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Plasma Physics

The Fourth State of Matter

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Chapter 1: The Fourth State

A solid holds its shape because its atoms are locked to their neighbors. Heat it and the lock breaks: the atoms slide, and the substance flows as a liquid. Heat it further and the sliding stops being a relationship at all: the atoms fly apart as a gas, touching nothing but the walls. The schoolroom story ends there, with three states, and for the kitchen it is a true story. The cosmos tells a different one. Add still more energy, enough to strip electrons off the atoms themselves, and the gas changes character once more. It is no longer a crowd of neutral particles but a mixed population of negative electrons and positive ions, and each member of that population carries an electric charge.

That charge is the whole revolution. A neutral atom ignores a passing field; a charged particle obeys one. Put an electric field across an ordinary gas and nothing much happens, because the gas is an insulator: this is why air between two wires stays quiet at low voltages. Put a strong enough field across it and, at breakdown, the air ionizes along a channel, the channel becomes a conductor, and the result is a spark. The gas that was refusing to carry current a moment ago is now carrying it enthusiastically. The state that does this has its own name and its own physics, because the charged population does things no neutral gas can do.

The transition is not a chemical reaction. The substance is the same substance; neon is neon before and after the sign is switched on. What changes is the accounting. In a neutral gas, every atom has matching positive and negative charges, so the net charge of any particle is zero. In a plasma, the charges are separated and mobile, and their motion is what the field acts on. The separation is usually small: most laboratory plasmas are only partly ionized, a whiff of charged particles moving through a majority of neutral atoms. Even a fraction of a percent of ionization can dominate the behavior, because the charged minority responds so strongly to fields. A gas with one ionized atom in ten thousand can act, for electrical purposes, like a metal.

The phrase fourth state of matter is older than the modern understanding. In 1879 the British physicist William Crookes, studying the glow inside his evacuated tubes, called the glowing region radiant matter and suspected it was a state beyond gas. The suspicion was right even where his details were wrong, and the tubes he built became the ancestors of neon signs, fluorescent lamps, plasma screens, and half a century of atomic physics. The full picture waited for the twentieth century, when the study of electric discharges, radio waves bouncing off the sky, and the new science of the ionosphere all converged on the same conclusion: this glowing, conducting, wave-carrying gas was not a variety of gas at all but its own subject.

The scale of the subject is the largest in physics. Ordinary matter, the kind made of atoms rather than the dark matter whose nature is another book's question, is overwhelmingly plasma where it is hot enough to be ionized, and the universe is overwhelmingly hot enough. The Sun is a ball of plasma heated by fusion at its core

and kept ionized throughout by its own temperature. The space between stars, thin beyond any laboratory vacuum, is a plasma because even at densities of one particle per cubic centimeter, ultraviolet light from hot stars keeps the gas ionized. The solar wind, the Sun's escaping atmosphere, carries plasma past Earth at hundreds of kilometers per second. By visible weight, the solid worlds of the solar system are a rounding error in a plasma universe.

The state is also, despite its cosmic dominance, the least domesticated. Solids can be held in the hand, liquids poured, gases bottled. A plasma at the temperatures where it is interesting would end any container made of atoms, and the effort to hold it anyway, with magnetic fields instead of walls, is the fusion project described in this book's middle chapters. That effort has consumed national budgets and scientific careers, and its ledger of progress and delay is kept honestly here, because the plasma refuses to pretend.

A fair question to ask of a fourth state is where its borders are. Dry air is not a plasma; a candle flame, though slightly ionized, barely qualifies; the ionosphere, a hundred kilometers up, qualifies without argument. The working borders are set in the next chapter, not by a temperature line but by two tests of distance and behavior, because a plasma's definition is not how it was made but what it does.

Chapter 2: How a Gas Becomes a Plasma

Ionization is the ticket of admission. Every atom holds its electrons with a binding energy, and anything that supplies that energy can tear one loose: a collision with a fast particle, a jolt of ultraviolet light, a strong field that simply pulls the electron away. In a hot gas the collisions do the work, and the hotter the gas the larger the fraction of atoms stripped. The stripped fractions span an enormous range. The plasma inside a fluorescent tube is faintly ionized, a rounding error among neutral atoms, and still lights a room. The Sun's core is fully ionized, every electron wandering free of every nucleus. Both are plasmas, which tells the reader that the temperature is not the definition; the behavior is.

