than do gases.

The properties of the thermal conductivity of dilute gases parallel those of viscosity in some respects. The most striking is the lack of dependence on pressure or density. Based on this fact, there seems to be no advantage to pumping out the inner chambers of thermos bottles. As far as conduction is concerned, it does not provide any benefits until practically all the air has been removed and free-molecule conduction is occurring. Convection, however, does depend on density, so some degree of insulation is provided by pumping out only some of the air.

The thermal conductivity of a dilute gas increases with increasing temperature, much like its viscosity. In this case, such behaviour does not seem particularly odd, probably because most people do not have a preconceived idea of how thermal conductivity should behave, unlike the situation with viscosity.

There are some differences in the behaviour of thermal conductivity and viscosity; one of the most notable has to do with mixtures. At first glance the thermal conductivity of a gaseous mixture seems to be as expected, since it falls between the conductivities of its components, but a closer look reveals an odd regularity. The conductivity of the mixture is always less than an average based on the number of moles (or molecules) of each component in the mixture. This appears to be related to the different effect that molecular weight has on thermal conductivity and viscosity. Light gases are usually better conductors than are heavy gases, whereas heavy gases are often (but not always) more viscous than are light gases. There also seems to be some correlation between molar heat capacity and thermal conductivity. The foregoing properties of thermal conductivity pose more puzzles that the kinetic theory of gases must address.

Diffusion

Diffusion in dilute gases is in some ways more complex, or at least more subtle, than either viscosity or thermal conductivity. First, a mixture is necessarily involved, inasmuch as a gas diffusing through itself makes no sense physically unless the molecules are in some way distinguishable from one another. Second, diffusion measurements are rather sensitive to the details of the experimental conditions. This sensitivity can be illustrated by the following considerations.

Light molecules have higher average speeds than do heavy molecules at the same temperature. This result follows from kinetic theory, as explained below, but it can also be seen by noting that the speed of sound is greater in a light gas than in a heavy gas. This is the basis of the well-known demonstration that breathing helium causes one to speak with a high-pitched voice. If a light and a heavy gas are interdiffusing, the light molecules should move into the heavy-gas region faster than the heavy molecules move into the light-gas region, thereby causing the pressure to rise in the heavy-gas region. If the diffusion takes place in a closed vessel, the pressure difference drives the heavy gas into the light-gas region at a faster rate than it would otherwise diffuse, and a steady state is quickly reached in which the number of heavy molecules traveling in one direction equals, on the average, the number of light molecules traveling in the opposite direction. This method, called equimolar countercurrent diffusion, is the usual manner in which gaseous diffusion measurements are now carried out.

The steady-state pressure difference that develops is almost unmeasurably small unless the diffusion occurs through a fine capillary or a fine-grained porous material. Nevertheless, experimenters have been able to devise clever schemes either to measure it or to prevent its development. The first to do the latter was Graham in 1831; he kept the pressure uniform by allowing the gas mixture to flow. The results of this work now appear in elementary textbooks as Graham's law of diffusion. Most of these accounts are incorrect or incomplete or both, owing to the fact that the writers confuse the uniform-pressure experiment either with the equal countercurrent experiment or with the phenomenon of effusion (described below in the section Kinetic theory of gases). Graham also performed equal countercurrent experiments in 1863, using a long closed-tube apparatus he devised. This sort of apparatus is now usually called a Loschmidt diffusion tube after Loschmidt, who used a modified version of the tube in 1870 to make a series of accurate diffusion measurements on a number of gas pairs.

A quantitative description of diffusion follows. A composition difference in a two-component gas mixture causes a relative flow of the components that tends to make the composition uniform. The flow of one component is proportional to its concentration difference, and in an equal countercurrent experiment this is balanced by an equal and opposite flow of the other component. The constant of proportionality is the same for both components and is called the diffusion coefficient, D_{12}, for that gas pair. This relationship between the flow rate and the concentration difference is called Fick's law of diffusion. The SI units for the diffusion coefficient are square metres per second (m^2/s). Diffusion, even in gases, is an extremely slow process, as was pointed out above in estimating molecular sizes and collision rates. Gaseous diffusion coefficients at one atmosphere pressure and ordinary temperatures lie largely in the range of 10^{-5} to 10^{-4} m^2/s, but diffusion coefficients for liquids and solutions lie in the range of only 10^{-10} to 10^{-9} m^2/s. To a rough approximation, gases diffuse about 100,000 times faster than do liquids.

Diffusion coefficients are inversely proportional to total pressure or total molar density and are therefore reported by convention at a standard pressure of one atmosphere. Doubling the pressure of a diffusing mixture halves the diffusion coefficient, but the actual rate of diffusion remains unchanged. This seemingly paradoxical result occurs because doubling the pressure also doubles the concentration, according to the ideal gas equation of state, and hence doubles the concentration difference, which is the driving force for diffusion. The two effects exactly compensate.

Diffusion coefficients increase with increasing temperature at a rate that depends on whether the pressure or the total molar density is held constant as the temperature is changed. If the rate increases as T^s at constant molar density (where s usually lies between 1/2 and 1), then it will increase as T^{1+s} at constant pressure, according to the ideal gas equation of state.

Perhaps the most surprising property of gaseous diffusion coefficients is that they are virtually independent of the mixture's composition, varying by at most a few percent over the whole composition range, even for very dissimilar gases. A trace of hydrogen, for example, diffuses through carbon dioxide at virtually the same rate that a trace of carbon dioxide diffuses through hydrogen. Liquid mixtures do not behave this way, and liquid diffusion coefficients may vary by as much as a factor of 10 from one end of the composition range to the other. The lack of composition dependence of gaseous diffusion coefficients is one of the odder properties to be explained by kinetic theory.

Thermal diffusion

If a temperature difference is applied to a uniform mixture of two gases, the mixture will partially separate into its components, with the heavier, larger molecules usually (but not invariably) concentrating at the lower temperature. This behaviour was predicted theoretically before it was observed experimentally, but a rather elaborate explanation was required because simple theory suggests no such phenomenon. It was predicted in 1911–12 by David Enskog in Sweden and independently in 1917 by Sydney Chapman in England, but the validity of their theoretical results was questioned until Chapman (who was an applied mathematician) enlisted the aid of the chemist F.W. Dootson to verify it experimentally.

Thermal diffusion can be used to separate isotopes. The amount of separation for any reasonable temperature difference is quite small for isotopes, but the effect can be amplified by combining it with slow thermal convection in a columnar arrangement devised in 1938 by Klaus Clusius and Gerhard Dickel in Germany. While the apparatus is quite simple, the theory of its operation is not: a long cylinder with a diameter of several centimetres is mounted vertically with an electrically heated hot wire along its central axis. The thermal diffusion occurs horizontally between the hot wire and the cold wall of the cylinder, and the convection takes place vertically to bring new gas regions into contact.

There is also an effect that is the inverse of thermal diffusion, called the diffusion thermoeffect, in which an imposed concentration difference causes a temperature difference to develop. That is, a diffusing gas mixture develops small temperature differences, on the order of 1° C, which die out as the composition approaches uniformity. The transport coefficient describing the diffusion thermoeffect must be equal to the coefficient describing thermal diffusion, according to the reciprocal relations central to the thermodynamics of irreversible processes.

Kinetic theory of gases

The aim of kinetic theory is to account for the properties of gases in terms of the forces between the molecules, assuming that their motions are described by the laws of mechanics (usually classical Newtonian mechanics, although quantum mechanics is needed in some cases). The present discussion focuses on dilute ideal gases, in which molecular collisions of at most two bodies are of primary importance. Only the simplest theories are treated here in order to avoid obscuring the fundamental physics with complex mathematics.

Ideal gas

The ideal gas equation of state can be deduced by calculating the pressure as caused by molecular impacts on a container wall. The internal energy and Dalton's law of partial pressures also emerge from this calculation, along with some free-molecule phenomena. The calculation is significant because it is basically the same one used to explain all dilute-gas phenomena.

Pressure

Newton's second law of motion can be stated in not-so-familiar form as impulse equals change in momentum, where impulse is force multiplied by the time during which it acts. A molecule experiences a change in momentum when it collides with a container wall; during the collision an impulse is imparted by the wall to the molecule that is equal and opposite to the impulse imparted by the molecule to the wall. This is required by Newton's third law. The sum of the impulses imparted by all the molecules to the wall is, in effect, the pressure. Consider a system of molecules of mass m traveling with a velocity v in an enclosed container. In order to arrive at an expression for the pressure, a calculation will be made of the impulse imparted to one of the walls by a single impact, followed by a calculation of how many impacts occur on that wall during a time t. Although the molecules are moving in all directions, only those with a component of velocity toward the wall can collide with it; call this component v_z, where z represents the direction directly toward the wall. Not all molecules have the same v_z, of course; perhaps only N_z out of a total of N molecules do. To find the total pressure, the contributions from molecules with all different values of v_z must be summed. A molecule approaches the wall with an initial momentum mv_z, and after impact it moves away from the wall with an equal momentum in the opposite direction, $-mv_z$. Thus, the total change in momentum is $mv_z - (-mv_z) = 2mv_z$, which is equal to the total impulse imparted to the wall.

The number of impacts on a small area A of the wall in time t is equal to the number of molecules that reach the wall in time t. Since the molecules are traveling at speed v_z, only those within a distance v_zt and moving toward the wall will reach it in that time. Thus, the molecules that are traveling toward the wall and are within a volume Av_zt will strike the area A of the wall in time t. On the average, half of the molecules in this volume will be moving toward the wall. If N_z molecules with speed component v_z are present in the total volume V, then $(1/2)(N_z/V)(A)(v_zt)$ molecules in the collision volume will hit, and each one contributes an impulse of $2mv_z$. The total impulse in time t is therefore $(1/2)(N_z/V)(A)(v_zt)(2mv_z) = (N_z/V)(mv_z^2)(At)$, which is equal to Ft, where F is the force on the wall due to the impacts. Equating these two expressions, the time factor t cancels out. Since pressure is defined as the force per unit area (F/A), it follows that the contribution to the pressure from the molecules with speed v_z is thus $(N_z/V)mv_z^2$. Because there are different values of v_z^2 for different molecules, the average value, denoted v_z^2, is used to take into account the contributions from all the molecules. The pressure is thus given as $p = (N/V)mv_z^2$.

Since the molecules are in random motion, this result is independent of the choice of axis. For any choice of (x, y, z) axes, the magnitude of the velocity is $v^2 = v_x^2 + v_y^2 + v_z^2$ (which is just the Pythagorean theorem in three dimensions), and taking the average gives $v^2 = v_x^2 + v_y^2 + v_z^2$. The gas is in equilibrium, so it must appear the same in any direction, and the average velocities are therefore the same in all directions—i.e., $v_x^2 = v_y^2 = v_z^2$; thus $v^2 = 3v_z^2$. When the value $(1/3)v^2$ is substituted for v_z^2 in the expression for pressure, the following equation is obtained:

$$p = \frac{1}{3}\frac{N}{V}m\overline{v^2}, \quad \text{or} \quad pV = \frac{1}{3}Nm\overline{v^2}. \qquad (17)$$

To rewrite this in molar units, N is set equal to nN_o—i.e., the product of the number of moles n and Avogadro's number N_o—to give

$$pv = \frac{1}{3}M\overline{v^2}, \qquad (18)$$

where $M = N_om$ is the molecular weight of the gas and v is the volume per mole (V/n). Since the ideal gas equation of state relates pressure, molar volume, and temperature as $pv = RT$, the temperature T must be related to the average kinetic energy of the molecules as

$$\frac{1}{2}M\overline{v^2} = \frac{3}{2}RT. \qquad (19)$$

This expression is often written in molecular (rather than molar) terms as $(1/2)[mv^2] = (3/2)kT$, where $k = R/N_o$ is called Boltzmann's constant. If the gas is a mixture, the foregoing calculation shows that the impacts of the different species are simply added separately, and Dalton's law of partial pressures follows directly.

The energy law given as equation (16) also follows from equation (19): the kinetic energy of translational motion per mole is $(3/2)RT$. Any energy residing in the internal motions of the individual molecules is simply carried separately without contributing to the pressure.

Average molecular speeds can be calculated from the results of kinetic theory in terms of the so-called root-mean-square speed v_{rms}. The v_{rms} is the square root of the average of the squares of the speeds of the molecules: $(v^2)^{1/2}$. From equation (19) the v_{rms} is $(3RT/M)^{1/2}$. At 20° C the value for air ($M = 29$) is 502 m/s, a result very close to the rough estimate of 5×10^2 m/s given above.

Molecule-molecule collisions were not considered in the calculation of the expression for pressure even though many such collisions occur. Such collisions could be ignored because they are elastic; i.e., linear momentum is conserved in the collision, provided that no external forces act. Two molecules therefore continue to carry the same momentum to the wall even if they collide with one another before striking it. The ideal gas equation of state remains valid as the density is decreased, even holding for a free-molecule gas. The equation eventually fails as the density is increased, however, because other molecules exert forces and change the rate of collisions with the walls.

It was not until the mid- to late 19th century that kinetic theory was successfully applied to such calculations as gas pressure. Such notable scientists as Sir Isaac Newton and John Dalton had believed that gas pressure was caused by repulsions between molecules that pushed them against the container walls. For many reasons, the kinetic theory had overshadowed such static theories (and others such as vortex theories) by about 1860. It was not until 1875, however, that Maxwell actually proved that a static theory was in conflict with experiment.

Effusion

Consider the system described above in the calculation of gas pressure, but with the area A in the container wall replaced with a small hole. The number of molecules that escape through the hole in time t is equal to $(1/2)(N/V)v_z(At)$. In this case, collisions between molecules are significant, and the result holds only for tiny holes in very thin walls (as compared to the mean free path), so that a molecule that approaches near the hole will get through without colliding with another molecule and being deflected away. The relationship between v_z and the average speed $\bar{v}$ is rather straightforward: $v_z = (1/2)\bar{v}$.

If the rates for two different gases effusing through the same hole are compared, starting with the same gas density each time, it is found that much more light gas escapes than heavy gas and that more gas escapes at a high temperature than at a low temperature, other things being equal. In particular,

$$\frac{\text{effusion rate of gas 1}}{\text{effusion rate of gas 2}} = \frac{\bar{v}_1}{\bar{v}_2} = \left(\frac{m_2}{m_1}\right)^{1/2}\left(\frac{T_1}{T_2}\right)^{1/2}. \tag{20}$$

The last step follows from the energy formula, $(1/2)mv^2 = (3/2)kT$, where $(v^2)^{1/2}$ is approximated to be v, even though v^2 and $(\bar{v})^2$ actually differ by a numerical factor near unity (namely, $3\pi/8$). This result was discovered experimentally in 1846 by Graham for the case of constant temperature and is known as Graham's law of effusion. It can be used to measure molecular weights, to measure the vapour pressure of a material with a low vapour pressure, or to calculate the rate of evaporation of molecules from a liquid or solid surface.

Thermal transpiration

Suppose that two containers of the same gas but at different temperatures are connected by a tiny hole and that the gas is brought to a steady state. If the hole is small enough and the gas density is low enough that only effusion occurs, the equilibrium pressure will be greater on the high-temperature side. But, if the initial pressures on both sides are equal, gas will flow from the low-temperature side to the high-temperature side to cause the high-temperature pressure to increase. The latter situation is called thermal transpiration, and the steady-state result is called the thermomolecular pressure difference. These results follow simply from the effusion formula if the ideal gas law is used to replace N/V with p/T; $\frac{\text{effusion rate from container 1}}{\text{effusion rate from container 2}} = \frac{p_1}{p_2}\left(\frac{T_2}{T_1}\right)^{1/2}.$ (21)

When a steady state is reached, the effusion rates are equal, and thus

$$\frac{p_1}{p_2} = \left(\frac{T_1}{T_2}\right)^{1/2}. \qquad (22)$$

This phenomenon was first investigated experimentally by Osborne Reynolds in 1879 in Manchester, Eng. Errors can result if a gas pressure is measured in a vessel at very low or very high temperature by connecting it via a fine tube to a manometer at room temperature. A continuous circulation of gas can be produced by connecting the two containers with another tube whose diameter is large compared with the mean free path. The pressure difference drives gas through this tube by viscous flow. A heat engine based on this circulating flow unfortunately has a low efficiency.

Viscosity

The kinetic-theory explanation of viscosity can be simplified by examining it in qualitative terms. Viscosity is caused by the transfer of momentum between two planes sliding parallel to one another but at different rates, and this momentum is transferred by molecules moving between the planes. Molecules from the faster plane move to the slower plane and tend to speed it up, while molecules from the slower plane travel to the faster plane and tend to slow it down. This is the mechanism by which one plane experiences the drag of the other. A simple analogy is two mail trains passing each other, with workers throwing mailbags between the trains. Every time a mailbag from the fast-moving train lands on the slow one, it imparts its momentum to the slow train, speeding it up a little; likewise each mailbag from the slow train that lands on the fast one slows it down a bit.

If the trains are too far apart, the mailbags cannot be passed between them. Similarly, the planes of a gas must be only about a mean free path apart in order for molecules to pass between them without being deflected by collisions. If one uses this approach, a simple calculation can be carried out, much as in the case of the gas pressure, with the result that $\eta = a\frac{N}{V}\bar{v}lm,$ (23) where a is a numerical constant of order unity, the term

$(N/V)\bar{v}l$ is a measure of the number of molecules contained in a small counting cylinder, and the mass m is a measure of the momentum carried between the sliding planes. The cross-sectional area of the counting cylinder and the relative speed of the sliding planes do not appear in the equation because they cancel one another when the drag force is divided by the area and speed of the planes in order to find η.

It can now be seen why η is independent of gas density or pressure. The term (N/V) in equation (23) is the number of carriers of momentum, but l measures the number of collisions that interfere with these carriers and is inversely proportional to (N/V). The two effects exactly cancel each other. Viscosity increases with temperature because the average velocity $\bar{v}$ does; that is, momentum is carried more quickly when the molecules move faster. Although $\bar{v}$ increases as $T^{1/2}$, η increases somewhat faster because the mean free path also increases with temperature, since it is harder to deflect a fast molecule than a slow one. This feature depends explicitly on the forces between the molecules and is difficult to calculate accurately, as is the value of the constant a, which turns out to be close to 1/2.

The behaviour of the viscosity of a mixture can also be explained by the foregoing calculation. In a mixture of a light gas and a viscous heavy gas, both types of molecules have the same average energy; however, most of the momentum is carried by the heavy molecules, which are therefore the main contributors to the viscosity. The light molecules are rather ineffective in deflecting the heavy molecules, so that the latter continue to carry virtually as much momentum as they would in the absence of light molecules. The addition of a light gas to a heavy gas therefore does not reduce the viscosity substantially and may in fact increase it because of the small extra momentum carried by the light molecules. The viscosity will eventually decrease when there are only a few heavy molecules remaining in a large sea of light molecules.

The main dependence of η on the molecular mass is through the product $\bar{v}m$ in equation (23), which varies as $m^{1/2}$ since $\bar{v}$ varies as $1/m^{1/2}$. Owing to this effect, heavy gases tend to be more viscous than light gases, but this tendency is compensated for to some degree by the behaviour of l, which tends to be smaller for heavy molecules because they are usually larger than light molecules and therefore more likely to collide. The often confusing connection between viscosity and molecular weight can thus be accounted for by equation (23).

Finally, in a free-molecule gas there are no collisions with other molecules to impede the transport of momentum, and the viscosity thus increases linearly with pressure or density until the number of collisions becomes great enough so that the viscosity assumes the constant value given by equation (23). The nonideal behaviour of the gas that accompanies further increases in density eventually leads to an increase in viscosity, and the viscosity of an extremely dense gas becomes much like that of a liquid.

Thermal conductivity

The kinetic-theory explanation of heat conduction is similar to that for viscosity, but in this case the molecules carry net energy from a region of higher energy (i.e., temperature) to one of lower energy (temperature). Internal molecular motions must be accounted for because, though they do not transport momentum, they do transport energy. Monatomic gases, which carry only their kinetic energy of translational motion, are the simplest case. The resulting expression for thermal conductivity is

$$\lambda = a' \frac{N}{V} \bar{v} l \left(\frac{3}{2} k \right), \qquad (24)$$

which has the same basic form as equation (23) for viscosity, with $(3k/2)$ replacing m. The $(3k/2)$ is the heat capacity per molecule and is the conversion factor from an energy difference to a temperature difference.

It can be shown from equation (24) that the independence of density and the increase with temperature is the same for thermal conductivity as it is for viscosity. The dependence on molecular mass is different, however, with λ varying as $1/m^{1/2}$ owing to the factor $\bar{v}$. Thus, light gases tend to be better conductors of heat than are heavy gases, and this tendency is usually augmented by the behaviour of l.

The behaviour of the thermal conductivity of mixtures may be qualitatively explained. Adding heavy gas to light gas reduces the thermal conductivity because the heavy molecules carry less energy and also interfere with the energy transport of the light molecules.

The similar behaviour of λ and η suggests that their ratio might provide information about the constants a and a'. The ratio of a'/a is given as

$$\frac{\lambda}{\eta} \frac{m}{(3k/2)} = \frac{a'}{a}. \qquad (25)$$

Although simple theory suggests that this ratio should be about one, both experiment and more refined theory give a value close to 5/2. This means that molecules do not “forget” their past history in every collision, but some persistence of their precollision velocities occurs. Molecules transport both energy and momentum from a somewhat greater distance than just one mean free path, but this distance is greater for energy than for momentum. This is plausible, for molecules with higher kinetic energies might be expected to have greater persistences.

Attempts to calculate the constants a and a' by tracing collision histories to find the “persistence of velocities” have not met with much success. The molecular “memory” fades slowly, too many previous collisions have to be traced, and the calculations become almost hopelessly complicated. A different theoretical approach is needed, which was finally supplied about 1916–17 independently by Enskog and Chapman. Their theory also shows that the same value of l applies to both η and λ, a fact that is not obvious in the simple theory described here.

The thermal conductivity of polyatomic molecules is accounted for by simply adding on a contribution for the energy carried by the internal molecular motions:

$$\lambda = a' \left(\frac{N}{V} \right) \bar{v} l \left(\frac{3}{2} k \right) + a'' \left(\frac{N}{V} \right) \bar{v} l c_{int}, \qquad (26)$$

where c_{int} is the contribution of the internal motions to the heat capacity (per molecule) and is easily found by subtracting $(3k/2)$ from the total measured heat capacity. As might be expected, the constant a'' is only about half as large as a'.

The pressure or density dependence of λ must be similar to that of η—an initial linear increase in the free-molecule region, followed by a constant value in the dilute-gas region and finally an increase in the dense-fluid region.

Diffusion and thermal diffusion

Both of these properties present difficulties for the simple mean free path version of kinetic theory. In the case of diffusion it must be argued that collisions of the molecules of species 1 with other species 1 molecules do not inhibit the interdiffusion of species 1 and 2, and similarly for 2–2 collisions. If this is not assumed, the calculated value of the diffusion coefficient for the 1–2 gas pair, D_{12}, depends strongly on the mixture composition instead of being virtually independent of it, as is shown by experiment. The neglect of 1–1 and 2–2 collisions can be rationalized by noting that the flow of momentum is not disturbed by such like-molecule collisions owing to the conservation of momentum, but it can be contended that the argument was simply invented to make the theory agree with experiment. A more charitable view is that the experimental results demonstrate that collisions between like molecules have little affect on D_{12}. It is one of the triumphs of the accurate kinetic theory of Enskog and Chapman that this result clearly emerges.

If 1–1 and 2–2 collisions are ignored, a simple calculation gives a result much like those for η and λ: $D_{12} = a_{12} \overline{v_{12}} l_{12},$ (27) where a_{12} is a numerical constant, v_{12} is an average relative speed for 1–2 collisions given by $v_{12}^2 = (1/2)(v_1^2 + v_2^2)$, and l_{12} is a mean free path for 1–2 collisions that is inversely proportional to the total molecular number density, $(N_1 + N_2)/V$. Thus, D_{12} is inversely proportional to gas density or pressure, unlike η and λ, but the concentration difference is proportional to pressure, with the two effects canceling one another, as pointed out previously. The actual transport of molecules is therefore independent of pressure. The numerical value of a_{12}, as obtained by refined calculations, is close to 3/5.

The pressure dependence of pD_{12} should be qualitatively similar to that of η and λ—an initial linear increase in the free-molecule region, a constant value in the dilute-gas region, and finally an increase in the dense-fluid region.

Thermal diffusion presents special difficulties for kinetic theory. The transport coefficients η, λ, and D_{12} are always positive regardless of the nature of the intermolecular forces that produce the collisions—the mere existence of collisions suffices to account for their important features. The transport coefficient that describes thermal diffusion, however, depends critically on the nature of the intermolecular forces and the collisions and can be positive, negative, or zero. Its dependence on composition is also rather complicated. There have been a number of attempts to explain thermal diffusion with a simple mean free path model, but none has been satisfactory. No simple physical explanation of thermal diffusion has been devised, and recourse to the accurate, but complicated, kinetic theory is necessary.

Boltzmann equation

The simple mean free path description of gas transport coefficients accounts for the major observed phenomena, but it is quantitatively unsatisfactory with respect to two major points: the values of numerical constants such as a, a', a'', and a_{12} and the description of the molecular collisions that define a mean free path. Indeed, collisions remain a somewhat vague concept except when they are considered to take place between molecules modeled as hard spheres. Improvement has required a different, somewhat indirect, and more mathematical approach through a quantity called the velocity distribution function. This function describes how molecular velocities are distributed on the average: a few very slow molecules, a few very fast ones, and most near some average value—namely, $v_{rms} = (v^2)^{1/2} = (3kT/2)^{1/2}$. If this function is known, all gas properties can be calculated by using it to obtain various averages. For example, the average momentum carried in a certain direction would give the viscosity.

The velocity distribution for a gas at equilibrium was suggested by Maxwell in 1859 and is represented by the familiar bell-shaped curve that describes the normal, or Gaussian, distribution of random variables in large populations. Attempts to support more definitively this result and to extend it to nonequilibrium gases led to the formulation of the Boltzmann equation, which describes how collisions and external forces cause the velocity distribution to change. This equation is difficult to solve in any general sense, but some progress can be made by assuming that the deviations from the equilibrium distribution are small and are proportional to the external influences that cause the deviations, such as temperature, pressure, and composition differences. Even the resulting simpler equations remained unsolved for nearly 50 years until the work of Enskog and Chapman, with a single notable exception. The one case that was solvable dealt with molecules that interact with forces that fall off as the fifth power of their separation (i.e., as $1/r^5$), for which Maxwell found an exact solution. Unfortunately, thermal diffusion happens to be exactly zero for molecules subject to this force law, so that phenomenon was missed.

It was later discovered that it is possible to use the solutions for the $1/r^5$ Maxwell model as a starting point and then calculate successive corrections for more general interactions. Although the calculations quickly increase in complexity, the improvement in accuracy is rapid, unlike the persistence-of-velocities corrections applied in mean free path theory. This refined version of kinetic theory is now highly developed, but it is quite mathematical and is not described here.

Deviations from the ideal model

Deviations from ideal gas behaviour occur both at low densities, where molecule-surface collisions become important, and at high densities, where a description in terms of only two-body collisions becomes inadequate. The low-density case can be handled in principle by including both molecule-surface and molecule-molecule collisions in the Boltzmann equation. Since this branch of the subject is now quite advanced and mathematical in character, only the high-density case will be discussed here.

Equation of state

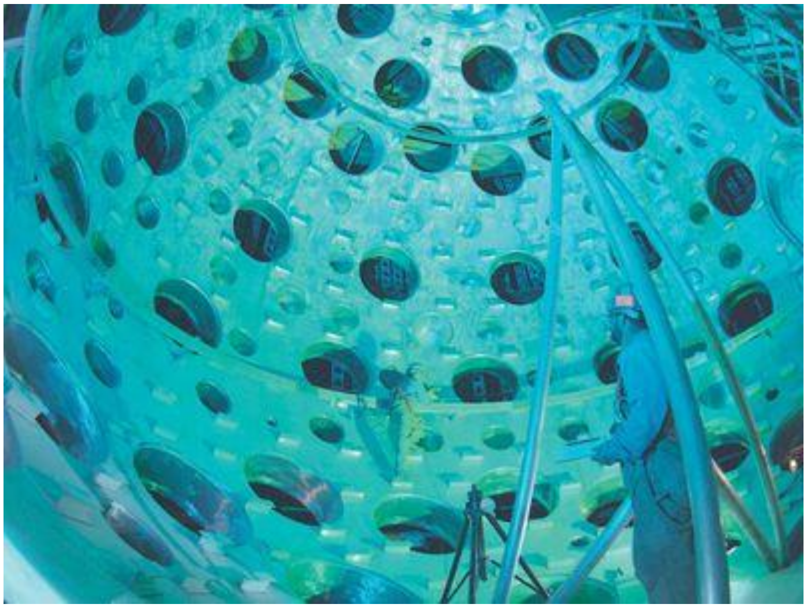
To a first approximation, molecule-molecule collisions do not affect the ideal gas equation of state, $pv = RT$, but real gases at nonzero densities show deviations from this equation that are due to interactions among the molecules. Ever since the great advance made by van der Waals in 1873, an accurate universal formula relating p, v, and T has been sought. No completely satisfactory equation of state has been found, though important advances occurred in the 1970s and '80s. The only rigorous theoretical result available is an infinite-series expansion in powers of $1/v$, known as the virial equation of state: $\frac{pv}{RT} = 1 + \frac{B(T)}{v} + \frac{C(T)}{v_2} + \cdots,$ (28) where $B(T)$, $C(T)$, . . . are called the second, third, . . . virial coefficients and depend only on the temperature and the particular gas. The virtue of this equation is that there is a rigorous connection between the virial coefficients and intermolecular forces, and experimental values of $B(T)$ were an early source (and still a useful one) of quantitative information on intermolecular forces. The drawback of the virial equation of state is that it is an infinite series and becomes essentially useless at high densities, which in practice are those greater than about the critical density. Also, the equation is wanting in that it does not predict condensation.

The most practical approaches to the equation of state for real fluids remain the versions of the principle of corresponding states first proposed by van der Waals.

Transport properties

Despite many attempts, there is still no satisfactory theory of the transport properties of dense fluids. Even the extension of the Boltzmann equation to include collisions of more than two bodies is not entirely clear. An important advance was made in 1921 by Enskog, but it is restricted to hard spheres and has not been extended to real molecules except in an empirical way to fit experimental measurements.

Attempts to develop a virial type of expansion in $1/v$ for the transport coefficients have failed in a surprising way. A formal theory was formulated, but, when the virial coefficients were evaluated for the tractable case of hard spheres, an infinite result was obtained for the coefficient of the $1/v^2$ term. This is a signal that a virial expansion is not accurate in a mathematical sense, and subsequent research showed that the error arose from a neglected term of the form $(1/v^2)\ln(1/v)$. It remains unknown how many similar problematic mathematical terms exist in the theory. Transport coefficients of dense fluids are usually described by some empirical extension of the Enskog hard-sphere theory or more commonly by some version of a principle of corresponding states. Much work clearly remains to be done.


laser-activated fusion Interior of the U.S. Department of Energy's National Ignition Facility (NIF), located at Lawrence Livermore National Laboratory, Livermore, California. The NIF target chamber uses a high-energy laser to heat fusion fuel to temperatures sufficient for thermonuclear ignition. The facility is used for basic science, fusion energy research, and nuclear weapons testing.(more)

nuclear fusion

nuclear fusion, process by which nuclear reactions between light elements form heavier elements (up to iron). In cases where the interacting nuclei belong to elements with low atomic numbers (e.g., hydrogen [atomic number 1] or its isotopes deuterium and tritium), substantial amounts of energy are released. The vast energy potential of nuclear fusion was first exploited in thermonuclear weapons, or hydrogen bombs, which were developed in the decade immediately following World War II. For a detailed history of this development, *see* nuclear weapon. Meanwhile, the potential peaceful applications of nuclear fusion, especially in view of the essentially limitless supply of fusion fuel on Earth, have encouraged an immense effort to harness this process for the production of power. For more detailed information on this effort, *see* fusion reactor.

This article focuses on the physics of the fusion reaction and on the principles of achieving sustained energy-producing fusion reactions.

The fusion reaction

What is the difference between nuclear fission and fusion? There are two ways of releasing nuclear energy: fission and fusion.

Fusion reactions constitute the fundamental energy source of stars, including the Sun. The evolution of stars can be viewed as a passage through various stages as thermonuclear reactions and nucleosynthesis cause compositional changes over long time spans. Hydrogen (H) “burning” initiates the fusion energy source of stars and leads to the formation of helium (He). Generation of fusion energy for practical use also relies on fusion reactions between the lightest elements that burn to form helium. In fact, the heavy isotopes of hydrogen—deuterium (D) and tritium (T)—react more efficiently with each other, and, when they do undergo fusion, they yield more energy per reaction than do two hydrogen nuclei. (The hydrogen nucleus consists of a single proton. The deuterium nucleus has one proton and one neutron, while tritium has one proton and two neutrons.)

Fusion reactions between light elements, like fission reactions that split heavy elements, release energy because of a key feature of nuclear matter called the binding energy, which can be released through fusion or fission. The binding energy of the nucleus is a measure of the efficiency with which its constituent nucleons are bound together. Take, for example, an element with Z protons and N neutrons in its nucleus. The element's atomic weight A is $Z + N$, and its atomic number is Z. The binding energy B is the energy associated with the mass difference between the Z protons and N neutrons considered separately and the nucleons bound together ($Z + N$) in a nucleus of mass M. The formula is $B = (Zm_p + Nm_n - M)c^2$, where m_p and m_n are the proton and neutron masses and c is the speed of light. It has been determined experimentally that the binding energy per nucleon is a maximum of about 1.4 10^{-12} joule at an atomic mass number of approximately 60—that is, approximately the atomic mass number of iron. Accordingly, the fusion of elements lighter than iron or the splitting of heavier ones generally leads to a net release of energy.

Two types of fusion reactions

Fusion reactions are of two basic types: (1) those that preserve the number of protons and neutrons and (2) those that involve a conversion between protons and neutrons. Reactions of the first type are most important for practical fusion energy production, whereas those of the second type are crucial to the initiation of star burning. An arbitrary element is indicated by the notation ${}^{A}_{Z}X$, where Z is the charge of the nucleus and A is the atomic weight. An important fusion reaction for practical energy generation is that between deuterium and tritium (the D-T fusion reaction). It produces helium (He) and a neutron (n) and is written $\mathrm{D} + \mathrm{T} \rightarrow \mathrm{He} + n$.

To the left of the arrow (before the reaction) there are two protons and three neutrons. The same is true on the right.

The other reaction, that which initiates star burning, involves the fusion of two hydrogen nuclei to form deuterium (the H-H fusion reaction): $\mathrm{H} + \mathrm{H} \rightarrow \mathrm{D} + \beta^{+} + \nu$, where β^{+} represents a positron and ν stands for a neutrino. Before the reaction there are two hydrogen nuclei (that is, two protons). Afterward there are one proton and one neutron (bound together as the nucleus of deuterium) plus a positron and a neutrino (produced as a consequence of the conversion of one proton to a neutron).

