

= Plasma (physics) =

Plasma (from Greek ?????? , " anything formed ") is one of the four fundamental states of matter , the others being solid , liquid , and gas . A plasma has properties unlike those of the other states .

A plasma can be created by heating a gas or subjecting it to a strong electromagnetic field , applied with a laser or microwave generator . This decreases or increases the number of electrons , creating positive or negative charged particles called ions , and is accompanied by the dissociation of molecular bonds , if present .

The presence of a significant number of charge carriers makes plasma electrically conductive so that it responds strongly to electromagnetic fields . Like gas , plasma does not have a definite shape or a definite volume unless enclosed in a container . Unlike gas , under the influence of a magnetic field , it may form structures such as filaments , beams and double layers .

Plasma is the most abundant form of ordinary matter in the Universe (of the forms proven to exist ; the more abundant dark matter is hypothetical and may or may not be explained by ordinary matter) , most of which is in the rarefied intergalactic regions , particularly the intracluster medium , and in stars , including the Sun . A common form of plasma on Earth is produced in neon signs .

Much of the understanding of plasma has come from the pursuit of controlled nuclear fusion and fusion power , for which plasma physics provides the scientific foundation .

= = Properties and parameters = =

= = = Definition = = =

Plasma is an electrically neutral medium of unbound positive and negative particles (i.e. the overall charge of a plasma is roughly zero) . It is important to note that although the particles are unbound , they are not ? free ? in the sense of not experiencing forces . When a charged particle moves , it generates an electric current with magnetic fields ; in plasma , the movement of a charged particle affects and is affected by the general field created by the movement of other charges . This governs collective behavior with many degrees of variation . Three factors are listed in the definition of a plasma stream :

The plasma approximation : Charged particles must be close enough together that each particle influences many nearby charged particles , rather than just interacting with the closest particle (these collective effects are a distinguishing feature of a plasma) . The plasma approximation is valid when the number of charge carriers within the sphere of influence (called the Debye sphere whose radius is the Debye screening length) of a particular particle is higher than unity to provide collective behavior of the charged particles . The average number of particles in the Debye sphere is given by the plasma parameter , " ? " (the Greek uppercase letter Lambda) .

Bulk interactions : The Debye screening length (defined above) is short compared to the physical size of the plasma . This criterion means that interactions in the bulk of the plasma are more important than those at its edges , where boundary effects may take place . When this criterion is satisfied , the plasma is quasineutral .

Plasma frequency : The electron plasma frequency (measuring plasma oscillations of the electrons) is large compared to the electron @-@ neutral collision frequency (measuring frequency of collisions between electrons and neutral particles) . When this condition is valid , electrostatic interactions dominate over the processes of ordinary gas kinetics .

= = = Ranges of parameters = = =

The factors of a plasma stream can vary by many orders of magnitude , but the properties of plasmas with apparently disparate parameters may be very similar (see plasma scaling) . The following chart considers only conventional atomic plasmas and not exotic phenomena like quark gluon plasmas :

=== Degree of ionization ===

For plasma to exist, ionization is necessary. The term "plasma density" by itself usually refers to the "electron density", that is, the number of free electrons per unit volume. The degree of ionization of a plasma is the proportion of atoms that have lost or gained electrons, and is controlled mostly by the temperature. Even a partially ionized gas in which as little as 1 % of the particles are ionized can have the characteristics of a plasma (i.e., response to magnetic fields and high electrical conductivity). The degree of ionization, α , is defined as $\alpha = \frac{n_i}{n_i + n_n}$, where n_i is the number density of ions and n_n is the number density of neutral atoms. The electron density is related to this by the average charge state \bar{Z} of the ions through $n_e = \alpha \bar{Z} n_{\text{atoms}}$, where n_e is the number density of electrons.

=== Temperatures ===

Plasma temperature is commonly measured in kelvins or electronvolts and is, informally, a measure of the thermal kinetic energy per particle. High temperatures are usually needed to sustain ionization, which is a defining feature of a plasma. The degree of plasma ionization is determined by the electron temperature relative to the ionization energy (and more weakly by the density), in a relationship called the Saha equation. At low temperatures, ions and electrons tend to recombine into bound states (atoms) and the plasma will eventually become a gas.

