PERSPECTIVES ON SPACE AND ASTROPHYSICAL PLASMA PHYSICS

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ABSTRACT

We summarize the discussion of the current status and future prospects of space and astrophysical plasma research prepared by the Panel on Space and Astrophysical plasmas, a part of the study on Physics administered by the National Research Council of the National Academy of Sciences. The Study on Physics is chaired by W. Brinkman of Bell Laboratories and will be completed in 1984.

1. INTRODUCTION

Developments in understanding plasmas in the laboratory, in space, and in astrophysics have gone hand in hand throughout the 20th century. In the 1920's plasma oscillations were discovered in the laboratory and and radio waves were first reflected from the plasma in the earth's ionosphere -the very edge of space. From 1930-1960, the foundations of plasma physics were created as a by-product of ionospheric, solar-terrestrial, and astrophysical research, motivated by such diverse concerns as understanding how radio waves propagate in the ionosphere, how solar activity creates magnetic storms and auroral displays at earth.

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By the 1950's, it was clear that fully ionized plasmas at high temperatures would be collision free -an essential property that forced us to focus on the processes that are fundamental to plasmas, as distinct from ordinary gases, and thereby to create the modern discipline of plasma physics.

Modern plasma physics began in the years 1957-1960. Two events symbolizing the deeper intellectual currents of those years were the first successful launch of an artificial earth satellite by the Soviet Union and the revelation, through declassification, that both the United States and the Soviet Union had been trying to harness the energy source of the sun -thermonuclear fusion -for peaceful purposes. Then as now, the obstacles to achieving controlled fusion lay, not in our ignorance of nuclear physics, but of plasma physics. In 1958, the terrestrial radiation belts were discovered and in 1960, the solar wind, both by spacecraft. Thus it became clear that our exploration and future understanding of the earth and sun's space environment would also be couched in terms of plasma physics.

After 1960, modern plasma physics would develop in two separate but converging directions. Fusion research seeks a source of energy accessible to human use that will last for a time comparable with the present age of the earth. Space research seeks useful comprehension of nature's processes on a global and, indeed, solar-system scale, in recognition of man's dependence on his environment. It is both symbolically and substantially significant that the same discipline of physics -plasma physics -defines the basic language used both in fusion research and in solar-system plasma physics. Moreover the plasma phenomena in the solar system have proven to be examples of general astrophysical processes. Not only do magnetohydrodynamics and plasma physics describe both solar system and astrophysical phenomena, but the solar system has become a laboratory in which astrophysical processes of great generality can be studied *in situ*.

2) RELATIONSHIP BETWEEN LABORATORY, SPACE, AND ASTROPHYSICAL PLASMA RESEARCH

2.1) Definitions of Space and Astrophysical Plasma Physics

Space and astrophysical plasma physics comprises many subjects with distinct historical origins. Solar system plasma physics includes solar and solar wind physics, planetary magnetopheric physics, ionospheric physics, and part of cosmic ray physics. Solar research stands at the interface between space physics and astrophysics. The sun's proximity makes possible measurements pertinent to the sun's interior structure (solar neutrinos, global oscillations) and of the plasma phenomena in its photosphere, chromosphere and corona that are obtainable for no other star. In astrophysics, our subject includes the generation of magnetic fields in planets, stars, and galaxies; the plasma phenomena occurring in stellar atmospheres, in the interstellar and intergalactic mediums, in neutron star magnetospheres, in active radio galaxies, in quasars; and, once again, part of cosmic ray physics. Each of these subjects depends upon, and contributes to, laboratory plasma physics. Each has traditionally been pursued independently. Only recently has there been a tendency to view them as one unified subject. For this reason, a discussion of the relationship between laboratory, space, and astrophysical plasma physics is timely.

