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A Survey of Plasmas and Their Applications

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Running Title: Plasma Applications Survey

ABSTRACT

Plasmas are everywhere and relevant to everyone. We bath in a sea of photons, quanta of electromagnetic radiation, whose sources (natural and artificial) are dominantly plasma-based (stars, fluorescent lights, arc lamps…). Plasma surface modification and materials processing contribute increasingly to a wide array of modern artifacts; e.g., tiny plasma discharge elements constitute the pixel arrays of plasma televisions and plasma processing provides roughly one-third of the steps to produce semiconductors, essential elements of our networking and computing infrastructure. Finally, plasmas are central to many cutting edge technologies with high potential (compact high-energy particle accelerators; plasma-enhanced waste processors; high tolerance surface preparation and multi-fuel preprocessors for transportation systems; fusion for energy production).

INTRODUCTION

Instead of considering plasmas as simply a fourth (dominant, naturally-occurring) state of matter, which they are, I find it more useful to consider plasmas as one of three (dominant, naturally-occurring) natural systems as shown in Table 1.

Table 1. Plasmas as a dominant, naturally-occurring natural system.

State of Matter	Primary Natural Systems	Human Environment (%)	Earth System (%)	Cosmos (%)
solids	condensed matter, compact (nuclear)	~ 50	~ 66	< 1
liquids, neutral gas	fluid (Navier-Stokes) systems	~ 50	~ 33	< 1
plasmas	electromagnetic (Maxwell-Boltzmann) systems	< 1	<< 1	> 99

Occurrence percentages (estimated by mass) for each system type are listed when considering the cosmos at large, the Earth system [solid earth (with outer core as "liquid"), ocean, atmosphere, and geospace or nearby space plasmas], and our immediate environment [roughly weighted by human interaction with the land, waterways, and lower atmosphere]. This table illustrates why plasmas, to date, have had little impact in human consciousness, the evening news, or even research investment; they are a small percentage of the immediate human environment. However, we would not even receive that news without electromagnetic and plasma systems. The impact of electromagnetic systems generally on human society is clearly evident when we consider how they constitute a high percentage of our global communications, computational, networking, and lighting infrastructure. This impact suggests the long-term potential of research and applications of electromagnetic and plasma systems overall.

PLASMAS – MORE THAN IONIZED GAS

Plasmas are often described as simply an ionized "gas," but this definition is too limited to account for actual usage in contemporary research such as for quasi-crystal plasmas that go beyond standard gas/solid distinctions. Historically, the term "gas" is associated with neutral systems or, more generally, with Navier-Stokes (fluid) systems. In contrast, plasmas most inclusively are ensembles of neutrals, ions, electrons, electric and magnetic fields, which can carry a current and exhibit collective effects [1].

A technical definition of a plasma is given in most texts [1, 2, 3, 4] and conveniently summarized in terms of the plasma parameter Λ [4, 5]. Λ represents the number of particles in a Debye sphere, which is the domain over which an ion's electric field has direct influence on other particles. For plasma conditions to apply, the mean time between collisions is typically long compared to the plasma oscillation period. And since the Debye length is proportional to the inverse square root of density, "the more particles in a Debye sphere the less dense the plasma" [4, p. 11] For values of $\Lambda >> 1$, the plasma is weakly coupled, electrostatic perturbations are intermittent, and the plasma is typically hot and diffuse. Most fusion, space and laboratory plasmas are weakly coupled plasmas. Strongly coupled plasmas have $\Lambda < 1$, electrostatic influence is continuous, and the plasma is typically relatively cold and dense. Examples are laser-cooled ions, laser ablation plasmas, arc discharges, neutron stars atmospheres, and plasma balls.

The new field of high energy density (HED) physics, including inertial confinement fusion and high-energy astrophysics, is the study of collective properties of matter under extremes in density and temperature [6]. HED studies to date are primarily focused on plasmas where the mediating force is the electrodynamic force. For hypothesized quark-gluon plasmas, the mediating force is instead the strong nuclear force and such "plasma" would be a phase of quantum chromodynamics.