In most cases the electrons are close enough to thermal equilibrium that their temperature is relatively well defined, even when there is a significant deviation from a Maxwellian energy distribution function, for example, due to UV radiation, energetic particles, or strong electric fields. Because of the large difference in mass, the electrons come to thermodynamic equilibrium amongst themselves much faster than they come into equilibrium with the ions or neutral atoms. For this reason, the ion temperature may be very different from (usually lower than) the electron temperature. This is especially common in weakly ionized technological plasmas, where the ions are often near the ambient temperature.

=== Thermal vs. nonthermal plasmas ===

Based on the relative temperatures of the electrons, ions and neutrals, plasmas are classified as "thermal" or "non-thermal". Thermal plasmas have electrons and the heavy particles at the same temperature, i.e. they are in thermal equilibrium with each other. Nonthermal plasmas on the other hand have the ions and neutrals at a much lower temperature (sometimes room temperature), whereas electrons are much "hotter" ($T_e \gg T_i$).

=== Complete vs. incomplete ionization ===

A plasma is sometimes referred to as being "hot" if it is nearly fully ionized, or "cold" if only a small fraction (for example 1 %) of the gas molecules are ionized, but other definitions of the terms "hot plasma" and "cold plasma" are common. Even in a "cold" plasma, the electron temperature is still typically several thousand degrees Celsius. Plasmas utilized in "plasma technology" ("technological plasmas") are usually cold plasmas in the sense that only a small fraction of the gas molecules are ionized.

=== Plasma potential ===

Since plasmas are very good electrical conductors, electric potentials play an important role. The potential as it exists on average in the space between charged particles, independent of the question of how it can be measured, is called the "plasma potential", or the "space potential". If an electrode is inserted into a plasma, its potential will generally lie considerably below the plasma

potential due to what is termed a Debye sheath . The good electrical conductivity of plasmas makes their electric fields very small . This results in the important concept of " quasineutrality " , which says the density of negative charges is approximately equal to the density of positive charges over large volumes of the plasma ($n_e \approx n_i$) , but on the scale of the Debye length there can be charge imbalance . In the special case that double layers are formed , the charge separation can extend some tens of Debye lengths .

The magnitude of the potentials and electric fields must be determined by means other than simply finding the net charge density . A common example is to assume that the electrons satisfy the Boltzmann relation :

$n_e = n_0 \exp(-e\phi/kT_e)$

Differentiating this relation provides a means to calculate the electric field from the density :

$E = -kT_e / e \cdot (1/n_e) \cdot (dn_e/dx)$

It is possible to produce a plasma that is not quasineutral . An electron beam , for example , has only negative charges . The density of a non @-@ neutral plasma must generally be very low , or it must be very small , otherwise it will be dissipated by the repulsive electrostatic force .

In astrophysical plasmas , Debye screening prevents electric fields from directly affecting the plasma over large distances , i.e. , greater than the Debye length . However , the existence of charged particles causes the plasma to generate , and be affected by , magnetic fields . This can and does cause extremely complex behavior , such as the generation of plasma double layers , an object that separates charge over a few tens of Debye lengths . The dynamics of plasmas interacting with external and self @-@ generated magnetic fields are studied in the academic discipline of magnetohydrodynamics .

== Magnetization ==

Plasma with a magnetic field strong enough to influence the motion of the charged particles is said to be magnetized . A common quantitative criterion is that a particle on average completes at least one gyration around the magnetic field before making a collision , i.e. , $\omega_{ce} > \nu_{ei}$, where ω_{ce} is the " electron gyrofrequency " and ν_{ei} is the " electron collision rate " . It is often the case that the electrons are magnetized while the ions are not . Magnetized plasmas are anisotropic , meaning that their properties in the direction parallel to the magnetic field are different from those perpendicular to it . While electric fields in plasmas are usually small due to the high conductivity , the electric field associated with a plasma moving in a magnetic field is given by $E = -v \times B$ (where E is the electric field , v is the velocity , and B is the magnetic field) , and is not affected by Debye shielding .

