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Space Technology Plasma Issues in 2001

Henry Garrett
Joan Feynman
Stephen Gabriel
Editors

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ABSTRACT

A workshop on Space Technology Plasma Issues in 2001 was held at the Jet Propulsion Laboratory on 24-26 September 1986, and was sponsored by the National Aeronautics and Space Administration's (NASA) Office of Aeronautics and Space Technology (OAST). The purpose of the workshop was to identify and discuss plasma issues that need to be resolved during the next 10 to 20 years (circa 2001) to facilitate the development of the advanced space technology that will be required 20 or 30 years into the future. The conference was attended by about 50 people. The workshop consisted of 2 days of invited papers and 2 sessions of contributed poster papers. During the third day the meeting broke into 5 working groups, each of which held discussions and then reported back to the conference as a whole. The five panels were: Measurements Technology and Active Experiments Working Group; Advanced High-Voltage, High-Power and Energy-Storage Space Systems Working Group; Large Structures and Tethers Working Group; Plasma Interactions and Surface/Materials Effects Working Group; and Beam Plasmas, Electronic Propulsion and Active Experiments Using Beams Working Group.

The Proceedings of the conference contains the working group reports, eighteen invited papers, and abstracts of the poster papers. In addition an appendix contains three papers contributed by Professors Alfvén and Fälthammar discussing the importance of certain selected space plasma issues to both science and technology.

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POSTER ABSTRACTS

PREFACE

A workshop on Space Technology Plasma Issues in 2001 was sponsored by the National Aeronautics and Space Administration's Office of Aeronautics and Space Technology, and held September 24-26, 1986 at the Jet Propulsion Laboratory, Pasadena, California. This volume contains the proceedings of that conference.

Critical new plasma issues can be expected to arise during the next few decades due to the inevitable increase in the number and sophistication of future space systems. In particular, there will be great increases in the structural complexity and physical size of space systems as well as major increases in the variety of interactions between the environment and objects in space due to EVA, multiple maneuvering bodies, exposed high voltage arrays, beams, tethers, etc. The purpose of the workshop was to address those plasma issues which will have important impact on the advanced technology to be introduced into space in the time frame from 20 to 30 years in the future (circa 2010). In particular, the workshop identified and discussed plasma issues that need to be resolved during the next 10 to 20 years (circa 2001) to facilitate the development of that future technology.

The permanently manned Space Station will provide a platform from which experiments can be conducted. The issues of major interest for the workshop were those that will require plasma experiments taking place in space for their clarification. The issues were relevant to one of the following areas:

1. The Space Station interaction with its environment.

2. The interaction of planned Space Station-associated technologies with the environment.

3. Other future advanced technologies involving manufacture or use in space.

The workshop consisted of 2 days of invited papers and 2 sessions of contributed poster papers. On the third day, the meeting broke into five working groups, each of which had about eight members. The charge to the working groups was to identify key plasma issues that will require attention during the next two decades and to develop an approach to their resolution. Each group was asked to provide the conference as a whole with a succinct report on their work. For each issue identified, the report was to contain a description of the issue and its importance, an identification of the gaps in our present knowledge, a brief description of the theoretical, computer modeling and experimental advances required to fill the gap and an identification of what needs to be done to facilitate those advances. The working groups were directed to concern themselves with in situ and created plasmas both near the Earth and other planets as well as cometary environments and dusty plasmas. The topics assigned to the five working groups were:

1. Meaurements technology and active experiments not using beams

2. Advanced high voltage, high power and energy storage space systems

3. Large structures and tethers

4. Plasma interactions and surface/materials effects

5. Beam plasmas, electronic propulsion and active experiments using beams.

The material collected in this volume consists of the invited papers presented at the conference, abstracts of contributed poster papers, and the working group reports. In addition, there is an appendix containing papers by Professors Alfvén and Fälthammar that describe the importance of certain plasma issues to our understanding of the behavior of plasmas in general and astrophysical plasmas in particular. These plasma issues can only be addressed by solar system and magnetospheric investigations.

WORKING GROUP REPORTS

N87-20056

PLASMA INTERACTIONS AND SURFACE/MATERIAL EFFECTS

M. Mandel (Chair), A. Chutjian,
W. Hall, P. Leung, P. Robinson, and N. J. Stevens

I. INTRODUCTION

This section is an executive summary of the discussion on plasma interactions and surface/material effects. During the discussion, the panel members unanimously agreed that the key issues in this area were: (1) the lack of data on the material properties of common spacecraft surface materials; (2) lack of understanding of the contamination and decontamination processes; and (3) insufficient analytical tools to model synergistic phenomena related to plasma interactions. Without an adequate database of material properties, accurate system performance predictions cannot be made. The interdisciplinary nature of the surface-plasma interactions area makes it difficult to plan and maintain a coherent theoretical and experimental program. The shuttle glow phenomenon is an excellent example of an unanticipated, complex interaction involving synergism between surface and plasma effects. Building an adequate technology base for understanding and predicting surface-plasma interactions will require the coordinated efforts of engineers, chemists, and physicists. An interdisciplinary R&D program should be organized to deal with similar problems that the space systems of the 21st century may encounter.

II. KEY ISSUES

A. Materials Characterization

A knowledge of the material properties of all spacecraft surfaces is essential to assure the long-term reliability and survivability of future space systems. This knowledge enables modeling of the thermal, electrostatic, and electrodynamic performance of space systems in the space environment in order to optimize design parameters. For example, the electrical properties (surface and bulk conductivity, photoemission, secondary emission) determine the amount of charging that can be caused by the plasma environment. The sputtering coefficients of surface materials determine not only the longevity of those materials, but also the enhanced plasma and chemical environment in the vicinity of the space system. The operation of such space systems as high-voltage solar arrays and RF communications systems are strongly dependent on the plasma environment in the vicinity of the spacecraft. Therefore, the performance of these systems is affected by the behavior of spacecraft surface materials.

The existing data on the electrical properties of common spacecraft materials range from outdated to nonexistent. In particular, there are virtually no data on candidate new and replacement materials. For new classes of materials, such as fluids, composites, and textured materials, the techniques for characterizing such electrical properties as secondary electron-emission coefficients and surface conductivities still remain to be developed. Also, there is little understanding of how various material properties change as a material ages in the space environment.

B. Contamination and Decontamination

The contamination processes to be discussed in this section deal only with those processes induced by plasma interactions or by operation of the space system in the space-plasma environment. At present, contamination has been unavoidable, and there is no proven technique to

decontaminate a space system. The main present and anticipated sources of contamination are outgassing, attitude control engine burns, manned servicing of spacecraft, water dumps, and spacecraft charging and discharging. The manned space station and other advanced space systems that require frequent servicing or revisitation will be periodically subjected to renewed sources of contaminants. This will drastically increase the need for contamination control.

Contamination can significantly alter the material properties of a surface. Optical mirrors are obviously sensitive to contamination. Contamination has also been observed to change a conductive surface to an insulating surface, or vice versa. Results from experiments on the characterization of electrical properties of exhaust plume contaminants emitted by a bipropellant engine (footnote 1) show that during the first hour of the condensation of the plume exhaust, the contaminant acts like a semiconductor with a resistivity of 10^4 ohm-cm. After exposing the plume condensate to the simulated space environment for several hours, the contaminant becomes an insulating material with a resistivity of 10^{10}ohm-cm. Therefore, contamination can completely alter the plasma interaction processes. Spacecraft charging/discharging can occur unexpectedly. High-voltage surfaces can become electrically shorted, causing an unforeseen failure of space systems. Other plasma-related contamination effects include: (1) errors in science measurements, (2) alteration of the enhanced spacecraft environment due to change in secondary electron-emission coefficients, and (3) degradation of thermal and optical properties.

At the present time, decontamination technology is virtually nonexistent. Innovative active and passive techniques for the dissipation of contaminants need to be developed. The existing models for contamination are crude, and the required data for their use are lacking. There are only isolated R&D efforts to obtain the essential surface material data where needed for a specific mission, e.g., Galileo. A more coherent program is needed.

C. Synergistic Surface Chemical and Physical Processes

The chemical and physical processes that can take place on or near a spacecraft surface affect the enhanced plasma environment in the vicinity of the surface. The glow phenomenon, which is believed to be a synergism between nonlinear plasma interaction processes and chemical reactions of free atomic oxygen with surface materials, is an example of a complex process that can take place in the space environment. The glow has caused unanticipated noise problems for several sensitive optical instruments. Undoubtedly, other space-unique processes will be found requiring synergisms not commonly encountered on the ground, such as reactions involving both atomic oxygen and solar ultraviolet. The unavoidable erosion of surface materials through chemical reaction with free oxygen atoms will definitely reduce the long-term reliability of space systems.

Models to predict space chemistry effects are in a rudimentary stage of development. One of the reasons for the lack of modeling effort is the unavailability of data on the cross-sections for the chemical reactions potentially important in space. Some of the required cross-sections are those for the chemical reactions of ground and excited states of atomic oxygen with spacecraft material (particularly organic materials). The intensity of glow could be related to the presence of a high-density plasma in the vicinity of spacecraft surfaces. The plasma processes responsible for the formation of this high-density plasma are believed to be caused by critical ionization and sheath ionization phenomena. Fundamental knowledge of these processes needs to be improved in order to predict and control the shuttle glow and other synergistic phenomena.

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III. PROPOSED PROGRAM

The key issues discussed above illustrate two common deficiencies:

(1) Lack of experimental data required for modeling system performance.

(2) Nonexistent theory and modeling frameworks for extrapolation of experimental data with respect to geometrical, environmental, and synergistic effects.

In order to prepare the space systems of the next century for possible adverse plasma surface-interaction effects, the following are needed:

(1) A ground-based test program including the following investigations:

   (a) Electrical properties (including bulk and surface conductivities, spacecraft surface materials and contaminants.

   (b) Outgassing data for new and existing spacecraft materials.

   (c) Chemical reaction rates for the ground and excited states of free oxygen atoms with solid materials and outgassed contaminants.

   (d) Sticking coefficients of contaminants.

   (e) Innovative decontamination techniques.

   (f) Space-unique chemical and physical processes.

(2) A space test facility to validate the ground-based measurements.

(3) A program to coordinate phenomenology and modeling development.

(4) A central database for data and phenomenology useful in predicting system performance.

Other space-unique effects, including micrometeoroids and debris, were discussed in the panel meeting. Since these topics are only remotely related to plasma interactions, they are not included in this summary.

N87-20057

LARGE STRUCTURES AND TETHERS WORKING GROUP

G. Murphy, Chair, H. Garrett, U. Samir, A. Barnett, J. Raitt, J. Sullivan,and I. Katz

I. INTRODUCTION

The Large Structures and Tethers Working Group sought to clarify the meaning of "large structures" and "tethers" as they related to space systems. "Large" was assumed to mean that the characteristic length of the structure was greater than one of such relevant plasma characteristics as ion gyroradius or debye length. Typically, anything greater than or equal to the Shuttle dimensions was considered "large." It was agreed that most large space systems and the tether could be better categorized as extended length, area, or volume structures. The key environmental interactions were then identified in terms of these three categories. In the following Working Group summary, these categories and the related interactions are defined in detail. The emphasis is on how increases in each of the three spatial dimensions uniquely determine the interactions with the near-Earth space environment. Interactions with the environments around the other planets and the solar wind were assumed to be similar or capable of being extrapolated from the near-Earth results. It should be remembered in the following that the effects on large systems do not just affect specific technologies but will quite likely impact whole missions. Finally, the possible effects of large systems on the plasma environment, although only briefly discussed, were felt to be of potentially great concern.

II. EXTENDED LENGTH

Structures for which one dimension is large relative to the plasma are best represented by the space tether although other systems could be envisioned. Examples include the Space Shuttle oriented with the nose-tail axis simultaneously along the magnetic field and velocity vector, such as sometimes occurs for polar orbits near the equator. In this case the wing axis is the large dimension – a narrow plasma beam before it has spread. Although both conducting and nonconducting structures were considered, the following discussion will focus on conducting structures, perhaps with a nonconducting surface to insulate them from the space plasma. For such structures, the primary interaction is the well known Lorentz force, which produces an induced electric field in the reference frame of the structure:

$$\bar{E} = \bar{v} \times \bar{B}$$

or

$$\bar{V} = \bar{E} \cdot \bar{L} = \bar{L} \cdot (\bar{v} \times \bar{B})$$

where:

E = induced electric field
V = induced potential drop
L = characteristic length of structure
v = velocity of vehicle
B = magnetic field

At Shuttle and Space Station altitudes, v is 7 to 8 km/s and B about .0.3 g so that typical potential drops are 0.3 V/m. As space tethers are expected to reach tens to hundreds of km, kilovolt or higher potentials are anticipated.

The existence of kV or greater potentials will lead to several key interaction issues. Chief among these for extended-length structures is the question of return currents where the plasma "contact" area may be only a few meters of conducting length on the two ends (large area and volume structures will have a similar problem but not, it is believed, nearly as severe as will the extended-length structures). Any application of the high voltages created in a conducting tether or similar extended-length structure will by necessity drive large return currents. It is anticipated that the ambient environment may not be able to directly support these currents so that any space systems wishing to draw power/current from the environment could be very inefficient. Plasma contactors are devices that have been proposed to eliminate this problem for extended-length systems by allowing efficient current collection from the ambient environment. Examples are electron beams, ion beams, neutral plasma generators, or large conducting spheres that could create artifically large current collection areas. The I-V curves of such devices at high potentials are not well characterized and represent a critical problem for the development of electrodynamic tethers. The consensus of the working group was that while in most areas of plasma interaction studies laboratory experiments were still timely and valuable, they have been essentially exhausted in this area and proper in-space experiments are critically needed.

The dynamics and stability of extended-length structures need to be carefully investigated. A specific concern in terms of the plasma environment are the electrodynamic torques and drag produced by the ambient plasma and fields. Whereas for most "normal" spacecraft, electrodynamic drag is small compared to neutral atmospheric drag, the large area-to-mass ratio of a tether will make it potentially sensitive to normally weak electrodynamic forces – although the cross section of a short segment is miniscule, the total cross section of a 100-km tether will be very large and is dependent on the details of the plasma interaction. (Note: in some applications, such as around Jupiter, it may actually be possible to draw electrical propulsion power from the tether, producing "antidrag"!) N. Stone has made a separate written contribution to the Working Group on tethers, which is included as an appendix.

III. AREA

"Large" area means that each dimension of the object's two-dimensional cross section is larger than the characteristic plasma dimensions. As an example, the cross sectional dimensions of a 1-m-diameter spacecraft are typically large compared to the electron gyroradius and the debye length – it is not compared to the ion gyroradius. In contrast, the Space Station cross section will be large compared with most plasma characteristic dimensions. Large solar arrays are another prime example of large-area structures.

The main concern with large-area interactions is the shadowing effect of the area. That is, the area will create a complex wake behind a surface in the direction of the velocity vector and, although primarily a three-dimensional structure, the wake will depend principally on the cross-sectional shape of the area normal to the velocity vector. Models currently exist, but more sophisticated models that incorporate magnetic field effects are lacking. In particular, in situ experiments and comparisons between in situ experiments and the models are desperately needed. Laboratory measurements have proven valuable but do not adequately address the relevant range of parameters and are generally limited in the $(Ro/Ld)^2$ ratios that can be measured (Ro=characteristic

body length; Ld=debye length). In situ measurements are needed where Ro>>Ld (i.e., Ro>10^4 Ld). Measurements for both large conducting and nonconducting surfaces are necessary. Both laboratory and in situ experiments need to concentrate more on varying the surface potential in order to determine wake variations dependent on this critical parameter. For truly large area-to-mass structures (such as the Solar Sail, the Space Based Radar, and the Solar Power Satellite), the electrostatic drag and the pondermotive forces may become as important as the neutral atmospheric drag; few accurate models of these phenomena currently exist. Finally, the basic issue of how the plasma wake and magnetic field couple to produce the observed EMI needs to be carefully studied – such noise may set a lower limit on noise levels in the vicinity of large structures. The scaling law that relates the EMI to size is not known since measurements aboard the Orbiter are complicated by the introduction of large amounts of outgassing products.

IV. LARGE VOLUMES

Unlike extended-lengths and large areas, it is much more difficult to determine the scaling laws for large volumes. Here we assume that "large volume" encompasses the concept of the perturbed volume around a body. In particular, we include the interaction of the local gas cloud (as from emitted gases) surrounding a body with the plasma and ambient neutrals and the resulting modification of the local environment in the concept of large volume.

Key outstanding issues, in addition to the definition of scaling laws, are how plasma heating can take place (as is observed in the Shuttle ram) and how the heating scales with size and composition. Although studied as a function of area, the breakdown characteristics of high-voltage solar arrays have yet to be determined in terms of the perturbed volume at the surface of the arrays – in particular, the volumetric effects and differences between ac, dc, and pulsed power (as in the SDIO beam weapons) systems need to be considered. The dynamics of emitted fluids (liquid or gas) need to be investigated in terms of collective behavior. The so-called "critical Alfven ionization velocity" effect whereby reflected, high-velocity neutral particles in the ram direction self-ionize is another potential plasma interaction issue about which we know little. As locally generated magnetic fields of very high amplitude are being considered for various experiments, their effects on a large volume must be characterized. Models and in situ experiments to evaluate these effects need to be carried out hand in hand.

A potentially dangerous problem was identified as regards one very complex system that depends on volume – liquid droplet cooling. In these systems, millions of tiny droplets are emitted in order to eliminate heat. Because of their large area-to-mass ratio, they would be much more efficient at emitting radiation than current solid-surface emitters or cooling vanes. The interactions of such systems of concentrated macroparticles with the environment (for instance, gravity effects could be dominated by electromagnetic effects) over a large volume are virtually unknown. In the early days of the space program, one attempt at creating such a population of macroparticles using thousands of tiny metallic needles to create an artificial, radio-reflecting layer was actually successfully carried out. It is not clear what the differences between conducting or nonconducting droplets would be. Although the system is intended to be closed (the particles would be captured and recycled), the environmental impact of such a cloud if the particles were to escape is frightening considering the current state of affairs vis-a-vis space debris.

Although a concern for all three systems, the adequate measurement of the ambient and perturbed environment around and within a large volume will be potentially difficult and expensive. As local variations may be critical to an adequate understanding of the interaction of a

large volume with the environment, it will be necessary to make many measurements simultaneously in time throughout the perturbed volume. To date, such measurements have been virtually impossible due to the expense of the many types of instruments required, the massive amounts of data that need to be correlated, and the shear difficulty of deployment. No easy answer currently exists for this problem although proliferation of cheap, simple, probe systems is currently being investigated. It is, however, more than likely that an entirely new technology, one encompassing measurment and analysis techniques, will be required before an adequate understanding of the interactions of large volumes with the environment will be possible.

V. SUMMARY

Table 1 summarizes the findings of the Large Structures and Tethers Working Group. Briefly, the key plasma technology issues have been defined in terms of large one-, two-, and three-dimensional systems. The addition of each spatial dimension compounds the potential plasma issues that need to be considered for successful missions in the year 2001 and beyond. The most critical issues are: (1) how will large, extended structures be grounded to the plasma environment? (2) what effects does the magnetic field have on wake shape and EMI for large areas? (3) how do large volumetric structures/environments respond to the ambient plasmas and fields? and, finally, (4) large structures may, by their very size, seriously impact the natural plasma environment – a plasma issue little studied in the past.

Table 1. Summary of Key Plasma Interactions for Large Space Structures and Tethers (see text for discussion of issues).

Spatial character	Key plasma issues
Extended length	$(\bar{V} \times \bar{B}) \cdot \bar{L}$
	Plasma contact (grounding)
	Current loop closure for conducting tethers
Large area	Wake structure
	Magnetic field effects
	Electromagnetic noise turbulence
	Electrostatic drag
	Variable surface potentials
	Pondermotive forces and effects on system dynamics
Large volume	Effects of emitted fluids (gases and liquids)
	Macroparticle assemblies
	High-voltage breakdown
	Plasma heating in the ram
General	Simultaneous measurements in three dimensions
	Scaling laws with size, magnetic field, and particle environment

APPENDIX I.

Comments by

N. Stone

Marshall Spaceflight Center

The use of a tethered satellite system to place an instrument package into a low-altitude orbit to map out the plasma characteristics, currents, winds, and in the lower thermosphere (i.e., altitudes in the range of 100 km) will require several extensions of existing technological capabilities. The following are examples:

(1) The presently designed NASA TSS is capable of deploying a satellite to a maximum of 100 km on a nonconducting tether. The Space Station will orbit at altitudes in the range of 350 to 500 km. Therefore, (i) a deployment system must be developed that can handle up to 400 km of tether. (ii) The dynamics of tether, once established by the TSS-1 and TSS-2 missions, should be reassessed to include very long tethers of the required length. A modification to the control system may be required.

(2) Tether degradation should be studied in more detail (this will be more important for long-duration Space Station tethers than the 4- to 7- day TSS missions). This includes, for example, micrometeorite strikes and atomic oxygen erosion.

(3) Tether and tethered satellite thermal control will be a critical issue for altitudes below 125 km. At 90 to 100 km (the most interesting range because of the turbopause), heating will be a significant problem and active thermal control techniques (such as phase change materials) will be required.

(4) Satellite aerodynamics/plasmadynamics will also be important at 90 to 130 km altitudes. The shape of the satellite and the location of instruments will be critical.

(5) Tethered system dynamic noise and its possible interference with experiments as well as other Space Station activities (in particular, microgravity experiments) will be important. Avoidance and/or control of dynamic noise will require careful evaluation of the theory and of data obtained from the TSS-1 and TSS-2 missions

N87-20058

WORKING GROUP REPORT ON ADVANCED HIGH-VOLTAGE HIGH-POWER, AND ENERGY-STORAGE SPACE SYSTEMS

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I. INTRODUCTION

Space systems in the future will probably include high-voltage, high-power energy-storage and -production systems. Two such technologies are high-voltage ac and dc systems and high-power electrodynamic tethers. Here high-voltage systems are ones in which the voltage significantly exceeds one or more of the characteristic energies associated with the surrounding plasma or surfaces. Two of the characteristic energies are the electron temperature and the ionization potential of the neutral environment. An understanding of this synergistic interaction is crucial to optimizing the operation of these systems.

The working group identified several plasma interaction phenomena that will occur in the operation of these power systems (see Table 1). The Space environment will induce arcing and power leakage in these systems, which can be especially significant since they are high-power systems. The environment will also couple to the system through electromagnetic interference and high-energy radiation, which has associated with it all the well-known charging issues. In the other direction, these power systems will couple to the environment in many ways. These include induction of electromagnetic waves in the environment, sheath structures that may be detached, outgassing into the environment and the possibility of ionization of the outgassed products, and deposition of large-scale plasma clouds and currents in the vicinity of the power system. All of these things may lead to long-term modification of the space environment that will then affect how the environment modifies the system.

The working group felt that building an understanding of these critical interaction issues meant that several gaps in our knowledge had to be filled (see Table 2). Such gaps will be filled by creative use of predictive theory, modeling, and definitive experiments. It was felt that definitive experiments were hampered in two ways. First, the measurement technology for designing definitive experiments often does not exist. For example, it was felt that developing techniques (and appropriate hardware/software) for measuring distribution functions rapidly and in detail was critical for understanding in all areas of plasma interactions. Second, the engineering community needs to build an understanding of how to scale appropriately from ground-based to space-based experiments. Without such understanding, the value of ground-based experimental results is never clear.

The working group felt that certain aspects of dc power systems have become fairly well understood. Examples of these are current collection in quiescent plasmas and snap over effects. However, high-voltage dc and almost all ac phenomena are, at best, inadequately understood. In addition, there is major uncertainty in our knowledge of coupling between plasmas and large-scale current flows in space plasmas. These gaps in our knowledge will be addressed in the following paragraphs.

II. AC PLASMA INTERACTIONS

There is very little available knowledge about terminal properties, including current collection and impedance, of devices that can radiate large amplitude ac into the space-plasma environment. We therefore are unable to predict plasma coupling, plasma heating, plasma instabilities, plasma noise, plasma-wave generation and the effects of these interactions on communication systems, power systems, and on-board experiments. Time-varying sheaths induced by high-voltage ac systems will induce unknown effects in other systems nearby.

We therefore need to develop the ability to numerically simulate ac-electrode-plasma interactions. Large-scale space experiments also appear crucial. We need both of these in order to gain understanding and the ability to predict for design purposes. Otherwise, we will be unable to design any large-scale, large-amplitude system.

III. CURRENT COLLECTION IN TURBULENT MAGNETOPLASMAS

Our fundamental understanding of plasma-turbulence mechanisms, especially in strong magnetic fields, is deficient and therefore we are unable to evaluate, in advance, the degree of turbulence and therefore its effects on the coupling currents between spacecraft components and their surroundings.

We therefore cannot intelligently design time baselines for concurrent running of various kinds of active space experiments. We therefore need ground experiments followed by larger-scaled experiments in space, involving turbulence generated by active experiments. We also need experiments in which high voltage on spacecraft surfaces is produced in some way other than by beam emissions.

IV. HIGH-VOLTAGE DISCHARGING

We do not know how to reliably predict surface flashover, breakdown thresholds, and system impacts including discharge currents, total released charge, and resulting EMI effects, in anything except simple situations already tested. We do not understand the mechanisms involved in surface flashover, and our understanding of negative-potential arcing contains important deficiencies. This will endanger operations of power systems for the space station. Induced RF noise from discharges can also disrupt communications.

We therefore need a vigorous program of ground tests that will reveal the mechanisms governing all types of arc discharge and will elucidate methods of controlling these.

V. RAM/WAKE EFFECTS AT HIGH VOLTAGE

We have very little experience in trying to understand ram/wake effects at high voltages. We therefore are limited in our ability to make detailed predictions of effects of the near-wake plasma environment on operational systems. This will increasingly affect our ability to design proposed arrangements of system components to avoid harmful interactions as these become progressively more complicated.

We therefore need a vigorous program of theory and simulation, together with ground experiments in order to extend our existing knowledge of lower-voltage spacecraft wake phenomena to high-voltage situations that will arise as a result of planned space activities and system designs.

VI. PLASMA-PLASMA, PLASMA-SYSTEM, AND PLASMA-CONTACTOR INTERACTIONS

The coupling between two or more distinct plasmas has been identified as a science/technology issue pertinent to large high-voltage systems. Such plasmas may be intentionally generated, or appear as an undesirable contaminant. Our present level of understanding is not sufficient to accurately model the interaction as potentially dangerous to anticipated systems. For example, a contactor plasma, expected to ground a structure while coupling a large current to the ambient plasma, could develop instabilities that would open the circuit, disrupt the power system, and create unwanted exotic plasma effects. Existing theory and experiment, some borrowed from other contexts, can be utilized to design new experiments, theoretical studies, and simulations to directly address this issue.

VII. TETHERS

We do not know how large-scale current flows move through the ionosphere including what limits the magnitude of such currents and how substantially they perturb the exosphere.

This is an essential element in the production of power using electrodynamic tethers, and may have an important impact on any system with impressed voltages separated by large distances. "Large" here means large compared to sheath size and ion gyroradii so that nonlocal currents are driven in the plasma.

To address this issue we need to develop theories for ionospheric nonuniformities on a large scale, and for flows around large (several gyroradii) structures. Space-based experiments are critical. These should include large space experiments to examine current flows and STS-based experiments for testing closure. Remote measurements of flows should also be attempted, to trace the "circuit" or flow paths.

Finally the working group felt that all of this suggested work needs to be performed in concert with the technology development. We suggest that a system of guidelines be developed early to direct work. These guidelines will have to be somewhat device specific in that a power system such as a tether is not free to match low-voltage specifications.

In general though, such systems as a solar power array should have an upper voltage specified in advance so that theory and experiment can be developed with a specific goal in mind. For an "early" system such as the space station, this should be done as rapidly as possible for all development considerations. For later facilities, guidelines should allow for future growth within these systems rather than guaranteeing a "planned obsolescence."

Table 1. Plasma Issues

environment --> system	system --> environment
Arcing	EMI
V X B induced potentials	Sheaths
EMI	Ionization
	Grounding issues
	Plasma couplings
	Closure path
	Amount of current
	How big a region
	Disturbance of large regions of the ionosphere
	Long-term modification of the environment - heating, mass additions to the environment

Table 2. Gaps in Our Knowledge

All ac interactions with plasma
High voltage ac/dc interactions with plasmas
Coupling between plasmas
Large-scale current flows
Measurement technology

N87-20059

WORKING GROUP REPORT ON BEAM PLASMAS, ELECTRONIC PROPULSION, AND ACTIVE EXPERIMENTS USING BEAMS

J. M. Dawson, T. Eastman, S. Gabriel, J. Hawkins, J. Matossian, J. Raitt, G. Reeves, S. Sasaki, E. Szuszczewicz (Chair), and J. R. Winkler

I. OVERVIEW

THE JPl Workshop addressed a number of plasma issues that bear on advanced spaceborne technology for the years 2000 and beyond. Primary interest was on the permanently manned Space Station with a focus on identifying environmentally related issues requiring early clarification by spaceborne plasma experimentation.

Five Working Groups were convened, each with a charter to identify specific issues, their relative importance, associated gaps in existing knowledge, and requirements on theory and experiment necessary to advance our understanding. The "Beams" Working Group was specifically asked to focus on environmentally related threats that platform operations could have on the conduct and integrity of spaceborne beam experiments and vice versa. Considerations were to include particle beams and plumes. For purposes of definition it was agreed that the term "particle beams" described a directed flow of charged or neutral particles allowing single-particle trajectories to represent the characteristics of the beam and its propagation. On the other hand, the word "plume" was adopted to describe a multidimensional flow (or expansion) of a plasma or neutral gas cloud. Within the framework of these definitions, experiment categories included:

(1) Neutral- and charged-particle beam propagation, with considerations extending to high powers and currents.

(2) Evolution and dynamics of naturally occurring and man-made plasma and neutral gas clouds.

In both categories, scientific interest focused on interactions with the ambient geoplasma and the evolution of particle densities, energy distribution functions, waves, and fields.

II. A PERSPECTIVE ON TECHNOLOGY LEVELS

The Beams Working Group adopted a general perspective on the planning and development of future experiments to be conducted on large spaceborne platforms (as will be the case on the Space Station). That perspective can be stated as follows:

> The basic-plasma, geoplasma, and astrophysical-plasma communities can be strong supporters of the Space Station as a uniquely useful laboratory in space <u>if and only if</u> induced environmental effects of the primary platform and its subsystems are reduced to noninterference levels in the conduct of the scientific experiments, and <u>if and only if</u> support subsystems provide a substantially broadened capability in power, telemetry, operations, and information technologies than currently available on Shuttle and dedicated satellite missions.

With this perspective, initial concerns reviewed Level-1 technologies (Table 1), including: (1) the dynamics and control of large structures, (2) fluid management, (3) energy systems, (4) information technologies, (5) automation and robotics, and (6) in-space operations. Of all Level-1 technologies, energy systems and in-space operations received the most attention. It was generally agreed that current plans for 25 to 50 kW power levels as primary support on the Space Station would hinder more creative scientific advances in the era beyond the year 2000. One such example includes the possible use of positrons as unique probes of the magnetosphere (Dawson, 1986). Such an endeavor requires a large energy resource, with 10 to 20 GeV a nominal requirement for the production of a single positron. While the total number of positrons would be low, the volume of space to be probed would easily tax the planned Space Station power system–a not too unfamiliar situation in which technology would lag the scientific requirement.

Panel attention to "in-space operations" quickly moved to Level-2 concerns on the "local scientific climatology" (Table 1), defined as the sum total of all prevailing conditions that affect and/or contribute to the integrity and merit of the scientific mission in question. These concerns, detailed in Level-3 considerations, involve the availability of free-flying or tethered satellites, the naturally occurring and induced environments, and the platform adaptability to sensor requirements.

Free-flying satellites were viewed as an important asset that would allow multipoint measurements in space with guaranteed observational perspectives free from possible contamination by the presence of the Space Station itself. Similar assets were attributed to tethered subsatellites, with applications including those geared to the development of an "Ionospheric Weather Station" (Szuszczewicz, 1986) and innovative approaches to power generation and propulsion (Purvis, 1986; Hastings, 1986; and Taylor et al., 1986).

A number of special issues were identified within the context of tether technology and associated applications. These included: (1) the very difficult problem of tethering to large separations (hundreds of kms), (2) extraordinarily high $\vec{V} \times \vec{B}$ potentials (Szuszczewicz, 1986; and Hastings, 1986), (3) requirements for new "in situ" measurement capabilities, (4) the necessity for large current contact with the ambient ionosphere and control of subsatellite potentials through the use of plasma contactors (Szuszczewicz, 1986; and Hastings, 1986); and (5) waves generated by large spacecraft configurations (Hastings, 1986; and Barnett, 1986). These all represented issues of special concern to the execution of beam and beam-related experiments in space (Winkler, 1986; Raitt, 1986; Szuszczewicz, 1986; and Murphy, 1986).

III. GENERIC ISSUES AND ENVIRONMENTAL IMPACTS

In terms of environmental influences, it was determined that the following generic categories could provide an encompassing description:

(1) Particle effluents.

(2) Electric and magnetic field emissions.

(3) Uncontrolled surface and body effects, including surface potentials, structure currents, and wakes.

Within the context of the working group charter, environmental issues were identified with specific concerns for the impact on the execution of a planned experiment, and alternatively, the potential threat of experiment execution on platform subsystems. Those results are summarized in Tables 2 and 3.

In keeping with the general position advanced in the opening of this summary report, it was agreed that unless substantial care was taken with regard to platform environmental controls many experiments would not meet full scientific accommodation on the Space Station. Gaseous effluents, power systems, and structures and surfaces of the Space Station and tethered subsatellites could have a degrading effect on the performance of beam and plume experiments. As Table 2 delineates, these environmental issues can impact not only the physics of the process under study but the integrity of the optical and electrical sensors being used for diagnostics in the investigation.

It was determined that environmental impacts could work both ways and that there exists the possibility that the execution of a number of experiments could lead to deterioration of several of the on-board subsystems. Table 3 delineates relevant interactions, not the least of which includes EMI, surface damage by energetic particle impact, and degradation of optical sensors used for spacecraft positioning and guidance.

IV. OVERALL RECOMMENDATIONS

Several issues in Tables 2 and 3 presented themselves as having serious gaps in our current understanding, giving rise to concern for concentrated efforts to relieve the deficiencies in the near- to mid-term. These issues include:

(1) The generation of waves and plasmas by large structures, plumes, and beams.

(2) Current systems in vehicle-plasma interactions, including $\vec{V} \times \vec{B}$ effects, surface and body currents, and vehicle charging.

(3) Effectiveness of plasma contactor technology to satisfy safety concerns relevant to vehicle charging and to perform the safety function on a noninterference basis with planned scientific programs.

An immediate and aggressive program of investigation is recommended, with synergistic approaches of theory, laboratory simulation, and spaceborne experimentation. Initial efforts should focus on large structures, their wave fields, differential potential and current systems, and adaptability to control with developing plasma contactor technology. In parallel, there should be a continuing development of strong scientific requirements for control over the generic areas of environmental impact so that negative influences can be eliminated, mitigated, or controlled. Where attitude control gases are viewed to have degrading effects, alternate technologies should be pursued – perhaps in some cases requiring a substantial research and development initiative. Similar approaches should be adopted with respect to the application of plasma contactors. While protection against high charging levels is one issue in contactor development, the possibilities for distortions of the natural particle and wave fields are abundant (Szuszczewicz, 1986). There should be serious concern with the latter aspect of contactor development and alternate technologies should be explored or plasma contactor noise-reduction-techniques developed. Overall the time

frame to the year 2000 is short, and nearsightedness on the approach to the "scientific climatology"of the Space Station could render it as a relatively unattractive platform for future scientific endeavors.

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Table 1. Hierarchy of Space Station Plasma Technology Issues

Level 1	
• Dynamics and control of large structures	• Information systems
• Fluid management	• Automation and robotics
• Energy systems and thermal management	• In-space operations

Level 2	
• Advanced life-support systems	• Propulsion
• Orbital transfer vehicles	• Maintenance and repair
• Local scientific climatology	

Level 3: Local scientific climatology
Prevailing conditions affecting and/or contributing to the scientific mission
• Availability of free-flying or tethered subsatellites
• The natural, induced, and controlled space environments
• Platform adaptability to sensor requirements

Table 2. Environmental Issues Resulting from Subsystem and Platform Operations With Potential Impact on Beam Experiments

Subsystems and platform operations (cause)	Scientific program execution (effects)
Gaseous effluents	Lifetime and evolution of processes under study (e.g., chemistry and dynamics of expanding plasmas)
• Controlled releases (e.g., thrusters, waste ejection, and thermal subsystems)	Degradation of optical sensors
• Uncontrolled sources (e.g., virtual leaks, real leaks, and outgassing)	Dielectric material deposition on critical electrical surfaces
	Generation of perturbing plasmas and waves
	Distortion of ionospheric currents to the platform and triggering of anomalous charging/discharging events
Power	Uncontrolled fields (electric and magnetic, dc and ac) and currents
• Solar arrays	
• Ac and pulsed-power systems	
• Ground loops	
• Power levels	Duty cycle of high-power beam experiments
Structures and surfaces	Large differential potentials (e.g., $\vec{V} \times \vec{B}$)
• Large structures	Uncontrolled and unknown potentials
• Tethered subsatellites	Wakes and resulting wave fields

Table 3. Environmental Issues Resulting from the Conduct of Beam Experiments With Potential Impact on Subsystem and Platform Performance

Scientific program execution (cause)	Program performance (effects)
Particle beam experiments	EMI
	Surface damage/erosion by energetic particle impact
	Spacecraft charging
	Potential interference with optical/attitude sensors
	Possible interruptions of C^3 systems
	Explosive release of stored energy
Heavy-particle "plumes"	Surface deposition and contamination
• Plasma injection	• Solar arrays
• Neutral gas cloud releases	• Optical surfaces
	• Thermal surfaces
	Possible interruptions of C^3 systems
	Safety of high-pressure systems

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WORKING GROUP 5: MEASUREMENTS TECHNOLOGY AND ACTIVE EXPERIMENTS

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TECHNOLOGY ISSUES IDENTIFIED BY WORKING GROUP 5:

(1) New instruments are needed to upgrade our ability to measure plasma properties in space.

(2) Facilities should be developed for conducting a broad range of plasma experiments in space.

(3) Our ability to predict plasma weather within magnetospheres should be improved and a capability to modify plasma weather developed.

(4) Methods of control of plasma spacecraft and spacecraft plasma interference should be upgraded.

(5) The Space Station laboratory facilities should be designed with attention to problems of flexibility to allow for future growth.

I. MEASUREMENTS OF SPACE PLASMAS

The successful operation of future space systems will require a detailed knowledge of interactions with the plasma environment and the ability to predict its dynamic variations (plasma weather). This will require advances in the measurement of local and remote plasma properties as well as an understanding of the basic physical processes.

In order to achieve these goals, several areas of plasma-measurement technology will need to be advanced to study regions in which measurements have not been previously made and to enhance the capability to measure certain critical items.

One area requiring development is the measurement of plasma properties at low-altitudes (~ 100 km) where the absence of platforms has limited previous data. Several issues need to be resolved regarding the ability to measure low-altitude properties without unduly disturbing the medium.

Another area requiring development is the remote-sensing capability of spaceborne transmitters, for instance as applied to plasmaspheric sounding from the region of geosynchronous orbit. Several areas of measurement will need to be improved in order to develop models of the sources, transport, energization, and loss processes involved in the transport of plasmas throughout the magnetosphere.

A particularly important parameter for which new measurement technology is needed is electric current.

Electric currents in space play a crucial role for plasma processes and for the whole dynamics of the magnetosphere, hence also for the plasma environment of spacecraft and the variations of this environment ("Space Weather"). However, except for low-to medium-altitude Birkeland

currents, which can reasonably well be inferred from magnetometer measurements, very little is known about the currents in the magnetosphere or how they are driven. The reason is that present technology offers no way of directly measuring currents.

An experimental technique for directly measuring electric currents is very much needed.

A strong effort to develop such a technique should be undertaken. A possibility that has been suggested is a technique using the Faraday rotation in optical fibres. This possibility should be investigated in depth.

II. CAPABILITY TO CONDUCT A BROAD RANGE OF PLASMA EXPERIMENTS IN SPACE

The Plasma Processes Laboratory is being defined as a Space Station facility capable of supporting a very broad range of advanced plasma-physics experiments. These experiments range from the creation of and experimentation on dusty plasmas in a microgravity environment, to the creation and study of artificially generated magnetospheres and formation and maintainance of large plasma toroids.

To perform these classes of advanced experiments, a number of enabling technologies need to be addressed and pursued over the next 10 to 15 years.

A. Power and Thermal Control Systems

Many of the classes of experiments being considered will require large amounts of energy to create the necessary energetic system. Thus, studies must be undertaken to provide power (and associated cooling) in the megawatt regime.

B. Lightweight Materials and Support Structures

Since many of the energetic plasma experiments will be contained by magnetic fields, a technology is needed to develop light weight materials and support systems to create and maintain these fields.

C. Techniques for the Development of Gas and Dust Sources and Microgravity Control

Experiments will be performed on dusty plasmas and suspended gases and fluids so controllable sources will be needed. Also since these classes of experiments will be adversely impacted by gravitational acceleration, techniques to maintain a microgravity environment will be required.

D. Commercial Electronic Interfaces

Costs to experimenters can be minimized if commercial electronic interfaces are used rather than the custom interfaces usually used on spacecraft. As an example, many of the plasma-physics experiments will be extensions of laboratory plasma physics on earth, so that the effective transitioning of these experiments requires that the commercial equipment used in earth-based labs be usable on Space Station. This will require the use of commercial interfaces.

III. PREDICTION AND MODIFICATION OF PLASMA WEATHER

The group identified the ability to predict and modify the plasma weather within magnetospheres as a future technology requiring new measurement technologies and the performance of active experiments.

There are several important gaps in the development of this technology; we do not now possess a reliable magnetospheric prediction capability and we are not yet able to induce magnetospheric events.

To upgrade the reliability of prediction, the geo-effective solar terrestrial input to the magnetosphere must be predicted and the response of the magnetosphere to that input modeled. This will allow us to describe the natural environment and to make decisions as to what parameters are to be modified and how that can be accomplished.

Several problems in measurement technology that must be faced in order to produce the required environmental description arose during our discussion and were described in Sections I and II.

Numerical models of the magnetosphere need also to be produced. It has been already demostrated that important advances in modeling can be made in the next 5 to 10 years using currently available computer technology but it was felt that the physical system was so complex that by 2001 new computer technology would be required. In addition, the ability to handle large coordinated data sets must be further developed. It was expected that both of these requirements would be met without magnetospheric modification acting as a driver for the technology.

To induce magnetospheric events, a technology is required to change the density, energy distribution, composition, and/or flow velocities of the plasma as well as to induce instabilities in the magnetosphere (i.e. control or modify the timing of substorm onsets). The following technologies need further development to facilitate modification of the magnetosphere.

(1) Injection of high levels of wave power (for example by using very long antennas and developing techniques to deploy them in directions other than the zenith and the nadir) and producing power in a variety of new wavelengths.

(2) Further development of positive-ion sources.

(3) Development of an Alfven maser (a proposed method for dumping electrons and protons from the radiation belts by producing a masing effect in a magnetospheric flux tube. See Burke et al., this conference, and references therein.)

IV. AVOIDANCE OF PLASMA INTERFERENCE ON SPACECRAFT SYSTEMS AND SPACECRAFT-SYSTEMS INTERFERENCE ON PLASMA EXPERIMENTS

The presence of the environmental plasma can cause interference with spacecraft systems and operations (e.g., charging, electrostatic discharges (ESD), energetic particle penetration and memory upsets, and optical surface degradation). Conversely, such phenomena as spacecraft electromagnetic noise, gaseous efflux, and particulate emission can interfere with plasma measurements and plasma experiments.

Present technology needs to be improved and new technology developed to deal with these problems.

Gaps in our present knowledge include:

(1) How and where electrostatic discharges occur.

(2) How to actively control charging at the spacecraft.

(3) How to reduce spacecraft-generated EM noise to a level at which it does not interfere with plasma experiments.

(4) How to reduce gaseous and particulate emission from manned spacecraft to a level that will not affect plasma experiments.

We need:

(1) A research program to investigate plasma effects on spacecraft, including experimental studies, additional analyses of existing in situ data and the development of a theoretical model.

(2) Development of a technology for the active control of charging on a spacecraft.

(3) Development of an improved method for reducing and/or shielding spacecraft-generated EM noise.

(4) Development of a technology for reducing and controlling the emission of gasses and particulates from manned spacecraft.

V. DESIGN AND DEVELOP SPACE STATION SYSTEMS FOR GROWTH

Space systems that are expected to grow, such as the Manned Space Station, must be designed and built to accommodate growth. To carry out plasma processes experiments, very high power levels will be required and provision for these technological advances must be made in initial operating capability designs.

NASA, being a project-oriented agency, typically plans projects for fixed costs. However, for systems such as the Manned Space Station that are intended to grow, the initial operating capability must be flexible enough to allow for future requirements. For example, initially the Manned Space Station will have a 25-kW power capability. In future missions powers above the megawatt range are needed and planned. This means that the initial design must include a power distribution system capable of distributing megawatts of power. The alternative, to add wiring and power distribution equipment in parallel with the initial equipment and wiring, would be more expensive in the long run.

The statements of work for the Manned Space Station developers must include provision for growth and evolution of all systems even though in some cases the initial costs will be higher than if the need for growth and evolution were neglected.

INVITED PAPERS

N87-20061

NASA OAST AND ITS ROLE IN SPACE TECHNOLOGY DEVELOPMENT

by

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INTRODUCTION

I would like to welcome the participants to the "Space Technology Plasma Issues in 2001" conference here at JPL. I understand that you are all experts in this field and have contributed many years of effort to the subject of space plasmas. It is therefore with real excitement and pleasure that I open this conference and look forward to your ideas on how we should carry out in-space plasma experiments. In my remarks today, I would like to introduce you to several new programs, of which this conference is an integral part, that OAST has begun to support your efforts in space research and technology. First, however, I want to briefly discuss the four key issues that currently are consuming NASA's energies and should be of great concern to you, the participants in this conference. NASA is placing its emphasis in space on:

1. reconstituting the Shuttle capability
2. maintaining the Space Station momentum
3. resolving the current science mission backlog
4. rebuilding the technology base

First, of course, NASA is seeking to reconstitute the Shuttle launch capability. It is Dr. Fletcher's number one priority. The second one is maintaining the program momentum for the Space Station. All of us are concerned about what is happening with the Space Station program that the President has directed: When is it going to get started? Is it in trouble? Is there sufficient money for it? I would like to state here that I think that the problems raised by Congress with the Space Station are being disposed of nicely and that we will see a very strong program start this coming year. Thirdly, there is the tremendous impact to the science missions and payloads that the Shuttle problem has given rise to. NASA Headquarters is trying to determine how to work around the delays, how to reschedule the missions, and how to protect the payloads that have already been built and are sitting in storage.

Before turning to the fourth issue, that of rebuilding the technology base and the technology capability of the agency, I would like to speak briefly about the Office of Aeronautics and Space Technology (OAST). OAST has the responsibility for developing the advanced space technologies that will enable or enhance future national missions. We are working towards developing a space infrastructure, the cornerstone of which is the Space Station. Much of the technology activity in OAST and much of the funds are going towards technologies that would support this infrastructure. By infrastructure, I mean systems ranging from launch vehicles, propulsion

systems, and structures for launch vehicles to advanced systems such as large, space-station types of structures, planetary missions, geoplatforms, lunar bases, and, in the distant future, long-duration manned missions to Mars.

As a planning guide, we in OAST use a mission chart that identifies driver missions (Figure 1). In developing this chart, driver missions are first identified. These are coordinated with as many people as possible to insure that our perspective of the future and the time frame are reasonable. Once everyone agrees that these missions are probably what will be happening 10, 15, or 20 years in the future, we can with some confidence begin to invest money in key technologies--money that is currently very scarce. The mission drivers are used to guide, to provide scope, and to give direction to OAST's research and technology activities. As shown in Figure 1, technologies that will enable the next-generation space-transportation systems are being worked on. Likewise, both next-generation spacecraft and large spacecraft systems technologies are being studied. These three categories are being used to provide a vertical cut to our program structure.

Now I would like to relate a sad story. Many of you here were doing space research in the 1960's. As shown in Figure 2, the funding in space research and technology in constant year dollars was well in excess of $900,000,000 a year from 1965 to 1967. That amount has eroded to a very flat level of about $200,000,000 a year--actually less--at present. The level has been about $175,000,000 a year for the last, almost 10 years. That investment has had to support the Space Transportation System (Shuttle) Program, the Space Station Program, and all the other activities that we're trying to do. That $200,000,000 doesn't really spread out very deeply. As demonstrated by the profile in Figure 2, the country is really suffering with respect to the amount of money going into research and technology for the space program.

Newspaper articles, the reports of blue-ribbon panels appointed by the President, and many other sources have all indicated that the country's space technology base is really deficient. NASA is living off the investments of the 1960's. The investment in advancing the state of technology to any great level has not been replenished. Technology no longer leads with solutions, it chases problems. Our expectations exceed what current technology can deliver. If the profile shown in Figure 2 is extrapolated to industry, it is not hard to understand why people are saying that the U.S. leadership in space is being challenged. NASA indeed recognized that its own expertise is on the decline--we are losing people and it is becoming more and more difficult to attract bright young graduates from the universities. We have a serious problem!

On that note I now want to introduce a new initiative that OAST has taken to the NASA Administrator. It is called the Civil Space Technology Initiative or CSTI--like SDI! It is OAST's response to the Administrator for a major augmentation within NASA for research and technology dollars. The actual dollar amounts are currently being reviewed by the Office of Management and Budget and will be released in the next six months. We are optimistic that the initiative will be successful and that it will provide the mechanism to reinvigorate the activities in research and technology for space. We intend to develop a focused thrust to remedy gaps in the technology base in order to enable high-priority programs. We plan to enable low-cost access to space and key NASA missions through developments in:

- launch-vehicle propulsion
- booster technology
- space-based propulsion
- launch-system autonomy

- aerobraking technology
- high capacity power
- spacecraft power
- automation and robotics
- large structures and control
- sensor device technology
- high data-rate systems

Ultimately these are the means to an end. This can be summarized in terms of the CSTI logic: restore agency technical strength; develop focused technology demonstrations; meet priority needs of NASA and National Security; rebuild the image, morale, and skills of the community; and make the program affordable. This last point, affordability, is very important and, as I will show, can be achieved. As illustrated by the National Commission on Space and its mandate to the nation and NASA to triple the investment in research and technology, many other groups have taken stands similar to ours.

As to affordability, OAST believes that the country can in fact invest very heavily in research and technology without having to make any commitments at this time to a major new program. This is an important point, since if each new program costs a billion dollars and there are 5 or 6 programs, then there is a 5- or 6-billion dollar a year commitment required. In contrast, the investment in research and technology can be on the order of 2- to 3-hundred-million dollars a year added to what we are currently spending. That is a very affordable investment without the necessity of commiting to the big, expensive programs of the past. It will permit us to make those kinds of big decisions farther in the future when the technology risk is much lower. This investment strategy will make this option viable. I think it is going to be a very exciting time for NASA beginning in FY88 with this infusion of money for research and technology.

The initial focus of the CSTI program will be in six areas:

1. Propulsion
   - Earth-to-orbit
   - Orbit transfer
   - Booster technology
2. Vehicle
   - Aeroassist flight experiment
3. Information systems
   - Science sensor technology
   - Data: High rate/capacity
4. Large structure and control
   - Control of flexible structures
   - Precision segmented reflectors
5. Power
   - High capacity
   - Spacecraft
6. Automation and robotics
   - Robotics
   - Autonomous systems

There are several areas in this list that are applicable to plasma interactions and, when we get approval, I am sure that the members of this group will be important participants in it.

I would now like to return to the subject of the conference--plasma interactions and in-space experiments. NASA has been conducting in-space experiments since 1960. Starting with 1960, we can construct an interesting profile of the type of experiments that have gone into orbit. In the earliest days, the experiments were basically associated with the programs and supported them--for example, the Gemini and Apollo programs. Since that time there has been a dip. More recently,

with the Shuttle, there has been a tremendous resurgence of activity. The Shuttle is a facility that lends itself very nicely to doing things in space and in-space experimentation has grown accordingly. Now NASA is in a temporary stand-down. Even so, with the experience gathered since 1960 and on the Shuttle, we feel that we have demonstrated the feasibility of doing in-space experimentation on a routine basis. For the first time, the space environment has become an extension of ground-based activities. Now when it's necessary to go into space to do something, it is feasible, it is affordable, and it is becoming a significant new area for future opportunities.

As an example of in-space experiments applicable to future programs, consider the construction by astronauts of a truss assembly in the Shuttle bay in December of 1985. The truss is a baseline concept for the Space Station. It was this in-space experiment that was the final proof of the concept. Even more exciting experiments are planned in this area over the next 3 to 5 years--one is the further study of the control of large flexible structures in space. There are, in fact, three succeeding experiments, each becoming more and more complex. They start with a single beam and move on to two-body and then multi-body configurations. Similarly, OAST plans an aeroassist experiment for the Orbiter. A re-entry shield will be flown in and out of the Earth's upper atmosphere to evaluate maneuvering and aerobreaking concepts similar to those planned for future planetary missions.

The Space Station is being designed to be a facility. It will be a facility in the sense that it is intended to be actively used for research. That is, it is intended to satisfy the needs of the science community, and the technology community and to take advantage of commercial opportunities. The Space Station will act as a cornerstone, as a node, in the infrastructure of our space system. It will help us to get to the outer planets, perhaps establish a base on the moon, and will be a facility for performing numerous in-space operational activities.

Today we are at a crossroads. We have demonstrated the feasibility of doing things in space. There is an emerging, vocal user's community made up of many different interest groups and organizations. In turn, user needs are being reflected in the design of future space facilities which are being developed as national resources. They present unique opportunities to do things in space and answer many critical questions. In particular we find an exponentially expanding program driven by the convergence of:

USER NEEDS:

- Research in:
  - Materials
  - Fluids
  - Devices
  - Structures, Controls
- Demonstration
  - Proof of concept
  - Engineering demonstration
  - Flight qualification

SPACE FACILITIES:

- Shuttle
  - Payload Bay
  - Mid-deck
  - Cannisters
  - Hitchhikers
- Space Station
  - Internal payloads
  - Externally mounted
  - Technology Laboratory Module
  - Platform based

These two efforts--user needs and space facilities--are coming together in a coherent program.

For the last year I have trying to build a program for in-space experimentation within OAST that will be accepted as a real, viable element of the space program. There is no doubt that as new technologies are going to be needed as the space infrastructure grows, one of the best ways to advance technology and transfer that technology to applications is to either conduct the experiment in space and/or have a demonstration in space. This allows the user to gain confidence that the technology does in fact work and that he can baseline his space system design. As part of the planning for this effort, we have developed seven theme areas: energy systems, space structures, automation and robotics, fluid management, information systems, in-space operations, and, the subject of this conference, space environmental effects.

To begin the study, a major workshop was carried out in Williamsburg, Virginia in October, 1985. Each of these theme areas was addressed in detail by the 400 attendees. The attendees represented a cross-section of civil service, industry, university, and DoD space workers. The major conclusion of the conference was that there are significant desires to do experiments in space that advance the seven research and technology areas just listed. The seven themes were determined to be valid planning mechanisms. This year we are sponsoring mini-workshops or symposiums in many of the the theme areas. Fluids, large structures, materials, and, here, plasma interactions are currently being reviewed. Thus many activities orchestrated under a common program umbrella are starting to happen. We can aggregate all these and build a case for developing an in-space experiment program. Thus we are establishing OAST as the national focal point for in-space research and technology. We are coordinating the user community requirements and plans through workshops and symposia.

We have built a lot of interest over the last year in this program. One of the pitfalls we have encountered, however, is that we may be building interest too fast and with it, false expectations. Certainly, with the Shuttle problem and not knowing how much capacity will be available over the next 5 years in terms of Shuttle manifesting, it is very easy to become trapped. We have, however, taken positive steps to stimulate cooperative ventures through a new program--the Outreach Program. In October 1985, at the Williamsburg Conference, Dr. Ray Colladay, my boss, stated to the conferees at the meeting:

"I'm willing to put up money. I'm willing to challenge you...I want to challenge you, and I'm willing to put up $10 million a year of my money, and I want you to match it. I want you to not necessarily match the money, but match resources. I want you to come back to me and tell me what you want to do in space and I will make my money and my resources available to you. Together we can fly the type of experiments that you in industry or the academic community want to do in space."

The intent of Dr. Colladay's remarks is to build advocacy for in-space experiments and build a program that would lead to maximum utilization of the Space Station when it becomes an operational entity. As a first step in the Industry/University Experiments Program or "Outreach" (as separate from the CSTI), a CBD announcement was released on June 30, 1986 and an RFP was released on August 15, 1986. The objective is to provide incentives to industry to better utilize the technology development potential of space. The approach is to: 1) select experiments of mutual benefit to industry and NASA; 2) jointly develop, program, and fund appropriate experiments; and 3) provide unique facilities (Shuttle or Space Station). There are two classes of ventures: those for which the concept has been developed and, perhaps, for which hardware is ready to go. In this case, OAST will provide funds for integration and a free flight. In the second case, the concept may be excellent, but it may have not been developed very far. In that case,

OAST will provide money, perhaps $100-$200 thousand per concept to allow further definition. In 1 to 2 years the concept will be recompeted to see if it should be taken to the hardware stage.

In terms of funding, in FY86, OAST has committed only about $32 million a year to flight experiments. It is currently projected that when the Space Station becomes operational, that $30 million will grow to $100 million. It may in fact grow to more but the baseline for my program is currently $100 million. This growth curve is shown in Figure 3 for the Outreach Program. With the combined efforts of universities and industries to match this level, the program should easily become a $200-million-a-year program by 1995. The potential for growth is even higher if the military in-space program is included. The nation could easily have a substantial half-billion dollar a year program in in-space technology. With this level of funding, there will be many opportunities to address such areas as plasma interactions. The potential is there!

This conference will be important in influencing our choices in this program. When we begin talking about Space-Station size facilities such as large deployable reflectors or even the Space Station itself, plasma interactions will play a key role in their performance. We have, for example, no real understanding of what effects plasma interactions will have on even such basic issues as contamination or safety. These issues will have to be addressed. The opportunity is here because NASA is going to have a Space Station and things have reached the point where such issues need to be addressed. There is no better group than those of you here today to identify the key plasma issues and to lay out a program that says "these issues have to be addressed over the next 10 years and these are the experiments that will answer those questions." The product of this conference is intended to support an investment of real dollars in a program in plasma interactions. The program may not be the size that you ask for but it will be the beginning of what we hope will be a long-term effort to answer at least some of the key questions in plasma interactions!