Plasmas (here mediated by the electrodynamic force) have the following characteristics:

- collective effects (functioning due to field interactions as an integrated system, and not just as a sum of neutral and charged particles)
- multi-scale (examples span almost the full time, space, and energy ranges known to modern science)
- filamentation (striations or inhomogeneous alignment naturally emerges in many plasma systems such as aurorae)
- directionality (conduction channels are aligned or directional, e.g., lightning)
- conductive (the ability to carry current partly defines plasmas)
- interactivity (the multi-scale, multiply interactive features of many space plasma systems are similar to home wiring; disrupting part of the circuit can impact the whole system)

In contrast to fluids (neutral gas and liquids), which can be represented using the Navier-Stokes fluid equations [1, p. 56], a full understanding of plasmas require Boltzmann's dynamical equation for mixed neutral and ionized media with the addition of electric and magnetic fields, which require Maxwell's electromagnetic equations. In a fluid-like approximation, this formalism can be converted to that of magnetohydrodynamics (MHD) [7], which is a very powerful and useful approximation for many plasma conditions provided that kinetic processes can be neglected, and that all relevant spatial scales are large compared to the ion gyroradius. Extending such approximations to the neglect of both fields and ionized particles enables a retrieval of the Navier-Stokes equations for neutral fluids. Given this context, it is incorrect to treat plasmas as merely a type of "gas." With qualification and for educational purposes, it is often useful to characterize plasmas as "ionized gas," but such usage can easily lead to incorrect results in research applications.

Wave modes represent one example of the contrast between neutral gases and plasmas. For gases, there is just one type of wave - acoustic waves. In contrast, due to additional parameters from ionized particles, electric and magnetic fields, plasmas have a large number of wave modes. Although any given plasma medium sustains not more than about 3-8 wave modes at a time, there are more than 40 types of plasmas waves overall. The complexity of plasmas, both in wave and instability modes, contributed greatly to the complexity of the fusion energy research program. Early optimistic claims were based more on experience from research on fluid systems; in contrast, contemporary fusion studies have finally succeeded in confronting this complexity although, as always, ongoing research support is essential for success in fusion.

The following brief survey of plasma applications is divided into two sections focused, respectively, on naturally-occurring plasmas and artificial plasmas. Each of these, in turn, can be distinguished by the following contrasts:

- thermal vs. nonthermal (In a thermal plasma, small values of electric field compared to pressure result in similar ion and electron temperatures; in contrast, the more general condition of different ion and electron temperatures corresponds to a nonthermal plasma [8, p. 6].
- equilibrium vs. nonequilibrium (Nonthermal plasmas are generally nonequilibrium plasmas, and thermal plasmas are in equilibrium - "Thermal plasmas are usually more powerful, while nonthermal plasmas are more selective." [8, p. 6]
- quasi-neutral vs. non-neutral (On multi-Debye scale, most plasmas are very closely neutral although not neutral on less than Debye scale – thus quasi-neutral; special laboratory conditions enable the study of nonneutral plasmas which are nonneutral on macroscopic scale.)

Once again, let us recall that plasmas are ensembles of neutrals, ions, electrons, electric and magnetic fields, which can carry a current and exhibit collective effects. Thus, what defines plasmas is a "potentiality" (to carry current) and some "emergent" process (to exhibit collective effects). Unlike most examples of solids, liquids and gases, plasmas are more naturally characterized in terms of functionality and process rather than substance or "thing" language [9].

NATURALLY-OCCURRING PLASMAS

To emphasize how pervasive plasmas are throughout the universe, Dr. Anthony Peratt coined the metaphor "Plasma Universe" and wrote a book by that same title [10]. Nobel prize winner Hannes Alfvén, who originated MHD theory, adopted this same title for his popular physics today article [11] based in part on personal discussions with Dr. Peratt. Finally, this same theme is featured in a brochure on "The Pervasive Plasma State" published by the Division of Plasma Physics of the American

Physical Society [12]. As an example of how pervasive plasmas are, Figure 1 shows a cluster of stars and plasma filaments within the Tarantula Nebula, which is dominated by plasma sources.