== Comparison of plasma and gas phases ==

Plasma is often called the fourth state of matter after solid , liquids and gases , despite plasma typically being an ionized gas . It is distinct from these and other lower @-@ energy states of matter . Although it is closely related to the gas phase in that it also has no definite form or volume , it differs in a number of ways , including the following :

== Common plasmas ==

Plasmas are by far the most common phase of ordinary matter in the universe , both by mass and by volume . Essentially , all of the visible light from space comes from stars , which are plasmas with a temperature such that they radiate strongly at visible wavelengths . Most of the ordinary (or baryonic) matter in the universe , however , is found in the intergalactic medium , which is also a plasma , but much hotter , so that it radiates primarily as X @-@ rays .

In 1937 , Hannes Alfvén argued that if plasma pervaded the universe , it could then carry electric currents capable of generating a galactic magnetic field . After winning the Nobel Prize , he emphasized that :

In order to understand the phenomena in a certain plasma region , it is necessary to map not only the magnetic but also the electric field and the electric currents . Space is filled with a network of currents which transfer energy and momentum over large or very large distances . The currents often pinch to filamentary or surface currents . The latter are likely to give space , as also interstellar and intergalactic space , a cellular structure .

By contrast the current scientific consensus is that about 96 % of the total energy density in the universe is not plasma or any other form of ordinary matter , but a combination of cold dark matter and dark energy . Our Sun , and all stars , are made of plasma , much of interstellar space is filled with a plasma , albeit a very sparse one , and intergalactic space too . Even black holes , which are not directly visible , are thought to be fuelled by accreting ionising matter (i.e. plasma) , and they are associated with astrophysical jets of luminous ejected plasma , such as M87 's jet that extends 50,000 light years .

In our solar system , interplanetary space is filled with the plasma of the Solar Wind that extends from the Sun out to the heliopause . However , the density of ordinary matter is much higher than average and much higher than that of either dark matter or dark energy . The planet Jupiter accounts for most of the non-plasma within the orbit of Pluto (about 0.1 % by mass , or 10 ? 15 % by volume) .

Dust and small grains within a plasma will also pick up a net negative charge , so that they in turn may act like a very heavy negative ion component of the plasma (see dusty plasmas) .

= = Complex plasma phenomena = =

Although the underlying equations governing plasmas are relatively simple , plasma behavior is extraordinarily varied and subtle : the emergence of unexpected behavior from a simple model is a typical feature of a complex system . Such systems lie in some sense on the boundary between ordered and disordered behavior and cannot typically be described either by simple , smooth , mathematical functions , or by pure randomness . The spontaneous formation of interesting spatial features on a wide range of length scales is one manifestation of plasma complexity . The features are interesting , for example , because they are very sharp , spatially intermittent (the distance between features is much larger than the features themselves) , or have a fractal form . Many of these features were first studied in the laboratory , and have subsequently been recognized throughout the universe . Examples of complexity and complex structures in plasmas include :

= = Filamentation = =

Striations or string-like structures , also known as birkeland currents , are seen in many plasmas , like the plasma ball , the aurora , lightning , electric arcs , solar flares , and supernova remnants . They are sometimes associated with larger current densities , and the interaction with the magnetic field can form a magnetic rope structure . High power microwave breakdown at atmospheric pressure also leads to the formation of filamentary structures . (See also Plasma pinch)

Filamentation also refers to the self-focusing of a high power laser pulse . At high powers , the nonlinear part of the index of refraction becomes important and causes a higher index of refraction in the center of the laser beam , where the laser is brighter than at the edges , causing a feedback that focuses the laser even more . The tighter focused laser has a higher peak brightness (irradiance) that forms a plasma . The plasma has an index of refraction lower than one , and causes a defocusing of the laser beam . The interplay of the focusing index of refraction , and the defocusing plasma makes the formation of a long filament of plasma that can be micrometers to kilometers in length . One interesting aspect of the filamentation generated plasma is the relatively low ion density due to defocusing effects of the ionized electrons . (See also Filament propagation)

= = Shocks or double layers = =

Plasma properties change rapidly (within a few Debye lengths) across a two @-@ dimensional sheet in the presence of a (moving) shock or (stationary) double layer . Double layers involve localized charge separation , which causes a large potential difference across the layer , but does not generate an electric field outside the layer . Double layers separate adjacent plasma regions with different physical characteristics , and are often found in current carrying plasmas . They accelerate both ions and electrons .