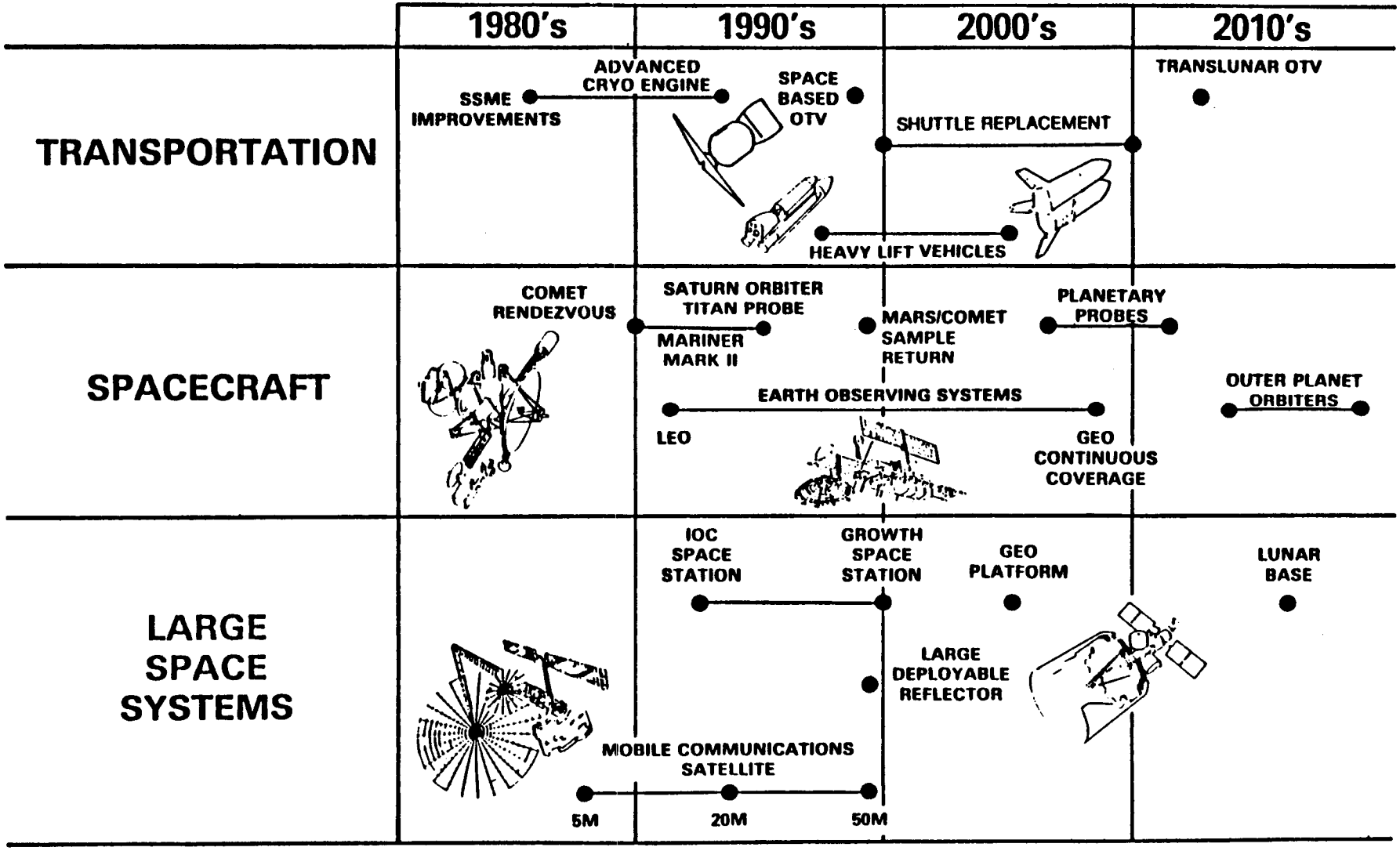

Fig. 1. Program Focus on Driver Missions

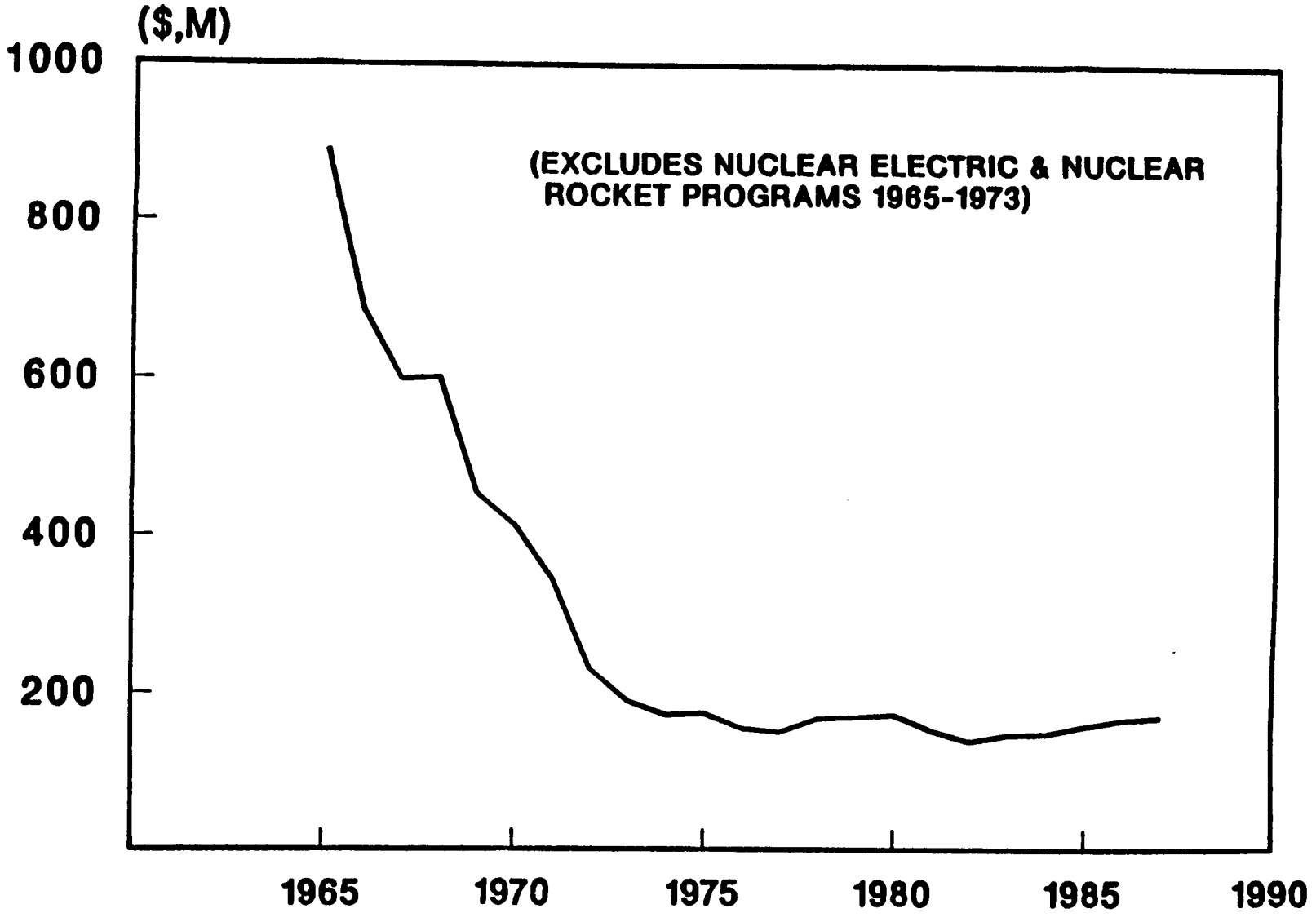

Fig. 2. Space Research and Technology Funding Trend (Constant FY 87 Dollars)

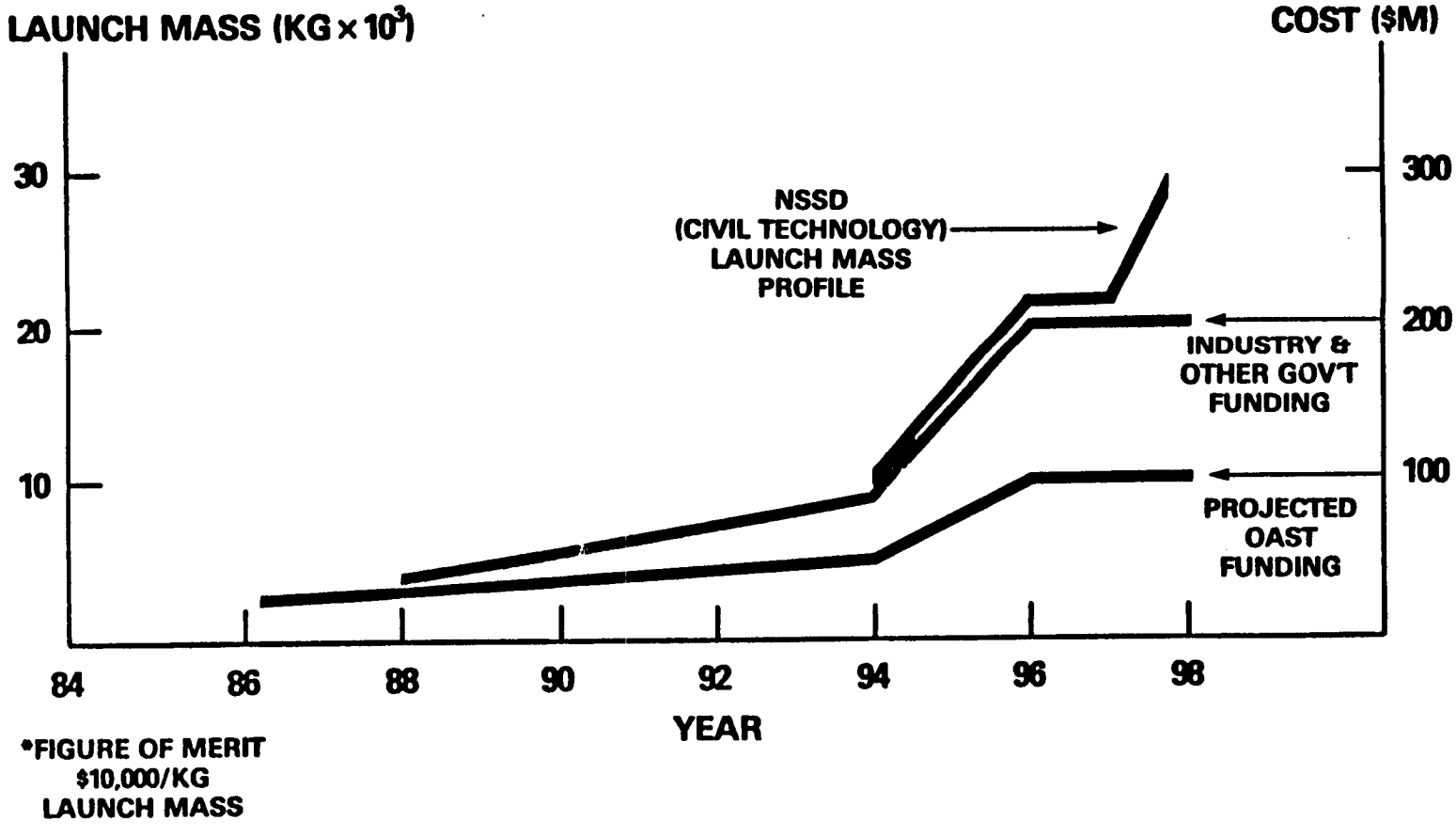

Fig. 3. In-Space Experiment Program Potentials

N87-20062

THE EARTH'S MAGNETOSPHERE AS A SAMPLE OF THE PLASMA UNIVERSE

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ABSTRACT

Plasma processes in the Earth's neighbourhood determine the environmental conditions under which space-based equipment for science or technology must operate. These processes are peculiar to a state of matter that is rare on Earth but dominates the universe as a whole. The physical, and especially the electrodynamic, properties of this state of matter is still far from well understood. By fortunate circumstances, the magnetosphere-ionosphere system of the Earth provides a rich sample of widely different plasma populations, and, even more importantly, it is the site of a remarkable variety of plasma processes. In different combinations such processes must be important throughout the universe, which is overwhelmingly dominated by matter in the plasma state. Therefore, observations and experiments in the near-Earth plasma serve a multitude of purposes. They will not only (1) clarify the dynamics of our space environment but also (2) widen our understanding of matter, (3) form a basis for interpretating remote observations of astrophysical objects, thereby even (4) help to reconstruct events that led to the evolution of our solar system. Last but not least they will (5) provide know-how required for adapting space-based technology to the plasma environment. Such observations and experiments will require a close mutual interplay between science and technology.

1. INTRODUCTION

Before scientific instruments had access to space the physical picture of space used to be a very simple one. It was based on the limited information carried by the small part of the electromagnetic spectrum that can reach the Earth's surface through the obscuring blanket of the atmosphere.

This changed greatly after access to Earth orbit allowed the previously inaccessible infrared, ultraviolet, X-ray and gamma-ray wavelength bands to be used for remote sensing of distant cosmic objects.

In the new wavelengths, cosmic objects often appear very different. By an analogy introduced by Hannes Alfvén, what was revealed is as different from our visual picture of the universe as an X-ray picture of a man's body is different from a visual light photo of it - and correspondingly more revealing: while "the visual picture is literally superficial ... the X-ray picture ... shows the skeleton and intestines and gives a better understanding of how his body works".

What the new picture of our universe reveals is, among other things, that not only in terms of the dominating state of matter, but also in terms of physical processes, our universe is a <u>plasma universe</u> (Alfvén, 1986a). This being the case, the results of <u>in situ</u> observations in

near-Earth space plasma take on a new significance as an indispensible complement to remote observations.

Since at this workshop we are going to look decades ahead, let us start by briefly recalling how the past couple of decades changed our concept of space surrounding the Earth. The pre-space-age concept of space was essentially one of a structureless void. Once scientific instruments could make direct measurements in space, the surprises started coming. The Störmer forbidden regions, rather than being empty, were copiously populated so as to form radiation belts. The geomagnetic field, rather than asymptotically approaching a dipole, terminated abruptly at the sunward limit of what we now call the magnetosphere. This so-called Cahill discontinuity, later identified as the sunward magnetopause, was the first and unexpected example of a sharp boundary separating the previously unstructured continuum of space into physically different regions. The early exploration of the magnetosphere was curtailed not only by understandable prejudice - e. g. nobody's instrument looked downward from satellite orbit to detect upstreaming ions coming from the ionosphere - but also by the state of the art in detector technology. This favoured measuring fluxes of relatively energetic particles over e. g. measuring medium and low energy plasmas. Gradually, the complexity of the magnetosphere grew, until in the late seventies all the major large-scale plasma regions were known.

However, even after this "modern" picture of the space environment, with most of the now known plasma regions, had been established, the origin of the magnetospheric plasma was still largely misconceived. Thus, until only a few years ago it was presumed as a matter of course that the plasma populating the magnetosphere was a (somewhat contaminated) hydrogen plasma from the sun. We now know that a major - and at times dominating - constituent is oxygen originating in the Earth's own atmosphere. (At the most recent solar terrestrial physics symposium a few months ago it was questioned whether there is any major contribution to magnetospheric plasma other than the terrestrial one (Chappell, 1986).)

The fact that such a misconception of the Earth's own close environment could prevail even after hundreds of satellites had circled the Earth, should inspire caution in considering the composition and properties of other invisible cosmic objects, whether they be stellar interiors, interstellar plasma, pulsar magnetospheres or intergalactic cosmic rays.

Similarly, any of the new insights into the physics of matter in the plasma state, which have been or will be gained in the Earth's magnetosphere, must be essential also for interpreting in correct physical terms the remote sensing results of astrophysical objects, visible and invisible, that can never be studied in situ. For example, one of the outstanding characteristics of cosmical plasmas is their ability to efficiently energize charged particles. Many kinds of particle energization do take place in the near Earth plasmas, where the mechanisms responsible can be studied in detail, and theories can be confronted with decisive tests. This has already given much insight into these mechanisms, but much still remains to be clarified. Based on the resulting understanding of how space plasmas really behave, one may with some confidence interpret also remotely observed manifestations of plasma processes in astrophysical plasmas. In fact, lessons learned in the Earth's magnetosphere must give important clues not only to the astrophysics of our contemporary universe, but also to events in the past, such as the evolution of our own solar

system, which undoubtedly took place in a plasma environment.

It has also become clear that the near Earth space environment is one that puts severe requirements on scientific and technical equipment in Earth orbit. To meet these requirements it is, again, important to understand the complex plasma processes which control this environment but which are, themselves, still far from well understood.

The reasons why the ionosphere-magnetosphere system is so useful as a potential source of knowledge is briefly discussed in Section 2. Taking full advantage of this system as a potential source of knowledge requires an improved understanding of the system itself beyond what has so far been achieved. This, in turn, requires observations that have not yet been performed to a sufficient accuracy or a sufficient extent - or at all. In particular a better knowledge is needed of the electric currents and electric fields in the magnetosphere (Sections 3-4). The achievement of such observations also requires technological developments. Closely related to the electric fields and currents are the mechanisms of release of magnetic energy and of chemical separation (Sections 5-6). Some processes essential to the plasma universe, which do not take place spontaneously in the near-Earth plasma, can be reproduced there by active experiments. An example of this is discussed in Section 7. It is concluded (Section 8) that in situ observations and experimentation in the Earth's own magnetosphere should be an essential complement to remote sensing of distant objects.

2. THE MAGNETOSPHERE - IONOSPHERE SYSTEM

The usefulness of the Earth's magnetosphere-ionosphere system as a source of understanding of cosmical plasmas is enhanced by the fact that it contains a rich variety of plasma populations with densities ranging from more than 10^{12} m^{-3} to less than 10^4 m^{-3} and (equivalent) temperatures from about 10^3 K to more than 10^7 K. However, even more importantly, this neighbourhood cosmical plasma is also the site of numerous and complex plasma physical processes.

The basic reason why the near Earth plasmas are so active in terms of plasma physical processes is the coupling that the geomagnetic field imposes between the hot thin magnetospheric plasma, which is dynamically coupled to the solar wind, and the cool, dense ionospheric plasma, which is tied by friction to the Earth.

Primarily, this coupling causes an exchange of momentum and of energy between the two regions. This exchange is executed through electric currents that flow between them - the Birkeland currents. Both directly and indirectly (through the instabilities and energization that they cause) the Birkeland currents also lead to an exchange of matter between the magnetosphere and the ionosphere.

The exchange of matter is selective, so that the magnetospheric plasma that has come from the ionosphere has a chemical composition which is very different from that at its region of origin. This very efficient chemical separation, which has unexpectedly been discovered in the near Earth plasma, and is accessible to in situ investigation there, should also be of considerable astrophysical interest. It shows that plasma physical processes, unrecognized until recently, can cause great changes in abundance

ratios even over distances that are, on a cosmical scale very small.

3. ELECTRIC CURRENTS

3.1 Current conduction in space plasma

Perhaps the most basic property of matter in the plasma state is its ability to carry electric current. The importance of this ability - and of its limitations - in the plasma universe follows from the fact that practically all cosmical plasmas are magnetized, and that the magnetic field is intimately coupled to the dynamics of the plasma. Except close to celestial bodies, where internally generated magnetic fields can be large, the sources of the magnetic fields in a cosmical plasma are currents that flow in the plasma itself. Even in the Earth's magnetosphere, major, and in the outer parts dominating, contributions come from currents in the plasma.

In classical plasma theory, the ability of a plasma to carry current was assumed to be well understood and its resistivity described in terms of a simple formula. According to this formula most cosmical plasmas would have negligible resistivity. Consequently ideal magnetohydrodynamics and the so-called frozen field condition were believed to be valid, and were applied both to the Earth's magnetosphere and to astrophysical plasmas. In the case of the magnetosphere, we now know, from in situ observations of the real space plasma that its electrical properties are much more complicated. The concept of the magnetospheric plasma as a simple magnetohydrodynamic medium has been shattered, and even the concepts of a locally defined resistivity or conductivity can cease to be meaningful. Rather than being a virtually resistanceless conductor of electric current along magnetic field lines, the real magnetospheric plasma can have a very limited capability of carrying electric current and can be capable of supporting magnetic-field-aligned electric fields with voltage drops of many kilovolts. (This particular aspect will be further discussed in Section 4.) Indeed, some of the most interesting physics of the magnetosphere, such as the auroral process, seems to critically depend on this non-classical behaviour of the space plasma.

Also closely related to the plasma's limited ability to carry electric current is the excitation of various current-driven instabilities. It has been suggested by Alfvén (1981) that plasmas fall into two distinct categories: "active" and "passive" plasmas, and that in general a plasma becomes "active" when it is forced to carry an electric current.

Another important aspect is how the electric currents are driven. In an ideal MHD medium the only emf available would be the $\underline{v} \times \underline{B}$ electric field, which can tap energy from the mass motion of the plasma. In the real space plasma another important possibility is that the plasma can act as a "thermoelectric" generator, tapping energy from the random motion of energy-rich particle populations.

In the magnetosphere both these sources of electric current seem to be important, but still very little is known about how the magnetospheric currents are driven.

In fact, the magnetosphere offers an excellent study object. The ultimate source of energy for most of the magnetospheric current systems is the solar wind, but the way its energy is fed to the interior of the magnetosphere is very complex and probably involves establishing internal secondary generators of both MHD and thermoelectric type. The study of this process should contribute much to the understanding of the electrodynamics of other cosmical plasmas, wherever energy is exchanged between interacting plasma regions.

Still another aspect of the way space plasmas carry electric current is filamentation. Filamentary structure is a pronounced feature of many astrophysical plasmas. From laboratory plasma experiments we know that plasma currents have a tendency toward filamentation. In the case of cosmical plasma the connection between filamentation and electric currents is not very well known, and studies of this in the magnetosphere should help clarify this problem.

A related problem is that of current sheets and their possible relation to a "cellular" structure of space (Alfvén, 1981). In the magnetosphere there are two major current sheets (at the magnetopause and in the tail), one of which is related to a boundary separating plasma region with different physical properties.

3.2 Measurement of electric currents in space

Although the magnetic fields in the magnetosphere have been measured routinely since the beginning of the space age, the knowledge of the geometry of magnetic field lines, and hence the magnetic conjugacy of widely separated plasma regions is still rather limited (cf *e.g.* Lui and Krimigis, 1984). Even more limited is the knowledge of how the sources of the magnetic field, *i. e.* the *electric currents*, are distributed in the magnetosphere. Since, in a mathematical sense, the electric current can be calculated if the magnetic field is known, it was long considered that the electric current itself was an uninteresting quantity. However, since in the real magnetosphere the plasma has a rather limited ability to carry electric current, and since many important processes like the auroral acceleration seem to depend critically on the current density, the electric current is indeed a relevant quantity.

Furthermore, what happens at a given point in a current-carrying plasma depends not only on the local conditions but on the whole circuit of which it is a part, *i. e.* we are faced with fundamentally *non-local* problems. For this and other reasons it is important to know how electric currents in space close, and how they are carried (*e.g.* what kind of charge carriers and what terms in the generalized Ohm's law are important). Knowledge of how the current systems close is also important in the context of large-scale auroral electrodynamics. For example, uncertainty of how the Birkeland currents close in the outer magnetosphere is an obstacle to the understanding of the substorm process. The importance of knowing the electric currents in order to understand cosmical plasmas has been eloquently spelled out by Alfvén (1981, 1986b).

Unfortunately, determination of the electric current systems in the magnetosphere is difficult. Very important progress has been made in determining the structure of the Birkeland currents, especially near the ionosphere, using satellite-borne magnetometers. However, from single

point measurements of the magnetic field the electric currents can only be determined if suitable geometric assumptions can be made, e.g. that the current flows in sheets. Such assumptions may be appropriate for Birkeland currents at intermediate altitudes in the ionosphere, but they become increasingly questionable with increasing distance. In order to make a unique determination of the local electric current density with existing techniques one would have to make very accurate measurements of the magnetic field at four points separated by distances small relative to the scale of current density variation. Although in principle possible with a multiple spacecraft mission, this has not yet been achieved or even attempted.

We know that very fine scales appear in auroral forms and in auroral electric fields. We do not know to what extent they are associated with current density variations on corresponding scales. These fine structures would hardly be accessible to multipoint measurements, and with present technology they would even be hard to detect at all by means of magnetometers, because the resultant magnetic field change over an individual structure is minute.

Especially for measurement of the fine structure of electric current but also for mapping out the large-scale current systems it would be extremely desirable to develop techniques for directly measuring the local current vectors. No such technique exists at the moment, but it is very interesting that attempts are now being made to develop one, using the Faraday effect in optical fibres. This principle of current measurement is already being used in high power technology. However, to be used in space its sensitivity has to be increased by many powers of ten. This poses a great technological challenge. If successful, this new technique could be one of the most important contributions to space plasma physics in the decades to come. (It should be noted that direct current measurements do not replace magnetic measurements but are a greatly needed complement.)

4. ELECTRIC FIELDS

Unlike most other physical quantities in the magnetosphere, the electric field was not subject to direct measurement until late in the space age. The reason for this was in part that the measurements are technically difficult and in part that, according to over-idealized theoretical models of the magnetospheric plasma, the electric field was believed to be of little significance. We now know that these theoretical models are of limited values in the real space plasmas, and that direct measurements of electric fields are important. However, until now, very few satellites have been equipped to measure them, except in low orbit, and extensive measurements throughout (relevant parts of) the magnetosphere is still a task that largely remains to be performed.

4.1 General properties

The direct measurements that have been made so far have confirmed some of the expected properties, such as the existence, in an average sense, of a general dawn-to-dusk electric field. However, they have also shown that the electric field in the outer magnetosphere has large time and space variations, which often exceed the average value. Indeed it is likely that these variations in the electric field are a more important

aspect of it than the average. Also, it has become apparent that induction fields play an important role. For this reason the usefulness of quantitative models representing the average configuration of the electric field is much more limited than in the case of the magnetic field.

4.2 Fine structure of auroral electric fields

One of the surprising discoveries of the S3-3 satellite was the occurrence over the auroral oval of extremely strong localized electric fields (Mozer et al., 1977). These phenomena, which came to be called "electrostatic shocks", are apparently associated with the auroral acceleration process. However, whether they are indeed essentially electrostatic or are of a different nature, e.g. associated with Alfvén waves as proposed by Haerendel (1983), is not yet known, and a different nomenclature may be appropriate. More detailed data now being taken by the Viking satellite (Viking Science Team, 1986) may perhaps help solve this problem. The Viking data show good agreement in terms of the intensity of the fields (several hundred mV/m) with earlier measurements, but are also able to resolve more of the fine structure. The fine structure of the electric fields above the aurora is probably an important feature of the auroral acceleration process and deserves much more attention in terms of direct measurements than it has had until now. It should be one of the important tasks of future space plasma research.

4.3 Magnetic-field-aligned electric fields

Perhaps the most important question concerning electric fields in the magnetosphere is whether any substantial electric field components do or do not exist along the geomagnetic field (Alfvén and Fälthammar, 1963). It is closely related to the question of the current-carrying ability of a collisionless plasma. When the existence of such fields was suggested long ago (Alfvén, 1958), it was almost universally rejected as impossible, because it was incompatible with prevailing theoretical ideas. Since then evidence of many kinds has accumulated.

The observational indications of parallel electric fields are now numerous and include:

. Precipitating auroral electrons with an "acceleration boundary" in velocity space.

. Upgoing beams of ions with a distribution function indicative of passage through a potential drop.

. Artificial ion beams injected upward from the ionosphere and observed to undergo sudden accelerations along the magnetic field.

. Artificial electron beams injected upwards and reflected in a way consistent with a potential barrier above (although other interpretations may not be excluded).

. Comparisons of electric fields measured at high and low altitude, which show that the spatial distributions differ in a way consistent with a parallel electric field prevailing in the intervening altitude range.

. Electric field measurements revealing the existence of numerous small-scale "electric double layers", which together may account for substantial potential drops.

. Measurement of large parallel components associated with strong localized auroral fields.

Due to this rather massive evidence the existence of parallel electric fields, at least above the aurora, is now widely, although not universally, accepted. It should, however, also be pointed out that parallel electric fields cannot alone account for all the features of auroral acceleration processes. Various kinds of wave particle interactions must contribute, too. (For a recent review of the evidence and references to the extensive original literature, see e.g. Fälthammar, 1986).

However, in spite of all these indications, very little is known about the actual properties of the parallel electric fields. For example, only the general altitude range where they belong is known, but not their detailed structure or other properties. Nor is it known what mechanism allows these electric fields to exist. There is only a small number of possibilities (Fälthammar, 1978). They are:

. The magnetic mirror force

. Electric fields of waves, with an intensity much larger than the parallel dc field

. Electric double layers

Their relative roles are unknown. At least the magnetic mirror force seems to be essential, but probably all of them play some role.

The existence and nature of parallel electric fields is a very fundamental question in the electrodynamics of matter in the plasma state. It also has important implications for the behaviour of cosmical plasmas. For example, one of the characteristics of cosmical plasmas is their ability to energize charged particles. Parallel electric fields allow such energization to take place much more efficiently than by stochastic processes. Furthermore, since parallel electric fields (with a non-vanishing curl) are a necessary condition for violating the "frozen field condition", the existence of such fields has direct implications for the coupling between magnetic fields and velocity fields in cosmical plasmas. E. g. unfreezing of magnetic fields seems to explain certain observations in comet tails (Ip and Mendis, 1976). If it occurs in the surroundings of rotating cosmical bodies, it may invalidate the law of isorotation. In a cosmogonic context it may be important in order to allow partial corotation (Alfvén and Arrhenius, 1976).

Because of these important aspects of parallel electric fields it should be a high priority task to study them experimentally in the regions of the Earth's magnetosphere where they exist.

4.4 Technical aspects

Part of the reason why direct electric field measurements by in situ probes were started late was the technical difficulties involved. Espe-

cially in the thin and hot plasmas of the outer magnetosphere, the requirements are stringent. Direct probe measurements require not only large probe separation and high configurational symmetry, but in adddition the spacecraft body and all its protrusions must have a high degree of electrostatic cleanliness, i.e. very nearly constitute a single equipotential surface.

Special precautions have to be taken to suppress possible errors from photoelectron clouds or from exchange of photoelectrons between probes and satellite body. Such precautions may involve active control of spacecraft potential, biased guards on the probe-supporting booms, and bias currents to the probes (to achieve an optimum operation point on the voltage-current characteristic of the probes). The probe surfaces themselves are subject to stringent requirements in terms of homogeneity of the work function and should at the same time have as high a photoelectron yield as possible.

It is interesting to note that the same method that is used to ensure the electrostatic cleanliness needed for scientific measurements of the electric field (and, in fact, very low energy particles as well) is well suited to cure the problems of differential charging of applications satellites.

In addition to the probe techniques there are others, such as those using artificial ion clouds or beams of electrons or ions, which have until now been used even less. Each method has its advantages and limitations, and needs to be technically perfected and used in complementary ways.

Particle measurements have until now provided some of the most convincing evidence of the existence of parallel electric fields. However, as shown by Greenspan et al. (1981), present day instruments do not allow determination of the spatial distribution of the potential drop. Improving the measurement technique to allow measurement down to low energy and a much improved time resolution is desirable. This is another technological challenge, which involves not only increasing the instrument sensitivity but also meticulous precautions to eliminate potentially harmful effects of the plasma environment, e. g. by ensuring strict electrostatic cleanliness of the spacecraft and control of spacecraft potential. These efforts to understand and protect against the plasma environment will of course benefit not only these sensitive scientific experiments but also environment-sensitive space-based technological equipment.

5. RAPID RELEASE OF MAGNETIC ENERGY

Also related to how electric currents are carried is one of the characteristic features of cosmical plasmas, namely the ability to very rapidly release large amounts of magnetically stored energy, e.g. in solar flares. Such rapid release takes place in the magnetosphere, too, namely in the magnetic substorm process. It is generally believed that there are close similarities between solar flares and substorms in terms of how the energy is released, but theories differ about what is the mechanism responsible. If this can be clarified by observations in the magnetosphere, it would probably also help understanding solar flares and other cosmical manifestations of rapid release of energy.

6. CHEMICAL SEPARATION

The discovery of large abundances of oxygen plasma in the magnetosphere is important not only for the understanding of magnetospheric and auroral physics. Its wider significance is to reveal the previously unknown and unexpected facts that
(1) very efficient chemical separation can take place in a cosmical plasma even over cosmically small distances, and
(2) at least one of these mechanisms (there may well be more than one) is available for *in situ* inspection at a convenient nearby location.

Although we know that the mechanism is intimately related with selective energization of plasma ions, there is not yet general agreement on exactly which of the proposed mechanisms is responsible. This is yet another example of a magnetospheric problem, whose solution should have a distinct astrophysical significance. It opens the possibility that astrophysical plasmas located close to each other may still have very different relative abundances of chemical elements.

7. CRITICAL VELOCITY INTERACTION

In addition to plasma phenomena occurring naturally in the magnetosphere, active experiments in the space plasma may further serve to clarify plasma physical processes that are of importance elsewhere. As an example with unusually wide applications ranging from technology to cosmogony we may consider Alfvén's Critical Velocity phenomenon.

The phenomenon was originally postulated by Alfvén as an element of his theory of planet and satellite formation. Years later it was observed experimentally by Block and Fahleson. Subsequently it has appeared in many different experimental configurations including a certain class of experiments for fusion research. Recent rocket experiments have proved that it can operate in space plasma (for a review see Newell, 1985) - which brings the experimental evidence much closer to the parameter range of the original application of the phenomenon.

The Critical Velocity has been invoked in explanations of the interaction of the solar wind with gas clouds from the moon, cometary comae and interstellar gas. Recent observations of the comets Giacobini-Zinner and Halley have been interpreted in terms of the Critical Velocity effect (Haerendel, 1986, Galeev *et al.*, 1986). If, as has been proposed (see *e.g.* Papadopoulos, 1983), this effect is responsible for environment anomalies at the space shuttle (optical and IR emissions, enhanced wave activity and energization of electrons and ions), it may also have important technological implications for the design and use of the space station.

8. CONCLUDING REMARKS

Both in terms of the dominating state of matter and in terms of physical processes, the plasma state plays a key role in the Universe, present and past. Thus both in astrophysics and cosmogony, plasma physical processes must be taken into account. The understanding of such processes is still limited, but can be improved by *in situ* observations and experiments in the magnetosphere of the Earth. Such observations and experiments

should therefore be an essential complement to the collecting of astrophysical data by remote sensing and should be a challenging task for space science and technology in the decades ahead.

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PLASMA INTERACTIONS WITH LARGE SPACECRAFT

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1. Introduction

Plasma interactions with large, high-power space structures have been shown to have an important influence on the operation of these systems. The importance of interactions of spacecraft with the environment was dramatically illustrated on the earliest shuttle flights, with the observation of shuttle glow and of high concentrations of particulates. Analysis and space experimentation have shown that environmental interaction effects on satellite performance grow nonlinearly with the size of the spacecraft and with power system voltages. The rapidly expanding role of satellite systems in civil sector communications and earth resources management, in the conduct of the Department of Defense mission and in NASA's plans for a space station and planetary missions of growing complexity, highlights the need to understand and model the space system plasma interactions and to develop techniques to mitigate systems-degrading interactions.

Future military systems to become operational in the 1990's require very large platforms, unprecedented memory and computational capability, enhanced power-generating systems, and must remain operational for decades. There is a quantitative change in the nature of the mechanical, electrical, thermal, and radiative interactions of these space systems with the environment. Space-Based Laser and Space-Based Relay Mirrors must be designed to minimize contamination effects on optics and mirror surface erosion. Planned SDI Systems and Space-Based Radar require orders of magnitude increases in power and must cope with enhanced plasma interactions which can cause unacceptable power losses. EVA required for spacecraft servicing on polar orbit flights must compensate for increased astronaut charging, particularly in the auroral zones. By the year 2000, the National Space Plane and the Space Station will become realities. The size and power requirements represent a real challenge to system developers. Designers of space systems contemplated for SDI must address all of the interactions under discussion.

2. Large-Body Space Plasma Interactions

A body moving through the space plasma at orbital speeds, approximately 8 km/sec, produces changes in the local environment and the local environment induces changes in the properties and performance of the vehicle. Some of the interactions of a satellite with the space environment are summarized in Figure 1. These interactions result in significant changes in the local environment properties and include enhancement of neutral and of ionized particle densities in the ram direction and rarefaction in the wake behind the spacecraft. Further, while ions and electrons are constrained by the Earth's magnetic field, neutral particles generated by the spacecraft are free to travel with the spacecraft until disturbed by collisional processes. The influence of the spacecraft on the environment can thus extend great distances. A brief discussion of some of the important large body interaction effects follows.

2.1 Ram-Related Effects

The first class of effects to be considered is related to the rapid (8 km/s) movement of spacecraft relative to the ambient neutral and plasma environment at low altitudes (H < 1000km). Two such effects will be considered here - glow and oxygen erosion. The presence of optical emission or glow above shuttle surfaces exposed to ram was observed on STS-3 by Banks et al. (1983) (see Figure 2 for an example). Mende et al. (1984) showed a clear dependence of the intensity of these faint visible emissions on the angle of attack. Glow had been previously observed on board the Atmospheric Explorer -C and -E spacecraft (see Yee and Abreu, 1983). Slanger (1983) suggested that the emission was related to the OH Meinel band system generated by the surface interactions with energetic oxygen atoms. Green (1984), on the other hand, proposed a chain of reactions resulting from dissociation of N_2 upon impact with the shuttle surface leading to the emission being the red N_2 first positive bands. Alternatively, Papadopoulis (1984) has suggested that physical mechanisms, namely beam plasma discharge and critical ionization phenomena, combine to produce the phenomena. Identification of the actual mechanism(s) awaits better spectral definition of the emissions.

Of particular interest to future space systems are the spectral content of the glow from IR to UV, the spatial extent of the glow, the variation with surface properties and other induced effects, and the potential degradation of optical measurements by its presence. Banks et al. (1983) estimated that the glow extended out about 10 cm from the surface. That distance may be variable dependent upon surface materials. Further, glow can be enhanced by the operation of thrusters and is altitude dependent. Thus, with a better understanding of the glow phenomena, materials selection or spacecraft and optical-bandwidth operations contraints may be able to mitigate the actual impacts on a given system.

Another ram-related effect at low altitude is the erosion of materials by neutral atomic oxygen. Because of the 8-km/s relative velocity, ambient oxygen atoms strike the ram surfaces with an energy of 5eV. This introduces a regime of gas surface chemistry about which little is known (see Arnold and Peplinski, 1985). In-flight studies by Visentine et al. (1985) have shown that the reaction between the environment and surfaces is to a first approximation not dependent on temperature, solar radiation, or electrically charged species. Reaction rates are material and incidence-angle dependent. In assessments of the effects to be seen by the NASA Space Station, Leger et al. (1985) indicated an enhanced susceptability of the materials used in solar power systems to oxygen erosion. While protective coatings are being selected, careful study is needed in order to identify practical candidates that fulfill both conductivity and oxygen erosion requirements in this orbital regime.

2.2 Wake-Related Effects

Just as the ram pressure causes interaction effects, similarly the lack of pressure or particles in the wake behind a large body has its own class of interactions. Figure 1 summarizes some of the interaction physics involved with both the ram and the wake regions. The supersonic motion of the body through the ionospheric plasma creates a shock wave in front and to the side and a large depleted volume behind the body. When the body size becomes very large comparable to Debye lengths or to ion gyro radii, the interaction effects relative to the filling in of the wake become more severe.

Measurements by Siskind et al. (1983) document nearly four orders-of-magnitude electron-density variations between the Shuttle ram and the wake. The lower limit of 10^2 electrons/cm^3 that they measured in the wake clearly results from instrument limitations. In fact, charged particle densities may go as low as $1/cm^3$ in the deep wake (Shawhan, private communication, 1985). Densities in the ram may reach $10^7/cm^3$ as indicated by saturation of the ion signal from the retarding potential analyser (SRPA) on STS-3 (Siskind et al. 1983). Thus, at least 7 orders of magnitude variation may be possible.

The shock structure from the ram flow and the strong gradients at the edge of the wake are obvious areas where turbulence could be expected. Siskind et al. (1983) and Raitt et al. (1983) found extreme plasma turbulence, especially when densities exceeded $10^5/cm^3$. They conclude that turbulence occurred from ram effects and from enhancements from shuttle generated gases. Turbulence was also increased when the vehicle became negatively charged relative to the ionosphere.

The filling of the wake behind a large body moving supersonically or the expansion of a plasma into a rarified area has been studied by a number of people and reviewed by Samir et al. (1983). Multiple charged-particle populations result in polarization electric fields which control particle motion along with flow expansion in the collisionless case and diffusion in cases where collisions must be considered. From these processes the wake region becomes a source of electron heating and ion acceleration, preferentially of lighter ions and of minor constituents. Other processes involve plasma oscillations and instabilities, strong "jump" discontinuities in plasma parameters at the expansion front, and rarefaction wave propagation into the ambient plasma. These phenomena all depend on the ionic constituents and concentrations, ambient electron temperature and density gradients, and the size of the body relative to the Debye length.

2.3 Charging

Spacecraft charging results when insufficient thermal plasma can be collected by a surface to offset the impingement of intense fluxes of energetic charged particles. The surface will adjust its charge to repel enough of the energetic particles to maintain a zero net flow of current.

The discovery of charging in the low-density plasmas at geosynchronous orbit by DeForest (1972) and the subsequent recognition of charge-induced anomalies in spacecraft operations sparked numerous conferences and a satellite program, Spacecraft Charging at High Altitudes (SCATHA), to investigate the phenomena. A discussion and compendium of references on surface charging can be found in reviews by Garrett (1981) and Whipple (1981).

DMSP observations by Gussenhoven et al.(1985) established that the conditions necessary for charging to occur can also be found in auroral zones at low altitude (840 km) in polar orbit. They found that charging of over 100V occurred at the poleward edge of the region of discrete aurora in darkness when the thermal plasma density was less than $10^4/cm^3$ and a high integral number flux of electrons greater than 14 keV was present. These conditions are just as easily met at Shuttle altitudes in the Shuttle wake. In fact, the aforementioned lower thermal plasma densities should make this a common phenomenon in the nightside auroral regions.

Because of differing surface properties, spacecraft or objects in the wake can be expected to differentially charge or independently charge to different voltages. Large potential gradients over small distances may develop which can lead to arc discharges. These discharges may, in turn, release energy that damages electrical circuits or causes permanent damage to insulators.

The above discussions refer primarily to surface charging. A second charging problem arises in insulators when the charge becomes trapped below the surface (see Denig and Fredrickson, 1985). Bulk charging of insulators, often referred to as deep dielectric charging, grows to the point where breakdown channels are created. These may be temporary or permanent. Material properties' changes have been shown to occur in a charging environment which may lead to more subtle, anomalous behavior (Fennell et al., 1985).

2.4 Contamination

Early observations indicated that the Shuttle's local environment was controlled by the movement of the Shuttle through the ambient medium and by contaminant sources on the Shuttle. These sources, in the form of particulates (Carrignan and Miller, 1983; Grebowski et al., 1983; Narcisi et al., 1983) and gases (Carrignan and Miller, 1983; Barengolz et al., 1982; Maag et al., 1982) are generated by Reaction Control System (RCS) and Orbital Maneuvering System (OMS) engine firings, cabin gas leaks, water releases and outgassing of materials. Initial operational concerns over contamination focused on particulates scattering light into Shuttle-based optical detectors to produce false signals, and on gaseous contaminants condensing on thermal control and optical sensing surfaces to degrade their performance.

Recent observations, summarized by Green et al. (1986), suggest that the Shuttle may be immersed in a large gas cloud, made of atoms and molecules from various outgassing sources, whose shape is governed by the Shuttle's interaction with the ambient neutral atmosphere and space plasma environment. Engine firings enhance the contaminant cloud and may produce their own characteristic contaminant cloud or plume that has an associated engine firing light-flash (Weinberg, 1983) which illuminates the Shuttle and enhances the surface glow phenomena (Mende, 1984). Particulate contamina-

tion is also enhanced when RCS engine exhaust plumes impinge directly on Shuttle surfaces (Barengolz et al., 1982; Maag et al., 1982). All of these observations suggest a close coupling between the various contaminant sources which contribute to the formation of a multi-species gas cloud surrounding the Shuttle.

Some of the key experimental questions relative to the gas could include:

a. What is the absolute concentration of ions and neutrals in the cloud region and shuttle bay? What is their relationship to Shuttle activity?

b. What are the optical radiation characteristics of the cloud in the infrared, visible, and ultraviolet?

c. What is the spatial extent and temporal history of the cloud?

d. What is the intensity of the foreground luminescence of the Shuttle gas cloud at various wavelengths versus the intensity of backgrounds including the aurora, airglow, and stars?

e. Where do the particulates originate? What is their size, distribution, and time history?

Only when these questions have been satisfactorily answered can initial operational concerns over contamination be resolved through application of a Shuttle contamination specification to the broad class of Shuttle users.

The question of spacecraft contamination is perhaps more general than the composition of the local atmosphere (or gas cloud) which surrounds the space shuttle. Erosion of materials in the environment of the space shuttle has been documented in a number of experiments (Peters et al., 1983; Leger et al., 1984; Whittaker et al., 1985) and it leads to the natural question of the fate of the materials which are removed. A corollary question is the transport of materials from one place to another in this local atmosphere. For example, TQCM measurements on a number of missions (Scialdone et al., 1978; Triolo et al., 1984; Ehlers et al., 1984) indicate that materials are deposited on detectors. This transport must be correlated with the materials removed from the other surfaces. How this transportation occurs will play a crucial role in the assessment of contamination and its effects on shuttle operations. An ancillary question is whether the erosion of materials gives rise only to particulates or to particulates and gaseous contaminants. Laboratory experiments with electron and ion bombardment of surfaces show that ions and neutrals characteristic of the surface layer are emitted (e.g., Shapira and Friedenberg, 1980). In space, similar effects have been reported (e.g., Hanson et al., (1981) report observation of Na^+ and K^+ because of sputtering from satellite surfaces by ambient ions and neutrals). It is important to establish the extent of sputtering phenomena occurring in the local environment of the space shuttle, particularly at high latitudes. Species emitted in this fashion then become contaminants.

2.5 Radiation Hazards

The highly variable fluxes of energetic particles throughout the magnetosphere-ionosphere system represent a significant threat to space systems' survivability. Regions of particular concern are the earth's radiation belts extending from 1.1 to 7 RE in the magnetic equatorial plane and the high-latitude auroral zones (Fig. 3). During geomagnetic disturbances, energetic charged particles with energies up to 100 MeV are trapped along the earth's magnetic field lines. Particles of energies greater than 2 MeV cannot be shielded without significant cost and weight increases. An example of the effect of an energetic positive ion or cosmic ray upon a single microelectronic memory cell is depicted in Figure 4. The particle loses energy as it traverses the cell and ionization is created along its path. This in turn changes the operating potential of the device which can produce single event upsets or complete latchup. Deep dielectric charging can also occur as a result of satellite bombardment by energetic particles. There is potential buildup on the outer conductor of spacecraft cables. The high potential can eventually cause breakdown of cable insulation with subsequent discharge to cable conductors, and permanent damage results.

2.6 High-Voltage Induced Leakage to Space Plasmas

Exposed voltages on any part of a space system cause current to flow between the element and the ambient low-energy plasma environment. For example, current flow to a solar array terminal often can result in unacceptable power losses. At present almost all satellites use 28-volt supplies. In order to meet the needs of planned systems, such a Space-Based Radar or space station, much higher power must be generated. It is planned to use up to 1200 volts. The NASA Lewis PIX experiments have shown that the leakage current nonlinearly increases for high positive voltages and arcing occurs for high negative voltages (Purvis, 1983; Grier, 1983). These results are summarized in Table 1. The problems of operating at high voltages and currents are discussed in separate Workshop papers by Purvis and Stevens.

2.7 Multi-Body Charging and Polar Orbit EVA

A free flying subsatellite launched from the Shuttle (or space station) or an astronaut in EVA will be subject to the same environmental interactions as the parent orbiting vehicle but, because of size and surface material differences, will react differently. Potential differences can be built up between the free flying body and the vehicle. Such multi-body interactions must be understood, modeled and mitigated before spacecraft servicing can become a viable operational capability. The effects are greatest in the near wake of the main body where high potentials can develop due to loss of ions from the region (see section 2.3).

3.0 Plasma Interactions Control and Mitigations

Several efforts have been intiated by the Air Force Geophysics Laboratory in order to understand, quantify and mitigate against the hazards presented by space plasma interactions with large structures. Critical measurements will yield the data necessary to identify and establish mitigation techniques. These in turn will be transitioned to the space community to provide designers with important new design criteria and options.

3.1 Mitigating Against Radiation Hazards

The Air Force Geophysics Laboratory has established a spaceflight project SPACERAD for the space test of emerging microelectronic technologies while simultaneously measuring the space radiation environment. A 1989 launch is planned. The spaceflight performance of approximately 65 memory and logic devices including VHSIC technologies will be determined. The seventeen diagnostic instruments include particle detectors over the energy range from electron volts to 50 BeV, magnetic and electric field sensors, plasma wave analyzers and dosimeters. At the same time a microelectronic ground test program will be conducted with the goal of establishing ground test procedures for future technologies. Some experts, for example, consider that existing test procedures designed to assess performance in space are too severe. The consequence is that needed microelectronic capability is not available and in some cases results in over design of spacecraft shielding. The results of the particle, plasma, wave and field measurements on the SPACERAD satellite will be used to develop the first dynamic radiation belt models.

3.2 Quantification of Large Body Interactions and Technology Transitions

To quantize the effects of environmental interactions on technologies for future systems, the Interactions Measurement Program for the Shuttle (IMPS) has been established by the Air Force Geophysics Laboratory (Fig. 5). The purpose of IMPS is to develop synergistic sets (instrument complements) of engineering and scientific investigations that measure the interactions of the space plasma environment with representative large space structures, materials, equipment and technologies. The IMPS experimental payloads will be integrated into a Shuttle Pallet Satellite (SPAS) - a flight-tested carrier capable of free flight in close proximity with the Shuttle, allowing measurements of large-body space plasmas' interactions' effects on elements of planned systems. The diagnostic complement to be flown with the first IMPS/SPAS will form a space-qualified diagnostic facility resource for future Department of Defense (or NASA) technology systems.

The IMPS program represents a new approach to cost-effective spacecraft design for the large space structures and complex technologies of future space systems. Under this program a series of spacecraft flights will be conducted in which new technology components can be tested in-situ with proper diagnostics before commitment to final design of the complete system. The synergism of combining adequate diagnostics with components of systems for testing in-situ is critical to the effective transition of novel engineering concepts to future systems.

Timely results from IMPS-1 will be transitioned into criteria for new system designs to be implemented in the early nineties. It is planned that follow-on IMPS will address contamination and material degradation issues. On subsequent IMPS flights the basic diagnostics electromagnetic interface measurements will be combined with new engineering investigations and as required diagnostic instruments will be added to the basic core instruments.

As test elements grow in size, they reach a point where they can no longer be hosted by a spacecraft of the size of IMPS/SPAS. A transition must be made to a capability where the diagnostics are flown on a companion vehicle to that carrying the engineering experiment. Still larger structures may require interactions' measurements be made by a means of a highly maneuverable probe that can determine the interaction effects at various points over the surface. IMPS/SPAS can serve in both a host and a companion mode. An astronaut's maneuvering unit coupled with diagnostic tools is one way of satisfying a maneuverable probe capability requirement.

IMPS-1 is the beginning of a new capability to study complex, high-technology space systems. Large, high-powered systems of the future will interact with the plasma environment in many unforeseen ways. IMPS therefore offers a unique test facility out of which will come the understanding needed to affect future designs and to mitigate against adverse interactions. The benefits of this approach are a cost-effective, reliable, survivable spacecraft design and the early application of emerging technologies.

3.3 Spacecraft Charging Mitigation

Plasma experiments conducted on the Air Force SCATHA satellite showed that emission of a neutral plasma from a spacecraft in geosynchronous orbit could act as a clamp electrically connecting the spacecraft to the background plasma and thus prevent buildup of hazardous charging levels or catastrophic discharging. A device that can detect the onset of charging and turn on a plasma source is an effective spacecraft charge control and mitigation tool. Such an instrument is being developed by AFGL for geosynchronous orbiting satellites. The charge control system uses several techniques to detect charging and a rapid turn-on plasma source to automatically control spacecraft potentials over the satellite's lifetime (Fig. 6).

A similar device would also be useful for control of the potential of structures in low-earth polar orbit. By using several plasma sources at strategic points on large space platforms, hazardous differential potentials created by the interaction of auroral fluxes with the wake region or by on-board particle accelerations could be eliminated.

4.0 Summary

Space is playing a rapidly expanding role in the conduct of the Air Force mission. Larger, more complex, high-power space platforms are planned and military astronauts will provide a new capability in spacecraft servicing. Interactions of operational satellites with the environment have been shown to degrade space sensors and electronics and to constrain systems operations. The environmental interaction effects grow nonlinearly with increasing size and power. Quantification of the interactions and development of mitigation techniques for systems-limiting interactions is essential to the success of future Air Force space operations.

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SOLAR ARRAY OPERATING VOLTAGE

VS PHYSICAL PHENOMENA

VOLTAGE LEVEL	PHYSICAL PHENOMENA
< 50V	STATE-OF-THE-ART
100-300V	PLASMA LEAKAGE LOSS >1%
200-500V	LEO PLASMA DISCHARGES
400-700V	PARTIAL-DISCHARGE INCEPTION IN SUBSTRATE
500-1200V	PUNCH-THROUGH AT SUBSTRATE IMPERFECTIONS

TABLE 1

SHUTTLE/PLASMA INTERACTION

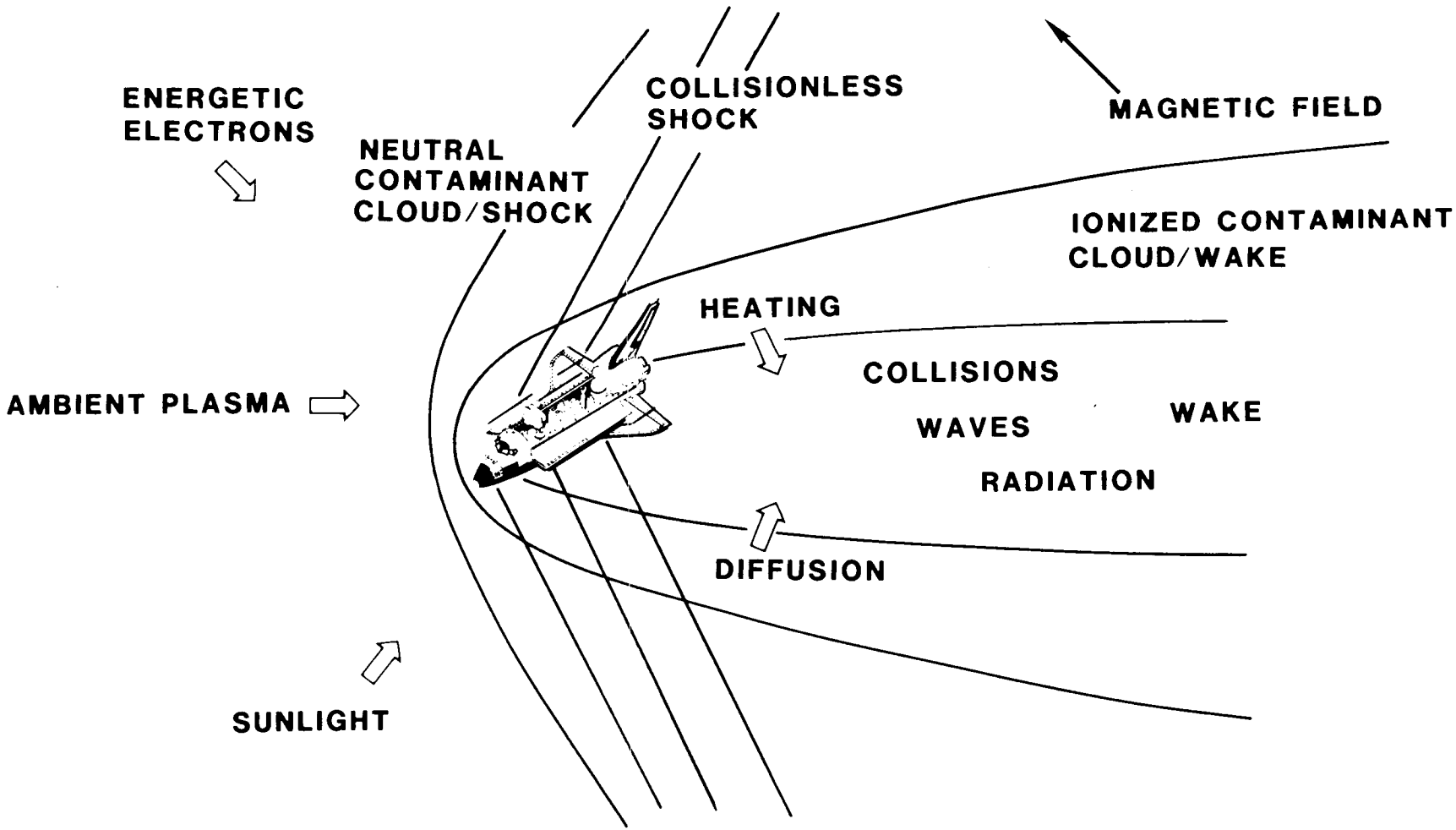

Figure 1. Illustration of impact of environment on a large space structure in low earth orbit.

Figure 2. Illustration of optical emissions from the Shuttle in the ram direction.

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Figure 3. Throughout the magnetosphere-ionosphere highly variable fluxes of charged particles interact with orbiting spacecraft. The regions of greatest interest include the earth's radiation belts and the auroral zones.