Figure 1. Hodge 301 Cluster within the Tarantula Nebula (source: NASA)

Modern astronomy or space science is made up of four interdisciplinary fields: space physics, planetary science, astrophysics and cosmology. In addition to Earth system science, these fields constitute the full range of understanding about our universe at large. In turn, each of these broad fields has a special non-universal focus. Space physics (or "heliophysics") is the study of the origin, evolution, and interactions of particles and fields throughout the solar system and beyond where direct in situ observation and remote sensing can be applied, but not including the study of planets, moons and asteroids and their immediate neutral atmospheres (planetary science) or the Earth system (Earth system science). Astrophysics is the study of distant astronomical systems, primarily through remote sensing. Studies of the sun as a star are part of astrophysics; studies of the sun as such or as the dominant plasma and photon source for the solar system are part of space physics. Space plasma and space weather research are major parts of contemporary space physics research [see Chapter 4]. Within the past decade there has been a rapid growth in applying space plasma research to astrophysical problems such as for radio jets, shocks, energetic particle acceleration, reconnection, and accretion disk models. Several excellent monographs on plasma astrophysics have recently appeared, which is beginning to offset the long-standing neglect of electromagnetic and plasma processes in astrophysical systems [7, 13, 14, 15, 16].

Substantial shielding of the long-range electromagnetic force is important for human survival, but this shielding is limited in solar-system space plasmas where interplanetary electric and magnetic fields, and not the relatively weak gravitational force, dominate charged particle motion throughout most of the heliosphere. Recent MHD modeling has shown the importance of electromagnetism and plasmas on scale length up to that of galaxies and galactic clusters. The assumption that effects of the electromagnetic force are "precisely" zero on scales important for cosmology and most astrophysical systems is beginning to appear increasingly artificial to many researchers [17]. One commonly held myth is that plasma processes are only significant for high ionization fraction; in fact, ionospheric plasmas at ~100 km altitude have ionization fractions less than about 1% and yet plasma processes are essential in treating ionospheric dynamics. Another commonly held myth is that plasma effects are 100% shielded out for scale lengths large compared to the Debye length; although direct electric field influences are typically shielded out within a few Debye lengths (an effect offset by overlapping Debye spheres), it is becoming increasingly recognized that long-range magnetic fields and currents have no known scale length limit [7, 10].

ARTIFICIAL PLASMAS AND APPLICATIONS

Plasmas have two major limitations for industrial applications. The first is that typically they need to be contained within a complicated enclosure; most often, some type of "vacuum" chamber of which fluorescent light bulbs with their plasma glow discharge are the most common example. Secondly, plasmas are intrinsically more complicated than fluids due to the extra variables associated with the presence of charged particles and electromagnetic fields. Thus, with respect to simple manufacturing needs, plasmas seem to be real "lemons" and have been studiously avoided by industry for decades.

However, there has been a recent awakening to the great promise of plasmas and methods for how to make "lemonade" with this "lemon." This is because, ironically, the great strength of plasmas arises from its complexity when properly controlled. In particular, the wide parameter range of plasmas (both thermal and non-thermal) can be used to transform or modify a wide range of surfaces and materials in ways that cannot be accomplished using neutral fluids. For example, active plasma media can be controlled using electromagnetic fields and non-equilibrium plasmas make possible selective target effects at efficiencies far higher than that possible using thermal, neutral fluids. A number of recent monographs in plasma applications and engineering [8, 18-24] provide details that can only be suggested by the following brief passages.

Lighting Plasmas - When another civilizations encounters us someday in this obscure corner of our Milky Way galaxy, they will first observe radio waves (which originate via plasma sources). Upon closer approach, they will analyze emission from city lights (see Figure 2) and realize their artificial origins. More than 75% of such lights are plasma based (fluorescent, high-intensity arc lamps). Light production in the U.S. accounts for about 20% of electrical energy use overall [25], which means that the greater efficiency of plasma-based lighting contributes significantly to better energy conservation, and energy efficiency is steadily improving.

Most electrical lamps transfer power to a filament or electrodes through direct electrical connection through the lamp envelope. However, research has led to new electrodeless plasma lamps where power is transferred by electromagnetic fields. Such lamps can have a service life beyond 10 years but require high-quality, expensive ballasts thus limiting their use to applications with high replacement costs [26].