= = = Electric fields and circuits = = =

Quasineutrality of a plasma requires that plasma currents close on themselves in electric circuits . Such circuits follow Kirchhoff 's circuit laws and possess a resistance and inductance . These circuits must generally be treated as a strongly coupled system , with the behavior in each plasma region dependent on the entire circuit . It is this strong coupling between system elements , together with nonlinearity , which may lead to complex behavior . Electrical circuits in plasmas store inductive (magnetic) energy , and should the circuit be disrupted , for example , by a plasma instability , the inductive energy will be released as plasma heating and acceleration . This is a common explanation for the heating that takes place in the solar corona . Electric currents , and in particular , magnetic @-@ field @-@ aligned electric currents (which are sometimes generically referred to as " Birkeland currents ") , are also observed in the Earth 's aurora , and in plasma filaments .

= = = Cellular structure = = =

Narrow sheets with sharp gradients may separate regions with different properties such as magnetization , density and temperature , resulting in cell @-@ like regions . Examples include the magnetosphere , heliosphere , and heliospheric current sheet . Hannes Alfvén wrote : " From the cosmological point of view , the most important new space research discovery is probably the cellular structure of space . As has been seen in every region of space accessible to in situ measurements , there are a number of ' cell walls ' , sheets of electric currents , which divide space into compartments with different magnetization , temperature , density , etc . "

= = = Critical ionization velocity = = =

The critical ionization velocity is the relative velocity between an ionized plasma and a neutral gas , above which a runaway ionization process takes place . The critical ionization process is a quite general mechanism for the conversion of the kinetic energy of a rapidly streaming gas into ionization and plasma thermal energy . Critical phenomena in general are typical of complex systems , and may lead to sharp spatial or temporal features .

= = = Ultracold plasma = = =

Ultracold plasmas are created in a magneto @-@ optical trap (MOT) by trapping and cooling neutral atoms , to temperatures of 1 mK or lower , and then using another laser to ionize the atoms by giving each of the outermost electrons just enough energy to escape the electrical attraction of its parent ion .

One advantage of ultracold plasmas are their well characterized and tunable initial conditions , including their size and electron temperature . By adjusting the wavelength of the ionizing laser , the kinetic energy of the liberated electrons can be tuned as low as 0 @. 1 K , a limit set by the frequency bandwidth of the laser pulse . The ions inherit the millikelvin temperatures of the neutral atoms , but are quickly heated through a process known as disorder induced heating (DIH) . This type of non @-@ equilibrium ultracold plasma evolves rapidly , and displays many other interesting phenomena .

One of the metastable states of a strongly nonideal plasma is Rydberg matter , which forms upon

condensation of excited atoms .

== Non @-@ neutral plasma ==

The strength and range of the electric force and the good conductivity of plasmas usually ensure that the densities of positive and negative charges in any sizeable region are equal (" quasineutrality ") . A plasma with a significant excess of charge density , or , in the extreme case , is composed of a single species , is called a non @-@ neutral plasma . In such a plasma , electric fields play a dominant role . Examples are charged particle beams , an electron cloud in a Penning trap and positron plasmas .

== Dusty plasma / grain plasma ==

A dusty plasma contains tiny charged particles of dust (typically found in space) . The dust particles acquire high charges and interact with each other . A plasma that contains larger particles is called grain plasma . Under laboratory conditions , dusty plasmas are also called complex plasmas .

== Impermeable plasma ==

Impermeable plasma is a type of thermal plasma which acts like an impermeable solid with respect to gas or cold plasma and can be physically pushed . Interaction of cold gas and thermal plasma was briefly studied by a group led by Hannes Alfvén in 1960s and 1970s for its possible applications in insulation of fusion plasma from the reactor walls . However , later it was found that the external magnetic fields in this configuration could induce kink instabilities in the plasma and subsequently lead to an unexpectedly high heat loss to the walls . In 2013 , a group of materials scientists reported that they have successfully generated stable impermeable plasma with no magnetic confinement using only an ultrahigh @-@ pressure blanket of cold gas . While spectroscopic data on the characteristics of plasma were claimed to be difficult to obtain due to the high pressure , the passive effect of plasma on synthesis of different nanostructures clearly suggested the effective confinement . They also showed that upon maintaining the impermeability for a few tens of seconds , screening of ions at the plasma @-@ gas interface could give rise to a strong secondary mode of heating (known as viscous heating) leading to different kinetics of reactions and formation of complex nanomaterials .