SCHEMATIC REPRESENTATION OF SENSITIVE REGION IN A SINGLE MEMORY CELL

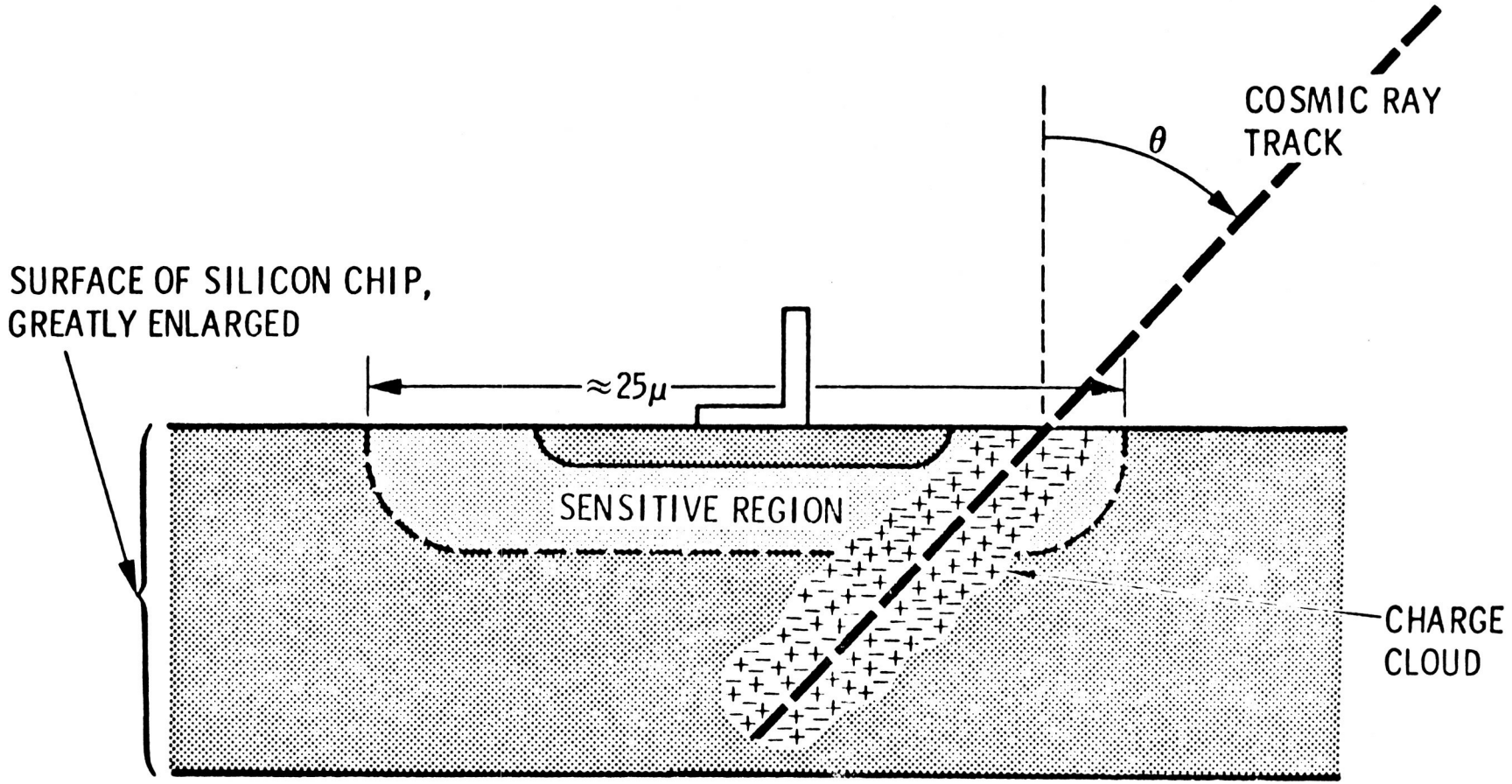

Figure 4. Depiction of the effects of energetic-particle traversal on a single memory cell.

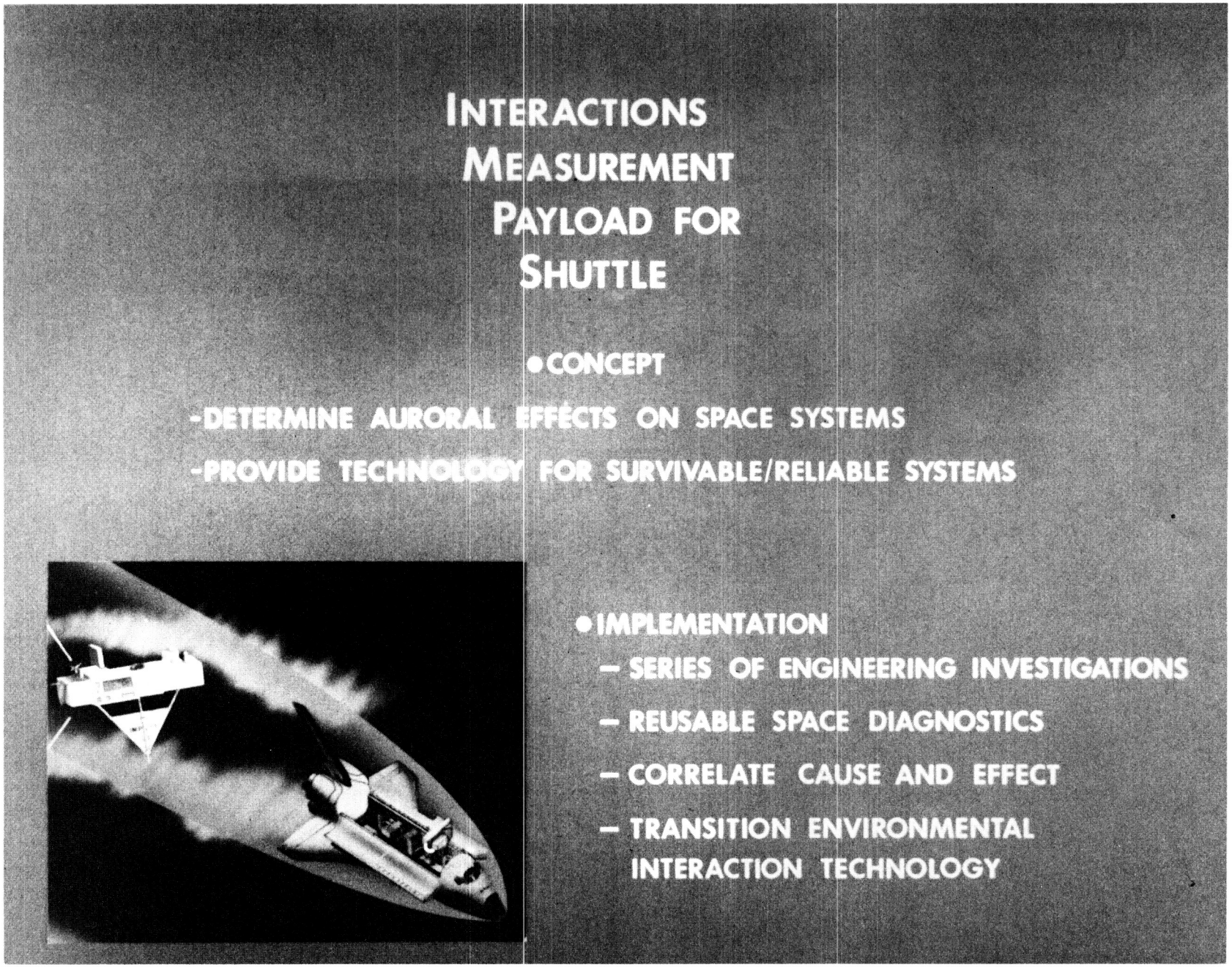

Figure 5. Interactions Measurements Program Satellite (IMPS) concept.

CHARGE CONTROL SYSTEM

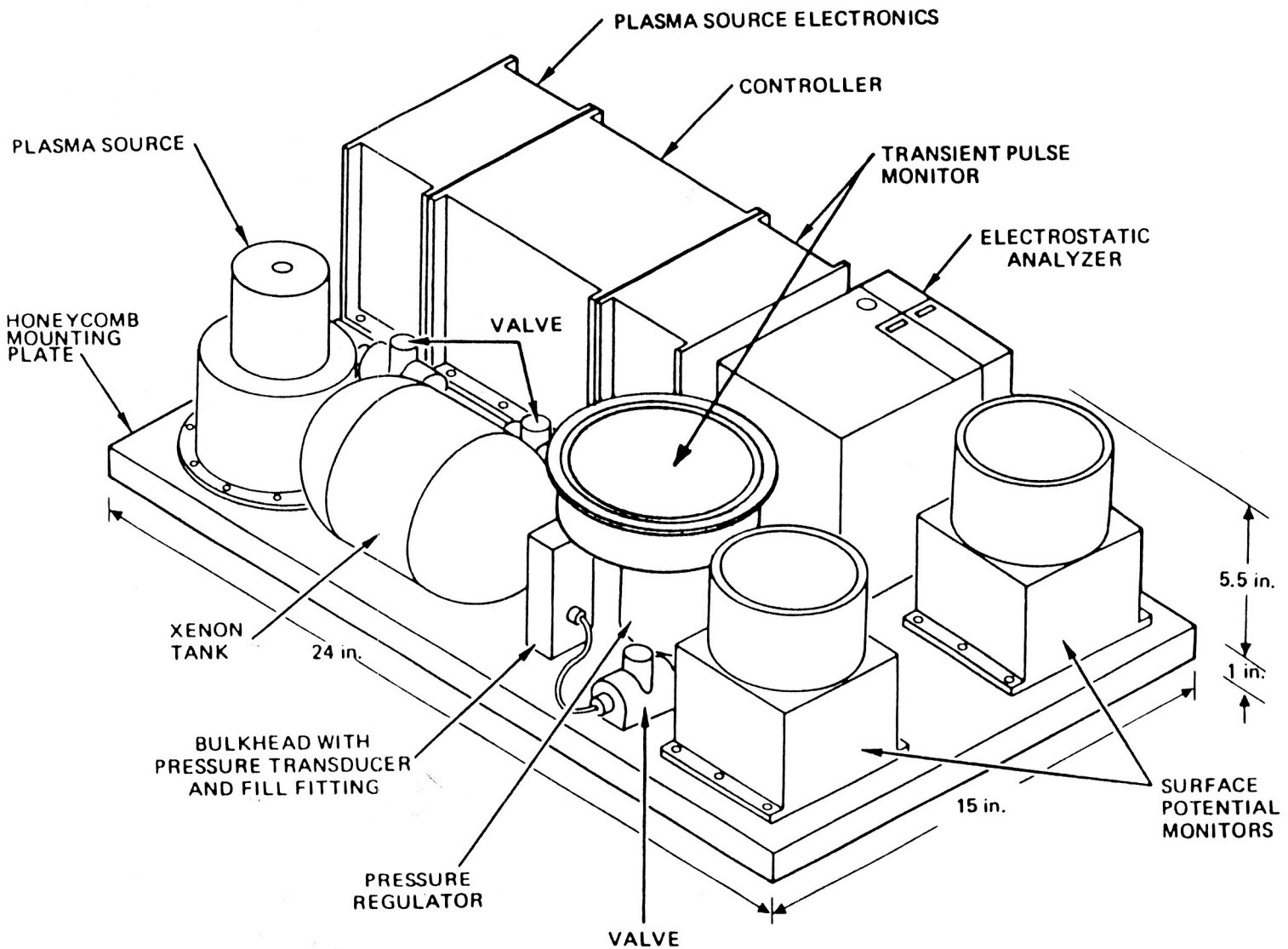

Figure 6. Block diagram of automatic charge control system.

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The Interaction of Small and Large Spacecraft with Their Environment

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Abstract: The most significant results from small scientific satellites and from the space shuttle mission STS-3 regarding body-plasma interactions are presented and discussed. The causes for the above information being meagre and fragmentary are given. The research avenues to be followed in the future in order to correct this situation are mentioned, including practical ways to achieve this goal.

1. GENERAL BACKGROUND

The interaction of a spacecraft (satellite, space shuttle, space station) with its environmental space plasma is a fundamental area of research in space plasma physics and in planetary geophysics. The interest in this area stems from both the science and application points of view.

From the general scientific point of view, we are dealing with the complex of phenomena and physical processes involved in the "electrodynamic interaction between an obstacle and its environmental rarefied plasma." Examples of such interactions in the solar system are the interactions between:

(1) Self-magnetized bodies such as the Earth, Jupiter, Saturn, Mercury, and Uranus with the solar wind.

(2) Non-magnetized bodies such as our moon and the moons of the large planets (e.g., Io and Titan) with the solar wind and/or with the magnetospheres of their parent planets (Jupiter and Saturn).

(3) Comets and the solar wind.

(4) Planetary ionospheres with the solar wind (e.g., Venus).

(5) Artificial bodies, i.e., small and large spacecraft with planetary ionospheres, magnetospheres, and the solar wind.

There are significant differences between the various interactions mentioned, but there also exist fundamental points of similarity. Hence, there can be no doubt that investigating "body-plasma interactions" under a wide range of plasma and body parameters will lead eventually to a UNIFIED approach in dealing with such interactions.

The interaction between a "body" and its surrounding plasma is MUTUAL. That is, both body and plasma are affected. The effects on the body result mainly in the charging of its surface, whereas the effects on the plasma result in the creation of shocks ahead of the body and very complicated wakes behind the body.

In addition to the scientific interest in understanding the complex phenomena and the relevant physical processes involved in the body-plasma interaction, there is also the practical aspect which is relevant to: (1) reliability, quality and the correct interpretation of low-energy particle and field measurements performed by probes mounted onboard satellites, (2) the optimal design of probes and their location on satellite surfaces and/or on booms. The latter aspect is of course essential for future space missions.

In the present paper we limit our discussion to the interaction of spacecraft, small and large, with their environmental ionospheric-plasmaspheric plasmas. Namely, our discussion is limited to the interaction of artificial non-magnetized bodies with a collisionless space plasma. The most significant results obtained from in situ measurements made by probes mounted on small scientific satellites and results obtained from some space shuttle missions will be presented and discussed. Within this framework we focus on the wake region and particularly on the variations of the [wake/ram] current ratio with several body and plasma parameters. We do not discuss spacecraft charging. Comprehensive reviews regarding spacecraft charging are given in Garrett, 1981; Whipple, 1981; Grard et al., 1983. Hence, we limit the discussion to one group of body-plasma interaction phenomena; i.e., effects on the plasma in the vicinity of artificial satellites. This limited group of body-plasma interactions, can further be classified to interactions based on the surface properties of the bodies; i.e., interactions which depend mainly on the degree of electrical conductivity.

It is possible to classify the interactions according to increasing/decreasing body-size or classify the interactions based on the specific plasma flow regime where the interaction takes place. For example, the interaction between the space-station and its ionospheric environment is a case of an interaction between a "large body" having, most likely, a relatively poor conducting surface, with a supersonic and sub-Alfvénic collisionless plasma. The interactions between a standard scientific satellite with the ionosphere, is a case of the interaction of a "small/medium" conducting body in a supersonic/hypersonic flow regime whereas the interaction between a spacecraft orbiting at plasmaspheric and magnetospheric altitudes takes place in a subsonic/transonic flow regime. It should be noted that a satellite orbiting the earth with a low altitude perigee and a high altitude apogee may go through several types of body-plasma interactions every orbit.

It should be noted that in dealing with "large-bodies", e.g. the Space Station, special attention should be given to the interactions between a variety of structural appendages mounted on the large body with the environmental plasma. Body parameters which are relevant to appendages are not necessarily the same as those representing the entire large-body. An example which illustrates that, is the parameter known as the "normalized body-size' (i.e., the ratio of the characteristic length of the body to its local Debye length). This parameter may be of the order of 10^3 - 10^5 for the entire large body and be of the order of 10 for specific appendages, each of which creates its own disturbance. And it is not obvious that the overall disturbance created behind the large body is a simple linear superposition of all the smaller disturbances.

As mentioned above we will focus on the wake region and on the (wake/ram) current ratio. It is therefore appropriate to state here that the wake region is the most structurally complicated region around the body. In this region plasma waves are excited, rarefaction waves (or: shocks) propagate, plasma instabilities are generated, wave-particle interactions take place and turbulent zones as well as potential wells exist. In principle, such phenomena are to be expected, since in the wake region, plasma beams collide, ion fronts propagate and strong density gradients exist at the body-plasma interface (e.g., Samir et al., 1983; Singh and Schunk, 1982, 1983; Gurevich and Meshcherkin, 1981a,b; Stone, 1981a,b,c; Al'pert, 1983).

Since the 1960's and particularly during the past decade, experimental and theoretical investigations regarding body-plasma interactions have been performed. The experimental effort consisted of: (1) using in situ measurements in order to investigate the angular distribution of thermal electrons and ions in the near vicinity to satellite's surfaces, (e.g., Samir et al., 1986a,b,c; Samir, 1981; Samir et al., 1979a,b,; Samir et al., 1973, 1975); (2) laboratory studies (e.g., Stone et al., 1981, 1978; Stone, 1981a,b; Hester and Sonin, 1970a,b,; Fournier and Pigache, 1975; Shuvalov, 1979, 1980, Chan et al., 1985, 1986) with applications to interplanetary and terrestrial phenomena. More recently, laboratory experiments were performed in the context of examining phenomena and physical processes relevant to the "expansion of a plasma into a vacuum" (e.g., Wright et al., 1985, 1986; Chan et al., 1984, Chan, 1986; Eselevich and Fainshtein, 1979, 1980, 1981; Raychandhuri et al., 1986). This latter subject will be discussed below. The theoretical effort devoted to study satellite-plasma interactions is by far more extensive compared with the corresponding experimental effort. Among the many papers published we cite: Gurevich et al., 1969; Gurevich et al., 1973; Gurevich and Pitaevsky, 1975; Al'pert, 1983; Parker, 1976, 1977, 1983; Kunemann, 1978; Grabowsky and Fischer, 1975; Liu, 1967, 1969; (Katz et al., 1985, 1984, 1979).

Generally speaking, the theoretical study of body-plasma interaction focuses on self-consistent solutions of the Vlasov-Poisson equations written for electrons and ions. As is known, solutions to the above equations under realistic conditions are not easy to obtain. Hence, simplifying physical assumptions are employed. However, the validity and ranges of applicability of some of the major simplifying assumptions have not yet been adequately tested. As could be expected, the major difficulties are with the studies which attempt to compute the distribution of charged particles and potential in the wake region.

Recently, the phenomena and physical processes involved in the "expansion of a rarefied plasma into a vacuum" were reviewed (Samir et al., 1983). Possible applications to space plasma physics and particularly to the area of "body-plasma" interactions were discussed. It becomes clear that a variety of wake characteristics can be explained in terms of processes involved in the "plasma expansion" complex (Samir et al., 1983, 1986b; Wright et al., 1985, 1986; Chan et al., 1986; Raychaundhuri et al., 1986; Singh et al., 1986). Without going into much detail, we state that the basic phenomena involved in the "expansion of a plasma into a vacuum" are: (1) the acceleration of ions to velocities which are far above their (thermal) ambient values, (2) the creation of a rarefaction wave which propagates into the ambient plasma at about the ion acoustic speed, (3) the formation of an ion front which expands into the vacuum region, and (4) the creation of strong discontinuities in the plasma parameters, and the creation of plasma oscillations and instabilities over certain spatial zones in the "vacuum" (e.g., wake) region.

It is interesting to note that the phenomena involved in the expansion of a plasma into a vacuum, particularly the acceleration of ions, the motion of ion fronts, and the propagation of rarefaction waves were studied theoretically and, to some lesser extent, experimentally in the last decade, e.g. Gurevich et al., 1966, 1968, 1973; Gurevich and Pitaevsky, 1975; Crow et al., 1975; Holm et al., 1981; Johnson and Lonngren, 1982; Eselevich and Fainstein, 1979. While the importance of such fundamental physical processes was recognized by laboratory plasma physicists, they went unnoticed by the space science community.

We submit that the distribution of charged particles and potential in the wake behind a body moving in a collisionless space plasma, can under certain conditions, be understood in terms of the expansion of a plasma into a void (vacuum) or into a more tenuous plasma (Samir et al., 1983). The application of the "plasma expansion" processes to body-plasma interactions is a significant step toward a unified approach in treating the above interactions.

It is therefore reasonable to predict that in studying the interactions of large bodies such as the space station with its surrounding ionospheric plasma, relevant "plasma expansion" processes will have to be considered.

In this paper we present and discuss some of the most significant results obtained from in situ measurements performed via: (1) small satellites orbiting in the ionosphere and the plasmasphere, and (2) the space shuttle mission STS-3/Columbia. We will emphasize a-priori limitations and technical shortcomings of earlier studies including studies which are now in progress. In this way, problems which need further investigation will become apparent.

2. PRESENTATION AND DISCUSSION OF THE MAIN RESULTS FROM SMALL SATELLITES

Most of the information available at the present time from in situ measurements which is relevant to satellite-ionosphere interactions comes mainly from: (1) the Ariel-I satellite (e.g., Samir and Willmore, 1965, 1966; Henderson and Samir, 1967; (2) the Explorer 31 satellite (Samir and Wrenn, 1969, 1972; Samir et al., 1973, 1975, Troy et al., 1975); (3) the Gemini-Agena 10 mission (Medved, 1969; Troy et al., 1970); (4) the Atmosphere Explorer C satellite (Samir et al., 1979a,b, 1980); (5) the USAF satellite S3-2 (Samir et

al., 1981); and (6) from the Plasma Diagnostic Package-PDP satellite on board the space shuttle STS-3/Columbia (Murphy et al., 1986; Kurth, 1986).

The Ariel I information (Samir and Willmore, 1965; Henderson and Samir, 1967) was exploratory in nature and showed for the first time the existence of a wake zone behind the satellite which is depleted of charged particles. Figure 1 shows the distribution of thermal electrons in the wake of the Ariel I as measured by a probe which was flush mounted on the surface of the satellite. Figure 2 shows the same kind of variation, obtained from a boom mounted probe at a distance of $4R_o$ from the surface of the satellite. This distance (Z) is about ($S \cdot R_o$) from the surface, where R_o = the effective radius of the satellite, and S = ionic Mach number. From Figures 1 and 2 the gradient of the [wake/ram] electron current ratio across a distance $\Delta Z = 4R_o$ along the wake axis can be obtained. The ratio $\left[\frac{I_{e(wake)}}{I_{e(ram)}}\right]$ at $Z \sim R_o$ is of the order of 10^{-2} whereas the same ratio for $Z \sim S \cdot R_o$ is of the order of 5×10^{-1} for a plasma with an ionic Mach number of $S \approx 4$.

From the measurements of the probe mounted on the boom and a spherical ion probe mounted on a stem on the satellite's spin axis, acting in itself as a wake creator, it was possible to obtain the variation of the angular distribution of normalized electron around the main body of the satellite and around the spherical ion probes. Figure 3 shows the normalized electron current $\left[\frac{I_{e(\theta)}}{I_{eo}}\right]$ as a function of the angle of attack for the cases: (a) the boom electron probe scans the disturbance created by the spherical ion probe, and (b) the boom electron probe scans the disturbance created by the main body of the satellite (Henderson and Samir, 1967). From this figure, it becomes clear that the (wake/ram) current ratio depends not only on the ionic Mach number but also on the body size and on the surface potential of the body. The spherical ion probe was biased 6 volts negative with respect to the main body, which in itself was between 0 and 1 volt negative with respect to the ambient plasma. The ratio $R_D (\equiv R_o/\lambda_D$, where: R_o = the radius of the satellite, λ_D = the ambient Debye length) was about 10 for the main body and about 2 for the ion probe. Moreover, the normalized distance (Z/R_o) of the electron boom probe from the center of the main body of the satellite was about 5 whereas the similar ratio (Z/R_o) for the spherical ion probe was about 33. The latter implies that the measurements of I_e were made at different distances downstream from the wake creating bodies. While it is not our purpose here to discuss that study in detail we demonstrate the importance of investigating the disturbances created by specific appendages mounted on satellites. In this specific case, the 'appendage' was the spherical ion probe. Unfortunately, until recently, there was no serious follow-on of such studies. Only in the space shuttle STS-3 mission, was attention given to the study of the wakes due to a variety of appendages located on the orbiter (Siskind, 1983; Siskind et al., 1984; Raitt et al., 1984). Such studies will have to be done when the space station becomes a reality.

The Explorer 31 satellite results enhanced our quantitative knowledge regarding the angular distribution of electrons and ions in the nearest vicinity to the satellite surface. Figure 4, which combines results from the Ariel I, the Explorer 31 and the Atmosphere Explorer C satellite measurements

shows the variation of electron current with angle of attack for several altitude ranges. The variation of $[\frac{I_{e(wake)}}{I_e(ram)}]$ with altitude, which can be easily deduced from Figure 4, gives the variation with a mixture of plasma and body parameters. Among such parameters we cite: (1) the ionic Mach number, (2) the normalized body size (R_D) and (3) the normalized body potential ($\phi_N = \frac{e\phi_s}{kT_e}$; where ϕ_s = body potential with respect to the local plasma potential, T_e = electron temperature). However, the information given in Figure 4 does not by itself provide for a scientifically meaningful analysis. What is needed is information regarding the variation of: $[\frac{I_{e(wake)}}{I_{e(ram)}}] = f(\theta,r)$ for specific body and plasma parameters. As will be discussed below, some preliminary investigations in this direction were performed utilizing measurements from the Atmosphere Explorer C satellite (e.g., Samir et al., 1979a,b, 1980) and from the USAF/S3-2 satellite (e.g., Samir et al., 1981). It is unfortunate that no serious attempt was made in the past to launch satellites which had the study of body-plasma interactions as a major scientific/technological objective. It is further unfortunate that the few satellites now planned for future launches do not seem to rectify this situation.

The Explorer 31 studies (e.g., Samir et al., 1973, 1975) also yielded a partial picture regarding the difference between the distribution of ion and electron fluxes for a typical ionospheric satellite in the wake. Figure 5 shows the variation of normalized ion current $\frac{I_{+(\theta)}}{I_{+(ambient)}}$ and normalized electron current $\frac{I_{e(\theta)}}{I_{e(ambient)}}$ in the wake of the Explorer 31 satellite for several altitude ranges. The quantitative difference between $I_+(\theta)$ and $I_e(\theta)$ for a limited angular range is clearly seen.

One of the most significant results from the Explorer 31 satellite was the finding that an enhancement in electron temperature in the near wake exists, i.e. $[T_e\ (wake)] > [T_e\ (ambient)]$. If one considers that $[T_e\ (ambient)] = [T_e\ (ram)]$, then this finding implies: $[T_e\ (wake)] > [T_e\ (ram)]$.

Some examples depicting the $[T_e\ (wake)]$ enhancement in the wake of the Explorer 31 satellite are given in Figure 6 (Samir and Wrenn, 1972). Similar results obtained by a different probe on the same satellite were presented and discussed by Troy et al. (1975). Earlier in-situ results from a wake experiment on the Gemini-Agena 10 spacecraft system also depicted a similar result (Medved, 1969; Troy et al., 1970). A similar phenomenon was also reported by Berthelier and Sturges (1967) during a rocket flight. Troy et al. (1975) examined the possibility that the $[T_e\ (wake)]$ enhancement may be due to geomagnetic field effects. The conclusion of that study was that if such effects are present, they are masked by the stronger effect due to the orbital velocity, i.e. by the 'wake-effect'. This conclusion is in accord with the results shown in Figure 6(c). Based on the Ariel I and the Explorer 31 measurements it was concluded that $[T_e(wake)] > [T_e(ambient)]$ is confined to the

very near wake zone, i.e. to distances $Z \lesssim S.R_o$. This conclusion is also supported by some laboratory experiments (e.g. Oran et al., 1975; Chan et al., 1986). On the other hand, the results from a cylindrical probe on the Explorer 31 do not show a [T_e (wake)] enhancement (Brace, private communication). The cylindrical probe results refer to measurements performed at a distance of about $Z \approx R_o$ from the surface of the satellite. Hence at the present time, based on in-situ measurements, the [T_e(wake)] enhancement was found only by probes flush mounted on the surface of the Explorer 31 satellite. As will be discussed in the next section, the existence of the [T_e(wake)] enhancement is now also supported by some measurements from the space shuttle (Murphy et al. 1986) and contradicted by others (Raitt et al., 1984; Siskind et al., 1984; Siskind, 1983).

A major disadvantage of most available in situ measurements is that they are confined to the very near vicinity of the satellite surface. Most probes whose data were used were flush-mounted on the surfaces of the spacecraft. In this region conceptual difficulties may arise concerning the exact meaning of [T_e(wake)]. Furthermore, it is possible to argue that when the probes are in the very near wake region, the measured currents are drastically reduced and the sensitivity limit of amplifiers can be encountered. This would result in fewer data points available for temperature determinations. This matter was discussed in detail by Samir and Wrenn [1972] and Troy et al. [1975], and it was concluded that the methods applied in the analysis of the probe measurements are an appropriate measure of the electron energy distribution in the wake. A discussion regarding the meaning of [T_e(wake)] and the reliability of measurements was also given by Illiano and Storey [1974] and by Stone [1981a] based on laboratory simulation experiments. Further laboratory studies regarding temperature in the wake were reported by Intriligator and Steel (1985).

After ruling out an explanation of the [T_e(wake)] enhancement in terms of instrumental effects, both Samir and Wrenn [1972] and Troy et al. [1975] speculated that wave-particle interactions take place in the negative potential well behind the body which results in energization of electrons. Alternatively, it is possible to infer the existence of heating mechanisms in the wake region due to stream interactions and/or instabilities correlated with plasma oscillations and turbulence in the near wake.

Whatever the cause of the enhancement in [T_e(wake)], and whatever the conditions required for its existence, no electron temperature enhancement, known to the authors, has been found for ram conditions on small satellites. We will return to this problem in the next section.

As mentioned earlier, most of the results prior to the mid 1970's focussed mainly on determining the angular distribution of electron current around the satellite at the closest vicinity to its surface. Another deficiency of the early studies is that they were not performed in a systematic parametric manner since the needed ensembles of plasma parameters were not always available.

Since the mid 1970's and particularly due to the studies made using measurements from the Atmosphere Explorer C and the S3-2 satellites, the deficiencies mentioned above were partly relaxed.

The angular distribution of the ions around the Atmosphere Explorer C (AE-C) and around the S3-2 satellite were determined for specific plasma parameter ranges (e.g., Samir et al., 1979a,b; 1980; 1981). Some significant results are shown in Figures 7 and 8. Figure 7(a) shows the variation of $\left[\frac{I_+(\Theta=165^0)}{I_+(\text{ambient})}\right]$ with average ionic Mach number S(AV) in the limited range of $3.5 < S(AV) < 4.2$. Figure 7(b) shows the variation of $\left[\frac{I_e(\text{wake})}{I_e(\text{ambient})}\right] = f(M_i(AV))$ for $M_i(AV)$ in the range 1-16. Figure 8 shows the variation of normalized ion density $\left[\frac{N_+(\Theta = 160^0)}{N_+(\text{ambient})}\right] = f(R_D)$. The latter result based on AE-C measurements (cylindrical probe) gives a quantitative measure of the importance of body size on the (wake/ram) current ratio. This study is a small-scale parametric investigation indicating the way for future parametric studies. It should be noted that the result for $R_D \gtrsim 10^2$ is already of direct interest to the interaction of large bodies with their environmental space plasmas.

Figure 9 gives the variation of $\left[\frac{I_+(\text{wake})}{I_+(\text{ambient})}\right]$ with electron temperature for various values of the ratio $\left[\frac{N(O^+)}{N(H^+)}\right]$. It is seen that the dependence on electron temperature is maximum for $N(H^+) > N(O^+)$ and minimum for $N(H^+) << N(O^+)$. This result was interpreted as being connected to the theoretical prediction of non-interacting streams upon filling in the wake zone (e.g. Al'pert et al., 1983; Stone and Samir, 1981). This issue will be further discussed below.

Recently, low energy ion measurements performed by probes on board the Dynamics Explorer 1 (DE-1) satellite were used to study some aspects of body plasma interactions in a subsonic-transonic plasma flow regime (Samir et al., 1986a). This study focussed on the wake region with particular attention given to the behavior of the (wake/ram) ion current ratio. This study deals with body-plasma interactions in a plasma flow regime not dealt with in the earlier studies. It should be noted that the lower and middle ionosphere are characterized by a supersonic/hypersonic plasma flow regime whereas the upper ionosphere and the plasmasphere are characterized essentially by a subsonic/transonic flow regime. Figure 10 shows the variation of $\frac{I_+(\text{wake})}{I_+(\text{ram})} \left(\equiv \frac{I_+(\Theta = 180^0 \pm 15^0)}{I_+(\Theta = 0^0 \pm 15^0}\right)$ with ionic Mach number, in the range of $0.46 < S < 2.4$. From this figure it follows that: (1) the ionic species (H^+ and H_e^+) act independently upon filling in the wake, or upon expanding into the wake region, and (2) there are other plasma and body parameters which control $\left[\frac{I_+(\text{wake})}{I_+(\text{ram})}\right]$ besides the ionic Mach number.

The first conclusion was also mentioned when we discussed the results of Figure 8 (see also: Samir et al., 1986a; Al'pert, 1983; Gurevich and Pitaevsky, 1975). The second conclusion was discussed in detail in Samir et al., 1979a,b; 1980; Samir, 1981.

The measurements from the DE-1 satellite were compared with a sample of measurements from the Explorer 31 satellite. Figure 11 shows the variation of $\left[\frac{I_+(\text{wake})}{I_+(\text{ram})}\right]$ with S(AV) for the DE-1 and the Explorer 31 results. As seen, both the DE-1 and the Explorer 31 results display a similar behavior despite the fact that the measurements were performed in two different flow regimes. Details of these and other DE-1 results are given in Samir et al., 1986a.

From the discussion given above it follows that the main results can be grouped as follows:

(1) Results relevant to the variaton of the (wake/ram) current ratio with a group of plasma and body parameters, namely S, R_D, ϕ_N.

(2) Results which indicate the existence of an electron temperature enhancement in the wake.

(3) In addition, from the Ariel I measurements (Samir and Willmore, 1985) it was inferred that density fluctuations exist in specific zones of the wake region, and that such fluctuations are indicative of plasma turbulence in the vicinity of the satellite. However not much attention was given to this finding until recently. Recent measurements from the space shuttle (Siskind, 1983; Siskind et al., 1984; Raitt et al., 1984; Murphy et al., 1986) revived this issue and its importance is now well recognized. However, we consider the turbulence discussed by Samir and Willmore (1965) and by Murphy et al. (1986) not to be identical to that discussed by Siskind et al. (1984) and by Raitt et al. (1984).

In summary, the main deficiencies and shortcomings of the studies discussed above are: (1) no systematic parametric investigations under a wide range of parameters were performed, therefore, the available information is fragmentary; (2) most of the studies performed so far are limited to the very near vicinity of body surfaces; and (3) the available information is meagre. This is so, since no attempt was made in the past to study in-depth the body-plasma interactions. This is not the case for spacecraft charging which was studied quite extensively. These main shortcomings do not allow yet for more in-depth studies regarding the physical processes and the main phenomena involved in body plasma interactions. These comments indicate the research avenues to be persued in future studies.

3. THE MAIN RESULTS OBTAINED SO FAR FROM THE SPACE SHUTTLE

The advent of the space shuttle with its wide range of capabilities provides an opportunity to perform controlled and carefully conceived in situ experiments of body-plasma interactions. The technology now developed for advanced missions offers opportunities not available in the past two decades of space exploration. The advantages of using space shuttle and space station capabilities such as tethered satellites, small throw-away detector packages (i.e. small satellites or "free flyers") and diagnostic packages (i.e. small satellites) mounted on remote manipulator arms significantly enhances the potential of body-plasma interaction studies. Such capabilities, used in a controlled manner, will enable the investigation of spatial regions (around

the bodies) which could not have been studied in the past. Furthermore, the availability of the space shuttle and the space station allows experimentation with the shuttle orbiter acting as a near-earth plasma laboratory. Detailed discussions regarding this experimental approach are given in Samir and Stone (1980).

It should be clear that a preliminary stage, preceeding an extensive scientific and technological study-program which utilizes the space shuttle in the above mentioned manner, should be concerned with the quantitative determination and the understanding of the interaction of the shuttle-orbiter with its environment. In fact, this stage is now in progress. Overviews regarding large vehicle-environment interactions (referring to the space shuttle) were given by Raitt (1986) and Kurth et al. (1986), representing the experience already gained by the Utah State/Stanford University and Iowa University teams, respectively (see also Samir et al., 1986c). Preliminary results obtained via the space shuttle mission STS-3 will be discussed below. They will be presented via comparison with the main results discussed in section 2.

Three groups of space shuttle results will be discussed. The first, represents the main results obtained from the measurements performed by the Utah State/Stanford University team (e.g., Siskind, 1983; Siskind et al., 1984; Raitt et al., 1984). The second represents the main results obtained from the measurements performed by the University of Iowa team (Shawhan et al., 1983, 1984 a,b; Murphy et al., 1986). The third represents the main results obtained from measurements performed by the NASA/MSFC team (Stone et al., 1983; 1986).

The results from the experiments done via the space shuttle by the above teams will be discussed in a similar manner to that of section 2. Namely, (1) the wake/ram current ratio, (2) the electron temperature in the wake and in the ram, (3) the turbulence (or density fluctuations) in the vicinity of the body, and (4) the existence of secondary ion beams in the vicinity of the body.

<u>The results for the (wake/ram) current ratio:</u> Very significant depletions in the ion and electron currents in the wake generated by the shuttle orbiter and by structural appendages were found. A result obtained by the Utah State/Stanford University team (Siskind, 1983; Siskind et al., 1984; Raitt et al., 1984) is shown in Figure 12. The amount of current depletion in the wake (i.e. the ratio $[I_e(\text{wake})/I_e(\text{ram})]$ was found to be of the order of 10^{-4}. Furthermore, Siskind (1983) reported that this value may be just an upper limit. A similar result was obtained by the University of Iowa team (Murphy et al., 1986) and shown in Figure 13. Figure 13 shows the variation of electron density with universal time. From this figure and from the corresponding attitude information (Murphy et al., 1986) it follows that the ratio $\left[\frac{N_e(\text{wake})}{N_e(\text{ram})}\right]$ is of the order of 10^{-3} when the wake is created essentially by the main body of the orbiter. Murphy et al. (1986) state that the three orders of magnitude depletion stated above may be a conservative estimate and in reality the above ratio may as well extend into the 10^{-4} - 10^{-5} range. This result is in agreement with the results of Siskind et al., 1984 and Raitt et al., 1984.

With the aid of the PDP, mounted on the Remote Manipulator System (RMS) arm (located on the shuttle orbiter), it was possible to measure the disturbances created by the orbiter at a distance of about 10 meters above the payload bay. This measurement is already an example showing the utilization of a space shuttle capability (the RMS) not available in the pre-shuttle era. It is worthwhile noting that only once, prior to the space shuttle era, was it possible to obtain the angular distribution of electrons at a distance $Z > R_o$ from the surface of the Ariel I satellite (i.e. Henderson and Samir, 1967).

Figure 14 shows the variation of electron density with universal time for the situation where the PDP was mounted on the end of the RMS arm above the payload bay (Murphy et al., 1986). For this case the wake measurements are those represented by the time interval 1700 to 1720 UT. Compared to the results shown in Figure 13 the electron depletion in the wake here is smaller. Murphy et al. (1986) claim this to be due to the fact that the measurement was taken at a distance of the order of 10 meters from the surface of the orbiter. They furthermore report that the fine structure seen correlates with the self-wakes of the PDP and the RMS (the PDP rotated while on the RMS arm). This case is more difficult to interpret unambiguously since the depletion of electron density observed in the wake is due to a mixture of causes. In any case it is interesting to note that $\left[\frac{N_e(\text{wake})}{N_e(\text{ambient})}\right]$ is of the order of 10^{-2} which is similar to the amount of electron depletion in the wake of small satellites having about the same linear dimensions as the PDP. Note that the PDP is a small satellite with a diameter of about 1 meter, and the diameter of the RMS arm is of the order of 0.3 meters. Despite the similarity to the small body, the result shown in Figure 14 requires further examination.

It is not yet possible to carry out a detailed quantitative comparison between the space shuttle results with those from the small satellites discussed in section 2. However, the greater depletion observed for the shuttle orbiter can be understood, at least qualitatively, in terms of its larger body size (see also Samir et al., 1980).

<u>The results for electron temperature enhancements.</u> In section 2 we discussed the temperature results (see Figure 6) from small satellites and stated that an enhancement in $[T_e(\text{wake})]$ is sometimes observed and that the enhancement is of the order of 30% to 100% above the $[T_e(\text{ram})] \approx [T_e(\text{ambient})]$ values.

Siskind et al. (1984) and Raitt et al. (1984) reported the finding of a very significant enhancement in electron temperature when their probe looked into the ram direction, and no enhancement in $[T_e(\text{wake})]$. This $[T_e(\text{ram})]$ enhancement is about a factor of 3 higher than the expected $[T_e(\text{ambient})]$ at an altitude of about 250 km. The elevated $[T_e(\text{ram})]$ values are considered by Siskind and Raitt to be a measure of heated electrons produced by the interaction of the shuttle orbiter and its environmental ionospheric plasma. It should be noted that such an enhancement has not been found before.

Contrary to the above findings, it was shown by Murphy et al. (1986) that no enhancement in $[T_e(\text{ram})]$ exists. Rather, an enhancement was found in $[T_e(\text{wake})]$. This enhancement is much higher than the $[T_e(\text{wake})]$ enhancements obtained from the small satellites. Figure 15(a) shows the variation of

electron temperature with universal time for the situation depicted in Figure 13 for electron density. It is clearly seen that a very significant enhancement in T_e exists when the probe looks into the wake of the main body of the orbiter. Figure 15(b) shows the variation of electron temperature with universal time for the situation given in Figure 14.

Comparing the shuttle results for [T_e(wake)] with those of small ionospheric satellites, we find that the enhancement in [T_e(wake)] increases with increasing particle depletion in the wake. If the occurence and magnitude of the [T_e(wake)] enhancement is indeed correlated with the magnitude of $[\frac{I_e(\text{wake})}{I_e(\text{ambient})}]$, then the physical processes responsible for such an enhancement, whenever and wherever it occurs should be density gradient related. It should be noted that the results from the laboratory experiment of Oran et al. (1975) and Chan et al. (1986) support the in-situ results of the small satellites. Possible physical mechanisms which may be responsible for the [T_e(wake)] enhancement were discussed in Samir and Wrenn (1972), Troy et al. (1975), and Murphy et al. (1986).

As mentioned earlier, Siskind et al., 1984, report the finding of an enhancement in [T_e(ram)]. If this enhancement is real, the question remains as to whether it is restricted only to bodies with surface properties similar to that of the space shuttle. If this phenomenon, however, is universal then many of the in situ measurements performed by current collecting probes on board satellites will have to be re-examined.

In summary, we submit that the issue of existence/non-existence and spatial locations of the [T_e(wake)] and [T_e(ram)] enhancements is an open problem. The [T_e(ram)] enhancement may have negative practical consequences regarding the interpretation and reliability of geophysical in situ measurements.

<u>The results for density fluctuations.</u> Measurements made by the Utah State/Stanford team on the space shuttle/STS-3 have revealed the existence of a high degree of turbulence in a wide spatial region around the orbiter (Siskind, 1983; Siskind et al., 1984; Raitt et al., 1984; Raitt, 1986). Hence, the turbulence found was not confined to the wake region only. Furthermore, it was found that the level of the turbulence increased when the probe was located in the ram direction and is in direct correlation with the plasma density.

Measurements of density fluctuations or turbulence made by the University of Iowa team (Murphy et al., 1986) show the turbulence, in specific frequency ranges, to be largest in a transition zone between ram and wake. Hence, it appears that the spatial location of the turbulence discussed by Murphy et al. (1986) is consistent with that reported by Samir and Willmore (1965) and is inconsistent with that of Siskind et al. (1984). This conclusion however may not depict the overall real situation since the spectral content of the two space shuttle experiments is not the same (Murphy et al., 1986; Siskind et al., 1984). In other words, the magnitude and location of the turbulence observed in the two shuttle experiments are given for different frequencies.

The question of turbulence (or density fluctuations) is important from both the scientific and technological points of view. The understanding of its nature may yield greater insight into special problems associated with the interaction of large bodies with the ionospheric plasma. Therefore further studies regarding the elevated electron temperature, in the wake and in the ram, and the turbulence are needed prior to the onset of the space station era.

The results for secondary ion streams: Measurements made by the NASA/MSFC team (Stone et al., 1983; 1986) are discussed in a companion paper (Stone and Samir) in this volume. Here we state the major result only; namely, the finding of secondary ion streams in the near vicinity of the Orbiter. The origin and acceleration mechanism of these streams are presently unknown.

Some Concluding Remarks

From the discussion given in this paper it follows that our present knowledge regarding the interaction of small and large spacecraft with their natural environment in space is still meagre and fragmentary.

In the past, the studies focused on the analysis of relatively few selected samples of measurements most of which were made by probes flush mounted on the surfaces of the satellites. Only in very few cases was it possible to obtain the disturbances created via spacecraft-space plasma interactions at distances further downstream or upstream of the spacecraft.

Recent results from the space shuttle STS-3 have extended our knowledge regarding the interaction of large space structures with the ionosphere. However, some of the major results concerning the plasma environment are in disagreement. The causes for these disagreements/inconsistencies are not yet known.

It may be possible to treat specific plasma phenomena relevant to the interaction of large structures via extrapolation, in terms of body-size, from the knowledge regarding small satellites. However, such extrapolations are limited to phenomena which are solely body-size dependent. Many other phenomena depend on other technical and scientific parameters.

The space shuttle environment, as we know it at the present time, is by far more complicated than the environment of small scientific satellites. The interaction of the space shuttle orbiter with its environment produced a cloud of outgassed material moving at orbital velocities. Such "contaminated" surroundings are due to a variety of scientific and technological causes. Among them we cite: glow, plasma turbulence, wave generation and oscillation, wake effects which spread to far distances from the body's surface, thruster operations, complex shape of the main body, structural appendages, surface erosion, dumps, induced $\underline{V} \times \underline{B}$ fields, surface charging. All the above complex of causes will exist for larger space structures and some of them will undoubtedly be more intensified.

Hence, the surfaces of the shuttle orbiter and the space station are not adequate for the location of plasma diagnostic probes. Small satellites (throw-away diagnostic packages, free-fliers, etc.) will have to be used.

Their use would be: (1) for studies of large body-environment interactions covering large regions of the "interaction space" around the body, and (2) for scientific and technological space plasma investigations.

We submit that prior to the space station era, in-depth experimental and theoretical investigations regarding the interaction of small and large structures, be conducted. There are various ways to conduct such studies with modest budgets.

The basic stage of such a study program should include in-depth empirical and theoretical investigations supported by laboratory experiments. The empirical-experimental aspect should involve the analysis of available measurements (from small satellites and from space shuttle missions). Such studies should be performed, in as much as possible, in a parametric manner rather than in a morphological one. Such studies would provide for a better quantitative understanding of the basic plasma processes common to a variety of interactions. Computer modeling (i.e., the theoretical aspect) should consider realistic situations and use realistic parameters based on the empirical-experimental results. The laboratory studies should be oriented towards ionospheric/magnetospheric space plasmas. Such an approach was not adopted in the past. Hence, we face problems that could have been solved by now if a real awareness to the problems involved in the interactions of bodies with plasmas had existed.

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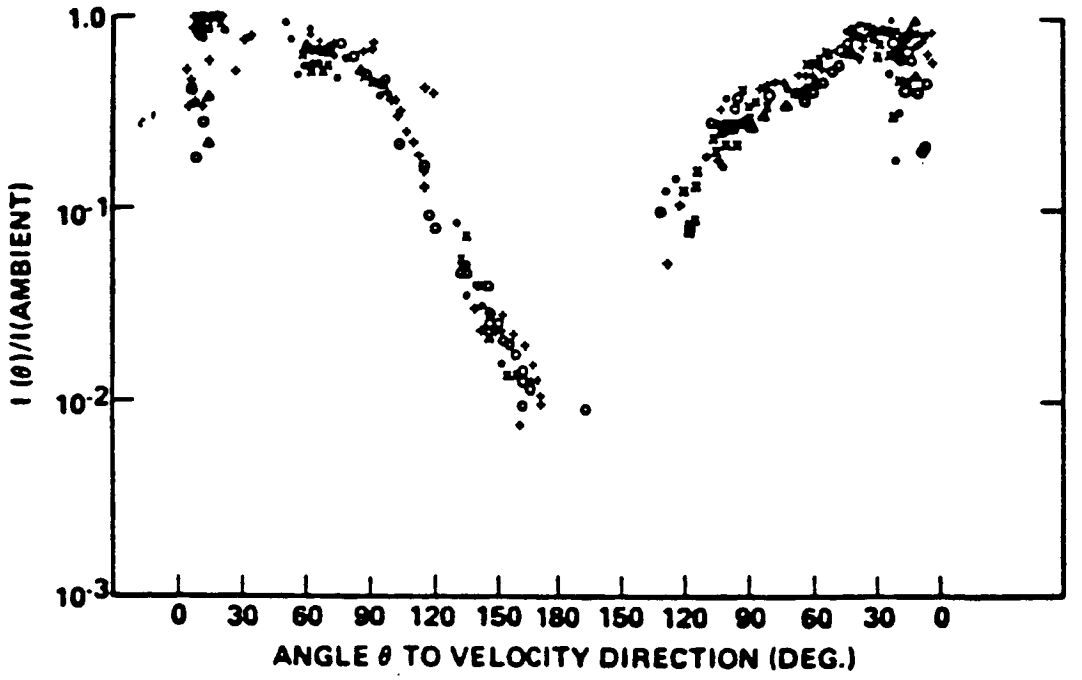

FIGURE 1:

VARIATION OF NORMALIZED ELECTRON CURRENT(I_e) WITH ANGLE OF ATTACK (θ). THE NORMALIZED CURRENT IS THE RATIO OF $I_e(\theta)$ TO $I_{e0}(\equiv I_e$ (AMBIENT)) MEASURED AT $Z \sim R_0$ i.e., AT THE NEAREST VICINITY TO THE SATELLITE'S SURFACE.

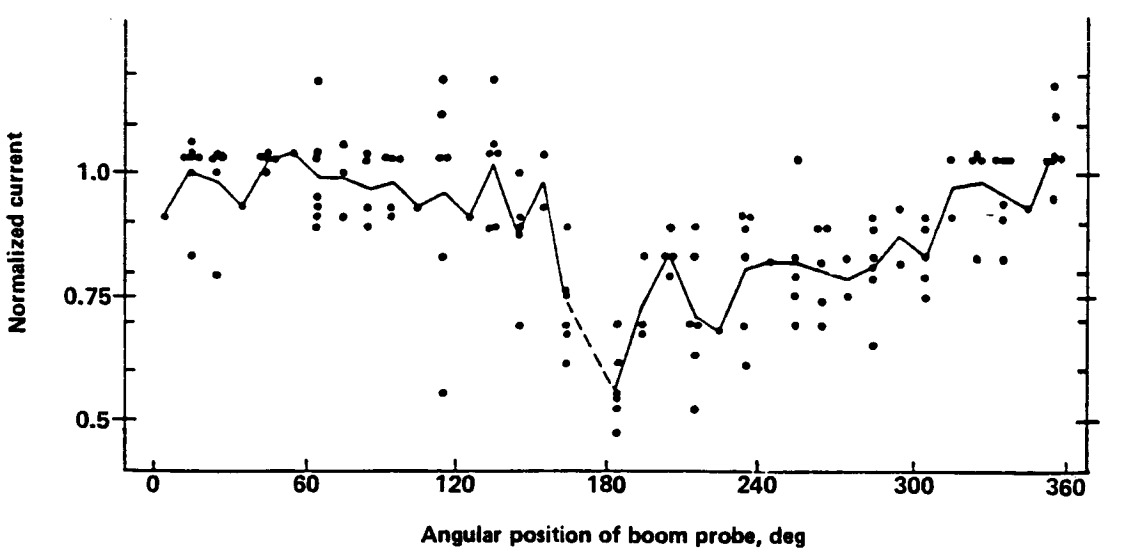

FIGURE 2:

VARIATION OF NORMALIZED ELECTRON CURRENT WITH ANGLE OF ATTACK AS MEASURED AT $Z \approx S \cdot R_0$.

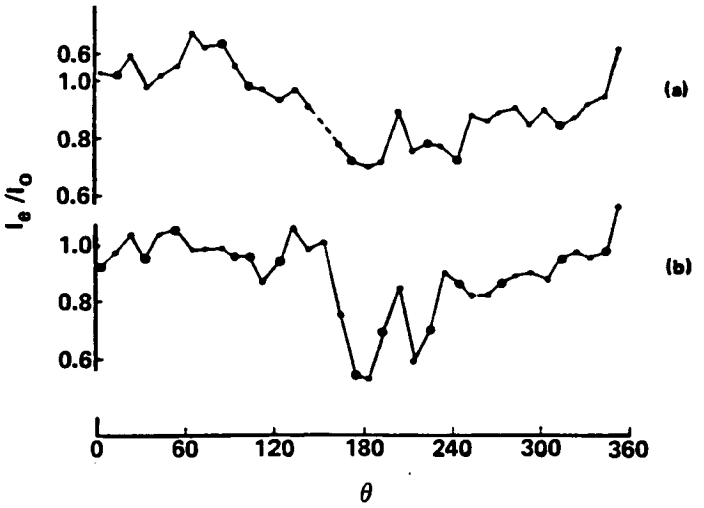

FIGURE 3:
VARIATION OF NORMALIZED ELECTRON CURRENT WITH ANGLE OF ATTACK FOR: (a) THE ION SPHERICAL PROBE AND (b) THE MAIN BODY OF THE SATELLITE.

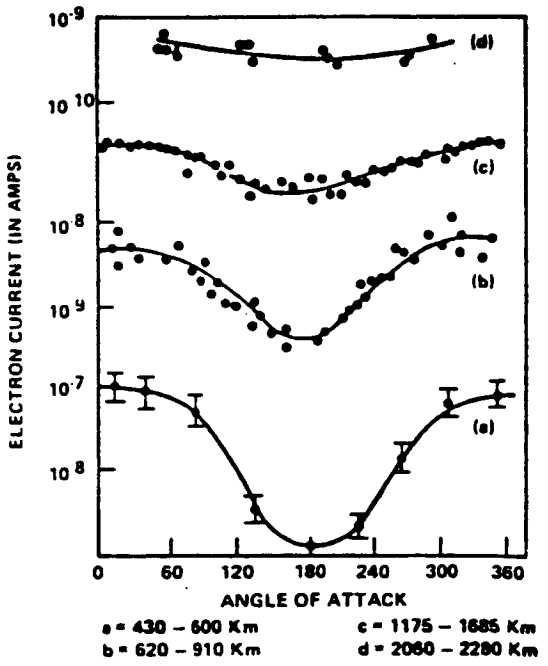

FIGURE 4:
VARIATION OF ELECTRON CURRENT (IN AMPERES) WITH ANGLE OF ATTACK FOR THE ALTITUDE RANGES: (a) 430 TO 600 KM, (b) 620 TO 910 KM, (c) 1175 TO 1685 KM AND (d) 2060 TO 2280 KM, BASED ON ARIEL I EXPLORER 31 AND ATMOSPHERE EXPLORER C MEASUREMENTS.

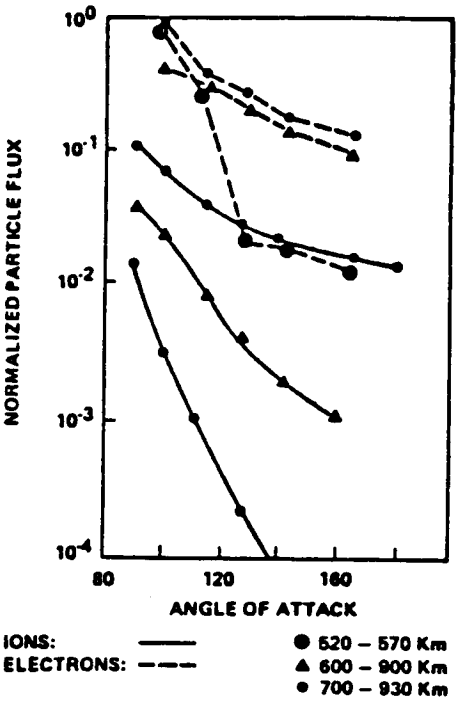

FIGURE 5:
VARIATION OF NORMALIZED ION CURRENTS (SOLID LINE) AND ELECTRON CURRENTS (DASHED LINE) IN THE WAKE OF THE EXPLORER 31 SATELLITE IN THE ALTITUDE RANGES: 520 TO 570 KM (●); 600 TO 900 KM (▲) AND 700-930 KM (•).