2.2) Relationship between Laboratory and Space Plasma Physics

The Study Committee on Space Plasma Physics (NAS/1978) expressed this relationship as follows:

> "Space and laboratory experiments are complementary. They explore different ranges of dimensionless physical parameters. Space Plasma configurations usually contain a much larger number of gyroradio and Coulomb mean free paths than is achieved in laboratory plasma configurations. In the laboratory, special plasma configurations are set up intentionally, whereas space plasmas assume spontaneous forms that are recognized only as a result of many single-point measurements. Space plasmas are free of boundary effects, laboratory plasmas are not, and often suffer severely from surface contamination. Because of the differences in scale, probing a laboratory plasma disturbs it; diagnosing a space plasma usually does not. The pursuit of static equilibria is central to high-temperature laboratory plasma physics, whereas space physics is concerned with large-scale time-dependent flows . . .
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> Certain problems are best studied in space . . . certain problems could be more conveniently addressed in the laboratory . . . Theory should make the results of either laboratory or space experiments available for the benefit of the whole field of plasma physics."

Upon the recommendation of the Study Committee, NASA took significant steps to strengthen theoretical space plasma physics. This, together with the increasing capability of space plasma instrumentation and the natural advantage of the space environment for certain types of measurements, means that the experimental diagnosis and theoretical interpretation of certain plasma processes now matches in precision the best of current laboratory practice. This is especially true in the field of wave-particle interactions, where non-Maxwellian particle distributions, and the plasma waves they create, were measured with such high resolution that theoretical instability models had to be increased in precision.

2.3) Relationship between Space and Astrophysical Plasma Research

The interplay between small and large scale processes is characteristic of space and astrophysical plasmas. Magnetohydrodynamics, or MHD, describes the large scale fluid systems in which can be identified the locations, scale sizes, and functions of the small scale plasma processes that regulate the global dynamics of such systems. In general, the MHD and associated plasma problems must be attacked simultaneously to achieve complete and self-consistent understanding.

Many of the MHD systems identified in solar system research have important analogs in astrophysics. These naturally give rise to similar plasma problems. We will illustrate these remarks by discussing two types of MHD systems, winds and magnetospheres, and two important plasma processes, reconnection and particle acceleration, that occur in them.

2.3a) Magnetohydrodynamic Winds

The outer layers of the sun are a convective heat engine producing both large and small-scale hydromagnetic motions. These motions create a dynamo magnetic field, in itself a poorly understood phenomenon. The solar magnetic field does not spread uniformly over the solar surface but is concentrated in intense, small-scale flux tubes. In addition, the turbulent motions in the outer convective layer of the sun heat the solar corona. Thus, activity at the solar surface sets the stage for the generation of the solar wind by providing a complex magnetic topology from which the heated solar corona must escape into interplanetary space. Since the coronal pressure greatly exceeds that of the interstellar medium, that part of the corona not strongly confined by the solar magnetic field expands in a flow that is subsonic near the sun and supersonic throughout interplanetary space. This solar wind carries a part of the solar magnetic field throughout the solar system; the wind speed also exceeds the Alfven speed -a characteristic speed for magnetic disturbances in a plasma. Thus the solar wind is a supersonic, super-Alfvenic, strongly ionized flow that transports plasma, energy, angular momentum, and magnetic field past all the planets of the solar system. It is finally decelerated to subsonic speeds by its interaction with interstellar matter at a distance of a few hundred astronomical units.

Expanding hydromagnetic flows, like the solar wind, are common. Plasma streams out into space from the planets' ionospheres in miniature versions of the solar wind -polar winds. Einstein observations of stellar coronal x-rays indicate that nearly all stars that have convective outer layers like the sun have surface magnetic activity that generates stellar winds like the sun's. The solar wind has carried off much of the sun's primordial angular momentum over the sun's lifetime, and since these late stars are observed to rotate slowly like the sun, we infer they too have winds. More massive stars, with radiative outer layers, are observed to have much stronger stellar winds driven by radiation pressure. Much of the interstellar medium is filled with hot, low density plasma from the blended winds of early stars. Naturally, the interstellar plasma's parameters are similar to the solar wind's. The interstellar plasma may also expand out of our galaxy as a wind. MHD winds that are confined by surrounding gas pressure take the form of collimated bi-polar jets, which are observed to flow away from such diverse systems as stars in the early phases of formation, the exotic compact stellar system SS-433, and from radio galaxies and quasars. Super high energy, relativistic plasma winds appear to flow away from pulsars and active galactic nuclei.