== Mathematical descriptions ==

To completely describe the state of a plasma , we would need to write down all the particle locations and velocities and describe the electromagnetic field in the plasma region . However , it is generally not practical or necessary to keep track of all the particles in a plasma . Therefore , plasma physicists commonly use less detailed descriptions , of which there are two main types :

== Fluid model ==

Fluid models describe plasmas in terms of smoothed quantities , like density and averaged velocity around each position (see Plasma parameters) . One simple fluid model , magnetohydrodynamics , treats the plasma as a single fluid governed by a combination of Maxwell 's equations and the Navier ? Stokes equations . A more general description is the two @-@ fluid plasma picture , where the ions and electrons are described separately . Fluid models are often accurate when collisionality is sufficiently high to keep the plasma velocity distribution close to a Maxwell ? Boltzmann distribution . Because fluid models usually describe the plasma in terms of a single flow at a certain temperature at each spatial location , they can neither capture velocity space structures like beams or double layers , nor resolve wave @-@ particle effects .

== Kinetic model ==

Kinetic models describe the particle velocity distribution function at each point in the plasma and therefore do not need to assume a Maxwell-Boltzmann distribution. A kinetic description is often necessary for collisionless plasmas. There are two common approaches to kinetic description of a plasma. One is based on representing the smoothed distribution function on a grid in velocity and position. The other, known as the particle-in-cell (PIC) technique, includes kinetic information by following the trajectories of a large number of individual particles. Kinetic models are generally more computationally intensive than fluid models. The Vlasov equation may be used to describe the dynamics of a system of charged particles interacting with an electromagnetic field. In magnetized plasmas, a gyrokinetic approach can substantially reduce the computational expense of a fully kinetic simulation.

== Artificial plasmas ==

Most artificial plasmas are generated by the application of electric and/or magnetic fields through a gas. Plasma generated in a laboratory setting and for industrial use can be generally categorized by:

The type of power source used to generate the plasma? DC, RF and microwave

The pressure they operate at? vacuum pressure (< 10 mTorr or 1 Pa), moderate pressure (~ 1 Torr or 100 Pa), atmospheric pressure (760 Torr or 100 kPa)

The degree of ionization within the plasma? fully, partially, or weakly ionized

The temperature relationships within the plasma? thermal plasma ($T_e \approx T_i$), non-thermal or "cold" plasma ($T_e \gg T_i$)

The electrode configuration used to generate the plasma

The magnetization of the particles within the plasma? magnetized (both ion and electrons are trapped in Larmor orbits by the magnetic field), partially magnetized (the electrons but not the ions are trapped by the magnetic field), non-magnetized (the magnetic field is too weak to trap the particles in orbits but may generate Lorentz forces)

== Generation of artificial plasma ==

Just like the many uses of plasma, there are several means for its generation, however, one principle is common to all of them: there must be energy input to produce and sustain it. For this case, plasma is generated when an electric current is applied across a dielectric gas or fluid (an electrically non-conducting material) as can be seen in the image to the right, which shows a discharge tube as a simple example (DC used for simplicity).

The potential difference and subsequent electric field pull the bound electrons (negative) toward the anode (positive electrode) while the cathode (negative electrode) pulls the nucleus. As the voltage increases, the current stresses the material (by electric polarization) beyond its dielectric limit (termed strength) into a stage of electrical breakdown, marked by an electric spark, where the material transforms from being an insulator into a conductor (as it becomes increasingly ionized). The underlying process is the Townsend avalanche, where collisions between electrons and neutral gas atoms create more ions and electrons (as can be seen in the figure on the right). The first impact of an electron on an atom results in one ion and two electrons. Therefore, the number of charged particles increases rapidly (in the millions) only after about 20 successive sets of collisions, mainly due to a small mean free path (average distance travelled between collisions).

