Types of plasma pdf

One of the four fundamental states of matter For other uses, see Plasma. Plasma Top: Lightning and neon lights are commonplace generators of plasma. Bottom left: A plasma globe, illustrating some of the more complex plasma phenomena, including filamentation. Bottom right: A plasma trail from the Space Shuttle Atlantis during re-entry into Earth's atmosphere, as seen from the International Space Station. Plasma (from Ancient Greek πλάσμα 'moldable substance'[1]) is one of the four fundamental states of matter, first systematically studied by Irving Langmuir in the 1920s.[2][3] It consists of a gas of ions – atoms or molecules which have one or more orbital electrons stripped (or, rarely, an extra electron attached), and free electrons. Plasma can be artificially generated by heating a neutral gas or subjecting it to a strong electromagnetic field. The presence of free charged particles makes plasma electrically conductive, with the dynamics of individual particles and macroscopic plasma motion governed by collective electromagnetic fields and very sensitive to externally applied fields.[4] The response of plasma to electromagnetic fields is used in many modern technological devices, such as plasma televisions or plasma etching.[5] Depending on temperature and density, a certain amount of neutral particles may also be present, in which case plasma is called partially ionized. Neon signs and lightning are examples of partially ionized plasmas.[6] Unlike the phase transitions between the other three states of matter, the transition to plasma is not well defined and is a matter of interpretation and context:[7] Whether a given degree of ionization suffices to call the substance "plasma" depends on a specific phenomenon being considered. In other words, plasma is a matter which cannot be correctly described without the presence of charged particles taken into account. Excluding dark matter and the even more elusive dark energy, plasma is the most abundant form of ordinary matter in the universe.[8] Plasma is mostly associated with stars,[9] including our Sun,[10][11] and extending to the rarefied intracluster medium and possibly the intergalactic regions.[12] Early history Play media Plasma microfields calculated by an N-body simulation. Note the fast moving electrons and slow ions. It resembles a bodily fluid. Plasma was first identified in laboratory by Sir William Crookes. Crookes presented a lecture on what he called "radiant matter" to the British Association for the Advancement of Science, in Sheffield, on Friday, 22 August 1879.[13] However, systematical studies of plasma began with the research of Irving Langmuir and his colleagues in 1920's. Langmuir also introduced the term "plasma" as a description of ionized gas in 1928:[14] 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. Lewi Tonks and Harold Mott-Smith, both of whom worked with Langmuir in the 1920's, recall that Langmuir first used the term by analogy with the blood plasma.[15][16] Mott-Smith recalls, in particular, that the transport of electrons from thermionic filaments reminded Langmuir of "the way blood plasma carries red and white corpuscles and germs."[17] Part of a series onContinuum mechanics Laws Conservations Mass Momentum Energy Inequalities Clausius–Duhem (entropy) Solid mechanics Deformation Elasticity linear Plasticity Hooke's law Stress Finite strain Infinitesimal strain Compatibility Bending Contact mechanics frictional Material failure theory Fracture mechanics Fluid mechanics Fluids Statics · Dynamics Archimedes' principle · Bernoulli's principle Navier–Stokes equations Poiseuille equation · Pascal's law Viscosity (Newtonian · non-Newtonian) Buoyancy · Mixing · Pressure Liquids Surface tension Capillary action Gases Atmosphere Boyle's law Charles's law Gay-Lussac's law Combined gas law Plasma Rheology Viscoelasticity Rheometry Rheometer Smart fluids Electrorheological Magnetorheological Ferrofluids Scientists Bernoulli Boyle Cauchy Charles Euler Gay-Lussac Hooke Newton Navier Noll Pascal Stokes Truesdell vte Definitions The fourth state of matter Plasma is called the fourth state of matter after solid, liquid, and gas.[18][19][20] It is a state of matter in which an ionized substance becomes highly electrically conductive to the point that long-range electric and magnetic fields dominate its behaviour.[21][22] Plasma is typically an electrically quasineutral medium of unbound positive and negative particles (i.e. the overall charge of a plasma is roughly zero). Although these particles are unbound, they are not "free" in the sense of not experiencing forces. Moving charged particles generate electric currents, and any movement of a charged plasma particle affects and is affected by the fields created by the other charges. In turn this governs collective behaviour with many degrees of variation.