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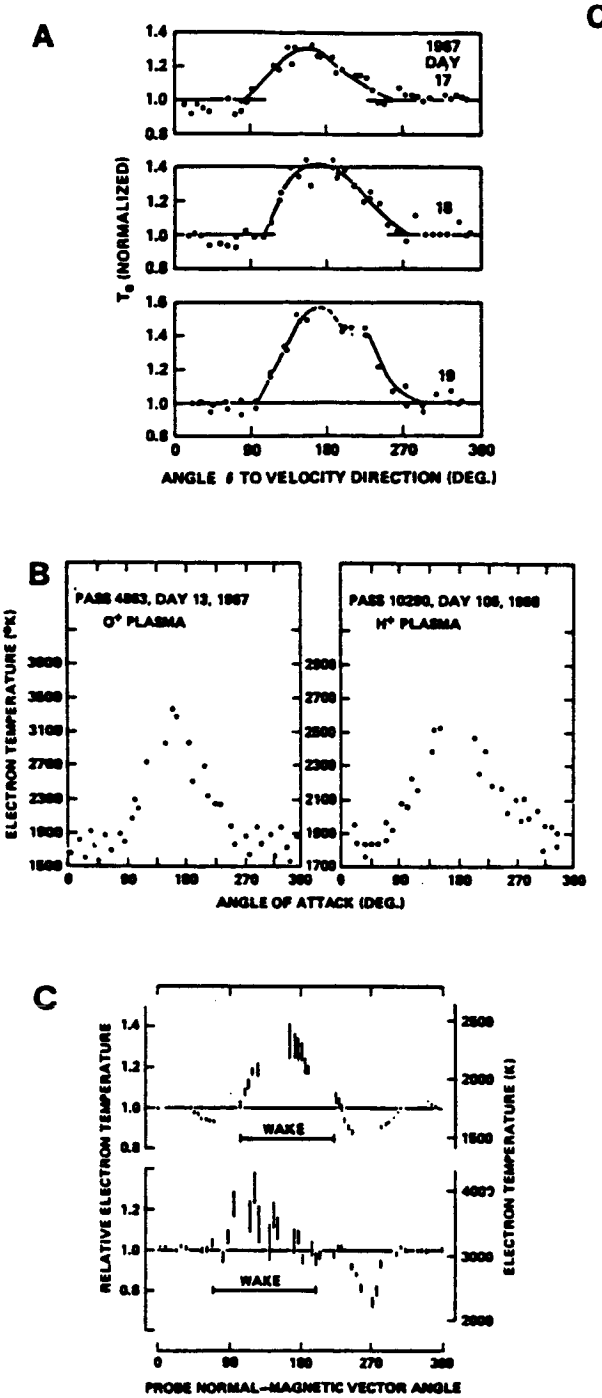
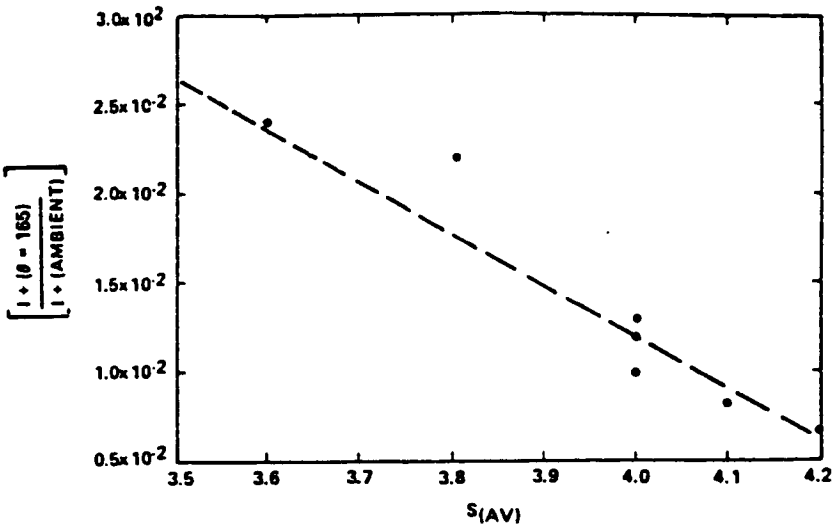


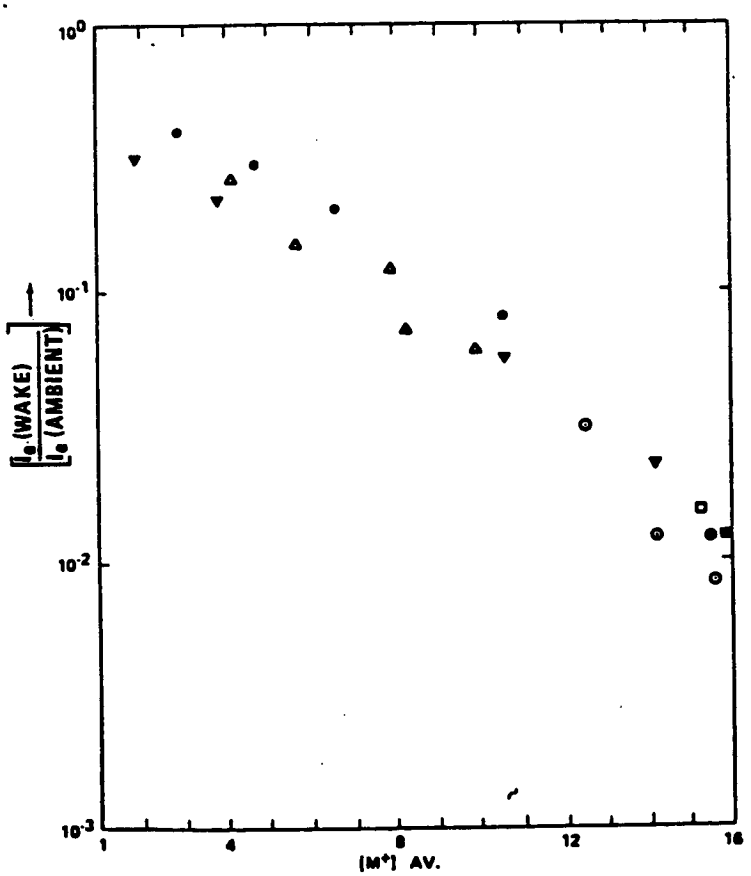
FIGURE 6:

VARIATION OF ELECTRON TEMPERATURE WITH ANGLE OF ATTACK DEPICTING THE T_e (WAKE) ENHANCEMENT.

- **(a)** **[T_e (WAKE)] ENHANCEMENT OBTAINED FOR SEVERAL DAYS AT THE ALTITUDE RANGE 800-900 KM.**
- **(b)** **TWO EXAMPLES SHOWING [T_e (WAKE)] FOR O^+ AND H^+ DOMINATED PLASMAS.**
- **(c)** **WAKE–EFFECT ON T_e OVERTAKES ANY VARIATION OF T_e WITH THE GEOMAGNETIC FIELD.**



(a) VARIATION OF $\left[\frac{I_+ (\theta = 165^o)}{I_+ (AMBIENT)}\right]$ WITH AVERAGE IONIC MACH NUMBER (S(AV)), BASED ON MEASUREMENTS FROM THE EXPLORER 31 SATELLITE.



(b) VARIATION OF $\left[\frac{I_{e^-}(WAKE)}{I_e (AMBIENT)}\right]$ WITH $M_+(AV)$ FOR SEVERAL SATELLITE PASSES OVER THE ALTITUDE RANGE 520 TO 1020 KM. EXPLORER 31 MEASUREMENTS.

FIGURE 7

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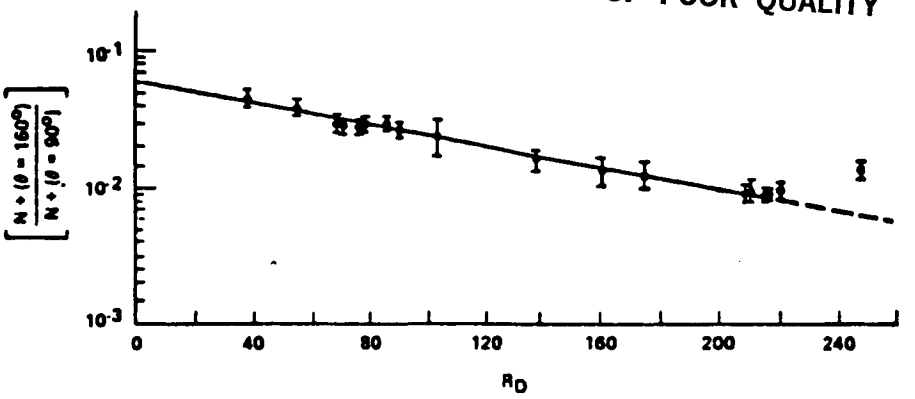


FIGURE 8:
VARIATION OF $\left[\frac{N_+(\theta = 160^0)}{N_+(\text{AMBIENT})}\right]$ WITH NORMALIZED BODY SIZE R_D, BASED ON MEASUREMENTS FROM THE ATMOSPHERE EXPLORER C SATELLITE.

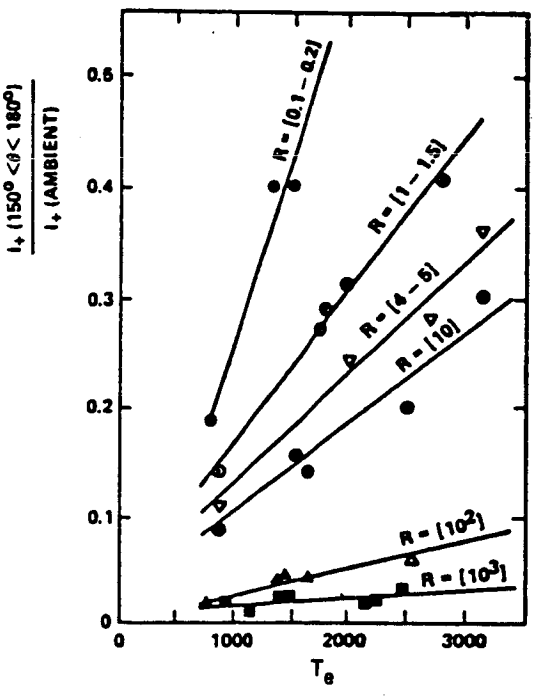


FIGURE 9:
VARIATION OF $\left[\frac{I_+(150^0 \leqslant \theta \leqslant 180^0)}{I_+(\text{AMBIENT})}\right]$ WITH ELECTRON TEMPERATURE (T_e) FOR SEVERAL RATIOS OF $R = N(O^+)/N(H^+)$ BASED ON MEASUREMENTS FROM THE ATMOSPHERE EXPLORER C SATELLITE

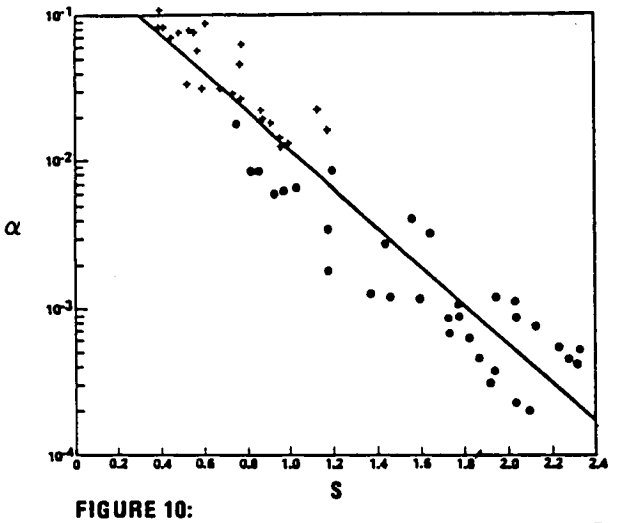


FIGURE 10:
VARIATION OF $\left[\frac{I_+ (WAKE)}{I_+ (RAM)}\right] = \left[\frac{I_+ (\theta = 180^0 \pm 15^0)}{I_+ (\theta = 0^0 \pm 15^0)}\right]$
WITH IONIC MACH NUMBER FOR $0.4 \leq S \leq 2.4$

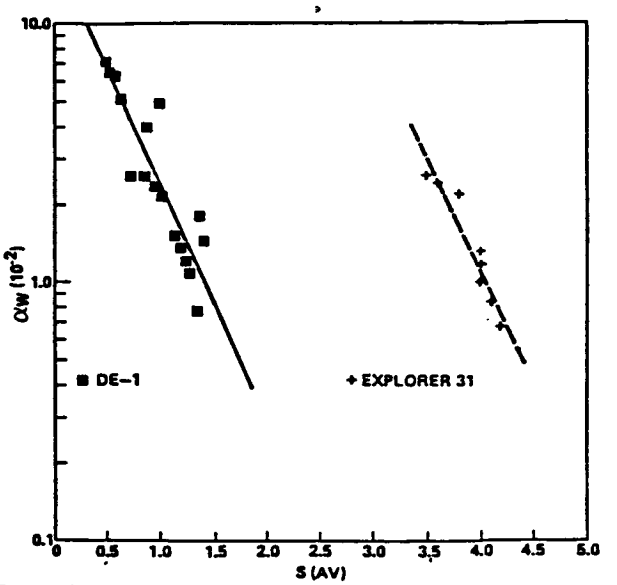


FIGURE 11:
VARIATION OF $\left[\frac{I_+ (WAKE)}{I_+ (RAM)}\right]$ WITH S(AV) FOR DYNAMICS EXPLORER 1 AND EXPLORER 31 MEASUREMENTS.

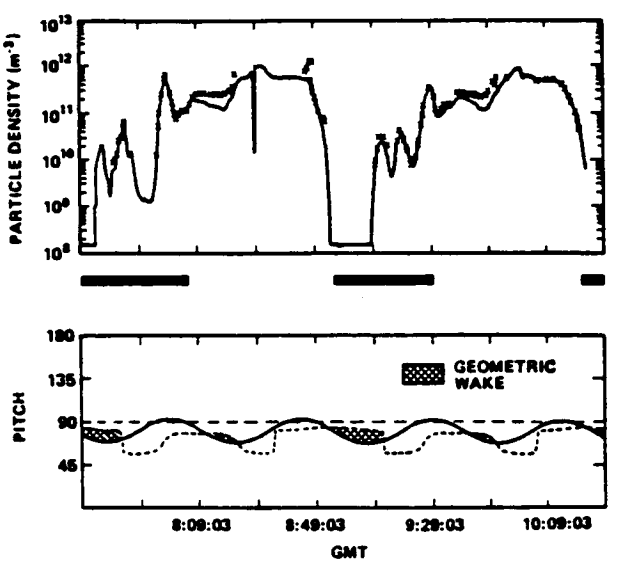


FIGURE 12:
VARIATION OF ELECTRON (SOLID CURVE) AND ION (X) DENSITY WITH CHANGES IN SHUTTLE/ORBITER ATTITUDE. HEAVY BARS BELOW THE TOP PANEL INDICATE NIGHT TIME PERIODS. THE LOWER PANEL GIVES THE TIME INTERVALS FOR WHICH WAKE MEASUREMENTS WERE PERFORMED. AFTER: SISKIND, 1983.

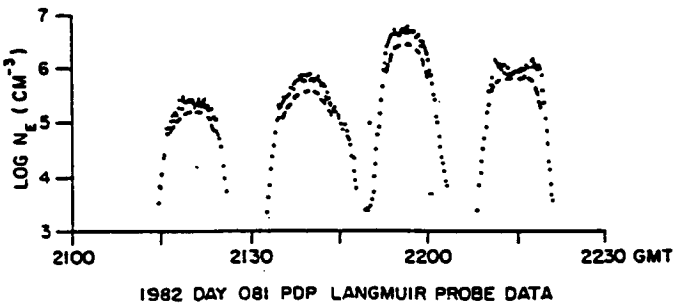


FIGURE 13:

VARIATION OF ELECTRON DENSITY WITH UNIVERSAL TIME FOR THE SITUATION WHERE THE PDP WAS IN THE SHUTTLE ORBITER BAY. HENCE, THE MEASUREMENTS THAT YIELD $\left[\frac{N_e\ (WAKE)}{N_e\ (AMBIENT)}\right]$ ARE FOR THE WAKE CREATED (ESSENTIALLY) BY THE ORBITER. AFTER: MURPHY ET AL, 1986.

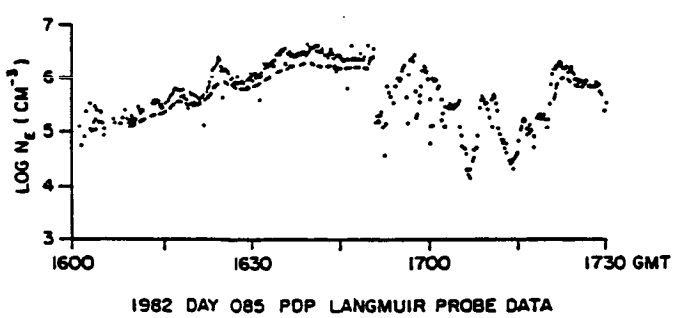


FIGURE 14:

VARIATION OF ELECTRON DENSITY WITH UNIVERSAL TIME FOR THE SITUATION WHERE THE PDP WAS MOUNTED AT THE END OF THE RMS ARM ABOVE THE PAYLOAD BAY. AFTER: MURPHY ET AL, 1986.

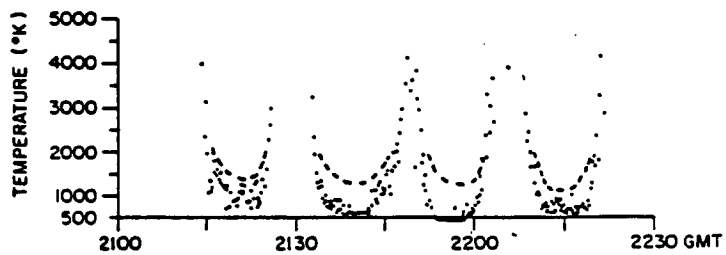
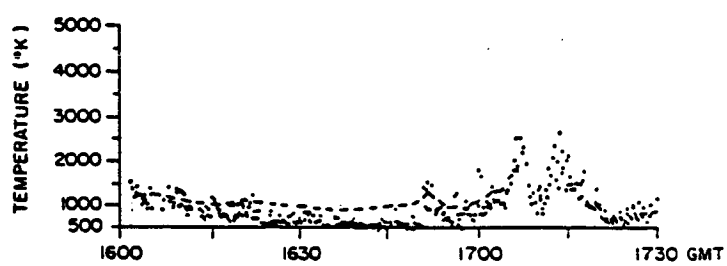


FIGURE 15:

(a) VARIATION OF ELECTRON TEMPERATURE WITH TIME FOR THE SITUATION GIVEN IN FIGURE 13.



(b) VARIATION OF ELECTRON TEMPERATURE WITH TIME FOR THE SITUATION GIVEN IN FIGURE 14.

N87-20065

PREDICTING THE MAGNETOSPHERIC PLASMA OF WEATHER

by

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I. INTRODUCTION

When I was asked to talk on plasma technology for the space station I had a little trouble deciding just what to talk about. Being basically a plasma physicist and not really an expert on the space station, I knew there were potentially a large number of technological applications; the subject of plasma physics is very broad and its technological applications are expanding every day. Probably the most important applications to the space station have not yet been thought of. Some topics which I considered but rejected were the following.

A. Applications of Fusion to the Space Station

Fusion research has made substantial gains in the last few years. Fusion as a power source for a space station would have many advantages. However, I do not expect that a fusion power source, particularly one that can be employed on the space station, will be available by the year 2000. But I do think this is something people who are interested in plasma technology for space should keep their eyes on.

I might interject at this stage that it recently has been realized that the lunar soil contains a large amount of ^{3}He; a very good and particularly clean fusion fuel. It appears that it is economical to mine it from the lunar soil and return it to Earth.

Finally towards the end of this talk I will mention one possible application of fusion technology which I think might find some interesting and useful immediate applications.

B. Building of Very Powerful Plasma Thrusters (100's of Kg thrust)

There seems to me to be some rather interesting possibilities here. However, I believe this application may find more use in things like manned Mars missions or sending large payloads on deep space missions, than on the space station.

C. Plasma Materials Processing

One might do something here, but plasma processes tend to be energy intensive and it is not clear that there is something that can be done on the space station that cannot be done better on Earth. However, there are probably important applications in fabricating space station components on Earth.

D. Investigations in Plasma Science

I think this will clearly be an important aspect of the space station. It will be flying in a interesting plasma supplied free by nature. We clearly will want to learn more about this plasma and it will offer unique opportunities for experiments. We may also want to create our own plasmas to experiment on in space. I regard this as an important activity of the space station but did not feel that it quite was in the spirit of technological applications of plasma to the space station.

II. PREDICTING THE PLASMA WEATHER FOR THE SPACE STATION

The subject I did decide to talk on, "Developing a Predictive Capability for the Plasma Condition at the Space Station", may seem rather theoretical, but I believe it truly comes under the heading of a plasma technological development of importance to the space station. What I am concerned with is predicting the plasma environment in time, the plasma weather, if you will. I know the space station will be operating in a relatively low orbit near to the equator where it is largely protected from larger variations produced by solar activity. It will be in a sheltered cove, so to speak. Nevertheless, we know that from time to time there are large magnetic storms that have produced aurora's as far south as Mexico City. It will be important to be able to predict when and what precautions to take both for the people on board and probably for such things as sensitive control (computer) equipment. We will also want to start establishing both a set of plasma weather records and records of our ability to predict similar to what has been accumulated for the Earth's weather over the last hundred years or so.

A successful forecasting system will require:

1. A set of satellite weather stations to provide data from which predictions can be made. It will be particularly important to have stations between the Earth and Sun so that data on the incoming solar wind can be obtained. One may want solar observations that can see regions of the sun not visible from Earth. The development of a capability for remotely sensing the conditions of the magnetosphere and solar wind plasmas would be very desirable.

2. A set of plasma weather codes capable of accurately forecasting the status of the Earth's magnetosphere in sufficient detail when provided with the data.

I will return to the data gathering shortly and start by discussing the problems of obtaining a predictive capability.

One of the efforts at UCLA has been in numerical modeling of the magnetosphere. These efforts have been aimed at using MHD fluid models to attempt to simulate the large scale behavior of the magnetosphere. With these models we have tried to reproduce many of the effects observed in the magnetosphere. We have had some success, but these efforts are still far from having a predictive capability. Nevertheless, they are sufficiently encouraging that over the

next twenty years or so I believe it is possible to develop a predictive capability if the effort is put into it.

Let me start by giving a quick review of some of the findings. The basic model is shown in Figure 1. The earth is represented as a simple dipole embedded in the solar wind flow. Simple MHD fluid equations are used to model the dynamics of this system; these are:

$$\rho \left(\frac{\partial \underset{\sim}{v}}{\partial t} + \underset{\sim}{v} \cdot \underset{\sim}{\nabla}\underset{\sim}{v}\right) = \frac{\underset{\sim}{j} \times \underset{\sim}{B}}{c} - \underset{\sim}{\nabla} p + g\rho + \mu\nabla^2 \underset{\sim}{v} \tag{1}$$

$$\frac{\partial p}{\partial t} + \underset{\sim}{\nabla} \cdot (p\underset{\sim}{v}) = D\nabla^2 p \tag{2}$$

$$\frac{\partial P}{\partial t} + \underset{\sim}{v} \cdot \underset{\sim}{\nabla} P = -\gamma P \underset{\sim}{\nabla} \cdot \underset{\sim}{v} + D_p \nabla^2 P \tag{3}$$

$$\frac{\partial \underset{\sim}{B}}{\partial t} = \underset{\sim}{\nabla} \times (\underset{\sim}{V} \times \underset{\sim}{B}) - \eta\nabla^2 \underset{\sim}{B} \tag{4}$$

$$j = \nabla \times \left(\underset{\sim}{B} - \underset{\sim}{B}_{dipole}\right) = \underset{\sim}{\nabla} \times \underset{\sim}{B} \tag{5}$$

$$\gamma = 5/3 \ , \quad N = N_o \ (T/T_o)^{-3/2}$$

Reynolds Numbers Run, S = 100-1000

The solar wind (containing its own magnetic field) flows in from the left and out at the right; the boundary conditions along the sides are such as to have only outgoing disturbances there. Typical parameters used in the model are the following:

Grid 48×48×24 (North-South Mirror Symmetry)

$\Delta x = \Delta y = \Delta z = 1 \ R_e$

$N_{SW} = 5/cm^3$, $V_{SW} = 300$ km/sec

$T_{SW} = 2\times10^{50}$ K

$\underset{\sim}{B}_{IMF} = (0, B_{IMF} \cos\theta, B_{IMF} \sin\theta)$

$|B_{IMF}| = 5$ nT

We have used this model to model the flow in the magnetosphere, the currents flowing into and out of the auroral regions, the magnetopause, the bow shock location and the magnetotail of the earth. Most of these, of course, would only indirectly effect the plasma weather at the Space Station.

Let me show you some general features of the flow that this model gives. There is, of course, the bow shock, magnetopause and plasma sheath in the tail. There are also large convective or vortex-like motions set up just as there are in the flow of fluid around an object. Figure 2 shows a sketch of such flows. Such vortexes can act as huge MHD generators that drive currents into and out of the auroral regions. The results of such 3-dimensional calculations can be very complex as shown by the so-called spider diagram for the magnetic field shown in Figure 3. We need some simpler ways to analyze and interpret what is going on.

One way to analyze the results of such calculations is by projecting the quantities of interest along the magnetic field line onto the polar regions of the earth. Such projections are shown in Figure 4.

In this figure we see the plasma pressure, the field aligned current, the vorticity and the plasma flow parallel to B projections. You see that these are quite complicated patterns looking much like conventional weather maps. One of the successes of the simulation was the prediction of the θ aurora; this was almost simultaneously discovered by satellite and in the simulation. Fig. 5 shows observations of the θ aurora; it occurs only when there is a northward IMF. I believe the observations preceded the calculation by a few months but the calculations were already being carried out and were not influenced by the observations.

In the computations, such a configuration was obtained by introducing a solar wind magnetic field in the northward direction. The resulting polar projections are shown in Figure 6.

One can see the currents flowing into and out of the ionosphere now form a θ pattern. As one goes down the figure one sees what happens as one rotates the solar wind magnetic field in the west/east direction; the pattern shifts east and west. At the bottom are shown results for a southward solar wind field.

We have also compared observed currents into the polar regions with our computations. The agreement that is obtained is shown in Figs. 7, 8 and 9.

We see regions where the current flows in and out as observed and as predicted; the agreement is fairly good.

These results give us some confidence that the models are predicting real effects; what needs to be done? There are many unrealistic aspects of the models. Below I have a list of some of the shortcomings of the present models:

1. The grid is much too coarse to give real details of what is happening near the earth. Grid size at least 1 R_e; projection patterns look good because of the convergence of the field lines.

2. There is no accurate treatment of the ionospheric or magnetospheric coupling. The physics of the ionosphere must be put in. Such physical processes including a saturation current (electron flow velocity) along the field lines and kinetic effects as magnetic mirroring of the electron need to be included.

3. The models are simple MHD ones and subtle physics of more realistic models is not contained in them. Relative slips between electrons and ions across B [the Hall effect]; individual electron and ion pressure effects, multicomponent plasmas [H, N, O, He, etc.], Vlasov [kinetic effects], the effects of microturbulence, ... The importance of all these effects is not yet known.

4. Lack of sufficient data so that something like a detailed prediction based on it can be made and compaired with observations.

The last of these points is quite a serious one, I believe, if we expect any kind of accurate predictions. We do have quite a number of satellites and spacecraft out observing the plasma conditions in the magnetosphere and in the solar wind, but these make measurements only at points along their orbits. We also have observations of the sun and we know something about what the occurrence of flares of a certain magnitude will do but I think it is safe to say we are a long way from a real predictive capability.

As far as the space station goes, it could launch a large number of observational satellites which it could monitor from its vantage point. It should also be able to make much better observations of the sun as has already been shown with sky lab and other satellites. However, I expect that all of these will not give the amount and quality of data we would want for a predictive capability.

Remote sensing of plasma conditions by scattering of electromagnetic waves from the plasma is used all the time in diagnosing fusion and laboratory plasma. It would be worthwhile to explore this possibility in some detail for the magnetospheric and solar wind plasmas, as illustrated in Fig. 10. A wide range of frequencies can be used. Also the scattered radiation could be measured by satellites at various places as well as by the space station. A second thing that can be done is to measure refraction and phase shifts of satellite signals which has to do with their passage through intervening plasma on the way to the space station.

Finally I would like to mention one more technique for monitoring the magnetosphere. This is to inject positrons into flux tubes, as illustrated in Fig. 11. These will follow the field lines and move with the $E \times B/B^2$ velocity. They are easily detected when they annihilate with electrons and the detection techniques are highly developed for medical PET scans, illustrated in Fig. 12. Relatively few positrons are required, I believe, because the background should be very low. I think $\sim 10^{-3}$ to 10^{-6} positrons per cubic meter will be enough. Nevertheless, a large number will be needed because of the large volume.

Positrons generally require a large amount of energy to create; typically ~10-20 Gev per positron and energy is a premium commodity on the space station. Here is where fusion technology might make a direct contribution.

The simplest way to make positrons is to create positron emitters by bombarding suitable isotopes with energetic protons; Table 1 lists some possibilities with thresholds' energies and half-lives. Generally the positron emitters are made by bombarding the isotopes with 10 MeV protons from a cyclotron. Typically these produce 100 μ A of 10 MeV protons and can generate 100 n A of positrons. This is much too small.

Fusion technology may help us. If we use the D-^{3}He reaction it makes a 14.7 Mev proton suitable for producing the (pn) reactions needed. Very powerful neutral D beams have been produced (10's to 100's of A) at about 100 Kev which are suitable for producing D-^{3}He reactions. These should be able to produce maybe ~10^{-2} to ~10^{-1} A of 14.7 Mev protons. It appears that by properly seeding the fusion plasma with the right fertile isotopes 10^{-3} of these protons can be converted to positron emitters so we might get 10^{-5} to 10^{-4} A of positrons. This is 2 to 3 orders of magnitude more positrons than from a cyclotron and would give us the number of positrons we need (~10^{14} -10^{17}) in (~1-3 hours); this is enough to be interesting.

TABLE 1. Some (pn) Reactions for Positron Production

$D + {}^3He \rightarrow {}^4He + p$ (14.7 MeV)

1. $p + {}^{11}B \rightarrow {}^{11}C + n$ (E_T = 2.76 MeV)
   ${}^{11}C \rightarrow {}^{11}B + {}^+\beta$ ($\tau_{1/2}$ = 20 min.)

2. $p + {}^{13}C \rightarrow {}^{13}N + n$ (E_T = 3 MeV)
   ${}^{13}N \rightarrow {}^{13}C + {}^+\beta$ ($\tau_{1/2}$ = 10 min.)

3. $p + {}^{15}N \rightarrow {}^{15}O + n$ (E_T = 3.53 MeV)
   ${}^{15}O \rightarrow {}^{15}N + e^+$ ($\tau_{1/2}$ = 2.03 min.)

$\sigma \approx 200$ mb

4. $p + {}^{17}O \rightarrow {}^{17}F + n$ (E_T = 3.55 MeV)
   ${}^{17}F \rightarrow {}^{17}O + {}^+e$ (τ_{V_2} = 66 sec.)

5. $p + {}^{18}O \rightarrow {}^{18}F + n$ (E_T = 2.45 MeV)
   ${}^{18}F \rightarrow {}^{18}O + {}^+e$ ($\tau_{1/2}$ = 1.87 hr.)

6. $p + {}^{19}F \rightarrow {}^{19}Ne + n$ (E_T = 4.03 MeV)
   ${}^{19}Ne \rightarrow {}^{19}F + {}^+e$ ($\tau_{1/2}$ = 18 sec.)

7. $p + {}^{26}Mg \rightarrow {}^{26}Al + n$ (E_T = 5.01 MeV)
   ${}^{26}Al \rightarrow {}^{26}Mg + {}^+e$ ($\tau_{1/2}$ = 6.5 sec.)

Acknowledgements

I wish to acknowledge valuable interactions with R.J. Walker, T. Ogino, M. Ashour-Abdalla and P. Pritchett on these research topics. This work was partially supported by NSF Contract No. ATM 85-21125.

FIGURE CAPTIONS

Fig. 1 Model of the Magnetosphere and Solar Wind.

Fig. 2 Vortex Flow Pattern from MHD Model of Ogino.

Fig. 3 Spider Diagram for the Magnetic Field Around the Earth from Ogino's MHD Calculation.

Fig. 4 Projection of Various Quantities Along B Lines onto the Polar Region - Taken from MHD Simulation of the Magnetosphere.

Fig. 5 Satellite Observations of θ Aurora.

Fig. 6 Polar Projections of the Vorticity, the Field-Aligned Current and the Open Field Region for Various Orientations of the Solar Wind Magnetic Field. 90° is northward, 270° is southward.

Fig. 7 Field Aligned Currents: Model and Observations (θ=105°, θ=150°).

Fig. 8 Field Aligned Currents: Model and Observations (θ=90°, θ=105°, θ=150°).

Fig. 9 Field Aligned Currents: Model and Observations (θ=180°, θ=210°).

Fig. 10 Schematic for Remote Sensing of Magnetospheric Plasma Conditions.

Fig. 11 Magnetosphere of Earth with Positron Sampling a Flux Region.

Fig. 12 Schematic of a Positron Detector.

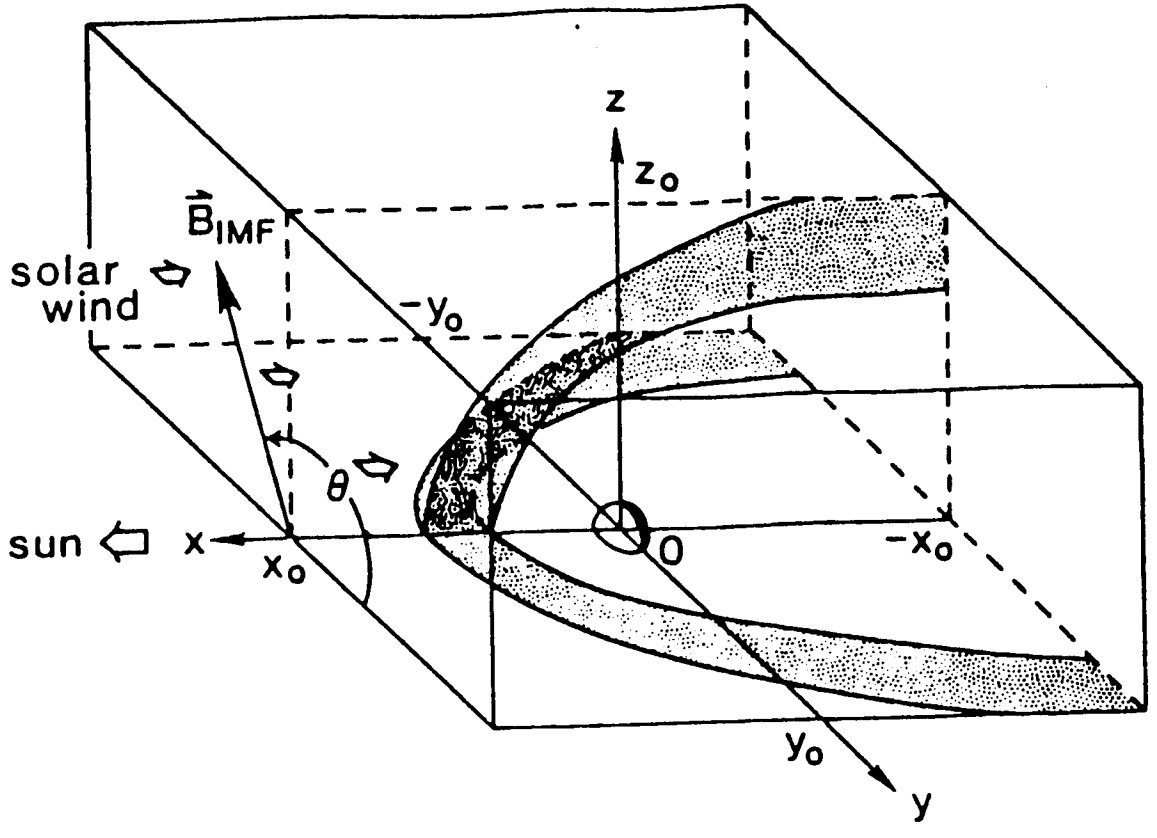
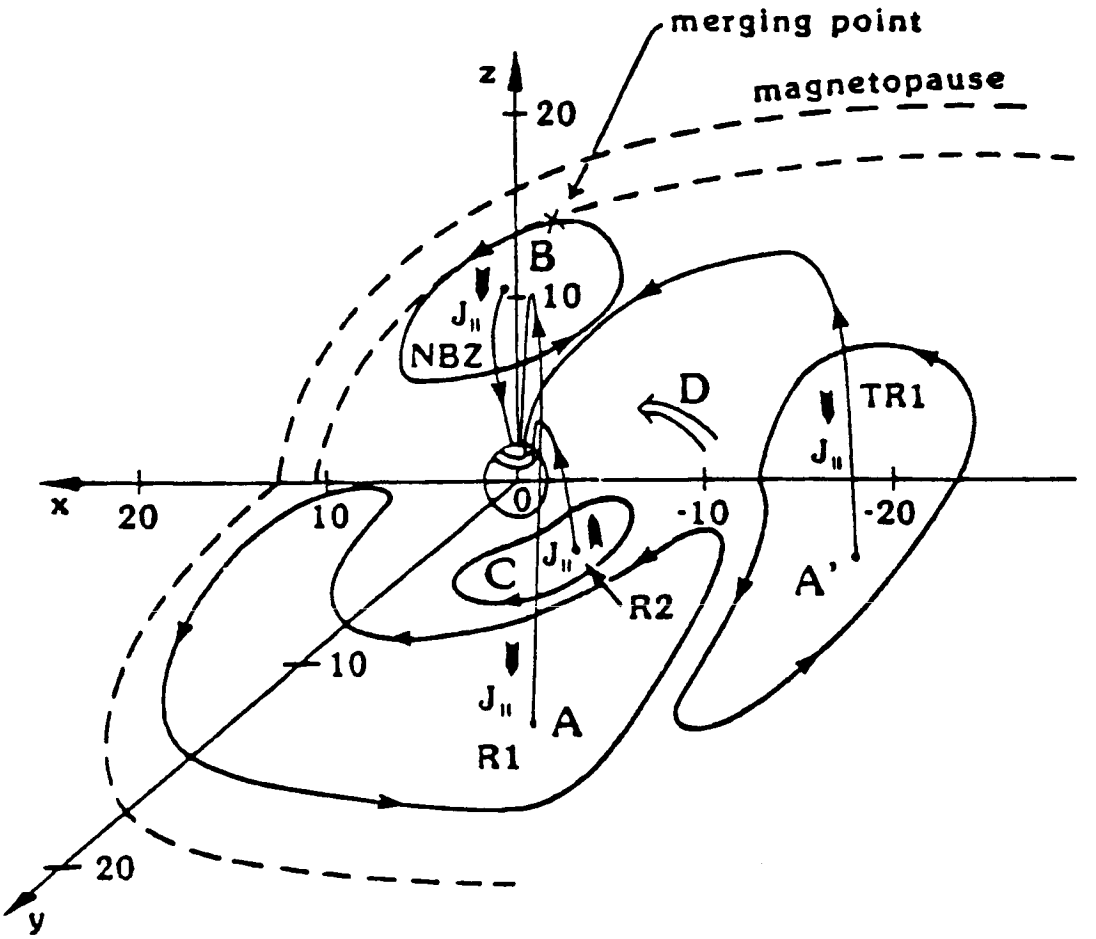


Fig. 1


merging point
magnetopause
z
20
B
10
$J_{\parallel}$
NBZ
D
TR1
$J_{\parallel}$
x
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10
0
-10
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$J_{\parallel}$
R2
A'
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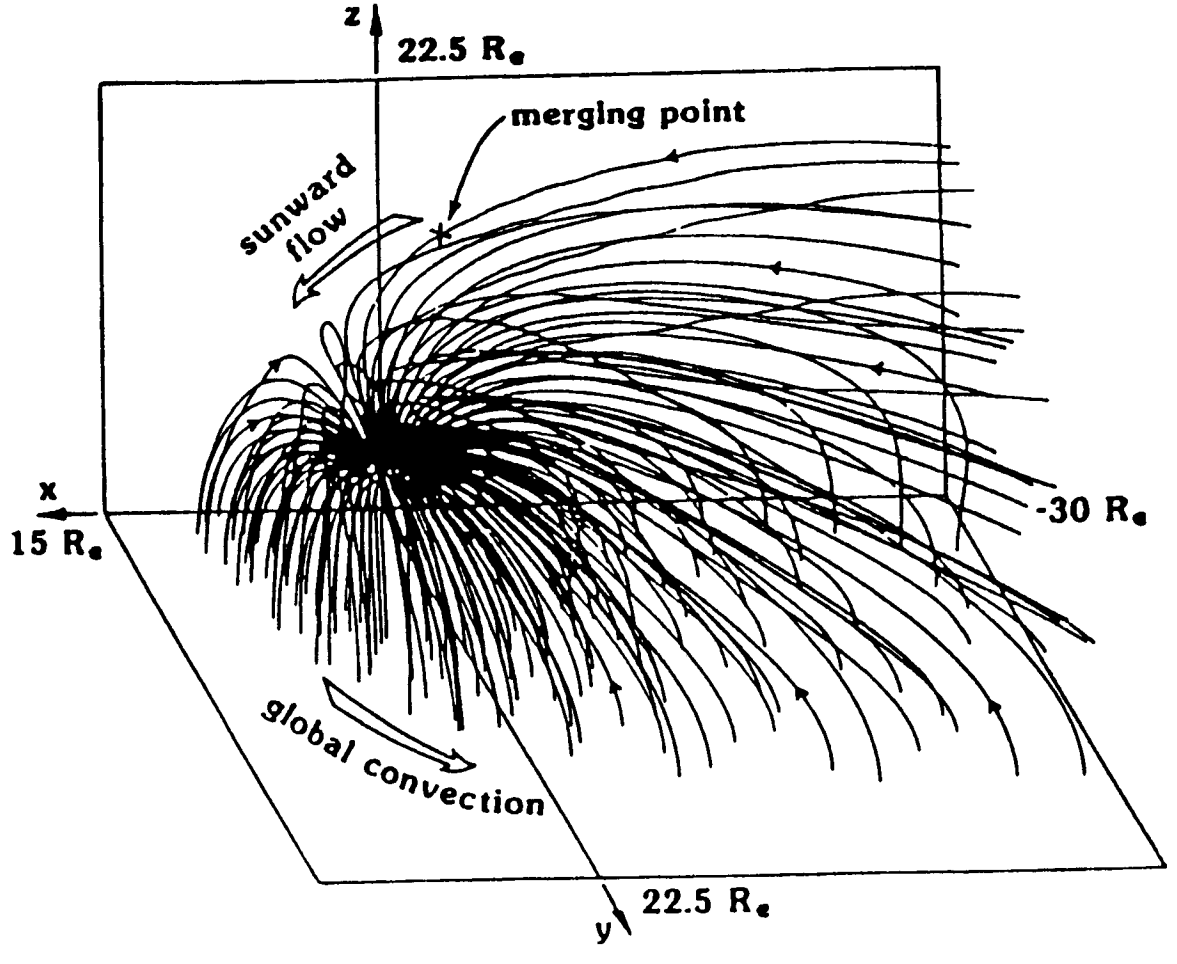
$J_{\parallel}$
A
R1
20
y

Fig. 2


z
22.5 R_e
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x
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-30 R_e
global convection
22.5 R_e
y

Fig. 3

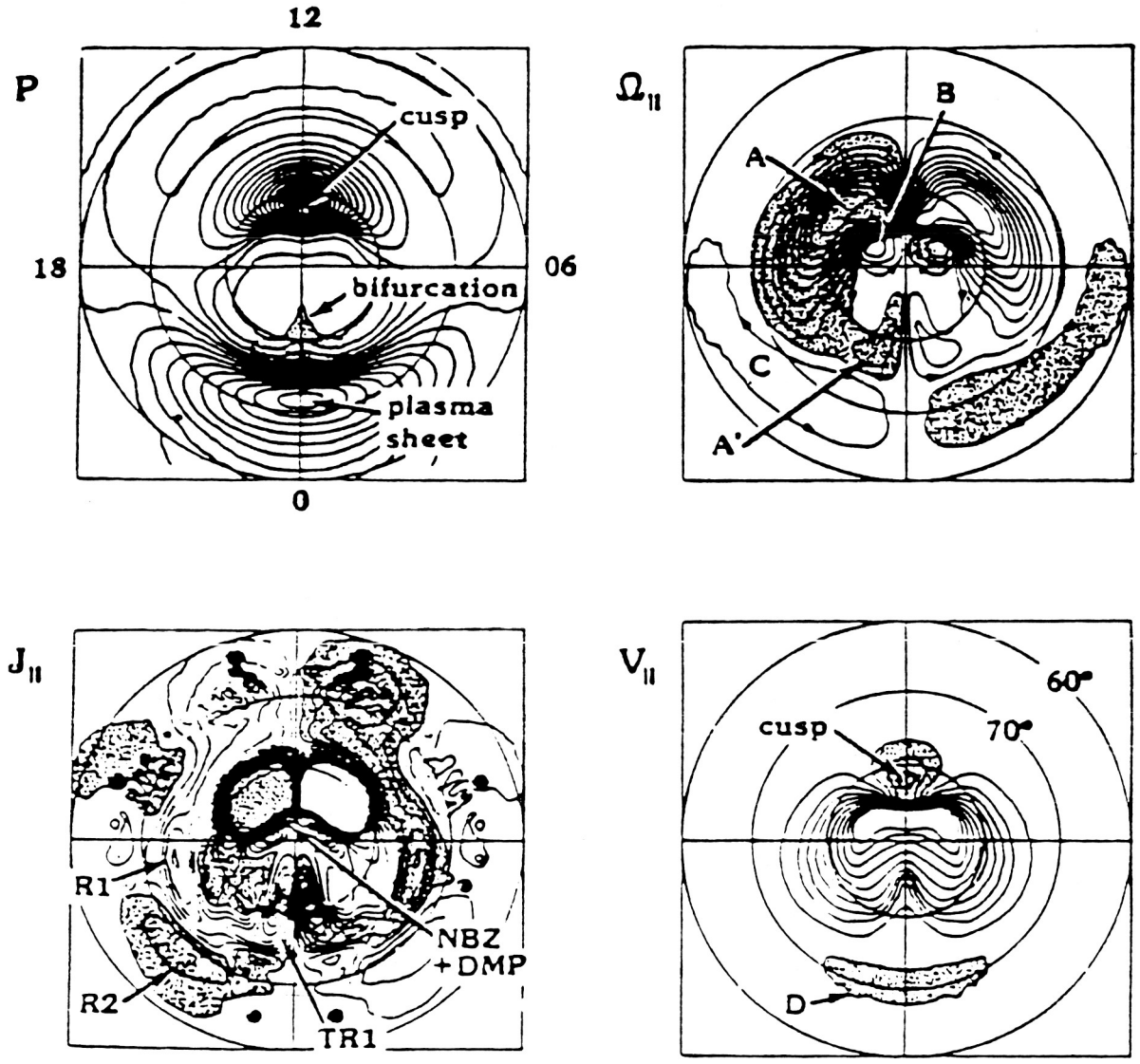
12
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Fig. 4

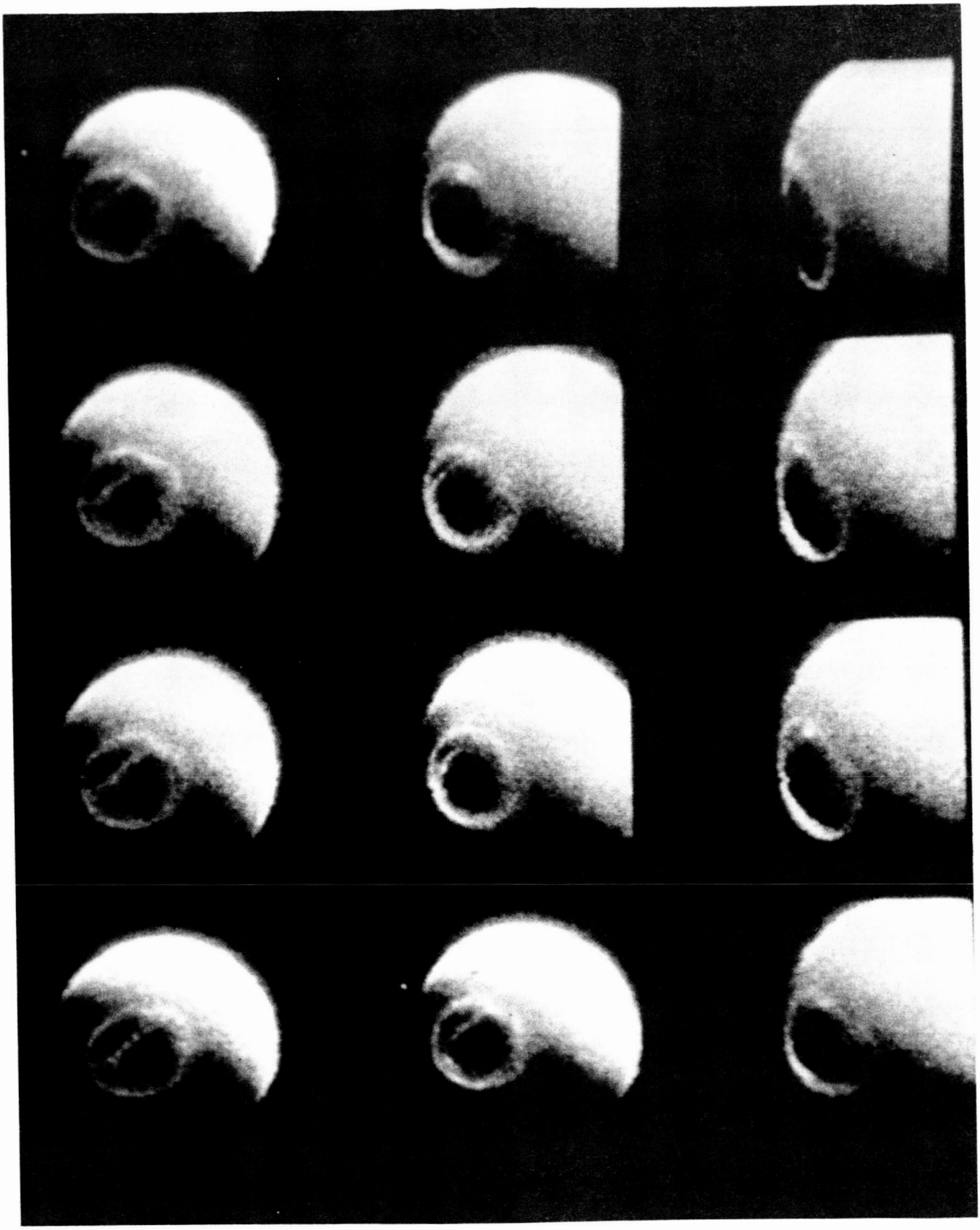

Fig. 5

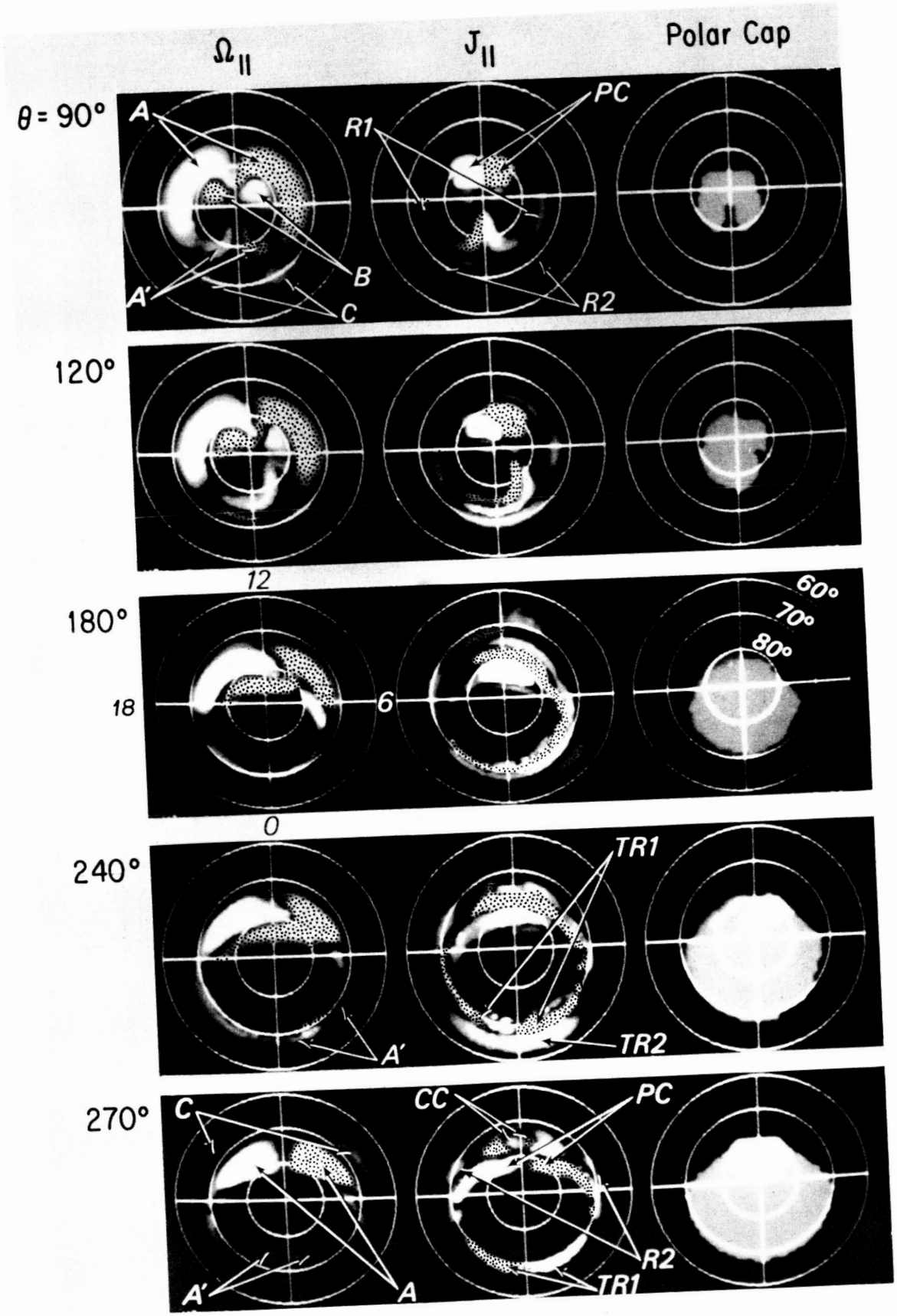

Fig. 6

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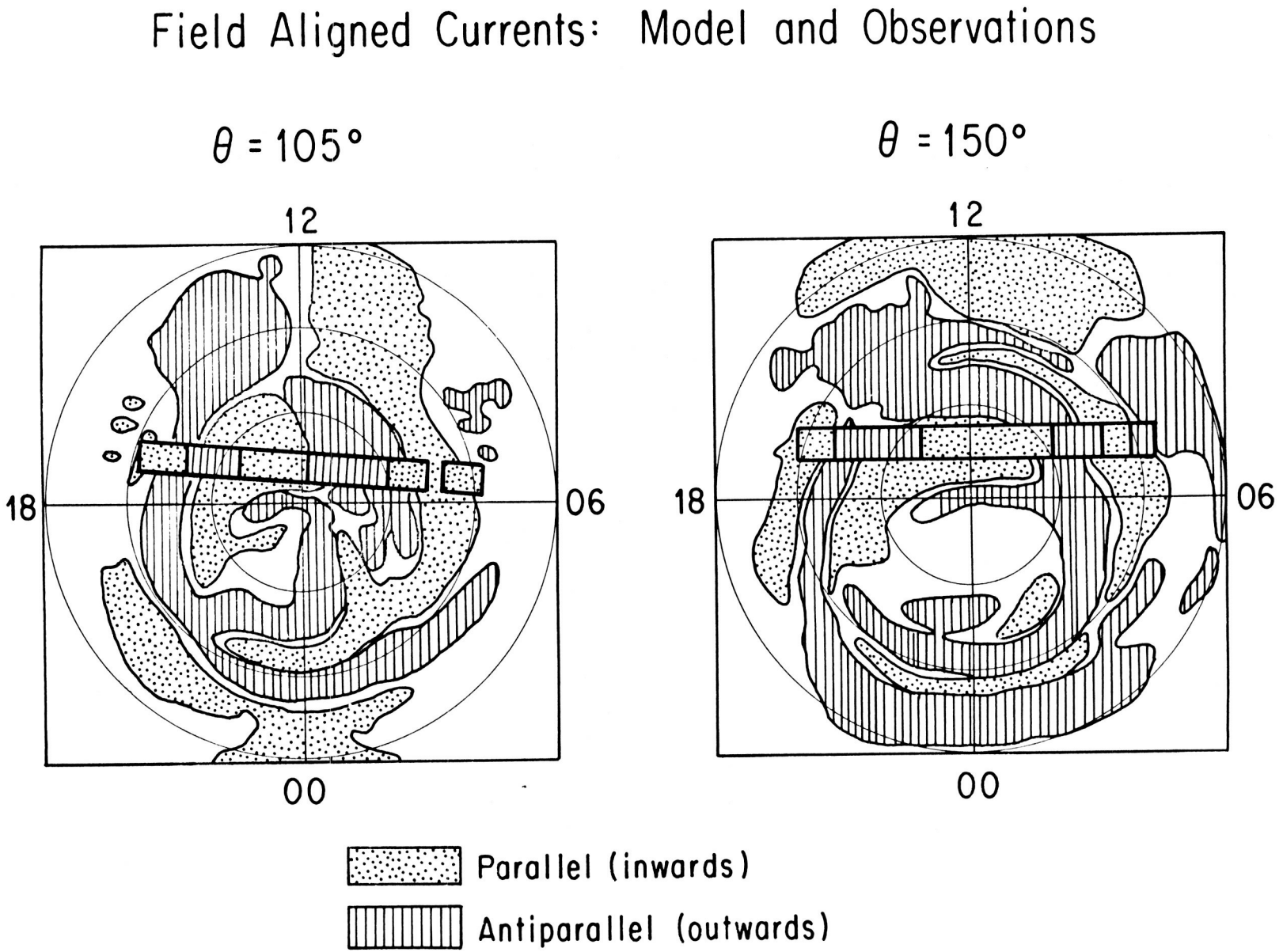
Field Aligned Currents: Model and Observations
θ = 105°
θ = 150°
12
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00
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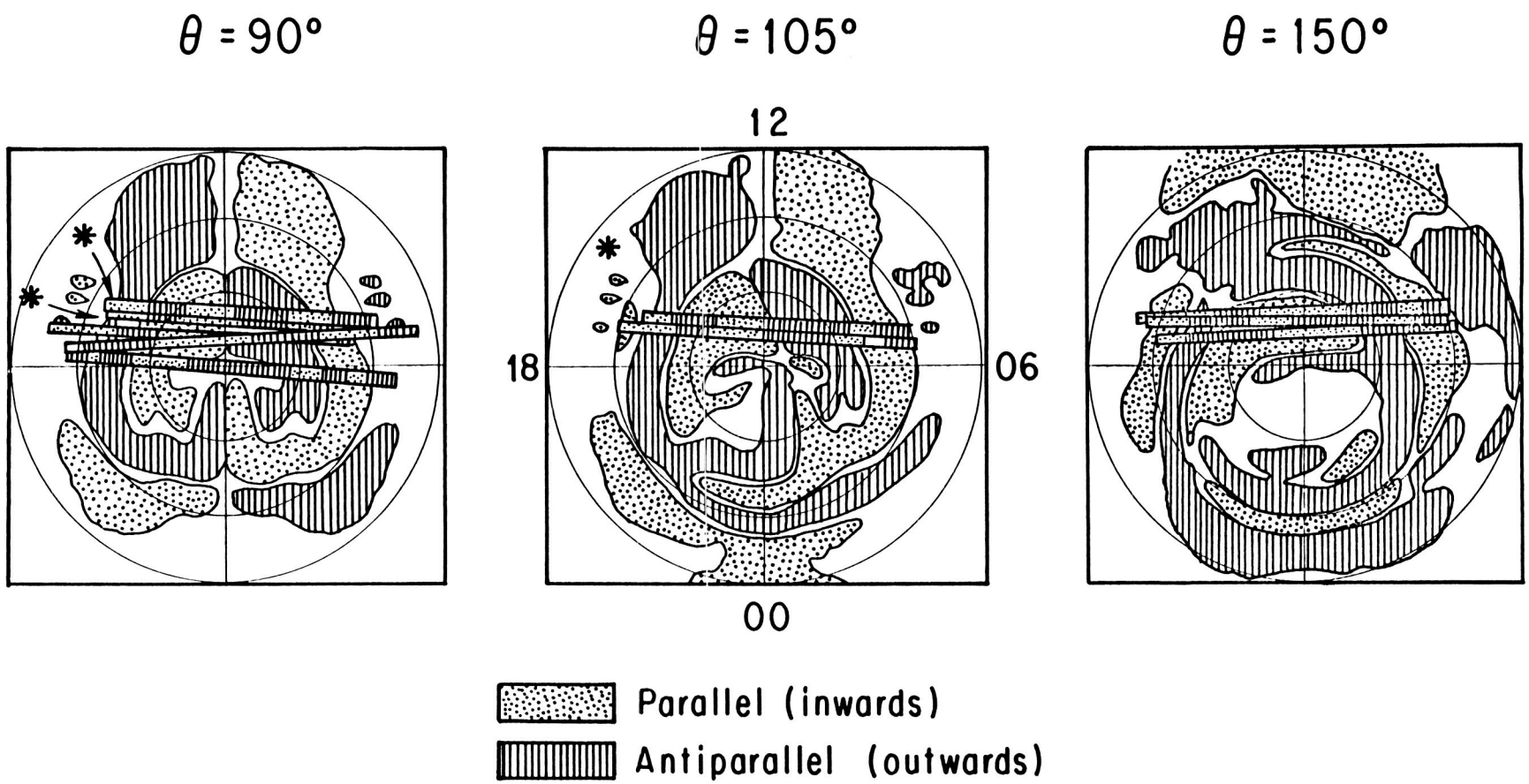
Parallel (inwards)
Antiparallel (outwards)