== Electric arc ==

With ample current density and ionization, this forms a luminous electric arc (a continuous electric discharge similar to lightning) between the electrodes. Electrical resistance along the continuous

electric arc creates heat , which dissociates more gas molecules and ionizes the resulting atoms (where degree of ionization is determined by temperature) , and as per the sequence : solid @-@ liquid @-@ gas @-@ plasma , the gas is gradually turned into a thermal plasma . A thermal plasma is in thermal equilibrium , which is to say that the temperature is relatively homogeneous throughout the heavy particles (i.e. atoms , molecules and ions) and electrons . This is so because when thermal plasmas are generated , electrical energy is given to electrons , which , due to their great mobility and large numbers , are able to disperse it rapidly and by elastic collision (without energy loss) to the heavy particles .

= = = Examples of industrial / commercial plasma = = =

Because of their sizable temperature and density ranges , plasmas find applications in many fields of research , technology and industry . For example , in : industrial and extractive metallurgy , surface treatments such as plasma spraying (coating) , etching in microelectronics , metal cutting and welding ; as well as in everyday vehicle exhaust cleanup and fluorescent / luminescent lamps , while even playing a part in supersonic combustion engines for aerospace engineering .

= = = Low @-@ pressure discharges = = =

Glow discharge plasmas : non @-@ thermal plasmas generated by the application of DC or low frequency RF (< 100 kHz) electric field to the gap between two metal electrodes . Probably the most common plasma ; this is the type of plasma generated within fluorescent light tubes .

Capacitively coupled plasma (CCP) : similar to glow discharge plasmas , but generated with high frequency RF electric fields , typically 13 @.@ 56 MHz . These differ from glow discharges in that the sheaths are much less intense . These are widely used in the microfabrication and integrated circuit manufacturing industries for plasma etching and plasma enhanced chemical vapor deposition .

Cascaded Arc Plasma Source : a device to produce low temperature (~ 1eV) high density plasmas (HDP) .

Inductively coupled plasma (ICP) : similar to a CCP and with similar applications but the electrode consists of a coil wrapped around the chamber where plasma is formed .

Wave heated plasma : similar to CCP and ICP in that it is typically RF (or microwave) . Examples include helicon discharge and electron cyclotron resonance (ECR) .

= = = Atmospheric pressure = = =

Arc discharge : this is a high power thermal discharge of very high temperature (~ 10 @, @ 000 K) . It can be generated using various power supplies . It is commonly used in metallurgical processes . For example , it is used to smelt minerals containing Al₂O₃ to produce aluminium .

Corona discharge : this is a non @-@ thermal discharge generated by the application of high voltage to sharp electrode tips . It is commonly used in ozone generators and particle precipitators .

Dielectric barrier discharge (DBD) : this is a non @-@ thermal discharge generated by the application of high voltages across small gaps wherein a non @-@ conducting coating prevents the transition of the plasma discharge into an arc . It is often mislabeled ' Corona ' discharge in industry and has similar application to corona discharges . It is also widely used in the web treatment of fabrics . The application of the discharge to synthetic fabrics and plastics functionalizes the surface and allows for paints , glues and similar materials to adhere .

Capacitive discharge : this is a nonthermal plasma generated by the application of RF power (e.g. , 13 @.@ 56 MHz) to one powered electrode , with a grounded electrode held at a small separation distance on the order of 1 cm . Such discharges are commonly stabilized using a noble gas such as helium or argon .

" Piezoelectric direct discharge plasma : " is a nonthermal plasma generated at the high @-@ side of a piezoelectric transformer (PT) . This generation variant is particularly suited for high efficient

and compact devices where a separate high voltage power supply is not desired .

= = History = =

Plasma was first identified in a Crookes tube , and so described by Sir William Crookes in 1879 (he called it " radiant matter ") . The nature of the Crookes tube " cathode ray " matter was subsequently identified by British physicist Sir J.J. Thomson in 1897 . The term " plasma " was coined by Irving Langmuir in 1928 , perhaps because the glowing discharge molds itself to the shape of the Crookes tube (Gr. ?????? ? a thing moulded or formed) . Langmuir described his observations as :

Except near the electrodes , where there are sheaths containing very few electrons , the ionized gas contains ions and electrons in about equal numbers so that the resultant space charge is very small . We shall use the name plasma to describe this region containing balanced charges of ions and electrons .

= = Research = =

Plasmas are the object of study of the academic field of plasma science or plasma physics , including sub @-@ disciplines such as space plasma physics . There are multiple journals devoted to the subject (see list) . It involves the following fields of active research (see also list of articles) :