The solar wind is the only astrophysical wind accessible to *in situ* measurement. Since the solar wind has been as completely diagnosed as any laboratory plasma, a detailed theoretical understanding of it is possible.

2.3b) Planetary and Astrophysical Magnetospheres

The planets' magnetospheres are cavities shielded from the solar wind by their intrinsic magnetic fields. Within each magnetosphere, the magnetic field organizes the behavior of charged particles, plasma waves, and electrical currents; it traps energetic particles to form radiation belts and confines ionospheric polar wind plasma escaping into space; finally it transmits hydromagnetic stresses between the magnetosphere and atmosphere, a process which leads to *aurorae*.

Each planetary body in the solar system has a distinctive magnetospheric interaction with the solar wind. The earth's magnetosphere was discovered in 1958. In the past 10 years, Pioneers 10 and 11 traversed the magnetosphere of Jupiter, and Mariner 10 discovered an unexpected magnetosphere at Mercury. Two Voyagers passed through the magnetospheres of Jupiter and Saturn, and Voyager 1 is now on its way to Uranus, which telescopic observations indicate has *aurorae*, and therefore a magnetosphere. The Pioneer Venus Orbiter subjected the plasma environment of Venus to especially detailed examination. In 1986, an international consortium of spacecraft will study the interactions of the solar wind with Comets Halley and Giacobini-Zinner.

In astrophysics, the concept of magnetosphere has been generalized to any magnetized plasma envelope of a compact central body. Our understanding of pulsars, stellar and galactic accreting x-ray sources, and tailed radio galaxies has benefitted from our awareness of analogous magnetospheric processes in the solar system. Although the parameters of space and astrophysical plasmas can differ so much that the day-to-day problems faced by researchers in these fields are quite different in detail, the fact that both types of system present similar problems of physics gives us confidence that there exists a deeper level at which the physics of planetary and astrophysical magnetospheres is unified.

2.3c) Reconnection

Suddenly the dark polar sky is pierced by a brilliant flash of light. Within minutes, dazzling array of auroral forms stretches from horizon-to-horizon, million ampere currents surge through the earth's atmosphere and out into space, and one hundred billion watts of power are dissipated in the earth's atmosphere -a magnetospheric substorm has begun. On the sun, a burst of x-rays near a dark sunspot signals the beginning of a catastrophic disruption of the solar corona -a solar flare. Relativistic flare electrons heat the chromosphere to x-ray temperatures. A strong shock wave moves through the corona and begins a journey into interplanetary space that will carry it beyond all the planets of the solar system. The optical and x-ray luminosity starts to build up in a distant quasar. Within a day, the quasar's luminosity will exceed the total power of a thousand galaxies. A sudden plasma loss occurs in a Tokamak fusion device. These diverse phenomena seem unrelated. Nonetheless, they may share a common origin -the explosive release of stored magnetic energy by the mixed MHD and plasma process of reconnection.

Violent reconnection can lead to spectacular events such as those above, but even in its more quiescent forms, reconnection is essential in determining the behavior of MHD systems. Consider the interaction between the magnetized solar wind and the earth's magnetosphere. Reconnection between solar wind and originally closed magnetospheric field lines opens some earth field lines to interplanetary space. Energetic particles that ordinarily would not hit the earth can be guided along open field lines into the earth's polar atmosphere. Thus, reconnection changes the topology of the earth's magnetic field. More importantly, reconnection enables the solar wind to do work on the magnetosphere, to set the plasma inside in motion. The basic energetics of the magnetosphere are in large part determined by the rate of reconnection. Or consider the magnetic fields in the solar corona. It is thought that a balance is set by the creation of magnetic field by turbulent convection below the solar surface and its destruction by reconnection, in "microflares," in the corona. Only when reconnection has been temporarily inhibited can the magnetic field increase enough to produce a spectacular flare by the reconnection that ultimately occurs.

In sum, the effects of reconnection must always be considered in MHD models of space and astrophysical objects. Not only can it influence their quiescent magnetic configurations, but it can cause sudden, dynamic reconfigurations of their structure.