The degree of ionization has a threshold behavior that surprises newcomers. Because a plasma carries current and responds to fields, even a small ionized minority can dominate the electrical life of the gas, the way a small amount of salt dominates the conductivity of water. Below the threshold, the gas is an insulator with curiosities. Above it, the gas organizes. The organization is the subject's signature: the charged particles do not act as independent atoms but as a population with its own laws.

Two of those laws give the working definition used by every plasma physicist, and both can be stated in words. The first is the law of shielding. Put a positive charge in a neutral gas and its electric field reaches outward, weakening with distance, indefinitely far. Put the same charge in a plasma and the surrounding electrons crowd toward it, the ions lean away, and within a short distance the crowd cancels the charge's field almost perfectly. Beyond that distance, the plasma looks neutral even though it is full of charge. The distance is named for the Dutch physicist Peter Debye,

who identified the effect in his 1923 work on electrolyte solutions, a reminder that the shielding idea was borrowed from chemistry and proved universal. The crowd's own size matters: the shielding only works if enough particles fit inside the shielding distance to do the canceling.

The second law is collective behavior. Disturb a neutral gas and the disturbance travels as ordinary sound, molecule bumping molecule. Disturb a plasma and it answers with its own vocabulary of waves, several kinds at once: the electrons can slosh against the ions like weights on springs, at a pace set by the density and called the plasma frequency; the whole population can ring at radio frequencies; and the magnetic fields the plasma carries can quake with waves that have no neutral-gas counterpart at all. The plasma frequency has a practical face: a plasma dense enough rings at frequencies above the rate of a radio wave trying to pass through, and so reflects that wave instead. This is why shortwave radio bounces off the ionosphere and why the same ionosphere blacked out radio to distant stations during the war years. The sky itself became a mirror made of plasma.

The two laws together define the subject. A cloud of charged particles is a plasma when it has enough members to shield an applied charge within its own size, and when its behavior is collective rather than particle-by-particle. A single ion in a vacuum chamber, though charged, is not a plasma; it has no crowd. A tube of glowing gas with a trillion particles in it is a plasma even if only one particle in a hundred thousand is ionized, because the crowd is there and answers fields together.

Temperature in a plasma needs its own honesty, because the electrons and the ions can have different temperatures, and often do. In a fluorescent tube the electrons run hot, tens of thousands of degrees on the temperature scale physicists use, while the gas itself stays cool enough to touch the glass. Such a plasma is called cold, not because its electrons are cold but because its heavy particles are. The distinction between hot and cold plasmas, or in the physicist's cleaner language between thermal and non-thermal plasmas, is one of the most practical divisions in the subject: hot plasmas belong to fusion and to stars, cold plasmas to industry, to medicine, and to the tubes that light offices. The fact that a gas can have electrons at stellar temperatures inside a lamp made of glass is not a paradox; it is the smallness of electrons, which lose their energy to the heavy atoms slowly, and can be kept running hot while everything around them stays cool.

One practical note belongs to the shielding law, because it sizes the plasma's own machinery. The shielding distance grows with temperature and shrinks with density, so a laboratory's dense, cool plasma is shielded within a fraction of a millimeter and behaves as a collective object the size of its tube, while the solar wind's thin, warm plasma is shielded over kilometers and its collective behavior spans the cavity it carves around a planet. The schoolroom ladder of states ends here with the top rung bending into a different thing altogether. The chapters that follow trace how the state was found, what its grammar allows, and where its consequences have been met, measured, and occasionally caged.

Chapter 3: The People and the Discovery

The state of matter was seen before it was understood. Lightning is a plasma channel, and every civilization had watched it; the aurora is plasma light, and the northern peoples had named it long before physics existed. But seeing is not the same as recognizing, and recognition had to wait for the laboratory and the vacuum pump.

The pump came first. In the 1850s and 1860s the German glassblower Heinrich Geissler built tubes that could hold a thin gas, and his tubes glowed in stripes and bands when current passed through them. The shows were beautiful enough to be staged in parlors, and physicists bought the tubes as instruments. Julius Plücker noticed that the glow responded to magnets; his student Johann Wilhelm Hittorf traced the current to rays that traveled from cathode to anode. In 1876 Eugen Goldstein named them cathode rays and, in the same decade, noticed that the rays came with a glow that behaved oddly, which he called, because it sat at right angles to the cathode, by a word meaning the other light. William Crookes in England, working with better pumps, declared the glowing region radiant matter in 1879 and argued it was matter in a fourth state. He was wrong about the rays' nature, in the way that mattered most: the cathode rays proved in 1897, in Joseph John Thomson's hands at the Cavendish Laboratory, to be streams of electrons, the first subatomic particles identified. But Crookes was right about the region. The gas left behind, ionized and glowing, was the new state.