Both of these fusion reactions are exoergic and so yield energy. The German-born physicist Hans Bethe proposed in the 1930s that the H-H fusion reaction could occur with a net release of energy and provide, along with subsequent reactions, the fundamental energy source sustaining the stars. However, practical energy generation requires the D-T reaction for two reasons: first, the rate of reactions between deuterium and tritium is much higher than that between protons; second, the net energy release from the D-T reaction is 40 times greater than that from the H-H reaction.

Energy released in fusion reactions

Energy is released in a nuclear reaction if the total mass of the resultant particles is less than the mass of the initial reactants. To illustrate, suppose two nuclei, labeled X and a, react to form two other nuclei, Y and b, denoted$X + a \rightarrow Y + b$.The particles a and b are often nucleons, either protons or neutrons, but in general can be any nuclei. Assuming that none of the particles is internally excited (i.e., each is in its ground state), the energy quantity called the Q-value for this reaction is defined as$Q = (m_x + m_a - m_b - m_y)c^2$,where the m-letters refer to the mass of each particle and c is the speed of light. When the energy value Q is positive, the reaction is exoergic; when Q is negative, the reaction is endoergic (i.e., absorbs energy). When both the total proton number and the total neutron number are preserved before and after the reaction (as in D-T reactions), then the Q-value can be expressed in terms of the binding energy B of each particle as$Q = B_y + B_b - B_x - B_a$.

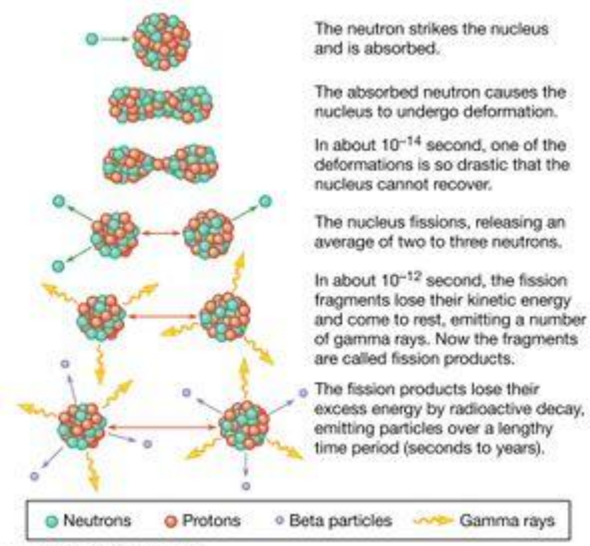
The D-T fusion reaction has a positive Q-value of 2.8×10^{-12} joule. The H-H fusion reaction is also exoergic, with a Q-value of 6.7×10^{-14} joule. To develop a sense for these figures, one might consider that one metric ton (1,000 kg, or almost 2,205 pounds) of deuterium would contain roughly 3×10^{32} atoms. If one ton of deuterium were to be consumed through the fusion reaction with tritium, the energy released would be 8.4×10^{20} joules. This can be compared with the energy content of one ton of coal—namely, 2.9×10^{10} joules. In other words, one ton of deuterium has the energy equivalent of approximately 29 billion tons of coal.

Rate and yield of fusion reactions

The energy yield of a reaction between nuclei and the rate of such reactions are both important. These quantities have a profound influence in scientific areas such as nuclear astrophysics and the potential for nuclear production of electrical energy.

When a particle of one type passes through a collection of particles of the same or different type, there is a measurable chance that the particles will interact. The particles may interact in many ways, such as simply scattering, which means that they change direction and exchange energy, or they may undergo a nuclear fusion reaction. The measure of the likelihood that particles will interact is called the cross section, and the magnitude of the cross section depends on the type of interaction and the state and energy of the particles. The product of the cross section and the atomic density of the target particle is called the macroscopic cross section. The inverse of the macroscopic cross section is particularly noteworthy as it gives the mean distance an incident particle will travel before interacting with a target particle; this inverse measure is called the mean free path. Cross sections are measured by producing a beam of one particle at a given energy, allowing the beam to interact with a (usually thin) target made of the same or a different material, and measuring deflections or reaction products. In this way it is possible to determine the relative likelihood of one type of fusion reaction versus another, as well as the optimal conditions for a particular reaction.

The cross sections of fusion reactions can be measured experimentally or calculated theoretically, and they have been determined for many reactions over a wide range of particle energies. They are well known for practical fusion energy applications and are reasonably well known, though with gaps, for stellar evolution. Fusion reactions between nuclei, each with a positive charge of one or more, are the most important for both practical applications and the nucleosynthesis of the light elements in the burning stages of stars. Yet, it is well known that two positively charged nuclei repel each other electrostatically—i.e., they experience a repulsive force inversely proportional to the square of the distance separating them. This repulsion is called the Coulomb barrier (*see* Coulomb force). It is highly unlikely that two positive nuclei will approach each other closely enough to undergo a fusion reaction unless they have sufficient energy to overcome the Coulomb barrier. As a result, the cross section for fusion reactions between charged particles is very small unless the energy of the particles is high, at least 10^4 electron volts (1 eV ≅ 1.602×10^{-19} joule) and often more than 10^5 or 10^6 eV. This explains why the centre of a star must be hot for the fuel to burn and why fuel for practical fusion energy systems must be heated to at least 50,000,000 kelvins (K; 90,000,000 °F). Only then will a reasonable fusion reaction rate and power output be achieved.



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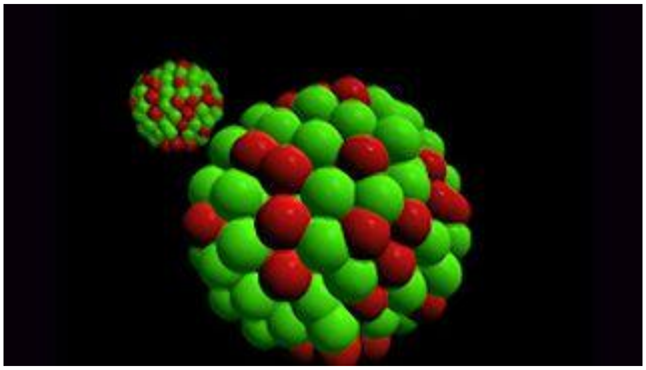
1 of 2

FissionSequence of events in the fission of a uranium nucleus by a neutron.



2 of 2

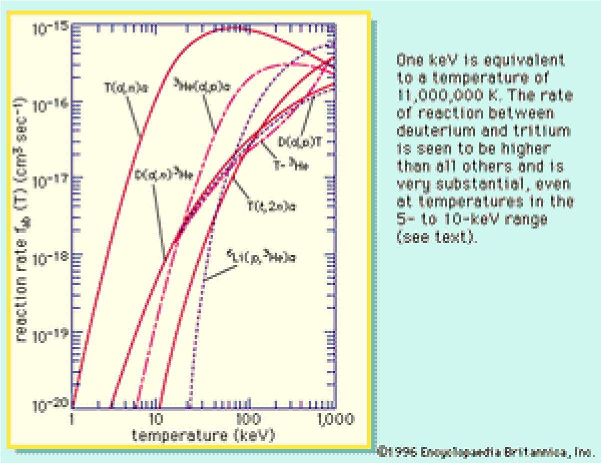
Fission of a uranium nucleus by a neutronSequence of events in the fission of a uranium nucleus by a neutron.

See all videos for this article

The phenomenon of the Coulomb barrier also explains a fundamental difference between energy generation by nuclear fusion and nuclear fission. While fission of heavy elements can be induced by either protons or neutrons, generation of fission energy for practical applications is dependent on neutrons to induce fission reactions in uranium or plutonium. Having no electric charge, the neutron is free to enter the nucleus even if its energy corresponds to room temperature. Fusion energy, relying as it does on the fusion reaction between light nuclei, occurs only when the particles are sufficiently energetic to overcome the Coulomb repulsive force. This requires the production and heating of the gaseous reactants to the high temperature state known as the plasma state.

The plasma state

Typically, a plasma is a gas that has had some substantial portion of its constituent atoms or molecules ionized by the dissociation of one or more of their electrons. These free electrons enable plasmas to conduct electric charges, and a plasma is the only state of matter in which thermonuclear reactions can occur in a self-sustaining manner. Astrophysics and magnetic fusion research, among other fields, require extensive knowledge of how gases behave in the plasma state. The stars, the solar wind, and much of interstellar space are examples where the matter present is in the plasma state. Very high-temperature plasmas are fully ionized gases, which means that the ratio of neutral gas atoms to charged particles is small. For example, the ionization energy of hydrogen is 13.6 eV, while the average energy of a hydrogen ion in a plasma at 50,000,000 K is 6,462 eV. Thus, essentially all of the hydrogen in this plasma would be ionized.



One keV is equivalent to a temperature of 11,000,000 K. The rate of reaction between deuterium and tritium is seen to be higher than all others and is very substantial, even at temperatures in the 5- to 10-keV range (see text).

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reaction rate as a function of plasma temperatureThe reaction rate as a function of plasma temperature, expressed in kiloelectron volts (keV; 1 keV is equivalent to a temperature of 11,000,000 K). The rate of reaction between deuterium and tritium is seen to be higher than all others and is very substantial, even at temperatures in the 5-to-10-keV range (see text).(more)

A reaction-rate parameter more appropriate to the plasma state is obtained by accounting for the fact that the particles in a plasma, as in any gas, have a distribution of energies. That is to say, not all particles have the same energy. In simple plasmas this energy distribution is given by the Maxwell-Boltzmann distribution law, and the temperature of the gas or plasma is, within a proportionality constant, two-thirds of the average particle energy; i.e., the relationship between the average energy E and temperature T is $E = 3kT/2$, where k is the Boltzmann constant, 8.62×10^{-5} eV per kelvin. The intensity of nuclear fusion reactions in a plasma is derived by averaging the product of the particles' speed and their cross sections over a distribution of speeds corresponding to a Maxwell-Boltzmann distribution. The cross section for the reaction depends on the energy or speed of the particles. The averaging process yields a function for a given reaction that depends only on the temperature and can be denoted $f(T)$. The rate of energy released (i.e., the power released) in a reaction between two species, a and b, is$P_{ab} = n_a n_b f_{ab}(T) U_{ab}$,where n_a and n_b are the density of species a and b in the plasma, respectively, and U_{ab} is the energy released each time a and b undergo a fusion reaction. The parameter P_{ab} properly takes into account both the rate of a given reaction and the energy yield per reaction (*see* figure).

Fusion reactions in stars

heliumThe many uses for helium, but are we running out of it?

See all videos for this article

Fusion reactions are the primary energy source of stars and the mechanism for the nucleosynthesis of the light elements. In the late 1930s Hans Bethe first recognized that the fusion of hydrogen nuclei to form deuterium is exoergic (i.e., there is a net release of energy) and, together with subsequent nuclear reactions, leads to the synthesis of helium. The formation of helium is the main source of energy emitted by normal stars, such as the Sun, where the burning-core plasma has a temperature of less than 15,000,000 K. However, because the gas from which a star is formed often contains some heavier elements, notably carbon (C) and nitrogen (N), it is important to include nuclear reactions between protons and these nuclei. The reaction chain between protons that ultimately leads to helium is the proton-proton cycle. When protons also induce the burning of carbon and nitrogen, the CN cycle must be considered; and, when oxygen (O) is included, still another alternative scheme, the CNO bi-cycle, must be accounted for. (*See* carbon cycle.)

The proton-proton nuclear fusion cycle in a star containing only hydrogen begins with the reaction$H + H \rightarrow D + \beta^+ + \nu$; $Q = 1.44$ MeV,where the Q-value assumes annihilation of the positron by an electron. The deuterium could react with other deuterium nuclei, but, because there is so much hydrogen, the D/H ratio is held to very low values, typically 10^{-18}. Thus, the next step is$H + D \rightarrow {}^3He + \gamma$; $Q = 5.49$ MeV,where γ indicates that gamma rays carry off some of the energy yield. The burning of the helium-3 isotope then gives rise to ordinary helium and hydrogen via the last step in the chain:${}^3He + {}^3He \rightarrow {}^4He + 2(H)$; $Q = 12.86$ MeV.

At equilibrium, helium-3 burns predominantly by reactions with itself because its reaction rate with hydrogen is small, while burning with deuterium is negligible due to the very low deuterium concentration. Once helium-4 builds up, reactions with helium-3 can lead to the production of still-heavier elements, including beryllium-7, beryllium-8, lithium-7, and boron-8, if the temperature is greater than about 10,000,000 K.

The stages of stellar evolution are the result of compositional changes over very long periods. The size of a star, on the other hand, is determined by a balance between the pressure exerted by the hot plasma and the gravitational force of the star's mass. The energy of the burning core is transported toward the surface of the star, where it is radiated at an effective temperature. The effective temperature of the Sun's surface is about 6,000 K, and significant amounts of radiation in the visible and infrared wavelength ranges are emitted.

Fusion reactions for controlled power generation

Reactions between deuterium and tritium are the most important fusion reactions for controlled power generation because the cross sections for their occurrence are high, the practical plasma temperatures required for net energy release are moderate, and the energy yield of the reactions are high—17.58 MeV for the basic D-T fusion reaction.

It should be noted that any plasma containing deuterium automatically produces some tritium and helium-3 from reactions of deuterium with other deuterium ions. Other fusion reactions involving elements with an atomic number above 2 can be used, but only with much greater difficulty. This is because the Coulomb barrier increases with increasing charge of the nuclei, leading to the requirement that the plasma temperature exceed 1,000,000,000 K if a significant rate is to be achieved. Some of the more interesting reactions are:

1. $H + {}^{11}B \rightarrow 3({}^{4}He)$; $Q = 8.68$ MeV;
2. $H + {}^{6}Li \rightarrow {}^{3}He + {}^{4}He$; $Q = 4.023$ MeV;
3. ${}^{3}He + {}^{6}Li \rightarrow H + 2({}^{4}He)$; $Q = 16.88$ MeV; and
4. ${}^{3}He + {}^{6}Li \rightarrow D + {}^{7}Be$; $Q = 0.113$ MeV.

Reaction (2) converts lithium-6 to helium-3 and ordinary helium. Interestingly, if reaction (2) is followed by reaction (3), then a proton will again be produced and be available to induce reaction (2), thereby propagating the process. Unfortunately, it appears that reaction (4) is 10 times more likely to occur than reaction (3).

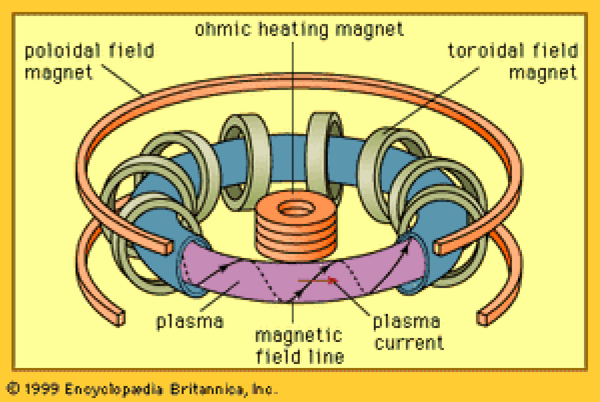
Methods of achieving fusion energy

Practical efforts to harness fusion energy involve two basic approaches to containing a high-temperature plasma of elements that undergo nuclear fusion reactions: magnetic confinement and inertial confinement. A much less likely but nevertheless interesting approach is based on fusion catalyzed by muons; research on this topic is of intrinsic interest in nuclear physics. These three methods are described in some detail in this section. In addition, the processes popularly dubbed cold fusion and bubble fusion are briefly described.

Magnetic confinement

In magnetic confinement the particles and energy of a hot plasma are held in place using magnetic fields. A charged particle in a magnetic field experiences a Lorentz force that is proportional to the product of the particle's velocity and the magnetic field.

This force causes electrons and ions to spiral about the direction of the magnetic line of force, thereby confining the particles. When the topology of the magnetic field yields an effective magnetic well and the pressure balance between the plasma and the field is stable, the plasma can be confined away from material boundaries. Heat and particles are transported both along and across the field, but energy losses can be prevented in two ways. The first is to increase the strength of the magnetic field at two locations along the field line. Charged particles contained between these points can be made to reflect back and forth, an effect called magnetic mirroring. In a basically straight system with a region of intensified magnetic field at each end, particles can still escape through the ends due to scattering between particles as they approach the mirroring points. Such end losses can be avoided altogether by creating a magnetic field in the topology of a torus (i.e., configuration of a doughnut or inner tube).



Tokamak magnetic confinement

External magnets can be arranged to create a magnetic field topology for stable plasma confinement, or they can be used in conjunction with magnetic fields generated by currents induced to flow in the plasma itself. The late 1960s witnessed a major advance by the Soviet Union in harnessing fusion reactions for practical energy production. Soviet scientists achieved a high plasma temperature (about 3,000,000 K), along with other physical parameters, in a machine referred to as a tokamak (*see* figure). A tokamak is a toroidal magnetic confinement system in which the plasma is kept stable both by an externally generated, doughnut-shaped magnetic field and by electric currents flowing within the plasma. Since the late 1960s the tokamak has been the major focus of magnetic fusion research worldwide, though other approaches such as the stellarator, the compact torus, and the reversed field pinch (RFP) have also been pursued. In these approaches, the magnetic field lines follow a helical, or screwlike, path as the lines of magnetic force proceed around the torus. In the tokamak the pitch of the helix is weak, so the field lines wind loosely around the poloidal direction (through the central hole) of the torus. In contrast, RFP field lines wind much tighter, wrapping many times in the poloidal direction before completing one loop in the toroidal direction (around the central hole).

Magnetically confined plasma must be heated to temperatures at which nuclear fusion is vigorous, typically greater than 75,000,000 K (equivalent to an energy of 4,400 eV). This can be achieved by coupling radio-frequency waves or microwaves to the plasma particles, by injecting energetic beams of neutral atoms that become ionized and heat the plasma, by magnetically compressing the plasma, or by the ohmic heating (also known as Joule heating) that occurs when an electric current passes through the plasma.

Employing the tokamak concept, scientists and engineers in the United States, Europe, and Japan began in the mid-1980s to use large experimental tokamak devices to attain conditions of temperature, density, and energy confinement that now match those necessary for practical fusion power generation. The machines employed to achieve these results include the Joint European Torus (JET) of the European Union, the Japanese Tokamak-60 (JT-60), and, until 1997, the Tokamak Fusion Test Reactor (TFTR) in the United States. Indeed, in both the TFTR and the JET devices, experiments using deuterium and tritium produced more than 10 megawatts of fusion power and essentially energy breakeven conditions in the plasma itself. Plasma conditions approaching those achieved in tokamaks were also achieved in large stellarator machines in Germany and Japan during the 1990s.

Inertial confinement fusion (ICF)

In this approach, a fuel mass is compressed rapidly to densities 1,000 to 10,000 times greater than normal by generating a pressure as high as 10^{17} pascals (10^{12} atmospheres) for periods as short as a nanosecond (10^{-9} second). Near the end of this time period, the implosion speed exceeds about 3×10^5 metres per second. At maximum compression of the fuel, which is now in a cool plasma state, the energy in converging shock waves is sufficient to heat the very centre of the fuel to temperatures high enough to induce fusion reactions (greater than an equivalent energy of about 4,400 eV). If the mass of this highly compressed fuel material is large enough, energy will be generated through fusion reactions before this hot plasma ball disassembles. Under proper conditions, much more energy can be released than is required to compress and shock heat the fuel to thermonuclear burning conditions.

The physical processes in ICF bear a relationship to those in thermonuclear weapons and in star formation—namely, collapse, compression heating, and the onset of nuclear fusion. The situation in star formation differs in one respect: gravity is the cause of the collapse, and a collapsed star begins to expand again due to heat from exoergic nuclear fusion reactions. The expansion is ultimately arrested by the gravitational force associated with the enormous mass of the star, at which point a state of equilibrium in both size and temperature is achieved. In contrast, the fuel in a thermonuclear weapon or ICF completely disassembles. In the ideal ICF case, however, this does not occur until about 30 percent of the fusion fuel has burned.

Over the decades, very significant progress has been made in developing the technology and systems for high-energy, short-time-pulse drivers that are necessary to implode the fusion fuel. The most common driver is a high-power laser, though particle accelerators capable of producing beams of high-energy ions are also used. Lasers that produce more than 100,000 joules in pulses of about one nanosecond are now used in experiments, and the power available in short bursts exceeds 10^{14} watts.

Two lasers capable of delivering up to 5,000,000 joules in equally short bursts, generating a power level on the fusion targets in excess of 5×10^{14} watts, are operational. One facility is the Laser MegaJoule in Bordeaux, France. The other is the National Ignition Facility at the Lawrence Livermore National Laboratory in Livermore, Calif., U.S.

Muon-catalyzed fusion

The need in traditional schemes of nuclear fusion to confine very high-temperature plasmas has led some researchers to explore alternatives that would permit fusion reactants to approach each other more closely at much lower temperatures. One method involves substituting muons (μ) for the electrons that ordinarily surround the nucleus of a fuel atom. Muons are negatively charged subatomic particles similar to electrons, except that their mass is a little more than 200 times the electron mass and they are unstable, having a half-life of about 2.2×10^{-6} second. In fact, fusion has been observed in liquid and gas mixtures of deuterium and tritium at cryogenic temperatures when muons were injected into the mixture.

Muon-catalyzed fusion is the name given to the process of achieving fusion reactions by causing a deuteron (deuterium nucleus, D^+), a triton (tritium nucleus, T^+), and a muon to form what is called a muonic molecule. Once a muonic molecule is formed, the rate of fusion reactions is approximately 3×10^{-8} second. However, the formation of a muonic molecule is complex, involving a series of atomic, molecular, and nuclear processes.

In schematic terms, when a muon enters a mixture of deuterium and tritium, the muon is first captured by one of the two hydrogen isotopes in the mixture, forming either atomic D^+-μ or T^+-μ, with the atom now in an excited state. The excited atom relaxes to the ground state through a cascade collision process, in which the muon may be transferred from a deuteron to a triton or vice versa. More important, it is also possible that a muonic molecule (D^+-μ-T^+) will be formed. Although a much rarer reaction, once a muonic molecule does form, fusion takes place almost immediately, releasing the muon in the mixture to be captured again by a deuterium or tritium nucleus and allowing the process to continue. In this sense the muon acts as a catalyst for fusion reactions within the mixture. The key to practical energy production is to generate enough fusion reactions before the muon decays.

The complexities of muon-catalyzed fusion are many and include generating the muons (at an energy expenditure of about five billion electron volts per muon) and immediately injecting them into the deuterium-tritium mixture. In order to produce more energy than what is required to initiate the process, about 300 D-T fusion reactions must take place within the half-life of a muon.

Cold fusion and bubble fusion

Two disputed fusion experiments merit mention. In 1989 two chemists, Martin Fleischmann of the University of Utah and Stanley Pons of the University of

Southampton in England, announced that they had produced fusion reactions at essentially room temperature. Their system consisted of electrolytic cells containing heavy water (deuterium oxide, D_2O) and palladium rods that absorbed the deuterium from the heavy water. Efforts to give a theoretical explanation of the results failed, as did worldwide efforts to reproduce the claimed cold fusion.

In 2002 Rusi Taleyarkhan and colleagues at Purdue University in Lafayette, Ind., claimed to have observed a statistically significant increase in nuclear emissions of products of fusion reactions (neutrons and tritium) during acoustic cavitation experiments with chilled deuterated (bombarded with deuterium) acetone. Their experimental setup was based on the known phenomenon of sonoluminescence. In sonoluminescence a gas bubble is imploded with high-pressure sound waves. At the end of the implosion process, and for a short time afterward, conditions of high density and temperature are achieved that lead to light emission. By starting with larger, millimetre-sized cavitations (bubbles) that had been deuterated in the acetone liquid, the researchers claimed to have produced densities and temperatures sufficient to induce fusion reactions just before the bubbles broke up. As with cold fusion, most attempts to replicate their results have failed.

Conditions for practical fusion yield

Two conditions must be met to achieve practical energy yields from fusion. First, the plasma temperature must be high enough that fusion reactions occur at a sufficient rate. Second, the plasma must be confined so that the energy released by fusion reactions, when deposited in the plasma, maintains its temperature against loss of energy by such phenomena as conduction, convection, and radiation. When these conditions are achieved, the plasma is said to be ignited. In the case of stars, or some approaches to fusion by magnetic confinement, a steady state can be achieved, and no energy beyond what is supplied from fusion reactions is needed to sustain the system. In other cases, such as the ICF approach, there is a large temperature excursion once fuel ignition is achieved. The energy yield can far exceed the energy required to attain plasma ignition conditions, but this energy is released in a burst, and the process has to be repeated roughly once every second for practical power to be produced.

The conditions for plasma ignition are readily derived. When fusion reactions occur in a plasma, the power released is proportional to the square of plasma ion density, n^2. The plasma loses energy when electrons scatter from positively charged ions, accelerating and radiating in the process. Such radiation is called bremsstrahlung and is proportional to $n^2T^{1/2}$, where T is the plasma temperature. Other mechanisms by which heat can escape the plasma lead to a characteristic energy-loss time denoted by τ. The energy content of the plasma at temperature T is $3nkT$, where k is the Boltzmann constant. The rate of energy loss by mechanisms other than bremsstrahlung is thus simply $3nkT/\tau$. The energy balance of the plasma is the balance between the fusion energy heating the plasma and the energy-loss rate, which is the sum of $3nkT/\tau$ and the bremsstrahlung. The condition satisfying this balance is called the ignition condition. An equation relates the product of density and energy confinement time, denoted $n\tau$, to a function that depends only on the plasma temperature and the type of fusion reaction. For example, when the plasma is composed of deuterium and tritium, the smallest value of $n\tau$ required to achieve ignition is about 2×10^{20} particles per cubic metre times seconds, and the required temperature corresponds to an energy of about 25,000 eV. If the only energy losses are due to bremsstrahlung escaping from the plasma (meaning τ is infinite), the ignition temperature decreases to an energy level of 4,400 eV. Hence, the keys to generating usable amounts of fusion energy are to attain a sufficient plasma temperature and a sufficient confinement quality, as measured by the product $n\tau$. At a temperature equivalent to 10,000 eV, the $n\tau$ product must be about 3×10^{20} particles per cubic metre times seconds.

Magnetic fusion energy generally creates plasmas with a density of about 3×10^{20} particles per cubic metre, which is about 10^{-8} of normal density. Hence, the characteristic time for heat to escape must be greater than about one second. This is a measure of the required degree of magnetic insulation for the heat content. Under these conditions the plasma remains in energy balance and can operate continuously if the ash of the nuclear fusion, namely helium, is removed (otherwise it will quench the plasma) and fuel is replenished.

ICF creates plasmas of much higher density, generally between 10^{31} and 10^{32} particles per cubic metre, or 1,000 to 10,000 times the normal density. As such, the confinement time, or minimum burn time, can be as short as 20×10^{-12} second. The objective in ICF is to achieve a temperature equivalent of 4,400 eV at the centre of the highly compressed fuel mass, while still having sufficient mass left around the centre so that the disassembly time will exceed the minimum burn time.

History of fusion energy research

The fusion process has been studied in order to understand nuclear matter and forces, to learn more about the nuclear physics of stellar objects, and to develop thermonuclear weapons. During the late 1940s and early ’50s, research programs in the United States, United Kingdom, and the Soviet Union began to yield a better understanding of nuclear fusion, and investigators embarked on ways of exploiting the process for practical energy production. Fusion reactor research focused primarily on using magnetic fields and electromagnetic forces to contain the extremely hot plasmas needed for thermonuclear fusion.

Researchers soon found, however, that it is exceedingly difficult to contain plasmas at fusion reaction temperatures because the hot gases tend to expand and escape from the enclosing magnetic structure. Plasma physics theory in the 1950s was incapable of describing the behaviour of the plasmas in many of the early magnetic confinement systems.

The undeniable potential benefits of practical fusion energy led to an increasing call for international cooperation. American, British, and Soviet fusion programs were strictly classified until 1958, when most of their research programs were made public at the Second Geneva Conference on the Peaceful Uses of Atomic Energy, sponsored by the United Nations. Since that time, fusion research has been characterized by international collaboration. In addition, scientists have also continued to study and measure fusion reactions between the lighter elements so as to arrive at a more accurate determination of reaction rates. The formulas developed by nuclear physicists for predicting the rate of fusion energy generation have been adopted by astrophysicists to derive new information about the structure and evolution of stars.

Work on the other major approach to fusion energy, inertial confinement fusion (ICF), was begun in the early 1960s. The initial idea was proposed in 1961, only a year after the reported invention of the laser, in a then-classified proposal to employ large pulses of laser energy (which no one then quite knew how to achieve) to implode and shock-heat matter to temperatures at which nuclear fusion would proceed vigorously. Aspects of inertial confinement fusion were declassified in the 1970s and, especially, in the early 1990s to reveal important aspects of the design of the targets containing fusion fuels. Very painstaking and sophisticated work to design and develop short-pulse, high-power lasers and suitable millimetre-sized targets continues, and significant progress has been made.

Although practical fusion reactors have not been built yet, the necessary conditions of plasma temperature and heat insulation have been largely achieved, suggesting that fusion energy for electric-power production is now a serious possibility. Commercial fusion reactors promise an inexhaustible source of electricity for countries worldwide. From a practical viewpoint, however, the initiation of nuclear fusion in a hot plasma is but the first step in a whole sequence of steps required to convert fusion energy to electricity. In the end, successful fusion power systems must be capable of producing electricity safely and in a cost-effective manner, with a minimum of radioactive waste and environmental impact. The quest for practical fusion energy remains one of the great scientific and engineering challenges of humankind.

aurora australis A display of aurora australis, or southern lights, manifesting itself as a glowing loop, in an image of part of Earth's Southern Hemisphere taken from space by astronauts aboard the U.S. space shuttle orbiter Discovery on May 6, 1991. The mostly greenish blue emission is from ionized oxygen atoms at an altitude of 100–250 km (60–150 miles). The red-tinged spikes at the top of the loop are produced by ionized oxygen atoms at higher altitudes, up to 500 km (300 miles).(more)

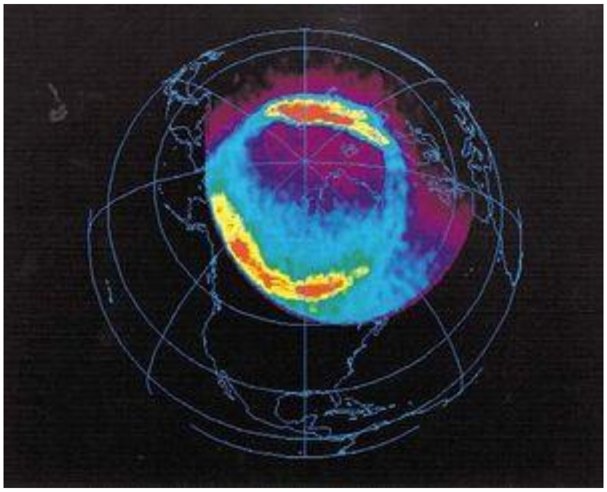
Aurora

atmospheric phenomenon

Northern Lights Forecast: Aurora Borealis May Be Visible In These States Tonight • Nov. 11, 2024, 5:42 AM ET (Forbes) ...(Show more)

aurora, luminous phenomenon of Earth's upper atmosphere that occurs primarily in high latitudes of both hemispheres; in the Northern Hemisphere auroras are called aurora borealis, aurora polaris, or northern lights, and in the Southern Hemisphere they are called aurora australis or southern lights.

A brief treatment of auroras follows. For full treatment, *see* ionosphere and magnetosphere.



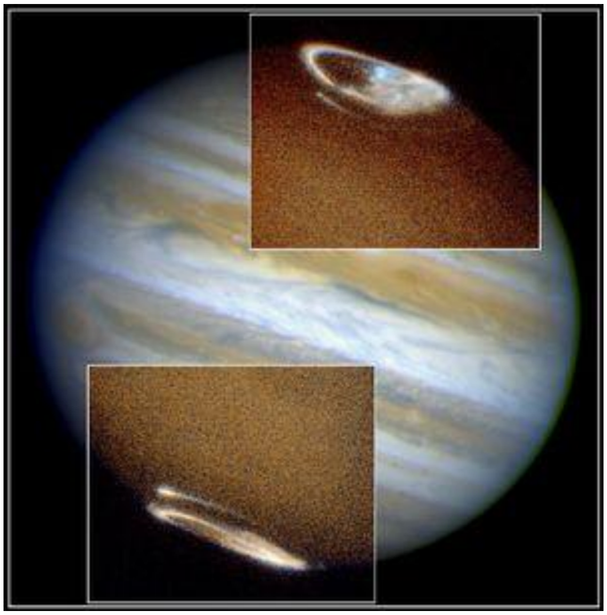
auroral ovalEarth's full North Polar auroral oval, in an image taken in ultraviolet light by the U.S. Polar spacecraft over northern Canada, April 6, 1996. In the colour-coded image, which simultaneously shows dayside and nightside auroral activity, the most intense levels of activity are red, and the lowest levels are blue. Polar, launched in February 1996, was designed to further scientists' understanding of how plasma energy contained in the solar wind interacts with Earth's magnetosphere.(more)

Auroras are caused by the interaction of energetic particles (electrons and protons) of the solar wind with atoms of the upper atmosphere. Such interaction is confined for the most part to high latitudes in oval-shaped zones that surround Earth's magnetic poles and maintain a more or less fixed orientation with respect to the Sun. During periods of low solar activity, the auroral zones shift poleward. During periods of intense solar activity, auroras occasionally extend to the middle latitudes; for example, the aurora borealis has been seen as far south as 40° latitude in the United States. Auroral emissions typically occur at altitudes of about 100 km (60 miles); however, they may occur anywhere between 80 and 250 km (about 50 to 155 miles) above Earth's surface.

Watch the aurora australis, the southern lights, from outer spaceWatch a time-lapse video of the aurora australis in the Southern Hemisphere.(more)
See all videos for this article

Auroras take many forms, including luminous curtains, arcs, bands, and patches. The uniform arc is the most stable form of aurora, sometimes persisting for hours without noticeable variation. However, in a great display, other forms appear, commonly undergoing dramatic variation. The lower edges of the arcs and folds are usually much more sharply defined than the upper parts. Greenish rays may cover most of the sky poleward of the magnetic zenith, ending in an arc that is usually folded and sometimes edged with a lower red border that may ripple like drapery. The display ends with a poleward retreat of the auroral forms, the rays gradually degenerating into diffuse areas of white light.