2.3d) Particle Acceleration and Cosmic Rays

An astonishingly large fraction of the energy in space and astrophysical plasmas is in the form of energetic particles. For example, cosmic rays comprise about 1/3 the energy density of the interstellar medium. The energetic particles themselves lead to important diagnostics of astrophysical systems. The observed cosmic ray elemental and isotopic abundances are beginning to constrain models of nucleosynthesis and galactic evolution. We can infer the magnetic fields in regions containing relativistic electrons from the synchrotron radiation emitted by such electrons, a first step in constructing a global MHD model of the system.

Analogs of cosmic acceleration processes are observed in solar system plasmas. Energetic particles have been observed from explosive reconnection events in the earth's magnetic tail, and from solar flares. The ~ 10 KeV electrons responsible for the terrestrial aurora are accelerated at 1000-5000 km altitudes above the earth in regions that carry strong magnetic field aligned currents and, contrary to MHD reasoning, generate parallel electric fields. The auroral acceleration region generates strong radio emission. Aurorae and radio emissions have also been observed at Jupiter and Saturn, and aurorae, at Uranus. Finally, collisionless shock waves, some propagating in the solar wind, and some standing ahead of the planets, are observed to accelerate particles by the same processes now thought to generate cosmic rays.

Supernova shock waves are the primary energy input to the interstellar medium. In 1977, it was proposed that shock acceleration could account for the spectrum of galactic cosmic rays, but it was unclear whether it was efficient enough to account for the high cosmic ray energy density. The parameters of the interstellar shocks are similar to those studied in the solar system. Because the interstellar shocks are older and larger, they have more time to accelerate particles to the enormous energies observed. Although it is not possible to measure the plasma structure of interstellar shocks, theories of their structure can be tested by direct measurements of solar system shocks, and by measurements of galactic cosmic-ray energy spectra and composition.

2.4) The Unifying Thread

The unifying thread linking laboratory, space and astrophysical plasma research is the set of problems of magnetohydrodynamics and plasma physics of true intellectual significance that they share. The NAS Committee on Space Plasma Physics (1978), identified six of these:

1. Magnetic field reconnection
2. The interaction of turbulence with magnetic fields
3. The behavior of large scale plasma flows and their interactions with magnetic and gravitational fields
4. The acceleration of energetic particles
5. Particle confinement and transport
6. Collisionless shocks

To the above six we add two more:

7. Beam-plasma interactions, and the generation of

electromagnetic radiation
8. Collective interactions between neutral gases and plasmas

Problem 3 is concerned with large scale plasma systems, and the others relate to microscopic plasma processes occurring in such systems.

The fact that such problems emerge from a variety of contexts is proof of their general significance, and suggests that solutions to particular problems will find further applicability in contexts we cannot imagine today. The existence of such paradigm problems provides a basis upon which a network of common interests, personal interactions, and ultimately a common discipline, is being built.

3) TEN YEARS RESEARCH ON CRITICAL PROBLEMS OF SPACE AND ASTROPHYSICAL PLASMA PHYSICS.

To communicate succinctly the flavor of space and astrophysical plasma research, we highlight here the progress over the last decade on the eight central problems defined in 2.4. Because problem 3 subsumes all our investigations of large scale plasma systems, discussing it first puts all the other problems in context.

Problem #3: "The behavior of large scale plasma flows . . ."

Planetary Magnetospheres. Mariner 10 discovered a small highly active magnetoshpere at Mercury, that is energized by the intense solar wind near the sun. The Pioneer-Venus Mission has provided a large volume of information about the interaction of the solar wind with the Venusian ionosphere. The Pioneer 10 and 11 missions established the enormous scale and variability of Jupiter's magnetopshere, and Pioneer 11 made the first traversal of Saturn's magnetic field. The Voyager 1 and 2 missions established that Jupiter's rotation powers a radial outflow of heavy ion plasma injected by volcanic activity at the satellite Io. The Voyagers found that Saturn's magnetic dipole and spin axes are aligned, a fact which challenges current theories of planetary magnetic field generation. Saturn's magnetosphere has an important interaction with the dense atmosphere of the satellite Titan.