The mathematical birth was slower. The equations of electricity and magnetism had been unified by James Clerk Maxwell in the 1860s, but the union said nothing about how a conducting fluid would move, and the physics of conductors and the physics of fluids sat in separate rooms. The door between them was opened by a young Swedish physicist working in a career the establishment kept trying to close.

Hannes Alfvén's doctoral thesis in 1934 argued a heretical position on the origin of cosmic rays, and his reward was a cold professional welcome and a job in a smaller city, which he credited with freeing him to think. In 1942, studying the sunspots and the Sun's magnetic weather, he proposed that a conducting fluid carries its magnetic field with it, as if the field lines were threads frozen into the flow, and that the marriage predicts a new wave, a ripple of the field and fluid together, traveling along the field. The wave was found in the laboratory the following year, in liquid mercury, and the theory of magnetohydrodynamics, the fluid mechanics of conducting matter, was founded. Alfvén's frozen-field picture and his waves would organize the plasma universe from the Sun's interior to the galaxies, and the Nobel committee, with its usual lag, gave him the 1970 prize.

The subject acquired its name and its discipline in America, in the General Electric laboratories where Irving Langmuir studied the ionized gases inside vacuum tubes. Langmuir was the most versatile industrial physicist of his generation, and in 1923 his colleague Tonks, working with him on the way plasma oscillated, needed a word for the oscillation itself. Langmuir supplied the naming in 1928, borrowing from medicine, and admitted it was a compromise. The name stuck to the field as well as the gas, and

Langmuir's probes, a bare wire inserted into the plasma to read its temperature and density from the current it draws, remain the subject's simplest and most used instrument.

The war then scattered the tools into the world. Radar, built in the 1940s, needed to know why the ionosphere bent and reflected radio, and the British ionosphere work became a plasma-physics school. The atomic secrets brought the problem of radiation moving through ionized matter. And in 1952, in the classified rooms of the weapons programs, the idea of a fusion reactor appeared, and with it the modern age of the subject: the plan to build a magnetic bottle for a plasma hotter than the Sun's core, on Earth, for electricity. The people and the discovery converge there, and the fusion chapters tell that story with its ledger intact.

One correction belongs to the record. The popular history hands the whole discovery to Langmuir, or Crookes, or Alfvén alone. The honest statement is that the fourth state was recognized the way most big things are recognized: by a glassblower's tubes, a physicist's rays, a chemist's word, a theorist's waves, and a war's instruments, each contribution named, dated, and dependent on the last.

Chapter 4: The Grammar of a Charged Gas

Every field of physics has a grammar, a short list of rules from which everything else is derived, and plasma physics states its own in three sentences. The members of the population respond to fields. The population makes fields of its own. And nothing in the resulting argument can be followed one particle at a time, because the members outnumber any patience.

The first rule gives the charged particle its motions. In a uniform magnetic field, a charged particle circles the field line, tightening into a helix as it drifts along, so that a particle in a magnetic field is caged in the two directions across the field and free along it. This single fact builds the structure of the universe's plasma machines. Around a planet with a magnet, the charged particles hop along the field lines from pole to pole, and the field lines funnel them into the upper atmosphere, where they light the auroras. Around a star, the same spiraling confines the hot gas of the corona. In a laboratory, the same spiraling is the wall of the fusion engineer's bottle, a magnetic cage whose bars are invisible precisely because they are the field lines themselves, and the plasma must be heated, fed, and kept from learning where the cage's edges are.

The second rule makes the plasma an author and not just an actor. Moving charge is current, and current makes magnetic field, and field guides motion. The population therefore adjusts itself, and the adjustment is why the state has moods: pinch, in which the plasma's own current squeezes it into a filament, the same force that gathers lightning into a narrow channel; kink, in which a squeezed filament bends like an annoyed rope; and instability, the general name for the plasma's tendency to find the shape that escapes its cage. The grammar is honest about this: a magnetized plasma is never at rest, and the engineer's work is less like holding water in a bucket

than like holding smoke in a wind with a promise.