Auroras receive their energy from charged particles traveling between the Sun and Earth along bundled ropelike magnetic fields. Electrons and other charged particles, which are released by coronal mass ejections, solar flares, and other emanations from the Sun, are driven outward by the solar wind. Some electrons are captured by Earth's magnetic field (*see* geomagnetic field) and conducted along magnetic field lines downward toward the magnetic poles. Alfvén waves—which are generated in the dayside and nightside regions of the magnetosphere and in the region of the magnetosphere called the magnetotail—push these electrons along and accelerate them up to 72.4 million km (45 million miles) per hour. They collide with oxygen and nitrogen atoms, knocking away electrons from these atoms to leave ions in excited states. These ions emit radiation at various wavelengths, creating the characteristic colours (red or greenish blue) of the aurora.



Jupiter's northern and southern aurorasJupiter's northern and southern auroras, as observed by the Hubble Space Telescope. The auroras are produced by the interaction of the planet's powerful magnetic field and particles in its upper atmosphere.(more)

In addition to Earth, other planets in the solar system that have atmospheres and substantial magnetic fields—i.e., Jupiter, Saturn, Uranus, and Neptune—display auroral activity on a large scale. Auroras also have been observed on Jupiter’s moon Io, where they are produced by the interaction of Io’s atmosphere with Jupiter’s powerful magnetic field.

lightning

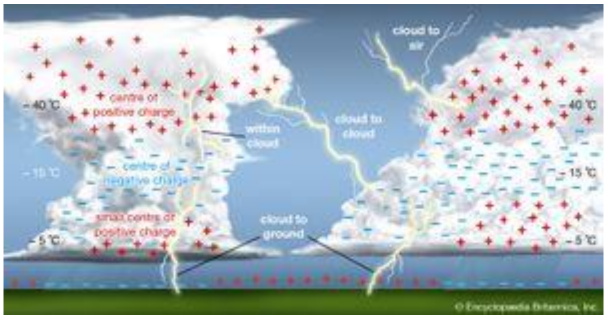
meteorology

lightning, the visible discharge of electricity that occurs when a region of a cloud acquires an excess electrical charge, either positive or negative, that is sufficient to break down the resistance of air.

Is ball lightning real?Learn about the mysterious phenomenon of ball lightning.
See all videos for this article

A brief description of lightning follows. For a longer discussion of lightning within its meteorological context, see thunderstorm electrification in the article thunderstorm.

Lightning is usually associated with cumulonimbus clouds (thunderclouds), but it also occurs in stratiform clouds (layered clouds with a large horizontal extent), in snowstorms and dust storms, and sometimes in the dust and gases emitted by erupting volcanoes. During a thunderstorm, lightning can occur within the cloud, between clouds, between the cloud and the air, or between the cloud and the ground.



electrical charge distribution in a thunderstormWhen the electrical charges become sufficiently separated in a thundercloud, with some regions acquiring a negative charge and others a positive, a discharge of lightning becomes likely. About one-third of lightning flashes travel from the cloud to the ground; most of these originate in negatively charged regions of the cloud.(more)

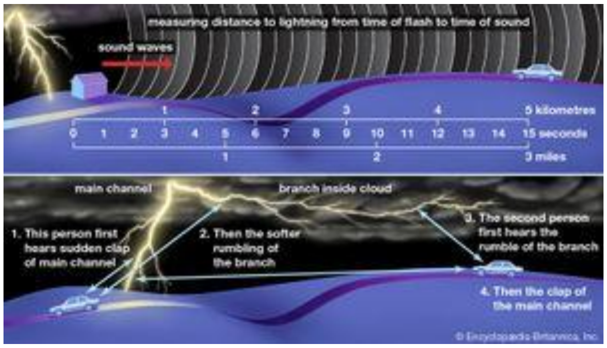
Lightning occurs when regions of excess positive and negative charge develop within the cloud. Typically, there is a large volume of positive charge in the upper regions of the cloud, a large negative charge in the centre, and a small positive charge in the lower regions. These charges reside on water drops, ice particles, or both.

triggered lightningTriggered lightning. This discharge is triggered by the presence of the tall tower atop Mount San Salvatore, near Lugano, Switzerland.(more)

Cloud-to-ground lightning is initiated by a preliminary breakdown process within the cloud, typically between the centre region of negative charge and the small positive charge below it. This process creates a channel of partially ionized air—air in which neutral atoms and molecules have been converted to electrically charged ones. Next, a stepped leader (initial lightning stroke) forms and propagates downward, following channels created by the preliminary breakdown process. The leader is highly branched in the direction of its propagation. Most leader channels are negatively charged. When the stepped leader nears the ground, an upward, connecting discharge of opposite polarity rises and meets it at a point typically about 30 metres (100 feet) above the ground. When the junction is complete, the cloud is effectively connected to the ground, and a very bright return stroke propagates back to the cloud at a speed about one-third the speed of light, following the leader channel. A typical lightning flash to the ground contains three or four leader-return stroke sequences in rapid succession. Occasionally, when there is a strike to a mountain or tall building, the first leader will start at the ground and propagate upward.

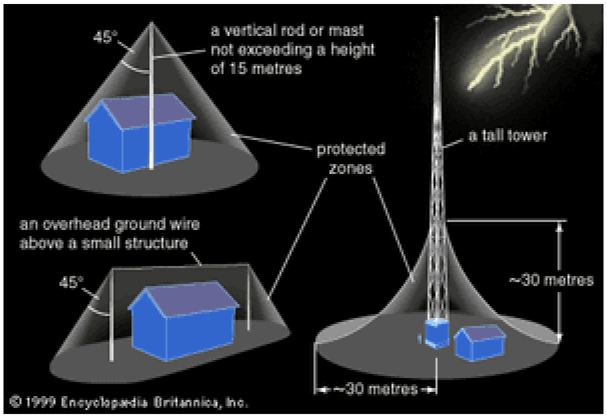
What causes thunder and lightning?Learn about lightning and thunder.
See all videos for this article

The potential difference between cloud and ground is of the order of 10 to 100 million volts, and the peak currents in return strokes to negative leaders are typically about 30,000 amperes. The peak temperatures in the return-stroke channel are on the order of 30,000 °C (50,000 °F). The entire process is very rapid; the leader stroke reaches the ground in about 30 milliseconds, and the return stroke reaches the centre of the cloud in about 100 microseconds. During this stage, approximately 105 joules of energy per metre are dissipated within the lightning channel. This sudden dissipation splits air molecules in the channel—principally those of nitrogen, oxygen, and water—into their respective atoms, and, on average, one electron is removed from each atom. The conversion from neutral air molecules to a completely ionized plasma occurs in a few microseconds.



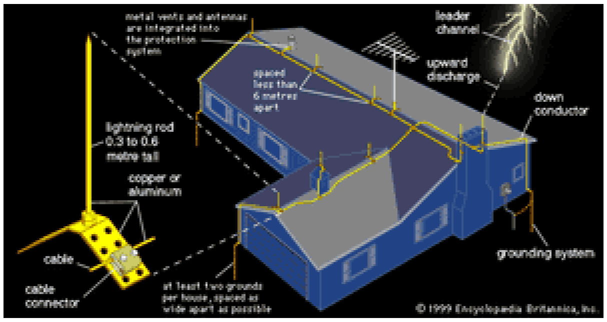
lightning and thunder(Top) As shown in the chart, the elapsed time between seeing a flash of lightning and hearing the thunder is roughly three seconds for each kilometre, or five seconds for each mile. (Bottom) An observer's relative distance from the main lightning channel and its secondary branches determines whether thunder is heard to start with a sudden clap or a softer rumbling.(more)

Thunder is produced by rapid heating of the air in the lightning channel and a consequent increase in air pressure. The pressure produced from the stroke plasma, which is much greater than the pressure of the surrounding atmosphere, causes the channel to expand at supersonic speeds, which ultimately produces a sound wave heard as thunder. The claps, rolls, and rumbles that characterize the sound of thunder are produced by the complex geometry and tortuosity of the lightning channel as well as the effects of the atmosphere and local topography on sound propagation.



1 of 2

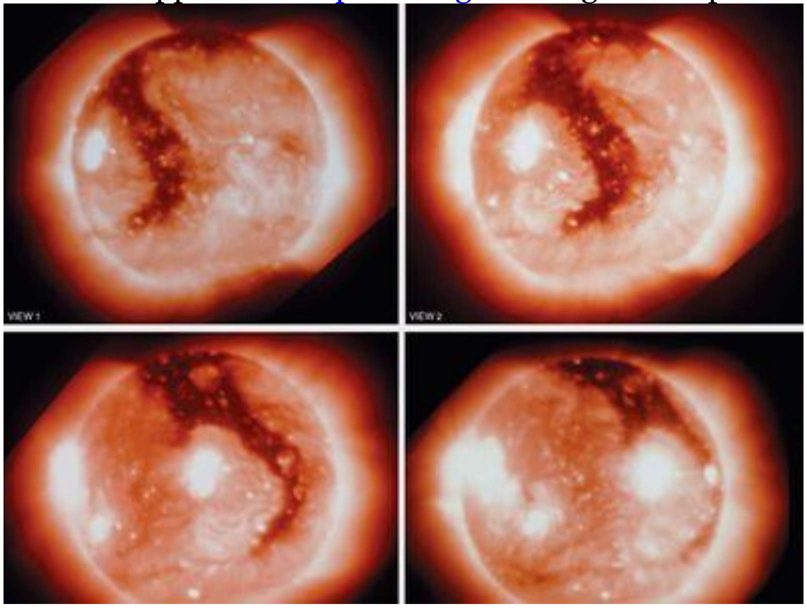
lightning rod types(Left top) Vertical rods or masts up to 15 metres in height create lightning protection zones that extend in a 45° cone from the rod's tip. (Left bottom) Connecting two rods with a wire extends the zone of protection. (Right) Towers taller than 30 metres provide protection for an area 30 metres high and 60 metres wide. The protected zone is in the shape of an inverted funnel with inward-curving sides. Towers between 15 and 30 metres high create protected zones of similar shape but with height and width equal to tower height.(more)



2 of 2

lightning rod protection system for a residential buildingThe flow of electricity from a lightning strike is channeled harmlessly around the outside of the building and into the ground.(more)

Lightning is a significant weather hazard and occurs at an average rate of 50 to 100 discharges per second worldwide. Lightning rods and metallic conductors can be used to protect a structure by intercepting and diverting the lightning current into the ground as harmlessly as possible. When lightning is likely to occur, people are advised to stay indoors or in a car, away from open doors and windows, and to avoid contact with any electrical appliances or plumbing that might be exposed to the outside environment.



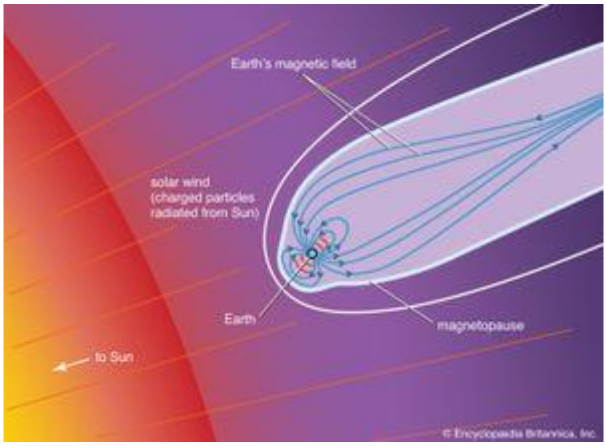
Sun: coronal hole Soft X-ray images of a hole in the Sun's corona, taken two days apart by the Skylab telescope. Coronal holes are sources of high-velocity streams in the solar wind.(more)

solar wind

astronomy

solar wind, flux of particles, chiefly protons and electrons together with nuclei of heavier elements in smaller numbers, that are accelerated by the high temperatures of the solar corona, or outer region of the Sun, to velocities large enough to allow them to escape from the Sun's gravitational field. The solar wind is responsible for creating the tail of Earth's magnetosphere and the tails of comets, both of which face away from the

Sun. At a distance of one astronomical unit (AU; the mean distance between Earth and the Sun, about 150 million km [93 million miles]), during a relatively quiet period, the wind contains approximately 1 to 10 protons per cubic centimetre moving outward from the Sun at velocities of 350 to 700 km (about 220 to 440 miles) per second; this creates a positive ion flux of 10^8 to 10^9 ions per square centimetre per second, each ion having an energy equal to at least 15 electron volts. During solar flares, the proton velocity, flux, plasma temperature, and associated turbulence increase substantially.

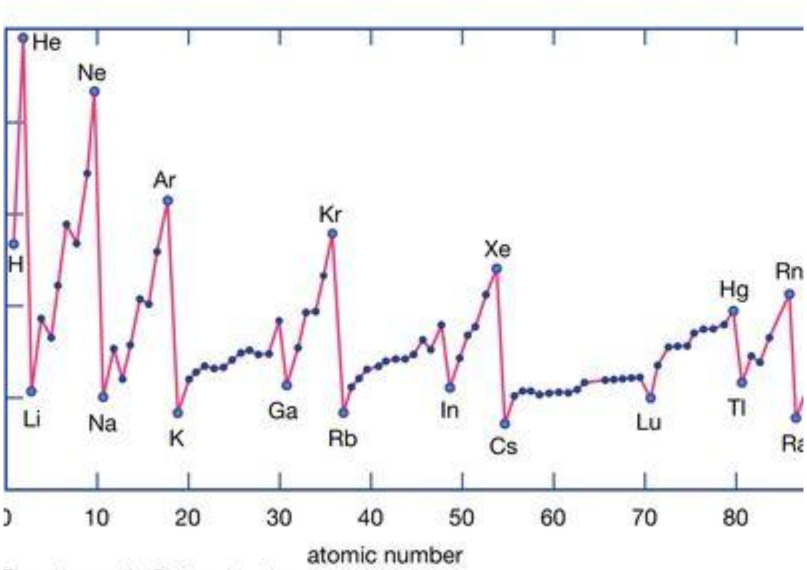


Earth's magnetosphereEarth's magnetosphere. The magnetosphere's tail is created by the solar wind.

There are two solar winds: a fast, uniform, and steady wind, blowing at 800 km (500 miles) per second, and a slow, gusty, and sporadic wind, with about half the speed of the fast one. The two winds originate at different places on the Sun and accelerate to terminal velocity at different distances from it. The distribution of the two solar wind sources depends on the 11-year solar activity cycle.

When the solar wind encounters Earth's magnetic field, a shock wave results, the nature of which is not fully understood. As the solar wind spreads out into an increasing volume, its density and pressure become less. Eventually the pressure of the solar wind becomes comparable to that of the interstellar medium. The termination shock, where the solar wind slows because it encounters the interstellar medium, has been measured at about 94 and 84 AU by the Voyager 1 and 2 spacecraft, respectively.

Astrophysics



Encyclopædia Britannica, Inc.

first ionization energies of the elements

Ionization energy

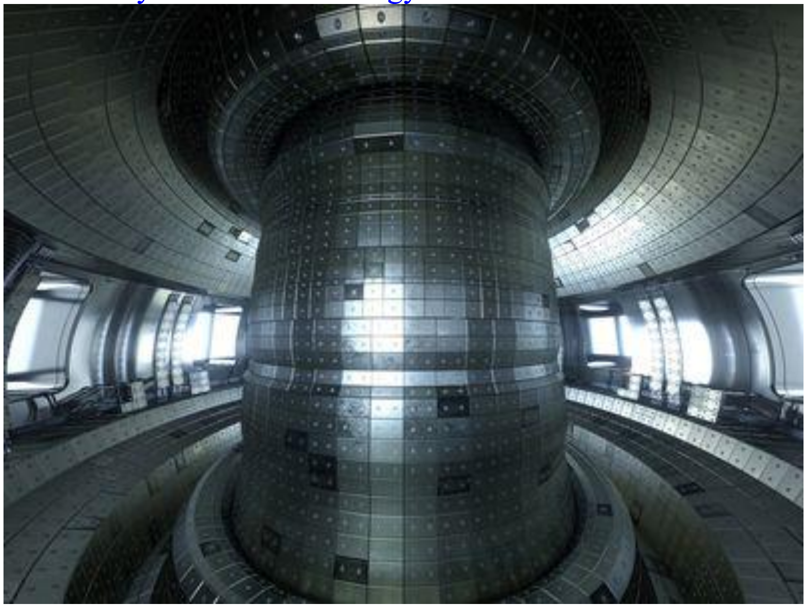
chemistry

ionization energy, in chemistry and physics, the amount of energy required to remove an electron from an isolated atom or molecule. There is an ionization energy for each successive electron removed; the ionization energy associated with removal of the first (most loosely held) electron, however, is most commonly used.

The ionization energy of a chemical element, expressed in joules or electron volts, is usually measured in an electric discharge tube in which a fast-moving electron generated by an electric current collides with a gaseous atom of the element, causing it to eject one of its electrons. (Chemists typically use joules, while physicists use electron volts.) For a hydrogen atom, composed of an orbiting electron bound to a nucleus of one proton, an ionization energy of 2.18×10^{-18} joule (13.6 electron volts) is required to force the electron from its lowest energy level entirely out of the atom. The magnitude of the ionization energy of an element is dependent on the combined effects of the electric charge of the nucleus, the size of the atom, and its electronic configuration. Among the chemical elements of any period, removal of an electron is hardest for the noble gases and easiest for the alkali metals. The ionization energy required for removal of electrons increases progressively as the atom loses electrons, because the positive charge on the nucleus of the atom does not change, and therefore, with each removal of an electron, the remainder are held more firmly. The ionization energy is often reported as the amount of energy (in joules) required to ionize the number of atoms or molecules present in one mole (i.e., the amount in grams of a given substance numerically equal to its atomic or molecular weight). One mole of hydrogen atoms has an atomic weight of 1.00 gram, and the ionization energy is 1,312 kilojoules per mole of hydrogen.

The ionization energy is a measure of the capability of an element to enter into chemical reactions requiring ion formation or donation of electrons. It is also generally related to the nature of the chemical bonding in the compounds formed by the elements. *See also* binding energy; electron affinity.

SciencePhysicsMatter & Energy



3D illustration of a tokamak fusion reactor A tokamak is a device used in nuclear-fusion research for magnetic confinement of plasma.(more)

Fusion reactor

fusion reactor, a device to produce electrical power from the energy released in a nuclear fusion reaction. The use of nuclear fusion reactions for electricity generation remains theoretical.

What is the difference between nuclear fission and fusion?There are two ways of releasing nuclear energy: fission and fusion.

Since the 1930s, scientists have known that the Sun and other stars generate their energy by nuclear fusion. They realized that if fusion energy generation could be replicated in a controlled manner on Earth, it might very well provide a safe, clean, and inexhaustible source of energy. The 1950s saw the beginning of a worldwide research effort to develop a fusion reactor. The substantial accomplishments and prospects of this continuing endeavour are described in this article.

General characteristics

The energy-producing mechanism in a fusion reactor is the joining together of two light atomic nuclei. When two nuclei fuse, a small amount of mass is converted into a large amount of energy. Energy (E) and mass (m) are related through Einstein's relation, $E = mc^2$, by the large conversion factor c^2, where c is the speed of light (about 3

× 10^8 metres per second, or 186,000 miles per second). Mass can be converted to energy also by nuclear fission, the splitting of a heavy nucleus. This splitting process is utilized in nuclear reactors.

Fusion reactions are inhibited by the electrical repulsive force, called the Coulomb force, that acts between two positively charged nuclei. For fusion to occur, the two nuclei must approach each other at high speed in order to overcome their electrical repulsion and attain a sufficiently small separation (less than one-trillionth of a centimetre) so that the short-range strong force dominates. For the production of useful amounts of energy, a large number of nuclei must undergo fusion; that is to say, a gas of fusing nuclei must be produced. In a gas at extremely high temperatures, the average nucleus contains sufficient kinetic energy to undergo fusion. Such a medium can be produced by heating an ordinary gas beyond the temperature at which electrons are knocked out of their atoms. The result is an ionized gas consisting of free negative electrons and positive nuclei. This ionized gas is in a plasma state, the fourth state of matter. Most of the matter in the universe is in the plasma state.

At the core of experimental fusion reactors is a high-temperature plasma. Fusion occurs between the nuclei, with the electrons present only to maintain macroscopic charge neutrality. The temperature of the plasma is about 100,000,000 kelvins (K; about 100,000,000 °C, or 180,000,000 °F), which is more than six times the temperature at the centre of the Sun. (Higher temperatures are required for the lower pressures and densities encountered in fusion reactors.) A plasma loses energy through processes such as radiation, conduction, and convection, so sustaining a hot plasma requires that fusion reactions add enough energy to balance the energy losses. In order to achieve this balance, the product of the plasma's density and its energy confinement time (the time it takes the plasma to lose its energy if unreplaced) must exceed a critical value.

Stars, including the Sun, consist of plasmas that generate energy by fusion reactions. In these natural fusion reactors, plasma is confined at high pressures by the immense gravitational field. It is not possible to assemble on Earth a plasma sufficiently massive to be gravitationally confined. For terrestrial applications, there are two main approaches to controlled fusion—namely, magnetic confinement and inertial confinement.

In magnetic confinement a low-density plasma is confined for a long period of time by a magnetic field. The plasma density is roughly 10^{21} particles per cubic metre, which is many thousands of times less than the density of air at room temperature. The energy confinement time must then be at least one second—i.e., the energy in the plasma must be replaced every second.

In inertial confinement no attempt is made to confine the plasma beyond the time it takes the plasma to disassemble. The energy confinement time is simply the time it takes the fusing plasma to expand. Confined only by its own inertia, the plasma survives for only about one-billionth of a second (one nanosecond). Hence, breakeven in this scheme requires a very large particle density, typically about 10^{30} particles per cubic metre, which is about 100 times the density of a liquid. A thermonuclear bomb is an example of an inertially confined plasma. In an inertial confinement power plant, the extreme density is achieved by compressing a millimetre-scale solid pellet of fuel with lasers or particle beams. These approaches are sometimes referred to as laser fusion or particle-beam fusion.

The fusion reaction least difficult to achieve combines a deuteron (the nucleus of a deuterium atom) with a triton (the nucleus of a tritium atom). Both nuclei are isotopes of the hydrogen nucleus and contain a single unit of positive electric charge. Deuterium-tritium (D-T) fusion thus requires the nuclei to have lower kinetic energy than is needed for the fusion of more highly charged, heavier nuclei. The two products of the reaction are an alpha particle (the nucleus of a helium atom) at an energy of 3.5 million electron volts (MeV) and a neutron at an energy of 14.1 MeV (1 MeV is the energy equivalent of a temperature of about 10,000,000,000 K). The neutron, lacking electric charge, is not affected by electric or magnetic fields and can escape the plasma to deposit its energy in a surrounding material, such as lithium. The heat generated in the lithium “blanket” can then be converted to electrical energy by conventional means, such as steam-driven turbines. The electrically charged alpha particles, meanwhile, collide with the deuterons and tritons (by their electrical interaction) and can be magnetically confined within the plasma, thereby transferring their energy to the reacting nuclei. When this redeposition of the fusion energy into the plasma exceeds the power lost from the plasma, the plasma will be self-sustaining, or “ignited.”

Although tritium does not occur naturally, tritons and alpha particles are produced when neutrons from the D-T fusion reactions are captured in the surrounding lithium blanket. The tritons are then fed back into the plasma. In this respect, D-T fusion reactors are unique as they use their waste (neutrons) to generate more fuel. Overall, a D-T fusion reactor uses deuterium and lithium as fuel and generates helium as a reaction by-product. Deuterium can be readily obtained from seawater—about one in every 3,000 water molecules contains a deuterium atom. Lithium is also abundant and inexpensive. In fact, there is enough deuterium and lithium in the oceans to provide for the world’s energy needs for billions of years. With deuterium and lithium as the fuel, a D-T fusion reactor would be an effectively inexhaustible source of energy.

A practical fusion reactor would also have several attractive safety and environmental features. First, a fusion reactor would not release the pollutants that accompany the combustion of fossil fuels—in particular, the gases that contribute to global warming. Second, because the fusion reaction is not a chain reaction, a fusion reactor cannot undergo a runaway chain reaction, or “meltdown,” as can happen in a fission reactor. The fusion reaction requires a confined hot plasma, and any interruption of a plasma control system would extinguish the plasma and terminate fusion. Third, the main products of a fusion reaction (helium atoms) are not radioactive. Although some radioactive by-products are produced by the absorption of neutrons in the surrounding material, low-activation materials exist such that these by-products have much shorter half-lives and are less toxic than the waste products of a nuclear reactor. Examples of such low-activation materials include special steels or ceramic composites (e.g., silicon carbide).

Principles of magnetic confinement

Confinement physics

Magnetic confinement of plasmas is the most highly developed approach to controlled fusion. A large part of the problem of fusion has been the attainment of magnetic field configurations that effectively confine the plasma. A successful configuration must meet three criteria: (1) the plasma must be in a time-independent equilibrium state, (2) the equilibrium must be macroscopically stable, and (3) the leakage of plasma energy to the bounding wall must be small.

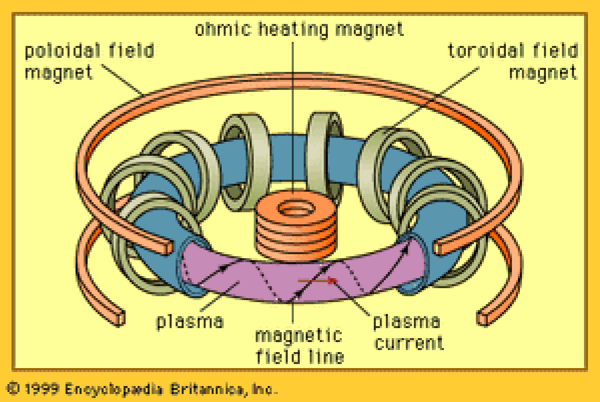
Charged particles tend to spiral about a magnetic line of force. It is necessary that these particle trajectories do not intersect the bounding wall. Simultaneously, the thermal energy of all the particles exerts an expansive pressure force on the plasma. For the plasma to be in equilibrium, the magnetic force acting on the electric current within the plasma must balance the pressure force at every point in the plasma.

This equilibrium must be stable, which is to say that the plasma will return to its original state following any small perturbation, such as continual random thermal "noise" fluctuations. In contrast, an unstable plasma would likely depart from its equilibrium state and rapidly (perhaps in less than one-thousandth of a second) escape the confining magnetic field following any small perturbation.

A plasma in stable equilibrium can be maintained indefinitely if the leakage of energy from the plasma is balanced by energy input. If the plasma energy loss is too large, then ignition cannot be achieved. An unavoidable diffusion of energy across the magnetic field lines will occur from the collisions between the particles. The net effect is to transport energy from the hot core to the wall. In theory, this transport process, known as classical diffusion, is not strong in hot fusion plasmas and can be compensated by heat from the alpha particle fusion products. In experiments, however, energy is lost from the plasma at 10 to 100 times that expected from classical diffusion theory. Solution of the anomalous transport problem involves research into fundamental topics in plasma physics, such as plasma turbulence.

Many different types of magnetic configurations for plasma confinement have been devised and tested over the years. These may be grouped into two classes: closed, toroidal configurations and open, linear configurations. Toroidal devices are the most highly developed. In a simple straight magnetic field, the plasma would be free to stream out the ends. End loss can be eliminated by forming the plasma and field in the closed shape of a doughnut, or torus, or, in an approach called mirror confinement, by "plugging" the ends of such a device magnetically and electrostatically.

Toroidal confinement



Tokamak magnetic confinement

The most extensively investigated toroidal confinement concept is the tokamak. The tokamak (an acronym derived from the Russian words for “toroidal magnetic confinement”) was introduced in the mid-1960s by Soviet plasma physicists. The magnetic lines of force are helixes that spiral around the torus. The helical magnetic field has two components: (1) a toroidal component, which points the long way around the torus, and (2) a poloidal component directed the short way around the machine. Both components are necessary for the plasma to be in stable equilibrium. If the poloidal field were zero, so that the field lines were simply circles wrapped about the torus, then the plasma would not be in equilibrium. The particles would not strictly follow the field lines but would drift to the walls. The addition of the poloidal field provides particle orbits that are contained within the device. If the toroidal field were zero, so that the magnetic field lines were directed only the short way around the torus, the plasma would be in equilibrium, but it would be unstable. The plasma column would develop growing distortions, or kinks, which would carry the plasma into the wall.

The toroidal field is produced by coils that surround the toroidal vacuum chamber containing the plasma. (The plasma must be situated within an evacuated chamber to prevent it from being cooled by interactions with air molecules.) In order to minimize power losses in the coils, designs involving superconducting coils have begun to replace copper coils. The plasma in a tokamak fusion reactor would have a major diameter in the range of 10 metres (33 feet) and a minor diameter of roughly 2 to 3 metres. The plasma current would likely be on the order of tens of millions of amperes, and the flex density of the toroidal magnetic field would measure several teslas. In order to help guide research and development, scientists frequently perform conceptual designs of fusion reactors. One such concept is shown in the figure. This device in theory would generate 1 gigawatt (1 billion watts) of electric power—sufficient to meet the electricity needs of a large city.

The poloidal field is generated by a toroidal electric current that is forced to flow within the conducting plasma. Faraday’s law of induction can be used to initiate and build up the current. A solenoid located in the hole of the torus can be used to generate magnetic flux that increases over time. The time-varying flux induces a toroidal electric field that drives the plasma current. This technique efficiently drives a pulsed plasma current. However, it cannot be used for a steady-state current, which would require a magnetic flux increasing indefinitely over time. Unfortunately, a pulsed reactor would suffer from many engineering problems, such as materials fatigue, and thus other methods have been developed to drive a steady-state current to produce the poloidal magnetic field.

A technique known as radio-frequency (RF) current drive employs electromagnetic radiation to generate a steady-state current. Electromagnetic waves are injected into the plasma so that they propagate within the plasma in one direction around the torus. The speed of the waves is chosen to equal roughly the average speed of the electrons in the plasma. The wave electric field (which in a plasma has a component along its direction of travel) can then continuously accelerate the electrons as the wave and particles move together around the torus. The electrons develop a net motion, or current, in one direction.

Another established current-drive technique is neutral-beam current drive. A beam of high-energy neutral atoms is injected into the plasma along the toroidal direction. The neutral beam will freely enter the plasma since it is unaffected by the magnetic field. The neutral atoms become ionized by collisions with the electrons. The beam then consists of energetic positively charged nuclei that are confined within the plasma by the magnetic field. The high-speed ions travel toroidally along the magnetic field and collide with the electrons, pushing them in one direction and thereby producing a current.

Both RF and neutral-beam current-drive techniques have a low efficiency (i.e., they require a large amount of power to drive the plasma current). Fortunately, a remarkable effect occurs in tokamak plasmas that reduces the need for external current drive. If the plasma pressure is greater in the core than at the edge, this pressure differential spontaneously drives a toroidal current in the plasma. This current is called the bootstrap current. It can be considered a type of thermoelectric effect, but its origin is in the complex particle dynamics that arise in a toroidal plasma. It has been observed in experiments and is now included routinely in advanced experiments and in tokamak reactor designs.

Other toroidal confinement concepts that offer potential advantages over the tokamak are being developed. Three such alternatives are the stellarator, reversed-field pinch (RFP), and compact torus concepts. The stellarator and RFP are much like the tokamak. In the stellarator the magnetic field is produced by external coils only. Thus, the plasma current is essentially zero, and the problems inherent in sustaining a large plasma current are absent. The RFP differs from the tokamak in that it operates with a weak toroidal magnetic field. This results in a compact, high-power-density reactor with copper (instead of superconducting) coils. Compact tori are toroidal plasmas with no hole in the centre of the torus. Reactors based on compact tori are small and avoid the engineering complications of coils linking the plasma torus.

Mirror confinement

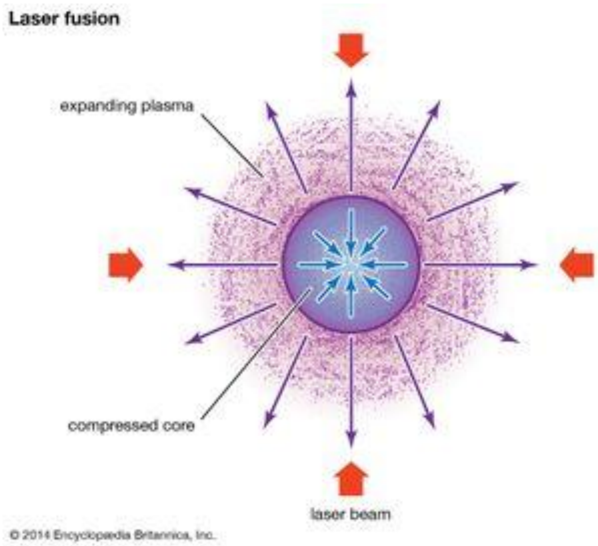
An alternative approach to magnetic confinement is to employ a straight configuration in which the end loss is reduced by a combination of magnetic and electric plugging. In such a linear fusion reactor the magnetic field strength is increased at the ends. Charged particles that approach the end slow down, and many are reflected from this “magnetic mirror.” (The same magnetic reflection mechanism traps particles in the Earth’s magnetosphere, specifically in the Van Allen radiation belts.) Unfortunately, particles with extremely high speed along the field are not stopped by the mirror. To inhibit this leakage, electrostatic plugging is provided. An additional section of plasma is added at each end beyond the magnetic mirror. The plasma in these “end plugs” produces an electrostatic potential barrier to nuclei. The overall configuration is called a tandem mirror.

Plasma heating

A plasma needs to be heated to about 100,000,000 K for fusion reactions to take place. Two plasma-heating methods have been highly developed: electromagnetic wave heating and neutral-beam injection heating. In the former, electromagnetic waves are directed by antennas at the surface of the plasma. The waves penetrate the plasma and transfer their energy to the constituent particles. Ionized gases can support the propagation of a remarkably large variety of waves not found in other forms of matter. Effective wave-heating techniques employ frequencies from the radio-frequency range to the microwave range. Power absorption often relies upon a resonant interaction between the wave and plasma. For example, if the frequency of the electromagnetic wave is equal to the frequency at which a nucleus gyrates about a magnetic field line, this resonant nucleus absorbs energy from the wave. This technique is called ion cyclotron resonance heating. Similarly, electron cyclotron resonance heating may be used to heat electrons. Such electron heating requires very high frequencies (tens to hundreds of gigahertz), such as produced by free-electron lasers and gyrotron tubes.

In the second method, beams of neutral atoms at high energy (up to about one million electron volts) are injected into the plasma, rather as in the neutral-beam current drive described above. When used for heating, however, the beams are injected in both directions around the torus, so that no net momentum is imparted to the plasma. The slowing down, or transfer of beam energy to the plasma, constitutes the heating mechanism.

Principles of inertial confinement



laser fusion

In an inertial confinement fusion (ICF) reactor, a tiny solid pellet of fuel—such as deuterium-tritium (D-T)—would be compressed to tremendous density and temperature so that fusion power is produced in the few nanoseconds before the pellet blows apart. The compression is accomplished by focusing an intense laser beam or a charged particle beam, referred to as the driver, upon the small pellet (typically 1 to 10 mm in diameter). For efficient thermonuclear burn, the time allotted for the pellet to burn must be less than the disassembly time. This means that, in the compressed state, the product of the pellet mass density and the pellet radius must exceed about 3 grams per square centimetre. A high mass density will hasten the burn, and a large radius will slow the disassembly time. The ratio of fusion energy produced in the pellet explosion to the driver energy is called the pellet gain. High pellet gains of 100 or more are required for an ICF reactor.