Magnetohydrodynamic Properties of the Earth's Magnetic Tail. The MHD flows in the earth's magnetic tail proved to be highly intermittent and variable, with intense flows often but not always correlated with substorm activity observed on the ground. Large scale convection cells were detected in the earth's magnetic tail. The field aligned current systems mapped near the earth and in the magnetic tail proved to be approximately consistent. Intense flows, and MHD and plasma turbulence, were associated with the field aligned currents in the tail; the field aligned currents corresponded to the auroral acceleration region near the earth.

Magnetohydrodynamic Structures near the Sun and in the solar wind. Measurements made on Skylab revealed the important difference between open and closed magnetic field regions near the sun. Open magnetic regions -solar coronal holes -generate fast streams in solar wind. Closed magnetic regions -solar coronal loops -are the regions in which solar flares occur.

The European Helios mission extended measurements of the solar wind within the orbit of Mercury, and the Pioneer 11 mission extended these measurements past the orbits of Neptune and Pluto. The solar wind magnetic field proved to reverse direction across a time variable, warped neutral sheet, in accordance with simple stellar wind models. Strong, corotating shocks were found in the distant solar wind, changing our picture of how galactic cosmic rays are modulated by the solar wind.

Magnetospheres of Neutron Stars. Our understanding of the two types of neutron star magnetospheres -those of pulsars and of accretion x-ray sources -was clarified. Phase resolved spectroscopy identified an x-ray line at the electron cyclotron frequency in an x-ray source, which proved that neutron stars can have superstrong magnetic fields, of order 10^{12} Gauss -a fundamental hypothesis of pulsar and x-ray source theories. This strengthened the picture that pulsars are rapidly rotating magnetized neutron stars. Detection of pulsed γ-ray lines from the Crab and Vela pulsars proved that they generate superhigh energy particles, and qualitatively supported the theoretical suggestion that electron-positron pair plasmas are created in pulsar magnetospheres. Simple MHD theories of radial transport in accretion disks proved inadequate, and it was suggested that processes similar to those in the solar corona may occur in accretion disk coronae.

Magnetohydrodynamic Jets. Active galactic nuclei frequently produce pairs of high speed jets that propagate in anti-parallel directions through the surrounding galaxy and out into the intergalactic medium, where they create the two component radio emission characteristic of radio galaxies. VLBI measurements proved that the jets, which were theoretically anticipated, are accurately aligned on the light year scale of the nuclei and on the $\sim 10^{5-6}$ light year scale of the double radio components. Some jets appear to expand faster than the speed of light, a kinematic effect which indicates that the flow speed can be relativistic.

Recently, we have learned that similar jets are associated with galactic objects, such as the energetic system SS-433, or stars in the early stages of formation.

Black Hole Electrodynamics. A new theory endows rotating black holes with electric and magnetic fields under appropriate circumstances, and suggests that the environment of black holes involves much more pulsar-like plasma physics than originally thought.

Problem #1: Reconnection

Two achievements, one experimental and one theoretical, stood out in the past decade. Bursts of MeV particles were detected and associated with rapid plasma flows in the earth's magnetic tail. The electric-fields corresponding to the measured flow speeds could account for the observed particle energies. These results showed that inductive electromotive forces are important to magnetospheric dynamics, and suggested that tail reconnection is unsteady, and perhaps explosive. Rigorous analytical theory and numerical simulations established that a slow shock model proposed in 1964 is the correct description of reconnection in the MHD limit.

Theoretical understanding of the collisionless tearing limit of reconnection was consolidated, and an explosive tearing instability was proposed analytically and simulated numerically. A laboratory experiment diagnosed with high precision the turbulent transport processes occurring in a strong guide field plasma regime appropriate, perhaps, to solar flare conditions.

Problem #2: Interaction of Turbulence with Magnetic Fields

The Einstein discovery that most stars exhibit solar-like surface activity, together with the fact that solar activity is determined by the interaction of solar magnetic fields with the ambient plasma, proved that plasma processes are central to the physics of stellar chromospheres and coronae. The observed correlation of stellar activity with stellar rotation will constrain theories of dynamo generation of stellar magnetic fields and the dissipation of these fields as they emerge through the stellar surface.