The third rule, collective behavior, is where the gas stops being chemistry and starts being physics. A neutral gas is described by temperature, pressure, and viscosity, three numbers. A plasma carries a larger vocabulary: the two populations can be at different temperatures, the population can ring at its plasma frequency, the shielding distance sets how much of the world each particle sees, and the magnetic field sets where the population can and cannot go. The vocabulary is the grammar's power. Given density, temperature, and field, the physicist can say how the plasma will respond to an antenna, why a wave will reflect, where a particle will drift, and how a cage will leak. These are not metaphors; they are the working predictions of the field, and the chapters on the laboratory and on space show them being used daily.

One piece of the grammar deserves its own paragraph, being the most cited and most abused: the idea that magnetic field lines are frozen into a perfectly conducting plasma. Alfvén's theorem, as it is now called, states that in the ideal case the plasma and the field move together, welded. The picture built the subject's first decades and remains the correct first answer for the Sun's interior, the solar wind, and the magnetosphere. It is also, Alfvén insisted in his later years, an idealization the real universe violates where it matters. Where the weld fails, reconnection takes over, described in the chapter on open questions, and the gap between idealized weld and real slippage is an active frontier at this writing. The grammar's honest summary: the frozen-field picture is the map, and reconnection is the territory's error bars.

The grammar closes with a number every reader should carry away. A plasma's shielding distance can range over fifteen orders of magnitude, from a fraction of a millimeter in a laboratory tube to kilometers in the solar wind, because it grows as the temperature rises and the density falls. The number explains the subject's flexibility: a plasma is the same physical object in a neon sign and in a galaxy's halo, and it is the grammar, not the size, that makes it so.

Chapter 5: The Fluid of the Cosmos

Before Alfvén, the cosmos was handled in pieces. Stars were spheres of gas obeying the fluid mechanics of neutral matter; magnetic fields were a complication for specialists in sunspots. After Alfvén, the two were one substance: a conducting fluid that carries its field as it moves and is steered by the field it carries. The marriage is magnetohydrodynamics, usually shortened to three letters, and it is the working language of every plasma larger than a laboratory.

The language's first sentence is the frozen-field rule: in a well-conducting plasma, the field lines move with the material. The second sentence is the mirror: where the field is strong, it pushes back, and the fluid must flow along the field's grain like wood along its own. From those two sentences follows the architecture of the universe's plasma machines.

The Sunspot is the oldest machine studied with this language. Sunspots are regions where the Sun's internal field has broken through the surface, and the field there is

strong enough to hold back the rising heat, which is why the spots look dark: they are cooler than their surroundings, even though they are still hotter than any furnace on Earth. The field then twists with the Sun's uneven rotation, the star being a fluid that spins faster at its equator than at its poles, and the twisting loads the atmosphere's field lines like wound springs. The release is the flare and the coronal mass ejection, described in the chapter on space weather. The language's predictions held: the sunspot cycle of roughly eleven years, the reversal of the Sun's magnetic poles each cycle, and the migration of spots toward the equator were all organized once the conducting fluid's grammar was applied.

The dynamo problem is the language's hardest sentence. Earth's magnetic field is made by the motion of its molten iron core, a conducting fluid whose churn, organized by the planet's rotation, generates the field that has kept a compass useful for centuries. The same mechanism, scaled up, runs in the Sun, in Jupiter, and in the giant magnetic stars. The problem is that the equations cannot yet be solved for a real planet: the churn is turbulent, the geometry is awkward, and the best results come from computer simulations that capture the spirit of the field's reversals without predicting any particular one. The honest grade is open, with progress real and dated: simulations now reverse their fields, and the models' field maps are close enough to the Earth's measured field to guide mineral prospecting.

The language's reach is best shown by three of its solutions.

The language also gave the Sun's corona a stethoscope. The corona's magnetic loops, mapped by the solar observatories, oscillate after the surface's own explosions, and the oscillation is Alfvén's wave itself, caught in its natural machine. Because the wave's pace depends on the field's strength and the plasma's density together, the observed swaying of a loop measures the field inside it, otherwise invisible, the way a struck bell reveals its metal by its ring. The method, called coronal seismology, now reads the corona's fields from its swaying, and its results anchor the models of the storms described in the space-weather chapter. First, the sunspot's darkness and the corona's strange heat, described later, both organize themselves once field lines are treated as ropes with tension. Second, the magnetosphere, the comet-shaped cavity a planet's field carves in the solar wind, is predictable from the frozen-field rule and the pressure balance, and the prediction was confirmed by the first satellites of the space age, which found the cavity's boundary exactly where the fluid mechanics said it would be. Third, the jets of active galaxies, threads of plasma tens of thousands of light-years long, align with their galaxies' rotation axes and hold their shape, over distances that should tear any material structure apart, because the fluid and field together can carry stress the way a wire carries tension, and the material that emerges is not fighting the field but flowing with it.