[23][24] Plasma is distinct from the other states of matter. In particular, describing a low-density plasma as merely an "ionized gas" is wrong and misleading, even though it is similar to the gas phase in that both assume no definite shape or volume. The following table summarizes some principal differences: Property Gas Plasma Interactions Binary: Two-particle collisions are the rule, three-body collisions extremely rare. Collective: Waves, or organized motion of plasma, are very important because the particles can interact at long ranges through the electric and magnetic forces. Electrical conductivity Very low: Gases are excellent insulators up to electric field strengths of tens of kilovolts per centimeter.[25] Very high: For many purposes, the conductivity of a plasma may be treated as infinite. Independently acting species One: All gas particles behave in a similar way, largely influenced by collisions with one another and by gravity. Two or more: Electrons and ions possess different charge and vastly different masses, so that they behave differently in many circumstances, with various types of plasma-specific waves and instabilities emerging as a result. Velocity distribution Maxwellian: Collisions usually lead to a Maxwellian velocity distribution of all gas particles. Often non-Maxwellian: Collisional interactions are relatively weak in hot plasmas and external forces can drive the plasma far from local equilibrium. Ideal plasma Three factors define an ideal plasma:[26][27] The plasma approximation: The plasma approximation applies when the plasma parameter Λ,[28] representing the number of charge carriers within the Debye sphere is much higher than unity.[21][22] It can be readily shown that this criterion is equivalent to smallness of the ratio of the plasma electrostatic and thermal energy densities. Such plasmas are called weakly coupled.[29] Bulk interactions: The Debye length is much smaller than 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.[30] Collisionesless: The electron plasma frequency (measuring plasma oscillations of the electrons) is much larger than the electron–neutral collision frequency. When this condition is valid, electrostatic interactions dominate over the processes of ordinary gas kinetics. Such plasmas are called collisionless.[31] 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.[32] Dusty 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.[33] Properties and parameters Artist's rendition of the Earth's plasma fountain, showing oxygen, helium, and hydrogen ions that gush into space from regions near the Earth's poles. The faint yellow area shown above the north pole represents gas lost from Earth into space; the green area is the aurora borealis, where plasma energy pours back into the atmosphere.[34] Density and ionization degree For plasma to exist, ionization is necessary. The term "plasma density" by itself usually refers to the electron density n e {\displaystyle n_{e}} , that is, the number of free electrons per unit volume. The degree of ionization α {\displaystyle \alpha } is defined as fraction of neutral particles that are ionized: α = n i n i + n n {\displaystyle \alpha ={\frac {n_{i}}{n_{i}+n_{n}}}} , where n i {\displaystyle n_{i}} is the ion density and n n {\displaystyle n_{n}} the neutral density (in number of particles per unit volume). In the case of fully ionized matter, α = 1 {\displaystyle \alpha =1} . Because of the quasineutrality of plasma, the electron and ion densities are related by n e = ⟨ Z i ⟩ n i {\displaystyle n_{e}=\langle Z_{i}\rangle n_{i}} , where ⟨ Z i ⟩ {\displaystyle \langle Z_{i}\rangle } is the average ion charge (in units of the elementary charge). Temperature Plasma temperature, commonly measured in kelvin or electronvolts, is 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 thermal equilibrium, the relationship is given by the Saha equation. At low temperatures, ions and electrons tend to recombine into bound states—atoms[35]—and the plasma will eventually become a gas. In most cases, the electrons and heavy plasma particles (ions and neutral atoms) separately have a relatively well-defined temperature; that is, their energy distribution function is close to a Maxwellian even in the presence of strong electric or magnetic fields. However, because of the large difference in mass between electrons and ions, their temperatures may be different, sometimes significantly so. This is especially common in weakly ionized technological plasmas, where the ions are often near the ambient temperature while electrons reach thousands of kelvin.