The solar surface magnetic field has proven to be concentrated in thin layers of strength $\sim 10^3$ G separated by larger regions of strength < 10G. There is essentially no evidence for a smooth uniform field at the solar surface. These remarkable observations challenge theories of turbulent magnetohydrodynamic convection.

A coherent program of active and passive radar experiments, chemical releases, rocket measurements, analytic theory, and numerical simulations led to clear understanding of the so-called "Spread-F Bubbles" in the equatorial ionosphere. This work is the most complete analysis of the nonlinear development of the Rayleigh-Taylor instability in plasma physics.

Problem #4: Acceleration of Energetic Particles

Measurements of the Be^{10}/Be^9 ratio in cosmic rays showed that their age -the time since they had been accelerated -is about 10 million years. Abundance and isotope measurements showed that most cosmic rays are accelerated, not out of enriched supernova material, but out of an interstellar medium whose composition differs only slightly from solar, presumably because of chemical evolution since the birth of the sun. The discovery that much of the volume of the interstellar medium is in a low density plasma phase meant that supernova shocks could propagate much further than originally thought. This led to the suggestion that supernova shocks Fermi-accelerate the cosmic rays out of the interstellar medium. The Fermi-acceleration particle energy spectrum was shown to be consistent with cosmic ray observations. Detailed measurements of the energetic particle distributions and plasma turbulence associated with interplanetary shocks and planetary bow shocks began to be used to test self-consistent shock acceleration theories.

Measurements of field aligned currents, electron and ion densities, electrostatic and electromagnetic waves, and energetic ion and electron distribution functions, in the auroral acceleration region were systematically assembled and combined with measurements of auroral light, ionization, motions, and structures, thereby setting the stage for comprehensive understanding of auroral acceleration in the next decade.

It was found that processes within Jupiter's magnetosphere accelerate nearly all the ~ 10 MeV electrons found in the heliosphere.

Impulsive particle acceleration events, probably associated with reconnection, were found to accompany rapid flow reconfigurations of the earth's magnetic tail.

The discovery of an "anomalous" component of low energy cosmic rays that has unusual abundances of Oxygen, Nitrogen, Carbon, and Helium nuclei, and is modulated by the solar cycle like other cosmic rays, suggested the existence of a second source of cosmic rays outside, or in the outer reaches, of the heliosphere. Air shower observations suggested that 10^{14}-10^{16} eV cosmic rays are richer in heavier elements than those at lower energies, and that cosmic rays with 10^{17-19} eV energies may be anisotropic, unlike cosmic rays of galactic origin.

Problem #5: Particle confinement and transport

Detailed models of the magnetic mirror confinement, radial diffusion, and turbulent pitch angle scattering of energetic ions and electrons were created and successfully tested by observations in the magnetospheres of earth and Jupiter.

A clear qualitative understanding of electron heat transport in the solar wind was achieved by means of systematic measurements of superthermal electrons, and analytic identification of the instabilities that can limit heat conduction in various solar wind conditions.

Quantitative studies of the conduction of heat by electrons between the solar corona and chromosphere, which promise to make interpretation of chomospheric line emissions more secure, were carried out.

Problem #6: Collisionless Shocks

The strong dependence of the earth's bowshock structure upon the parameters of the upstream solar wind was demonstrated by synopsis of individual detailed case studies, by the ISEE and other spacecraft.

The clear understanding of the discontinuous change in shock structure at the so-called first critical Mach number, achieved by a combination of spacecraft measurements, analytic theory, and numerical simulation, is the major single accomplishment in collisionless shock physics in the past ten years.

Quasi-parallel shocks, which propagate nearly parallel to the upstream magnetic field direction, proved to have extensive regions upstream which contain shock accelerated particles and large amplitude MHD turbulence, a property required by Fermi-acceleration theories.