The language has known limits, and the subject is honest about them. The fluid description assumes the plasma can be treated as a continuous medium, which fails at the smallest scales and at the sharpest boundaries; kinetic theory, which follows the particles' velocities individually, must take over there. The frozen-field idealization breaks down at reconnection sites, where the field lines change partners and the

stored energy is released, a process whose details remain open. And turbulence, the subject's oldest unsolved fluid problem, remains unsolved in its plasma version with extra cruelty, because the conducting version couples the swirls to the field and turns the turbulence magneto-active.

The chapter's takeaway is one image: the cosmos, at the scale where it glows, is a fluid threaded by ropes. Pull the rope and the fluid follows; drag the fluid and the rope follows. Every machine in the next chapters is that image with different numbers.

Chapter 6: Making Plasma in the Laboratory

The universe makes plasma by accident, with stars. The laboratory has to make it deliberately, in a bottle, from ordinary gas, and the ways it has found are as various as the uses they serve. The common principle is simple and absolute: energy must be pumped in, because a plasma left alone recombines into a plain gas, its electrons finding their ways home.

The oldest method is the electric discharge, the successor of Geissler's tubes. Two electrodes sit in a gas at low pressure; a voltage is applied; and at first nothing happens, because the gas is an insulator. Raise the voltage and the first stray electrons, always present from cosmic rays and background radiation, are accelerated until they strike gas atoms hard enough to knock electrons loose. The freed electrons are accelerated in turn, strike again, and the population multiplies: the Townsend avalanche, named for the British physicist John Townsend, who mapped it in 1900. Once the avalanche reaches the anode, the gas has become a conductor, and the current flows as a glow.

The glow is the subject's familiar face, the light of neon signs and fluorescent tubes. Its colors are chemical signatures: neon glows red-orange, argon lavender, and the different gases mark different city districts and different decades. The light is not the current itself but the gas's after-cough: an electron that has been kicked into a higher orbit falls back and pays out the difference as light, and each gas pays in its own colors. The fluorescent tube is the discharge's cleverest descendant: its gas is chosen to pay in ultraviolet, which is invisible, and the tube's inner wall is painted with phosphor, a solid that converts ultraviolet to visible light, taking the invisible payment of the plasma and re-invoicing it in daylight tones. Fluorescent lighting was commercialized in the 1930s and became the twentieth century's standard light, and its plasma ran cool, electrons hot and glass cool, in the non-thermal arrangement of an earlier chapter.

The arc is the discharge's large sibling. At higher currents the gas heats fully, the thermal balance takes over, and the discharge becomes an arc: the blinding blue-white column of a welding torch, the channel of a lightning bolt, the furnace of an industrial smelter. The arc's temperatures, around ten thousand degrees in ordinary air and higher when confined, are the highest working temperatures available to industry, and the arc furnace, a descendant of processes patented by the twentieth century's steelmakers, melts scrap by the megaton. Lightning, scaled up beyond

human power, is the same process: a leader opens a conductive channel by avalanche and thermal breakdown, and the return stroke then carries tens of thousands of amperes through a finger-wide path hotter than the Sun's surface, heating the air to a shock wave heard as thunder.

The corona is the discharge's aristocratic variant: not across electrodes but from sharp points and thin wires, where the field concentrates enough to ionize the nearby air without letting the avalanche run away into an arc. The crackle heard under high-voltage lines in damp weather is corona, and its deliberate uses are industrial: the ozone generator, the electrostatic precipitator that charges smoke particles so they stick to collection plates, and the surface treatment of plastics, which a corona's kiss makes wettable so that glue and paint will hold.

The barrier discharge adds an insulating layer between the electrodes so that the plasma cannot bridge the gap into an arc, and the result is a cold plasma that runs in open air. The mid-1990s discovery, made with bacterial cells on treated surfaces, opened the field now called plasma medicine: cold plasmas that kill bacteria on living tissue without cooking it, now under clinical study for wound healing and dental care, with the mechanism graded partly open, because the plasma's chemistry and its charges are both doing work and their shares are not yet assigned.