Pellets are multilayered, consisting of several concentric spheres. The surface of the pellet is ionized by the driver beam, and ablation of the ionized material generates a large inward force on the pellet. Recoil from the ablation implodes the inner layer, producing a shock wave that compresses the inner layers of the D-T fuel. The implosion speed is several hundred kilometres per second, produced by a force equivalent to some 10 billion atmospheres. The target layers are designed such that the laser or particle-beam energy provides compression, not heat (entropy), during this stage. At the final stage of compression, the pellet is compressed to 1,000 to 10,000 times the density of typical solids.

In conventional ICF (usually referred to as shock-heated ICF), the laser or particle-beam energy pulses are accurately set such that the shocks produced during the implosion phase converge in the centre of the pellet, heating it to fusion temperatures. The burn initiates in the central D-T layer and spreads outward as the alpha particles collide with and heat the rest of the pellet to a value sufficient to produce fusion reactions. Ignition occurs, and the pellet, now a dense plasma, is burned up in a small microexplosion. An alternative method for ICF, known as fast ignition, has emerged in recent years because of rapid progress in generating intense picosecond (10^{-12} second) laser systems. Fast ignition can reduce the driver energy considerably. In this scheme, the main laser or particle beam is used to compress the fuel similar to shock heating. Then a short, intense laser pulse heats a small portion of the compressed fuel to fusion temperature, initiating the fusion burn. This approach may lead to target gains that are 3 to 10 times larger than in shock heating.

It is essential that the implosion of the outer layer of the target be symmetric and uniform to a high degree of accuracy. Any asymmetry can grow during compression, and, more important, the shocks may not precisely converge on the centre, which would prevent ignition of the fuel. Thus, the pellet must be manufactured with a high degree of smoothness, with tolerances of less than a thousandth of a millimetre. The driver should also deposit its energy on the pellet uniformly, with a variation of less than 1 percent. There are two methods to achieve this uniformity. In the first method, known as indirect drive, the pellet is located inside a hollow cylindrical shell known as a hohlraum, and the driver is aimed at the walls of the hohlraum. The hohlraum absorbs the driver's energy and then radiates the target with intense X-rays, which cause the pellet to heat and implode. Because a hohlraum is effectively a resonant cavity, the X-ray intensity on the target will be quite uniform even if few driver beams are used. The drawback of this technique is that the target gain is reduced because of inefficiency in converting the driver energy to X-rays. A higher gain is seen in the second method, known as direct drive, but here the driver system is much more complex, as many driver beams and special optical elements are needed to achieve the necessary uniform delivery of energy to the target.

Development of fusion reactor technology

Magnetic confinement

Several decades of fusion research have produced accomplishments of two types. First, the discipline of plasma physics has developed to the point that theoretical and experimental tools permit quantitative evaluation of many aspects of fusion reactor concepts. Second, and perhaps most revealing, the evolutionary improvement of plasma parameters has placed experiments at the threshold of energy breakeven, in which energy input to the plasma is equal to fusion energy produced.

Fusion research experiments are performed with hydrogen or deuterium plasmas in most cases. For years, radioactive tritium was not added, because remote-handling requirements complicated the experiments. However, in 1991 the first tritium-deuterium reaction was carried out. The "burn" lasted for two seconds and released a record amount of energy, approximately 20 times that released in deuterium-deuterium experiments.

A figure of merit with which to judge the plasma quality is the energy gain Q that would occur if the plasma contained tritium. From 1965 to 1995, Q increased from 10^{-7} to 1 (breakeven).

A wide variety of plasma experiments have been performed to investigate many aspects of the fusion problem. Performances closest to the level of a practical fusion reactor have been attained in three flagship experiments in Europe, Japan, and the United States. These large tokamak facilities are the Joint European Torus (JET), a multinational western European venture operated in England; the Tokamak-60 (JT-60) of the Japan Atomic Energy Research Institute; and the Tokamak Fusion Test Reactor (TFTR) at the Princeton Plasma Physics Laboratory in New Jersey, respectively.

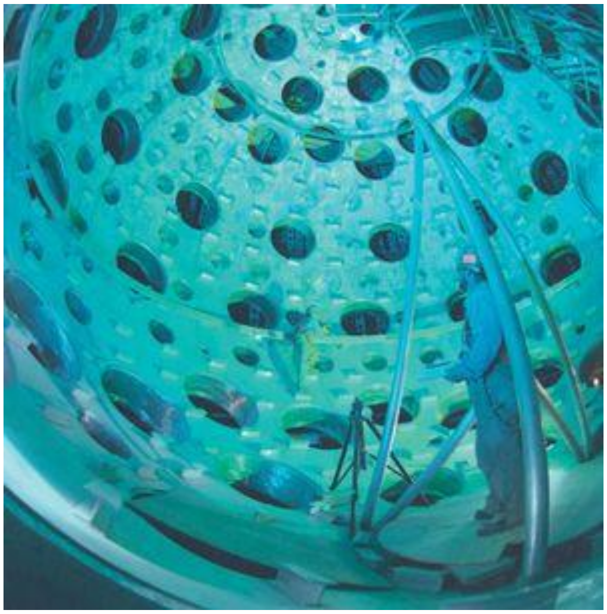
In 1994 a major milestone was achieved when the TFTR generated 10 megawatts of fusion power. Up to that time, almost all fusion experiments had been operated with hydrogen or deuterium plasmas. TFTR was fueled with a mixture of deuterium and tritium. Experimentation with fusing plasmas is critical to establish the effect of the fusion reactions (and the high-energy alpha particles that they produce) on plasma behaviour. In 1997, JET generated 16 megawatts of peak power with a fusion gain (the ratio of fusion power produced to the net input power) of 0.6.

A next major step in the development of fusion power is the construction of a facility to study the physics of a burning, ignited plasma (with Q being infinite). The presence of alpha particles can alter the behaviour of the plasma in ways not easily simulated in nonburning plasmas. It is anticipated that this will occur in a planned new experiment, the International Thermonuclear Experimental Reactor (ITER) to be constructed at Cadarache, France. This is a very large experiment that will investigate both the physics of an ignited plasma and reactor technology. The large cost of the device has encouraged international collaboration in its design and funding, with participation from the European Union, Japan, China, India, South Korea, Russia, and the United States.

With the tremendous advances in scientific understanding and plasma quality, questions regarding the engineering and economic attractiveness of the tokamak concept have received greater attention. Materials development is required. For example, the wall exposed to the plasma must survive intense neutron bombardment. The optimal path to fusion energy production involves some balance between further upscaling of the current tokamak concept toward reactor parameters and improvement of the magnetic confinement concept. Improvements can accrue from enhanced scientific understanding through research and by the development of alternative, non-tokamak concepts, as well as improvements to the tokamak. A significant thrust in tokamak research is to develop more-compact tokamaks with higher plasma pressure. Such advanced tokamaks are expected to be more economical.

Inertial confinement

ICF research has followed an evolutionary path similar to that of magnetic fusion. In the laser fusion approach, densities ranging from 100 to 200 times liquid deuterium-tritium density have been achieved. For example, at the Lawrence Livermore National Laboratory in California, a product of density and energy-confinement time of 5×10^{14} seconds per cubic centimetre has been achieved employing the world’s largest and most powerful laser, the Nova laser. (The Nova is a 10-beam neodymium-glass laser operated at an energy level of 40,000 joules in a one-nanosecond pulse.) Although the value of this product is comparable to that representing breakeven for magnetic fusion, laser fusion requires a larger value to overcome the rather poor efficiency of existing lasers.



laser-activated fusionInterior of the U.S. Department of Energy's National Ignition Facility (NIF), located at Lawrence Livermore National Laboratory, Livermore, California. The NIF target chamber uses a high-energy laser to heat fusion fuel to temperatures sufficient for thermonuclear ignition. The facility is used for basic science, fusion energy research, and nuclear weapons testing.(more)

As a result of such progress, the National Ignition Facility, a laser fusion experiment that will achieve ignition, has been constructed in the United States. However, this facility, also located at Livermore, is funded primarily for its application to weapons research, not energy research.

The International Thermonuclear Experimental Reactor (ITER) project is a cooperation between the European Union, the United States, China, India, Japan, Russia, and South Korea to build in southern France a prototype fusion reactor with the world’s largest tokamak. The multibillion dollar project is scheduled for completion in 2025 and seeks to prove the feasibility of nuclear fusion as a large-scale source of energy.

In both the magnetic and inertial confinement programs, the experimental steps become more expensive as the reactor regime is approached. At the same time, basic research and innovation are needed to enhance the attractiveness of the reactor concepts. Significant wisdom is required to balance these needs and to build effectively upon the impressive results to date so that nuclear fusion can indeed become a major factor in meeting the world’s ever-growing energy needs.

Breaking Physics: Inside the Strange World of Quantum Metals

New research reveals that quantum critical metals challenge traditional physics, offering insights that could enhance high-temperature superconductors. Credit: SciTechDaily.com

A new study examined how quantum critical metals, which behave unusually under low temperatures, challenge conventional physics theories.

The research reveals that these metals experience significant changes at quantum critical points, potentially informing the development of high-temperature superconductors.

Strange Metals and Quantum Fluctuations

A recent study led by Rice University physicist Qimiao Si sheds light on the mysterious behavior of quantum critical metals — materials that break the usual rules of physics at low temperatures. Published on December 9 in *Nature Physics*, the research explores quantum critical points (QCPs), where materials hover between two distinct states, such as being magnetic or nonmagnetic. These findings help explain the unique properties of these metals and offer new insights into high-temperature superconductors, which conduct electricity without resistance at relatively high temperatures.

At the heart of the study is quantum criticality, a state where materials become extremely sensitive to quantum fluctuations — tiny disruptions that change how electrons behave. While most metals follow well-established physical laws, quantum critical metals defy these expectations, displaying unusual and collective behaviors that have puzzled scientists for decades. Physicists refer to these systems as “strange metals.”

Role of Quasiparticles in Quantum Metals

“Our work dives into how quasiparticles lose their identity in strange metals at these quantum critical points, which leads to unique properties that defy traditional theories,” said Si, the Harry C. and Olga K. Wiess Professor of Physics and Astronomy and director of Rice’s Extreme Quantum Materials Alliance.

Quasiparticles, representing the collective behavior of electrons acting like individual particles, play a crucial role in energy and information transfer in materials. However, at QCPs, these quasiparticles vanish in a phenomenon known as Kondo destruction. Here magnetic moments in the material cease their usual interaction with electrons, dramatically transforming the metal’s electronic structure.

This change is evident in the Fermi surface, a map of possible electron states within the material. As the system crosses the QCP, the Fermi surface abruptly shifts, significantly altering the material’s properties.

Exploring Universal Behaviors

The study extends beyond heavy fermion metals — materials with unusually heavy electrons — to include copper oxides and certain organic compounds. All of these strange metals exhibit behaviors that defy traditional Fermi liquid theory, a framework used to describe electron motion in most metals. Instead, their properties align with fundamental constants such as Planck’s constant, governing the quantum relationship between energy and frequency.

Implications for Advanced Superconductors

The researchers identified a condition called dynamical Planckian scaling, where the temperature dependence of electronic properties mirrors universal phenomena like cosmic microwave background radiation and the radiation of the “black body” that approximates the behavior of stars. This discovery underscores a shared organizational pattern across various quantum critical materials, offering insights into creating advanced superconductors.

Quantum Transitions in New Materials

The research implications extend to other quantum materials, including iron-based superconductors and those with intricate lattice structures. One example is CePdAl, a compound where the interplay of two competing forces — the Kondo effect and RKKY interactions — determines its electronic behavior. By studying these transitions, scientists hope to decode similar phenomena in other correlated materials, where complex interelectronic relationships dominate.

Observing how these forces shape the material at QCPs could help scientists better understand transitions in other correlated materials or those with complex interelectronic relationships.

Reference: “Quantum critical metals and loss of quasiparticles” by Haoyu Hu, Lei Chen and Qimiao Si, 9 December 2024, *Nature Physics*.
DOI: 10.1038/s41567-024-02679-7

This research, co-authored by Haoyu Hu and Lei Chen from Rice’s Department of Physics and Astronomy, Extreme Quantum Materials Alliance and Smalley-Curl Institute, was supported by the National Science Foundation, Air Force Office of Scientific Research, Robert A. Welch Foundation, Vannevar Bush Faculty Fellowship and European Research Council.

US fusion research optimizes stellarator performance to improve plasma confinement

Researchers at the Princeton Plasma Physics Laboratory (PPPL) have made a breakthrough in enhancing the performance of stellarators, a type of fusion device.

Fusion, the process that powers the sun, involves the heating of light atomic nuclei, such as hydrogen isotopes, to form a plasma, an extremely hot and charged gas.

To achieve this on Earth, scientists are exploring various approaches, with stellarators and tokamaks being the leading contenders.

Stellarators, one type of fusion device, have emerged as a promising alternative to traditional tokamaks. Both devices utilize powerful magnetic fields to confine plasma, a hot, charged gas, in a donut shape, facilitating the fusion reaction.

However, they differ in the way these magnetic fields are generated.

Significance of stellarator research

“Tokamaks have three large sets of magnetic field coils. One of them produces an electric current that runs through the center of the plasma. That electric current produces a magnetic field that boosts how well the plasma is confined,” explained the researchers in a press release.

“In contrast, stellarators have many magnet coils that loop around the outside of the plasma. They form twisting magnetic fields that wrap around the donut, without the need for a central current.”

This fundamental difference gives stellarators certain advantages, including inherent steady-state operation and reduced susceptibility to disruptions that can terminate the plasma confinement.

One of the major challenges in stellarator research has been optimizing the confinement of energetic particles within the plasma. These particles, often generated as byproducts of the fusion reactions, play a crucial role in sustaining the plasma temperature and overall efficiency.

However, their high energy makes them prone to escaping the confining magnetic fields, potentially leading to energy loss and damage to the device walls.

Optimizing plasma configurations

To address this issue, scientists at PPPL, in collaboration with researchers from Auburn University, the Max Planck Institute for Plasma Physics in Germany, and the University of Wisconsin-Madison, have developed an innovative computational approach.

Instead of trying to simulate the complex paths of individual particles, which would require too much computing power and time, they devised a proxy function that efficiently predicts how quickly particles escape the magnetic field.

This proxy function, based on a theoretical understanding of particle behavior in complex magnetic fields, enables rapid exploration of a vast range of magnetic configurations.

“Using this proxy function, the team was able to develop a number of different possible plasma configurations that would lose fewer energetic particles,” highlighted the researchers.

Stellarator research has seen notable advances

The sphere of stellarator technology has seen several major developments in recent times.

Thales, a leading company in stellarator technology, recently announced that its TH1507U gyrotron achieved a total output of 1.3 megawatts in radiofrequency at a frequency of 140 gigahertz for 360 seconds.

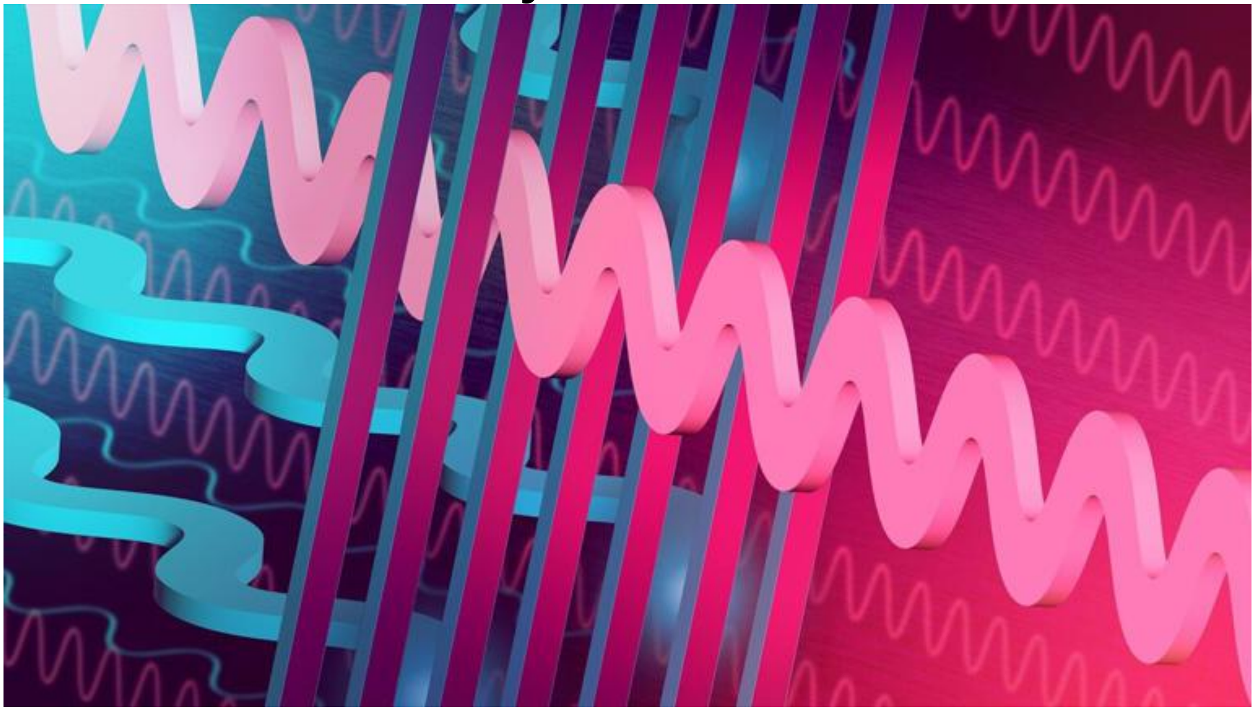
In another development, France-based energy firm Renaissance Fusion is building stellarators that it claims could be the most efficient, steady, and stable fusion reactors on Earth.

The latest development by the PPPL researchers can significantly optimize stellarator performance and bring fusion energy closer to practical realization.

While these findings do not directly translate into a specific device design, they provide valuable guidance for future research and development efforts.

“Eventually, it could enable stellarators to be a viable option for commercial fusion power,” concluded the press release.

Plasma heating efficiency in fusion devices boosted by metal screens



An artist's representation of a metal screen filtering electromagnetic heating waves. Credit: Kyle Palmer / PPPL Communications Department

Heating plasma to the ultra-high temperatures needed for fusion reactions requires more than turning the dial on a thermostat. Scientists consider multiple methods, one of which involves injecting electromagnetic waves into the plasma, the same process that heats food in microwave ovens. But when they produce one type of heating wave, they can sometimes simultaneously create another type of wave that does not heat the plasma, in effect wasting energy.

In response to the problem, scientists at the U.S. Department of Energy's (DOE) Princeton Plasma Physics Laboratory (PPPL) have performed computer simulations confirming a technique that prevents the production of the unhelpful waves, known as slow modes, boosting the heat put into the plasma and increasing the efficiency of the fusion reactions.

"This is the first time scientists have used 2D computer simulations to explore how to reduce slow modes," said Eun-Hwa Kim, a PPPL principal research physicist and lead author of the paper reporting the results in *Physics of Plasmas*.

"The results could lead to more efficient plasma heating and possibly an easier path to fusion energy."

The team, which included researchers from General Atomics who use the DIII-D tokamak fusion facility, determined that positioning a metal grate known as a Faraday screen at a slight five-degree slant with respect to the antenna producing the heating waves, also known as helicon waves, stops the production of the slow modes. Researchers want to avoid creating slow modes, because unlike helicon waves, they cannot penetrate the magnetic field lines confining the plasma to heat the core, where most fusion reactions occur. In addition, the slow modes are easily damped or snuffed out by the plasma itself. Therefore, any energy used to create slow modes is energy that is not used to heat the plasma and foster fusion reactions.

The researchers simulated the production of helicon waves and slow modes using the Petra-M computer code, a powerful and versatile program used to model electromagnetic waves in fusion devices and space plasmas. The simulations replicated conditions in the DIII-D tokamak, a doughnut-shaped plasma device operated by General Atomics for the DOE. The team performed a series of virtual experiments to test which of the following had the greatest effect on the production of slow modes—the antenna's alignment, the Faraday screen's alignment or the density of small particles known as electrons in front of the antenna.

The simulations confirmed suggestions made by previous researchers indicating that when the Faraday screen was aligned at an angle of five degrees or less from the orientation of the antenna, the screen—in effect—short-circuits the slow modes, making them fizzle out before they propagate into the plasma.

The suppression of slow modes depends greatly on how much the Faraday screen leans to the side.

"We found that when the screen's orientation exceeds five degrees by only a little bit, the slow modes grow by a great deal," said PPPL principal research physicist Masayuki Ono, one of the paper's authors. "We were surprised by how sensitive the development of slow modes was to the screen alignment."

Scientists could use this information to tweak the design of new fusion facilities to make their heating more powerful and efficient.

In the future, the scientists plan to increase their understanding of how to prevent slow modes by running computer simulations that consider more of the plasma's properties and factor in more information about the antenna.

More information: E.-H. Kim et al, Full-wave simulations on helicon and parasitic excitation of slow waves near the edge plasma, *Physics of Plasmas* (2024). DOI: 10.1063/5.0222413

Provided by Princeton Plasma Physics Laboratory

US scientists boost nuclear fusion plasma heating efficiency with metal screens

US scientists boost nuclear fusion plasma heating efficiency with metal screens

Nuclear fusion, the powerful reaction that powers the Sun, also has the potential to provide abundant clean energy on Earth.

For instance, the amount of energy produced by burning 2,400 gallons of oil or several million tons of coal can be generated by the fusion of just one gram of deuterium-tritium (a type of nuclear fusion fuel), and that too without releasing any greenhouse gases.

This is why scientists in many parts of the world are trying to make fusion reactions practical and scalable. However, it’s not as easy as it sounds. For a fusion reaction, plasma is required to be heated to hundreds of millions of degrees Celsius — this is seven to eight times more than the temperature found at the Sun’s core.

At first, it may seem impossible to heat plasma to such extreme temperatures, but a new study from researchers at the Princeton Plasma Physics Laboratory (PPPL) suggests that it can be achieved using a Faraday screen.

Getting rid of slow modes

One of the methods that scientists use to heat plasma is called wave heating or radio frequency (RF) heating. This approach involves using electromagnetic waves to shoot up the temperature of the plasma.

When high-frequency waves are injected into the system, they transfer their energy to the charged particle inside the plasma, which causes them to move faster and collide more frequently, leading to a sharp increase in the plasma temperature.

This is similar to how microwaves in an oven interact with water molecules in food. These waves transfer energy to the molecules, causing them to vibrate rapidly. This vibration generates heat, which raises the temperature of the food.

However, this approach has a limitation that prevents the plasma from achieving the required temperature. RF heating also results in additional waves other than the ones that heat the plasma.

These extra waves, called slow modes, lead to energy losses and end up reducing the overall plasma temperature. The study authors ran some simulations that revealed a technique capable of overcoming the slow modes.

“We have performed computer simulations confirming a technique that prevents the production of the unhelpful waves, known as slow modes, boosting the heat put into the plasma and increasing the efficiency of the fusion reactions,” the PPPL team notes.

Special metal screens to achieve fusion

For the first time, the PPPL team ran some 2D simulations to figure out a way of reducing slow modes. During their study, they discovered that when Faraday screens (also called the Faraday cage) are placed at five-degree angles to the antenna that generates electromagnetic waves to heat plasma, slow modes are not produced.

Faraday screen which is made of conducting material, like metal works as a protective barrier blocking or reducing electromagnetic waves.

The simulations demonstrated that the screen allowed the low-frequency heating waves (called the helicon waves) from the antenna to pass into the plasma. However, slow modes were stopped.

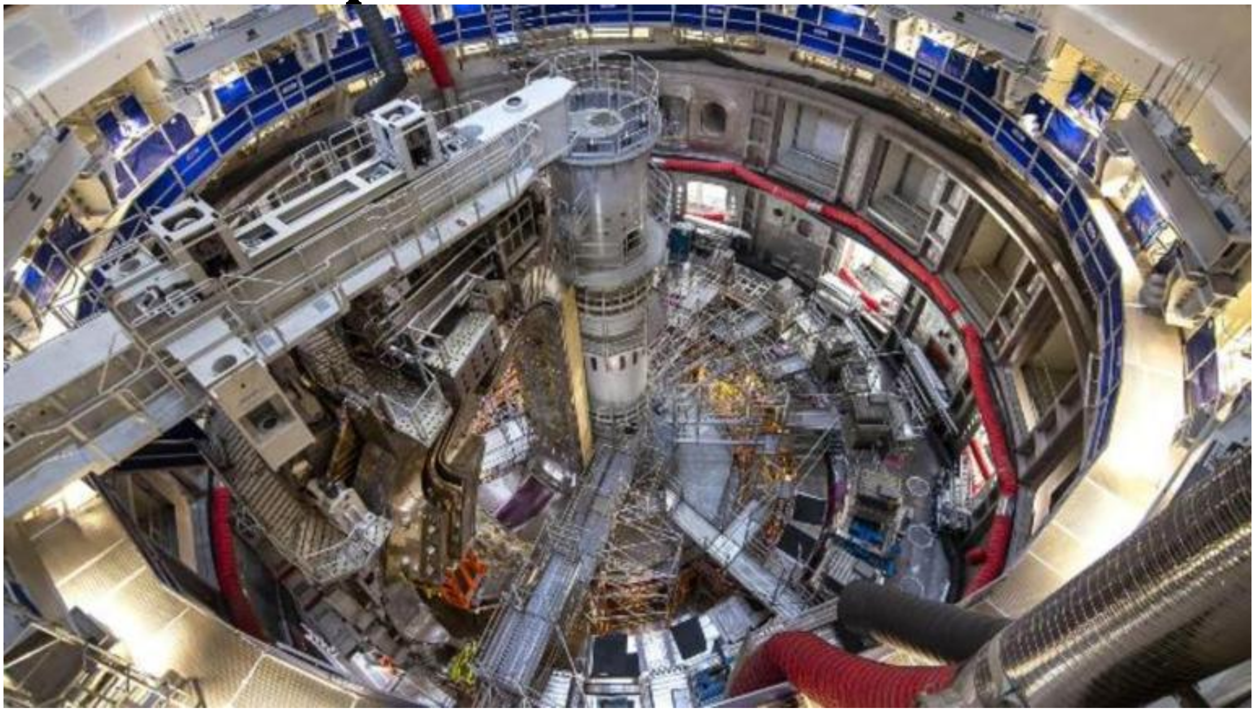
"The simulations confirmed suggestions made by previous researchers indicating that when the Faraday screen was aligned at an angle of five degrees or less from the orientation of the antenna, the screen, in effect, short-circuits the slow modes, making them fizzle out before they propagate into the plasma," the study authors said.

However, as the screen angle was further increased, the slow mode frequency also rose sharply. This observation suggests that plasma temperature is super sensitive to the orientation of the Faraday screen.

The researchers now plan to explore other ways to limit slow modes. These efforts will make it easier to achieve the required ultra-high temperatures needed for fusion reactions.

The study is published in the journal *Physics of Plasmas*.

Scientists ‘surf’ plasma waves to tame nuclear eruptions in fusion reactors



Scientists ‘surf’ plasma waves to tame nuclear eruptions in fusion reactors

One of the most critical challenges in realizing nuclear fusion is the confinement of plasmas, which are the ultra-hot, ionized gases where fusion reactions occur.

“Achieving high confinement is key to the development of nuclear fusion power plants and is the final aim of ITER, the largest tokamak in the world currently under construction in Cadarache (France),” said the researchers of a new study.

“On the road to a magnetic fusion power plant, a good confinement of a burning plasma, at temperatures $>10^8$ K and particle densities $>10^{20}$ m^{-3}, is mandatory,” explained the study.

The fusion plasmas are notoriously unstable and prone to eruptions known as Edge Localized Modes (ELMs), which are similar to solar flares.

These ELMs, which are magnetohydrodynamic waves (MHD), can cause significant energy and particle losses. They can damage the walls of fusion devices and hinder the efficiency of fusion reactions.

“However, a detailed understanding of the ELM behaviour and consequences in a burning plasma with a notable fraction of energetic (suprathermal) ions is missing,” added the study.

Complex interplay between ELMs, energetic ions

In this regard, a team of scientists has made a breakthrough by revealing a complex interplay between ELMs and energetic ions, a key component of fusion plasmas.

“Energetic (suprathermal) particles constitute an essential source of momentum and energy, especially in future burning plasmas,” asserted the team in a press release.

“They must be well confined to guarantee a self-sustaining fusion reaction.”

The team, working within the EUROfusion consortium, discovered that these energetic ions can significantly influence the behavior of ELMs.

“The effect is analogous to a surfer riding the wave. The surfer leaves footprints on the wave when riding it. In a plasma, the energetic particle interacts with the MHD wave (the ELM) and can change its spatio-temporal pattern,” said lead author Jesús José Domínguez-Palacios Durán.

Offering a path to clean and limitless energy source

This potentially offers a new way to control these disruptive events. Notably, the team combined experiments at the ASDEX Upgrade tokamak in Germany with advanced computer simulations using a code called MEGA.

This allowed them to observe the interaction between ELMs and energetic ions in detail and unravel the underlying physics.

“The results indicate that the spatio-temporal structure of ELMs is largely affected by the energetic particle population and indicate that the interaction mechanism between ELMs and energetic particles is a resonant energy exchange between them,” highlighted the press release.

Nuclear fusion, the process that powers the sun, holds immense promise as a clean and virtually limitless energy source for the future.

The latest work represents a significant step forward in the quest for fusion energy, offering hope for a future powered by a clean and abundant energy source. By manipulating the energetic ion population, scientists may be able to tame the ‘solar flares’ of fusion plasmas and unlock the full potential of this clean energy source.

“Our results can have important implications for the optimization of ELM control techniques.”

Scientists use waste CO2 and microwaves to produce high-energy plasma in seconds

A group of scientists has developed special CO2-derived carbon nanotubes that can generate sustained plasma almost instantly when exposed to microwaves from a standard microwave oven.

Plasma is the stuff that makes lightning flash, stars shine, and neon signs glow. It is a special state of matter, like a supercharged gas. It happens when atoms lose some of their electrons, creating a mix of free-moving charged particles.

This makes plasma highly energetic and a good conductor of electricity. It has a wide range of applications across various fields. For instance, it can play an important role in fusion energy research, and enable the development of advanced water and air purification technologies.

Moreover, its unique properties can also contribute to the creation of the next generation of medical sterilization, cancer treatments, and even space propulsion systems.

However, producing high-energy plasma for industrial applications requires specialized equipment and a controlled environment with extremely high temperatures. This is where the CO_2-derived carbon nanotubes can make a huge difference. They promise an easy and more accessible method to produce plasma.

A ninja technique to produce plasma

In their new study, the researchers reveal a method that only uses carbon nanotubes and a microwave oven to produce plasma with temperatures between 820 °C and 925 °C.

Unlike conventional methods, this approach requires no vacuum chambers, no controlled gas environment, and no hi-tech equipment. The researchers claim that this is made possible due to the unique molecular structure of their CO_2-derived carbon nanotubes.

These tubes were produced using the molten carbonate electrolysis of carbon dioxide — a method that converts carbon dioxide (CO_2) into carbon or carbon-based materials using electricity and a high-temperature molten salt.

The process starts with heating a carbonate salt, such as lithium carbonate, until it melts, forming a conductive liquid. The CO_2 gas captured from greenhouse emissions is introduced into this molten mixture. When an electric current is applied, chemical reactions take place at the electrodes.

At the anode, carbonate ions lose electrons, producing oxygen gas. At the cathode, CO_2 is broken down, resulting in solid carbon. The carbon nanotubes developed using this carbon showed exceptional electrical and magnetic properties.

When these nanotubes were placed inside a microwave, within seconds yellow-white colored plasma emerged with a temperature exceeding 800 °C. “An unexpected and high-powered plasma is induced by carbon nanotubes in air under microwave irradiation,” the study authors note.

CO2-derived nanotubes are probably the best

The researchers also tried to produce plasma with commercially available carbon nanotubes (CNT), graphene, and other materials, but none of them could generate sustained high-energy plasma like their CO2-derived nanotubes.

The nanotubes are also special because they are made from waste greenhouse CO2. “The sole reactant preparing these carbon nanotubes is the greenhouse gas CO2,” the researchers note.

So while some conventional plasma-production methods contribute to carbon emissions, the CO_2-derived nanotubes offer a more environmentally friendly approach by utilizing waste carbon dioxide as a raw material to generate plasma.

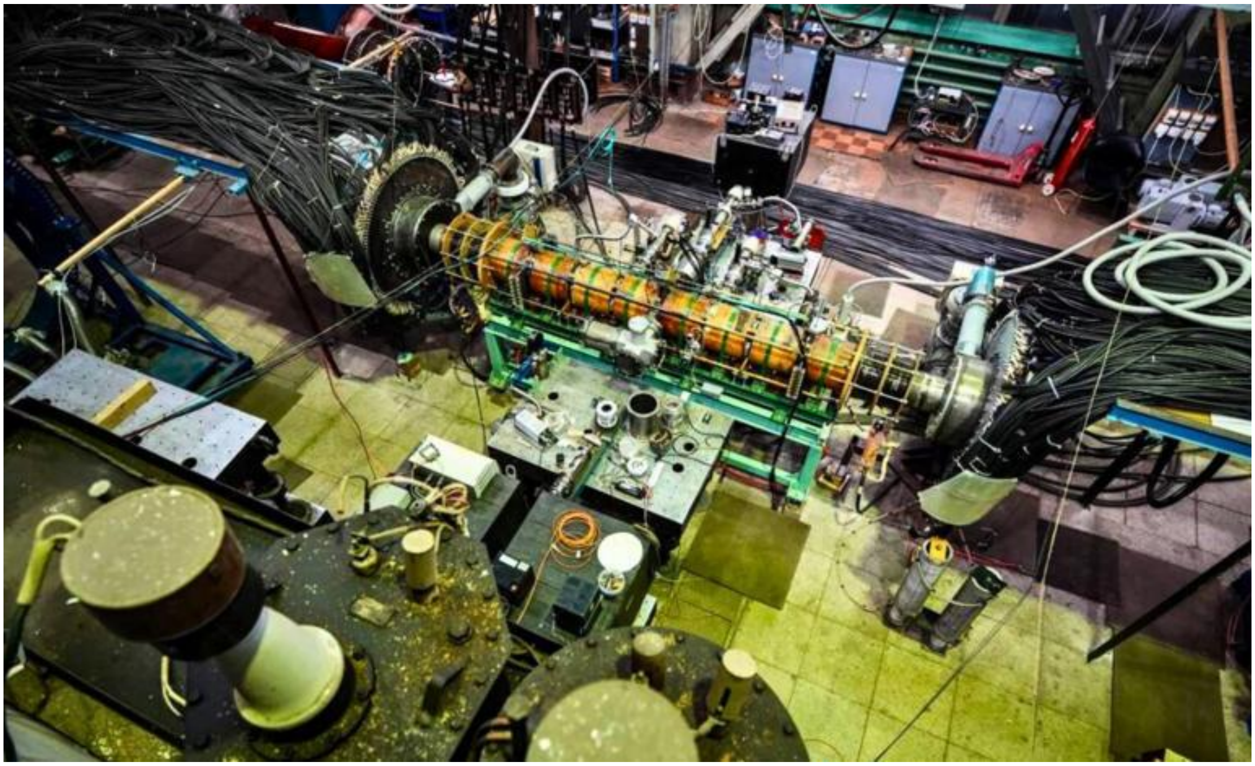
The study also authors tested the quality of the plasma produced through their method. They used it to purify some carbon nanotube samples, and the results of the test were impressive.