Fig. 7


Field Aligned Currents:
Model and Observations
θ = 90°
θ = 105°
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Parallel (inwards)
Antiparallel (outwards)

Fig. 8

Field Aligned Currents: Model and Observations

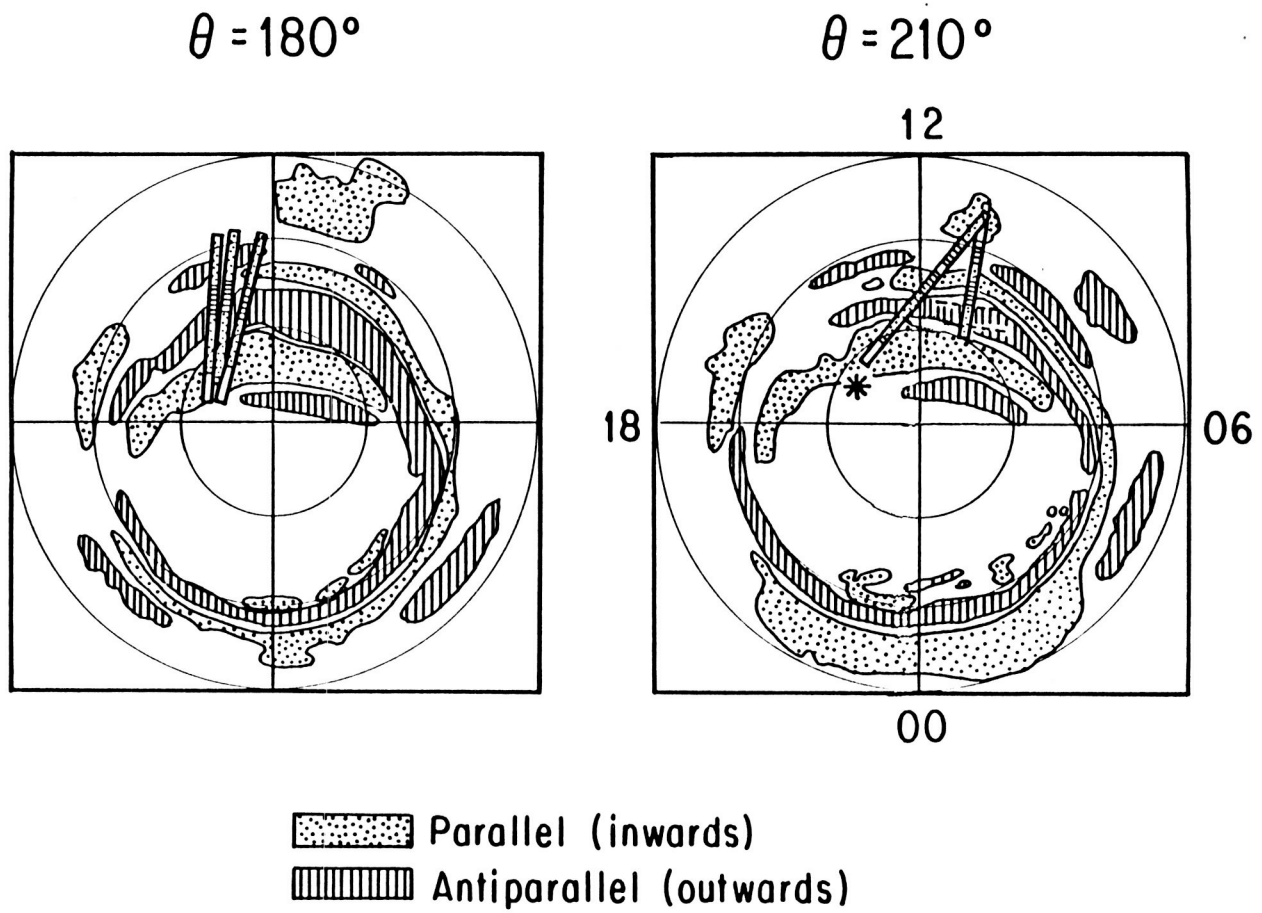

Fig. 9

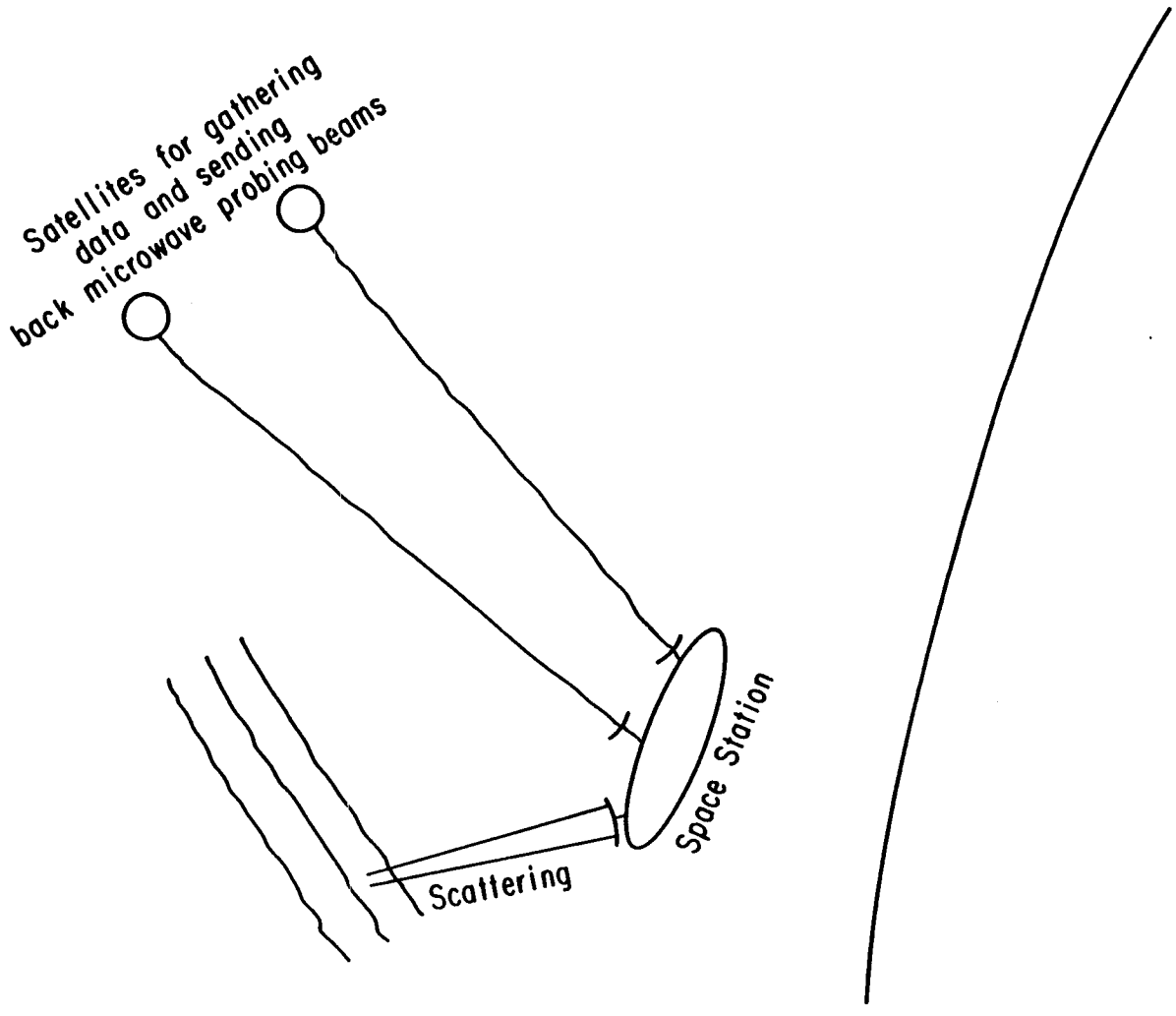
Satellites for gathering
data and sending
back microwave probing beams
Space Station
Scattering

Fig. 10

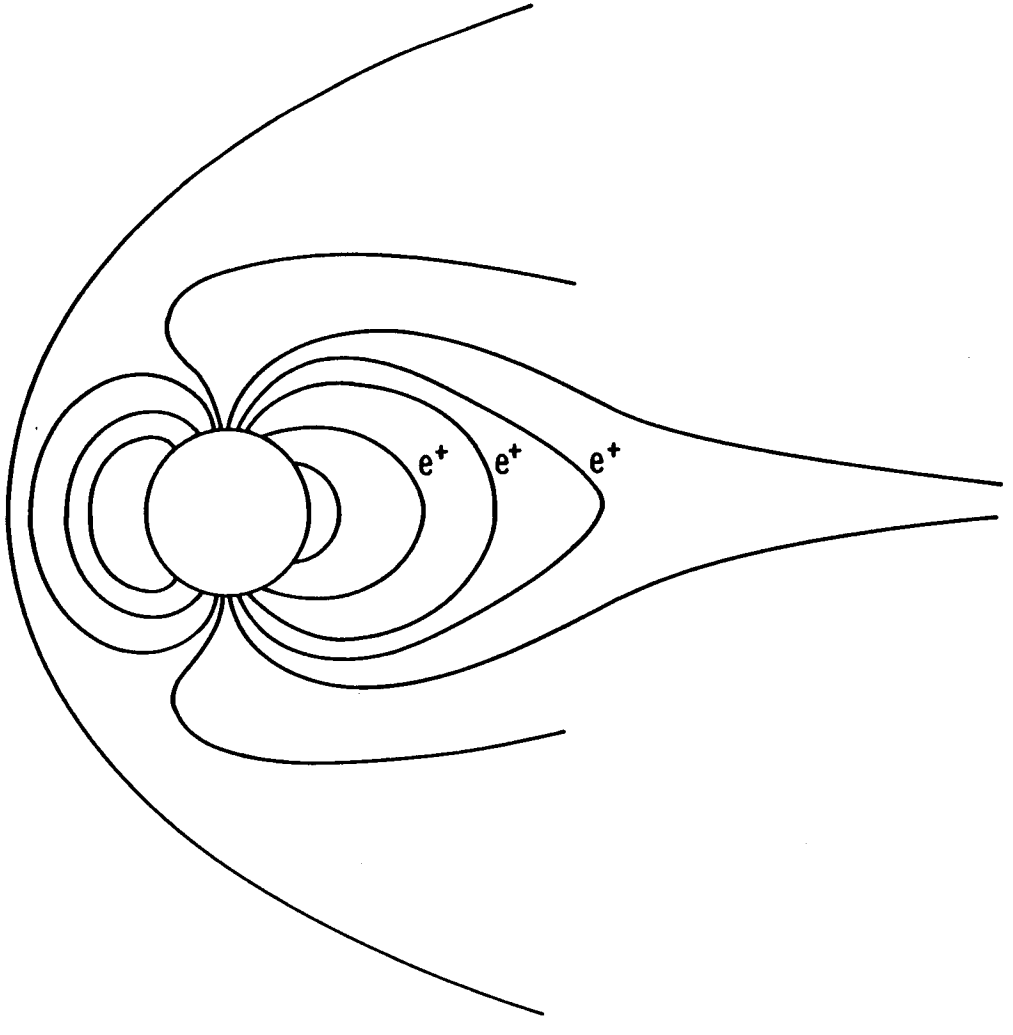

Fig. 11

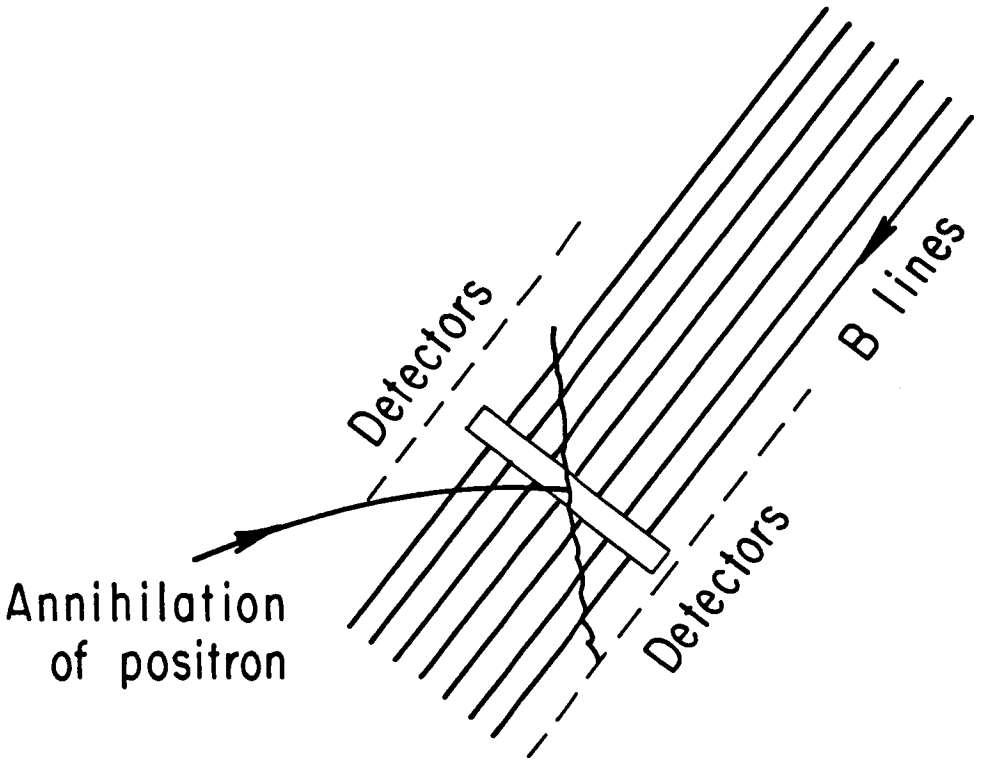

Fig. 12

N87-20066

A Unified Approach to Computer Analysis and Modeling of Spacecraft Environmental Interactions

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In the past decade we have developed a good understanding of many spacecraft/environment interaction processes. These include geosynchronous orbit charging, high voltage sheaths, ram/wake density variations, and certain surface processes. There are also many processes of which we are aware, but do not yet understand. Some of the outstanding questions include broadband noise in the ram, multiple ion streams, and electron heating. Advancing our knowledge is complicated by the fact that the various processes interact with one another.

In recent years, we have had successes in modeling some aspects of environmental interactions. This modeling has involved building our theoretical and phenomenological understandings into large, three dimensional computer codes. Each such code requires several man-years of theory, programming, and verification. The NASA Charging Analyzer Program (NASCAP) (Katz et al., 1977; Katz et al., 1979; Mandell et al., 1984) models spacecraft charging at geosynchronous orbit; NASCAP/LEO (Mandell et al., 1982) models large, high voltage spacecraft in low earth orbit; and POLAR (Cooke et al., 1985) models the charging of spacecraft due to auroral electrons. Comparisons with experimental data show good agreement, and we have consistently employed experimental results (both ground test and flight data) to help develop the computer models.

Despite these and other successes, there are serious weaknesses in the present approach to computer modeling. The most obvious problem is limited access to the various codes. Most researchers don't have handy a computer with NASCAP/LEO installed on it, and there is no easy way for them to get it.

What's more, even a researcher with access to all the computer models available from all sources will probably not make good use of them, if only because he doesn't have time to learn the different user interfaces required by each code. And even if he understood all the interfaces, he still couldn't use the codes unless he also had access to the half-dozen different computers for which they were designed.

Fortunately, there are several historical forces at work to make the job easier. Hardware is getting cheaper and faster at a breathtaking pace. Equally important, there are new software techniques and packages that routinely solve problems which, until recently, were impossibly difficult. There are several independently developed packages, such as PATRAN[1] which may

1 PATRAN is a registered trademark of PDA Engineering, Santa Ana, California.

be used to define general, three-dimensional objects in a form suitable for use by a finite element computer code. Presently, an effort is underway to make one interactions model, NASCAP/LEO, compatible with PATRAN objects.

Even more important, there are now operating systems that are 100% compatible across entire lines of computers from several different manufacturers. UNIX[2] is the best example. You can write a program in standard FORTRAN, and it will run, without a single change, on all of the popular workstation computers available. Also, it will give the same answer, with the same accuracy. This kind of dependable interchangeability of parts is as important to the computing community today as it was to the manufacturing community in 1800, when Eli Whitney "amazed government representatives by assembling guns from pieces chosen at random from piles of parts." (Latham, 1967)

The experimentalists and the engineering community have already realized the benefits of these advances. They routinely use standardized instrument controllers, connectors, and data handling protocols. This allows them to focus their efforts on the unique scientific and developmental aspects of their particular experiments.

Characteristics of UNISIM

As a way to make use of all these advances, we propose a new, coordinated, unified approach to the development of spacecraft plasma interaction models. The objective is to eliminate the unnecessary duplicative work in order to allow researchers to concentrate on the scientific aspects. By streamlining the developmental process, we can enhance the interchange between theorists and experimentalists and speed the transfer of technology to the spacecraft engineering community. We call this approach the UNIfied Spacecraft Interaction Model (UNISIM).

UNISIM is a coordinated system of software, hardware, and specifications. It is a tool for modeling and analyzing spacecraft interactions. It will be used to design experiments, to interpret results of experiments, and to aid in future spacecraft design. It breaks a Spacecraft Interaction analysis into several modules. Each module will perform an analysis for some physical process, using phenomenology and algorithms which are well documented and have been subject to review. The result is a system with the following features:

- Modularized software (object oriented);

- Generalized geometry;

- Peer review for new modules;

- Open system, coordinated effort;

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2 UNIX is a trademark of Bell Laboratories, Murray Hill, New Jersey.

- Codes, documentation, and information exchange via network;

- Artificial Intelligence based user interface;

- Standardized coding, documentation, and units.

Some of these concepts are already in use for other scientific areas, such as the NASA/Langley IDEAS package (Integrated Design and Evaluation of Advanced Spacecraft; Garrett, 1981; Wright et al., 1984). Tying together available geometric and interactions models via a commercially available CAD/CAM data base has been suggested by P. R. Williamson (Private Communication). The uniqueness of UNISIM centers on the openness of the system and the focus on coordinated multiresearcher participation along with the scientific peer review process. The idea underlying UNISIM is to extend scientific communication from just the print medium to both print and electronic media for the field of spacecraft interactions modeling.

Modularized Software

The current method of developing computer models requires a lot of redundant effort. Every individual computer code includes certain sections - object definition, grid generation, matrix calculation, graphical results display, and so on - each of which is reproduced in a slightly different form in every other code. The writing of these essentially similar parts often takes more effort than working out the details of the science.

Figure 1 illustrates the type of structure we envision for UNISIM. Each task of the sort mentioned in the preceding paragraph would be handled by a utility module which could be used for any scientific purpose. Then, if you want to add a new scientific model, you only have to create a single new module to plug into the overall system.

Not only will scientific modules be dramatically easier to write than currently, but each module will have easy access to calculations by other modules. For example, a high voltage collection calculation needs to know the variations of the plasma density caused by wakes. This kind of data availability is an important feature of UNISIM.

One important aspect of these modules is that they communicate by sending requests for information back and forth. One module does not have to know how the other module does its work; it just needs to know how to obtain the data calculated by the other module, or how to request a calculation if the data is not current. In this way, true independence between modules is maintained. This is a concept of Object Oriented Programming (Love, 1983; Ledbetter and Cox, 1985), which we will implement to the degree possible within the programming language used.

Generalized Geometries

An experiment on a space station with other experiments around it is inherently a three dimensional problem. The spacecraft itself is not symmetrical, and, commonly, other influences such as sunlight or variations

in the environment destroy any symmetries that may exist. To get results that are usable in the real world, it is necessary that computer codes allow general, three dimensional spacecraft models.

UNISIM will accept geometric input from commercial CAD/CAM solid modelers to allow accurate specification of the spacecraft and experiment geometries. Many modules will include subgrid refinement to resolve small details of instruments.

Peer Review Process

UNISIM will include a formal peer review process for the addition of new modules to the system. This will include analysis of the scientific approximations employed in the model, verification of the algorithms, and verification that the code actually executes the algorithms correctly.

Peer review has long been a requirement for scientific papers published in the open literature. By extending this practice to computer codes, we ensure that users can have confidence in the results they get using UNISIM.

Open System, Coordinated Effort

The UNISIM specifications and requirements will be openly available, allowing space scientists at various sites to contribute. All users will be able to communicate with each other about results, problems, and suggestions for further work.

Module specifications will be explicitly stated, so anyone will be able to design a new module, or substitute at his own site a locally written module in place of the one normally used.

To make it clear what each module does, source code and a complete description of the algorithms used will be included in the module itself. Then any change in a module will be accompanied by a simultaneous change in the on-line documentation.

The openness of the system makes it easy to add new features as our understanding of the physics advances. New modules can be introduced with ease, and old modules can be superseded or replaced without disrupting the system.

Network Availability

One of the fundamental features of UNISIM is that it will be available over a network such as SPAN or ARPANET. This means that as soon as a new module is included, it will be available to everyone. The developers will not be plagued with requests for installation, the users will not have to wait impatiently for updated capabilities, and no one will have to fiddle with magnetic tapes.

In addition to being a medium for access to the program itself, the network will provide an information exchange including a catalog and descriptions of the online modules. Through a bulletin board or an

electronic newsletter, bugs, errors, and other problems can be identified and corrected quickly.

User Interface

Scientific codes which model spacecraft interactions are complicated to use due to their highly technical nature. It requires a certain level of expertise just to know what a program is supposed to do, and what kind of input is meaningful. On top of this, the user needs to know the instructions and commands that the program accepts.

One of the great benefits of a modular system like UNISIM is that a single user interface can be used for the entire system. This saves the user from needing to learn a multiplicity of interfaces, and it allows the development effort to focus on making a single natural, easy to use interface. In particular, it makes it profitable to take the time to apply Artificial Intelligence principles, such as expert system techniques, to making the modules usable by scientists and engineers who are not specialists in computer simulation.

Standards

The concept of standards is extremely important to UNISIM. The system requires standards in three areas - coding, documentation and units. All programming will be done in ANSI Standard FORTRAN. The use of a standard operating system, preferably UNIX, assures transportability of both source code and data files. (UNIX is not tied to a single computer manufacturer. Other operating systems are also usable, but some of the transportability is lost.) A precision standard (e. g. IEEE floating point) will ensure that all modules will produce same results regardless of which machine is used to actually run the code.

Standard programming techniques will be enforced. These will include such things as a standard form for control structures, required comment headings for all subroutines, and other internal documentation standards. Data access will be through separately compiled subroutines, so that the individual data and file structures are hidden. Variable names will be as descriptive as possible, in order to enhance the readability of the source code. The use of a uniform coding style will not only help researchers who want to look at the details of the algorithms, but it will be a great help in maintaining and debugging the codes.

User manuals for each of the modules will also conform to appropriate standards. This task will be simplified because all modules will use the same utility modules for tasks like input and output, which are often the most confusing part of a manual. Manuals will contain physical models, algorithms, numerical techniques, and program, file and data structures.

All computational results will be specified in Systeme International units (Mechtly, 1973). Unit confusion is often a big problem in codes that report their results in "code units" or in non-dimensional units. But even

if a module uses unique units for internal computation, it will use standard units to interact with the other modules. Standard "include" files with names and values for common physical quantities will be available to the individual module developers.

IMPLEMENTING UNISIM

The first step to implementation of UNISIM is to create an overall system definition. This will include a definition of what constitutes a module and how modules communicate with each other. The module definition will be general enough to contain currently planned modules and new modules which cannot yet be foreseen. It will include specifications both for the code parts and for data protocols for communication between modules. Also required will be the procedures for developing and accessing experimental modules, for the peer review process, for including modules which have passed the review process, and for revising or deleting previously qualified modules.

The first modules to be built will be the utility modules. Since the PATRAN solid object modeler is used at several NASA centers, a PATRAN to UNISIM translator will be a good candidate for early inclusion. This would be a natural extension of the present conversion of NASCAP/LEO to use PATRAN objects, but there are now a number of CAD-based solid object modelers. UNISIM will not contain any commercial, proprietary modules.

All the concepts in the world of generalized geometry don't help if you don't have algorithms that can use them to do the calculations. We are currently developing a Generalized Blended Element algorithm which is for implementation in NASCAP/LEO. This is a way to automatically generate matrix elements for Poisson's equation (or any elliptical equation on a three-dimensional grid) in the space surrounding a general object. The method is quite general, allowing grid elements of any shape, with any desired resolution. The algorithm generates the matrix elements completely automatically.

Spacecraft interaction calculations that work with real spacecraft models also require sophisticated graphical output. There are now several packages and terminals which are specifically designed to display three dimensional models and calculational results. Figure 2 shows wireframe, surface material, and surface potential plots of a spacecraft defined using NASCAP as a CAD program. Figure 3 shows a surface material plot of a spacecraft defined using SLIC[3] as a CAD program.

UNISIM graphics utilities will be designed to be easily interfaced to all such facilities. It will also be possible to transfer and exchange data via standard file structures such as IGES (Smith and Wellington, 1986) or MOVIE.BYU[4] (Christiansen and Stephenson, 1986).

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3 SLIC is a product of GCN/Hydronet Services, Stockton, CA.

4 MOVIE.BYU is distributed by Graphics Utah Style, 1980 North 1450 East, Provo, Utah 84604.

BENEFITS OF UNISIM

UNISIM offers benefits at every step of its implementation. It advances the technology of spacecraft environment interactions modeling. Each of its features is something that has to be done anyway, and implementing the whole thing in a coordinated effort greatly decreases the costs in time and money.

UNISIM will directly cause a closer coordination between theory, experiment, and engineering. The instant availability of the UNISIM codes will allow experimentalists to get computational results without waiting weeks or months. Theorists will benefit greatly from a freer exchange, both among themselves and with the experimentalists, caused by the open nature of the system.

UNISIM supports Telescience (Black, 1986) by making available computer models of spacecraft environment interactions for use during mission simulation and planning. The same geometrical descriptions that are used for mechanical simulation and analysis can be used for environment interactions modeling.

UNISIM enables scientific issues to be addressed more quickly because the theorist can focus on the physics rather than the rest of the required coding. Since computations and comparisons with experiment can be performed and reported more quickly, weaknesses in the theories will be exposed sooner, leading to improved theories.

UNISIM makes transfer of the developed technology to spacecraft designers and engineers simple, because the whole approach is compatible with the existing engineering software which they already use. Structural analysis is routinely performed using solid modelers, finite element mesh generators and analysis packages with the results shipped to a graphics display device.

UNISIM increases the coordination and reduces the risk of developing spacecraft environment interactions models as transferable technology. Since all the models are part of a single, well documented, system, managing the development and communicating the advances among the space science community is relatively simple. And, finally, the risk associated with the system is small, since there are no irreplaceable links, no critical pieces; rather, there is a prescription for generating pieces that will work together.

ACKNOWLEDGEMENT

The authors have benefitted from discussions of this concept with William N. Hall.

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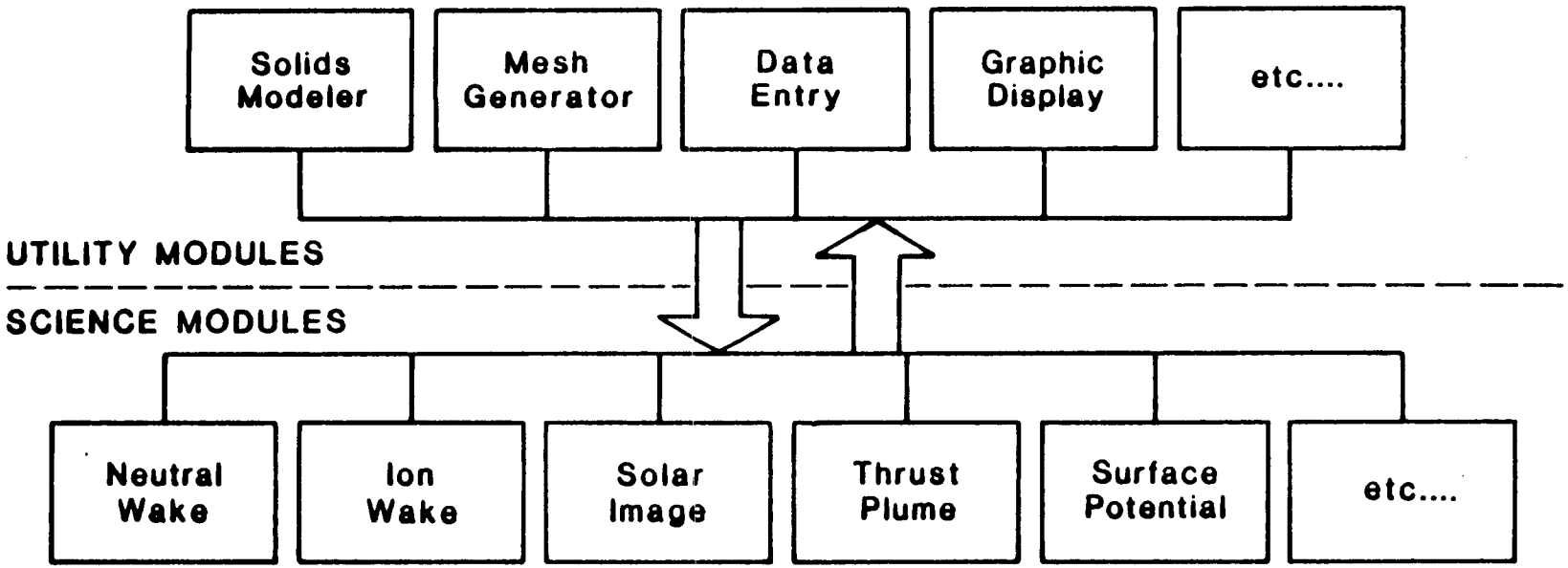

Fig. 1. Block diagram showing the modular structure of UNISIM.

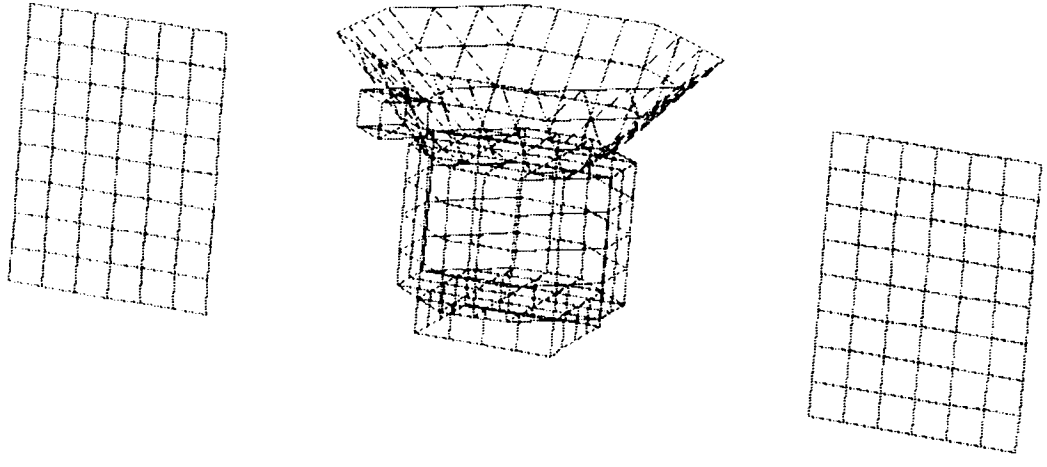

Fig. 2a. Wire frame model of spacecraft defined using NASCAP as a CAD program.

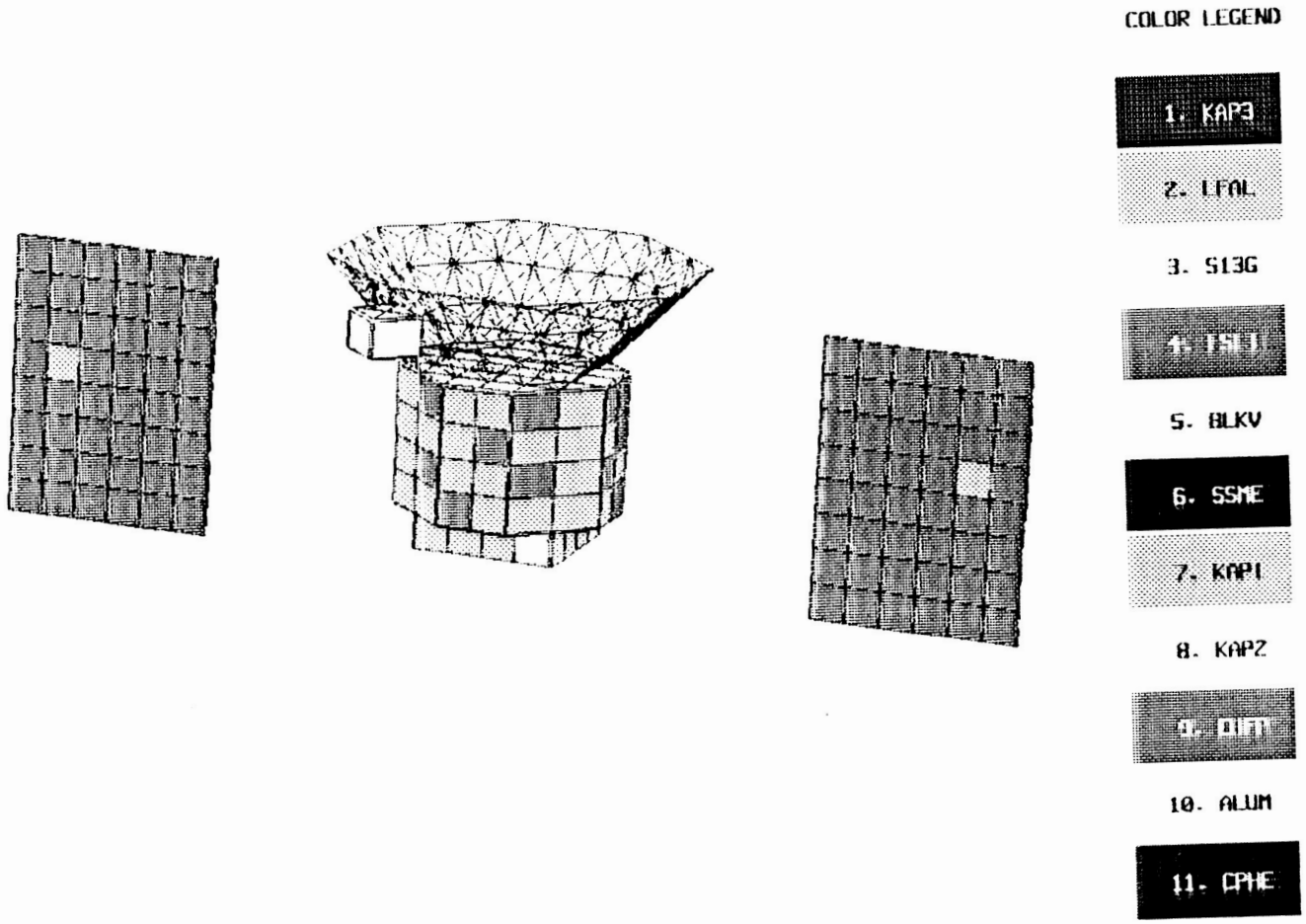

Fig. 2b. Surface material plot of the same object as figure 2a, with orientation preserved. The same plotting algorithm could be used for any discrete-valued property. [The original colors have been replaced by grays to minimize reproduction costs.]

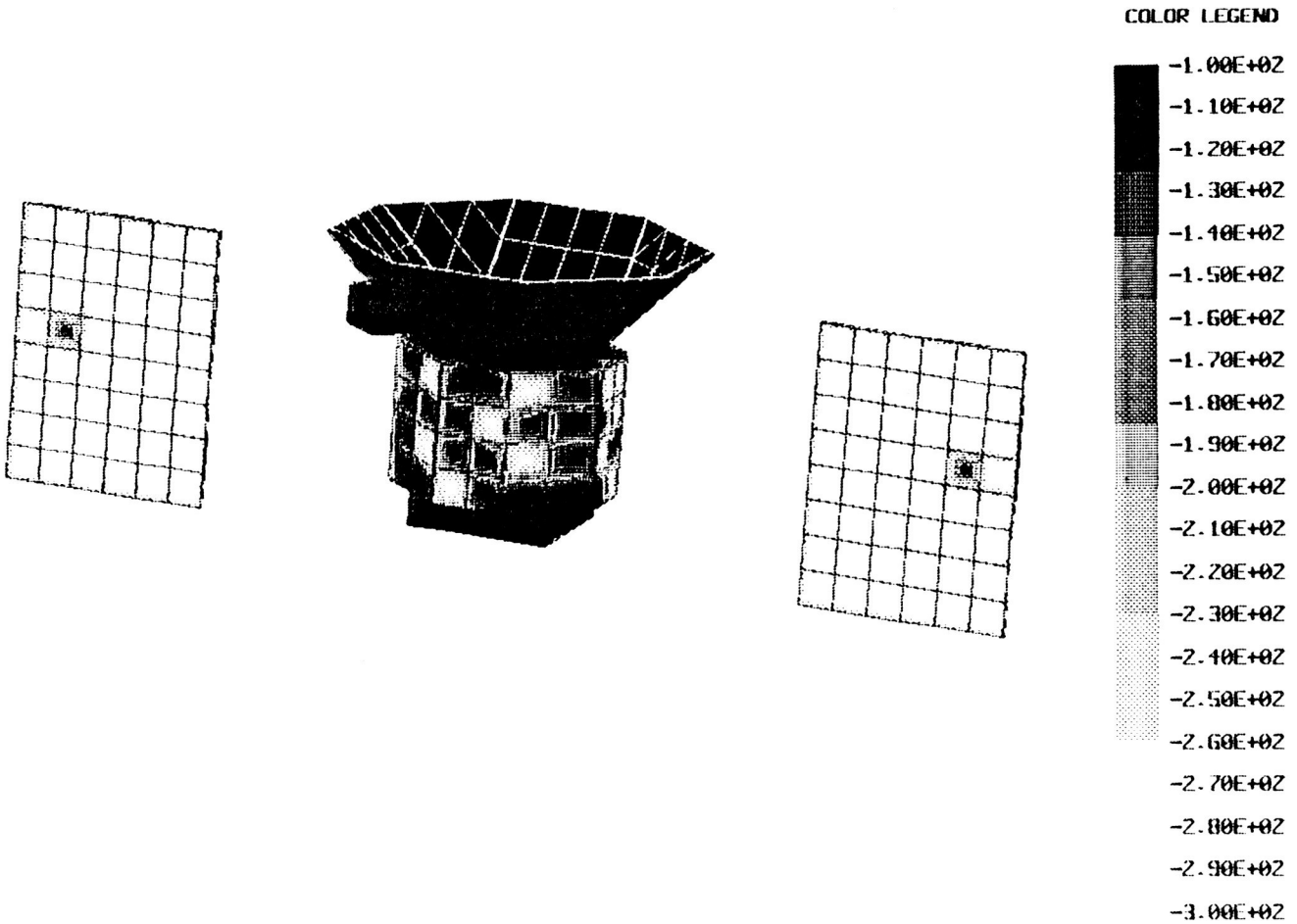

Fig. 2c. Surface potential plot of the same object as figure 2a, with orientation preserved. The same plotting algorithm could be used for any continuous-valued property. [The original colors have been replaced by grays to minimize reproduction costs.]

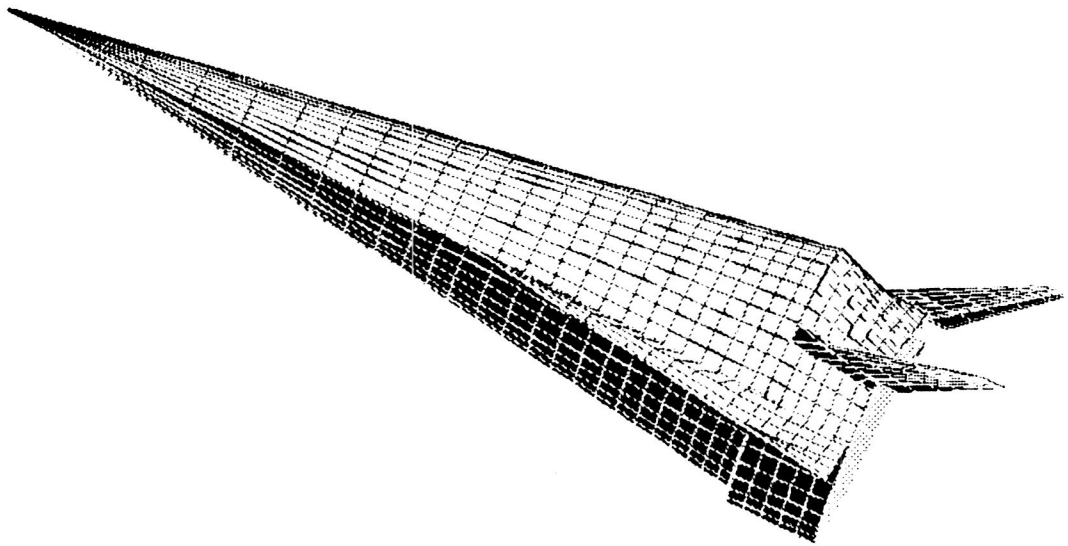

Fig. 3. Surface material plot of an object defined by the SLIC program. [The original colors have been replaced by grays to minimize reproduction costs.]

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The Plasma Dynamics of Hypersonic Spacecraft: Applications of Laboratory Simulations and Active In Situ Experiments

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Abstract: Attempts to gain an understanding of spacecraft plasma dynamics via experimental investigation of the interaction between artificially synthesized, collisionless, flowing plasmas and laboratory test bodies date back to the early 1960's. In the past 25 years, a number of researchers have succeeded in simulating certain limited aspects of the complex spacecraft-space plasma interaction reasonably well. Theoretical treatments have also provided limited models of the phenomena. However, the available in situ data was fragmentary, incomplete, and unable to provide a good test for the results from ground based experiments and theory. Several active experiments were recently conducted from the space shuttle that specifically attempted to observe the Orbiter-ionospheric interaction. These experiments have contributed greatly to an appreciation for the complexity of spacecraft-space plasma interaction but, so far, have answered few questions. Therefore, even though the plasma dynamics of hypersonic spacecraft is fundamental to space technology, it remains largely an open issue. This paper provides a brief overview of the primary results from previous ground-based experimental investigations and the preliminary results of investigations conducted on the STS-3 and Spacelab 2 missions. In addition, several, as yet unexplained, aspects of the spacecraft-space plasma interaction are suggested for future research.

1. INTRODUCTION

Any object placed in space will be immersed in a macroscopically neutral conglomeration of positively and negatively charged particles, as well as neutral particles, generally called a plasma. The space plasma is, although very tenuous, an important component of the space environment--of critical importance to many geophysical and active plasma investigations as well as to the environmental dynamics of large space structures such as the space station. However, today after three decades of space flight, there still remain a number of open questions and unexplained effects that require the attention of future research efforts.

The physics of a body immersed in a quiescent, collisionless plasma is well understood: the body takes on an electric (floating) potential which

tends to balance the flux of charged particles to its surface so that no net electrical current flows. The plasma tends to shield itself from this potential by creating a region of unequal ion and electron number density surrounding the body, called the plasma sheath, in which the floating potential on the body is matched to the space potential of the plasma. However, when a relative motion exists between a body and its environmental space plasma, an interaction occurs which is far more complex than the simple quiescent case. A redistribution of surface charge occurs on the body and the zone of disturbance in the plasma is no longer radially symmetric, regardless of body geometry. When the relative motion between the body and plasma is mesosonic, as it is in the lower ionosphere, several characteristic processes have been found to occur: the plasma sheath on the frontal side of the body may be compressed to some extent by the directed motion of the ions; immediately behind the body, the more massive particles are swept out leaving a region essentially void of ions and neutrals; potential wells and oscillations may occur, ions are accelerated into the void region and ion beams and plasma waves propagate into, and away from, the wake. Although the electron mobility is sufficiently great to populate the void region from relative velocity considerations, a negative space charge potential is created by their presence which tends to impede their motion into the region. Hence, the void region that occurs in the wake near the body is highly depleted of all charged and neutral particles and forms the most intense feature of the body-plasma interaction.

The way in which the void region is repopulated may result from a variety of mechanisms including the focusing of ions by electric fields in the plasma sheath surrounding the front half of the body, ambipolar diffusion, thermal diffusion, the plasma expansion phenomena, and scattering by various plasma oscillations or instabilities. Other characteristics of hypersonic plamsa dynamics include the spatial extent of the interaction region, the rate at which the disturbances propagate outward downstream from the body, and effects that occur in the wake after the void region has been repopulated (Figure 1). For example, in cases where the electrostatic focusing in the plasma sheath dominates, some ions may be deflected onto the trailing surfaces of the body and a region of significant ion number density enhancement has been observed to occur downstream on the wake axis at the crossing point of the deflected ion trajectories.

The dominate characteristics of plasma flow interactions and the governing physical mechanisms depend on the various body and plasma parameters such as scale size, electron-to-ion temperature ratio, ion acoustic Mach number, and body potential--the effects of which are understood only over limited regions of parameter space. Moreover, the discussion, so far, has dealt only with simple conducting bodies and non-magnetized, collisionless plasmas. Clearly, other complicating factors exist, such as neutral gas emissions from the spacecraft, collisional effects, secondary electron emission, solar UV, chemical reactions, multiple ion species, and magnetic fields. Since the relative motion between the body and the plasma is supersonic with respect to certain ion plasma waves, a collisionless shock wave may be expected to occur under some circumstanes. It is further thought that secondary electron emission may lead to a non-monotonical matching in the plasma sheath of the floating potential on the body with the, generally more positive, space potential of the environmental plasma. Although it is recognized that these effects can occur in space, they have been beyond the scope of most experimental and theoretical studies, which usually treated only small scale,

conducting bodies of relatively simple geometry, in collisionless, unmagnetized plasmas of a single ionic species (for a review see Stone, 1981a).

Although it has long been recognized that the spacecraft-space plasma interaction occurs and can adversely affect spacecraft systems as well as scientific instrumentation (Stone et al., 1978), most space missions have involved single satellites which, a priori, could provide only very limited information. Therefore, with the possible exception of the Gemini-Agena 10 and 11 missions, no deliberate and systematic attempt has been made to study the problem in space prior to the advent of the space shuttle. As a result, the in situ data available from the 60's and 70's are incomplete in spatial coverage and fragmentary in the sense that seldom were all the necessary measurements made (for a review see Samir, 1973).

In the absence of definitive in situ measurements, a large number of theoretical and ground-based experimental studies were made during this period. Although much valuable information has been gained from these efforts, both approaches have limitatins and the field of spacecraft plasma dynamics, or ionospheric aerodynamics, is far from being well understood. The results from recent space shuttle missions have answered few questions to date, but rather, have contributed to a greater appreciation for the complexity of spacecraft-space plasma interactions.

The intent of this paper is to touch briefly on the major contributions of previous experimental investigations, provide examples of the corroboration of the interpretation of in situ measurements by the understanding gained from groundbased investigations, and discuss the main features of the STS-3 and Spacelab 2 space shuttle investigations.

2. MATHEMATICAL FORMULATION

In the kinetic, formulation of plasma flow problems, since a plasma consists of a number of different types of particles, including electrons, ions, and neutral molecules, a complete statistical description of the state of the plasma requires a separate function, $f_\alpha(\vec{x},\vec{v},t)$, to describe the distribution of each constituent in six dimensional phase space at some given time. Each of these distribution functions is the solution of a Boltzmann equation of the form:

$$\frac{\partial f_\alpha}{\partial t} + \vec{v}\,\frac{\partial f_\alpha}{\partial \vec{x}} + q_\alpha[\vec{E} + \vec{v} \times \vec{B}/C]\,\frac{\partial f_\alpha}{\partial \vec{v}} = \left(\frac{\partial f_\alpha}{\partial t}\right)_c , \qquad (1)$$

which describes the rate of change of the distribution of the α-constituent, f_α, in space and time. Alternatively, this equation can be viewed as a statement of the conservation of particles existing in an elemental volume of phase space, $d^3x\ d^3v$.

The term on the right-hand side of the equation, $(\partial f_\alpha/\partial t)$, accounts for short range, discrete collisions, which may be electrostatic in nature (between two charged particles) or "hard sphere" type collisions.

The Lorentz force, $q_\alpha[\vec{E} + \vec{v} \times \vec{B}/C]$, results from the self-consistent electrostatic and magnetic fields which account for "distant collisions" of particles with long range forces. A collective behavior then results from Coulomb interactions between groups of charged particles.

The Lorentz force is made self-consistent by requiring it to satisfy the Maxwell equations:

$$\nabla \times \vec{B} = \frac{1}{c}\frac{\partial \vec{E}}{\partial t} + 4\pi\vec{J} \tag{2}$$

$$\nabla \times \vec{E} = -\frac{1}{c}\frac{\partial \vec{B}}{\partial t}, \tag{3}$$

and the Poisson equation:

$$\nabla \cdot \vec{E} = 4\pi\rho_c, \tag{4}$$

where $\vec{J}$ is the total current flow and ρ_c is the net charge density.

The current and net charge density, in turn, depend on the distribution functions of the plasma constituents (solutions of the Boltzmann equations) through the relations

$$\vec{J} = \vec{J}_{ext} + \sum_\alpha q_\alpha \int \vec{v} f_\alpha(\vec{x},\vec{v},t)\, d^3v \tag{5}$$

and

$$\rho_c = \sum_\alpha q_\alpha \int f_\alpha(\vec{x},\vec{v},t)\, d^3v . \tag{6}$$

Equations (1) through (4), subject to the definitions (5) and (6), form the governing equations for plasma flow interactions. This set of partial differential equations is coupled and nonlinear. Therefore, a number of simplifying assumptions and approximations are generally made in kinetic treatments to obtain a tractable problem. In effect, most experimental models have made many of the same simplifications.

First, it is generally assumed that the flow interaction exists in a steady state. While this obviously has a great impact on the complexity of the equations, its physical justification is questionable. There is no description of time dependent effects. There exist, however, experimental evidence that suggests the presence of wave particle interactions in the wake region.

A second widely used assumption is that the magnetic field can be omitted, which reduces the Lorentz force to $q_\alpha\vec{E}$. There is some experimental justification for this assumption under certain conditions. This assumption coupled with the previous assumption that $\partial/\partial t = 0$ eliminates Maxwell equations (2) and (3), leaving only the Poisson equation (4) that the electric field must satisfy. From equation (5), we see that the only currents possible are those resulting from external forces, which are generally omitted.

The third major assumption is that the plasma is "collisionless." This means that, although long range, collective interactions will occur and must be considered, the short range, discrete collisions occur so infrequently as to have a negligible effect. Since the discrete collisions are negligible, we set $(\partial f_\alpha/\partial t) = 0$ and equation (1) becomes homogeneous (the Vlasov equation). Moreover, since neutral particles interact through discrete collisions (which are assumed to be negligible) they can be completely neglected. We, therefore, only require time independent collisions Boltzmann (or Vlasov) equations for ions and electrons; i.e.,

$$\vec{v}\cdot\frac{\partial d_{i,e}}{\partial \vec{x}} + q_{i,e}\vec{E}\cdot\frac{\partial f_{i,e}}{\partial \vec{v}} = 0 \ . \tag{7}$$

A fifth general assumption is that the flow is mesothermal; i.e., $\bar{c}_i \ll V_o \ll \bar{c}_e$, where $\bar{c}_{i,e}$ is the mean thermal speed of ions or electrons and V_o is the orbital speed. Since the mean thermal velocity of the ions is negligibly small compared to the relative motion between the body and the plasma, the ions can be assumed to behave as a monoenergetic stream (no thermal motion). The electrons, on the other hand, have a mean thermal speed much greater than the orbital speed and maintain a Maxwellian distribution in the presence of a repulsive body potential.

The boundary condition generally assumed at the body states that the body is an equipotential surface and that all incident charged particles are neutralized; i.e., no charged particles are reflected from the surface. The potential is assumed to go to zero (plasma potential) infinitely far from the body.

3. SCALING LAWS

The dimensionless parameters that must be invariant in order to obtain strict similitude between two flow interactions of different scale sizes can be derived formally from the governing equations (1-4). We also apply here the general assumptions discussed above. Making the variable substitutions:

$$x = R_o X \qquad t = \tau/\omega \qquad v = V_o u \qquad f_i = n_o F$$

$$\phi = P\Phi \qquad q_i = eZ \qquad m_i = m_p M \qquad n_{i,e} = n_o N_{i,e},$$

$$\hat{\nabla} = \nabla/R_o \ ,$$

the governing equations take the dimensionless form:

$$N_e = \exp\left[\Phi\left(\frac{eP}{kT_e}\right)\right] \tag{7}$$

$$\left(\frac{\omega R_o}{V_o}\right)\frac{\partial F}{\partial t} + \vec{u}\cdot\nabla F_i - \left(\frac{ZeP}{m_p M V_o^2}\right)\nabla\Phi\cdot\frac{\partial F_i}{\partial \vec{u}} = 0 \tag{8}$$

and

$$\nabla^2\Phi = -\left(\frac{4\pi e n_o R_o^2}{P}\right) [ZN_i - N_e] \ . \tag{9}$$

The equations (7-9) will remain invariant if we require $P = kT_e/e$ and the following parameter groups to remain constant:

$$Z \equiv \text{number of charges per ion} \tag{10}$$

$$\left[\frac{e\phi}{kT_e}\right] = \Phi \tag{11}$$

$$\left[\frac{\omega}{V_o/R_o}\right] \tag{12}$$

$$\left[\frac{ZeP}{m_p M V_o^2}\right] = \frac{ZkT_e}{m_i V_o^2} = \left(\frac{Z}{2}\right) S^{-2} \tag{13}$$

$$\left[\frac{4\pi e n_o R_o^2}{P}\right] = \left(\frac{4\pi n_o e^2}{kTe}\right) R_o^2 = \left(\frac{R_o}{\lambda_D}\right)^2 = R_d^2 \ . \tag{14}$$

Hence, the dimensinoless parameters, Debye ratio, R_d, Ion acoustic Mach number, S, and normalized electric potential, Φ, arise naturally from the governing equations. The necessity of scaling all three parameter groups was shown experimentally by Skvortsov and Nosachev (1968a) in that measurements taken for constant values of R_d, S, and Φ_b, obtained at different values of T_e, show little variation while a significant variation appears in some cases when only the ratios R_d and ϕ_b/S^2 were preserved.

In principle, it should be possible to obtain any arbitrary combination of the dimensionless scaling parameters R_d, S, and Φ_b by appriopriate choices of the physical variables n_o, T_e, V_o, and R_o. Unfortunately, this is not the case since, in practice, several of these variables are subject to experimental limitations. The test body size must be smaller than the plasma stream, therefore, making the plasma source radius an upper bound for the body radius, R_o. Further, due to the nature of ion accelerators, it is difficult to obtain high number densities in low energy streams.

The above limits impose no constraint on Φ_b ($\sim\phi_b/T_o$) since, in the laboratory, ϕ_b is independent of all other variables and can be adjusted to any desired value by an external voltage source. Similarly, R_d ($\sim n_o R_o^2/T_e$) can be made arbitrarily small and S ($\sim V_o^2/T_e$) arbitrarily large by making R_o small and V_o large, respectively. However, R_d cannot be made arbitrarily large while making S small. Since R_o must be less than the beam radius, any further increase of R_d must be accomplished by increasing n_o and/or decreasing T_e. However, this is inconsistent with small S which requires small V_o (and

therefore small n_o) and/or large T_e. The conditions of large R_d and small S are therefore mutually exclusive in the laboratory and can only be approached within certain practical limits.

As a result of the practical constraints on R_d and S, it will be possible to correctly scale very few of the wide range of conditions possible for orbiting satellites or diagnostic instruments in the ionospheric plasma according to the strict Vlasov scaling laws developed above. In recent years, however, a concept known as qualitative scaling has evolved which allows a considerable relaxation of the rigid Vlasov laws (Fälthammar, 1974). Under qualitative scaling, parameters much greater (or smaller) than unity are required to remain so but are not required to maintain the same order of magnitude. Only parameters which are of order unity must be scaled closely; i.e.,

$$P_{space} \begin{array}{c} \gg 1 \\ \ll 1 \\ \sim 1 \end{array} \qquad P_{LA_B} \begin{array}{c} \gg 1 \\ \ll 1 \\ \simeq P_{space} \end{array}$$

Qualitative scaling has greatly extended the applicability of groundbased experiments to natural in situ phenomena. Further, it allows additional aspects of the problem, such as magnetic and temporal effects, to be included.

4. AN OVERVIEW OF GROUNDBASED LABORATORY INVESTIGATIONS

Most laboratory research has centered around the near to mid-wake regions of small bodies ($R_d \sim 1$ to 10) in nonmagnetized plasma streams. The primary results for this case will be discussed below. For a discussion of the upstream and far-wake disturbance, the reader is referred to the work of Fournier (1971), Hester and Sonin (1970a,b), and Woodroffe and Sonin (1974). The dynamics of magnetized plasmas has been studied by Astrelin et al. (1973) and Bogasheohento et al. (1971).