Theories of the propagation, scattering, and energization of the upstream particles were created and tested by data from interplanetary shocks and planetary bow shocks. These results are providing a solid basis for theories of the acceleration of cosmic rays by supernova shocks.

Problem #7: Beam-plasma Interactions, and the Generation of radio emissions

The Jovian radio emissions were measured directly from space from the first time. They extended a factor 10 lower in frequency than was possible to measure from the ground, and their characteristic frequency-time structure illuminated how they were modulated by the interactio on between Jupiter's magnetosphere and its satellite Io. Saturnian radio emissions were discovered, and shown by the Voyagers to have a modulation entirely different from the Jupiter-Io system's. Detailed studies of the intensity, frequency spectrum, and polarizations of the analogous Auroral Kilometric Radiation at earth, and their correlations with other auroral phenomena, motivated a generous development of theory. It now appears that the auroral electron beam may linearly excite the Auroral Kilometric Radiation directly, in which case the aurora would be a giant gyrotron in space.

The magnetospheres of Earth, Jupiter, and Saturn confine a diffuse continuum of radio noise, whose lower cutoff frequency is the most sensitive indicator of the plasma number density. Detection of Jovian continuum radiation proved that Jupiter's magnetic tail is 5 AU long and is the best vacuum so far encountered by man, with a density ~ 10^{-5} particles -per cm^3. Detailed studies of the fine structure of continuum radiation illuminated how it is generated near the terrestrial plasmapause, and by the interaction of Saturn's magnetosphere with its satellites.

A nonlinear theory of Type III radio emissions in which streaming energetic electrons create electron plasma oscillations which then couple to radio waves in a background of plasma turbulence, was created and supported by observation in the solar wind.

Detailed studies of pulsar radio emissions provided the most complete diagnosis to date of the microstructure of a highly relativistic plasma. Some pulsars' radio emissions were shown to consist entirely of discrete bursts, suggesting the action of nonlinear plasma processes.

Problem #8: Interactions between plasmas and neutral gases

It was suggested in 1954 that a neutral gas would be rapidly ionized when its velocity through a plasma exceeds the so-called critical ionization velocity, given by equating an atom's kinetic energy to its ionization energy. This effect is now thought important to rotating plasma devices such as centrifuges, the formation of minor bodies in the early solar system, comets, satellite -magnetosphere interactions, neutral gas releases in space, and, to the interaction of the Space Shuttle with the plasma through which it moves. Recent laboratory experiments, together with theory, showed that the rapid ionization results from collective electron heating by lower hybrid plasma waves plus classical ionization.

An extensive series of chemical releases was used to diagnose the plasma flows in the magnetosphere and in the auroral acceleration region.

4) SPACE AND ASTROPHYSICAL PLASMA PHYSICS IN THE NEXT TEN YEARS

As it is more difficult to predict the future than to review the past, we restrict ourselves to a few general assessments of the state of our subject after the next ten years.

The exploration of Solar System Plasmas will have been nearly completed. The International Solar Polar Mission will study the solar wind, and its effects on cosmic rays, in three dimensions for the first time. A Pioneer or Voyager spacecraft might leave the heliosphere by the end of the decade, and thus detect interstellar matter and galactic cosmic rays directly. The first *in situ* measurements of comets and of Uranus' magnetosphere will occur. The *Galileo* mission will diagnose Jovian magnetospheric plasma as completely as any space plasma to date. *In situ* measurements of solar plasmas will be the primary unfinished task.

The plasma environment of the earth will have been subjected to controlled study, and, perhaps, to a measure of control, through the systematic use of active experiments, and by synoptic measurements provided by the OPEN spacecraft project.

High resolution optical and radio observations will have provided essential information defining quantitative models of solar surface magnetic fields and dynamics, solar flares, and coronal heating, thereby creating the basis for general understanding of stellar activity.

The growing ability to make series of detailed high resolution observations in many wavelength bands will render many astrophysical objects increasingly subject to theoretical models that explicitly take plasma processes into account.

Understanding of many space plasma processes will be sufficiently quantitative to make them reliable components of models of large scale space and astrophysical systems. In addition to radiation belt dynamics, the list of generally understood space plasma processes may include auroral acceleration, reconnection, collisionless shocks, and neutral-gas plasma interactions.