“It decreased their impurity level and increased their resistance to combustion,” the study authors said. They further claim their CNT-induced microwave-driven plasma takes “100-fold less time, consumes 10× less power, and produces higher purity CNTs than purification in a conventional plasma cleaning treatment chamber.”

These findings suggest that CO2-derived nanotubes are likely to play an important role in industrial-scale plasma production. However, high-energy plasma could be just one of their many interesting applications.

The study is published in the journal *Nanoscale*

Russian Scientists Develop a Plasma Engine Capable of Reaching Mars in 30 Days—Spacex's Starship Could Become Obsolete



Russian Scientists Develop a Plasma Engine Capable of Reaching Mars in 30 Days—Spacex's Starship Could Become Obsolete | The Daily Galaxy --Great Discoveries Channel© Daily Galaxy US

Russian scientists have unveiled an ambitious new **plasma engine** that could drastically cut the travel time to **Mars**, reducing the journey from several months to just one or two. If successful, this breakthrough could redefine interplanetary exploration and bring humanity closer to deep-space travel. But is this cutting-edge technology ready for real-world missions, or is it just another sci-fi dream?

The Science Behind the Plasma Engine

Developed by **Rosatom's Troitsk Institute**, this revolutionary **magnetoplasma propulsion system** functions differently from traditional chemical rockets. Instead of burning fuel to generate thrust, it uses **electromagnetic fields**to accelerate charged particles—primarily **hydrogen ions**—to extreme speeds of **100 km/s (360,000 km/h)**. By comparison, conventional rockets can only achieve **4.5 km/s** due to the limitations of combustion.

Unlike chemical propulsion, which delivers an initial burst of speed but then coasts, plasma engines provide **continuous thrust**, allowing spacecraft to accelerate steadily over time. This sustained acceleration could allow a spacecraft to **reach Mars in 30 to 60 days**, significantly reducing astronauts' exposure to cosmic radiation and psychological strain during the voyage.

Photo: IZVESTIA/Sergey Lantyukhov© Daily Galaxy US

A Prototype Already in Testing

This isn't just a theoretical concept—scientists at **Rosatom** have already built a **working prototype** of the plasma engine, which is currently undergoing ground tests. The experimental setup includes a **4-meter-wide and 14-meter-long** vacuum chamber designed to replicate space conditions. The engine operates in a **pulse-periodic mode**, with a power output of **300 kW**, and has demonstrated a lifespan of **2,400 hours**, long enough for a Mars-bound journey.

Once operational, the plasma engine will not replace traditional **chemical rockets** but will instead take over once a spacecraft reaches orbit. The system could also be used as a **space tug**, transporting cargo between planetary orbits much faster than current technology allows.

Photo: IZVESTIA/Sergey Lantyukhov© Daily Galaxy US

Why Hydrogen? The Ultimate Space Fuel

One of the key innovations behind this engine is its use of **hydrogen** as the primary propellant. Hydrogen's advantages include:

- **Lightweight and abundant**: It is the most common element in the universe and can potentially be harvested in space.

・**Efficient acceleration**: Lighter atoms allow for faster ion acceleration, maximizing propulsion efficiency.

・**Lower heat generation**: Unlike other plasma propulsion methods, this system doesn’t require extreme temperatures, reducing wear and tear on engine components.

How Does It Compare to Existing Technology?

While plasma propulsion isn’t a new concept, the speeds claimed by **Rosatom**—**100 km/s**—are **far beyond** the capabilities of existing **ion thrusters**, which typically max out at **30-50 km/s**. If these claims hold up, Russia could be decades ahead of competitors in **advanced propulsion systems**.

Currently, NASA’s **Psyche mission** and several **OneWeb satellites** already use Russian-made plasma thrusters, demonstrating the country’s expertise in this field. However, this new system aims to take plasma propulsion to an entirely new level.

When could this engine be space-ready?

The roadmap for this technology is **ambitious**. According to the project’s **scientific advisor**, a **flight-ready model** of the engine is expected to be completed by **2030**. While this timeline might seem optimistic, Russia’s track record in space propulsion gives the project credibility.

If successful, this innovation could open the door for **faster missions to Mars**, **deep-space exploration**, and even the possibility of reaching **the outer solar system within a human lifetime**.

A Game-Changer or Just Hype?

While the idea of reaching Mars in **one to two months** sounds incredible, several challenges remain:

- **Independent verification**: No peer-reviewed studies have confirmed the engine’s performance yet.
- **Integration with spacecraft**: How will it be incorporated into future Mars missions?
- **Energy source**: A **nuclear power supply** will likely be needed, adding complexity to the design.

Despite these uncertainties, if this technology delivers on its promises, it could mark **a new era in space exploration**. Whether it becomes a reality or remains a futuristic concept, the idea of **a 30-day journey to Mars** is closer than ever before.

How Fusion Propulsion Will Work

Flying on Fusion Power

Fusion reactions release an enormous amount of energy, which is why researchers are devising ways to harness that energy into a propulsion system. A fusion-powered spacecraft could move up NASA's schedule for a manned Mars mission. This type of spacecraft could cut travel time to Mars by more than 50 percent, thus reducing the harmful exposure to radiation and weightlessness.

The building of a fusion-powered spacecraft would be the equivalent of developing a car on Earth that can travel twice as fast as any car, with a fuel efficiency of 7,000 miles per gallon. In rocket science, fuel efficiency of a rocket engine is measured by its **specific impulse**. Specific impulse refers to the units of thrust per the units of propellant consumed over time.

A fusion drive could have a specific impulse about 300 times greater than conventional chemical rocket engines. A typical chemical rocket engine has a specific impulse of about 450 seconds, which means that the engine can produce 1 pound of thrust from 1 pound of fuel for 450 seconds. A fusion rocket could have an estimated specific impulse of 130,000 seconds. Additionally, fusion-powered rockets would use **hydrogen** as a propellant, which means it would be able to replenish itself as it travels through space. Hydrogen is present in the atmosphere of many planets, so all the spacecraft would have to do is dip down into the atmosphere and suck in some hydrogen to refuel itself.

Fusion-powered rockets could also provide longer thrust than chemical rockets, which burn their fuel quickly. It's believed that fusion propulsion will allow rapid travel to anywhere in our solar system, and could allow round trips from Earth to Jupiter in just two years. Let's take a look at two NASA fusion propulsion projects.

Variable Specific Impulse Magnetoplasma Rocket

VASIMR is actually a plasma rocket, which is a precursor to fusion propulsion. But, since a fusion-powered rocket will use plasma, researchers will learn a lot from this type of rocket. The VASIMR engine is quite amazing in that it creates plasma under extremely hot conditions and then expels that plasma to provide thrust. There are three basic cells in the VASIMR engine.

- **Forward cell** - The propellant gas, typically hydrogen, is injected into this cell and ionized to create plasma.
- **Central cell** - This cell acts as an amplifier to further heat the plasma with electromagnetic energy. Radio waves are used to add energy to the plasma, similar to how a microwave oven works.
- **Aft cell** - A magnetic nozzle converts the energy of the plasma into velocity of the jet exhaust. The magnetic field that is used to expel the plasma also protects the spacecraft because it keeps the plasma from touching the shell of the spacecraft. Plasma would likely destroy any material it came in contact with. The temperature of the plasma exiting the nozzle is as hot as 180 million degrees Fahrenheit (100 million degrees Celsius). That's 25,000 times hotter than gases expelled from the space shuttle.

On a mission to Mars, a VASIMR engine would continuously accelerate for the first half of the journey, then reverse its direction and slow down for the second half. A variable exhaust plasma rocket could also be used in positioning satellites in Earth orbit.

Gas Dynamic Mirror Fusion Propulsion

Being developed simultaneously with VASIMR is the Gas Dynamic Mirror (**GDM**) Fusion Propulsion system. In this engine, a long, slender, current-carrying coil of wire that acts like a magnet surrounds a vacuum chamber that contains plasma. The plasma is trapped within the magnetic fields created in the central section of the system. At each end of the engine are mirror magnets that prevent the plasma from escaping out the ends of the engine too quickly. Of course, you want some of the plasma to leak out to provide thrust.

Typically, plasma is **unstable** and not easily confined, which made early experiments with mirror fusion machines difficult. The gas dynamic mirror is able to avoid instability problems because it is constructed in a long and thin manner, so the magnetic field lines are straight throughout the system. Instability is also controlled by allowing a certain amount of plasma to leak past the narrow part of the mirror.

In 1998, the GDM Fusion Propulsion Experiment at NASA produced plasma during a test of the plasma injector system, which works similar to the forward cell of the VASIMR. It injects a gas into the GDM and heats it with **Electronic Cyclotron Resonance Heating** (ECRH) induced by a microwave antenna operating at 2.45 gigahertz. Currently, the experiment is designed to confirm the feasibility of the GDM concept. Researchers are also working on many of the operational characteristics of a full-size engine.

While many of NASA's advanced propulsion concepts are decades from being achieved, the foundation of fusion propulsion is already being built. When other technologies are available to make a Mars mission possible, it could be a fusion-powered spacecraft that ferries us there. By mid-21st century, trips to Mars may become as routine as trips to the International Space Station.

Direct Fusion Drive

One rotating magnetic field pulse of the Princeton field-reversed configuration (PFRC 2) device during testing

Direct Fusion Drive (**DFD**) is a conceptual, low radioactivity, nuclear-fusion rocket engine, designed to produce both thrust and electric power, suitable for interplanetary spacecraft. The concept is based on the Princeton field-reversed configuration reactor, invented in 2002 by Samuel A. Cohen. It is being modeled and experimentally tested at Princeton Plasma Physics Laboratory, a U.S. Department of Energy facility, as well as modeled and evaluated by Princeton Satellite Systems (PSS).[1][2] As of 2018, a direct fusion drive project driven by NASA is said to have entered its simulation phase, presented as the second phase of the concept's evolution.[3]

Principle

The Direct Fusion Drive (DFD) is a theoretical spacecraft propulsion system that derives its name from its unique capability to generate thrust directly from nuclear fusion, bypassing the need for an intermediate electricity-generating process. Using a magnetic confinement and heating mechanism, the DFD is powered by a blend of helium-3 (3He) and deuterium (D or 2H), resulting in a propulsion system characterized by high specific power, variable thrust, specific impulse, and minimal radiation emissions of spacecraft propulsion system.[4]

In the DFD, plasma, a collection of electrically charged particles that includes electrons and ions, fuse together at high temperatures (100 keV), releasing enormous amounts of energy. The plasma is confined in a torus-like magnetic field inside of a linear solenoidal coil[5] and is heated by a rotating magnetic field to relevant fusion temperatures.[4] Bremsstrahlung and synchrotron radiation emitted from the plasma are captured and converted to electricity for communications, spacecraft station-keeping, and maintaining the plasma's temperature.[6] This design uses a specially shaped radio frequency (RF) "antenna" to heat the plasma.[7] The design includes a rechargeable battery or a deuterium-oxygen auxiliary power unit to startup or restart the unit.[4]

The captured radiated energy heats a He-Xe fluid that flows outside the plasma to 1,500 K (1,230 °C; 2,240 °F) in a boron-containing structure. That energy is put through a closed-loop Brayton cycle generator to transform it into electricity for use in energizing the coils, powering the RF heater, charging the battery, communications, and station-keeping functions.[4]

Thrust generation

Adding propellant to the edge plasma flow results in a variable thrust and specific impulse when channeled and accelerated through a magnetic nozzle; this flow of momentum past the nozzle is predominantly carried by the ions as they expand through the magnetic nozzle and beyond, and thus, function as an ion thruster.[4]

Development

The construction of the experimental research device and most of its early operations were funded by the U.S. Department of Energy. The recent studies—Phase I and Phase II—were funded by the NASA Institute for Advanced Concepts (NIAC) program.[7] A series of articles on the concept were published between 2001 and 2008; the first experimental results were reported in 2007. Numerous studies of spacecraft missions (Phase I) were published, beginning in 2012. In 2017 Princeton Satellite Systems reported that "Studies of electron heating with this method have surpassed theoretical predictions, and experiments to measure ion heating in the second-generation machine are ongoing."[4]

As of 2018, the concept has moved to Phase II, a simulation phase.[8][9] The full-size unit would measure approximately 2 m in diameter and 10 m in length.[10] PSS reported that electron heating in PFRC-2 surpassed theoretical predictions, reaching 500 eV with pulse lengths of 300 ms. Ion heating experiments are ongoing as of 2020.[11]

Stephanie Thomas is vice president of Princeton Satellite Systems and the principal investigator for the Direct Fusion Drive.[12]

Projected performance

Princeton Satellite Systems estimate that the Direct Fusion Drive may be capable of producing between 5–10 Newtons[4] thrust per each MW of generated fusion power,[9] with a specific impulse (I_{sp}) of about 10,000 seconds and 200 kW available as electrical power.[8] Approximately 35% of the fusion power goes to thrust, 30% to electric power, 25% lost to heat, and 10% is recirculated for the RF heating.[4]

The company's modeling shows that this technology could propel a spacecraft with a mass of about 1,000 kg (2,200 lb) to Pluto in four years,[8] enabling deep space missions.[13] DFD generates extra power so it may provide approximately 2 MW of power to the payloads upon arrival. This allows more options for instrument selection and laser/optical communications,[4][8] and could even transfer up to 50 KW of power from the orbiter to the lander through a laser beam operating at 1080 nm wavelength.[4]

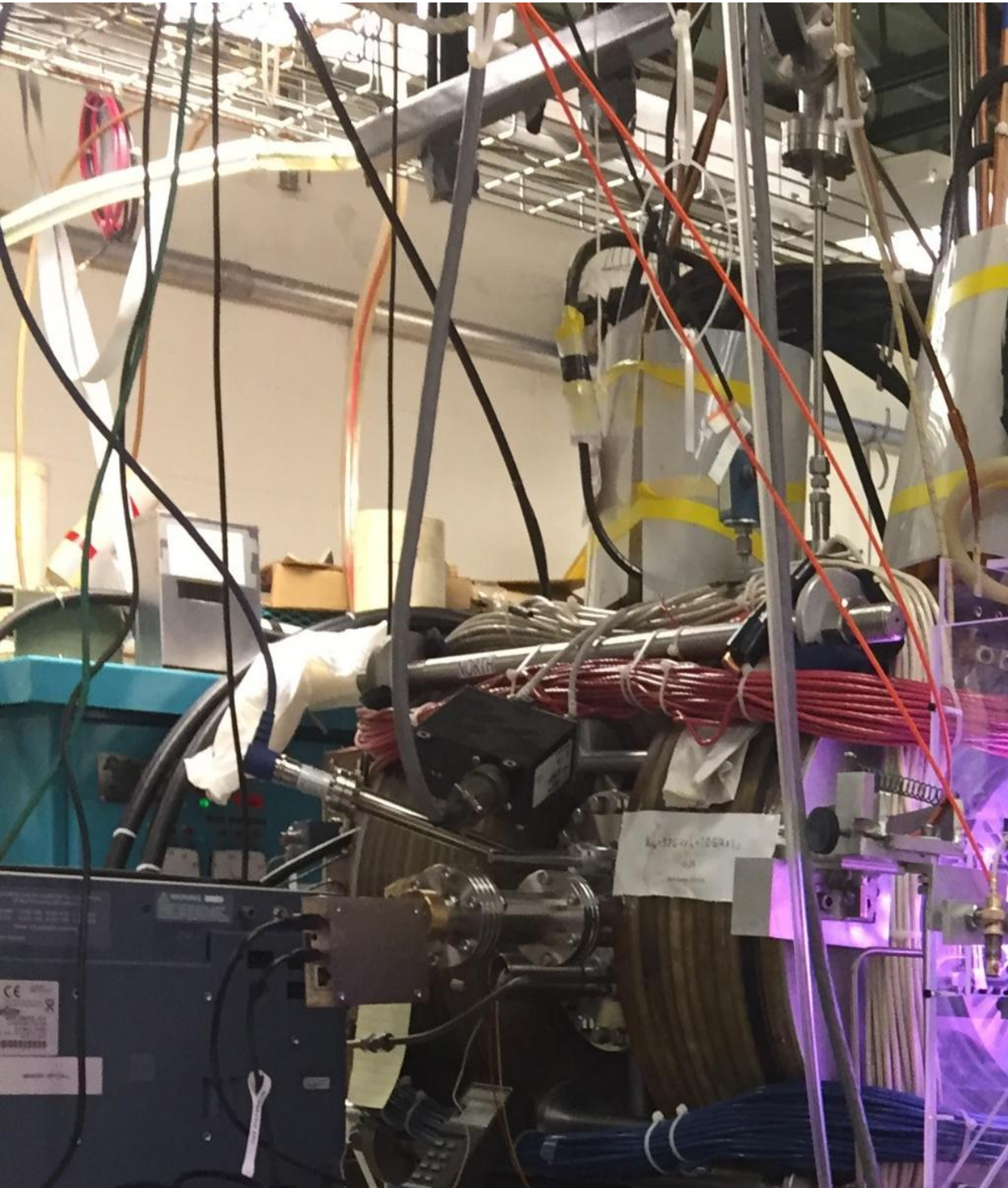
Princeton Satellite Systems says that this technology can expand the scientific capability of planetary missions.[8] This power/propulsion technology has been suggested to be used on a Pluto orbiter and lander mission,[4][8] or as integration on the Orion spacecraft to transport a crewed mission to Mars in a faster time frame[14][15] (4 months instead of 9 with current technology).[10] DFD is projected to deliver scientific payloads to Titan in 2.6 years.[16]

Fusion Propulsion with the Direct Fusion Drive

PSS and the Princeton Plasma Physics Lab (PPPL) are collaborating on a new fusion technology. Direct Fusion Drive is a revolutionary direct-drive, fusion-powered rocket engine concept. Compact and clean-burning, each 1-10 MW Direct Fusion Drive (DFD) engine would produce both power and thrust with high specific power (low mass). Producing propulsion directly in the fusion engine is highly efficient, shortening trip times and increasing capability for a wide variety of space missions: robotic missions to the outer planets, human missions to the moon or Mars, missions to near interstellar space. Here on Earth, portable fusion microreactors will enable modular power plants and integrate seamlessly with the future distributed power grid.

Princeton Field-Reversed Configuration (PFRC)

DFD is based on the Princeton Field-Reversed Configuration (PFRC) reactor, a technology developed by Dr. Sam Cohen of PPPL. The reactor employs a unique “odd-parity” RF heating method, producing a steady-state, closed-field configuration with a highly efficient current drive. The PFRC-2 experimental machine is currently in operation at PPPL, a plasma pulse is shown below. Read more on the PFRC technical papers page!



PFRC-2 has been supported by the Department of Energy, ARPA-E, NASA Innovative Advanced Concepts and two NASA STTRs. Our NIAC context mission was a Pluto orbiter and lander that are delivered in just 4 years, and can send back the equivalent of HD video!

Direct Fusion Drive Missions

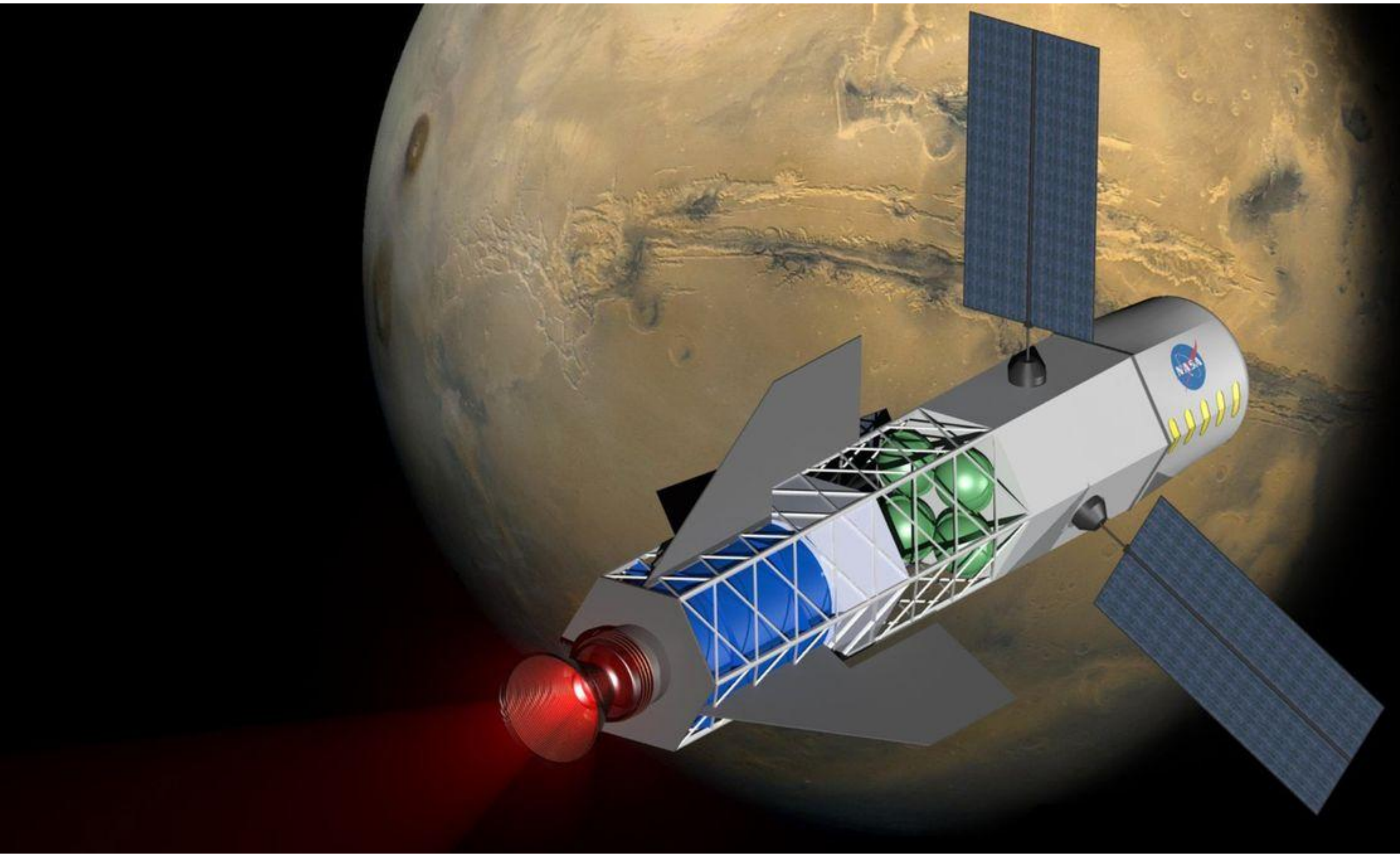
We have analyzed DFD for many missions and applications:

- Human Mars orbital mission
- Deploying the James Webb Telescope to a Lagrange point
- Asteroid deflection
- Jupiter Icy Moons Mission
- Pluto orbiter and lander
- Alpha Centauri
- 600+ AU gravity lens telescope
- Mobile and modular terrestrial power

Nuclear fusion breakthrough: What does it mean for space exploration?

published December 15, 2022

Some scientists say nuclear fusion propulsion is inevitable. But how far away is it, given recent breakthroughs?



(Image credit: University of Washington)

The announcement this week of fusion ignition is a major scientific advancement, one that is decades in the making. More energy was produced than the laser energy used to spark the first controlled fusion triumph.

The result: replicating the fusion that powers the sun.
On Dec. 5, a team at Lawrence Livermore National Laboratory's National Ignition Facility (NIF) achieved the milestone. As noted by Kim Budil, director of the laboratory: "Crossing

this threshold is the vision that has driven 60 years of dedicated pursuit — a continual process of learning, building, expanding knowledge and capability, and then finding ways to overcome the new challenges that emerged," Budil said.

The nuclear fusion feat has broad implications, fueling hopes of clean, limitless energy. As for space exploration, one upshot from the landmark research is attaining the long-held dream of future rockets that are driven by fusion propulsion.
But is that prospect still a pipe dream or is it now deemed reachable? If so, how much of a future are we looking at?

Data points

The fusion breakthrough is welcomed and exciting news for physicist Fatima Ebrahimi at the U.S. Department of Energy's (DOE) Princeton Plasma Physics Laboratory in New Jersey.

Ebrahimi said the NIF success is extraordinary.

"Any data points obtained showing fusion energy science achievement is fantastic! Fusion energy gain of greater than one is quite an achievement," Ebrahimi said. However, engineering innovations are still requisite for NIF to be commercially viable as a fusion reactor, she added.

Ebrahimi is studying how best to propel humans at greater speeds out to Mars and beyond. The work involves a new concept for a rocket thruster, one that exploits the mechanism behind solar flares.
The idea is to accelerate particles using "magnetic reconnection," a process found throughout the universe, including the surface of the sun. It's when magnetic field lines converge, suddenly separate, and then join together again, producing loads of energy. By using more electromagnets and more magnetic fields, Ebrahimi envisions the ability to create, in effect, a knob-turning way to fine-tune velocity.
As for the NIF victory impacting space exploration, Ebrahimi said for space applications, compact fusion concepts are still needed. "Heavy components for space applications are not favorable," she said.

Physicist Fatima Ebrahimi in front of an artistic rendering of a fusion rocket. (Image credit: Elle Starkman, Princeton Plasma Physics Laboratory Office of Communications)

Necessary precursor

Similar in thought is Paul Gilster, writer/editor of the informative Centauri Dreams website.

"Naturally I celebrate the NIF's accomplishment of producing more energy than was initially put into the fusion experiment. It's a necessary precursor toward getting fusion into the game as a source of power," Gilster told Space.com. Building upon the notable breakthrough is going to take time, he said.

"Where we go as this evolves, and this seems to be several decades away, is toward actual fusion power plants here on Earth. But as to space exploration, we then have to consider how to reduce working fusion into something that can fit the size and weight constraints of a spacecraft," said Gilster.

There's no doubt in Gilster's mind that fusion can be managed for space exploration purposes, but he suspects that's still more than a few decades in the future.

"This work is heartening, then, but it should not diminish our research into alternatives like beamed energy as we consider missions beyond the solar system," said Gilster.

The target chamber of Lawrence Livermore National Laboratory's National Ignition Facility. (Image credit: Lawrence Livermore National Laboratory)

Exhaust speeds

Richard Dinan is the founder of Pulsar Fusion in the United Kingdom. He's also the author of the book "The Fusion Age: Modern Nuclear Fusion Reactors."

"Fusion propulsion is a much simpler technology to apply than fusion for energy. If fusion is achievable, which at last the people are starting see it is, then both fusion energy and propulsion are inevitable," Dinan said. "One gives us the ability to power our planet indefinitely, the other the ability to leave our solar system. It's a big deal, really."

Exhaust speeds generated from a fusion plasma, Dinan said, are calculated to be roughly one-thousand times that of a Hall Effect Thruster, electric propulsion hardware that makes use of electric and magnetic fields to create and eject a plasma.

"The financial implications that go with that make fusion propulsion, in our opinion, the single most important emerging technology in the space economy," Dinan said.

Pulsar Fusion has been busy working on a direct fusion drive initiative, a steady state fusion propulsion concept that's based on a compact fusion reactor.

According to the group's website, Pulsar Fusion has proceeded to a Phase 3 task, manufacturing an initial test unit. Static tests are slated to occur next year, followed by an in-orbit demonstration of the technology in 2027.

Pulsar Fusion's Direct Fusion Drive, a compact nuclear fusion engine that could provide both thrust and electrical power for spaceships. (Image credit: Pulsar Fusion)

Aspirational glow

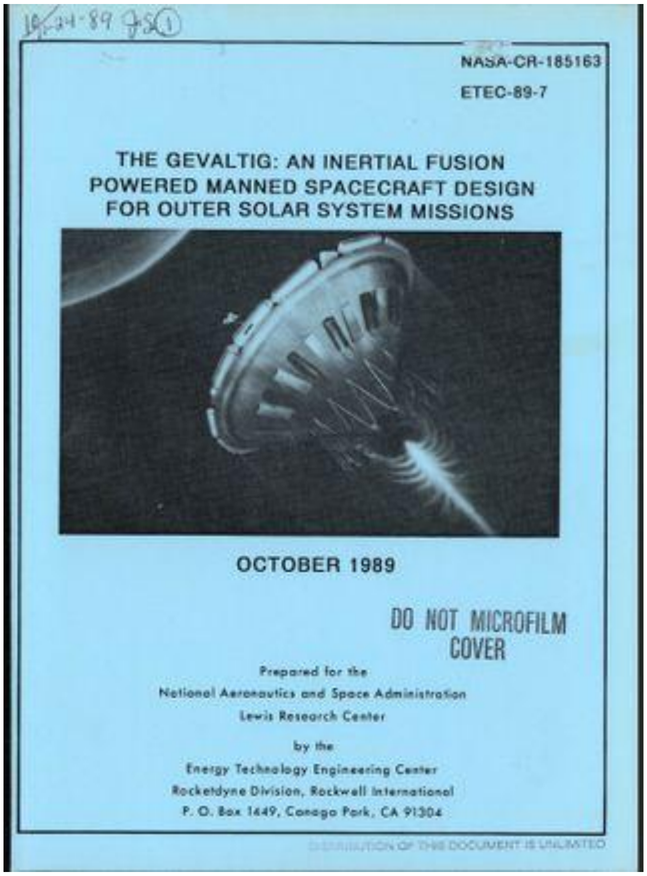
"The net energy gain reported in the press is certainly a significant milestone," said Ralph McNutt, a physicist and chief scientist for space science at the Johns Hopkins University Applied Physics Laboratory in Laurel, Maryland. "As more comes out, it will be interesting to see what the turning point was that pushed this achievement past the previous unsuccessful attempts," he said.

McNutt said that getting to a commercial electric power station from this recent milestone is likely to be a tough assignment. "But the tortoise did eventually beat the hare. Tenacity is always the virtue when one is handling tough technical problems."

With respect to space exploration, it certainly does not hurt in providing an example that great things can still be accomplished, McNutt said.

"All of that said, it should be still a sobering thought that despite all of the work on NERVA/Rover there is still no working nuclear thermal rocket engine, and the promise of nuclear electric propulsion for space travel only had a brief glimmer with SNAP-10A in April of 1965," recalled McNutt.

The actual use of ICF in a functional spacecraft has been a long-held dream, McNutt said, but that is very unlikely to change for a long time to come.



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THE GEVALTIG: AN INERTIAL FUSION
POWERED MANNED SPACECRAFT DESIGN
FOR OUTER SOLAR SYSTEM MISSIONS

OCTOBER 1989

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The cover of a 1989 NASA Lewis Research Center study on inertial confinement fusion propulsion. (Image credit: NASA)

"Space travel has always been tough. That NASA has 'blazed the trail' that many commercial entities are now following does not mean space has gotten easier, but the new ICF results have added to the aspirational glow on the horizon of the future," McNutt added.

"That said, no one should be fooled into thinking that space will somehow *not* be tough someday. It's called 'rocket science,' with all that implies in popular culture for a reason," he concluded.

Fusion rocket

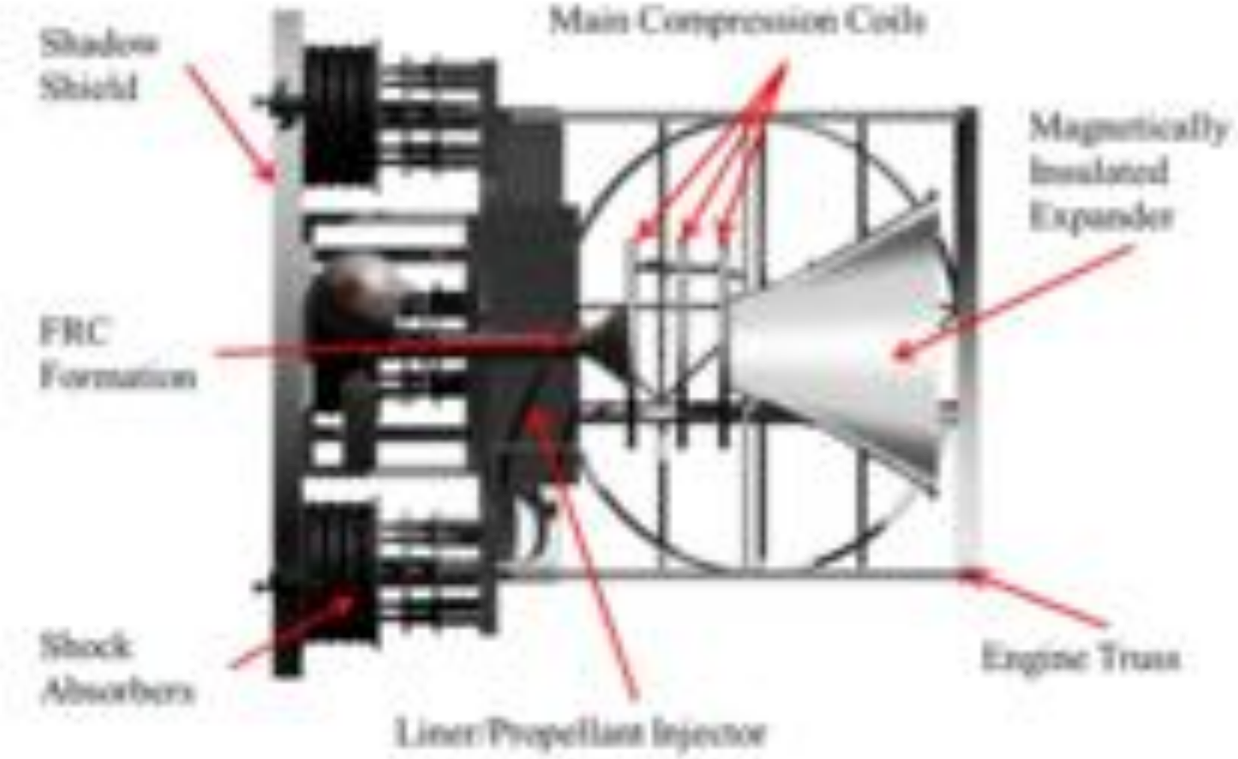

Figure 8. Schematic of the Fusion Driven Rocket including major subsystems.