1. Simulation of the Spacecraft-Ionospheric Interaction

(1) The Disturbance Envelope

The envelope of the zone of disturbance, defined by the boundary between freestream conditions ($J_i/J_{io} = 1$) and disturbed flow ($J_i/J_{io} \neq 1$), depends on two factors: the initial width of the disturbance at the largest cross section of the test body, and the rate at which the disturbance propagates away from the Z-axis as it moves downstream. The initial radial extent of the disturbance, defined by the sum of the test body radius and the sheath thickness, was found to increase in proportion to the ion acoustic Mach number and the negative body potential as $|-\Phi_b|^{1/2}/S$ (Figure 2). It can also be expected to increase with the Debye length. The propagation of the disturbance boundary away from the wake axis was found to define a Mach cone (Skrortsov and Nosachev, 1968b, and Stone et al., 1978) based on the ion acoustic Mach number, S. This result is in agreement with several theoretical treatments, including those of Rand (1960a,b) and Maslennikov and Sigov (1965, 1967, 1969) which predict a Mach cone structure for bodies with a small

potential Φ_b. The rarefaction wave, which is the most spatially extensive characteristic of the disturbance, was found to decrease the ambient ion current density by as much as a factor of three at distances as great as $2(S \cdot R_o)$ downstream (Stone et al., 1978).

The above conclusions are based on the parameter range $R_d = 4$ to 6, $S \simeq 11$, and $\Phi_b = -3.8$ to -47. Measurements by Hester and Sonin (1969a,b; 1970) show the existence of pseudowaves (streams of ions deflected across the wake axis by the sheath fields) for $\Phi_b >> S$. These ion streams may overrun the rarefaction wave, under certain conditions, and extend the zone of disturbance beyond the mach cone.

(2) Ion Trajectory Focusing by the Plasma Sheath

The focusing of ion streams onto the wake axis by the electric field existing in the plasma sheath surrounding a test body was inferred in early studies by the presence of diverging wave-like structures in the far-wake region (Hester and Sonin, 1970a,b and Stone et al., 1972, 1974). More recent, direct vector measurements of deflected ion streams show their angle of attack to be proportional to Φ_b in the near wake for small scale bodies (Stone, 1981b).

The vector ion flow measurements also revealed a "bunching" of the ion trajectories at the radial boundaries of the ion void region, which can be seen in the current density profiles of Figure 3. This effect was not discussed in early theoretical or experimental studies (Stone, 1981a), although it is apparent in the theoretical results calculated by Maslennikov and Sigov (1969).

The present experimental data are not sufficient to reveal the physical mechanism which produces the observed ion trajectory "bunching" in the near wake. Neither do the calculations of Maslennikov and Sigov allow an explanation, and the the effect does not even occur in other theoretical treatments such as the one by Call (1969), which predicts a "fanning out" of the deflected ion trajectories. The near-wake ion trajectory grouping may be produced either by a collective effect on the ions (possibly a result of instabilities set up by the large density gradient at the void boundary) or by a nonmonotonic potential gradient in the plasma sheath.

(3) The Axial Ion Peak

Early investigations by Hall, Kemp, and Sellen (1964) clearly show the ion void in the near-wake region and an axial ion peak for a spherical test body. The ion current density was measured at a number of stations across the wake for a wide range of body potentials, revealing a distinct dependence of the axial ion peak on Φ_b. More detailed measurements of the ion peak, including both transverse and axial profiles for a variety of potentials, were published a year later by Clayden and Hurdle (1966). These measurements, in addition to showing a dependence on Φ_b, show the axial ion peak to rise rapidly behind the body and trail off slowly, extending more than 20 R_o downstream. Similar results were found for a sphere and a conical body oriented with its apex into the flow.

Converging ion streams at the boundaries of the wake void region were found to create the initial ion peak on the wake axis (Stone, 1981c). The position of this peak was found to depend on S, R_d, and Φ_b as shown in Figure 4. This result agrees closely in its S and Φ_b dependences with the theoretical predictions by Martin (1974). A second peak may also created on the wake axis further downstream. The two types of axial ion peaks are normally superpositioned for small Φ_b and cannot be distinguished from each other. However, they tend to separate at highly negative Φ_b values, indicating that a second casual mechanisms with a different dependence on Φ_b may be involved--possibly the collisionless plasma expansion phenomenon.

The height and width of the axial ion peak at the location of its maximum amplitude were also investigated (Stone, 1981c). The maximum peak height for spherical test bodies was found to be proportional to $[S/|\Phi_b|]^{1/2}$ as shown in Figure 5. The peak width (normalized by the test body radius, R_o) was found to depend only on $|\Phi_b|^{-1/2}$ (Figure 6). This dependence is taken to represent a balance between the momentum the particles obtain due to deflection toward the Z-axis, produced by ϕ_b, and the magnitude of the space charge potential barrier on the Z-axis, which is proportional to kT_e. (Note that $\Phi_b = e\phi_b/kT_e$.)

It was also found that the nature of the axial ion peak depends strongly on the cross-sectional geometry of the test body. This can be explained simply by the behavior of the plasma sheath, which is directly pro portional to $|\Phi_b|^{1/2}/S)$. For small Φ_b and large R_d, the sheath is thin compared to the test body dimensions and conforms closely to its geometry. For a test body having a square cross section, the ion streams were found to be deflected onto lines that are orthogonal at the Z-axis and approximately a body diameter in length. This produces a wider peak of lower amplitude. As Φ_b becomes large or R_d becomes small, the sheath becomes relatively thick, expands away from the body and acquires a more spherical shape. Hence, the ions are deflected more toward a point on the Z-axis and the axial ion peak structure will take on a behavior more characteristic of spherical test bodies.

The effects of test body geometry were studied in a preliminary manner and indicate that the wake of a geometrically complex body may be explained in terms of a linear superposition of the wakes of its different, simple, geometric constituents (Stone, 1981a).

(4) Deflection of Ion Trajectories in the Mid-Wake Region

The deflection of ion trajectories in the mid-wake region was first predicted theoretially by Maslennikov and Sigov (1969) and later by Call (1969) although not to the same degree due to the limitations imposed by his flux tube technique. In both cases, the ion trajectories were found to be deflected away from the Z-axis by the positive space charge potential associated wih the mid-wake axial ion peak. this effect was inferred by Hester and Sonin (1970) from the nature of the diverging wave-like structure they observed in the far wake. More recent vector ion flow measurements show that ion streams exist within the plasma wake with angles of inclination to

the Z-axis smaller than the geometric angle defined by the radial extent of the test body (Stone, 1981a). Since ion streams obviously cannot pass through the test body and do not originate on its rear surface, this is taken as clear evidence that the streams, initially deflected toward the Z-axis, subsequently underwent an additional deflection away from the Z-axis somewhere downstream--presumably at the location of the axial ion peak.

(5) Effects of Ion Thermal Motion

An extensive experimental study of this effect was carried out by Fournier and Pigache (1975) and it has been studied theoretically by Taylor (1967), Gurevich, et al. (1969), and Fournier (1971). While it is clear that the general effect of ion thermal motion is to diffuse the detailed wake structure discussed above, the more quantitative question as to how effective this diffusion process is, or at what T_e/T_i value the structure vanishes, has not been satisfactorily resolved. The calculations by Fournier for a long cylindrical body show that a nonmonotonic n_i distribution continued to exist in the wake for $\Phi_b < -2.75$ when $T_e/T_i = 2$ and for $\Phi_b < -6$ when $T_e/T_i = 1$. Moreover, the experimental observations by Fournier and Pigache (1975) show the peak structure to completely vanish only for small Φ_b and $T_e/T_i < 1$ (Figure 7). It appears that the opposing effects of Φ_b and T_e/T_i are such that for small Φ_b the axial ion peak vanishes for $T_e/T_i \simeq 1$, but can be recreated by a sufficiently negative value of Φ_b. We may, therefore, conclude that in the ionosphere, where for $T_e/T_i \simeq 2$ and $\Phi_b \simeq -5$, the axial ion peak can be expected to occur to some extent. This conclusion is supported by the clear presence of an axial electron peak (which in laboratory studies is smaller than the ion peak) in the wakes of the Ariel I satellite and its spherical ion probe (Henderson and Samir, 1967).

(6) Effects of Large R_d Values

Laboratory and theoretical studies have been limited to R_d values less than 50, which do not approach the R_d range of large space platforms. However, several parametric trends have been established that may be cautiously extrapolated to describe large bodies in Earth orbit.

It was pointed out above that the amplitude of the axial ion peak significantly depends only on S and Φ_b and, further, that the peak width (normalized by body radius) depends only on Φ_b. If these observations, made over a relatively small range of R_d, can be extrapolated to large R_d values, then, on this basis, the axial ion peak would be expected to maintain an approximately constant width (relative to the body radius) and amplitude as R_d increased arbitrarily.

This conclusion is incomplete, however, without considering the effects of ion thermal motion. The tendency of random motion to spread out and diminish the wake structure can be expected to increase with the distance traveled by the ions, and hence with R_d. Therefore, it becomes doubtful that the detailed wake structure discussed above would be observed for very large bodies in the ionosphere at floating potential. However, if the body potential became elevated (such as may occur in the case of the Space Shuttle orbiter when charged particle accelerators are fired or as the result of $(\vec{v} \times \vec{B}) \cdot \vec{L}$ potentials on very large structures such as the Space Station) the wake structure may appear as a result of the opposing effect of Φ_b shown by Fournier.

(8) Magnetic Field Effect

The effects of the geomagnetic field on spacecraft plasma dynamics have been included in only a few laboratory investigations; e.g., Bogashchento et al. (1971) and Astrelin et al. (1973). In particular, it was found that the net result of a parallel magnetic field is the generation of standing axial ion current density oscillations along the wake axis with a period proportional to $(Z\omega_{ci}/2\pi V_o)$. Evaluating these results for typical ionospheric conditions shows that such oscillations would be very small in amplitude and that the period would extend far beyond the mid-wake zone. Therefore, it is concluded that the omission of the geomagnetic field in studies of the near- and mid-wake regions of small to medium sized bodies is justifiable.

2. Process Simulation Experiments

As stated in section 3, process scaling involves the philosophy of qualitative scaling to study an individual physical process that may be one of many involved in a complete phenomonon. Activity in this area has picked up considerably in recent years. We will briefly discuss three examples: the investigation of collisionless plasma expansion across a strong density gradient, the possible coupling between widely separated current sources in the magnetized ionospheric plasma, and electron heating of the near wake.

(1) Expansion of a Collisionless Plasma:

The collisionless expansion of a large reservoir of plasma across a strong density gradient is greatly influenced by an electric field created at the expansion front by high speed electrons separating from the massive ion component. The ions are, in turn, accelerated to high velocities (several times the ion acoustic speed) by the field, which is maintained by a continual replenishment of fast electrons at the front from the plasma reservoir. A recent review of the phenomenon and its possible occurrence in space plasmas is given by Samir et al. (1983). A laboratory process simulation investigation of collisionless plasma expansion is in progress at MSFC (Wright et al., 1985; 1986, and several other institutions (Chan et al., 1984).

Figure 8 is a schematic of the basic process as depicted by the self-consistent theory. Note that ion acceleration is constant over the period for which the self-consistent equations remain valid. An experimental study by Wright et al. (1985) was conducted in a steady-state plasma flow with the density gradient created by a plate oriented perpendicular to the flow. Figure 9 provides a comparison of experimental data with the expansion front velocity predicted by the theory. It is apparent that with proper scaling of S and Φ_d, this process must be simular to the process(s) responsible for filling in the near-wake void of orbiting spacecraft; particularly in the case of large scale spacecraft.

(2) A Tethered Satellite-Electron Beam Current System

Stenzel and Urratia (1986) have investigated the current flow between a field-aligned electron beam and an electrode collecting return current on a different flux tube in a large laboratory magnetoplasma. This investigation has revealed the existence of anomalous cross-field currents

that shunt the field aligned current system, and temporal current disruptions. If these processes reflect a valid picture of large scale current systems in the earth's ionosphere, this study will be of vital importance to investigations planned with long, conducting tethered satellites (e.g., the NASA TSS-1 mission) or charged particle beam experiments on large scale structures such as the Space Station.

(3) Enhancement of Electron Temperature in the Near-Wake

An apparent electron temperature enhancement, which coincided spatially with the ion void region, was reported by Samir et al., 1974 (Figure 10). The heating of electrons may be partially explained by the effects expected to occur in the presence of a potential well, or they may result from a two-stream instability produced by an interaction between fast and slow moving ions.

5. COMPARISON OF LABORATORY AND IN SITU RESULTS

A number of laboratory experiments have allowed direct quantitative comparison with, and sometime a better understanding of, in situ measurements. Here we consider of few examples.

Several observations of an elevated electron temperature in the wake of ionospheric satellites have been reported (Samir and Wrenn, 1972; and Troy et al., 1975). This effect was investigated in the laboratory by Illiano and Storey (1974) and by Samir et al., (1974), the latter revealing electron temperature enhancements in the wake of a test body in a collisionless streaming plasma as discussed above in Section 4.2.3. The enhancement ranged up to 200 percent of the ambient stream's temperature and was confined to the void region of the plasma wake - in complete agreement with with the in situ observations. The Samir et al. study did not establish the mechanism for electron heating in plasma wakes, but suggested it may result from a potential well in the void region or from wave particle interactions (instabilities) within the strong density gradient at the wake boundary.

Stone and Samir (1981) report on a comparison between laboratory wake experiments in which ion focusing by plasma sheath electric fields were studied (Stone, 1981b), and in situ observations of structure in the wakes of the Ariel 1 satellite and its spherical ion probe (Henderson and Samir, 1967). The laboratory results show the ion current peaks, observed at only a one axial distance in the in situ wake, to be part of an extended complex structure such as shown in Figure 3 (Stone and Samir, 1981). Moreover, the effects of body potential on the wake structure observed and quantified in the laboratory (discussed in Section 4.1.2-3) explain the similarity observed between the wakes of the satellite and the small, but negatively biased, spherical probe.

A second example presented by Stone and Samir (1981) shows that the ram/wake current ratio data, obtained from the AE-C satellite (as a function of plasma composition, electron temperature and satellite potential) can be collapsed to a single curve using the body-potential and ion acoustic Mach number dependences established in the laboratory (section 4.1.3). This example also shows that dimensionless parameters must be calculated using specific ionic mass and concentration values rather than average values.

6. INITIAL RESULTS FROM SPACE SHUTTLE MISSIONS (STS-3 AND SL-2)

By far, the most elaborate insitu investigations of spacecraft plasma electrodynamics to date have been conducted from the space shuttle. It was anticipated that the more detailed shuttle-borne experiments would complement existing in situ data and provide a sufficient data base for resolving several spacecraft-space plasma interaction issues. However the orbiter environment proved far more complex than anticipated and the main contribution to date has been a greater appreciation for the complexity of spacecraft-space plasma interactions.

The third space shuttle mission (STS-3) provided the first opportunity to measure the Orbiters plasma and field environment. This was accomplished on mission days three and four by manuevering the Plasma Diagnostic Package (PDP) up to 15 m above the Orbiter payload bay with the Remote Manipulator System (RMS) as, for example, shown in Figure 11. Differential vector measurements of ion flow direction, current density, and energy were made during this period with a Differential Ion Flux Probe (DIFP) (Stone et al., 1985). These measurements revealed the existence of secondary ion streams in the vicinity of the Orbiter at high angles of attack as great as 50° with respect to the ram direction and from 10 to 40% of the ram current intensity (see Figure 12). The source or generating mechanism for these high inclination secondary ion streams was not identified. However, their energy was close to that of the ram ions and it was concluded that they were not of geophysical origin (Stone et al., 1983).

The existence of ion streams in the disturbed plasma surrounding an orbiting body is not surprising; in fact, the existence of ion streams was inferred by Henderson and Samir (1967) and has been studied in the laboratory, as discussed in section 4.1.2. In all previous cases, the ion streams were associated with the wake region downstream from the satellite or test body and such streams were anticipated in the wake of the Orbiter. However, the secondary streams observed near the Orbiter during the STS-3 mission were totally unexpected in that they were measured when the PDP was not in the Orbiter's wake and, in some cases, when it was extended upstream from the Orbiter.

Futher analysis revealed several additional effects. Not only were high inclination ion streams typically observed, but the ion ram current direction did not, in general, correspond closely to the direction of the orbital velocity vector (see Figure 12). Moreover, in one case in which the PDP was extended above the Orbiter and oriented such that the DIFP faced directly into one of the secondary streams, the stream vanished (Stone et al., 1986). The ion current density of both the Ram and secondary streams was also found to be directly proportional to the neutral particle density as shown in Figure 13 (Stone et al., 1986).

These observations should be considered in the context of wave measurements that revealed the existence of broad band (30 H_z to 178 kH_z) electrostatic noise in the vicinity of the Orbiter (Shawhan et al., 1984) and the observation of higher than normal ambient ionospheric plasma densities (Raitt et al., 1984; Siskind et al., 1984).

The above observations, taken together, are evidence that the Orbiter travels within a neutral gas cloud that results from outgasing, thruster burns, waste dumps, etc., and that the presence of this gas cloud significantly affects the way in which the Orbiter interacts with the ambient mangetoplasma. The proportionality of the ram and secondary ion stream intensities to the density neutral particles very near the Orbiter suggest a very effective ionization mechanism. The vanishing of the secondary streams at about 10 m ahead of the Orbiter suggests that the interaction with the ionosphere may be confined within an envelope that extends on the order of 10 m in the forward direction but presumably trails out to greater distances down stream. If an electric field exists at this gas cloud-ionosphere interface, the ambient ions would be deflected such that the ramed ion current would be skewed from the Orbital velocity vector at all points except in the Orbiter's XY-plane, where the envelope would be normal, and hence the electric field parallel, to the velocity vector. This is in agreement with the trend of the data as shown in Figures 11 and 12. The motion of the secondary ion streams through the background plasma represents a large source of free energy that may be expected to generate instabilities. Recently Hwang et al. (1986) have developed a model which shows that ion streams in a background ionospheric plasma can generate electrostatic noise over the oberved spectrum.

7. CONCLUSIONS AND OPEN ISSUES

The application of laboratory plasma physics to space plasma physics and technology has proven successful in addresssing a number of issues over the past 25 years; particularly in addressing, through qualitative simulation, the overall interaction of small ionospheric satellites and instruments with the ionospheric plasma (for a review see Stone, 1981a). In the past few years, process simulation has been used to address several specific aspects of natural physical phenomenon, such as plasma expansion (Wright et al., 1986) and the bahavior of current systems in magnetosplasmas (Stenzel and Urratia, 1986). The conclusions reached in these studes have not been verified by in situ data yet and their usefulness remains to be determined - although the preliminary analysis of Spacelab 2 data suggests the existence of a process very much like the collisionless plasma expansion process studied in laboratory plasmas by Wright et al.

Through the combined efforts of laboratory and in situ investigations together with theoretical treatments, the physics of geometrically simple conducting bodies of 1 to 50 Debye lengths scale size is reasonably well understood--although certain details remain to be determined; e.g. the effects of a magnetic field on the far wake and the mechanisms producing changes in the electron distribution. This is not true, however, either for geometrically complex bodies (although previous studies (Stone, 1981a) suggest a linear superpositioning of the wakes of the simple geometric constituents, this must be more universally established), bodies with complex surface characteristics, bodies with an associated neutral gas cloud, large scale size bodies (in excess of 1,000 Debye lengths), or bodies of any type with an elevated electric potential. Future investigations of spacecraft plasma electrodynamics should therefore center around five issues; i.e.,

(1) The effects of body scale size, particularly for large scale bodies (with respect to both the Debye length and cyclotron radius).

(2) The physics of a neutral gas cloud in a hypersonic magnetoplasma.

(3) The effect of body potentials well in excess of the ionization potentials for neutral constituents.

(4) The effects of complex spacecraft geometry.

(5) The effects of complex spacecraft surface characteristics.

Moreover, these issues are of such complexity that their resolution will require laboratory investigations (that offer the advantage of comparatively low cost and fast turnaround) and theoretical treatments (that make use of recent gains in computer technology), as well as deliberate and systematic in situ experiments designed to provide data capable of corroborating the ground-based results. The previous in situ results from small ionospheric satellites were not systematic and too limited in scope, while the experiments conducted on the space shuttle involved an extremely complex body. Clearly, the required in situ experiments must be systematic, closely controlled, and use cleaner test bodies (in terms of geometric complexity, surface characteristics, gas emissions, and EMI). An understanding of the fundamental physics of hypersonic spcecraft plasma dynamics will be important to the practical application and operation of large space platforms and should not be taken lightly in planning wide usage of the space station.

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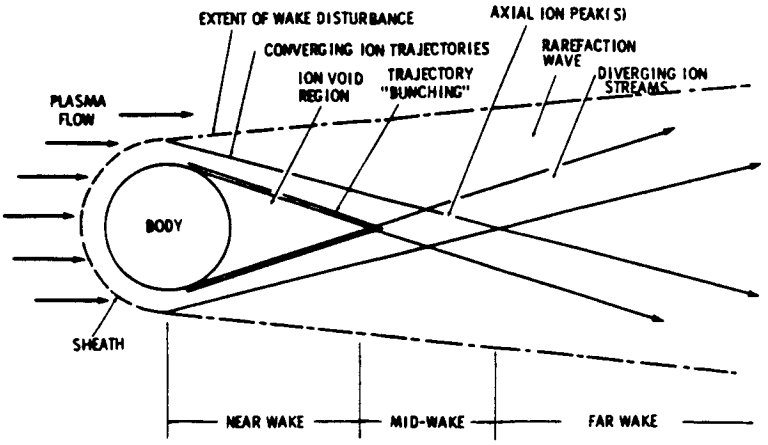

Figure 1. Ion behavior within disturbed zone. After Stone [1981a].

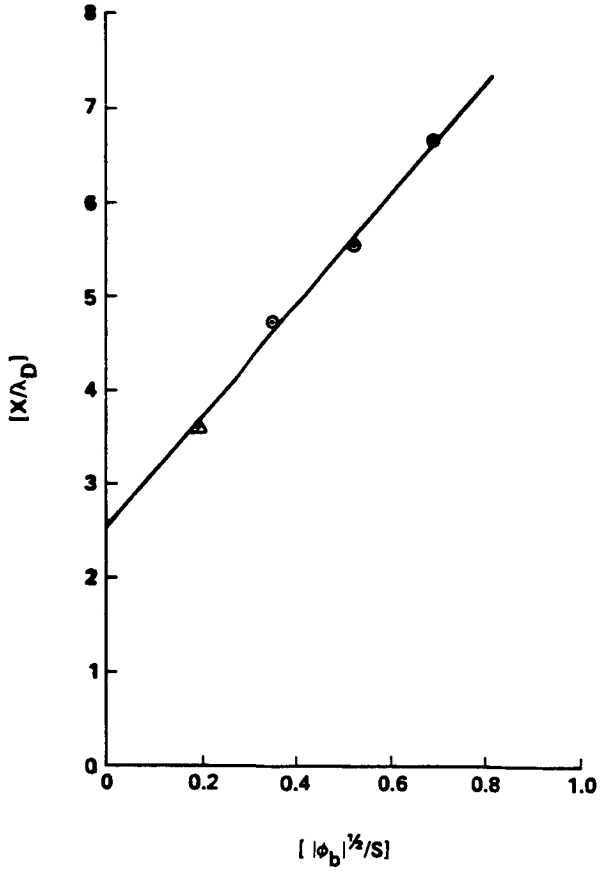

Figure 2. Dependence of the sheath width at the critical cross-section of a test body (x/λ_D) on body potential and ion acoustic Mach number. Open circles represent data for a sphere and open triangles for a parallel cylinder. After Stone et al. [1978].

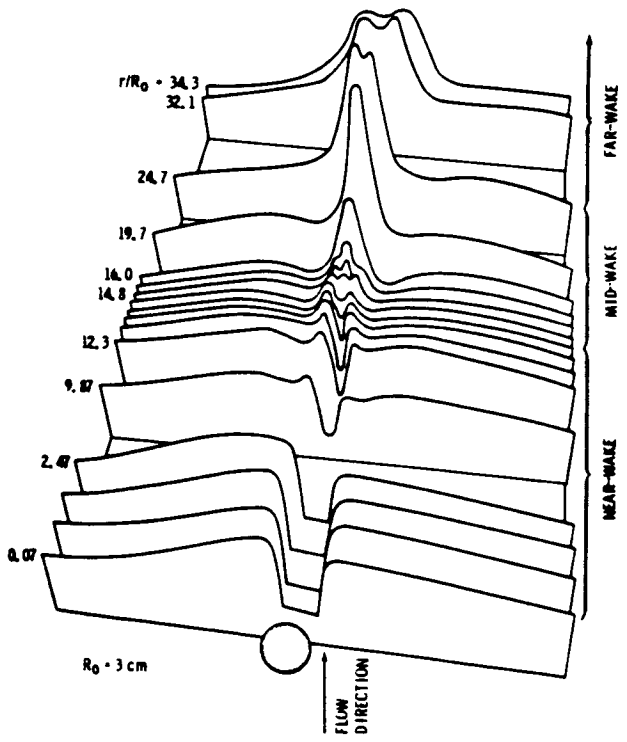

Figure 3. Ion current density profiles downstream from a conducting sphere (R_o = 3 cm) for $R_d \cong 0.8$, $S \approx 17$, and $\Phi_b \approx -5$, data after Stone et al. [1972].

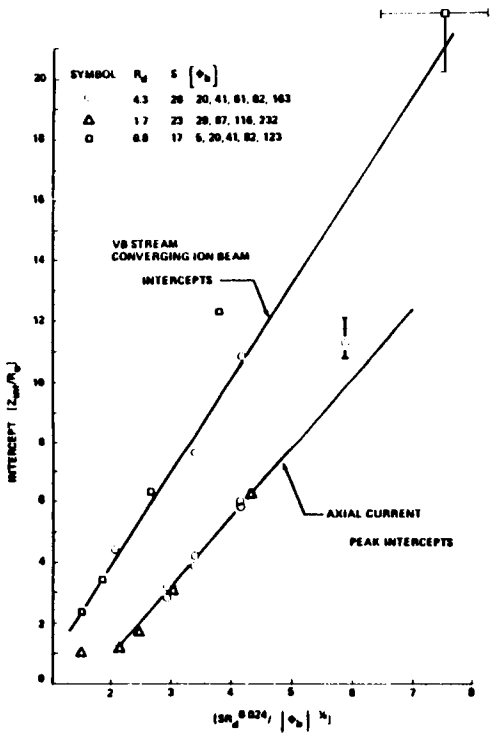

Figure 4. Variation of axial ion peak intercepts and the crossing point for converging ion streams with $[S\ R_o^{\alpha}/|\phi_b|^{1/2}]$. After Stone [1981c].

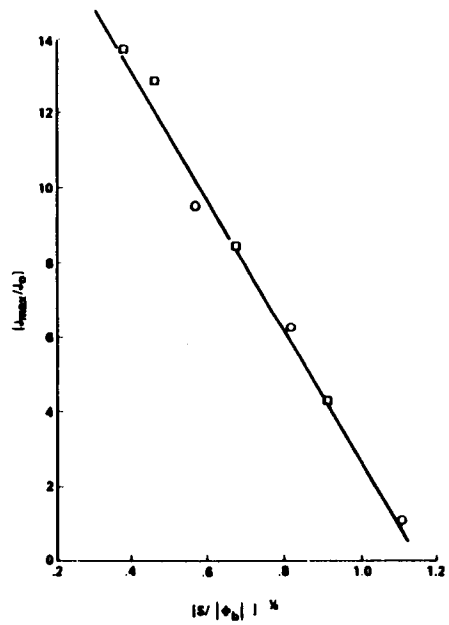

Figure 5. Variation of the normalized maximum amplitude of the axial ion peak, $[J_{max}/J_o]$ with $[S/|\phi_b|]^{1/2}$. After Stone [1981c].

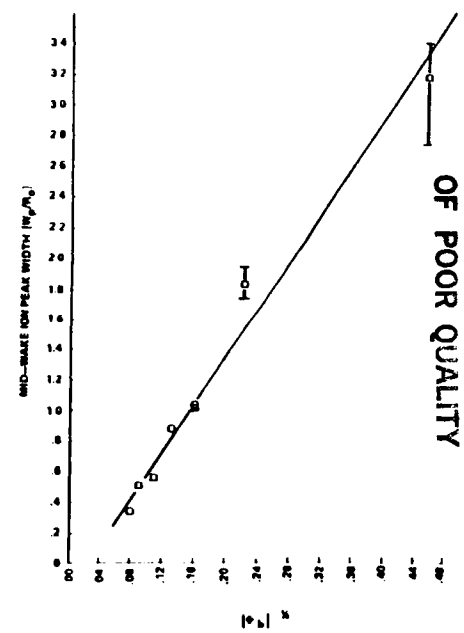

Figure 6. Variation of the axial ion peak width at half maximum with $|\phi_b|^{-1/2}$. After Stone [1981c].

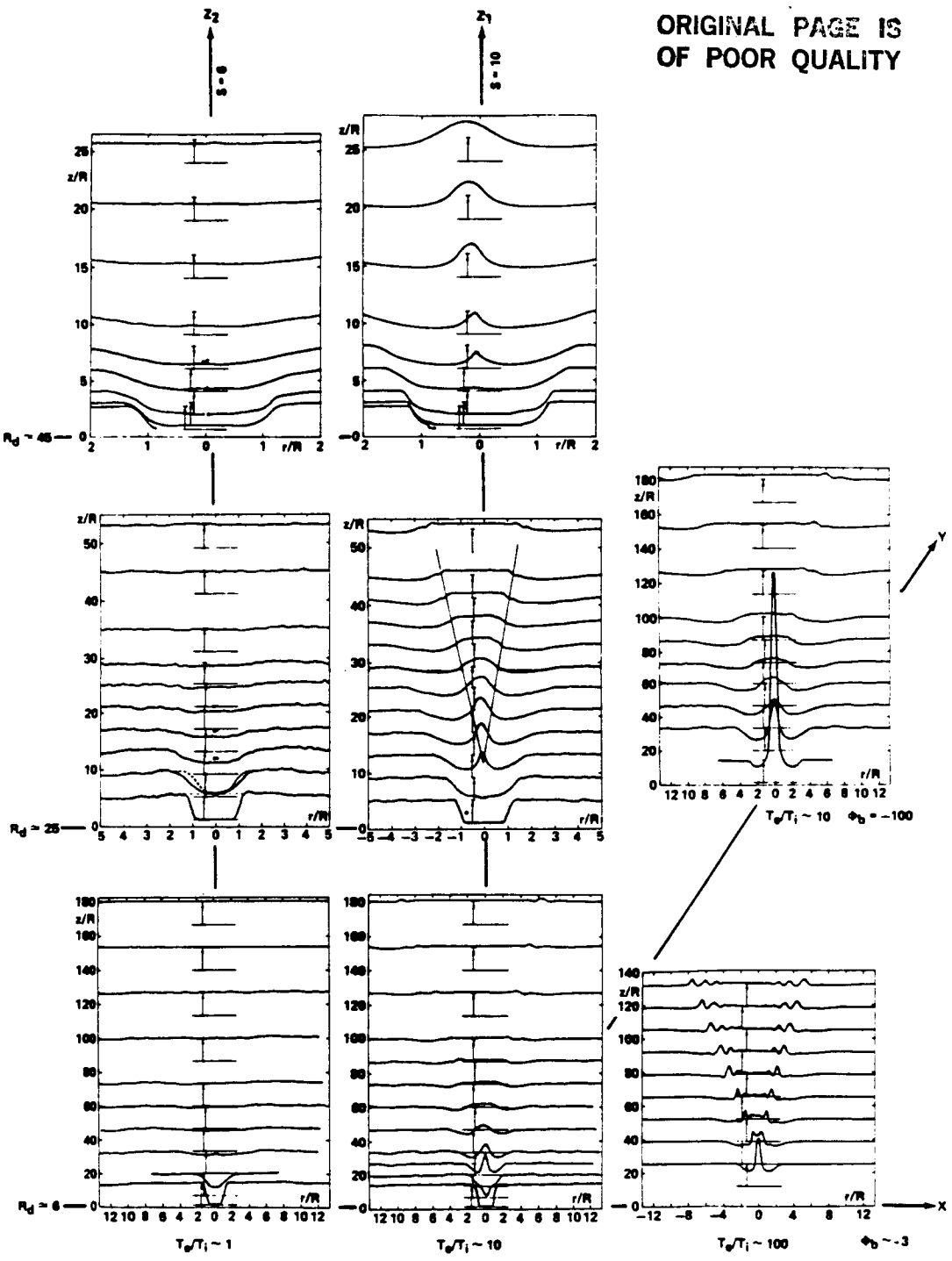

Figure 7. The ion current density in the wakes of spherical test bodies for the conditions, $P \cong 1.6 \times 10^{-7}$ torr, S - 10 (except under the Z_2 -axis where $S \cong 6$), E_i = 20 eV, T_{eo} = 1400 to 2000°K, X-axis = $f(T_e/T_i)$, Y-axis = $f(\Phi_b)$ and Z-axis = $f(R_d)$. After Fournier and Pigache [1975].

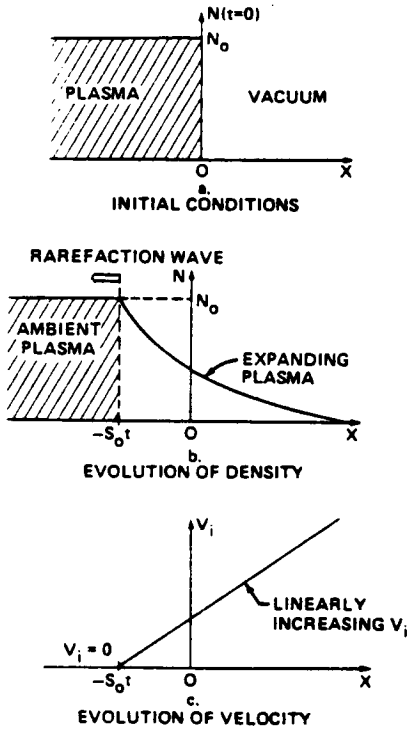

Figure 8. Schematic of plasma expansion into a vacuum. (a) Initial condition, (b) Evolution of density, (c) Evolution of ion velocity according to the self-similar treatment. After Samir et al. [1983].

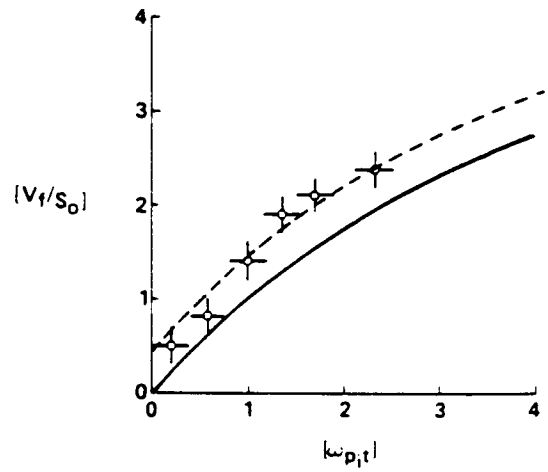

Figure 9. Ion velocity at the expansion front vs time. O, laboratory measurements, --, theoretical model. After Wright et al. [1986].

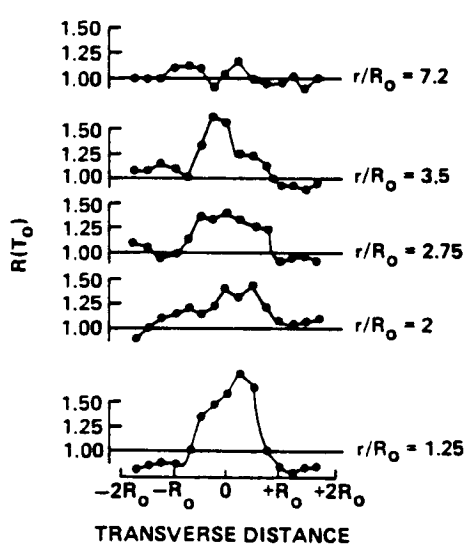

Figure 10. Transverse profiles of $[T_e\ (\text{wake})/T_{eo}]$ downstream from a conducting sphere for T_e = 1200 K°, count n = 7.5 x $10^4/cm^3$, E_i = 5.3 eV. After Samir et al. [1974].

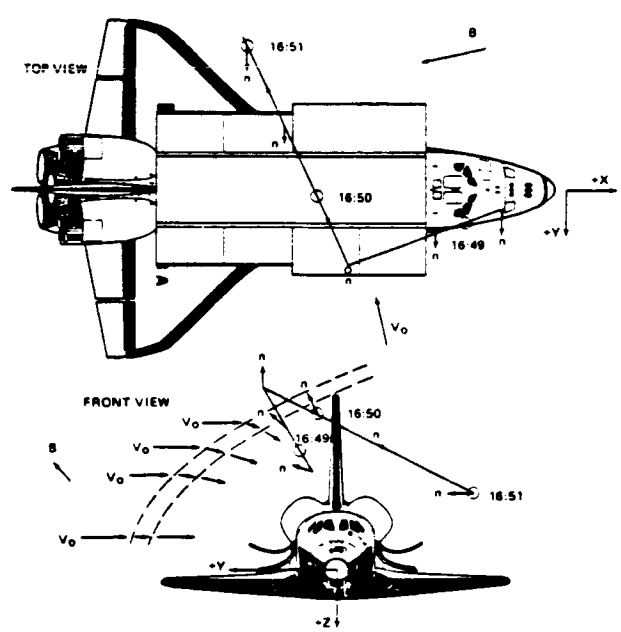

Figure 11. PDP track on Julian day 85 for the period 16:48:40 to 16:51:05. DIFP normal is indicated by n. Dashed lines indicate the inferred boundary of the interaction region. After Stone et al. [1986].

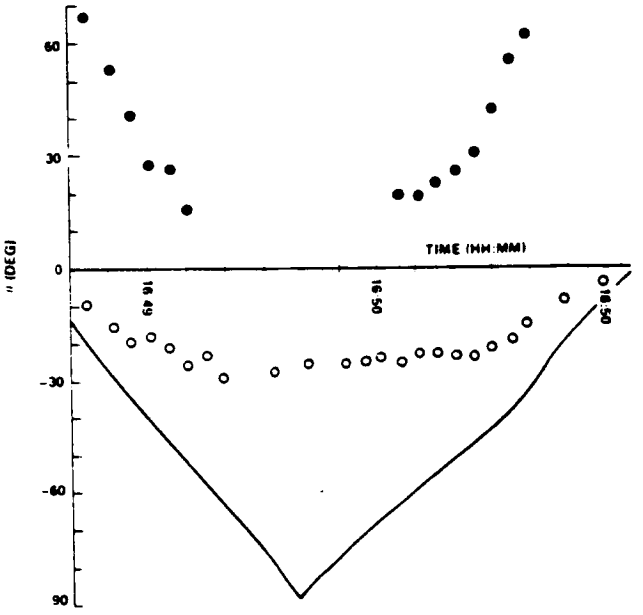

Figure 12. Angles-of-attack of the ram ion current (open circles) and secondary ion steam (closed circles) for the period indicated in Fig. 11. Solid line is the angle between the DIFP normal and the orbital velocity vector. After Stone et al. [1986].

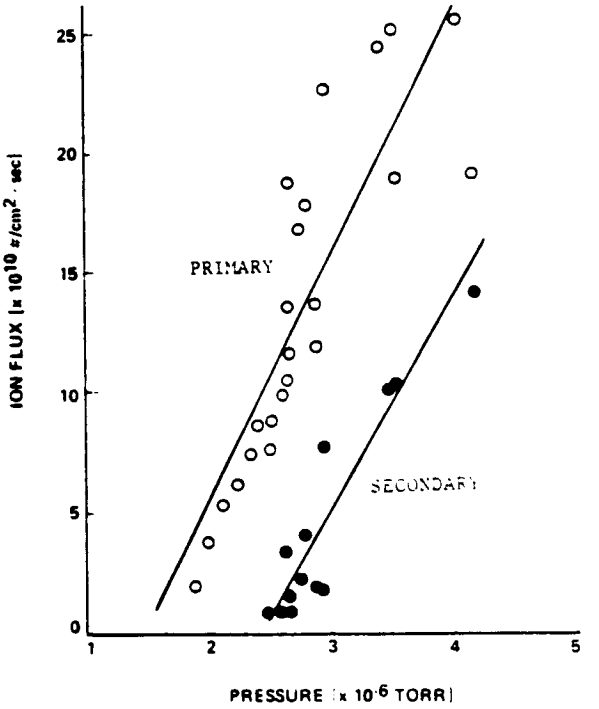

Figure 13. Ion current density vs pressure (neutral particle density) for the period indicated in Fig. 11. After Stone et al. [1986].

N87-20068

SOLAR TERRESTRIAL AND PLASMA PROCESSES EXPERIMENTS ON SPACE STATION

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ABSTRACT

This paper outlines the currently planned utilization of the Space Station to perform investigations in solar terrestrial physics and plasma physics. We will describe the investigations and instrumentation planned for the Solar Terrestrial Observatory and its associated Space Station accommodation requirements. In addition, the planned placement of the STO instruments will be discussed along with typical operational scenarios. In the area of plasma physics, we will outline some preliminary plans for scientific investigations and for the accommodation of a plasma physics facility attached to the Space Station called the Plasma Processes Laboratory. These preliminary experiment concepts use the space environment around the Space Station as an unconfined plasma laboratory.

INTRODUCTION

The Space Station will offer new opportunities to the scientific community by providing a long duration manned platform with sufficient electrical power, data rate, thermal control, servicing, and other capabilities to host several large observatories and research facilities. These observatories and research facilities will be attached to the manned Space Station and will make use of the provided resources. In addition, the presence of a science crewman to control and interact with the experiments and observations will provide additional capabilities for the conduct of new and unique types of research not previously possible.

In the following sections, we will describe two such attached payloads.

SOLAR TERRESTRIAL OBSERVATORY

Over the past ten years concepts for a Solar Terrestrial Observatory (STO) have been developed, including a space platform concept, a geosynchronous platform concept and a high inclination Manned Space Station concept. Now that the Space Station program has been initiated, the concept for the initial version of the STO is being more fully defined.

The STO is a specific, problem-oriented instrument payload structured to investigate and acquire an understanding of the physical processes that occur in, and couple, the major regions of solar terrestrial space. The STO encompasses investigations of the sun, the interplanetary medium, the Earth's magnetosphere and ionosphere, and the atmosphere of the Earth. The initial STO involves the use of a number of large instruments, originally designed for Shuttle Spacelab missions. These instruments will be placed on the Space Station elements to take advantage of: (1) long duration in orbit; (2) high power availability; (3) in-orbit servicing; (4) multidirectional pointing; and (5) coordinated operations.

The STO will also make use of data from other missions such as the International Solar Terrestrial Physics (ISTP) Program, Advanced Solar Observatory, the Environmental Observation System, and the Upper Atmospheric Research Satellite.

The STO will consist of instrument groupings on the Space Station top and lower keels and on the polar platform. The instruments for the initial Solar Terrestrial Observatory are shown in Table 1 along with their planned initial placement. Since the instruments for the initial STO are (with few exceptions) currently under development for flight on Shuttle/Spacelab missions, it is expected that the STO offers a cost effective and realizable payload for the initial Space Station.

Studies are currently underway to determine what modifications and upgradings of these instruments will be required to effectively use them on the Space Station. The initial selection and placement of the STO instruments will enable scientists to begin a program of interactive, cause-and-effect experiments which will be directed toward acquiring a better understanding of the Earth-space system. The upper boom of the manned Space Station will incorporate a solar cluster of instruments which will conduct long-term studies of the solar irradiance output and its variability. This data will allow us to develop a data base of the solar output as an input to the Earth-space environment. The solar cluster is planned to remain on the manned Space Station for a number of years. The solar cluster data will be augmented by data from the Advanced Solar Observatory, and may actually be replaced by the ASO as the ASO approaches its evolutionary maturity.

The active instruments and their supporting diagnostics (WISP, SEPAC, Tether, RPDP, and TEBPP) are placed on the

Table 1.

Solar Terrestrial Observatory
Implementation on Space Station

Instrument	Location	Discipline
Tether	Space Station (top)	Space Plasma Physics
White-Light Coronagraph (WLC) UV Coronal Spectrometer (UVCS) Active Cavity Radiometer (ACR) Solar UV Spectral Intensity Monitor (SUSIM) High-Resolution Telescope and Spectrograph (HRTS) Soft X-Ray Telescope (SXRT)		Solar Physics
Wave Injector (WISP) Particle Injector (SEPAC) Plasma Monitor (TEBPP) Recoverable Plasma Diagnostics Package (RPDP)	Space Station (bottom)	Space Plasma Physics
Imaging Spectrometers (ISO) Atmospheric Emissions Photometric Imaging (AEPI) Wide-Angle Michelson Doppler Imaging Interferometer (WAMDII)	Polar Platform	Atmospheric Physics
Magnetopheric Multiprobes (MMP) Vehicle Charging and Potential (VCAP)	Polar Platform	Space Plasma Physics
MMP/CHEMSAT	Coorbiting Platform	

manned Space Station to initiate a program of controlled, active experiments at low inclinations. The experiments to be performed by these instruments include beam-plasma interactions, wave-particle interactions, wave propagation, ionospheric sounding, plasma physics, and short-duration interactive experiments between the manned Space Station and the Polar Platform STO atmospheric and magnetospheric instruments.

The STO free flyer, the Recoverable Plasma Diagnostics Package (RPDP), will be deployed to operate in conjunction with other instruments on the manned Space Station. The RPDP will provide diagnostic data not only to support the active experiments, but also to provide information on the space environment within 10 km to 1000 km from the Space Station. The RPDP will be controlled and serviced from the Space Station. Figure 1 shows a tentative location of the STO solar cluster and tether on Space Station, and Figure 2 shows the expected placement of the STO active instruments.

The STO Polar Platform will initially host the atmospheric and auroral imaging instruments (AEPI, ISO, and WAMDII) plus a small electron accelerator package and a set of ejectable probes. Figure 3 shows a concept of the initial STO Polar Platform. The atmospheric instruments will operate continuously to acquire and establish a corollative data base on global atmospheric dynamics. When experiments are performed by the active instruments, or when a solar event occurs to trigger enhanced atmospheric response the atmospheric instruments will be commanded (perhaps automatically) to operate in the high resolution and therefore high data rate mode. Periodic experiments will be conducted in conjunction with the electron accelerator (VCAP), and the ejectable diagnostic/chemical release probes (MMP/CHEMSAT).

The currently planned STO operations require nearly continuous monitoring of atmospheric, ionospheric and magnetospheric constituents, and dynamics. In order to better understand the processes which couple the Earth-space regions, controlled, active experiments are also planned which introduce perturbations that simulate or stimulate natural phenomena. These controlled experiments will be performed periodically during the STO missions as campaigns. These campaign modes may be scheduled well ahead to perform a series of experiments to investigate specific physical processes. Alternatively, the campaign modes may be triggered by specific solar events which require experiments designed to investigate the evolution of naturally occurring processes.

Solar Terrestrial Observatory

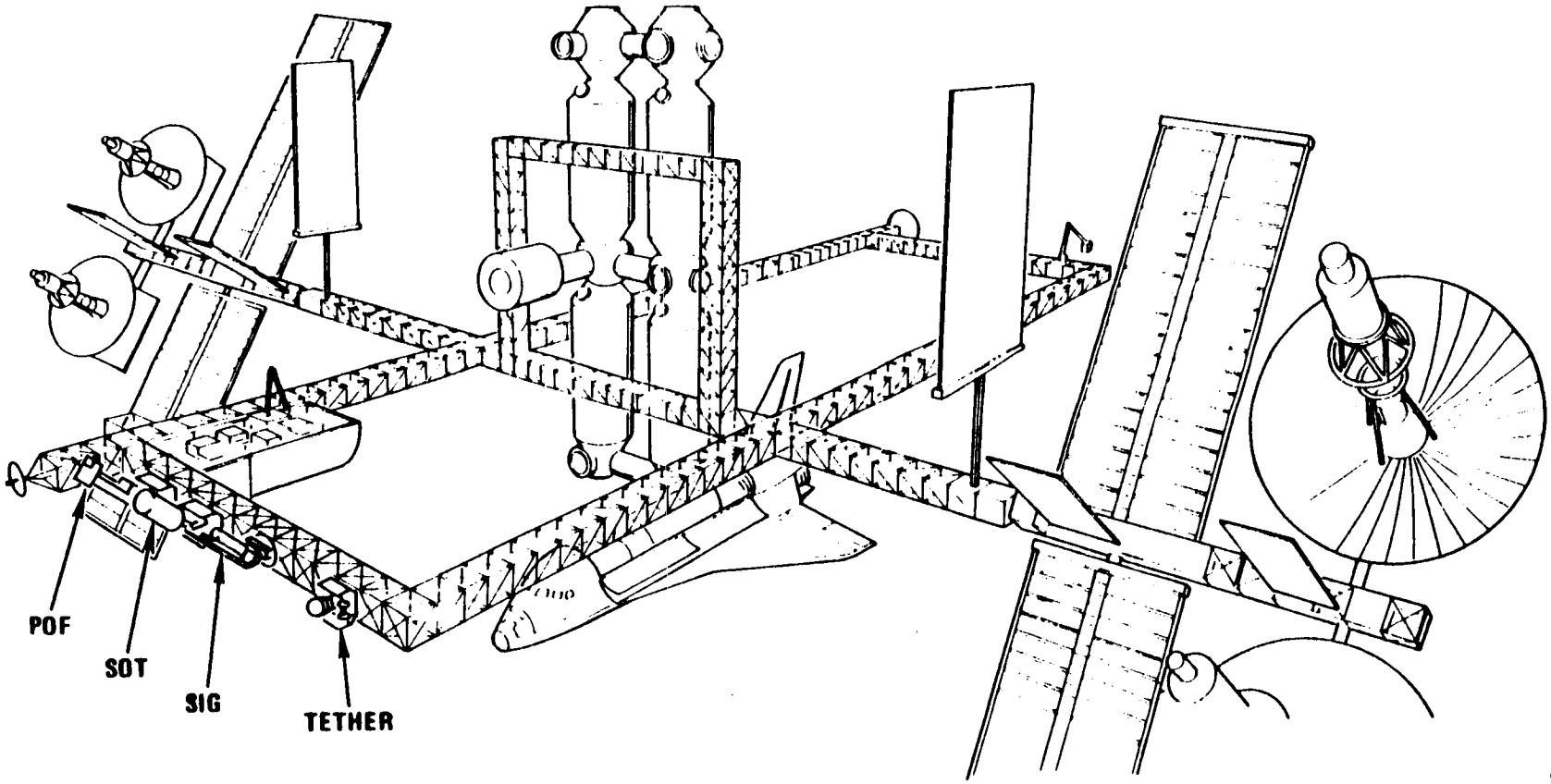

Figure 1. STO Tether and Solar Cluster

Solar Terrestrial Observatory

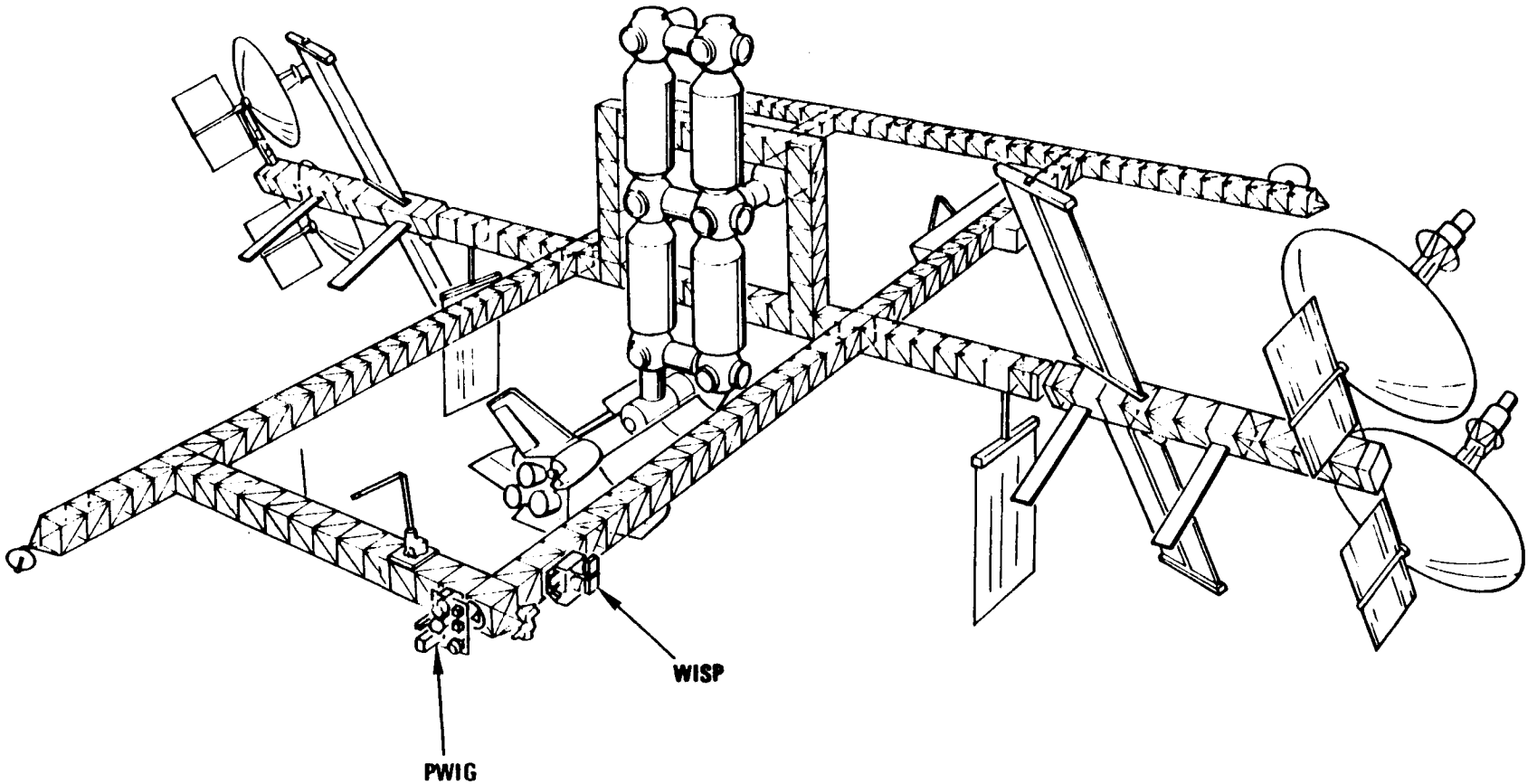

Figure 2. STO Active Instruments

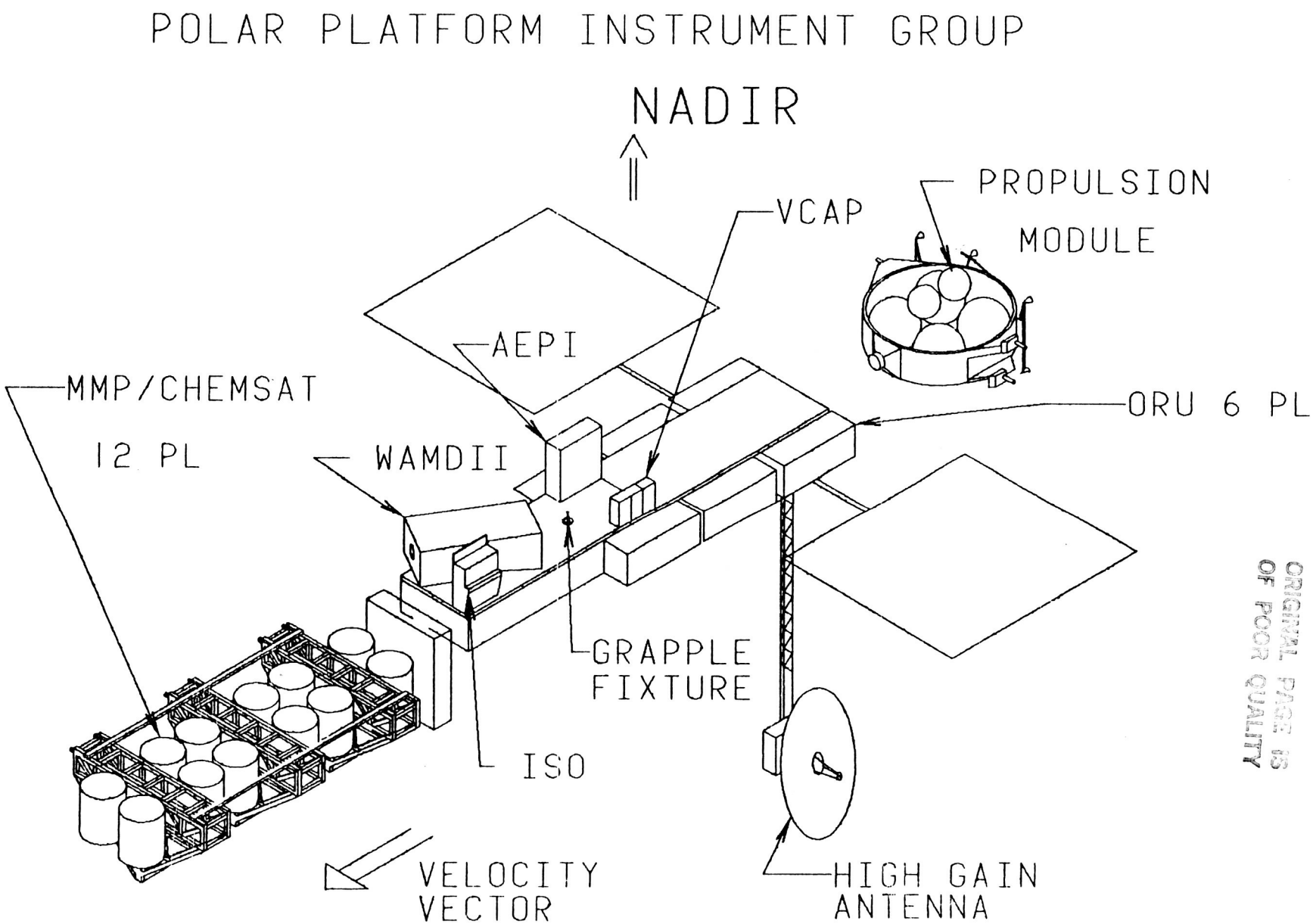

Figure 3. STO Polar Platform

Some STO operational modes could be scheduled for times when the manned Space Station and the Polar Platform orbits cross the same geomagnetic lines of force. Although this conjugate situation will only occur for a few seconds, the opportunity afforded for coordinated experiments between the Manned Station and the Polar Platform will be unique and valuable.