[citation needed] The opposite case is the z-pinch plasma where the ion temperature may exceed that of electrons.[36] See also: Nonthermal plasma and Anisothermal plasma Plasma potential Lightning as an example of plasma present at Earth's surface: Typically, lightning discharges 30 kiloamperes at up to 100 megavolts, and emits radio waves, light, X- and even gamma rays.[37] Plasma temperatures can approach 30000 K and electron densities may exceed 1024 m−3. Since plasmas are very good electrical conductors, electric potentials play an important role.[clarification needed] The average potential in the space between charged particles, independent 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 = ⟨ Z ⟩ n i {\displaystyle n_{e}=\langle Z\rangle 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.[citation needed] 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 ∝ e e Φ / k B T e . {\displaystyle n_{e}\propto e^{e\Phi /k_{B}T_{e}}.} Differentiating this relation provides a means to calculate the electric field from the density: E → = (k B T e / e) (∇ n e / n e) . {\displaystyle {\vec {E}}=(k_{B}T_{e}/e)(abla n_{e}/n_{e}).} 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.[38] 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 behaviour, 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.[39] 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 line before making a collision, i.e., ν c e / ν c o l l > 1 {\displaystyle u _{\mathrm {ce} }/u _{\mathrm {coll} }>1} , where ν c e {\displaystyle u _{\mathrm {ce} }} is the electron gyrofrequency and ν c o l l {\displaystyle u _{\mathrm {coll} }} 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 plasma high conductivity, the electric field associated with a plasma moving with velocity v {\displaystyle \mathbf {v} } in the magnetic field B {\displaystyle \mathbf {B} } is given by the usual Lorentz formula E = − v × B {\displaystyle \mathbf {E} =-\mathbf {v} \times \mathbf {B} } , and is not affected by Debye shielding.[40] Mathematical descriptions The complex self-constricting magnetic field lines and current paths in a field-aligned Birkeland current that can develop in a plasma.[41] Main article: Plasma modeling To completely describe the state of a plasma, all of the particle locations and velocities that describe the electromagnetic field in the plasma region would need to be written down. However, it is generally not practical or necessary to keep track of all the particles in a plasma.[citation needed] 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,[42] 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.[citation needed] 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.[citation needed] Plasma science and technology Plasmas are the object of study of the academic field of plasma science or plasma physics,[43] including sub-disciplines such as space plasma physics. It currently involves the following fields of active research and features across many journals, whose interest includes: Plasma theory Plasma equilibria and stability Plasma interactions with waves and beams Guiding center Adiabatic invariant Debye sheath Coulomb collision Plasmas in nature Astrophysical plasma Northern and southern (polar) lights The Earth's ionosphere Interplanetary medium Planetary magnetospheres Space plasma Industrial plasmas Plasma chemistry Plasma processing Plasma spray Plasma display Plasma sources Dusty plasmas Plasma diagnostics Thomson scattering Langmuir probe Ball-pen probe Faraday cup Spectroscopy Interferometry Ionospheric heating Incoherent scatter radar Plasma applications Dielectric barrier discharge Enhanced oil recovery Fusion power Plasma Actuator (e.g. Serpentine geometry plasma actuator[44] Magnetic fusion energy (MFE) — Tokamak Stellarator Reversed field pinch Magnetic mirror Dense plasma focus Inertial confinement fusion (ICF) Plasma weapons Ion implantation Ion thruster MAGPIE (Implosion experiments) Plasma ashing Food processing Nonthermal plasma or "cold plasma" Plasma arc waste disposal, recycling. Plasma acceleration Plasma medicine (e. g. Dentistry[45]) Plasma window Plasmas can appear in nature in various forms and locations, which can be usefully broadly summarised in the following Table: Common forms of plasma Artificially produced Terrestrial plasmas Space and astrophysical plasmas Those found in plasma displays, including TV screens. Inside fluorescent lamps (low energy lighting), neon signs[46] Rocket exhaust and ion thrusters The area in front of a spacecraft's heat shield during re-entry into the atmosphere Inside a corona discharge ozone generator Fusion energy research The electric arc in an arc lamp, an