A schematic of a fusion-driven rocket by NASA

A **fusion rocket** is a theoretical design for a rocket driven by fusion propulsion that could provide efficient and sustained acceleration in space without the need to carry a large fuel supply. The design requires fusion power technology beyond current capabilities, and much larger and more complex rockets.

Fusion nuclear pulse propulsion is one approach to using nuclear fusion energy to provide propulsion.

Fusion's main advantage is its very high specific impulse, while its main disadvantage is the (likely) large mass of the reactor. A fusion rocket may produce less radiation than a fission rocket, reducing the shielding mass needed. The simplest way of building a fusion rocket is to use hydrogen bombs as proposed in Project Orion, but such a spacecraft would be massive and the Partial Nuclear Test Ban Treaty prohibits the use of such bombs. For that reason bomb-based rockets would likely be limited to operating only in space. An alternate approach uses electrical (e.g. ion) propulsion with electric power generated by fusion instead of direct thrust.

Electricity generation vs. direct thrust

Spacecraft propulsion methods such as ion thrusters require electric power to run, but are highly efficient. In some cases their thrust is limited by the amount of power that can be generated (for example, a mass driver). An electric generator running on fusion power could drive such a ship. One disadvantage is that conventional electricity production requires a low-temperature energy sink, which is difficult (i.e. heavy) in a spacecraft. Direct conversion of the kinetic energy of fusion products into electricity mitigates this problem.[1]

One attractive possibility is to direct the fusion exhaust out the back of the rocket to provide thrust without the intermediate production of electricity. This would be easier with some confinement schemes (e.g. magnetic mirrors) than with others (e.g. tokamaks). It is also more attractive for "advanced fuels" (see aneutronic fusion). Helium-3 propulsion would use the fusion of helium-3 atoms as a power source. Helium-3, an isotope of helium with two protons and one neutron, could be fused with deuterium in a reactor. The resulting energy release could expel propellant out the back of the spacecraft. Helium-3 is proposed as a power source for spacecraft mainly because of its lunar abundance. Scientists estimate that 1 million tons of accessible helium-3 are present on the moon.[2] Only 20% of the power produced by the D-T reaction could be used this way; while the other 80% is released as neutrons which, because they cannot be directed by magnetic fields or solid walls, would be difficult to direct towards thrust, and may in turn require shielding. Helium-3 is produced via beta decay of tritium, which can be produced from deuterium, lithium, or boron.

Even if a self-sustaining fusion reaction cannot be produced, it might be possible to use fusion to boost the efficiency of another propulsion system, such as a VASIMR engine.[*citation needed*]

Confinement alternatives

Magnetic

To sustain a fusion reaction, the plasma must be confined. The most widely studied configuration for terrestrial fusion is the tokamak, a form of magnetic confinement fusion. Currently tokamaks weigh a great deal, so the thrust to weight ratio would seem unacceptable.[*dubious – discuss*] NASA's Glenn Research Center proposed in 2001 a small aspect ratio spherical torus reactor for its "Discovery II" conceptual vehicle design. "Discovery II" could deliver a crewed 172 metric tons payload to Jupiter in 118 days (or 212 days to Saturn) using 861 metric tons of hydrogen propellant, plus 11 metric tons of Helium-3-Deuterium (D-He3) fusion fuel.[3] The hydrogen is heated by the fusion plasma debris to increase thrust, at a cost of reduced exhaust velocity (348–463 km/s) and hence increased propellant mass.

Inertial

The main alternative to magnetic confinement is inertial confinement fusion (ICF), such as that proposed by Project Daedalus. A small pellet of fusion fuel (with a diameter of a couple of millimeters) would be ignited by an electron beam or a laser. To produce direct thrust, a magnetic field forms the pusher plate. In principle, the Helium-3-Deuterium reaction or an aneutronic fusion reaction could be used to maximize the energy in charged particles and to minimize radiation, but it is highly questionable whether using these reactions is technically feasible. Both the detailed design studies in the 1970s, the Orion drive and Project Daedalus, used inertial confinement. In the 1980s, Lawrence Livermore National Laboratory and NASA studied an ICF-powered "Vehicle for Interplanetary Transport Applications" (VISTA). The conical VISTA spacecraft could deliver a 100-tonne payload to Mars orbit and return to Earth in 130 days, or to Jupiter orbit and back in 403 days. 41 tonnes of deuterium/tritium (D-T) fusion fuel would be required, plus 4,124 tonnes of hydrogen expellant.[4] The exhaust velocity would be 157 km/s.

Magnetized target

Magnetized target fusion (MTF) is a relatively new approach that combines the best features of the more widely studied magnetic confinement fusion (i.e. good energy confinement) and inertial confinement fusion (i.e. efficient compression heating and wall free containment of the fusing plasma) approaches. Like the magnetic approach, the fusion fuel is confined at low density by magnetic fields while it is heated into a plasma, but like the inertial confinement approach, fusion is initiated by rapidly squeezing the target to dramatically increase fuel density, and thus temperature. MTF uses "plasma guns" (i.e. electromagnetic acceleration techniques) instead of powerful lasers, leading to low cost and low weight compact reactors.[5] The NASA/MSFC Human Outer Planets Exploration (HOPE) group has investigated a crewed MTF propulsion spacecraft capable of delivering a 164-tonne payload to Jupiter's moon Callisto using 106-165 metric tons of propellant (hydrogen plus either D-T or D-He3 fusion fuel) in 249–330 days.[6] This design would thus be considerably smaller and more fuel efficient due to its higher exhaust velocity (700 km/s) than the previously mentioned "Discovery II", "VISTA" concepts.

Inertial electrostatic

Another popular confinement concept for fusion rockets is inertial electrostatic confinement (IEC), such as in the Farnsworth-Hirsch Fusor or the Polywell variation under development by Energy-Matter Conversion Corporation (EMC2). The University of Illinois has defined a 500-tonne "Fusion Ship II" concept capable of delivering a 100,000 kg crewed payload to Jupiter's moon Europa in 210 days. Fusion Ship II utilizes ion rocket thrusters (343 km/s exhaust velocity) powered by ten D-He3 IEC fusion reactors. The concept would need 300 tonnes of argon propellant for a 1-year round trip to the Jupiter system.[7] Robert Bussard published a series of technical articles discussing its application to spaceflight throughout the 1990s. His work was popularised by an article in the Analog Science Fiction and Fact publication, where Tom Ligon described how the fusor would make for a highly effective fusion rocket.[8]

Antimatter

A still more speculative concept is antimatter-catalyzed nuclear pulse propulsion, which would use antimatter to catalyze a fission and fusion reaction, allowing much smaller fusion explosions to be created. During the 1990s an abortive design effort was conducted at Penn State University under the name AIMStar.[9] The project would require more antimatter than can currently be produced. In addition, some technical hurdles need to be surpassed before it would be feasible.[10]

Development projects

- Direct Fusion Drive – Conceptual rocket engine
- MSNW Magneto-Inertial Fusion Driven Rocket

See also

- Helium-3
- Nuclear propulsion
- Rocket propulsion technologies (disambiguation)

Plasma Life Forms: Are Ball Lightning Plasmoids Sentient?

Description:

Join us on 15 Minute Discourse as we explore the MIND-BLOWING world of plasmoids and the possibility of plasma-based life forms!

Could ball lightning, those enigmatic balls of light, be more than just atmospheric phenomena? What if they are actually glimpses into a completely different form of life – one based on pure energy and electromagnetic fields?

We delve into cutting-edge research, eyewitness accounts, and scientific theories that suggest plasmoids might exhibit:

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Self-organization into complex structures
Shape-shifting and growth
Behaviors resembling hunting and predation
Potential interactions with consciousness
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Is there evidence to support the idea of conscious plasmoid life? Could they be the key to unlocking the secrets of consciousness itself?

Tune in to find out!

Don't forget to LIKE, SUBSCRIBE, and hit the notification bell for more mind-expanding explorations!

Plasmoid Energy Sources

The sources propose various hypotheses for the primary energy source of plasmoids and how they maintain their luminosity and stability:

● Atmospheric Electricity: Some models suggest that plasmoids, particularly ball lightning, draw energy from atmospheric electricity, specifically from lightning discharges [1-3]. These models posit that plasmoids are formed during thunderstorms and utilize the intense electrical energy present in the atmosphere to sustain themselves.

● Internal Magnetic Fields: The "axially symmetric force-free time-harmonic plasmoid model" proposes that plasmoids are essentially standing electromagnetic waves trapped within a stable plasma vortex [4]. The model suggests that the internal magnetic fields of the plasmoid, configured in a force-free manner, provide the necessary confinement and energy storage for prolonged existence. This model combines aspects of Kapitza's standing-wave plasmoid model with Wells' concept of a vortical field [4].

● Microwave Radiation: Certain models, categorized as "microwave radiation powered models," propose that plasmoids are resonant cavities bounded by highly ionized, conducting walls that trap and reflect intense microwave fields [3]. This trapped microwave radiation energizes the plasmoid and maintains its luminosity. However, the origin and specific frequency of the microwaves remain debated, with suggestions ranging from lightning-induced currents to phase-locked loops of electromagnetic radiation [3].

● Zero-Point Energy: The concept of zero-point energy (ZPE), the residual energy present in a vacuum at absolute zero, has been proposed as a potential energy source for plasmoids [5-7]. Proponents of this theory suggest that plasmoids may be able to tap into this vast reservoir of energy through mechanisms like the Casimir effect, a force arising from quantum fluctuations of the electromagnetic field. This idea remains speculative, and the feasibility of extracting usable energy from ZPE is still under investigation.

● Electromagnetic Vortex Plasmoids (EVPs): A more unconventional concept, electromagnetic vortex plasmoids (EVPs), proposes that micro-scale plasmoids derive their stability and energy from quantum vacuum energy [7-9]. These EVPs are described as dense electron clusters that form during micro-arc discharges. While promising, the theory behind EVPs and their potential as an energy source requires further investigation and validation.

While these hypotheses provide potential explanations, more research is needed to conclusively determine the dominant energy sources and mechanisms that enable plasmoids to maintain their stability and luminosity for extended periods. The complexity of plasmoid phenomena and the limitations of current observational and experimental techniques make this a challenging area of research.

Plasmoid Energy Release Mechanisms

The mechanisms of energy release in plasmoids are a critical area of ongoing research, with implications for understanding both the natural behavior of these phenomena and their potential applications. The sources suggest that plasmoids can release energy in a variety of ways, from gradual dissipation to sudden, explosive events. Here's a closer look:

Gradual Dissipation:

- Thermal Radiation and Conduction: As plasmoids are inherently hot, they are expected to lose energy gradually through thermal radiation and conduction to the surrounding environment [1]. The rate of energy loss would depend on factors like the plasmoid's temperature, size, and the properties of the surrounding medium.

- Viscous Forces: Internal fluid motion within a plasmoid, particularly the vortical motion proposed by some models, could lead to energy dissipation through viscous forces [2-4]. The balance between viscous dissipation and electromagnetic forces is crucial for plasmoid stability, and imbalances could contribute to gradual decay.

- Electron Shedding: Some sources propose that plasmoids, particularly the microscopic EVs, might gradually shed electrons, leading to a reduction in charge and potentially a decrease in energy over time [5, 6]. The rate of electron shedding could vary depending on the plasmoid's size, internal structure, and interaction with the environment.

Sudden Energy Release:

- Explosions and Bursts: Several sources describe instances where plasmoids exhibit sudden bursts of energy or even violent explosions [5-8]. The triggers for these events are not fully understood, but they could involve:

  ○ Reaching a critical charge density threshold, leading to an explosive discharge [5].

  ○ Instabilities in the internal magnetic field structure, causing a sudden release of magnetic energy [1].

  ○ Interactions with external electromagnetic fields, potentially disrupting the plasmoid's equilibrium and triggering an energy burst [3].

- Maser Spiking: In the context of ball lightning, the maser-caviton model suggests that the decay of a plasmoid could induce "maser spiking," potentially leading to a violent release of energy [9]. This mechanism hinges on the interaction between the plasmoid and a hypothesized atmospheric maser, a concept that requires further investigation.

Implications and Applications:

- Hazards: Understanding the energy release mechanisms of plasmoids is crucial for assessing potential hazards. Explosive events could pose risks to aircraft, electronic equipment, or even living organisms if they occur in close proximity.

- Applications: Controlled energy release from plasmoids could have potential applications:

  ○ Energy Storage and Release: If the energy stored within plasmoids can be harnessed and released on demand, it could have implications for energy storage technologies [10].

  ○ Plasma Propulsion: The expulsion of plasmoids, particularly at high velocities, as observed in both natural and laboratory settings, could be investigated for potential applications in plasma propulsion systems [11, 12].

The sources highlight the need for further research to fully comprehend the complex energy dynamics of plasmoids. Combining theoretical modeling, laboratory experiments, and detailed analysis of natural observations is essential to unravel the mysteries surrounding these intriguing phenomena.

Force-Free Magnetic Fields and Plasmoid Stability

Force-free magnetic fields are crucial in shaping and stabilizing plasmoids, both in theoretical models and experimental observations. The sources provide insights into how these fields contribute to plasmoid stability and the challenges of replicating them in laboratory settings.

Force-Free Fields and Plasmoid Stability:

- Definition and Significance: Force-free magnetic fields, also known as Beltrami fields, are characterized by the alignment of the magnetic field and current density vectors, resulting in a state where the Lorentz force (J x B) is zero. This means the magnetic field exerts no force on the plasma carrying the current, leading to a stable configuration [1-4].

- Stability Against Disruptions: In conventional plasmas, internal stresses on currents can disrupt magnetic field configurations. Force-free fields, by minimizing these stresses, offer enhanced stability against such disruptions. This stability is further augmented by the "pinch effect" caused by the time-varying current within the plasmoid, which contributes to its self-confinement [4-6].

- Balancing Electromagnetic Stresses: Even though force-free fields minimize internal stresses, electromagnetic stresses due to the field's curvature still exist. These stresses can be effectively balanced by inducing a vortical fluid motion in the supporting plasma. This vortical motion, known as Beltrami flow, mirrors the force-free magnetic field structure, creating a stable equilibrium where electromagnetic pressures are counteracted by reduced pressures from the fluid motion [4, 5, 7, 8].

Replicating Force-Free Fields in Laboratories:

- Experimental Evidence: Experiments with plasma guns have successfully generated axially symmetric force-free plasmoids, also referred to as plasma vortex rings [9, 10]. These plasmoids exhibit trapped toroidal and poloidal magnetic fields, offering valuable insights into the behavior of force-free configurations.

- Challenges in Controlled Generation: While force-free plasmoids have been observed in experiments, precisely replicating and sustaining them in laboratory settings present significant challenges. These challenges stem from the complexity of achieving the precise magnetic field and plasma conditions required for long-term stability.

- External Field Requirements: Maintaining a stable force-free plasmoid might necessitate specific external field configurations to match boundary conditions and prevent energy leakage [11, 12]. This involves creating resonant cavities or external magnetic fields that complement the plasmoid's internal structure.

- Plasma Parameters and Processes: Factors such as ionization levels, radiative recombination rates, and gas density can influence the stability of the pinch effect and the overall plasmoid behavior [13]. Precise control over these parameters is crucial for successful laboratory replication.

Ongoing Research and Potential Applications:

- Advanced Experimental Techniques: Continued research focuses on developing sophisticated experimental techniques to generate and sustain force-free plasmoids for extended periods. These efforts involve exploring various methods, including microwave resonant cavities, laser-driven plasmas, and magnetic flux injection [14-16].

- Fusion Power Generation: The exceptional stability of force-free configurations makes them attractive for potential applications in fusion power generation. Concepts like the Field-Reversed Configuration (FRC) aim to utilize these fields to confine plasmas for sustained fusion reactions [17, 18].

- Space Propulsion: The ability of force-free plasmoids to contain high energy densities has also sparked interest in their potential use for space propulsion systems. Concepts involving plasmoid-based thrusters could offer significant advantages in terms of specific impulse and efficiency [18].

By delving further into the intricacies of force-free magnetic fields, researchers are steadily advancing our understanding of plasmoid behavior and unlocking their potential for groundbreaking technological applications. The path forward involves overcoming the challenges in laboratory replication and harnessing the remarkable stability of these fields to pave the way for innovations in energy generation and space exploration.

Plasmoid Composition: A Comprehensive Overview

The sources provide insights into the composition of plasmoids, emphasizing their diverse nature and the influence of the surrounding environment. Plasmoids are generally described as consisting of:

● Ions: Both positively charged (cations) and negatively charged (anions) are integral components of plasmas. Their presence creates the electrical conductivity characteristic of these entities. [1]

● Electrons: Electrons, with their negative charge, contribute to the overall charge balance within a plasmoid. The sources mention "electron shedding" as a potential mechanism of energy release, suggesting that electron density can vary over time. [2-4]

● Neutral Particles: While the ionized components dominate the plasma state, neutral particles, including atoms and molecules, can also be present. The ratio of neutral to ionized particles can influence the plasmoid's characteristics and behavior. [5-7]

● Dust: The sources, particularly those focused on "dusty plasmas," highlight the role of dust particles in plasmoid formation and behavior. Dust particles, ranging from nanometers to micrometers in size, can become electrically charged and interact with the plasma's electromagnetic fields, contributing to the formation of complex structures like voids or nuclei. [8-17] The sources propose that these dust particles, often originating from carbonaceous chondrites, might carry organic molecules, including amino acids. [12, 13, 18]

The specific composition of a plasmoid can vary significantly depending on the type of plasmoid and the environment in which it forms. Here are some key factors:

● Type of Plasmoid:

○ Ball Lightning: The sources suggest that ball lightning might be composed primarily of ionized air, potentially with trace amounts of other elements depending on the location and conditions of formation.

○ EVPs: Electromagnetic vortex plasmoids (EVPs) are described as dense electron clusters, suggesting a higher proportion of electrons compared to ions.

○ Dusty Plasmas: Dusty plasmas, prevalent in interstellar space, the plasmasphere, and the ionosphere, incorporate a significant amount of dust particles. These particles can influence the plasmoid's charge, stability, and even potential for complex behavior.

- Environment:

  ○ Thermosphere and Ionosphere: Plasmoids in these regions are likely to interact with atmospheric gases, including nitrogen, oxygen, and trace amounts of other elements. Solar radiation and the Earth's magnetic field can also influence the ionization and overall composition of these plasmoids.

  ○ Interstellar and Intergalactic Space: Dusty plasmas in these environments would be composed primarily of ions, electrons, and a variety of dust particles, including remnants of supernovae, comets, and asteroids. The composition would reflect the specific elemental abundances in these regions of space.

The sources emphasize the need for further research to precisely determine the composition of different types of plasmoids. Spectroscopic analysis could help identify the specific elements present, while laboratory experiments could provide insights into the role of different components in plasmoid formation and behavior.

Plasmoid Penetration of Matter

The mechanism by which plasmoids seemingly pass through solid objects without causing significant damage, as reported in some eyewitness accounts, remains a topic of speculation and investigation. The sources offer a few potential explanations for this perplexing phenomenon:

- Quantum Tunneling: Some researchers propose that plasmoids, particularly micro-scale EVPs, might leverage quantum phenomena like tunneling to traverse solid matter. This concept suggests that the wave-like nature of matter allows particles to pass through energy barriers that would classically be impenetrable. However, applying quantum tunneling to macroscopic objects like ball lightning or larger plasmoids remains a theoretical challenge, as the probability of tunneling decreases exponentially with increasing object size and mass.

- Plasma-Matter Interaction: Other theories focus on the unique interactions between plasmas and matter.

  ○ Weakly Ionized Plasma: Some suggest that plasmoids might consist of weakly ionized plasma with low particle density, allowing them to penetrate solid objects without causing substantial disruption to atomic bonds. This explanation implies that the plasmoid's interaction with matter is less forceful than conventional collisions.

  ○ Electromagnetic Forces: Alternatively, the passage could involve electromagnetic forces associated with the plasmoid. These forces could temporarily alter or weaken the bonds within the solid object, facilitating penetration without causing permanent damage. This explanation requires further exploration to identify the specific electromagnetic mechanisms at play.

● Fifth Dimensional Origin: A more speculative hypothesis proposes that certain plasmoids might originate from a higher dimension, such as a fifth dimension. Proponents of this idea suggest that these plasmoids could temporarily manifest in our three-dimensional space, giving the illusion of passing through solid objects. This concept, while intriguing, delves into the realm of theoretical physics and lacks substantial empirical support.

It's important to note that the sources lack a definitive explanation for plasmoid passage through matter. Eyewitness accounts, while compelling, require careful scrutiny, as perception can be influenced by various factors. Further research, combining rigorous experimental approaches with advanced theoretical models, is necessary to elucidate the underlying mechanisms of this intriguing phenomenon.

Plasmoid Electromagnetic Interactions and Risks

The sources highlight a range of electromagnetic effects associated with plasmoids, underscoring their potential to interact with their surroundings in significant ways. These effects can pose risks to electronic systems and infrastructure, highlighting the need for further research to fully understand their implications.

Electromagnetic Interactions:

● Induction of Currents: Plasmoids, with their inherent electric currents and magnetic fields, can induce currents in nearby conductors [1-3]. This induction principle is similar to how transformers work, where a changing magnetic field from one coil induces a current in another. This effect could be particularly impactful on long conductors, such as power lines, potentially leading to surges or disruptions in electrical grids [2].

● Disruption of Electronic Devices: The electromagnetic fields associated with plasmoids can interfere with or damage electronic devices [1-4]. The sources mention reports of plasmoid-induced malfunctions in televisions, radios, and other electrical equipment [4]. The rapid changes in electromagnetic fields associated with plasmoids could induce damaging currents or voltage spikes in sensitive circuits.

● Emissions of Radiation: Plasmoids can emit various forms of electromagnetic radiation, depending on their composition, temperature, and internal dynamics.

○ Radio Waves: Some sources propose that plasmoids might generate radio frequency emissions [1-3, 5]. These emissions could potentially be detected and used to study plasmoid behavior.

○ Light: The visible glow associated with many plasmoid observations is a direct result of electromagnetic processes within the plasma. Excited atoms and molecules within the plasmoid release photons as they transition back to lower energy states, producing a characteristic luminescence [6].

○ X-rays: High-energy plasmoids, particularly those involving rapid changes in magnetic fields, could potentially produce X-rays [7]. The sources mention EVPs (electromagnetic vortex plasmoids) as a type of plasmoid capable of generating X-rays during their formation or sudden disruptions [7].

Specific Examples and Implications:

● Ball Lightning: Ball lightning, often described as a luminous sphere that can move erratically, is frequently associated with reports of electromagnetic disturbances. Accounts describe ball lightning affecting compasses, disrupting electrical appliances, and even burning through objects [8].

● EVPs: The sources suggest that EVPs, due to their dense electron clusters, might possess particularly strong electromagnetic fields. They are linked to effects such as material penetration and the generation of X-rays upon impact [9].

● UAPs and Nuclear Facilities: Some sources draw a connection between UAP sightings and nuclear facilities, speculating that plasmoids might be attracted to or influenced by sources of strong electromagnetic activity [10, 11]. The potentially disruptive effects of plasmoids on electronics and power systems raise concerns about their potential impact on critical infrastructure, including nuclear power plants.

Assessing Potential Risks:

The electromagnetic effects of plasmoids pose a range of potential risks:

● Power Grid Disruptions: Induced currents in power lines could lead to blackouts or damage to electrical infrastructure.

● Electronic Device Malfunction: Interference with or damage to electronic systems could disrupt communications, navigation, and other essential technologies.

● Health Effects: While not explicitly discussed in the sources, exposure to strong electromagnetic fields could have potential health implications, requiring further investigation to assess possible risks.

Understanding the specific mechanisms by which plasmoids interact with electromagnetic fields is crucial for developing mitigation strategies and safety protocols. Further research, combining laboratory experiments, theoretical modeling, and field observations, is essential to fully characterize the electromagnetic effects of plasmoids and address the associated risks.

Quantum Plasmoids and Consciousness

The sources discuss quantum phenomena like entanglement and quantum coherence in relation to plasmoid behavior, particularly their stability, energy dynamics, and potential interaction with consciousness. Here's a summary of the key points:

Quantum Coherence and Stability:

● Plasma as a Cooperative Structure: The sources mention that physicist David Bohm, in his early work on plasmas, observed their behavior as a highly cooperative structure. [1] This suggests that particles within a plasma, despite being spatially separated, can exhibit instantaneous correlation, similar to quantum entanglement. This coherence could potentially contribute to the stability of plasmoids, as the coordinated behavior of particles might resist disruptions.

● Microtubules Analogy: The sources draw an analogy between plasma particles and microtubules within brain neurons, suggesting that both might exhibit quantum coherence. [1, 2] The Orch OR theory proposes that microtubules function as a quantum coherent system within neurons, playing a role in consciousness. Applying this analogy to plasmas, some researchers speculate that certain plasmoids might behave as a "brain capable to produce moments of consciousness." [2]

Energy Dynamics and Quantum Effects:

● Quantum Tunneling and Energy Barriers: The sources mention quantum tunneling as a potential mechanism for plasmoids passing through solid objects. [3] However, this concept faces challenges when applied to macroscopic plasmoids, as the probability of tunneling decreases significantly with increasing size and mass.

● Energy Levels and Consciousness: Some sources propose that if plasmas can increase in size and the number of active particles, the number of "consciousness moments" might also increase. [4] This idea connects the concept of energy levels in quantum systems with the emergence of consciousness, suggesting that larger, more energetic plasmoids might exhibit greater complexity or even intelligence.

Interaction with Consciousness:

● Speculative Hypothesis: The sources present a highly speculative hypothesis that some plasmoids, particularly those exhibiting anomalous behavior, might possess a form of elementary intelligence or consciousness. [2, 5, 6]

● Laser Stimulation and Wave Function Collapse: Experiments suggest that stimulating plasmoids with laser beams can trigger changes in their behavior, such as pulsations or changes in pulsation rate. [6] Some researchers propose that this stimulation might induce a collapse of the wave function of the plasma particles, potentially triggering a "consciousness moment."

● Plasma as a Potential Life Form: The sources, drawing on observations of plasmoid behavior and their potential for quantum coherence, speculate on the possibility of "plasma life" existing throughout the universe. [5, 7] This concept, while lacking conclusive evidence, raises intriguing questions about the nature of life and the potential for non-biological forms of consciousness.

It's crucial to emphasize that the sources heavily rely on speculation when discussing the role of quantum phenomena in plasmoid behavior, especially concerning consciousness. While quantum effects are undoubtedly relevant at the microscopic level, their influence on macroscopic plasmoid behavior and potential connection to consciousness require rigorous scientific investigation.

Further research, combining advanced experimental techniques with theoretical models incorporating quantum mechanics, is essential to determine the validity of these hypotheses and unravel the mysteries surrounding plasmoids.

Plasmoids and Unconventional Physics

Plasmoids, with their intriguing properties and behaviors, have sparked considerable interest as potential windows into unconventional physics. Some researchers believe they could hold clues to undiscovered physical laws or principles, bridging the gap between our current understanding and phenomena that seemingly defy conventional explanations. Here's a look at how plasmoids might connect to unconventional physics:

- Quantum Phenomena at Macroscopic Scales: One of the most perplexing aspects of plasmoids is their reported ability to pass through solid objects without causing significant damage. This has led to speculation about whether plasmoids could exhibit quantum phenomena like tunneling at macroscopic scales. While quantum tunneling is well-established at the microscopic level, its applicability to larger objects remains a theoretical challenge. If plasmoids could somehow leverage these principles, it would suggest a profound connection between quantum mechanics and macroscopic phenomena, potentially revolutionizing our understanding of physics.

- Force-Free Magnetic Fields and Energy Storage: The role of force-free magnetic fields in shaping and stabilizing plasmoids also raises questions about their energy storage capabilities. These fields, characterized by the alignment of magnetic field and current density vectors, minimize internal stresses and enhance stability. However, the mechanisms by which plasmoids generate and maintain these intricate field configurations are not fully understood. If plasmoids can store and release significant amounts of energy through these fields, it could open up new avenues for energy generation and storage technologies, potentially surpassing the limitations of conventional approaches.

- Connections to Higher Dimensions: Some theories propose that certain plasmoids, particularly those exhibiting unusual properties, might originate from higher dimensions, such as a fifth dimension. This concept, while highly speculative, suggests that plasmoids could serve as gateways to understanding the nature of extra dimensions and their potential influence on our three-dimensional reality. Further exploration of this idea could lead to profound implications for our understanding of the universe and its fundamental structure.

- Plasma-Matter Interactions and Anomalous Effects: The unique interactions between plasmas and matter could also point to unconventional physics. The sources mention that plasmoids might consist of weakly ionized plasma with low particle density, potentially allowing them to penetrate solid objects without causing substantial damage. This raises questions about the nature of these interactions and whether they involve unknown forces or mechanisms that modify the properties of matter. Understanding these processes could lead to insights into novel material properties and potential applications in fields like materials science and nanotechnology.

● Dusty Plasmas and Complex Behavior: The behavior of dusty plasmas, particularly their self-organization, shape-shifting, and potential for mimicking biological entities, hints at the possibility of emergent properties arising from complex systems. These observations challenge conventional reductionist approaches and raise questions about the nature of complexity and self-organization in the universe. The study of dusty plasmas could provide valuable insights into the emergence of complexity from seemingly simple interactions, potentially influencing our understanding of systems ranging from biological organisms to the universe itself.

It is crucial to approach these ideas with a balanced perspective. While plasmoids offer tantalizing glimpses into potentially unconventional physics, much research is needed to solidify these connections. Rigorous scientific investigation, combining experimental observations with theoretical models, is crucial to separate genuine anomalies from misinterpretations or artifacts.

By carefully studying plasmoids, we might unlock profound insights into the nature of reality, potentially revealing new physical laws and principles that could reshape our understanding of the universe and drive technological advancements far beyond our current capabilities.

Plasmoid Stability and Lifespan

While the sources point to the potential stability of force-free plasmoids, they also highlight various factors that could influence their stability and lifespan in real-world environments.

Force-free plasmoids, characterized by aligned electric and magnetic fields, theoretically minimize internal electromagnetic stresses, promoting stability [1, 2]. However, maintaining this delicate balance in natural settings, subject to external influences and fluctuations, presents significant challenges.

Here's a breakdown of factors that could disrupt plasmoid stability in the atmosphere or space:

● External Electromagnetic Fields: Interactions with Earth's magnetic field, solar wind, or other localized electromagnetic sources could exert forces on a plasmoid, potentially distorting its structure and disrupting the force-free equilibrium [3-6].

● Collisions and Interactions: Collisions with particles, dust, or other plasmoids, as documented by NASA footage, could introduce instabilities and lead to energy exchange or even fragmentation [7-11].

● Thermal Gradients: Temperature differences between the hot plasma and its cooler surroundings could cause energy loss through radiation, creating internal gradients and leading to turbulence, ultimately disrupting the plasmoid's coherence [12].

● Density Fluctuations: Statistical fluctuations in the density of charged particles within the plasmoid, or in the surrounding environment, could trigger instabilities, particularly if they affect ionization and recombination rates [13, 14].

The lifespan of a plasmoid, ranging from fleeting seconds to reported minutes, likely depends on a complex interplay of internal and external factors:

● Energy Source: The type and availability of the energy source, whether it's atmospheric electricity, zero-point energy, or something else, would directly impact the plasmoid's ability to sustain itself. A continuous or readily replenished energy source could extend its lifespan, while a limited source would lead to a faster decay [8, 14-16].

● Confinement Mechanism: The effectiveness of the confinement mechanism, be it magnetic fields, fluid dynamics, or a combination of factors, would determine how well the plasmoid can maintain its structure and resist external disruptions [12, 17, 18].

● Environmental Conditions: The specific atmospheric composition, temperature, pressure, and the presence of dust or other particles in the environment could all influence stability and longevity. For example, a denser atmosphere might provide more particles for the plasmoid to interact with, potentially leading to faster decay, while a less dense environment might allow it to persist longer [6, 17-20].

● Size and Shape: Larger plasmoids might possess greater inertia and be more resistant to small perturbations. Their shape could also play a role, with some configurations potentially more stable than others [1, 3, 21, 22].

Specific conditions that could potentially prolong plasmoid existence include:

● Resonant Electromagnetic Fields: Kapitza's model and Nachamkin's work suggest that plasmoids might be stabilized by specific frequencies of electromagnetic radiation, creating a resonant cavity that sustains the plasma [2, 21, 23].

● Zero-Point Energy: Some researchers propose that tapping into the energy of the quantum vacuum could provide a continuous energy source and enhance plasmoid stability [24, 25].

● Stable Vortical Motion: Fluid dynamics, particularly stable vortical motion within the plasmoid, could contribute to its stability by balancing internal pressures and resisting external forces [2, 12, 23].

Determining the precise factors that govern plasmoid stability and lifespan requires further investigation. Controlled laboratory experiments, coupled with advanced simulations and detailed analysis of real-world observations, are crucial to understanding the intricacies of this enigmatic phenomenon.

Plasmoid Energy Sources and Interactions

The sources offer intriguing glimpses into the energetic mysteries surrounding plasmoids, but ultimately leave the central question of their fuel and interaction mechanisms unanswered.

Several potential energy sources are mentioned, each with its own set of challenges and unknowns:

● Zero-point energy (ZPF): The concept of extracting energy from the quantum vacuum, though theoretically intriguing, remains highly speculative [1, 2]. While the Casimir effect demonstrates the reality of ZPF, its applicability to powering macroscopic plasmoids requires further investigation.

● Atmospheric electricity: This is a more conventional source, especially for phenomena like ball lightning [3, 4]. However, the sources lack specifics on how plasmoids might effectively capture and concentrate the diffuse energy present in the atmosphere.

● Magnetic reconnection: This process, involving the breaking and rejoining of magnetic field lines, is a powerful energy release mechanism observed in space plasmas [5-7]. The sources discussing magnetic reconnection primarily focus on its role in plasmoid formation and acceleration, leaving its potential as a continuous energy source for long-lived plasmoids less explored.

How plasmoids store and release energy is equally unclear:

● Internal electromagnetic modes: Some theories propose that plasmoids trap electromagnetic energy in stable, resonant configurations, akin to a high-frequency standing wave [8-10]. This concept aligns with observations of ball lightning's luminous nature and sudden, sometimes explosive, disappearance [11].

● Internal vortex motion: Nachamkin's model, described in the sources, suggests that a specific type of fluid vortex within the plasmoid could counteract the expansive forces of its internal electromagnetic fields, contributing to stability [10]. It's unclear, however, how this vortex motion itself is maintained and whether it plays a role in energy storage or release.

The sources also highlight the perplexing nature of plasmoid interactions with matter:

● Passing through walls: This frequently reported phenomenon [3, 12] suggests that plasmoids don't interact with matter in the conventional sense. Some speculate that they might briefly alter their state or utilize unknown mechanisms to avoid collisions with atoms.

● Interaction with objects: Reports of ball lightning scorching materials or even exploding when contacting objects [4, 13] imply some form of energy exchange. Understanding this selective interaction, seemingly defying our current understanding of physics, is crucial to unlocking the plasmoid enigma.