Plasma Discharge - Plasma or glow discharge tubes were used throughout the 19th century by Faraday and others in studies of the new field of electricity. It was not until 1927 that Irving Langmuir coined the term "plasma" based on his research with electrical discharges. He noted the apparent similarity of how an electrified fluid carries ions and electrons with how blood plasma carries corpuscles [27]. Naturally-occurring plasma discharges include the auroras and lightning, the latter in both its common low-altitude form from cloud-to-cloud or cloud-to-ground [28; see also Chapter 4] and its exotic high-altitude form of so-called sprites and elves, discovered in 1993, extending upward from high-altitude clouds to as far as the ionosphere! [29]

Fluorescent lamps are a type of glow discharge tube. The plasma in such lamps "produces non-visible ultraviolet light, which is converted to visible light by the phosphor coating on the tube's inside wall." [25] High-intensity arc plasma lamps, in contrast, produce visible light directly. Their enhanced brightness and efficiency make them the lightning option of choice for many industrial settings and street lights, thus dominating sources observed from space. One researcher observed that "in terms of total quantities of plasma being continuously generated, lighting plasmas are far and away the predominant practical application of plasma science." [25]

Very small scale plasma discharges constitute the millions of cells that make up modern plasma televisions. The plasmas for each tiny cell are "cold" in that the background gas remains "relatively cold while the electrons (and ions) in the plasma are heated by the applied voltage" [30]. Plasma televisions are especially competitive as high fidelity, high intensity large-format displays. Their recent introduction to the market has been made possible through many years of research and major advances in manufacturing methods and electronics.

Surface Modification - Plasma surface treatment systems enable the production of far superior products in terms of hardness, increased corrosion resistance, biocompatibility, and changed optical and electronic properties. Integrated Circuit (IC) fabrication is a major plasma application, which contributes to about 1/3 of the steps for semiconductor production. Plasmas are created in a processing chamber to activate a controlled sequence of chemical reactions at a substrate surface. Such thin-film processing primarily delivers activation energy, instead of heat, to target surfaces providing for critical etching,.deposition, and implantation functions on IC materials [20, 22, 24, 31]. Dusty plasma research is rapidly expanding due to internal contamination phenomena of industrial plasma reactors used for IC systems, thin-film processing, sputtering and etching. Nanoparticle cluster growth within such systems can adversely affect discharge behavior for plasma reactors [8, p. 743; see also Chapters 5 and 6].

Plasma enhanced chemical vapor deposition (PECVD) provides for direct control of film forming species, which constitutes a significant fraction of the plasma. Such PECVD processes provide for thin film deposition of metals, alloys, polymers and ceramics onto a diverse array of substrates. PECVD systems are non-equilibrium, low-pressure discharges with hot electrons combined with cold ion and gas species. The electrons convert cold neutral atoms into highly reactive ionic species, which enable chemical reactions at far lower temperatures than possible via equilibrium chemistry. In addition to enhanced thin film deposition, these nonequilibrium systems are an effective tool for new compound synthesis [8, 32].

Ion implantation was developed for the doping of semiconductor components of integrated circuits and has become a standard for this application. Plasma source ion Implantation (PSII) optimizes the implanting process and reduces sputtering [33]. Ion implantation and PSII are now used routinely for a wide variety of applications from preparing artificial knee and hip joints to coatings for high-wear engine components.

Substantial advances in plasma surface treatment have made possible custom tuning of plasma treatment parameters to optimize surface cleaning, adhesion enhancement, surface energy control, biocompatibility, and polymer surface enhancement [34].

One-atmosphere cold plasma techniques for sterilization and decontamination have been developed that avoid the expense and complication of "vacuum" chambers. These cold plasmas can destroy biological hazards faster than conventional methods and without toxic residues [35].

Materials Processing - Both equilibrium (thermal) plasma and non-equilibrium (nonthermal) plasma methods are applied in materials processing and are often described simply as hot and cold plasma processing, respectively. For example, complementary hot and cold plasma techniques have led to dramatic progress in waste processing techniques, from room temperature to more than 10,000°C. The hot plasmas can melt down waste and form stable nonleachable products. Complex, toxic molecules are decomposed into simpler molecules that are benign or easily treated by standard scrubbing methods. Plasma furnaces and plasma-enhanced melter systems have been deployed successfully for processing waste streams at hospitals, municipalities, and even mixed-waste sites (including low-level radioactive waste) [36].

Plasma-enhanced waste processing have several powerful features compared to standard combustion systems: (1) any waste stream can be managed, (2) toxic emissions are essentially eliminated, (3) volume reduction can be 1000 or more (nonleachable processor output can be safely used for roadways and building materials), and (4) synthetic gas output can be recycled to run the generator for the processor itself (in some cases, the overall system can produce more energy than it consumes!). The principal impediment to large-scale adoption of plasma waste systems is their relatively high up-front cost. However, their total cost of ownership may already be lower than conventional combustion systems, especially where clean air standards are fully enforced. In the long term, deployment of plasma waste processors promises to ultimately eliminate the need for hazardous and unsightly landfills. For waste processing at atmospheric pressure, arc plasmas can fulfill demanding high-throughput applications such as toxic soil decontamination.