The first generation of large scale numerical models of space and astrophysical systems will have been completed. Foreseeable advances in computing technology will lead to their creation virtually simultaneously through space physics and astrophysics. Such models will probably have made plasma physics central to the observation of many astronomical observations, and have motivated new and different kinds of observations. One member of this class of models will have been tested by direct *in situ* measurements of the terrestrial magnetosphere's global dynamics provided by the OPEN spacecraft project.

5) MOTIVATIONS FOR RESEARCH ON SPACE AND ASTROPHYSICAL PLASMAS

Research in this century has revealed a chain of interactions, largely plasma physical, that connects activity at the surface of the sun to the solar wind, and then on to the magnetosphere and atmosphere. The most spectacular manifestation of this solar-terrestrial interaction-chain is the magnetic storm. The first evidence that a large solar flare might occur is the appearance of a complex sunspot group in the sun's photosphere. Prompt electromagnetic radiation arrives at earth a few minutes after the energy in the coronal magnetic fields associated with the sunspot group is explosively released. Energetic solar-flare protons are guided by the solar wind and magnetospheric magnetic field into the polar atmosphere soon afterward. The enhanced ionospheric plasma that they produce attenuates the radio noise received from cosmic radio sources. A day or so later, a shock wave passes over earth, enveloping it in dense, hot solar-flare plasma that compresses the magnetosphere. Substorms increase in frequency and strength, and inject hot plasma into the earth's inner magnetosphere to form a "ring current," which creates the geomagnetic field depression and activity that first motivated the name magnetic storm. The *aurorae intensify* and move to unusually low latitudes, creating a dense *highly* disturbed ionospheric plasma that interferes with radio communication and on occasion blacks it out altogether. Intense wind systems, sometimes of a world wide scale, are generated in the upper atmosphere.

The Committee on Solar-Terrestrial Research, in its report, Solar-Terrestrial Research for the 1980's, (NAS/1981) has identified four areas where research on the solar-terrestrial interaction chain can clarify important impacts on society and technology:

1. Predictions about the space environment
2. Effects on stratospheric ozone, which shields the life at the earth's surface from the harmful effects of solar ultraviolet radiation
3. Effects on ionospheric physics and radio propagation
4. Elucidating a potential connection between solar variability, weather, and climate

Although items (2) and (4), above, have significant long-term implications, item (1) is the most directly and immediately important. Many practical systems, both civilian and defense, and all our manned space endeavors, must operate in the highly variable and potentially hostile plasma environment of the earth and solar system. Plasma processes in this environment also influence and even disrupt important ground-based systems over local and regional scales. Ground based HF communication systems in the earth's polar regions can be blacked out by magnetic storms. Entire spacecraft have been electronically disabled by violent electrical discharges that occur when hot "ring-current" plasma envelops the spacecraft. The risk of such disasters can be reduced only by continuing attention to the effects of the plasma environment on space-craft systems. It is clear that to work in the space environment, we must understand it.

The Astronomy Survey Committee (NAS/1982) has characterized the motivations for astronomical research as follows:

> "Astronomy . . . is sustained by two of the most fundamental traits of human nature: the need to explore and the need to understand. Through the interplay of discovery, the aim of exploration, and analysis, the key to understanding, answers to questions about the universe have been sought since the earliest times, for astronomy is the oldest of the sciences. Yet it has never been, since its beginnings, more vigorous or exciting than it is today."

Our own branch of astronomy, astrophysical plasma physics, is driven by the need to understand the unusual plasmas surrounding some of the most exotic objects brought to light by recent astronomical research. Our imaginations are challenged, and we are forced to extend plasma physics to comprehend them.

Mature scientific disciplines are characterized by deep philosophical motivations, a unified body of powerful theoretical and experimental techniques, and a wide range of applications. It is our conviction that when space and astrophysical plasma physics are integrated with one another, and with laboratory and fusion research, plasma physics will have become mature. When a scientific discipline matures, technological innovation soon follows. Plasma physics is only beginning to have its impact.

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