Figure 4 shows an example of the timeline for a typical campaign mode of operation. Usually these timelines will be scheduled well in advance. Prior to the start of the campaign mode, the electrodynamic tether will be deployed and the ejectable probe(s) will be released (from the platforms). The tether diagnostics will be operated for the full time that the tether is deployed, but the use of the tether in its electrodynamic mode will be performed in conjunction with the wave injector and the particle accelerators. Wave injection and particle accelerator operations will require some coordinated operations and some independent operations. For example, off-on modulation of the electron accelerator will generate waves which may be detected by the wave injector instruments. This would be an opportunity to perform coordinated investigations of the use of the electron beam as a virtual antenna. Likewise the wave injector using high frequency sounding techniques will be needed to detect and monitor ionospheric disturbances caused by the operation of the particle injectors. Numerous other examples of coordinated experiments involving the simultaneous operation of the wave injectors and the particle accelerators could be discussed. Typically the wave injector operations will have a duration of about one orbital period (90 minutes) whereas the typical duration for a particle injection experiment is about five minutes.

There are also classes of investigations in which the wave injectors and the particle accelerators do not want the disturbances caused by the other system. Time is therefore scheduled for WISP only, and for SEPAC only, operations.

During the seven days of the typical campaign mode of operation, one day will be devoted to analysis of the data acquired in the first three days, and to perform any replanning necessary for the remaining time. The daily experiment operations will be planned to be accomplished within one 12-hour shift each day. This will leave adequate flexibility for the analysis and allow replanning for the following days' activities. This operational scenario has been derived as a result of our Shuttle/Spacelab experience which demonstrated the need for analysis and replanning, and also maintains the effectiveness of the flight and ground operations personnel.

Solar Terrestrial Observatory
Operating Strategy

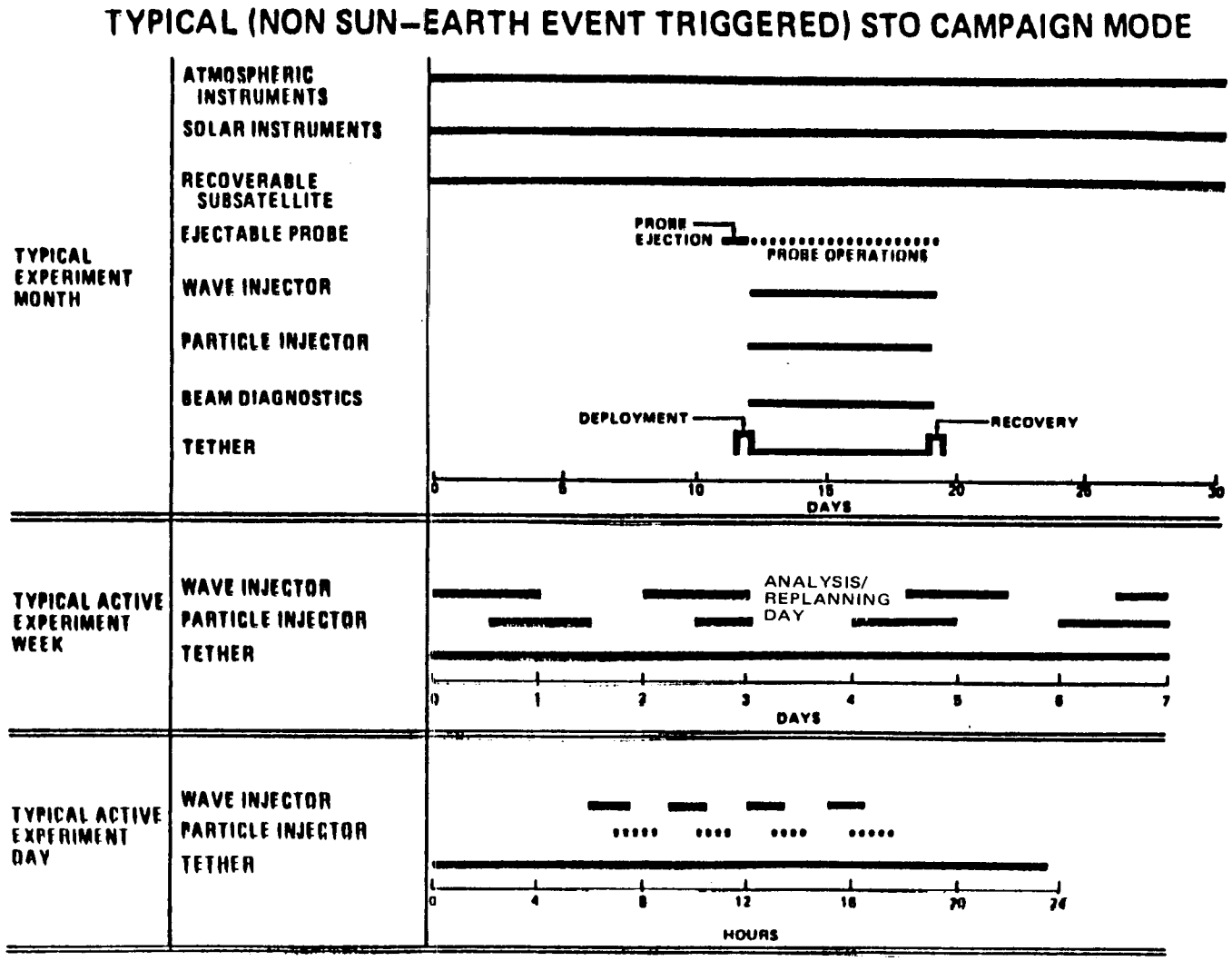

Figure 4. STO Typical Operations

The second class of STO campaign mode operations -- solar event triggered campaign modes -- is shown in Figure 5. This figure shows what would occur if a particular type of solar event (coronal hole) is observed on the Sun, triggering the subsequent operational timeline. The solar instruments would be operated in a high data rate mode as will the atmospheric instruments. Data from other programs would also provide critical information during these times. For example, data from the International Solar Terrestrial Physics (ISTP) Program satellites would be particularly important for solar wind and magnetospheric data. Data from the Upper Atmospheric Research Satellite (UARS) and the Earth Observing System (EOS) would also be very useful to determine atmospheric effects. Ejectable diagnostic and chemical release probes may be deployed from the polar platform to aid in the investigations of particle and field effects in the magnetosphere/ionosphere system. Likewise the particle accelerators could be used to detect and investigate the occurrence of parallel electric fields. The wave injector would be very useful in mapping traveling ionospheric disturbances resulting from the deposition of energy into the auroral zone and other sources.

This type of campaign mode, unlike the campaign mode discussed earlier, will require full operations 24 hours per day. This does not say that all instruments will be continuously operated, but rather that the operational scenario will accommodate single and coordinated operations of all the STO instruments and experiments 24 hours per day. In this way, the flight and ground crews will be available to perform detailed experiments and support continuous monitoring of the evolution of the solar terrestrial processes as they occur.

Ultimately we expect the STO active instruments initially placed on the manned Space Station to be moved to the Polar Platform. This will be done to accommodate the scientific goals of performing cause-and-effect experiments which study the coupling of the interplanetary environment to the Earth's magnetosphere, ionosphere and atmosphere.

The vacancy left on the manned Space Station will be adequately filled by a follow-on payload, the Plasma Processes Laboratory.

PLASMA PROCESSES LABORATORY

In 1985 a workshop was held to explore the feasibility of the Plasma Processes Laboratory for Space Station. Scientists from plasma and fusion research laboratories from throughout the United States attended and participated in this

Solar Terrestrial Observatory
Operating Strategy (Continued)

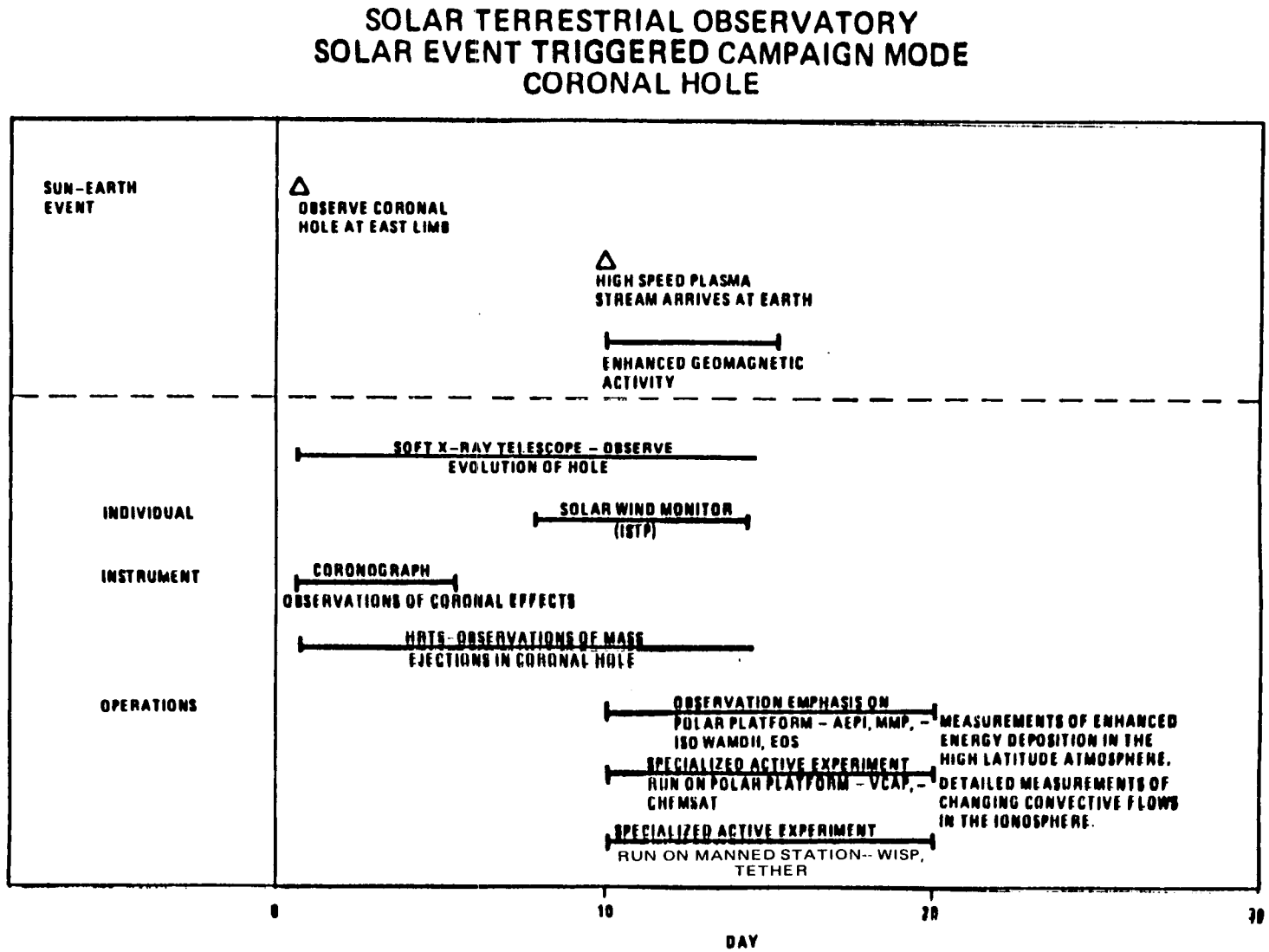

Figure 5. STO Solar Event Triggered Operations

workshop. For many of the participants this was a new interaction with NASA programs.

After three days of vigorous and intense discussion, the workshop participants identified a number of interesting ideas for basic scientific and technological experiments on the Space Station. In each case there is a solid scientific reason for pursuing the concepts developed on the Space Station as opposed to laboratory based experiments. Also, plasma physics as a discipline has much to offer the Space Station complex in understanding the plasma environment that surrounds it, and the interaction of a large electrically conducting structure (like Space Station) with this environment. The development of the basic technologies that would enhance the capabilities of future Space Station investigations is also important.

The Space Station will be a large structure, with large electrical power systems, a significant neutral gas outflux in a plasma and traveling at 7 km/sec through the geomagnetic field. It is reasonable to expect that this condition will create new and unique problems of plasma interactions. The Space Station will certainly cause significant perturbations to the natural plasma environment, and it is not unreasonable to expect that the plasma and magnetic field environment will effect the Space Station. For these reasons, it has been proposed that the Space Station develop a set of diagnostic instruments (a Plasma Interaction Monitoring System) to be attached to various places on the structures to measure and understand the nature and extent of this problem. The initial placement of these diagnostics should accompany the very first on-orbit station elements. By acquiring an early data base on possible deleterious effects of these plasma interactions, it may be possible for subsequent elements to be reconfigured to minimize the effects. Also this Plasma Interactions Monitoring System will hopefully be designed to provide data on environmental modifications resulting from Shuttle rendezvous and docking, station reboost, and possible venting from modules (the so-called "smokestack effect").

The advantages of the Space Station to plasma processes experiments per se may be categorized into two areas -- environmental and operational.

The environmental considerations include:

- The possibility of creating ultrahigh vacuum over a large volume. This may be accomplished by shielding the desired volume from the ambient neutral and plasma flow, creating a high-vacuum wake region.

- An ambient plasma environment uniform over large scale lengths. This makes it possible to perform experimental studies of processes requiring homogeneous background conditions over interaction lengths attainable only in space.

- The absence of walls and accompanying effects, such as impurity injection, wall currents, and field shorting.

- The large scale steady plasma flow past the Space Station due to its orbital velocity. This condition is difficult to achieve in the laboratory.

- Combinations of plasma parameters in the Space Station environment that are ideal for qualitative scaling of space phenomena.

- The absence of gravity. This permits a class of experiments which are difficult on Earth, involving colloidal or dusty plasmas as well as certain technology studies involving such effects as breakdown of insulation in mists. Additionally, levitation of components for achieving various boundary conditions or magnetic fields is simplified, possibly leading to previously unattainable field topologies.

Operational considerations include such factors as:

- Long-duration data bases. In contrast to Shuttle-borne missions one will have the ability to explore wider variations of experimental and environmental parameters with correspondingly more comprehensive investigations. Experiments which would yield too little data during a Shuttle flight may be contemplated.

- The ability to modify experiments during the course of an investigation. The scientific return from Space Station-based experiments can be qualitatively greater because of an investigator's ability to respond to unanticipated results or to modify (to some degree) the experimental configuration as new objectives are indicated by interim data. This mode of operation will lead to a hands-on laboratory-like capability.

- Maneuverable platforms, tethers, and other adjuncts. These will allow great flexibility in experimental configurations and diagnostics.

- The large scale sizes available in space, already mentioned above in the context of enabling experiments involving long interaction lengths, will also permit much greater diagnostic access than in ground-based experiments.

The workshop participants, after developing basic evaluation criteria, described nine very broad experiment categories which could effectively be addressed by the Plasma Processes Laboratory.

1. Investigations of the interaction of the large Space Station with the surrounding plasma environment.

2. Investigations of charge buildup causing high potentials on objects in the space plasma environment.

3. Studies of the plasma flow about objects.

4. Investigations of the basic mechanisms of nonlinear particle and wave interactions.

5. Studies of plasma shocks.

6. Investigations of beam-plasma interactions.

7. Investigations of plasma toroids.

8. Studies of the fundamental physics of dusty plasmas.

9. Studies of the physics of plasmas in a microgravity environment.

In general the Plasma Processes Laboratory (PPL) will require three types of facilities on Space Station: (1) a Core Facility, (2) an Exposed Experiment Facility, (3) a Remote Experiment Site.

The Core Facility, shown in Figure 6, will include a capability for data acquisition and processing and for control of the experiments. This shirtsleeve facility also includes a workbench and storage area to which specific instruments may be brought for on-orbit repair, servicing or up-grading and modification. This manned module may also include experimental microgravity chambers. A large airlock will also be needed.

Figure 7 is an artist's concept of the PPL Exposed Experiment Facility. This facility is attached to the Space Station and provides a pallet on which the PPL instruments may be mounted. Experiments in basic plasma physics, plasma interaction experiments and beam plasma physics may be conducted from this facility. The facility will be operated from the Core Facility.

Finally, Figure 8 shows the requirement for a PPL Remote Experiment Site. Some of the Plasma Processes Laboratory

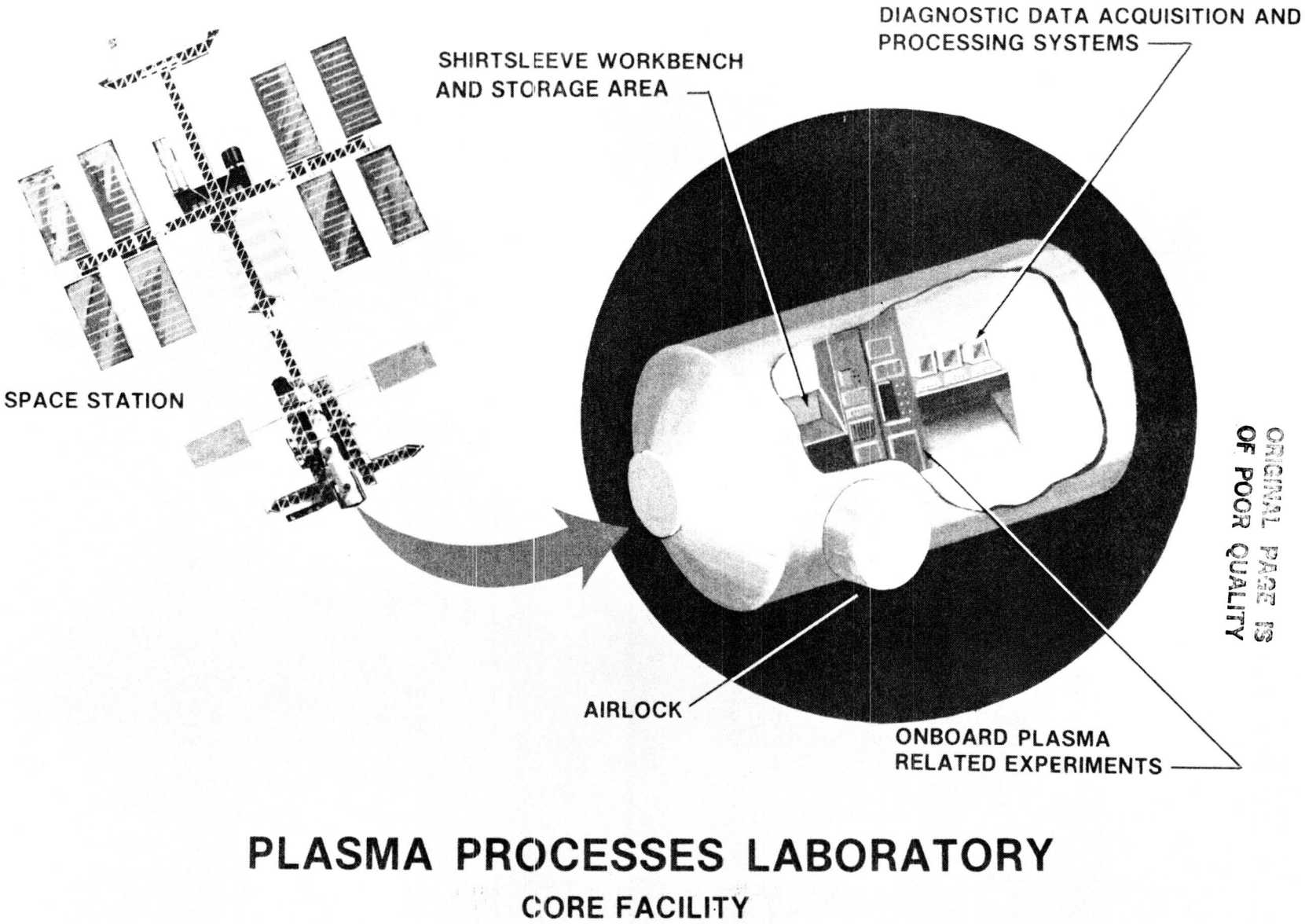

Figure 6. PPL Core Facility

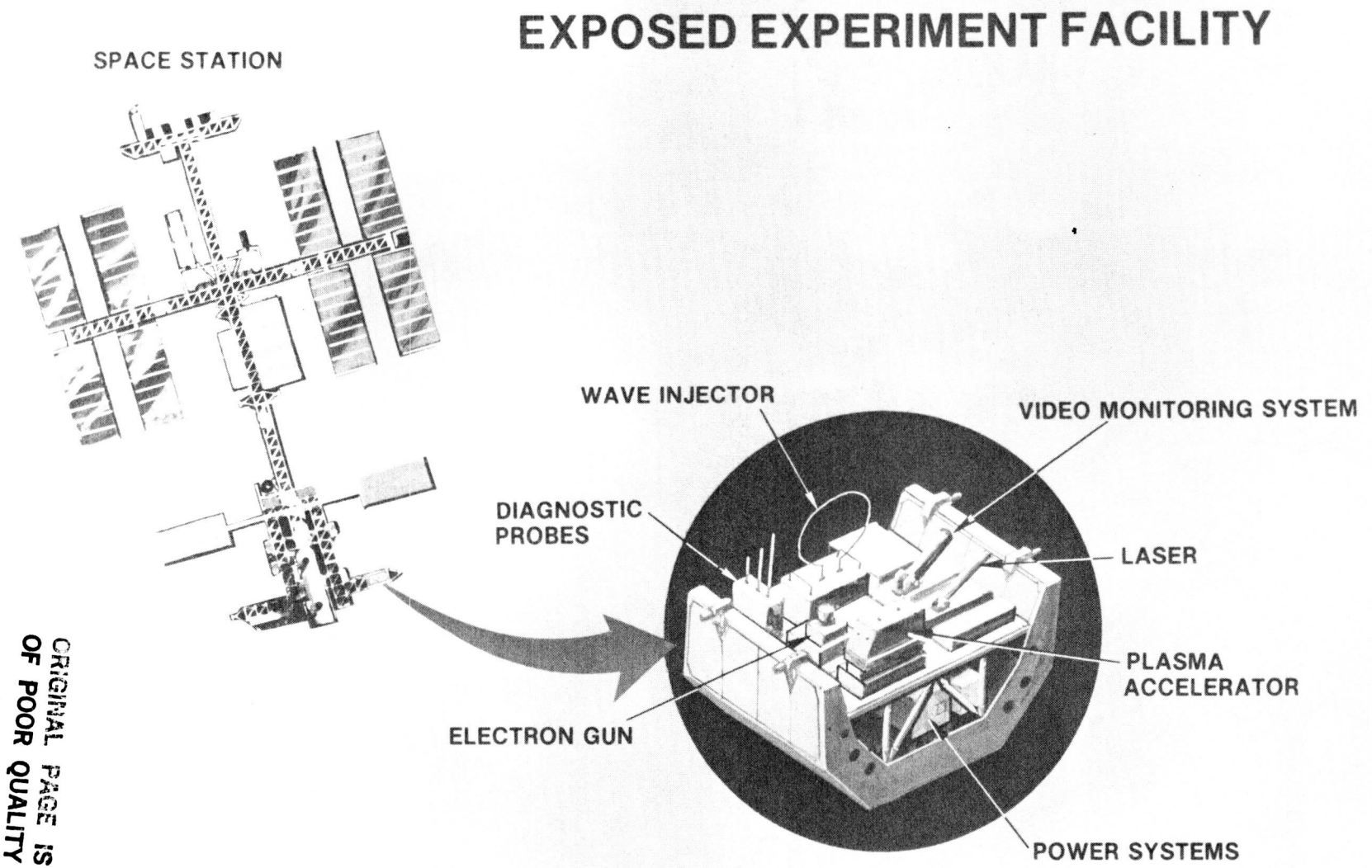

Figure 7. PPL Exposed Experiment Facility

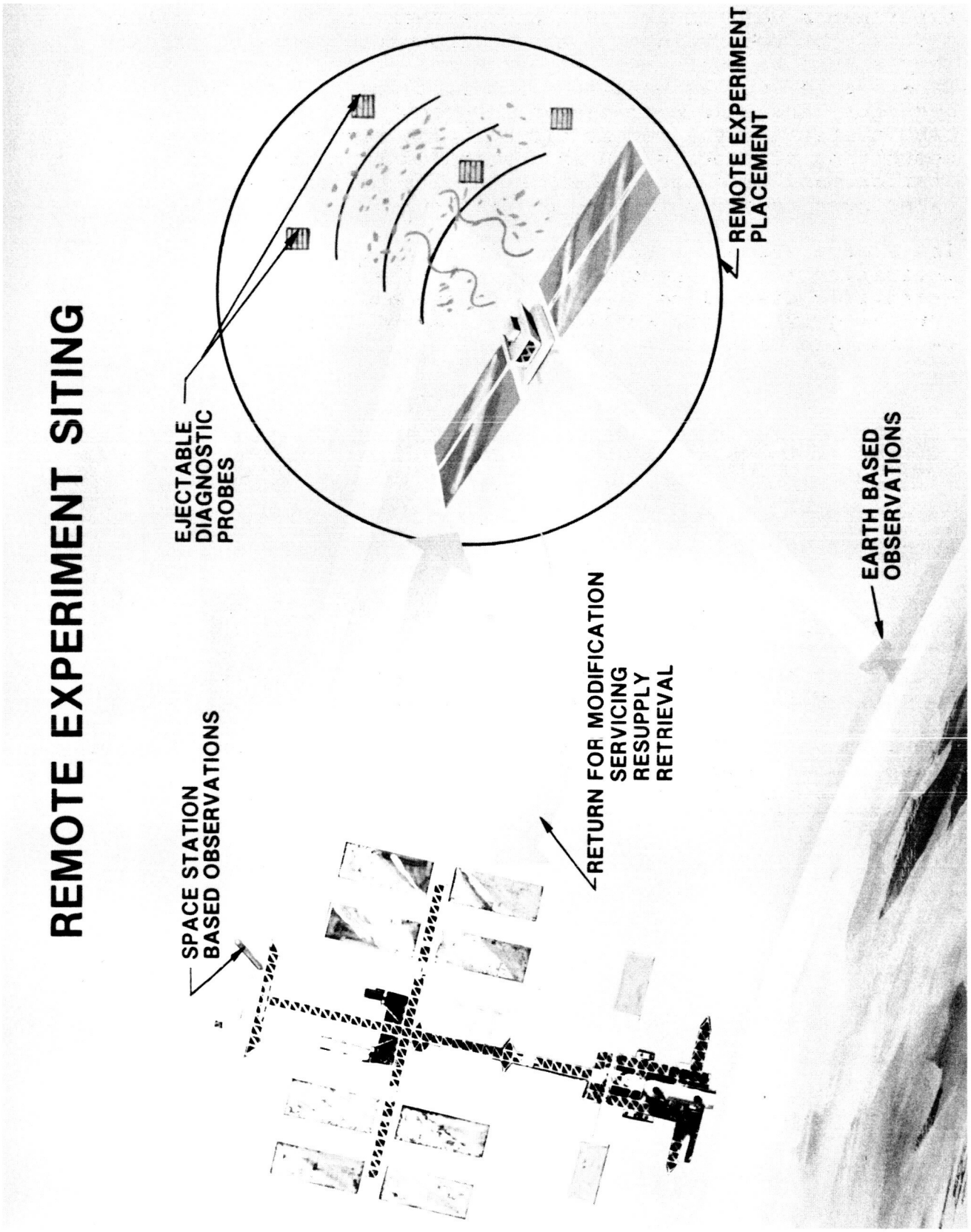

Figure 8. PPL Remote Experiment Siting

experiments defined are such that either due to environments induced, or uncertainty of the environmental loading effects, they should be performed away from the manned Space Station. Experiments such as nonlinear interactions, plasma toroid dynamics, and some beam-plasma interaction experiments are best suited for the remote siting. The remote site may be a coorbiting platform which is controlled from the Space Station, and uses the Space Station for periodic servicing, experiment reconfiguration, and instrument repair.

The Plasma Processes Laboratory is in a very early stage of definition at the present time. Nevertheless, this scientific discipline appears as a new and exciting customer for the growth Space Station -- a discipline that would not be possible without the Space Station.

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HIGH VOLTAGE SYSTEM - PLASMA INTERACTION SUMMARY

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ABSTRACT

This paper reviews the possible interactions that could exist between a high voltage system and the space plasma environment. A solar array is used as an example of such a system. The emphasis in this review is on the discrepancies that exist in this technology in both flight and ground experiment data. It has been found that, in ground testing, there are facility effects, cell size effects and area scaling uncertainities. For space applications there are area scaling and discharge concerns for an array as well as the influence of the large space structures on the collection process. There are still considerable uncertainities in the high voltage-space plasma interaction technology even after several years of effort.

INTRODUCTION

A technology investigation of high voltage system interactions with plasma environments was launched about 17 years ago to satisfy a preceived need for such applications as direct drive electric propulsion and advanced communications systems (1-3). This investigation consisted of ground studies and an auxiliary payload spacecraft project called SPHINX, an acronym standing for Space Plasma High-Voltage Interaction Experiment (4). About the same time that this spacecraft was launched and lost (1974), interest in high voltage system interactions decayed.

In the past several years, however, NASA has been conducting mission studies calling for larger satellites to be placed in low earth orbits by the Shuttle (5-8). The culmination of this activity is the proposed Space Station which has a baseline power requirement to the load of 75 KW (9). If a photovoltaic array is used to produce this power, then the array must generate about 200 KW to be able to supply the load, maintain the battery charging, account for line losses and allow for the degradation of the array. The large power numbers used in these studies has stimulated the desire to increase the operating voltages thereby reducing the line current. However, the operation of high voltage systems in space can result in interactions with the space plasma environment that can impact the system performance.

The interactions of concern in high voltage system operations in space can be illustrated using solar arrays as an example. Consider the system shown schematically in Figure 1. This system consists of two large solar array wings surrounding a central body or spacecraft. The solar arrays are assumed to be assembled such that the solar cell covers do not completely shield the metallic interconnects from the environment. These cell interconnects are at various voltages depending upon their location in the array circuits. Hence, the interconnects can act as plasma probes attracting or repelling charged particles. At some location in the array, the generated voltages are equal to the space plasma potential. Since the electrons are more mobile than the ions, the array floats at a voltage that is more negative than positive with respect to the plasma potential. This arrangement gives rise to possible current collection and breakdown phenomena.

The severity of these plasma interactions depends upon the array operational voltage and the plasma environment. The operating voltages are determined from power system requirements while the plasma environment ranges are established by the orbit. Since the operational voltages considered are large enough to affect only the thermal plasma (plasma particle energies less than 2 eV), these interactions are of more concern in the lower altitudes where the density is the highest (see Figure 2).

These interactions have been studied in ground simulation facilities using solar array segments and dielectrics with pinholes as test samples. Tests with pinholes produce repeatable results in the various test facilities. The solar array tests did have discrepancies in the data. Therefore, only the solar array tests will be discussed in this report. The tests were conducted at the Hughes Research Center (10), Boeing Aerospace Company (11), TRW (12), NASA-Lewis Research Center (13-16) and NASA Johnson Space Center (17,18). Two auxiliary payload experiments were also flown (19,20). In the following paragraphs, the results from these studies are discussed with emphasis placed upon the differences arising from the tests. This can be then used to indicate a direction for future programs.

GROUND SIMULATION STUDIES

The majority of tests conducted in this interaction study were done at NASA-Lewis Research Center and at Boeing. This report uses the Lewis data as baseline and will discuss the other data as deviations from this data. This is not intended to suggest that the Lewis data is correct and the other is wrong; it is just an convenient way to explain the interactions and point out discrepancies.

Tests of solar array segments exposed to plasma environments and biased by external power supplies have been conducted for years. The philosophy implicit in such tests is that the interaction measured at each

voltage step in the laboratory can be summed to obtain the performance of a distributed voltage solar array. Hence, it is assumed that there are no interactions between the various parts of the array at different voltages and the phenomena measured should produce worst-case results.

Such plasma interaction tests have been typically conducted in an experimental facility shown schematically in Figure 3. The vacuum chamber is capable of maintaining a background pressure in the 10^{-6} Torr range with the plasma source operating. This source creates the environment by ionizing a gas such as nitrogen, argon or helium. The plasma parameters (number density and particle temperature) are determined by plasma probe measurements. The test sample is mounted in the chamber, electrically isolated, and connected to the bias power supply. A current sensor is placed in the line between the power supply and the sample to measure the plasma coupling current from the sample to ground. A surface voltage probe (such as the one manufactured by TREK) (21) can be used to measure the voltage across the sample during the test. It should be noted that the tank ground is not necessarily the plasma potential. The plasma potential must be determined from the plasma probe readings and corrections to the sample voltage relative to the plasma potential must be made in order to interpret the results of the experiments.

Lewis Research Center Data

Plasma interaction tests have been conducted in various facilities at the NASA-Lewis Research Center since 1969 to support both technology investigation and space flight experiments. It represents the largest body of test data available.

Solar array segments ranging in size from 100 to 13,600 square cm areas were tested in plasma environments ranging from 10^3 to 5×10^4 particles per cm^3. This data represented a reasonable cross-section of possible panel areas and, at the time, was believed to be adequate for developing area scaling laws.

In order to minimize the number of variables in these studies the collected current was non-dimensionalized and the voltage used was corrected for the plasma potential. The results are shown in Figure 4 A and B for positive and negative bias test data. The current, I(0), is the thermal plasma current to the sample:

$$I(0)_e = 2.7 \times 10^{-12} N_e \quad T_e A \qquad \text{for positive bias}$$

and

$$I(0)_i = K N_i \quad T_i A \qquad \text{for negative bias}$$

where $K = 9.89 \times 10^{-15}$ for Argon and $K = 1.4 \times 10^{-14}$ for Nitrogen and A is the panel area.

The error bars represent the range of results for a specific voltage, not a variation about a mean.

The major uncertainty in this data is the plasma parameters. The majority of this data lists only an approximate value for density as are values of electron and ion temperatures. The plasma potential is rarely specified. Probe measurements in the chamber indicated that the density was not uniform and before and after tests probe readings indicated that the environment would not be stable during the test. The uncertainty in the plasma parameters during the tests was stated as being uniform within a factor of two. This condition seems to have existed in tests at other facilities that did provide the plasma parameters.

In spite of the variations in the data, it is apparent that the positive bias data shows a transition at +100 volts. This transition has been called "snap-over phenomenon" (22). This data can be empirically fit by using two relationships:

$$I = I(0)_e \times (1.5 \times 10^{-3}\ A) \times (1 + V/T_e) \qquad 0 \leq V \leq 100$$
$$I = I(0)_e \times (A/4) \times (1 + V-100/T_e) \qquad V > 100$$

The model predictions are plotted in Figure 4 A. The agreement between the data and predictions is excellent with the exception of the region between 50 and 100 volts where the collection process is undergoing the transition to snap-over conditions.

In negative bias tests, discharges did occur. The threshold for these discharges appeared to be dependent upon the plasma density even though the non-dimensionalization of the data does seem to mask this effect. Below the breakdown threshold the negative bias current data seems to be linearly proportional to the voltage. This relationship can be fit by an expression:

$$I = I(0)_i \times (1.25 \times 10^{-2}\ A)\ (1 + V/T_i) \qquad V < 0$$

The comparison between the predictions and data is shown in Figure 4 B. There is no way to predict, with this model, the transition to a discharge.

Discharge occurrences in the negative bias positions of the array are an important consideration in the use of these systems for space applications. It could be the limiting factor in their operation in space. The original concept for breakdown was that there was a voltage threshold that was plasma density dependent (see Figure 5). Subsequent data analysis at Lewis, however, has indicated that there may be an arc rate phenomenon that must also be considered (23). While there may still be a voltage threshold, arcing can occur at low voltages if held there for long times. The test data was usually taken over relatively short time intervals.

Effect of Facility on Results

Tests have been conducted in facilities other than Lewis Research Center (LeRC). These test results have been reviewed and are summarized here as small segment tests and panel tests.

Small Segment Tests

These tests were conducted in Boeing Aerospace Company facilities under contract to LeRC (11). The tests were conducted in a similar manner to the LeRC tests using nitrogen for the plasma. The principal differences between the two sets of experiments were that the Boeing tests were conducted in an ion pumped chamber and used a Burrowbridge plasma source (24). This plasma source consisted of two large screens separated by a small distance. The ionization was initiated between them and filled the chamber. This type of device generated a plasma with relatively high energy (about 6 to 7 eV electrons and 25 eV ions). The LeRC plasma characteristics were about 1 eV for both electrons and ions.

The principal difference between these tests results is that the Boeing data does not show the snap-over phenomenon in the positive voltage collection (see Figure 6). The electron collection tends to be a uniformly increasing curve with about an order of magnitude larger current at voltages less than 100 volts and about an order of magnitude less at voltages greater than 100 volts. This data can be fit by the following expression:

$$I = I(0)_e \times B \times A \, (1 + V/T_e) \qquad V > 0$$

where (B x A) is the array panel interconnect area.

The negative voltage data obtained in both sets of tests seemed to be in reasonable agreement.

Panel Tests

There have been several tests conducted on high voltage solar array interactions in the 40 foot diameter chamber at Johnson Space Center (JSC) (17). The test that will be discussed here is the one that was conducted jointly by JSC and LeRC personnel to evaluate the effect of facilities on plasma-high voltage interactions (15). The tests at the LeRC were conducted in a 15 foot diameter chamber. The test specimens were a nine panel array (13,6000 cm x 2) and a single panel (1400 cm x 2).

The determination of facility effects can be best shown by comparing the results of the positive bias tests on the smaller, single panel. The data

is shown in Figure 7. Both tests used Argon for the plasma and the densities were within a factor of three. The initial collection characteristics indicated a positive plasma potential in the JSC tests (about 8 to 12 volts) whereas the LeRC tests showed a negative potential (about -5 to -10 volts). The low voltage collection in the JSC tests is about an order of magnitude larger than that obtained in the LeRC tests. Snap-over occurred at about 100 volts in the LeRC tests but at 150 volts in the JSC. The magnitude of the snap-over in the JSC tests was also considerably less than in the LeRC tests. Finally, the positive tests in the JSC facility terminated at about 400 volts with a discharge. Negative bias collection in both facilities produced similar results.

A solar simulation test was run in the JSC chamber using the large nine panel array. The panels were connected in series and illuminated to provide a test on a large array operating open circuit at about 225 Volts in a plasma environment. The voltage of each segment relative to tank ground was measured as was the current flow between the segments. By correcting for the plasma potential, this test indicated that the positive end of the array was at +25 volts while the negative end was at -200 volts. By using the voltage of each panel in sunlight, the voltage distribution in the array was obtained. If the average voltage relative to the plasma potential was used, the average panel current collection should be computed from empirical models developed from the LeRC tests. This, unfortunately, results in predicted electron currents that are an order of magnitude too low while the ions collection predictions seem to be proper.

Therefore, there is still considerable work to be done in understanding the basic plasma collection process in solar arrays.

Discharges

As stated previously all of the data seemed to be in reasonable agreement for negative bias collections. The question of discharges, however, is still not resolved. These threshold variations are indicated in Figure 8. While the onset of discharges is still an unresolved question, a statistical study using arc rates seems to be producing some uniformity in this data (see Figure 9) (23).

SPACE FLIGHT RESULTS

There are really only two sets of space flight data available on this interaction; the Plasma Interaction Experiments 1 and 2 (PIX-1 and PIX-2) data (19, 20). Of the two sets of data, the PIX-2 is the more complete and will be considered here.

The PIX-2 hardware and orbit characteristics have been previously described in the literature and will only be briefly summarized here. PIX-2 was designed to be an auxiliary payload experiment remaining on the second stage of the DELTA launch vehicle and using the DELTA telemetry system after deployment of the payload. The PIX-2 hardware was flown on the IRAS mission on January 25, 1983 and functioned for a total of 19 hours.

The PIX-2 hardware consisted of two parts: the experiment plate and the electrons enclosure. These parts were located 180 degrees apart on the transition area of the DELTA second stage (see Figure 10). The experiments consisted of four solar array segments, about 490 cm^2 each, that could be biased separately or as groups to potentials of up to +/- 1000 volts. The bias electronics and measurement circuits were housed in the electronics enclosure.

The positive bias voltage collection tended to follow the laboratory results when the experiment was run in the thermal or wake modes (after correcting for the structure potential). The data showed a snap-over effect at about 100 volts for both single and multiple samples (see Figure 11). The only discrepancy was in fitting the data for the electron collection below 100 volts. Here, the flight data indicated a stronger voltage dependence than the ground data.

In the ram direction, the electron collection was completely different from the ground simulation data. Here, snap-over was suppressed and the current seemed to fit a 3/2 power of the voltage over the full range of data (see Figure 12).

The negative bias data seemed to show a slope transition at about 100 volts regardless of the velocity mode (see Figure 13). This curve could be fit with empirical expressions that agreed with the laboratory data above 100 volts negative. Below 100 volts negative, the flight data indicated a lower dependance on voltage than the laboratory values.

For discharges under negative bias voltage, the comparison between ground and flight data is shown in Figure 14. Here, discharges are assumed to occur in the flight data when the system shut off completely. The ground data discharge is assumed to occur when there is a deviation from linearity in the current voltage curve. Hence, there is a discrepancy in the definition of breakdown in the two data sets. However, the flight data does indicate a uniformly lower threshold than the ground data. The comparison for the arc rate (23) indicates that the flight arc rate has a stronger voltage dependence than the ground test data (see Figure 15). This has not been answered or explained.

SYSTEM APPLICATIONS

The empirical relationship can be used to predict the behavior of large solar array systems in space even with the differences in the models. For a 300 KW system divided into 8 wings consisting of 32 parallel branches of 26 blocks in series (the Space Station configuration) the floating potential relative to space is shown in Figure 16. It is assumed that the series blocks generate a total 250 volts for operations. It is shown here that the average block voltages are about 5% positive and 95% negative. All of the modifications considered in the previous sections of this report would not change this distribution more than 5%. However, the uncertainty in the technology could be important in the extrapolation of this information to other systems.

Whether or not there would be discharges in this array is also an open question. Arc rate studies indicate that discharges can occur over long mission times. These discharges may be too small to seriously affect the load, but multiple transients on components may still cause failures. The impact of transients on component lifetime has not been adequately evaluated.

If the power supply is connected to the structure, then there is another unknown: the plasma collection of large structure. There are three possible models to be considered for this collection: sphere, plate and thermal. The sphere model assumes a spherical Langmuir probe relationship. The plate model assumes collection based upon Childs-Langmuir sheath sizes (22). The thermal model assumes that the large area collects from the plasma independently of the voltage. As shown in Figure 17, there is considerable difference in the predicted currents resulting form the models. There is a data set from large plate tests in ground simulation facilities at Johnson Space Center (18). This data indicates that large plates would collect more like the thermal model. The tests were conducted using flat metal plates and no information is available for metal/dielectric plates or curved plates.

Applying these models to the prediction of large, high voltage system space performance leads to considerable discrepancies. Using the sphere and plate models, the floating potentials can be changed to be significantly more positive resulting in power losses of up to 10%. Under the thermal or JSC models the power losses are always less than 1%. This discrepancy should be resolved.

One of the engineering responses to the concern for plasma effects in high voltage space systems is to recommend the use of an AC transmission line to carry power from the generator to the load. This would make the space system comparable to the ground power generating systems. Unfortunately, even less is known about AC effects in plasmas than DC. It is known that the desired frequencies are close to the ion resonance frequencies of the plasma (20 KHz). The effects of the Earth's magnetic

field and AC breakdown processes in this plasma are unknown and must be evaluated.

CONCLUDING REMARKS

The concept of high voltage systems for space applications has been evaluated over the past 17 years in both ground simulators and auxiliary payload flight experiments. There are considerable gaps in understanding this technology. The models for plasma collection of both electrons and ions are uncertain when nonuniform structures are considered. The possibility of discharges exist and the effect of discharge transients on system component lifetimes are unknown.

Applying this uncertain technology to system performance computations is also risky. The behavior of a power system coupled to a large structure can not be predicted with any surety. The effect can either be somewhere between none and 10% loss in power. The possible engineering solutions considered to date only have the comfort of having insufficient information to show that they would have a detrimental effect.

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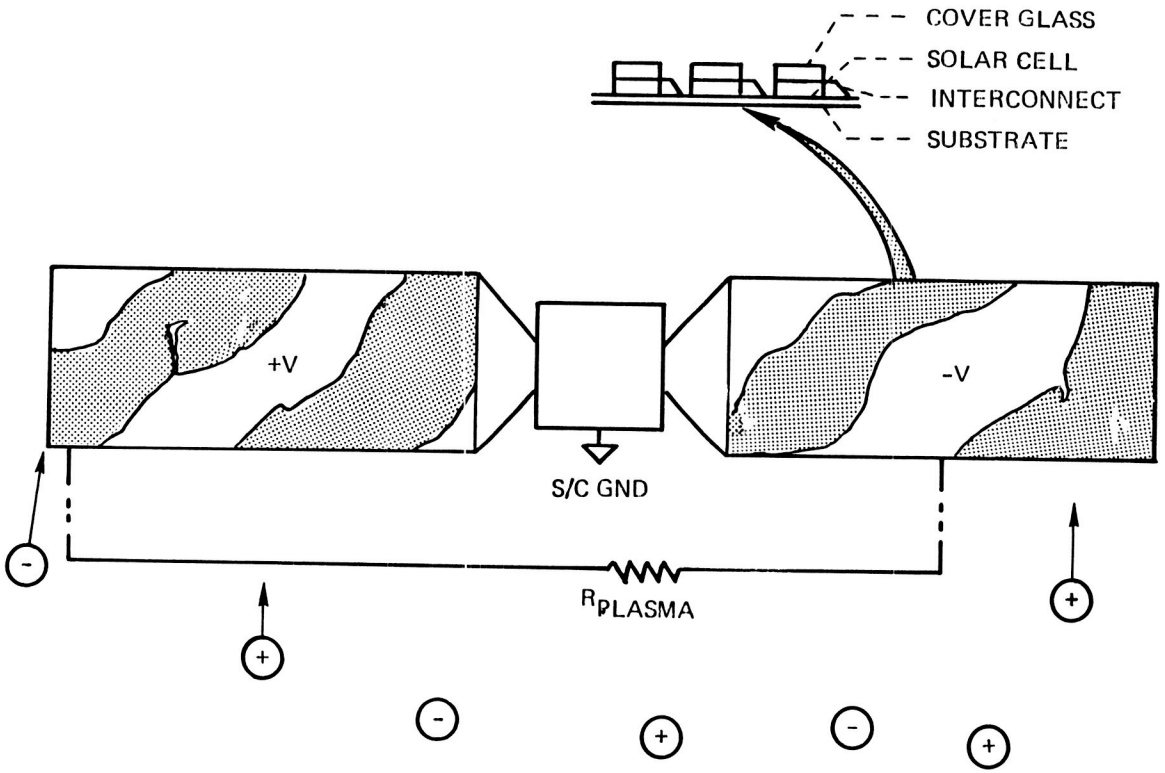