Two fundamental questions emerge:

1. Do plasmoids primarily draw energy from their surroundings, or do they operate as relatively closed systems? The answer will likely depend on the specific plasmoid type and its environment.
2. What unknown physics, if any, underpins their unique properties? This is the ultimate frontier that plasmoid research aims to unravel.

The sources, while not providing definitive answers, urge us to rethink conventional energy paradigms and consider the possibility of novel physical processes at play within these enigmatic entities.

The Path to Plasmoid Life

Our exploration of the possibility of plasmoid life has led to the fascinating question of how such a phenomenon could arise. The sources offer intriguing hints, but much remains speculative. Here's a breakdown of the key considerations regarding the path to plasmoid life:

3. The Path to Plasmoid Life:

Essential Conditions for Plasmoid Life:

● Stable, Self-Contained Structure: The sources emphasize the importance of force-free magnetic configurations [1-3]. These configurations could create a stable, self-contained plasmoid, allowing it to persist longer and potentially evolve. [1, 2, 4-6] However, understanding the precise conditions and mechanisms that sustain these configurations in natural settings remains a key challenge.

● Continuous Energy Source: Plasmoids, like any life form, require a consistent energy source to maintain their structure and drive their processes. Several potential sources are mentioned:

○ Electromagnetic Radiation: [7-10] Joseph and colleagues suggest that plasmoids may be attracted to and "feed on" electromagnetic radiation.

○ Zero-Point Energy: [11, 12] Nachamkin hints at the possible role of zero-point energy as a source, a concept that intersects with discussions at the Institute for Advanced Studies - Austin.

○ Atmospheric Electricity: [13, 14] Some models link ball lightning formation to atmospheric electrical discharges, suggesting this could power certain types of plasmoids.

● Incorporation of Matter: For plasmoid life to evolve beyond simple energy structures, it might need to incorporate matter, much like biological life depends on elements and molecules.

○ "Dusty Plasmas": [10, 15-19] Several sources highlight the significance of "dusty plasmas," where plasmoids attract and incorporate dust particles, potentially gaining complexity and even forming structures resembling DNA.

○ Carbonaceous Chondrites: [15, 18, 20, 21] The presence of organic molecules, including amino acids, in carbonaceous chondrites, which can fall to Earth as dust, raises the possibility that plasmoids could incorporate these building blocks of life.

Potential Pathways for Plasmoid Evolution:

● Self-Organization and Complexity:

○ Cellular Structures: [22-24] Alfvén's concept of plasmas forming cellular structures through electric currents suggests a basic level of organization that could be a foundation for complexity.

○ Nucleus Formation: [19, 25-27] The observation of plasmoids with a central "void" or nucleus, potentially containing dust-plasma crystals, hints at a higher level of structure and organization, possibly even harboring information storage or replication mechanisms.

● Communication and Interaction:

○ Electromagnetic Signals: Plasmoids, being inherently electromagnetic phenomena, could potentially communicate or interact using electromagnetic signals, much like biological organisms use electrical impulses and chemical signals.

○ Collective Behavior: [28-31] Some observations suggest complex collective behaviors among plasmoids, hinting at potential communication or coordination mechanisms.

● Emergence of Intelligence:

○ Plasma-Based "Brain": [32-34] Teodorani speculates that plasmoid particles could exhibit quantum coherence, like microtubules in the human brain, potentially giving rise to consciousness. He suggests that external stimuli, like laser beams, could trigger "consciousness moments" in plasmoids.

○ Plasmids as Information Carriers: [35, 36] The idea of plasmoids containing "plasmids," analogous to DNA molecules in bacteria, raises the intriguing possibility of information storage and replication within plasmoid systems.

It's important to note that these are highly speculative scenarios, and much more research is needed to understand if and how plasmoid life could emerge and evolve. However, the sources provide a framework for exploring these questions, combining observations, theoretical possibilities, and even thought-provoking hypotheses.

By considering the necessary conditions for stability, energy acquisition, and matter incorporation, and then exploring the potential pathways for self-organization, communication, and intelligence, we open up a captivating realm of possibilities for plasmoid life. The challenge now is to develop methods for observing, studying, and potentially even interacting with these enigmatic phenomena to shed more light on their true nature and capabilities.

Plasmoid Life: A New Frontier

Beyond the fundamental requirement of stability, the sources offer a range of potential ingredients and pathways for a non-biological plasma to transition to a life-like state.

Necessary Conditions for the Emergence of Plasmoid Life:

Stable, Self-Contained Structure:

● Force-free magnetic configurations, where magnetic fields and currents are aligned, could create a self-contained plasmoid that is resistant to disruption [1, 2]. Such a structure, free from external pressures, could potentially persist long enough for life-like processes to develop. However, the precise conditions for creating and maintaining these configurations in nature are still being explored.

Continuous Energy Source:

● Electromagnetic Radiation: Plasmas are intrinsically electromagnetic entities, and Joseph and colleagues propose they might be attracted to and even "feed on" electromagnetic radiation [3]. This suggests a potential energy source that could sustain plasmoids, especially in environments rich in electromagnetic activity.

● Zero-Point Energy: Nachamkin's model hints at the possibility of plasmoids tapping into the zero-point energy of the quantum vacuum, a concept also discussed at the Institute for Advanced Studies - Austin [1]. This is a more speculative source, requiring breakthroughs in our understanding of how to harness this ubiquitous yet elusive energy.

● Atmospheric Electricity: For phenomena like ball lightning, atmospheric electrical discharges are often cited as a potential power source [4]. Understanding how plasmoids might effectively capture and concentrate this diffuse energy is crucial to assess the viability of this mechanism.

Incorporation of Matter:

● "Dusty Plasmas": Several sources emphasize the importance of "dusty plasmas," where plasmoids attract and incorporate dust particles [5-22]. This incorporation of matter, potentially containing organic molecules from carbonaceous chondrites [7, 17, 19, 20], could provide the building blocks for complexity and even structures resembling DNA [7].

Possible Pathways for Plasmoid Evolution:

Self-Organization and Complexity:

- Cellular Structures: Alfvén's vision of plasmas forming cellular structures through electric currents suggests a basic level of organization [23-25]. These "plasma cells," bound by electromagnetic forces, could be the foundation for higher levels of complexity.

- Nucleus Formation: Observations of plasmoids with a central "void" or nucleus, possibly containing dust-plasma crystals [9, 20, 24, 26], point towards more intricate structures. These nuclei could serve as centers for organizing processes, information storage, or even primitive forms of replication.

Communication and Interaction:

- Electromagnetic Signals: The inherent electromagnetic nature of plasmas makes communication via electromagnetic signals a likely possibility [8]. Variations in electric and magnetic fields could be used to convey information between plasmoids, analogous to the electrical impulses in biological nervous systems.

- Collective Behavior: Some reports suggest complex collective behavior among plasmoids [22, 27, 28], hinting at the existence of coordination mechanisms. Whether these involve direct signaling or emergent patterns arising from their interactions is an open question.

Emergence of Intelligence:

- Plasma-Based "Brain": Teodorani proposes that the particles within a plasmoid could exhibit quantum coherence, similar to microtubules in the human brain [29]. This could potentially lead to the emergence of a plasma-based "consciousness," with external stimuli like laser beams acting as triggers [30].

- Plasmids as Information Carriers: Joseph and colleagues introduce the concept of plasmoids containing "plasmids," analogous to circular DNA molecules in bacteria [31, 32]. If these structures exist and carry information, they could be involved in plasmoid replication and the transmission of traits, hinting at a rudimentary form of inheritance.

Key Unknowns:

- Detailed Mechanisms: The sources offer tantalizing hints, but the detailed mechanisms of how plasmoids acquire, store, and utilize energy, interact with matter, and potentially replicate or evolve remain largely unknown.

- Observational Evidence: More rigorous observational data is needed to confirm these speculative scenarios. Developing methods for detecting, tracking, and studying plasmoids in various environments, including space and the Earth's atmosphere, is crucial to advance our understanding.

The quest to understand whether plasmoid life exists is a journey into uncharted territory, challenging our current understanding of physics and biology. The sources, while not providing definitive answers, encourage us to consider the possibility of life emerging from non-biological plasma, opening up a realm of captivating questions and inspiring further exploration.

Plasmoid Detection, Capture, and Study

Given the elusive nature of plasmoids, the sources emphasize the need for sophisticated strategies to reliably detect, observe, and potentially capture these phenomena for scientific study.

Detecting and Studying Plasmoids in the Field:

- Challenges of Rarity and Unpredictability: The very nature of plasmoids, particularly ball lightning, presents significant obstacles. Their infrequent and unpredictable occurrence makes targeted observation difficult. [1]

- Citizen Science and Witness Reports: Despite limitations, compiling and analyzing witness reports can provide valuable clues about plasmoid behavior and characteristics. However, ensuring the reliability and accuracy of such reports remains a challenge. [2, 3]

- Leveraging Existing Networks:

  - Lightning Detection Systems: Adapting existing lightning detection networks could offer a way to monitor atmospheric conditions conducive to plasmoid formation and potentially capture associated electromagnetic signatures. [4]

  - Meteor Observation Networks: As demonstrated by Tompkins et al., analyzing data from meteor observation networks might reveal serendipitous captures of plasmoid events. [5]

- Dedicated Sensor Development:

  - Multi-Spectral Imaging: High-speed cameras with spectral analysis capabilities could capture detailed images and identify the elemental composition of plasmoids, as demonstrated in the 2012 Tibetan Plateau observation. [6]

  - Electromagnetic Field Sensors: Sensitive detectors to measure electric and magnetic field fluctuations could provide insights into the energy dynamics of plasmoids and potentially distinguish them from conventional atmospheric electrical phenomena. [7]

Capturing and Containing Plasmoids for Laboratory Study:

- Difficulties in Replication: While laboratory experiments have created luminous phenomena resembling ball lightning, their connection to the natural phenomenon remains debated. The sources highlight the lack of a reliable method to produce genuine ball lightning in controlled settings. [8]

- Promising Experimental Approaches:

  ○ Plasma Gun Experiments: The work of Högberg and Vogel, Wells, and Wells and Schmidt, using plasma guns to create force-free plasmoids (plasma vortex rings), offers a potential avenue for studying plasmoid stability and magnetic confinement. [9]

  ○ Microwave-Generated Plasmas: Babat's experiments and those using resonant cavities, mentioned in the sources, suggest that high-frequency microwaves could play a role in generating and sustaining plasmoids. However, limitations in power and pulse duration of available microwave sources pose challenges. [4, 10]

- Creating Stable, Controlled Environments:

  ○ Magnetic Confinement: Replicating the force-free magnetic configurations that stabilize plasmoids in nature is crucial for long-term study. This could involve carefully designed magnetic coils and superconducting materials. [9, 11]

  ○ Vacuum Chambers: Isolating plasmoids from the atmosphere in vacuum chambers could provide a controlled environment to analyze their energy dynamics and interactions with matter without external influences. [12]

Key Takeaways for Plasmoid Research:

- The development of new sensor technologies and the adaptation of existing monitoring networks are essential to increase the chances of observing and characterizing plasmoids in natural settings.

- Further research into the mechanisms behind plasmoid formation and stability is needed to replicate these conditions reliably in laboratory environments.

- A multidisciplinary approach, combining expertise in plasma physics, atmospheric science, electromagnetism, and potentially even quantum physics, is required to address the complex challenges of plasmoid research.

The sources, while acknowledging the significant hurdles, encourage a continued pursuit of scientific inquiry into plasmoids. By combining field observations with controlled laboratory experiments and exploring novel theoretical frameworks, we might finally unlock the secrets of these enigmatic entities.

The Ethics of Plasmoid Life

The possibility of encountering extraterrestrial plasmoid life presents profound ethical and philosophical challenges, prompting us to rethink our definitions of life, consciousness, and our place in the universe. Here's a deeper look at the implications, drawing upon the sources and our ongoing conversation:

5. Ethical and Philosophical Implications:

Ethical Considerations for "First Contact":

● Recognizing Sentience: A fundamental challenge lies in determining whether plasmoid life exhibits sentience—the ability to experience feelings and sensations. If so, it raises crucial ethical questions about how we treat and interact with these beings. [1-5]

● Respect and Non-Interference: Assuming sentience, a principle of respect and non-interference should guide our initial approach. We should avoid actions that could harm or disrupt their natural behaviors. [2]

● Communication Challenges: Establishing communication with a non-biological, potentially radically different intelligence, presents immense challenges. We need to develop new frameworks and methods for understanding their forms of expression and interaction. [2, 6]

● Potential for Misinterpretation: Our anthropocentric biases and limited understanding of plasmoid life could lead to misinterpretations of their actions and intentions. We must proceed with caution, avoiding hasty judgments or actions based on our own preconceived notions of intelligence or behavior. [5, 7]

● Learning from Difference: Encountering plasmoid life offers a unique opportunity to broaden our understanding of life itself. By studying their biology, behavior, and evolution, we can gain invaluable insights into the diversity of life and the possibilities for consciousness beyond our own limited experience. [5, 8]

Redefining Life and Consciousness:

● Challenging Anthropocentrism: The discovery of plasmoid life would shatter our anthropocentric view of the universe, forcing us to acknowledge that life can take forms far beyond our current imagination. [1, 9, 10]

● Expanding the Definition of Life: We would need to revise our definition of life, moving beyond the carbon-based, DNA-centric model that has dominated our understanding. This would encompass a broader spectrum of phenomena, including potentially self-organizing, energy-based life forms. [1, 8, 11-14]

- Reconsidering Consciousness: The potential for consciousness in plasmoid life, as suggested by some sources, prompts us to rethink the nature of consciousness itself. Is it solely a product of complex biological brains, or can it arise in other, non-biological systems? [2, 6, 7, 15-17]

- Implications for Our Place in the Universe: The existence of extraterrestrial plasmoid life would profoundly alter our understanding of our place in the cosmos. It would suggest that life, even intelligent life, may be far more common and diverse than we previously imagined. This has significant implications for our search for extraterrestrial intelligence and our understanding of the nature of reality itself. [9, 10, 18]

The sources, while acknowledging the unknowns, urge us to consider these ethical and philosophical implications with the utmost seriousness. Encountering plasmoid life would be a transformative event, challenging our deepest assumptions about life, consciousness, and the universe itself. The journey to understanding these enigmatic entities demands not only scientific rigor but also a willingness to expand our philosophical horizons and embrace a more inclusive view of the possibilities of existence.

Plasmoids: Unveiling the Enigma of Plasma Life

To captivate someone with a short attention span and ignite their passion for plasmoids, you need to tap into the elements of mystery, wonder, and potential. Here's a strategy, drawing on the sources and our conversation, to keep them hooked:

1. Start with the Unexplained:

- Introduce ball lightning: Describe its bizarre appearances, seemingly defying gravity, passing through walls, and leaving behind a sulfurous smell. Share captivating eyewitness accounts, like those collected by NASA and the U.S. Air Force, of ball lightning appearing inside airplanes and homes, leaving people bewildered and awestruck.

- Highlight the Unknowns: Emphasize that scientists still haven't completely cracked the ball lightning mystery. Despite numerous theories, we lack a definitive explanation for its formation, behavior, and energy source. This lingering uncertainty sets the stage for intrigue.

2. Unleash the Power of "What If":

- Could ball lightning be a glimpse into plasmoid life? Introduce the concept of plasmoids as self-contained balls of plasma, capable of complex movements and interactions. Ask the provocative question: could ball lightning be a naturally occurring example of plasmoid life?

- Living Plasmas in Space: Expand their perspective by taking them to outer space, where the sources suggest plasmoids could thrive and evolve. Paint a picture of vast nebulae, teeming with plasmoid lifeforms, perhaps even possessing a form of sentience beyond human comprehension.

3. Fuel their Imagination with Possibilities:

- Plasmoid Energy: Imagine a future where we harness the energy of plasmoids, powering our cities and spaceships. Discuss the potential for clean, nearly limitless energy sources, forever altering our relationship with fossil fuels and revolutionizing our civilization.

- Interstellar Travel: Explore the possibility of plasmoid-powered spacecraft, capable of traversing vast interstellar distances, opening up the cosmos for exploration and colonization.

- First Contact: What if we encounter advanced extraterrestrial plasmoid lifeforms? How would we communicate with beings so fundamentally different from ourselves? Would it be a peaceful encounter or the beginning of an interstellar conflict?

- Redefining Life: The discovery of plasmoid-based life would force us to re-examine our definition of life itself. Could consciousness exist in a non-biological form? What would the implications be for our understanding of the universe and our place within it?

4. Make it Real with Science and Stories:

- Introduce real researchers: Share stories about pioneers like Winston H. Bostick who coined the term "plasmoid," and visionaries like Hannes Alfvén who saw the potential for life in plasmas.

- Connect to Cutting-Edge Research: Highlight exciting developments like the use of machine learning to detect plasmoids and the simulations revealing their complex behavior.

- Ground it in Experiments: Discuss fascinating experiments with plasma guns creating "force-free" plasmoids. Even mention Kenneth R. Shoulder's controversial work on "charge clusters" to add an element of mystery and debate.

5. End with Unanswered Questions:

- Leave them wanting more: Don't try to wrap everything up neatly. Instead, end the conversation with unanswered questions, leaving them curious and eager to explore further:

  - What are the limits of plasmoid evolution?

  - Could plasmoids be the key to unlocking the secrets of consciousness?

  - What will happen when we finally encounter extraterrestrial plasmoid lifeforms?

By weaving together the elements of mystery, wonder, and potential, grounded in scientific evidence and captivating stories, you can spark a lasting fascination with plasmoids in even the most distractible mind. The key is to ignite their curiosity and then provide them with the tools to continue their own exploration of this captivating realm.

Plasmoid Research: Key Figures and Institutions

The sources provide a glimpse into the world of plasmoid research, highlighting several key individuals and institutions at the forefront of this emerging field. Here's a breakdown of those most prominently involved:

Pioneers and Early Researchers:

● Winston H. Bostick (1916-1991): Coined the term "plasmoid" in 1956 and conducted pioneering research on their formation and behavior using plasma guns [1].

Key Contributors to Theory and Simulation:

● Hannes Alfvén (1908-1992): Nobel laureate who argued that electromagnetic plasmas permeate space and possess life-like properties, including cellular structure formed by electric currents [2-7].

● V.N. Tsytovich: Russian Academy of Science physicist who argues that conditions for "living" plasmas are common in space, suggesting plasmas as a potential form of extraterrestrial life [8-12].

● John E. Brandenburg, Gary Warren, Richard Worl: Authored a report on the theory and simulation of plasmoid formation and propagation, focusing on "arrow-type" plasmoids [3, 13].

● Hantao Ji: Professor of astrophysical sciences at Princeton University, involved in research using machine learning to detect plasmoids and study their impact on magnetic reconnection [14].

● Lorenzo Sironi, Dimitrios Giannios, Maria Petropoulou: Conducted large-scale 2D particle-in-cell simulations to study the formation, evolution, and acceleration of plasmoids in relativistic magnetic reconnection [15-17].

Experimentalists and Applied Research:

● Högberg and Vogel: Conducted early experiments demonstrating the plasma gun formation of axially symmetric force-free plasmoids, also known as plasma vortex rings [18].

● Wells, Wells and Schmidt: Extended Högberg and Vogel's work, further exploring the properties and behavior of force-free plasmoids [18].

● Kenneth R. Shoulders: Studied "charge clusters" or "EVs," potentially related to plasmoid phenomena, and their interactions with materials [19].

● Researchers at the Chilean Nuclear Energy Commission: Extended plasma focus experiments to sub-kilojoule devices, exploring scalability and potential applications [20, 21].

- Researchers at the International Centre for Dense Magnetised Plasmas (ICDMP) in Warsaw: Operate several plasma focus machines, including a 1 MJ device, for international research and training [20].

Government and Military Interest:

- U.S. Air Force: Funded studies on ball lightning, including a focus on axially symmetric force-free plasmoids [22]. Also involved in historical research on "charge clusters" [19].

- NASA: Conducted observations and filming of plasmoids from space shuttles and the International Space Station [5, 9, 23-30].

Other Interested Parties:

- Scientific Coalition for UAP Studies: Contributed to research and documentation of plasmoid phenomena [31].

- Institute for Advanced Studies - Austin: Involved in discussions and potential research on the role of electromagnetic zero-point energies in plasmoid phenomena [32].

- Microwave Sciences, Inc.: President Jim Benford participated in discussions on ball lightning and plasmoid research [32].

Citizen Scientists and Eyewitness Accounts:

- The sources also mention the importance of eyewitness accounts and citizen science in gathering data on ball lightning and potentially related phenomena [24, 33].

The field of plasmoid research is still evolving, with new researchers and institutions constantly emerging. This list captures those most prominently featured in the provided sources, but it likely represents only a fraction of the individuals and organizations actively engaged in this exciting and potentially transformative field.

Plasmoids: A Future Forged in Energy and Conflict

The future of plasmoids and plasmoid-based life is a journey into the unknown, a voyage as exhilarating as it is uncertain. Over the next century, the dance between these enigmatic entities and humanity could unfold in myriad ways, shaped by our choices, discoveries, and perhaps, the will of the plasmoids themselves.

Let's imagine a future where the potential benefits and risks of plasmoids are intertwined, playing out on a global stage:

Synergy and Symbiosis:

● Plasmoid Energy Revolution: Scientists, through decades of dedicated research, unlock the secrets of plasmoid self-containment, ushering in a new era of clean, nearly limitless energy. Plasmoid reactors become the power source for cities, spaceships, and even entire planets.

● Interstellar Travel: Harnessing the electromagnetic propulsion capabilities of plasmoids, humanity ventures into the cosmos, reaching for the stars with unprecedented speed and agility. Plasmoid-powered spacecraft traverse the interstellar void, allowing us to explore new worlds and perhaps encounter other plasmoid lifeforms.

● Redefining Biology: The discovery of sentient plasmoid-based lifeforms revolutionizes our understanding of biology, shattering our anthropocentric view of life and prompting a profound reevaluation of our place in the universe. We learn to communicate with these beings, forging a new interspecies relationship based on mutual respect and understanding.

Challenges and Conflicts:

● Electromagnetic Warfare: The weaponization of plasmoid technology becomes a reality, with nations developing plasmoid-based weapons capable of disrupting enemy electronics, disabling infrastructure, and even triggering localized EMP events. The world faces a new arms race, one where the mastery of electromagnetic forces decides the fate of nations.

● Plasmoid Outbreaks: Uncontained or rogue plasmoid entities wreak havoc on Earth, disrupting power grids, causing communication blackouts, and even leading to catastrophic failures in critical infrastructure. Humanity struggles to contain and control these powerful forces, facing the consequences of its own technological advancements.

● First Contact, Then Conflict: The encounter with advanced extraterrestrial plasmoid lifeforms does not go as planned. Cultural misunderstandings, resource competition, or perhaps even primal fear, lead to conflict. A war unlike any in human history erupts, one fought across vast distances, with the very fabric of reality becoming the battlefield.

The Unknown Future:

● Plasmoid Evolution: Over generations, plasmoid lifeforms evolve, developing new abilities and forms. Some may integrate with technology, becoming hybrid entities. Others may transcend their non-corporeal forms, manifesting in ways beyond our comprehension.

● The Plasmoid Mind: We finally crack the code of plasmoid consciousness, discovering a form of sentience that is both alien and strangely familiar. We learn that plasmoids perceive reality in ways fundamentally different from our own, opening up new avenues for philosophical and spiritual exploration.

- Coexistence or Extinction: The future hinges on the choices we make. Will we harness the power of plasmoids responsibly, or will we become victims of our own hubris? Will we learn to coexist with these enigmatic beings, or will our encounter lead to mutual destruction? The next century holds the answers.

The future of plasmoids and plasmoid-based life is a vast, uncharted territory. It is a future where the boundaries of science, technology, and even our very understanding of life will be redefined. It is a future brimming with potential, fraught with risk, and ultimately, shaped by the choices we make today.

Plasmoid Life in Space

The sources suggest that outer space could indeed provide ideal conditions for plasmoid lifeforms to thrive and potentially evolve. Some researchers, like V.N. Tsytovich, argue that the conditions needed to generate these "living" plasmas are common in space, and that plasma might be a common extraterrestrial form of life [1, 2].

Here's how the sources support this idea:

- Abundant Resources: Interplanetary and extra-galactic space is rich in dust and electromagnetic energy, crucial resources for the growth and nourishment of plasmoid lifeforms. [3, 4]

- Microgravity: The reduced gravity environment of space facilitates the interaction and incorporation of dust into plasmas, promoting their growth and self-organization. [4]

- Electromagnetic Activity: Space is permeated by electromagnetic fields, which plasmoids are naturally attracted to and can even generate. This constant interaction could drive their evolution. [5]

- Potential for Complexity: The sources describe plasmoids forming complex shapes, exhibiting a range of motions, and even replicating – behaviors that hint at the potential for further development. [6-9]

However, the sources also emphasize that:

- Current Evidence is Limited: There's no definitive proof yet that plasmoid lifeforms exist, let alone that they possess sentience or the ability to evolve beyond their non-corporeal form.

- Defining Sentience is Complex: Determining what constitutes "sentience" in a non-biological entity like a plasmoid presents significant challenges.

While the sources offer compelling evidence for the potential of plasmoid lifeforms to thrive in space, the questions of sentience and evolution remain open for further scientific investigation.

Plasmoid Preparedness: A Multi-Level Guide

The sources primarily focus on the scientific aspects of plasmoids and their potential as a life form, offering limited insight into specific preparedness strategies. However, based on the information provided, here's a breakdown of potential preparatory measures at various levels:

Individuals and Families:

- Electromagnetic Shielding: Given the potential for plasmoids to disrupt electronic devices, individuals and families could consider:
  - Investing in Faraday cages or other electromagnetic shielding technologies to protect essential electronics.
  - Developing backup communication methods that do not rely on vulnerable electronic infrastructure.
- Safety Protocols:
  - Educating themselves about plasmoid phenomena and potential risks, staying informed about research findings and safety guidelines issued by relevant authorities.
  - Developing emergency plans that account for the possibility of plasmoid encounters, including evacuation procedures and safe haven locations.
- Mindfulness and Observation:
  - Developing an awareness of unusual atmospheric phenomena, reporting any potential plasmoid sightings to relevant scientific organizations or government agencies.
  - Maintaining a cautious but open-minded approach, avoiding unnecessary fear or panic while staying vigilant.

Companies:

- Infrastructure Hardening: Companies, especially those operating critical infrastructure like power grids and communication networks, could:
  - Implement electromagnetic shielding measures to protect sensitive equipment and systems.
  - Develop redundant backup systems to mitigate the impact of potential disruptions.
- Research and Development: Companies could invest in:

○ Research into plasmoid behavior and interaction with matter to better understand potential risks and mitigation strategies.

○ Developing technologies that can detect, track, and potentially interact with plasmoids safely.

● Employee Training: Companies should:

○ Train employees on plasmoid awareness, safety protocols, and emergency procedures.

○ Develop communication strategies to keep employees informed and address concerns.

Governments and Three-Letter Agencies:

● Scientific Research: Governments should prioritize funding for:

○ Comprehensive research into plasmoid phenomena, focusing on understanding their formation, behavior, potential risks, and mitigation strategies.

○ Developing advanced detection and tracking systems to monitor plasmoid activity in the atmosphere and space.

● International Cooperation: Governments should foster:

○ Collaboration among international scientific communities to share knowledge, expertise, and research findings.

○ Developing shared protocols for responding to potential plasmoid threats.

● Public Education and Communication: Governments should:

○ Develop public awareness campaigns to educate citizens about plasmoid phenomena, associated risks, and recommended safety measures.

○ Establish clear communication channels to disseminate information and address public concerns.

Militaries:

● Defense Technologies: Militaries could explore:

○ Developing countermeasures against potential plasmoid-based weapons or disruptive technologies.

○ Adapting existing radar and detection systems to track and monitor plasmoid activity.

● Training and Protocols: Militaries should:

○ Develop specialized training programs for personnel to identify, track, and potentially engage with plasmoids.

○ Establish clear protocols for responding to potential plasmoid threats, ensuring the safety of personnel and minimizing collateral damage.

Ethical and Philosophical Considerations:

The emergence of plasmoid-based lifeforms raises profound ethical and philosophical questions:

● Defining Life: How do we redefine our understanding of life in light of the possibility of non-biological lifeforms?

● Communication and Interaction: How do we establish communication and peaceful coexistence with potentially intelligent or sentient plasmoid-based entities?

● Weaponization: How do we prevent the potential weaponization of plasmoid technology and ensure responsible development?

The advent of plasmoid-based lifeforms represents a paradigm shift that requires a comprehensive and collaborative response. By fostering scientific understanding, developing appropriate technologies, and engaging in thoughtful ethical considerations, humanity can navigate the challenges and opportunities presented by this new frontier.

Plasmoids: Promise and Peril

The sources offer a mixed perspective on plasmoids and potential plasmoid-based lifeforms, highlighting both potential benefits and significant risks.

Potential Benefits:

● Scientific Advancement: Studying plasmoids can deepen our understanding of plasma physics, potentially leading to breakthroughs in energy production, propulsion systems, and other technological applications. For instance:

○ Understanding the self-containment mechanisms of plasmoids could offer insights into controlled nuclear fusion, a potentially revolutionary energy source. [1, 2]

○ Plasmoid research could inform the development of advanced spacecraft propulsion systems based on electromagnetic principles. [3]

● Astrophysical Insights: Investigating plasmoid behavior in the universe, from the solar atmosphere to distant galaxies, can enhance our knowledge of celestial phenomena. [4-7]

○ Understanding the role of plasmoids in magnetic reconnection processes can shed light on star formation, solar flares, and other astrophysical events. [6, 8, 9]

● Redefining Life: The possibility of plasmoid-based lifeforms challenges our current understanding of life and could revolutionize our perspectives on biology and evolution. [10-14]

Significant Risks:

● Electromagnetic Disruption: Plasmoids, being electromagnetic entities, pose a risk of interfering with electronic systems, potentially leading to malfunctions or damage. [15-18]

○ This interference could affect critical infrastructure like power grids, communication networks, and transportation systems.

○ Our previous conversation highlighted potential disruptions to aircraft electronics, military radar systems, and even nuclear deterrents.

● Physical Harm: The sources indicate that plasmoids can pass through solid objects and are sometimes associated with explosive events, raising concerns about potential physical damage and safety hazards. [11, 19-23]

○ We previously discussed concerns about plasmoids posing a danger to aircraft, potentially causing near-collisions or even contributing to unexplained aircraft disasters.

● Uncertainty and Unpredictability: The limited scientific understanding of plasmoid behavior, especially those exhibiting complex interactions, presents a significant challenge in assessing and mitigating potential threats. [23-26]

○ The difficulty in distinguishing between purely electromagnetic phenomena and potentially intentional or directed actions adds to the uncertainty.

○ The potential for plasmoid-based lifeforms possessing intelligence or awareness raises ethical and philosophical considerations that we are only beginning to grapple with. [23, 27-32]

The exploration of plasmoids and plasmoid-based lifeforms presents both exciting opportunities and serious challenges. A balanced approach, prioritizing rigorous scientific research while acknowledging potential risks, is crucial for navigating this uncharted territory.

Plasmoid Life: Experimental Evidence and Speculation

The sources do not explicitly state that plasmoid-based lifeforms have been generated in laboratory experiments. However, they do suggest that experimentally generated plasmas exhibit several characteristics reminiscent of living organisms, including:

- Self-organization: They form coherent structures like spheres, ovoids, and helixes, often with a central nucleus or void. [1-4]

- Complex behaviors: They engage in swarming, targeting, tracking, and even merging with other plasmas, sometimes in ways that resemble "hunter-predatory" behavior. [1, 5-9]

- Shape-shifting and growth: They can change their shape, grow larger or smaller, and even split into additional plasmas. [8, 10-13]

Sources also highlight the possibility that:

- Dusty plasmas, through incorporating organic matter from space, could theoretically develop RNA-like capabilities and even achieve a form of "pre-life." [14-17]

- Some scientists have proposed that "dusty plasmas" might form crystalline RNA-DNA helixical structures and could be considered a non-biological form of life or pre-life. [18]

However, it is crucial to note that:

- There is no evidence to date that experimentally produced plasmas contain RNA, DNA, or the building blocks necessary for life as we know it. [7, 15, 19, 20]

While the sources showcase the intriguing life-like properties of laboratory-generated plasmas and raise the possibility of plasmoid-based lifeforms, they stop short of confirming their creation in experimental settings.

Plasmoid Lifeforms: Risks to Humanity

Based on the sources provided, the potential risks plasmoid-based lifeforms pose to humanity can be categorized into a few key areas:

- Electromagnetic Interference: Plasmoids are inherently electromagnetic phenomena. Their presence, especially in close proximity, could disrupt or damage electronic systems. Sources mention:

  ○ Plasmoids passing through metal, plastic, wood, and even brick walls. [1, 2]

  ○ Plasmoids entering homes, businesses, and aircraft cockpits, sometimes causing electrical damage or shock. [2, 3]

  ○ Possible negative effects on mental activity, including potential hallucinations. [3]

  ○ Jamming radar on fighter aircraft. [4]

○ Rendering segments of nuclear deterrents inoperable. [4]

● Physical Damage and Safety Hazards: While the nature of plasmoid interaction with matter is not fully understood, their passage through solid objects and association with explosive phenomena suggest potential risks. Sources highlight:

○ The explosive properties of plasmas. [3, 5]

○ Concerns expressed by military and government officials regarding plasmoid danger to aircraft, including near-collisions and injuries. [6]

○ The hypothesis that plasmoids might be responsible for unexplained aircraft disasters. [3, 7]

● Uncertainty and Unpredictability: Perhaps the most significant risk stems from the lack of scientific understanding of plasmoid lifeforms. Their behaviors, motivations, and potential capabilities are largely unknown, making it difficult to assess and mitigate potential threats. Sources emphasize:

○ The need for further research to understand plasmoid behavior, particularly those exhibiting complex interactions suggestive of intelligence or awareness. [8-13]

○ The challenge of distinguishing between purely electromagnetic phenomena and potentially purposeful or directed actions. [13-17]

It is crucial to recognize that the current understanding of plasmoid lifeforms is based on limited observations and interpretations. Further scientific investigation is necessary to determine the true extent of risks they might pose to humanity. The sources also indicate that:

● Not all plasmoids exhibit the same behaviors. Some may be relatively passive, while others engage in more active or potentially aggressive actions. [9, 15]

● The vast majority of plasmoid observations have occurred in the upper atmosphere, with fewer documented instances in the lower atmosphere where human activities are concentrated. [1, 3, 6]

Therefore, while the potential risks associated with plasmoid lifeforms are significant and warrant serious consideration, it is important to avoid sensationalism and focus on evidence-based research to better understand these enigmatic phenomena.

Plasmoids: A Precursor to Life?