arc welder or plasma torch Plasma ball (sometimes called a plasma sphere or plasma globe) Arcs produced by Tesla coils (resonant air core transformer or disruptor coil that produces arcs similar to lightning, but with alternating current rather than static electricity) Plasmas used in semiconductor device fabrication including reactive-ion etching, sputtering, surface cleaning and plasma-enhanced chemical vapor deposition Laser-produced plasmas (LPP), found when high power lasers interact with materials. Inductively coupled plasmas (ICP), formed typically in argon gas for optical emission spectroscopy or mass spectrometry Magnetically induced plasmas (MIP), typically produced using microwaves as a resonant coupling method Static electric sparks Capacitively coupled plasmas (CCP) Dielectric Barrier Discharges (DBD) Lightning The magnetosphere contains plasma in the Earth's surrounding space environment The ionosphere The plasmasphere The polar aurorae The polar wind, a plasma fountain Upper-atmospheric lightning (e.g. Blue jets, Blue starters, Gigantic jets, ELVES) Sprites St. Elmo's fire Fire (if sufficiently hot)[47] Stars(plasmas heated by nuclear fusion) The solar wind The interplanetary medium(space between planets) The interstellar medium(space between star systems) The Intergalactic medium(space between galaxies) The Io-Jupiter flux tube Accretion disks Interstellar nebulae Space and astrophysics Further information: Astrophysical plasma Plasmas are by far the most common phase of ordinary matter in the universe, both by mass and by volume.[48] Above the Earth's surface, the ionosphere is a plasma,[49] and the magnetosphere contains plasma.[50] Within our Solar System, interplanetary space is filled with the plasma expelled via the solar wind, extending from the Sun's surface out to the heliopause. Furthermore, all the distant stars, and much of interstellar space or intergalactic space is also likely filled with plasma, albeit at very low densities. Astrophysical plasmas are also observed in Accretion disks around stars or compact objects like white dwarfs, neutron stars, or black holes in close binary star systems.[51] Plasma is associated with ejection of material in astrophysical jets, which have been observed with accreting black holes[52] or in active galaxies like M87's jet that possibly extends out to 5,000 light-years.[53] 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, AC (typically with radio frequency (RF)) and microwave[citation needed] 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)[citation needed] The degree of ionization within the plasma—fully, partially, or weakly ionized[citation needed] The temperature relationships within the plasma—thermal plasma (T e = T i = T g a s {\displaystyle T_{e}=T_{i}=T_{gas}}), non-thermal or "cold" plasma (T e ≫ T i = T g a s {\displaystyle T_{e}\gg T_{i}=T_{gas}})[citation needed] The electrode configuration used to generate the plasma[citation needed] 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)[citation needed] Generation of artificial plasma Artificial plasma produced in air by a Jacob's Ladder 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.[54] 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 adjacent image, which shows a discharge tube as a simple example (DC used for simplicity).[citation needed] 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.[55] 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",[56] mainly due to a small mean free path (average distance travelled between collisions).[citation needed] Electric arc Cascade process of ionization. Electrons are "e−", neutral atoms "o", and cations "+". Avalanche effect between two electrodes. The original ionization event liberates one electron, and each subsequent collision liberates a further electron, so two electrons emerge from each collision: the ionizing electron and the liberated electron.[citation needed] With ample current density and ionization, this forms a luminous electric arc (a continuous electric discharge similar to lightning) between the electrodes.[Note 1] 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.[Note 2] 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.[57][Note 3] 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,[57][58] surface treatments such as plasma spraying (coating), etching in microelectronics,[59] metal cutting[60] and welding; as well as in everyday vehicle exhaust cleanup and fluorescent/luminescent lamps,[54] fuel ignition, while even playing a part in supersonic combustion engines for aerospace engineering.[61] Low-pressure discharges Glow discharge plasmas: non-thermal plasmas generated by the application of DC or low frequency RF (