For the microchip industry the requirement is finer: plasma that etches silicon with the precision of light, in chambers whose design has become one of the quietest technological achievements of the century. Two designs dominate, the capacitively coupled chamber, where the plasma forms between flat plates driven by radio-frequency power, and the inductively coupled chamber, where the plasma forms inside a coil's field like water in a kettle, each with its niche in the making of the patterns on which computing runs. The details belong to the industry chapter, which also covers the plasma thruster, the rocket that carries no fire, only plasma.

The laboratory's menu extends by the need. High power and low pressure: the arc. Cold and gentle: the barrier discharge. Controllable and repeatable: the radio-frequency chambers. What ties the menu together is that no laboratory plasma is self-sustaining: pull the plug and the plasma recombines, politely, in microseconds to milliseconds, and the glow goes home.

Chapter 7: Reading the Invisible: The Art of Diagnostics

A plasma cannot be weighed on a scale or read with a thermometer, and not only because at fusion temperatures the thermometer would be the first casualty. The state's real quantities, its density, its two temperatures, its field strength, its currents and flows, are invisible in the ordinary sense, and the physicist's craft is to make each one leave a measurable fingerprint without disturbing it. The instruments that do this are called diagnostics, and the subject's history is largely the history of learning to ask a plasma questions it cannot refuse to answer.

The oldest question is the one Irving Langmuir asked in the 1920s, with a bare wire. Insert a small electrode into the plasma, sweep the voltage on it, and the current it draws traces a curve whose bends reveal the electron temperature and density, the same wire reads the plasma's potential, and the whole measurement costs a few centimeters of tungsten. The Langmuir probe remains the subject's everyday instrument, carried into the ionosphere on rockets and into laboratory chambers through vacuum feedthroughs, and its endurance over nearly a century is a tribute to a simple idea: the plasma's response to a small object is itself a physical quantity, and can be read as such.

The second oldest question is the one the plasma answers for free: what is it made of. The glow's colors, dissected by a spectrometer into sharp lines, are the plasma's full inventory. Each species of atom or ion radiates at its own fixed wavelengths, from hydrogen's red of the visible set to the ultraviolet lines of the hotter states, and the ratios of the lines give temperatures, since the hotter the plasma, the more its higher orbits are populated. Spectroscopy identified the chemical makeup of the stars in the nineteenth century, proving the Sun made of the same elements as the Earth, and it remains the subject's universal language, the reason a plasma in Andromeda can be measured from a mountain in Chile.

The harder questions are the plasma's collective ones, and they needed the laser. Fire a pulse of light into a plasma and a few photons bounce off free electrons, shifting wavelength by an amount that reveals the electrons' speed, and thus their temperature: Thomson scattering, demonstrated in the laboratory by the radio experiments of the interwar years and now the standard measurement of fusion machines, where a laser beam slices through the bottle and its scattered light reads the plasma's temperature without touching its walls. The same principle in a different costume, radar, reads the ionosphere, the solar wind, and the solar corona: radio waves sent upward return with the imprint of the plasma that reflected or crossed them, and the space age's maps of the magnetosphere were built from such echoes.

Interferometry asks the question of density: a plasma slows light by a small, measurable amount, so a beam split around the plasma recombines with a shifted phase, and the shift is a direct count of the particles in the path. Density is the fusion engineer's obsession, since the machine's power scales with the square of it, and interferometers count it, holographically in some machines, every shot.

The magnetic questions needed their own invention. A field can be read by its effect on the polarization of light passing through it, the Zeeman effect that splits spectral lines, and the modern fusion machines also read their fields from the magnetic probes coiled around the vessel's walls and from the motion of beams of neutral atoms fired through the plasma, whose light, excited by collisions, is Doppler-shifted by the flow. In the cosmos the same measurements are made by waiting: the auroras and the radio emissions of the magnetized planets report the field's strength and shape across distances no instrument could cross.

The modern question is the one the whole subject now leans on: what is the plasma doing everywhere at once. A single probe reads a point; a spectrograph reads a line of

ABOUT THE AUTHOR

Aira Astralis is a science writer specializing in astronomy and space exploration. Her work spans the full breadth of humanity's relationship with the cosmos -- from the earliest naked-eye observations to the engineering marvels of modern space missions.

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She believes that the most important frontier is not out there but in the gap between what scientists discover and what the public understands. Her books exist to close that gap.