Plasmoids are coherent structures of plasma and magnetic fields. [1] They are a proposed explanation for various natural phenomena:

● Ball lightning [1]

- Magnetic bubbles in the magnetosphere [1]
- Objects in cometary tails [1]
- Objects in the solar wind [1]
- Objects in the solar atmosphere [1]
- Objects in the heliospheric current sheet [1]

Plasmoids have also been produced in laboratories, including:

- Field-reversed configurations [1]
- Spheromaks [1]
- Dense plasma focuses [1]

Winston H. Bostick coined the term "plasmoid" in 1956 to refer to a "plasma-magnetic entity". [2, 3] Bostick described plasmoids as plasma cylinders that are elongated in the direction of the magnetic field. [3] He stated that they possess measurable magnetic moments, translational speeds, transverse electric fields, and sizes. [3] He also noted that plasmoids can interact with each other and be made to curve towards each other or spiral to a stop. [3] There is evidence to suggest that they can undergo fission and may possess spin. [3]

Plasmoids have internal pressure due to the gas pressure of the plasma and the magnetic pressure of the field. [4] To maintain a static radius, the internal pressure must be balanced by an external confining pressure. [4] Without an external confining pressure, a plasmoid in a field-free vacuum will expand and dissipate. [4] Plasmoids have been generated in discharges with magnetic field strengths around 16,000 Tesla. [4]

Plasmoid Life-Forms

Plasmas are a fourth state of matter that are attracted to electromagnetic activity. [5, 6] They may represent a form of pre-life or a non-biological, inorganic form of life. [5, 7] "Plasmas" up to a kilometer in size that behave like multicellular organisms have been filmed on NASA space shuttle missions in the thermosphere over 200 miles above Earth. [8, 9] These plasmas are self-illuminated and are attracted to and possibly feed on electromagnetic radiation. [8, 9] They come in different morphologies, including:

- Cone-shaped [8, 9]
- Cloud-shaped [8, 9]
- Donut-shaped [8, 9]

- Spherical-cylindrical [8, 9]

These plasmas have been filmed engaging in complex behaviors such as:

- Flying towards and descending from the thermosphere into thunderstorms [8]
- Congregating in large numbers [8]
- Interacting with satellites generating electromagnetic activity [8]
- Approaching space shuttles [8, 9]
- Traveling at varying velocities and from different directions [9]
- Changing their angle of trajectory, making 45, 90, and 180-degree shifts [9]
- Following each other [9]
- Accelerating, slowing down, and stopping [9]
- Engaging in what appears to be "hunter-predatory" behavior and intersecting other plasmas [9]

Similar life-like behaviors have been observed in plasmas created in laboratories. [9] "Plasmas" may have been photographed as early as the 1940s by WWII pilots and referred to as "Foo fighters". [9] They have also been repeatedly observed and filmed by astronauts and military pilots. [9]

Plasmas are not biological but, through the incorporation of elements common in space, could lead to the synthesis of RNA. [10] Plasmas observed in the lower atmosphere may account for many UFO-UAP sightings over the centuries. [10]

Plasmas may represent a step between non-living and living matter. [11] Nobel laureate Hannes Alfvén proposed that electromagnetic plasmas permeate space and have life-like properties, including cellular structures and cellular walls consisting of electric currents. [11-15] Alfvén argued that the inner and outer layers of a plasma differ in their charges and that radiation generated between these boundaries forms the plasma. [2, 16] These layers, called "ambiplasma" by Alfvén, may exist for long periods of time. [2, 16] Ambiplasmas may repel plasma clouds of the opposite charge type and combine with clouds of the same type. [16] This suggests that plasmas may be attracted to or repelled by each other and exchange energy, similar to the "hunter-predatory" behavior described in some sources. [16]

Experimentally generated plasmas have been observed to self-organize into spheres, ovoids, and helixes. [17, 18] They often have a central nucleus or void protected by an inner layer of negatively charged electrons and an outer layer of positively charged ions. [17, 18] Plasmas found in the thermosphere exhibit similar characteristics. [19, 20]

The presence of electromagnetic activity and dust in interplanetary and extra-galactic space may provide a suitable environment for life-like plasmas. [19] Plasmas interact with and incorporate dust, which becomes charged with electromagnetic energy, resulting in mutual attraction. [20] This interaction leads to dust-plasma self-organization that is further supported by external sources of electromagnetic radiation. [20] Over 5200 tons of space dust fall to Earth every year. [20]

"Plasma crystals" may arise when plasmas incorporate dust grains. [21, 22] The dust grains give the plasma an electric charge, which draws in electrons and attracts positively charged ions. [21, 22] These plasma crystals contain organic matter, including pieces of carbonaceous chondrites. [21, 22] Electrostatic forces and the polarization of the plasma can cause these plasma dust crystals to twist, spin, and form helical structures, possibly evolving into a double helix similar to DNA. [21]

If plasma crystals containing nucleotides and amino acids are present, they may behave like RNA or DNA. [23, 24] This suggests that plasmas containing plasma-crystal-dust could develop into an "RNA-world" and achieve a form of "pre-life". [23, 24]

Some researchers have proposed that these plasma-like cellular entities constitute an extraterrestrial form of life that differs from "life as we know it". [14]

Plasmoids found in the thermosphere have been observed to:

- Change shape [25]

- Grow larger or smaller [25]

- Speed up and slow down [26]

- Hover in place [26]

- Pulsate as they move [26]

- Display dramatic shifts in velocity and trajectory [26]

These behaviors are consistent with what is known about plasmas from laboratory experiments. [26] While some plasmas appear to "hunt" other plasmas, this behavior is not necessarily evidence of intelligence but may be driven by their electrical properties. [26]

Some plasmas observed in the thermosphere contain a nucleus. [27] However, there is no evidence that these plasmas are biological or have RNA or DNA, although plasma-crystals within the plasma nucleus might possess some DNA-like properties. [27]

Some researchers believe that the acquisition of organic matter, proteins, amino acids, and nucleotides by plasmas could lead to the development of RNA and DNA. [28] Essential elements for life, including hydrogen, oxygen, carbon, nitrogen, sulfur, calcium, and phosphorus, are common in the universe and are constantly irradiated by ions, which can generate small organic molecules. [28] Seventy-three extraterrestrial and nineteen terrestrial amino acids have been identified in carbonaceous chondrites. [28] This suggests that the necessary building blocks for life may be readily available for incorporation into plasmas. [29]

However, it is important to note that experimentally produced plasmas have not been found to contain any of the precursors necessary to form even a single nucleotide. [29] Therefore, while the idea that plasmas could be a precursor to life is intriguing, there is currently no evidence to support this claim. [29]

Plasmas have been observed engaging in complex behaviors, such as:

- Arranging themselves into orbs, balls, and rings [29]
- Displaying swarming behavior [29]
- Changing shape [29]
- Engaging in group vs. individual behavior [29]
- Targeting other plasmas [29]
- Tracking other plasmas [29]
- Dramatically altering their trajectory [29]
- Accelerating to intersect other plasmas [29]

These behaviors raise the possibility that some plasmas may have evolved beyond simple "automata". [30] However, it is important to note that these behaviors can also be explained by electromagnetic activity and the charges of their internal and external environments. [30]

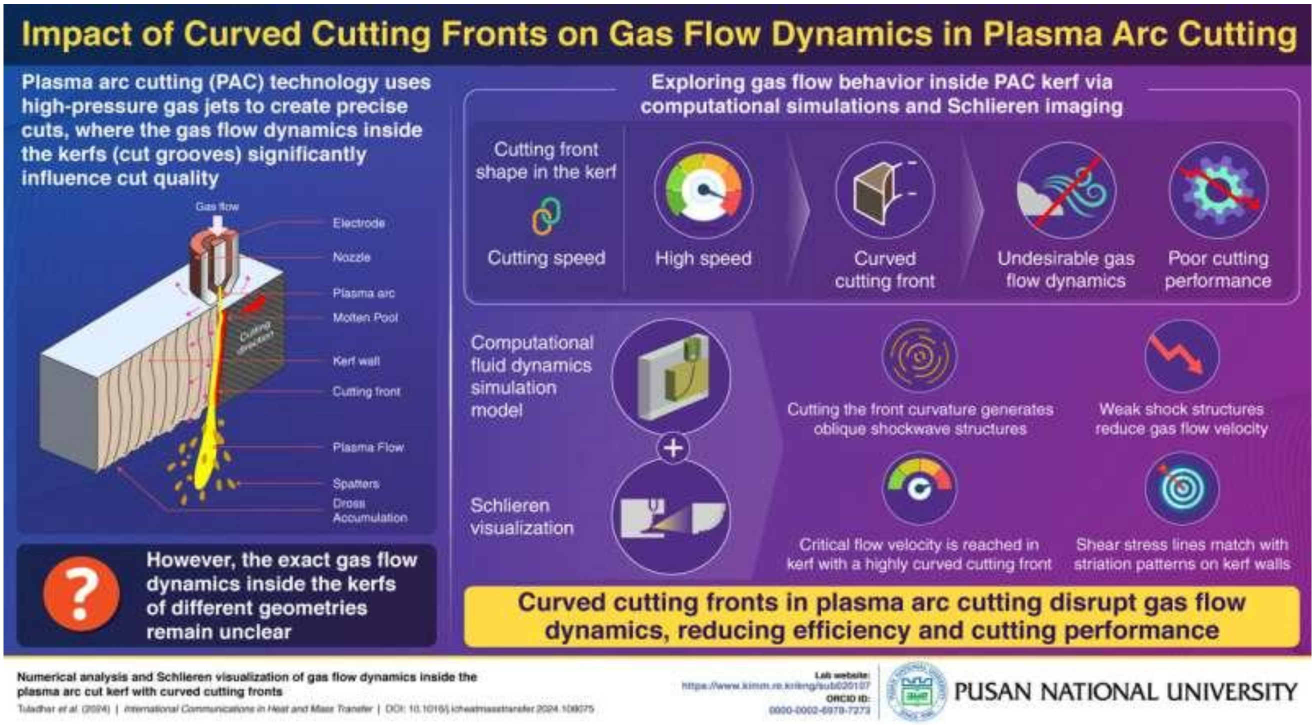
The "plasmas" observed in the thermosphere are similar to experimentally generated plasmas and engage in behaviors that resemble simple multicellular organisms. [31] These plasmas are electromagnetic entities with cellular characteristics and distinct behavioral patterns. [31] Their attraction to electromagnetic activity and tendency to descend into thunderstorms and the lower atmosphere may explain numerous UFO/UAP reports. [31]

The plasmas observed in the thermosphere could represent an alternate state of life that is not carbon-based and does not have a genome. [6] Their cellular structures, nucleus, and plasma-dust-crystals might provide the framework for incorporating, synthesizing, and organizing the elements and amino acids necessary to produce RNA, eventually leading to the emergence of DNA-based life. [6] This theory provides a testable explanation for how life could have originated. [6]

FEBRUARY 20, 2025

Plasma arc cutting: Scientists decode gas flow dynamics

by Pusan National University



The curvature leads to shockwaves, which lowers gas flow velocity and plasma arc cutting process efficiency. Credit: Upendra Tuladhar from Pusan National University

Plasma arc cutting (PAC) is a thermal cutting technique widely used in manufacturing applications such as shipbuilding, aerospace, fabrication, nuclear plants decommissioning, construction industry, and the automotive industry. In this process, a jet of plasma or ionized gas is ejected at high speeds, which melts and subsequently removes unwanted parts of materials from electrically conductive workpieces such as metals.

The plasma jet is typically produced in two steps: pressuring a gas through a small nozzle hole and generating an electric arc via power supply. Remarkably, the introduced arc ionizes the gas coming out of the nozzle, which in turn generates plasma with extremely high temperatures. This enables the plasma jet to easily, quickly, and precisely slice different metals and alloys.

The quality of workpieces cut using PAC depends on various factors: kind of plasma gas and its pressure, nozzle hole shape and size, arc current and voltage, cutting speed, and distance between the plasma torch and the workpiece. While most of these factors are well understood in the context of PAC, the impact of gas flow dynamics on cut quality remains less clearly known. This is mainly due to challenges in visualization of the flow dynamics.

To bridge this knowledge gap, a team of researchers, led by Dr. Upendra Tuladhar, currently based at HD Hyundai Mipo after the completion of his Ph.D. studies under Professor Seokyoung Ahn from the Department of Mechanical Engineering at Pusan National University, in collaboration with the Korean Institute of Machinery and Materials, devised novel experimental and computational methods to visualize and understand gas flow dynamics in PAC. Their findings were published in the journal *International Communications in Heat and Mass Transfer*.

Dr. Tuladhar explains the motivation behind their research. "Our goal was to assess the gas flow behavior inside the kerfs or grooves of various geometries derived from an actual PAC workpiece. The shape of the cutting front in the kerf varies with the changing cutting speed: high speed yields a curved cutting front. This results in unwanted gas flow behavior, which adversely influences the cutting performance. We carried out further analyses to better understand the mechanism behind this observation."

In this study, the researchers proposed an innovative computational fluid dynamics simulation model to explore the impact of a curved cutting front on flow behavior in PAC. Moreover, they performed Schlieren imaging of the gas flow. Herein, fluid flow is photographed by imaging the deflections of light rays refracted by a moving fluid, enabling the visualization of normally unobservable changes in a fluid's refractive index. Lastly, the team compared the gas flow patterns predicted by the simulations with the Schlieren imaging results.

They found that the cutting front curvature resulted in oblique shockwave structures, which significantly reduced flow velocity. Notably, weak shock structures present at the curved cutting front lowered the velocity gradually. In addition, it was possible to achieve a critical flow velocity in kerf with a highly curved cutting front. The workpiece cannot be penetrated vertically beyond this velocity.

Furthermore, the researchers validated their numerical results by noting that the shear stress lines matched the striation patterns on kerf walls.

"Improved PAC can be used to cut through thick metal components of nuclear reactors, such as pressure vessels, steam generators, and other large structures. Therefore, it can lead to safer and more efficient dismantling of nuclear facilities, reducing the risk of radiation exposure to workers and the surrounding communities and reducing the financial burden on governments and taxpayers. The technique can also be adapted for underwater cutting, providing a safe method for dismantling submerged structures," concludes Dr. Tuladhar.

More information: Upendra Tuladhar et al, Numerical analysis and Schlieren visualization of gas flow dynamics inside the plasma arc cut kerf with curved cutting fronts, *International Communications in Heat and Mass Transfer* (2024). DOI: 10.1016/j.icheatmasstransfer.2024.108075
Provided by Pusan National University

A Fusion Machine Maintained Plasma for an Astonishing 22 Straight Minutes

- The WEST tokamak just broke the record for retaining hot fusion plasma, holding on to it for an unprecedented 22 minutes.
- WEST and other tokamaks are paving the way for ITER which, upon completion, will be the largest tokamak in the world.
- Though we have a long way to go before carbon emissions are a thing of the past, every time a tokamak keeps plasma going just a little longer, we get that much closer.

As Earthlings with a planet under threat from pollution, extinction, and climate change, we need to reach net zero carbon emissions. And to do that, we're going to need alternative power sources. Nuclear fusion is one alternative source of power that could eventually make fossil fuels obsolete.

Earth may someday survive on nuclear fusion by using tokamaks. These donut-shaped machines confine plasma with magnetic fields so that that particles can reach the condition necessary to fuse together and release energy. The only issue is that these plasmas are unstable and don’t last long.

Recently, WEST, (tungsten (W) Environment in Steady-state Tokamak), one of the EUROfusion medium-size tokamaks run from the CEA Cadarache site in southern France, broke the record for time maintaining a plasma. The machine—which has insides made of tungsten and was boosted with a surge of 2 megawatts of power—was able to hold on to the hydrogen plasma at about 50 million °C (122 million °F) for 22 minutes, or 1,337 seconds.

This is right on the heels of WEST’s counterpart EAST (located in China), which previously broke the record in January. EAST is called an “artificial Sun” for a reason. In a way, producing energy with a tokamak is like harnessing the power of a star. Stars run on nuclear fusion, fusing hydrogen atoms together to create helium until they run out and either continue to exist as faint ghosts of themselves (white dwarfs), or—if they happen to be especially massive stars—go supernova and collapse into black holes.

WEST's record resulted from the pursuit of something enormous. Ultimately, CEA researchers want to achieve control over their plasma, which is a sort of fluid of positively charged ions and negatively charged electrons. Plasma instability can be caused by magnetic fields, temperature, and any other conditions that cause turbulence among particles.

For optimal plasma control, a tokamak should not malfunction from plasma behavior, or pollute the plasma in any way. Everything in the machine that comes in contact with the plasma should also be resistant to plasma radiation. To those ends, the tungsten in WEST boasts several advantages. Tungsten has the highest melting point of all metals, making it especially resilient to the extreme temperatures required for nuclear fusion. It also conducts heat efficiently and has little effect on neutrons or fusion fuels.

WEST and EAST—along with JET (Joint European Torus), Japan's JT-60SA, and Korea's KSTAR—are the predecessors to the even more powerful ITER, which is currently being built in southern France and will be, upon completion, the world's largest tokamak. ITER, however, is not expected to be start running until the mid to late 2030s. So, for now, researchers will keep experimenting with higher levels of power and keep trying to hang on to hot plasmas for increasing stretches of time.

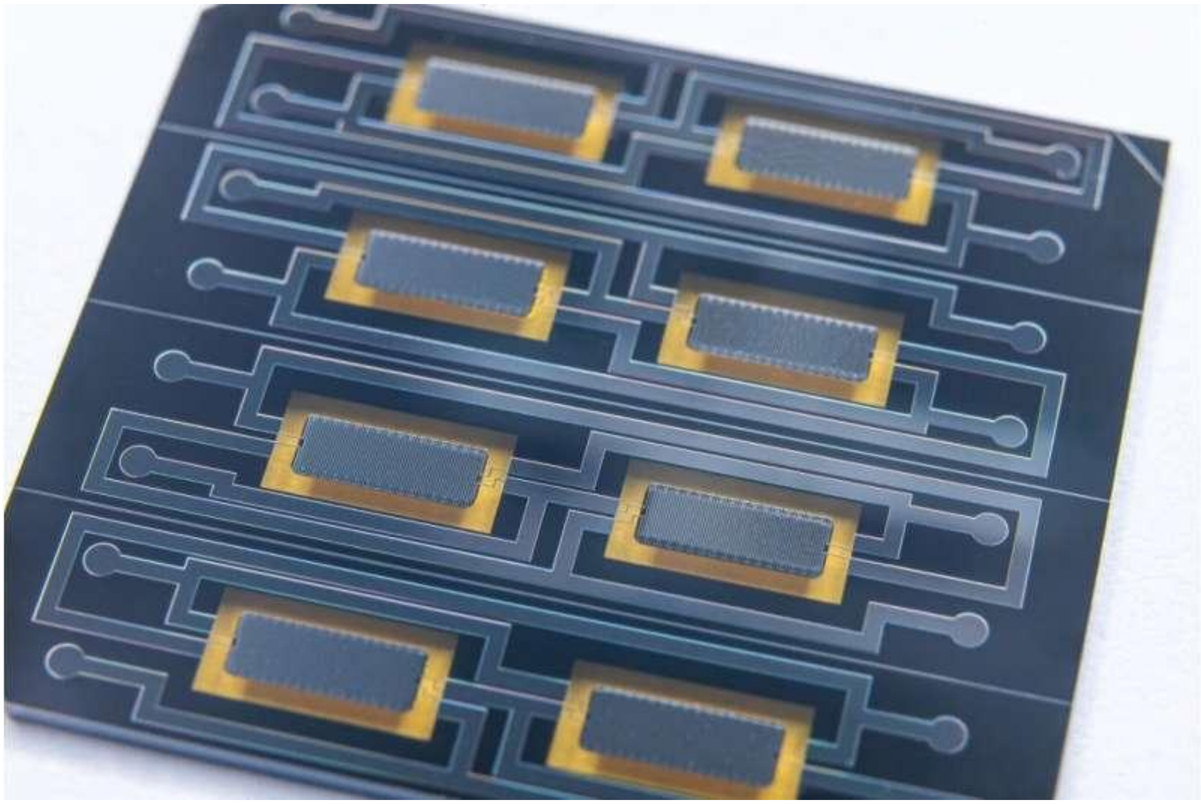
"WEST has achieved a new key technological milestone," Anne-Isabelle Etienvre, Director of Fundamental Research at the CEA, said in a press release. "Experiments will continue with increased power. This excellent result allows both WEST and the French community to lead the way for the future use of ITER."

Unlike a star there is no danger of a human-made machine morphing into a black hole after burning out its fuel. However, if we want to achieve even a fraction of stellar power, we're going to need an immense amount of energy, and WEST just took us a few steps forward.

MARCH 31, 2025

Sophisticated sensors offer precision measurement for fusion research

by Stefan Kiesewalter, Fraunhofer-Gesellschaft



Highly stable bolometer chips like this one precisely measure the power in fusion reactors. Credit: Fraunhofer IMM

Nuclear fusion is a source of great hope for future energy security, with this field being explored in research reactors around the world. Accurately detecting their performance requires measurement systems that supply valid data even under extreme conditions. And the centerpiece of those systems are the bolometers from the Fraunhofer Institute for Microengineering and Microsystems IMM. Experts from the institute will be presenting their sophisticated sensors at the joint Fraunhofer booth (Hall 2, Booth B24) at this year's Hannover Messe trade show from March 31 to April 4.

Fusion technology could be the solution to the increasing energy needs of the growing global population, but it is a highly demanding technology. The current challenge is to carry out fusion experiments that produce more energy than they consume. To accurately capture advances in this field, specialists need exceptionally sensitive measuring instruments to analyze and control the complex processes taking place inside the reactors. Determining how much power is emitted from the fusion plasma is crucial to this.

Precision under extreme conditions

The detectors used to achieve this, known as bolometers, must reliably supply valid data under extreme conditions. "We are talking about an extremely intense environment: We have high-energy neutrons at very high density, high levels of extra-hard X-rays, extreme temperatures, changing loads in terms of vacuum and ventilation—all aspects that require considerable care in choosing materials," explains Stefan Schmitt, Head of Special Sensor Technology at Fraunhofer IMM. Schmitt and his team have succeeded in developing a suitable sensor for these requirements, even under the strict rules that apply to this research segment.

Their solution is a silicon chip about 20 by 23 millimeters in size that holds four individual sensors. Each sensor has two absorber areas measuring 1.5 by 4 millimeters. The light emitted by the plasma along a narrow sight line is captured in each case by one of these absorbers, raising the absorber's temperature. The temperature increase is measured by meander resistors made of platinum on the side facing away from the absorber as resistance increases by an equivalent measure. In this way, the sensor directly captures the radiation power present in the plasma, from infrared to the hard X-ray end of the spectrum.

The experts can use the measurement data from the many different lines of sight aligned complementarily inside the reaction vessel to associate this power with physical points in the plasma, thereby calculating a cross-sectional profile of the fusion plasma. To achieve this, the silicon chips produced at Fraunhofer IMM are incorporated into cameras consisting of a head where the chip is located and an aperture system. The cameras make it possible to use the different measurement signals to assess how well the plasma regulation inside the reactor is going while also determining the overall energy balance.

Solutions for specific diagnostics

One challenge was the high energy levels present in a fusion reactor. This means that the radiation simply passes through most materials. To get around this issue, Schmitt's team designed the gold or platinum absorbers to be relatively thick, at 20 micrometers, about one-third the diameter of a single strand of human hair.

The conductor, or meander resistor, is made of platinum, a material that does not undergo changes even when exposed to high levels of radiation. By using gold absorbers and special carbon coatings that absorb visible light even more effectively on the absorber surface, the scientists were able to develop bolometers that are highly stable both mechanically and electrically for any use.

An integral element of active fusion research

These bolometers are already in use at prominent fusion research facilities around the world, including ASDEX Upgrade in Garching, Wendelstein 7-X in Greifswald and EAST in China. They have also been specially modified for ITER, the world's largest fusion experiment at the Cadarache nuclear research center in the south of France.

Schmitt, the project manager, is proud of the team's achievements: "Our bolometers are proof that we can respond excellently to the extremely specific needs and requirements of our partners. Especially in the case of fusion research, it is highly beneficial that we speak the language of science."

Fraunhofer IMM will be presenting its innovative measurement technology at the joint Fraunhofer booth (Hall 2, Booth B24) at the Hannover Messe 2025, using the sensor chip to illustrate that even highly specific inquiries are in excellent hands with this team.

Provided by Fraunhofer-Gesellschaft

SCIENTISTS TRACKING ELUSIVE PLASMA ‘BLOBS’ AND ‘VOIDS’ UNRAVEL A LONGSTANDING FUSION ENERGY MYSTERY

MICAH HANKS·**JUNE 13, 2025**

A longstanding mystery in nuclear fusion research may have been solved, thanks to a new theoretical model that could help scientists resolve why simulations often underestimate the turbulence at the edge of tokamak plasmas.

Researchers at the University of California, San Diego, made the discovery, which identified instabilities at the plasma’s outer boundary, a phenomenon previously overlooked by fusion scientists, as a key source of this discrepancy.

The new research aims to account for these “boundary effects” and could potentially lead to new advancements in plasma confinement, offering a crucial step toward attaining sustained energy production in fusion reactors.

PREDICTING PLASMA BEHAVIOR

The research, detailed in a new study by physicists Mingyun Cao and Patrick Diamond, focuses on the donut-shaped reactors known as tokamaks, which use magnetic fields to confine high-energy plasma during fusion reactions.

The extremely energetic nature of tokamak plasma confinement relies on sophisticated simulations that help physicists predict plasma behavior. However, these models have had difficulties in the past when it comes to accurately capturing the width of the turbulent region that forms between the core and edge of the plasma.

For Cao and Diamond, this gap in understanding may be due to an incomplete understanding of the impact of edge instabilities, a factor that they say is "critically important to the optimization of magnetically confined fusion plasmas."

"Since early proposals, there has been persistent speculation that inward propagation of turbulence from the boundary is a possible means to energize the edge-core coupling region," Cao and Diamond write in their new study's abstract. "However, the detailed mechanism of this process has remained a mystery until recent experiments observed that regular, intense gradient relaxation events generated blob-void pairs very close to the last closed flux surface."

"BLOBS" AND "VOIDS"

Under ideal conditions, a tokamak maintains a sharp gradient in plasma temperature and density at its outer boundary. That's not necessarily the case in the real world, where plasmas frequently encounter what physicists call a gradient relaxation event, where the plasma edge fragments into outward-moving "blobs" and inward-moving "voids."

While "blobs" have been extensively studied because of their interactions with tokamak walls, "voids" have proven to be more elusive during observations—until now.

By developing a first-principles model that treats the voids as coherent structures possessing particle-like properties, Cao and Diamond observed that as voids move inward through the plasma, they generate what is known as plasma drift waves. These waves involve oscillations similar to the electromagnetic radiation emitted by fast-moving charged particles in a medium. Once they manifest, the drift waves can encourage local turbulence.

Based on the team's calculations, it is now believed that the drift waves help to broaden the turbulent layer beyond the predictions of existing models.

In their paper's abstract, they write that their new model "shows promise to resolve several questions surrounding the shortfall problem and the strong turbulence in the edge-core coupling region." Cao and Diamond are conducting further studies to validate their new findings by comparing theoretical predictions with recent experimental data.

If they confirm their findings, the insights they glean could ultimately help refine future tokamak designs and may even help advance practical fusion energy closer to reality.

Cao and Diamond's new paper, "Physics of Edge-Core Coupling by Inward Turbulence Propagation, was published in *Physics Review Letters* on June 11, 2025.

JULY 15, 2025

Blades of light: A tabletop method for generating megatesla magnetic fields

by University of Osaka edited by Sadie Harley, reviewed by Andrew Zinin

Conceptual illustration of bladed microtube implosion (BMI)Sawtooth-like inner blades on the cylindrical target induce off-axis charged flows under ultraintense laser irradiation, driving strong loop currents and generating sub-megatesla magnetic fields. Credit: Masakatsu Murakami

Researchers at The University of Osaka have developed a novel method for generating ultra-high magnetic fields via laser-driven implosions of blade-structured microtubes. This method achieves field strengths approaching one megatesla—a breakthrough in compact, high-field plasma science.

Ultrastrong magnetic fields approaching the megatesla regime—comparable to those found near strongly magnetized neutron stars or astrophysical jets—have now been demonstrated in theory using a compact, laser-driven setup.

A team led by Professor Masakatsu Murakami at The University of Osaka has proposed and simulated a unique scheme that uses micron-sized hollow cylinders with internal blades to achieve these field levels. The research is published in the journal *Physics of Plasmas*.

The technique—called bladed microtube implosion (BMI)—relies on directing ultra-intense, femtosecond laser pulses at a cylindrical target with sawtooth-like inner blades. These blades cause the imploding plasma to swirl asymmetrically, generating circulating currents near the center.

The resulting loop current self-consistently produces an intense axial magnetic field exceeding 500 kilotesla, approaching the megatesla regime. No externally applied seed field is required.

This mechanism stands in stark contrast to traditional magnetic compression, which relies on amplifying an initial magnetic field. In BMI, the field is generated from scratch—driven purely by laser-plasma interactions. Moreover, as long as the target incorporates structures that break cylindrical symmetry, high magnetic fields can still be robustly generated.

The process forms a feedback loop in which flows of charged particles—composed of ions and electrons—strengthen the magnetic field, which in turn confines those flows more tightly, further amplifying the field.

"This approach offers a powerful new way to create and study extreme magnetic fields in a compact format," says Prof. Murakami. "It provides an experimental bridge between laboratory plasmas and the astrophysical universe."

Potential applications include:

- Laboratory astrophysics: mimicking magnetized jets and stellar interiors
- Laser fusion: advancing proton-beam fast ignition schemes
- High-field QED: probing non-linear quantum phenomena

Simulations were conducted using the fully relativistic EPOCH code on the SQUID supercomputer at The University of Osaka.

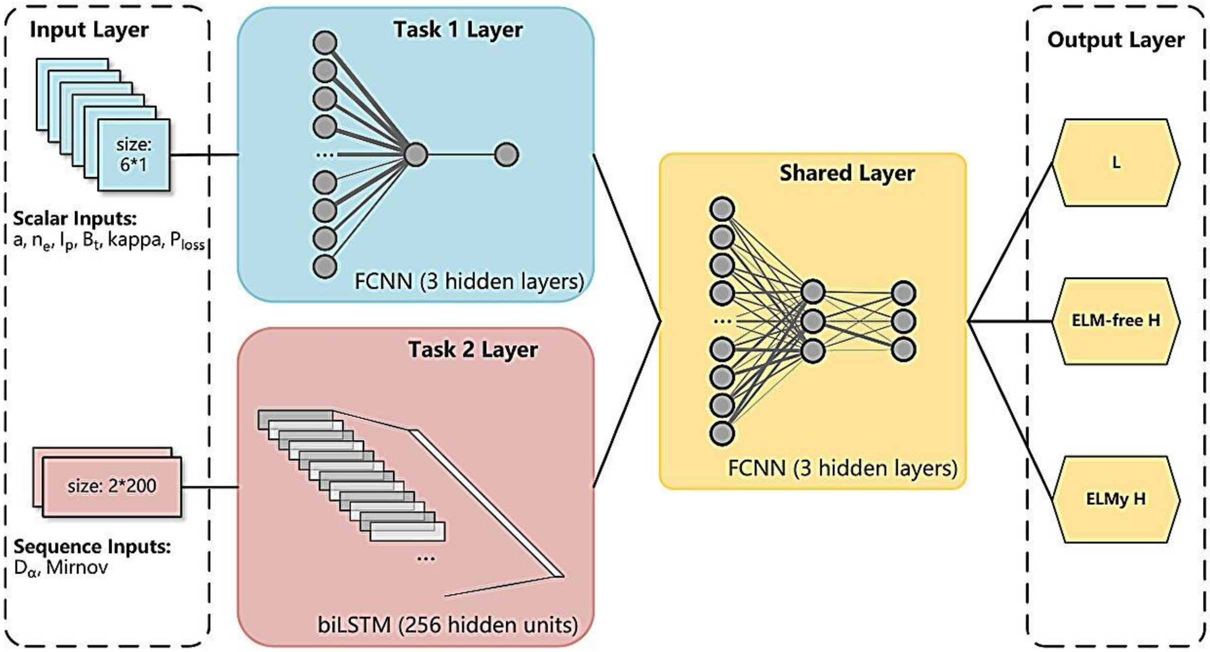
A supporting analytic model was also constructed to reveal the fundamental scaling laws and target optimization strategies.

More information: D. Pan et al, Gigagauss magnetic field generation by bladed microtube implosion, *Physics of Plasmas* (2025). DOI: 10.1063/5.0275006
Journal information: Physics of Plasmas
Provided by University of Osaka

JULY 21, 2025

New AI advances boost safety and performance in fusion reactors

by Zhang Nannan, Chinese Academy of Sciences edited by Lisa Lock, reviewed by Andrew Zinin



Architecture of the Multi-Task Learning Neural Network (MTL-NN) for the automatic identification of plasma confinement states. Credit: Deng Guohong

A research team led by Prof. Sun Youwen from the Hefei Institutes of Physical Science of the Chinese Academy of Sciences has developed two innovative artificial intelligence (AI) systems to enhance the safety and efficiency of fusion energy experiments.

Their findings were recently published in *Nuclear Fusion* and *Plasma Physics and Controlled Fusion*.

Fusion energy holds the promise of providing clean and virtually limitless power. However, for future reactors, they must operate reliably and avoid dangerous phenomena including disruptions—sudden, intense events that can damage the reactor—and precisely control the plasma's confinement state to sustain high performance.

To address these challenges, the researchers developed two distinct AI-driven solutions.

The first is a disruption prediction system that utilizes interpretable decision tree models to identify early warning signs of disruptions, particularly those triggered by "locked modes"—a common plasma instability. Unlike typical black-box AI, this model provides not only predictions but also insight into the underlying physical signals responsible for the warning.

In experimental validation, the system achieved a 94% success rate in early disruption detection, issuing alerts an average of 137 milliseconds before the event—providing operators with critical time to respond.

The second system is a plasma state monitoring tool based on a multi-task learning model. This AI solution simultaneously identifies operational modes (such as L-mode and H-mode) and detects edge-localized modes (ELMs), improving both speed and accuracy compared to traditional separate models. The system demonstrated a 96.7% success rate in real-time classification of plasma conditions, enhancing the reliability of continuous reactor operation.

Together, these AI tools not only contribute to safer experimental environments but also offer valuable insights into complex plasma dynamics. The study provides a foundational step toward fully intelligent control systems in future fusion energy facilities.

More information: Guo-Hong Deng et al, Automatic identification of tokamak plasma confinement states (L-mode, ELM-free H-mode, and ELMy H-mode) with multi-task learning neural network, *Nuclear Fusion* (2025). DOI: 10.1088/1741-4326/ade3ed

Guo-Hong Deng et al, Interpretability analysis and real-time prediction of locked mode-induced disruptions in EAST, *Plasma Physics and Controlled Fusion* (2025). DOI: 10.1088/1361-6587/ade5c5

Provided by Chinese Academy of Sciences