Thermal (hot) plasmas are close to equilibrium with similar electron, ion and neutral temperatures. Ion and neutral temperatures are much higher than in discharge tubes (discussed above) and other low-pressure plasmas. Welding is the most familiar thermal plasma technology. Other examples are plasma spraying, thermal physical vapor deposition and plasma chemical deposition (nonthermal PECVD discussed above), thermal plasma etching, analytical chemistry, sintering, and arc furnaces. Thermal plasma production is created by direct current (DC) or radio frequency (RF) arcs or by inductively-coupled torches.

Plasma chemistry is carried out in both non-equilibrium and equilibrium conditions and "can be effective in nonhomogeneous systems as well" [8, p.351] However, striations and contraction from instabilities add a challenge for such applications but, as before, such instabilities may provide new opportunities for setting up unusual reaction conditions. A major advance in fuel preprocessing provides for the conversion of any hydrogen-rich fuel (oil, kerosene, ethanol, diesel…) into combustion ready fuel [see Chapter 3]. Recent successful tests of a plasmatron system indicate that significant gains in fuel efficiency and fuel flexibility are possible at costs of only a few hundred dollars more per vehicle (this cost is small compared to the savings in total cost of ownership) [37].

Nonthermal, nonequilibrium (cold) plasma methods have been applied to the cleaning of air and water. Hot electrons and activated chemical species created by such electrons can be used to efficiently and selectively destroy contaminants in air and water such as volatile organic compounds and automobile exhaust. With plasma sources, intense ultraviolet (UV) air and water purification systems are especially promising for developing countries due to ease of use, low maintenance, and low cost (if produced in high quantity) [38].

Electron beam arrays have been shown to produce "large-area planar plasmas with high efficiency, minimal gas heating, low electron temperature, high uniformity, and high microwave reflectivity…high degrees of gas excitation, dissociation, and ionization can thus be produced and maintained in gases at near room temperature" [39] In this way, materials adjacent to the plasma can be processed quickly with minimal thermal stress as illustrated above for the IC processing application. This large-area array method enables new applications such as the creation of fast, low maintenance radar systems due to the absence of a large metallic radar dish [40]. Another application is large volume air and water purification.

Nonneutral Plasmas and Accelerators – Unlike all other plasmas discussed in this survey, nonneutral plasmas do not have overall charge neutrality. They have self-generated electric and magnetic fields. Pure electron and ion plasmas have been studied in laboratory devices and can be confined for many hours. They have contributed substantially to new results in fundamental plasma physics. Examples of nonneutral plasma systems include, among others, particle beam fusion, coherent radiation sources (from intense charge particle beams), trapped ion plasmas for fundamental physics, antimatter confinement, and advanced accelerator concepts [41]

Very recently, key advances have been made towards compact, high-energy particle accelerators. "First, high-quality beams of relativistic electrons traveling at near the speed of light have been directly produced by firing a short-pulse laser into a plasma. Second, researchers have demonstrated that plasmas can be incorporated effectively into conventional accelerators to significantly boost the energy of the electron beams"[42]. Mono-energetic electron beams produced from laser-produced plasmas make possible tabletop particle accelerators in the GeV per cm energy range. These results promise to dramatically reduce the cost of future high-energy particle accelerators [see Chapter 8].

Fusion - Historically, the primary boost for plasma research came in the 1950s with major advances in both fusion (from declassification) and space plasmas (from new space-based discoveries of space plasmas), the latter discussed above under *Naturally-Occurring Plasmas*. With the exception of mechanical or thermal coupling with the Earth (enabling wind, tidal, and geothermal sources), the two truly long-term energy sources are both plasma based. We can either produce energy the way the Sun does, which is fusion, or take advantage of the Sun's radiative power, which is solar power. All other options (oil, gas, coal, nuclear) depend on finite resources with depletion time scales of ~200 (for oil) to ~2000 years (for coal and fissionable materials). Due to habit, convenience, and lack of foresight, the least viable option (oil) is ironically the very one for which we spend most of our efforts in expending and protecting!

Within the past two to three decades, there have been major advances towards the very important goal of achieving practical fusion power [see Chapter 7]. In addition to Tokamak magnetic confinement systems for fusion, the first to achieve scientific breakthrough, there are at least 16 alternative fusion concepts [43]. Budget choices have been very difficult to adequately sustain Tokamak-focused research and, at the same time, to pursue the most promising of these alternative approaches. Plasma focus devices, for example, are excellent systems for pursuing high-technology research and teaching at reduced costs, which is especially important for developing countries [44]. Scaling up some alternatives, such as the Dense Plasma Focus, might yield more cost effective approaches to practical fusion power [45].

High Energy Density (HED) physics - There are two principle methods for plasma confinement in fusion devices: magnetic confinement and inertial confinement. Because fusion requires 10's of million degree Centrigrade temperatures, no known materials can provide confinement. Confinement is instead provided by a torus-shaped magnetic field in Tokamak devices, or other field configurations in alternative devices. In contrast, inertial confinement devices operate by guiding multiple, high-energy laser or particle beams to converge on a small fusion fuel pellet or filament. Rapid compression leads to fusion conditions and ignition followed by an efflux of energy exceeding the input, thus providing energy gain. Research in inertial confinement fusion has led to the creation of the new discipline of HED physics, including inertial confinement fusion, pulsed power systems, astrophysics and nuclear weapons research. HED is the study of collective properties of matter under extremes in density and temperature [6]. In addition to potential fusion or particle acceleration applications, HED physics is important for understanding conditions in the center of stars, including compact stellar objects like neutron stars.

Other Applications - Commensurate with the pervasiveness of plasmas and their multi-scale character, covering the full span of time, space, and energy ranges known to modern science, plasmas have an extremely diverse range of topics and applications. For example, about 200 of these are listed at my plasma website [46] (if fully updated, this list would be at least 30% longer!). Trying to cover all of these applications even briefly is beyond the scope of this or, perhaps, any review. As a sample, I recommend that you enter the key word "plasmas" into a Google search. For more organized surveys, I recommend one or more of the many fine monographs listed in the references below, along with perusing the many excellent web sites listed at plasmas.org covering all aspects of plasma science and applications.

EDUCATIONAL PROGRAMS

Education and outreach efforts have typically focused on interests of each specialized discipline (fusion, space plasmas, lighting, etc.). Although there are several books for the general public on fusion or space plasmas, the first book written for the general public about plasmas of all types is by Yaffa and Shalom Eliezer [47] and, to the best of my knowledge, it remains the only one!

The long-standing absence of cross-cutting basic plasma science investment in the U.S. research portfolio became the focus of a major report by the National Academy of Sciences in 1995 [40]. Seeing a lack of response to recommendations of the NAS report, and recognizing significant growth in plasma-related research and education needs, about a dozen representatives of research laboratories, universities, and industry (including myself) began meeting in Washington, D.C. in 1997. From those meetings arose an independent organization, the Coalition for Plasma Science (CPS) [48], which promotes and coordinates education and outreach activities in all areas of plasma science and applications. CPS now has more than 50 member institutions from Australia, Canada, Europe, India and the USA. As an example of a CPS project, a series of high-quality "two-page" writeups are available from the CPS web site on many key topics, including to date space plasmas, fusion, lighting plasmas, destroying biological hazards, welding, plasma display panels, lightning, and cleaning the environment. Suggestions for additional topics are welcome.

RESOURCES

Major resources for plasma science and applications until around 1990 were primarily discipline specific with few books or materials that transcended such disciplinary boundaries (e.g., fusion plasmas, space plasmas, industrial plasmas, etc.). When creating a web-based resource for all areas of plasma science in 1994 (later becoming plasmas.org) and , in that same year, when creating the newsgroup sci.physics.plasma, I found very few cross-cutting materials. Fortunately, this lack has been greatly offset over the past decade with a rapid expansion of excellent texts, books, research papers, and web sites that emphasize interdisciplinary topics or results.

The Resources page of the plasmas.org website provides a concise compilation of materials for all areas of plasma science that includes, among other materials, the following:
plasma formulary, plasma dictionary, conferences, databases, who's who, properties of atoms, molecules and plasmas, frequently-asked questions, professional societies, and journals.

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