Fig. 1. Spacecraft High Voltage System-Environment Interactions

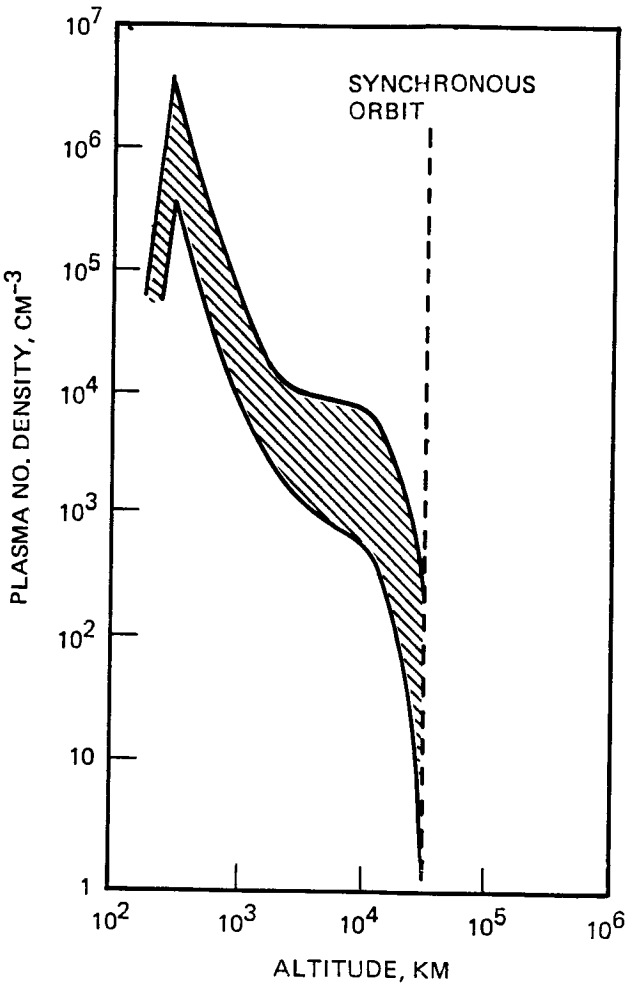


Fig. 2. Plasma Density as Function of Altitude Equatorial Orbit

C-3

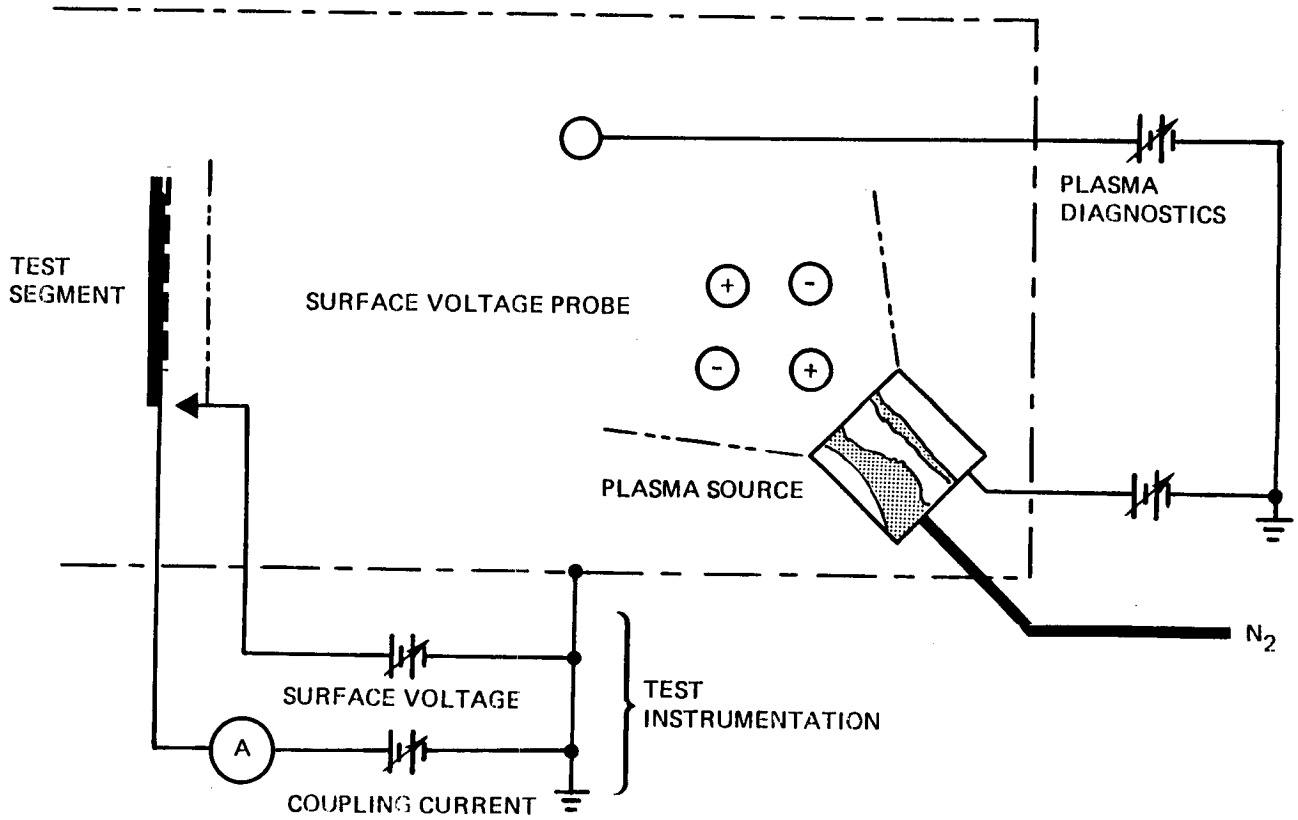


Fig. 3. Schematic Diagram of Test Management

A. Positive Bias Voltages

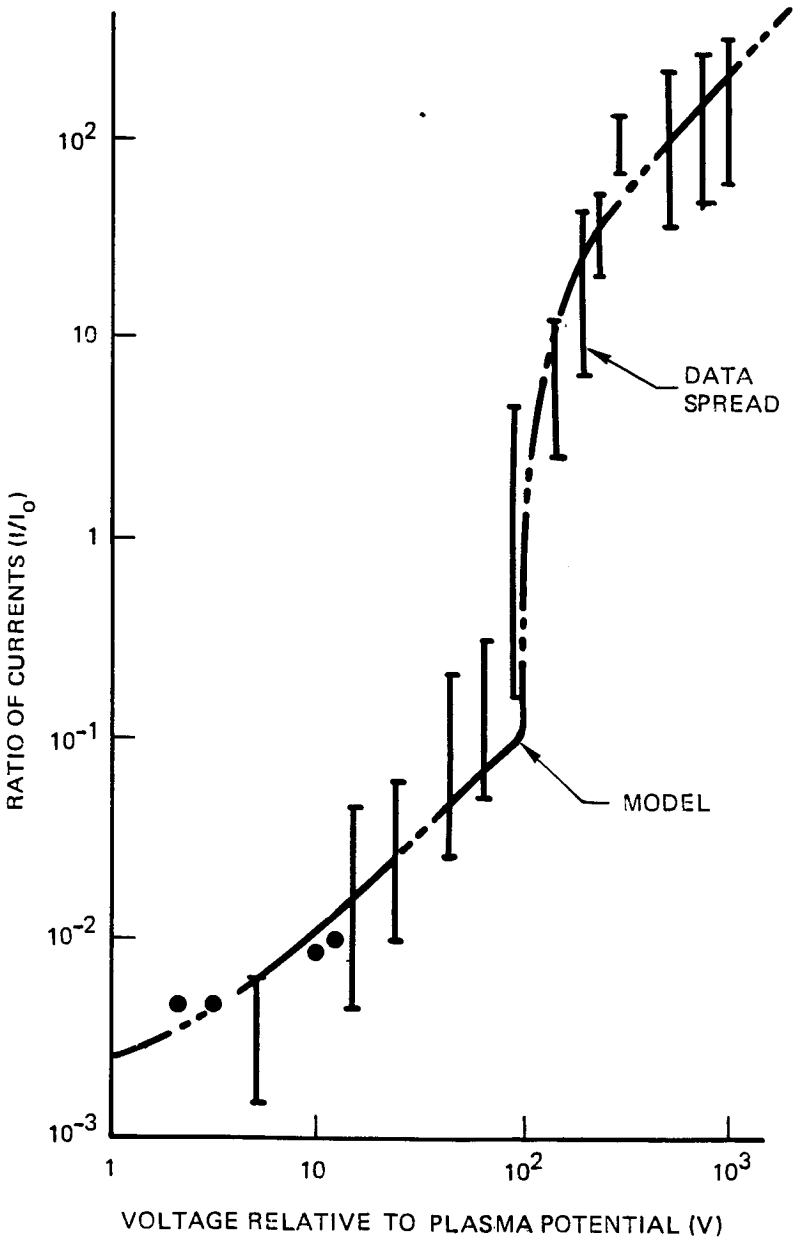


Fig. 4. Summary of Ground Test Data – LeRC

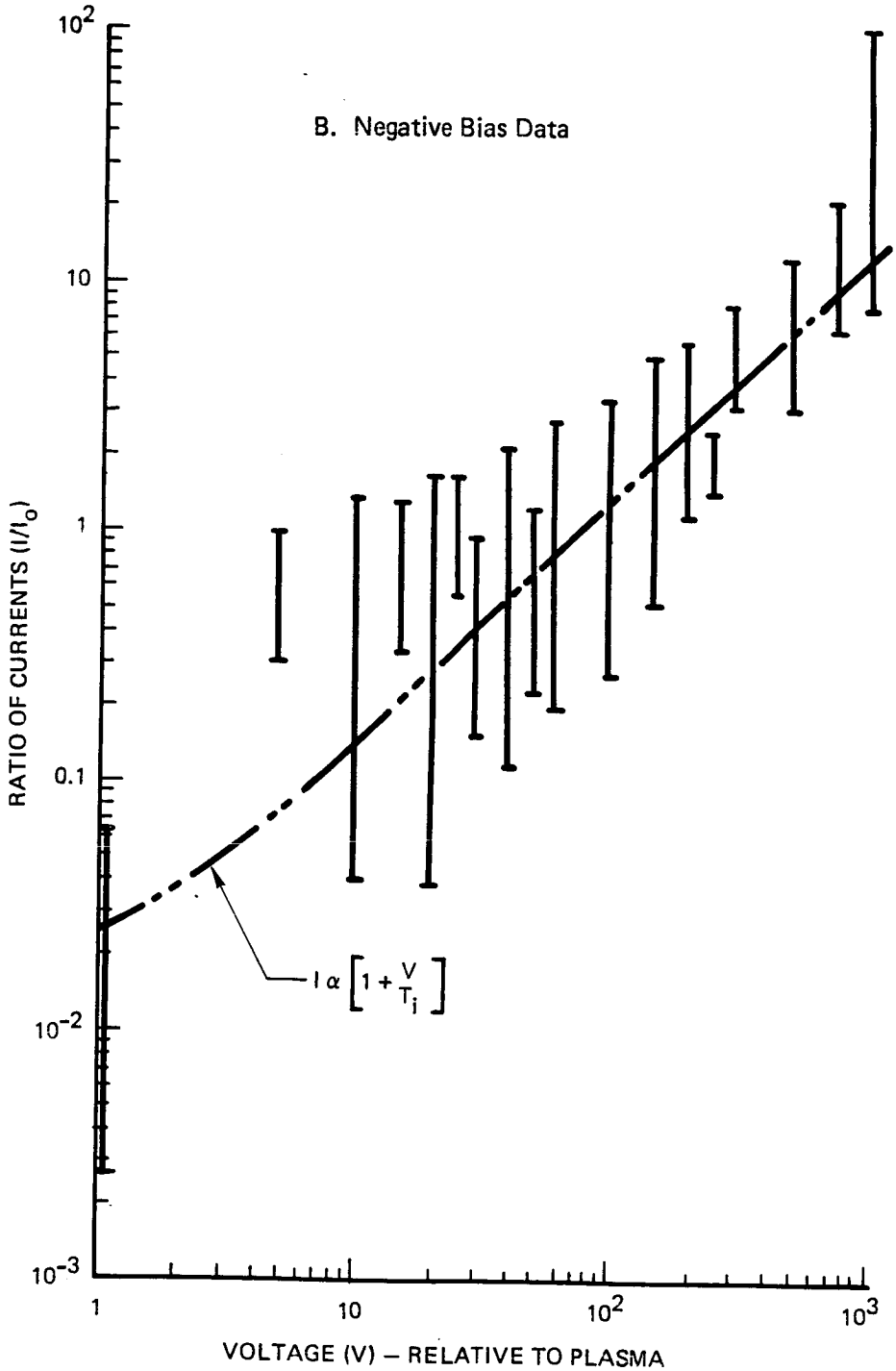


Fig. 4. Summary of Ground Test Data – LeRC

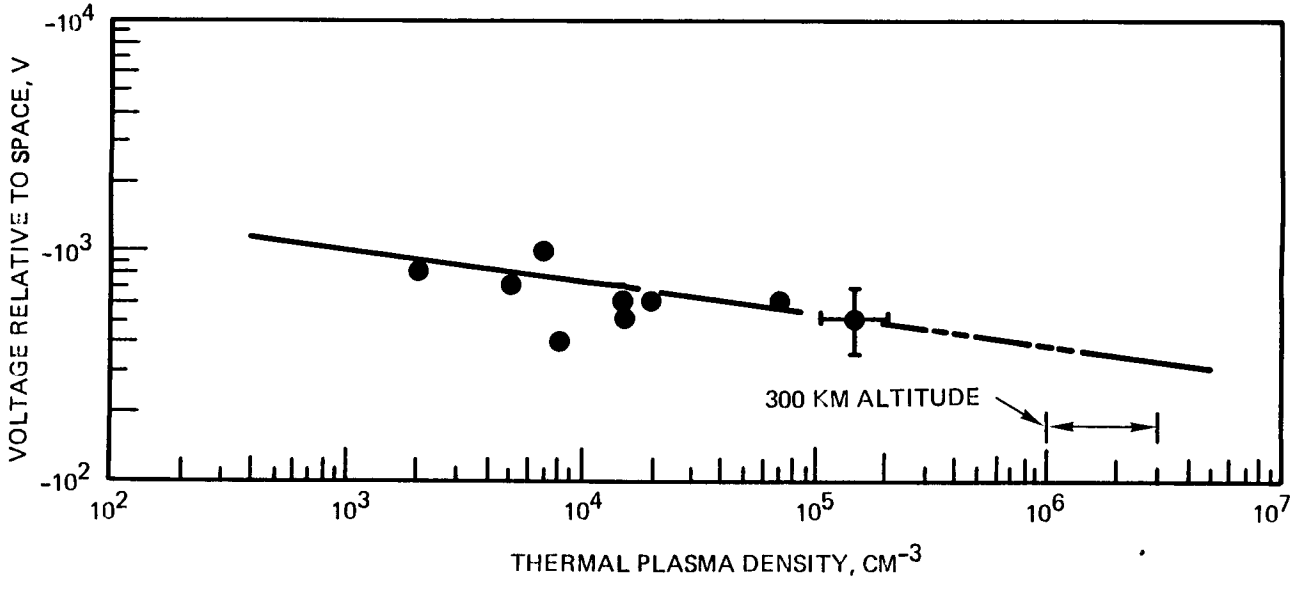


Fig. 5. Voltage Threshold for Breakdown

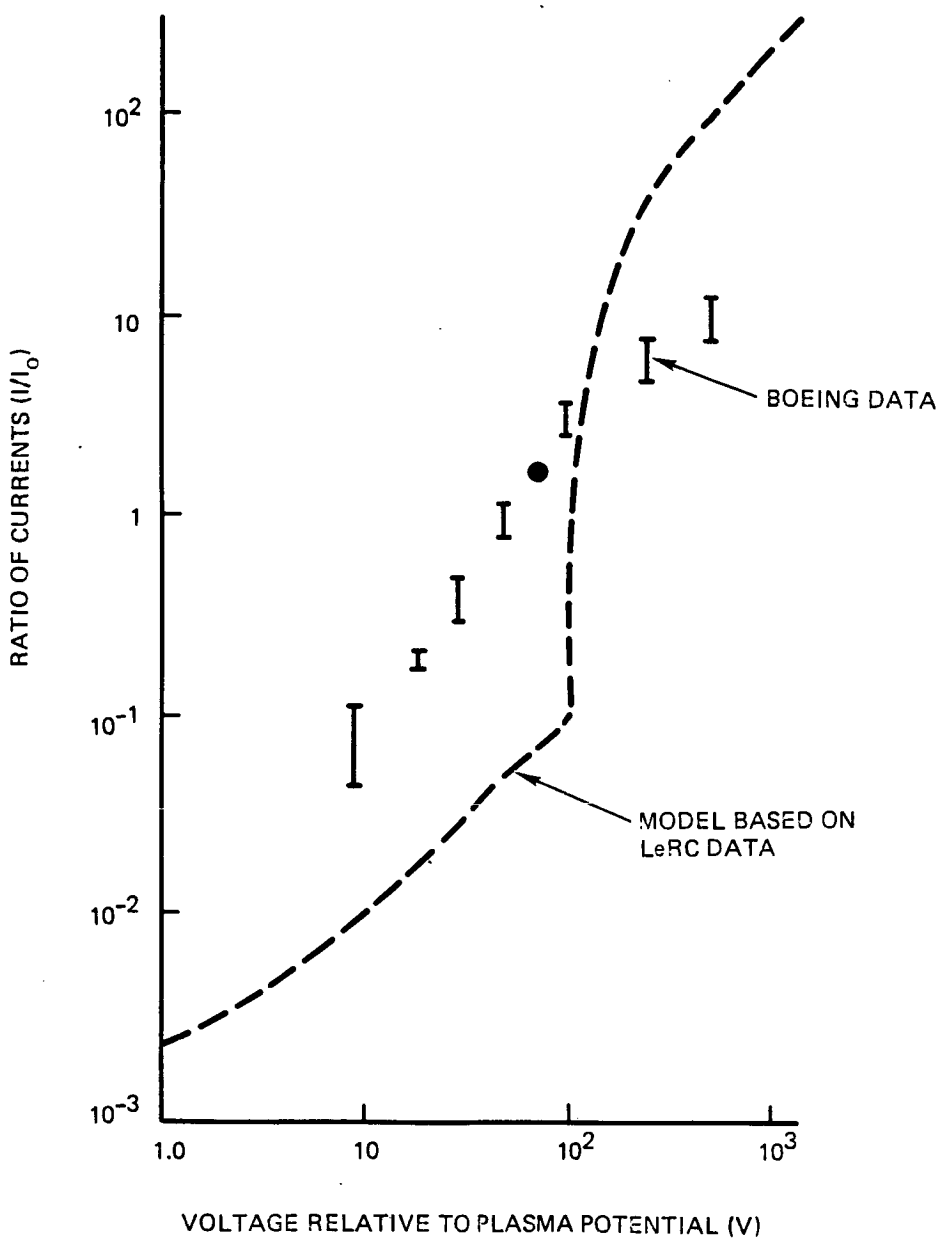


Fig. 6. Comparison of Ground Test Results

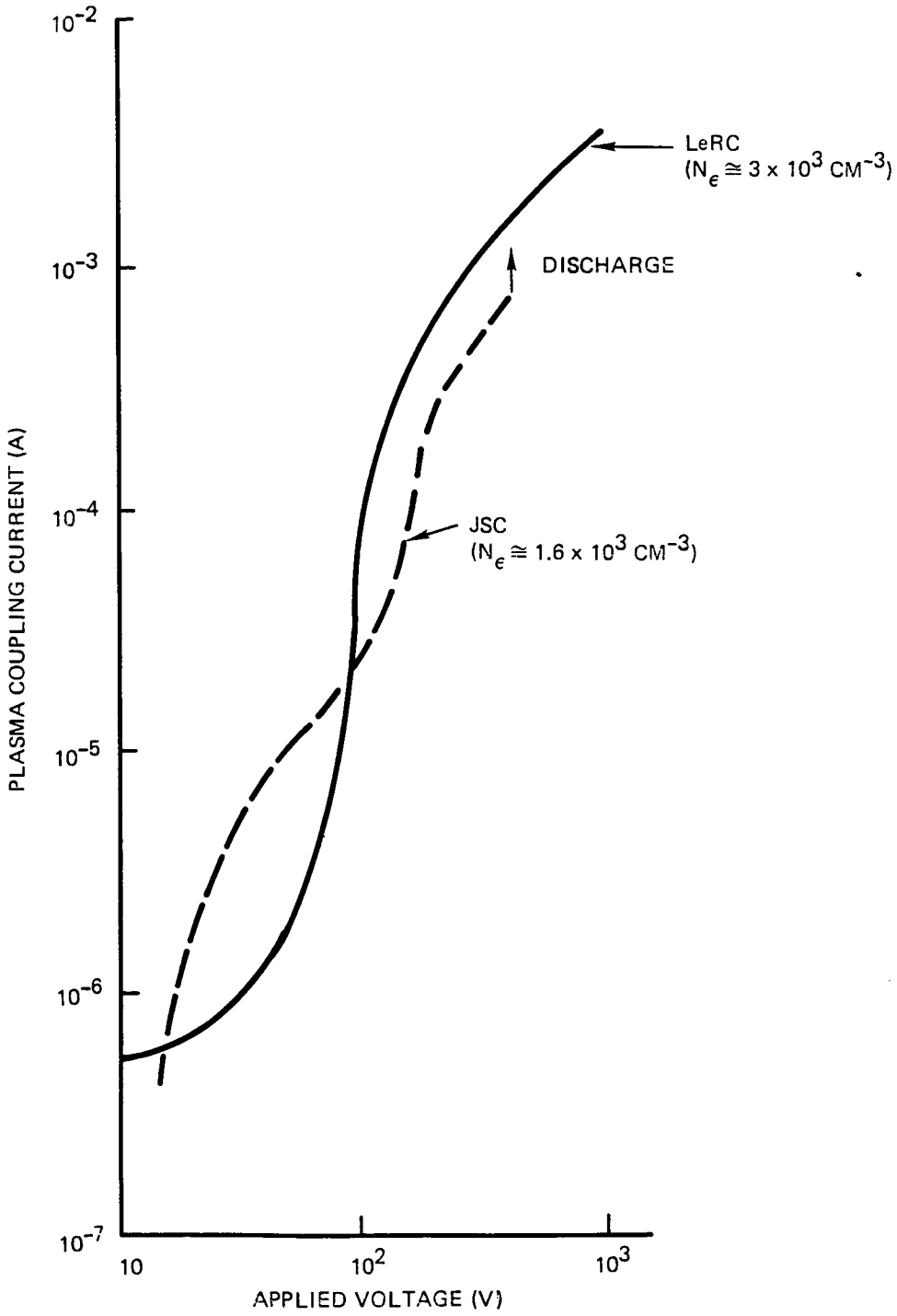


Fig. 7. Comparison of Tests in Different Facilities

1400 cm^2 Solar Array Panel

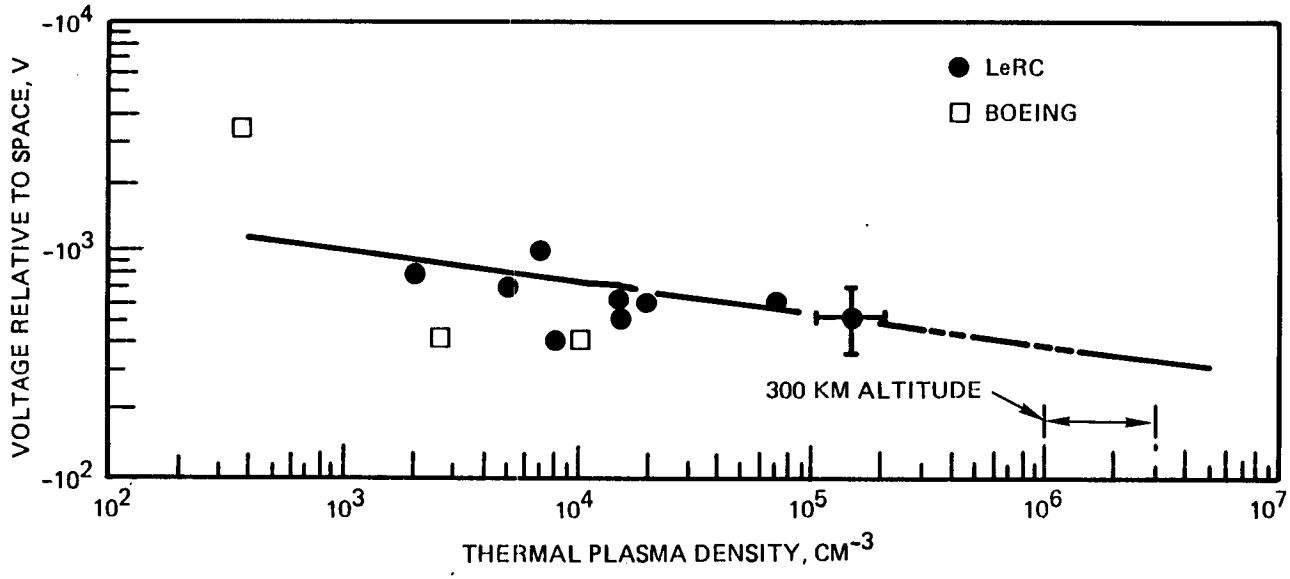


Fig. 8. Voltage Threshold for Breakdown

LeRC and Boeing Data

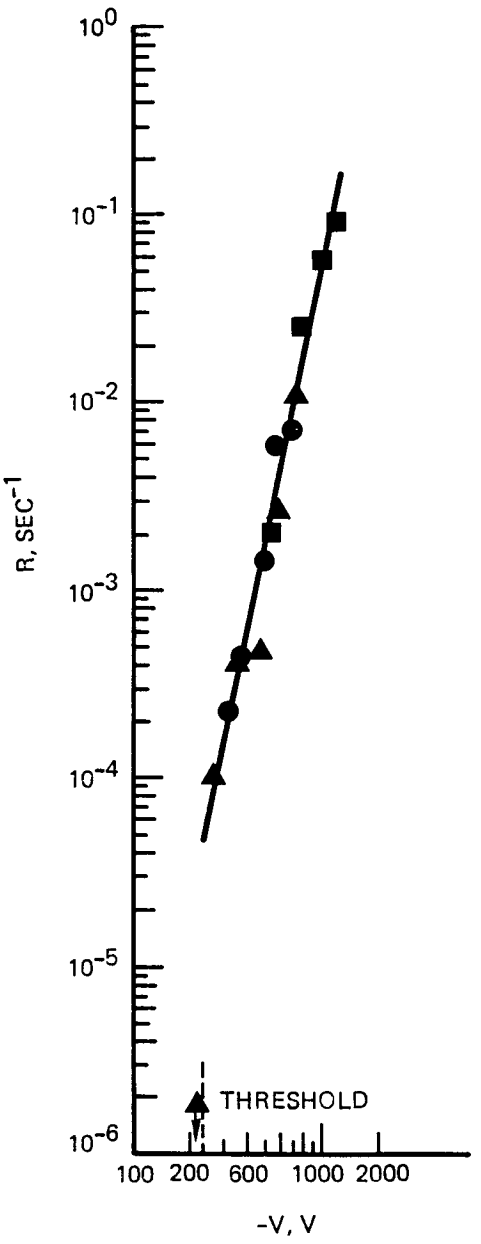


Fig. 9. Arc Rate Predictions Based on Ground Test Data

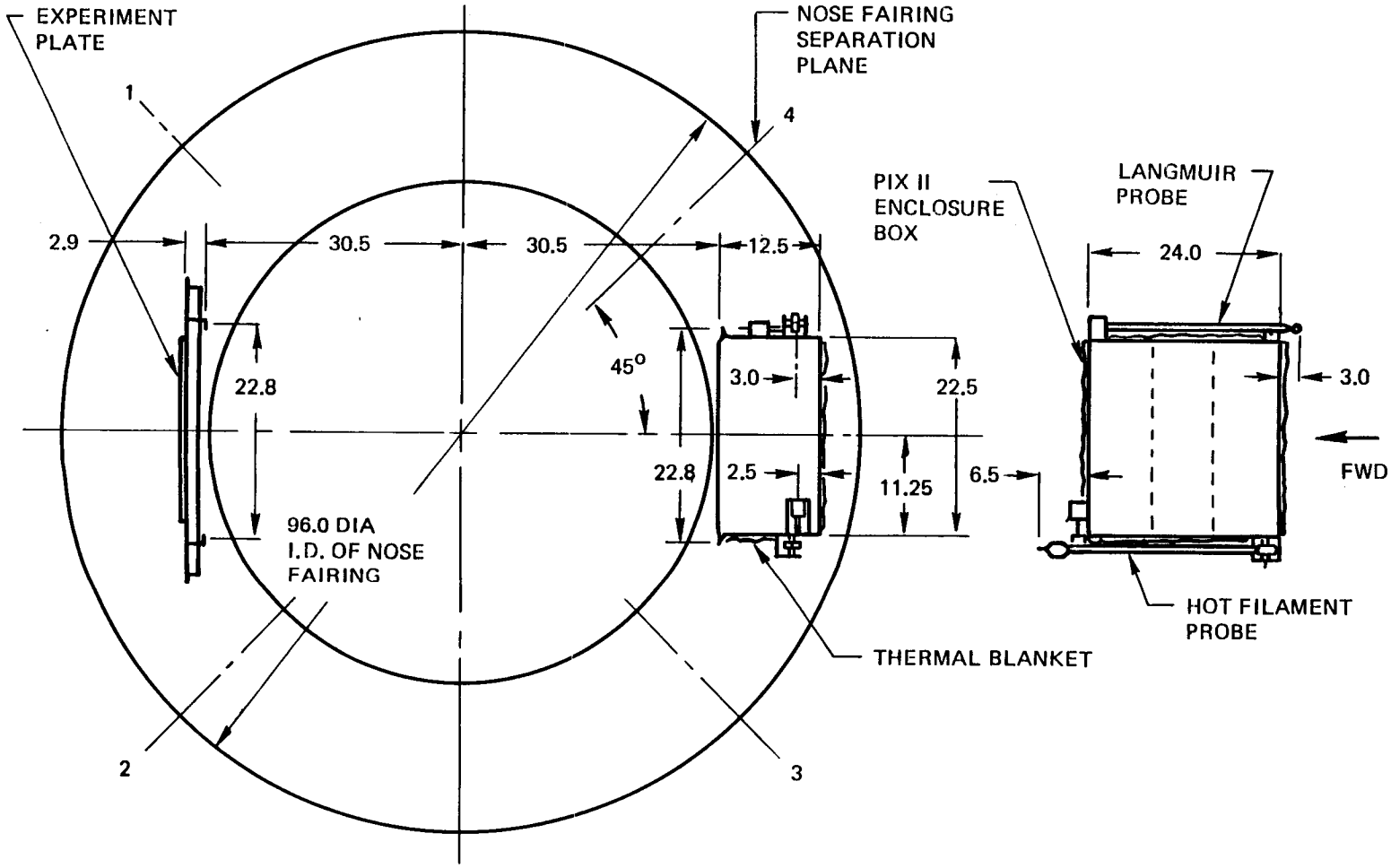


Fig. 10. PIX II/DELTA

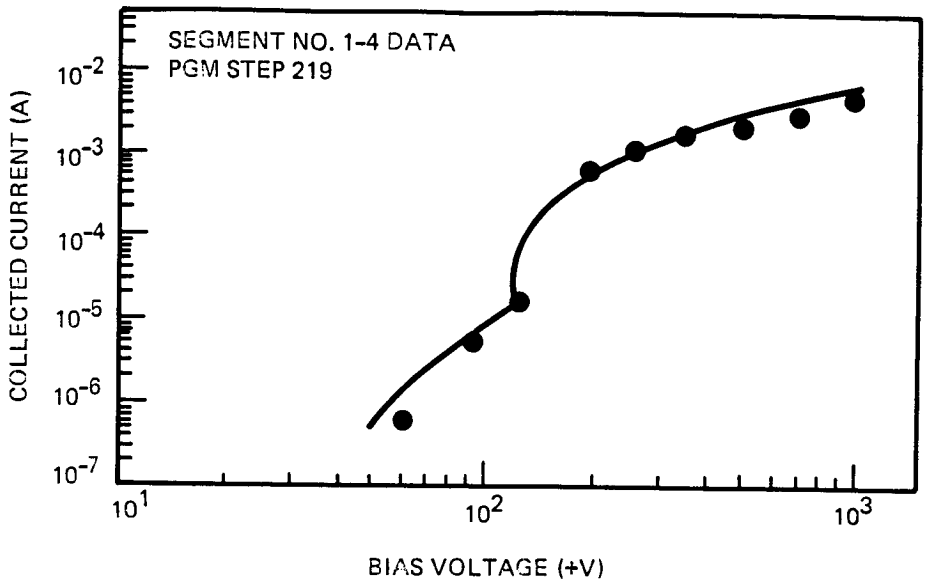


Fig. 11. PIX-2 Data Comparison to Model Predictions

Positive Bias Voltage – Wake and Thermal Modes

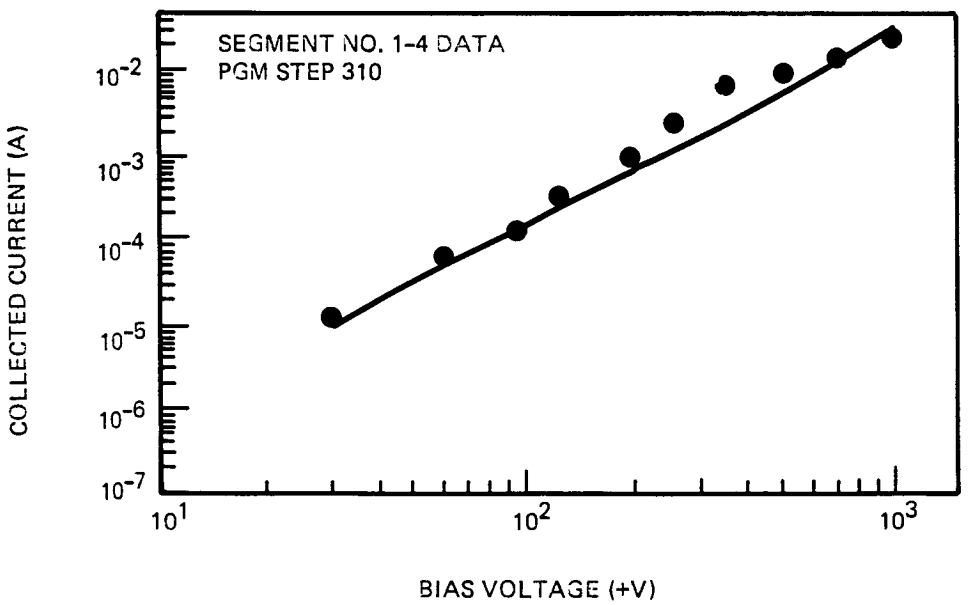
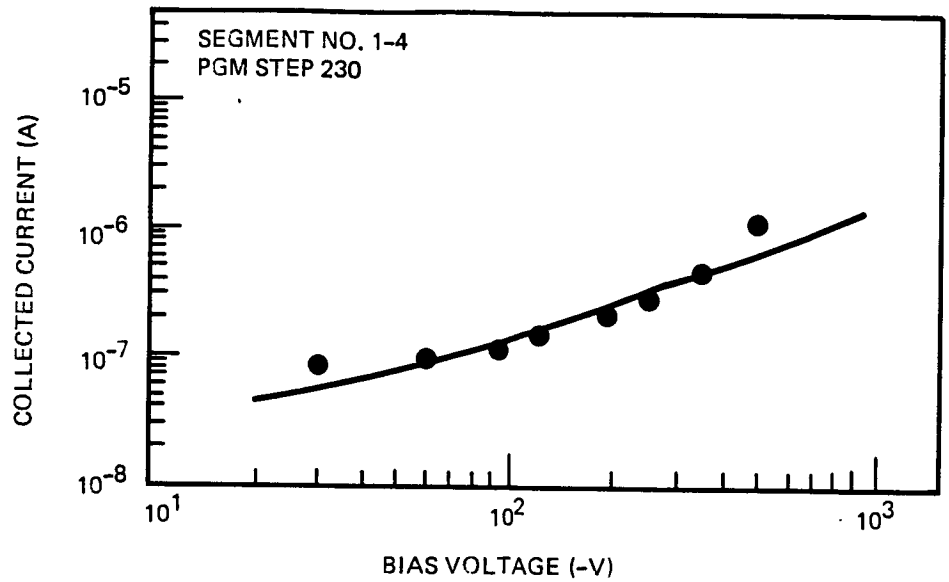


Fig. 12. PIX-2 Data Comparison to Model Predictions

Positive Bias Voltage – RAM Mode



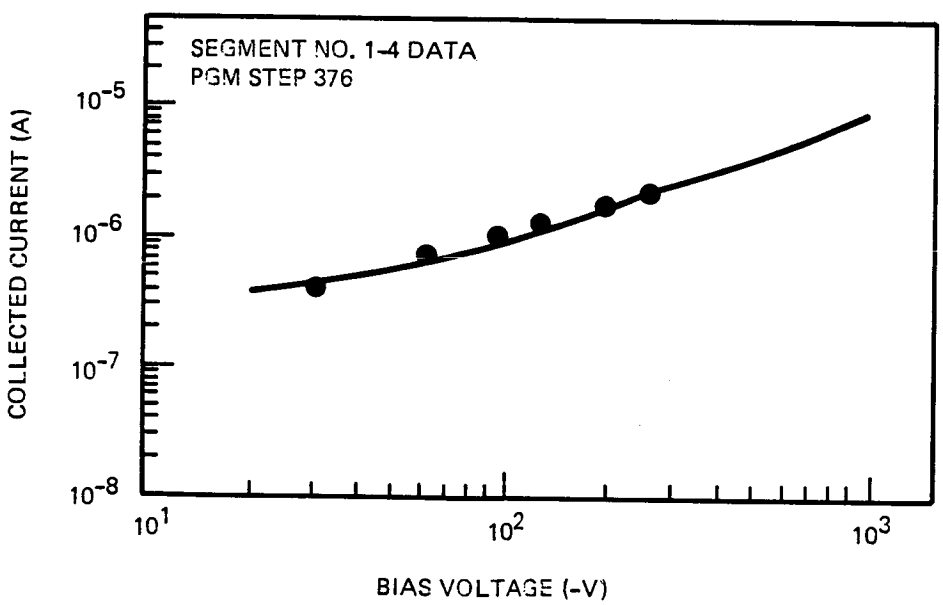


Fig. 13. PIX-2 Data Negative Bias-Ion Collection

4 Segments Biased

A – WAKE

B – THERMAL

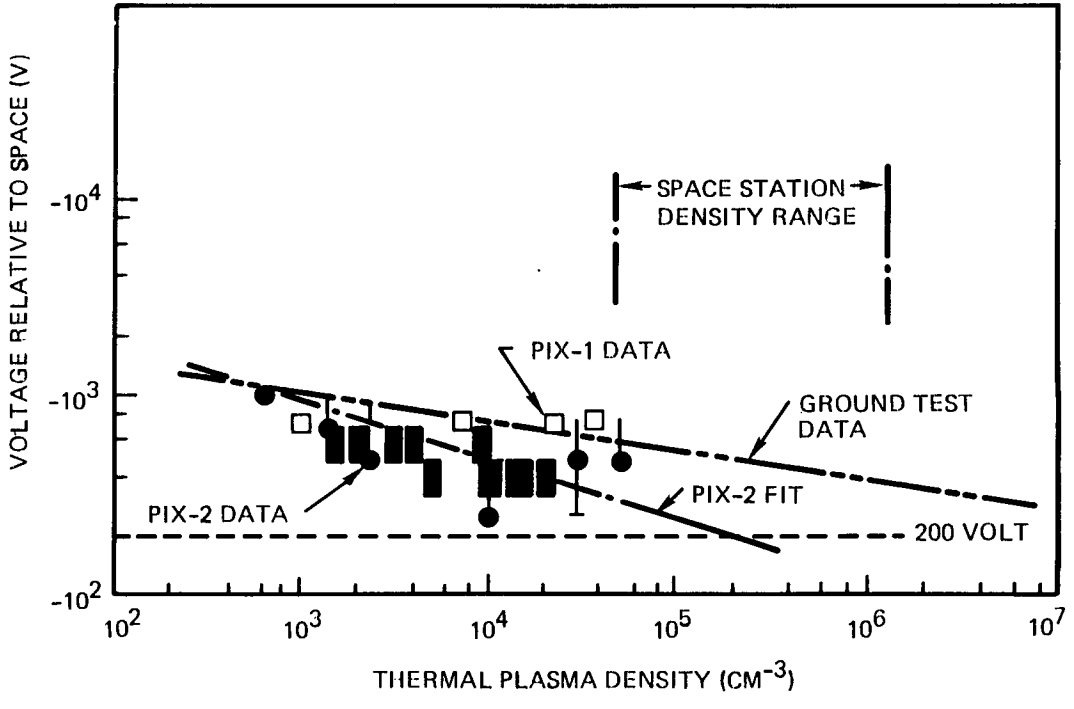


Fig. 14. Shutdown Thresholds

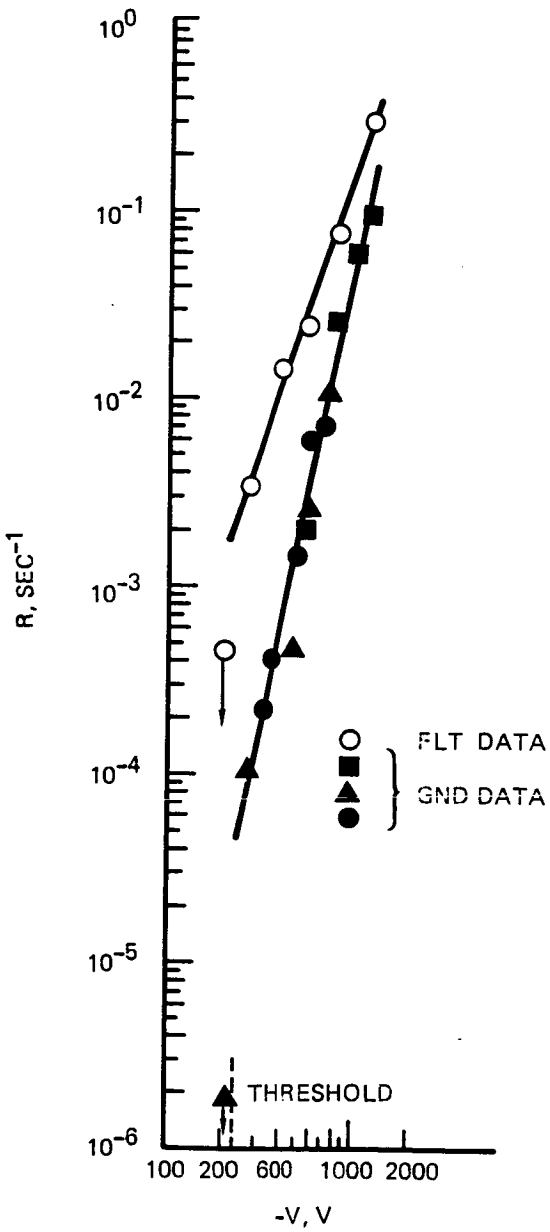


Fig. 15. Arc Rate Comparison Between Ground and Flight Data

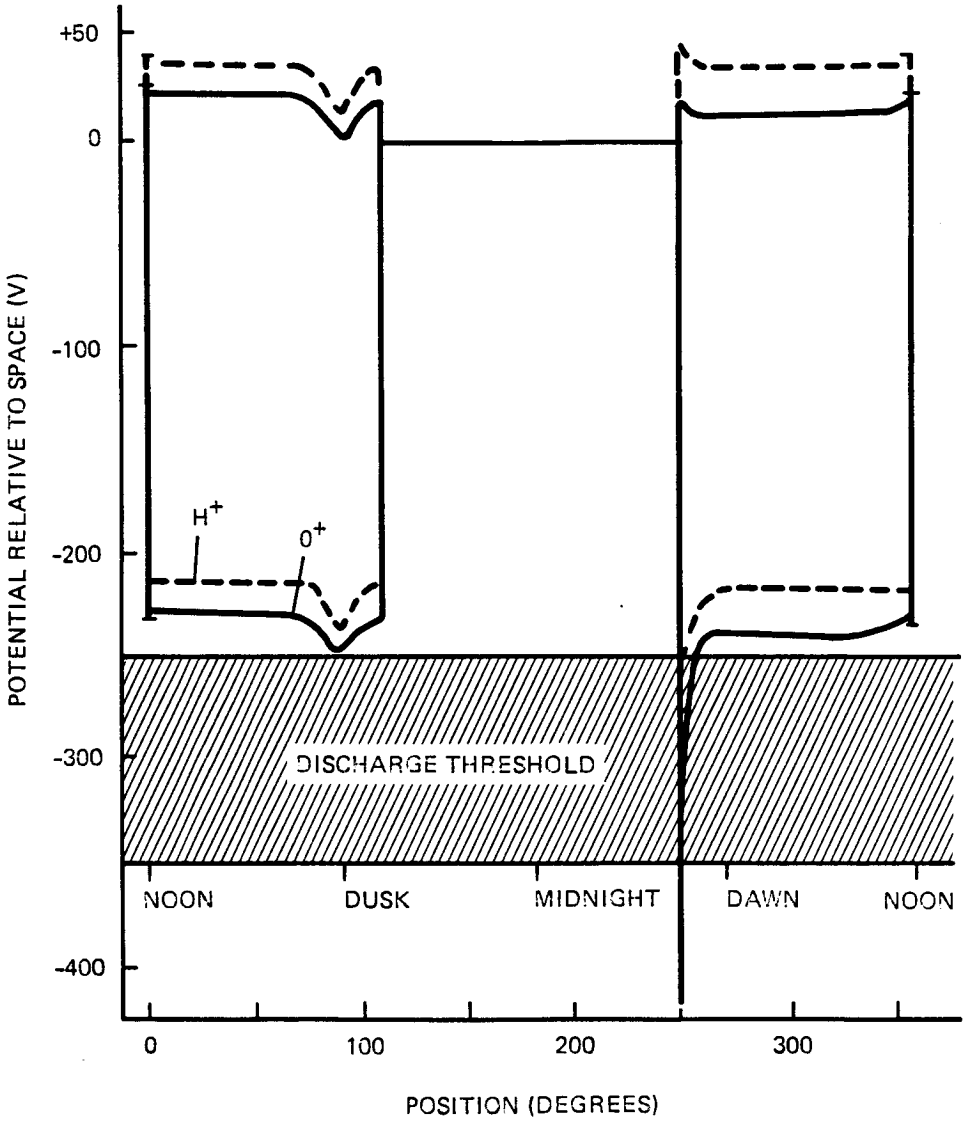


Fig. 16. Floating Potential for 215 kW Array 250 volt Operation — 8 x 8 cm Cells

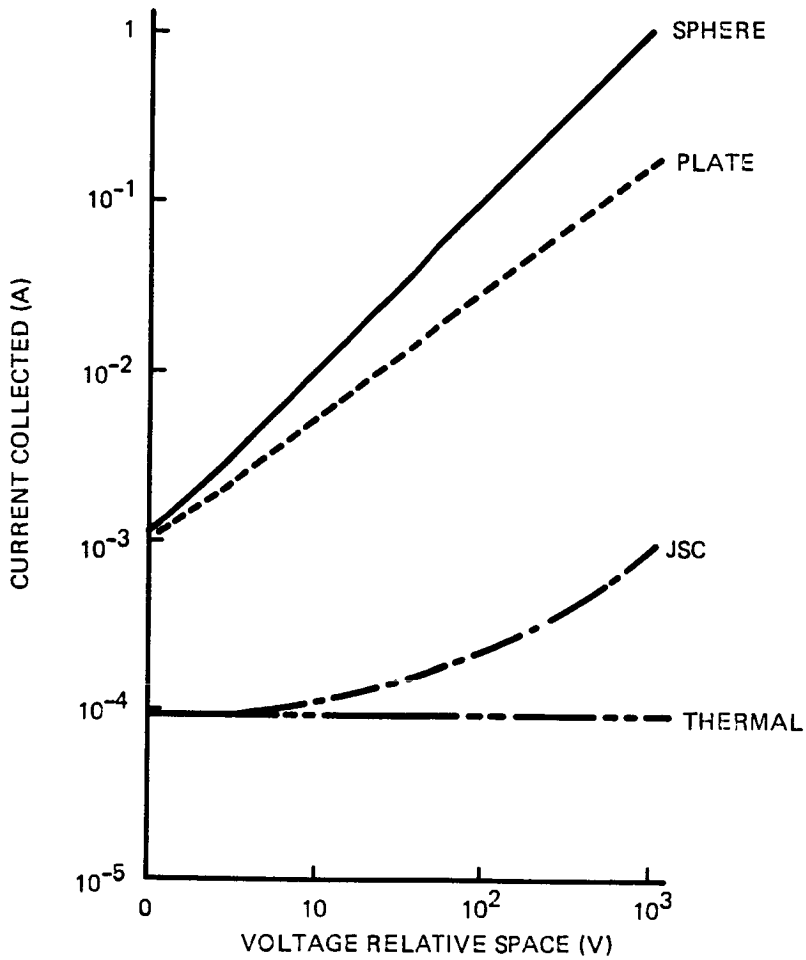


Fig. 17. Flat Plate Plasma Currents (Model Predictions)

10 M^2 Plate — 400 km Plasma

PLASMA-SYSTEMS INTERACTIONS TECHNOLOGY

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NASA/LEWIS RESEARCH CENTER

CLEVELAND, OHIO

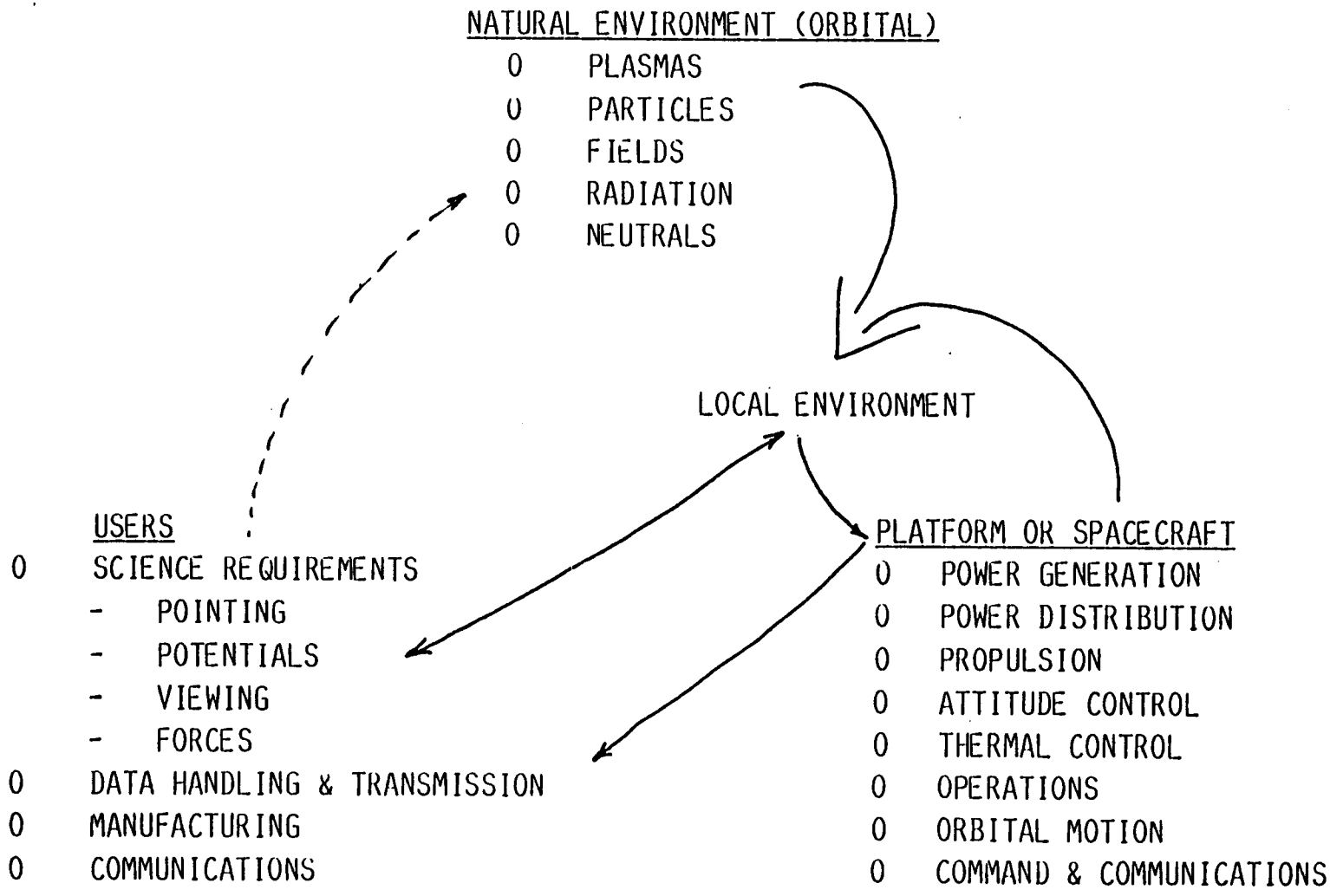
SEPTEMBER 24, 1986

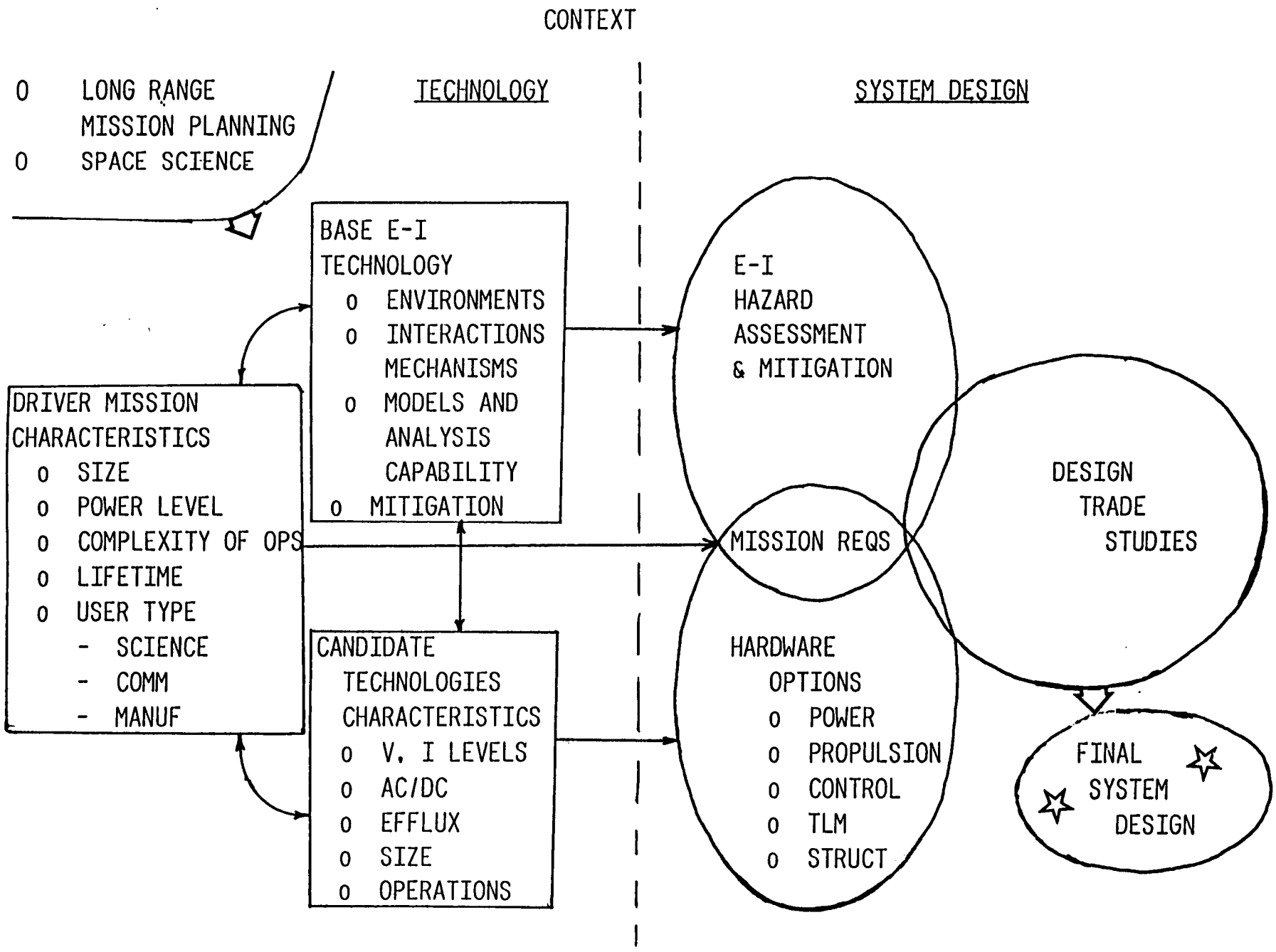
THE TERRESTRIAL SPACE ENVIRONMENT

-EFFECTS ON SPACE SYSTEMS-

ENVIRONMENTAL FACTOR	EFFECTS
GRAVITY	ACCELERATION, TORQUES
SUNLIGHT & ALBEDO	HEATING, POWER, DRAG, TORQUES, PHOTOEMISSION, MATERIAL DAMAGE, SENSOR NOISE
METEOROIDS & DEBRIS	MECHANICAL DAMAGE, ENHANCED PLASMA INTERACTIONS
NEUTRAL ATMOSPHERE	DRAG, TORQUE, MATERIAL DEGRADATION, HEATING
FIELDS	TORQUES, DRAG, SURFACE CHARGES, POTENTIALS
PLASMAS	CHARGING, INDUCED ARCING, POWER LOSSES, POTENTIALS, ENHANCED CONTAMINATION, CHANGE OF E-M REFRACTIVE INDEX, PLASMA WAVES & TURBULENCE
FAST CHARGED PARTICLES	RADIATION DAMAGE, ARCING, SINGLE EVENT UPSETS, NOISE, HAZARD TO MAN
SYSTEM GENERATED	SYSTEM DEPENDENT: NEUTRALS, PLASMAS, FIELDS VIBRATION, TORQUES, RADIATION, PARTICULATES
ENHANCED	EMP & RELATED

ENVIRONMENTAL INTERACTIONS CONCEPT




CONTEXT
O LONG RANGE MISSION PLANNING
O SPACE SCIENCE
TECHNOLOGY
SYSTEM DESIGN
BASE E-I TECHNOLOGY
o ENVIRONMENTS
o INTERACTIONS MECHANISMS
o MODELS AND ANALYSIS CAPABILITY
o MITIGATION
DRIVER MISSION CHARACTERISTICS
o SIZE
o POWER LEVEL
o COMPLEXITY OF OPS
o LIFETIME
o USER TYPE
- SCIENCE
- COMM
- MANUF
CANDIDATE TECHNOLOGIES CHARACTERISTICS
o V, I LEVELS
o AC/DC
o EFFLUX
o SIZE
o OPERATIONS
E-I HAZARD ASSESSMENT & MITIGATION
MISSION REQS
HARDWARE OPTIONS
o POWER
o PROPULSION
o CONTROL
o TLM
o STRUCT
DESIGN TRADE STUDIES
FINAL SYSTEM DESIGN

INTERACTIONS

- SURFACE AND BULK CHARGING
  - ENVIRONMENT DRIVEN
  - SYSTEM DRIVEN
  - STATIC & DYNAMIC
- PLASMA AND SHEATH EFFECTS
  - DC
  - AC: EM & PLASMA COUPLING
  - MULTICOMPONENT PLASMAS
  - DYNAMIC EFFECTS, INCLUDING TURBULENCE, INSTABILITIES, ES & EM NOISE
- RAM/WAKE EFFECTS
  - LARGE BODIES
  - MULTIPLE SPECIES
- EMI/RFI ASSOCIATED WITH
  - ARCING
  - AC SYSTEMS
  - DYNAMIC PLASMA EFFECTS
  - WAKE EFFECTS
- SYNERGISM WITH OTHER ENVIRONMENTAL FACTORS
  - METEROID DAMAGE
  - RADIATION
  - ETC.

HISTORY: PLASMA-SYSTEM INTERACTIONS TECHNOLOGY

MID 1960'S TO 1974

HIGH VOLTAGE ARRAYS FOR DIRECT DRIVE OF COMMUNICATIONS EQUIPMENT

- 0 LABORATORY STUDIES OF PHENOMENOLOGY: LERC, HUGHES, BOEING, TRW
  - CURRENT COLLECTION, PINHOLES
- 0 SPHINX FLIGHT EXPERIMENT (1974)
  - LOST DUE TO LAUNCH VEHICLE MALFUNCTION

1975-1981

SPACECRAFT CHARGING IN GEO: NASA/AF JOINT PROGRAM

- 0 ELECTRON BEAM TESTING
- 0 NASCAP
- 0 DESIGN G/L

LOW LEVEL PLASMA-HV ARRAY EFFORT

- 0 LAB TESTING AND ANALYSIS
- 0 PIX-I (1978)
- 0 SEP SUPPORT

1981 TO PRESENT

SPACECRAFT-ENVIRONMENTAL INTERACTIONS: NASA/AF PROGRAM

- 0 AF: POLAR ORBIT CHARGING
- 0 NASA: HIGHER VOLTAGE SYSTEM EFFECTS
  - EARLY FOCUS ON ARRAYS IN LEO
  - LABORATORY TESTING
  - THEORY
  - NASCAP/LEO DEVELOPMENT
  - PIX-II (1983)
- 0 OAST PROGRAM REFOCUSSED IN SS ERA

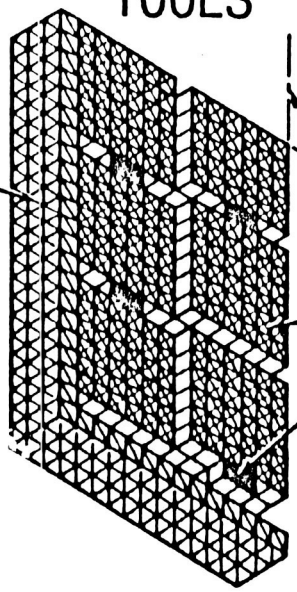
Lewis Research Center

NASA/AF ENVIRONMENTAL INTERACTIONS INVESTIGATION

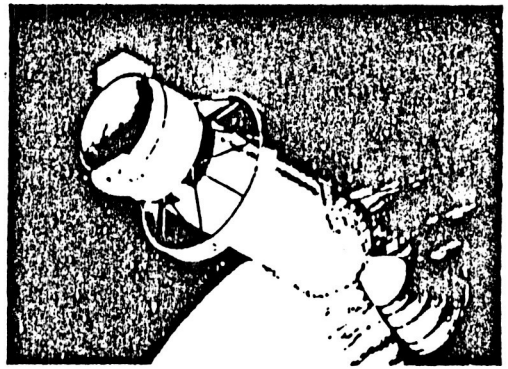
ENVIRONMENTAL INTERACTIONS

ENVIRONMENTAL MODELS

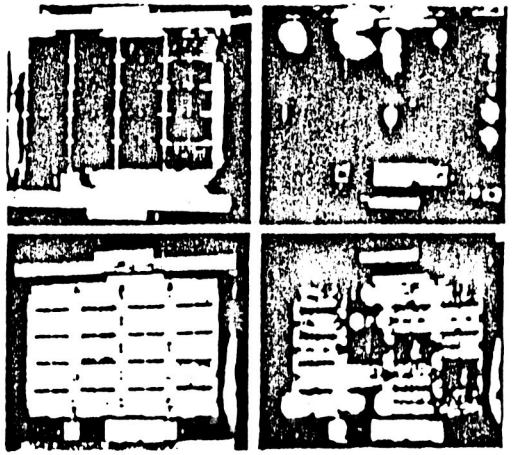
ANALYTICAL TOOLS



FLIGHT EXPTS



GROUND BASED SIMULATION



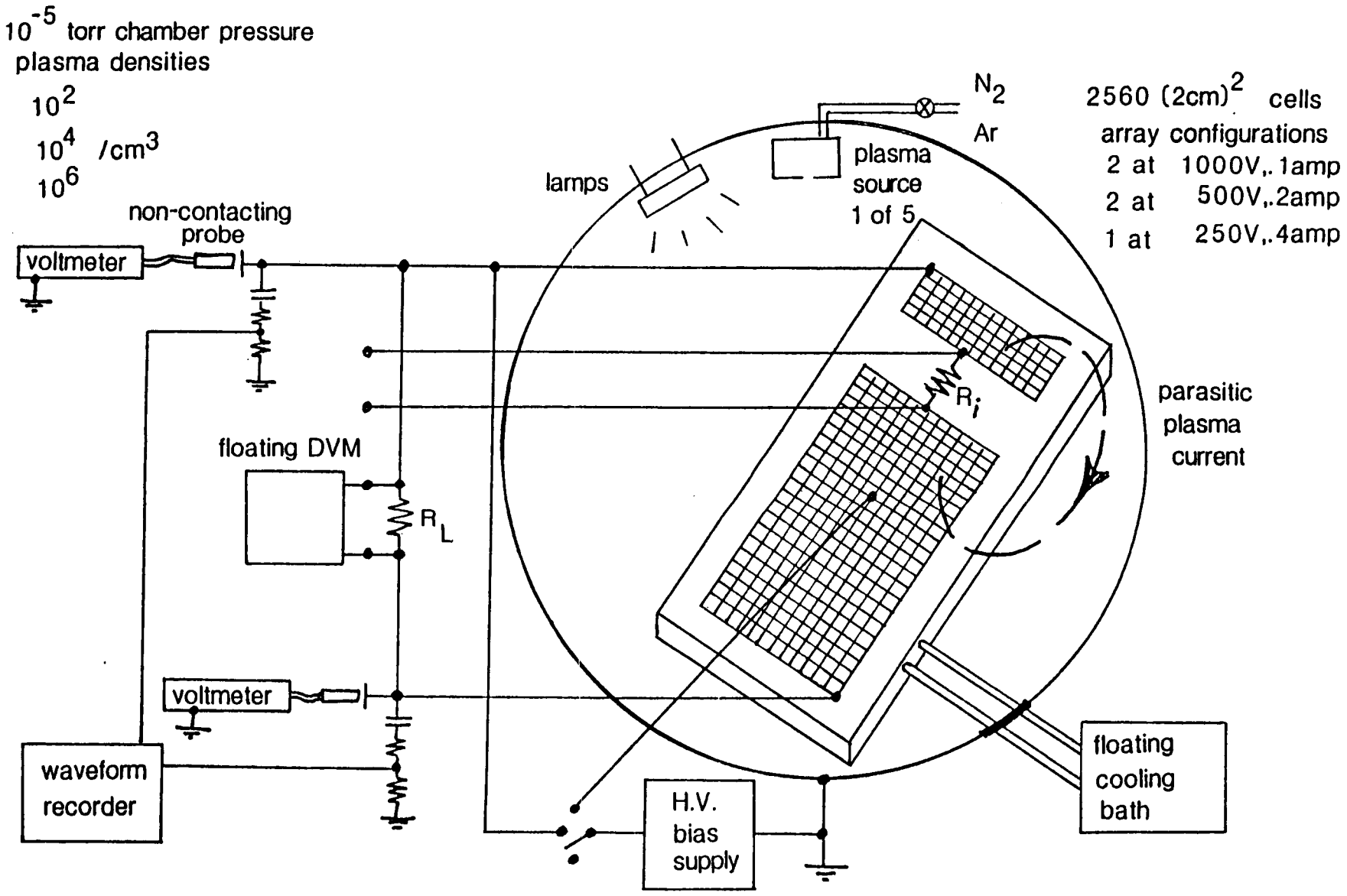
DESIGN CRITERIA AND TEST STANDARD DOCUMENTS

3-D Model Capabilities Comparison

	NASCAP/GEO	NASCAP/LEO	POLAR
STATUS	Completed	Under Development	Under Development
PURPOSE	Charging in GEO	LEO Orbit Effects	Polar Orbit Effects
ENVIRONMENT	Substorm Plasmas Electron Beams	Ionospheric Plasma	Ionospheric Plasma Auroral Electron Beams
OBJECT SIZE*	Small	Large	Large
MOTION EFFECTS	No	Simple	Yes
COMPLEX OBJECTS	Yes	No	Yes
APPLIED VOLTAGES	Yes	Yes	No
GRID SUBDIVISION	No	Yes	No

* Compared to plasma Debye length

HIGH VOLTAGE SOLAR ARRAY-PLASMA INTERACTION TEST



ACTIVE HIGH VOLTAGE SOLAR ARRAY TESTS

CONDITIONS:

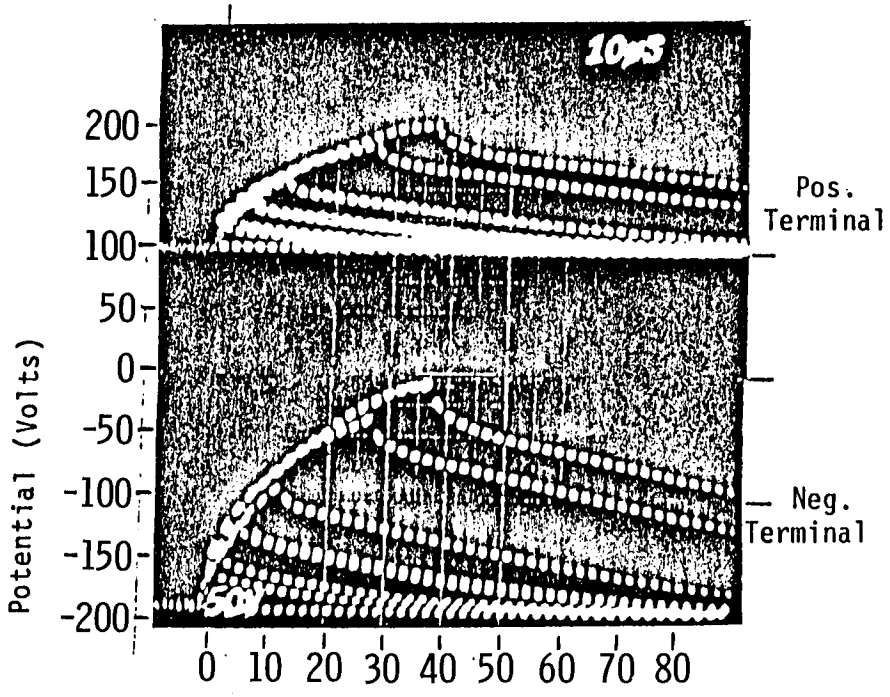
PLASMA: $\eta_e \sim 7 \times 10^6/cm^3$ $T_e \sim .8$ eV

$\phi_p \sim 4.3$ V $T_i \sim 3.3$ eV

ARRAY: OPEN CIRCUIT

$V_{term} \sim 300$ V BEFORE ARCS

$\Delta V_{term} \sim 80$ V DURING LARGEST ARC



Arcs on Active HVSA

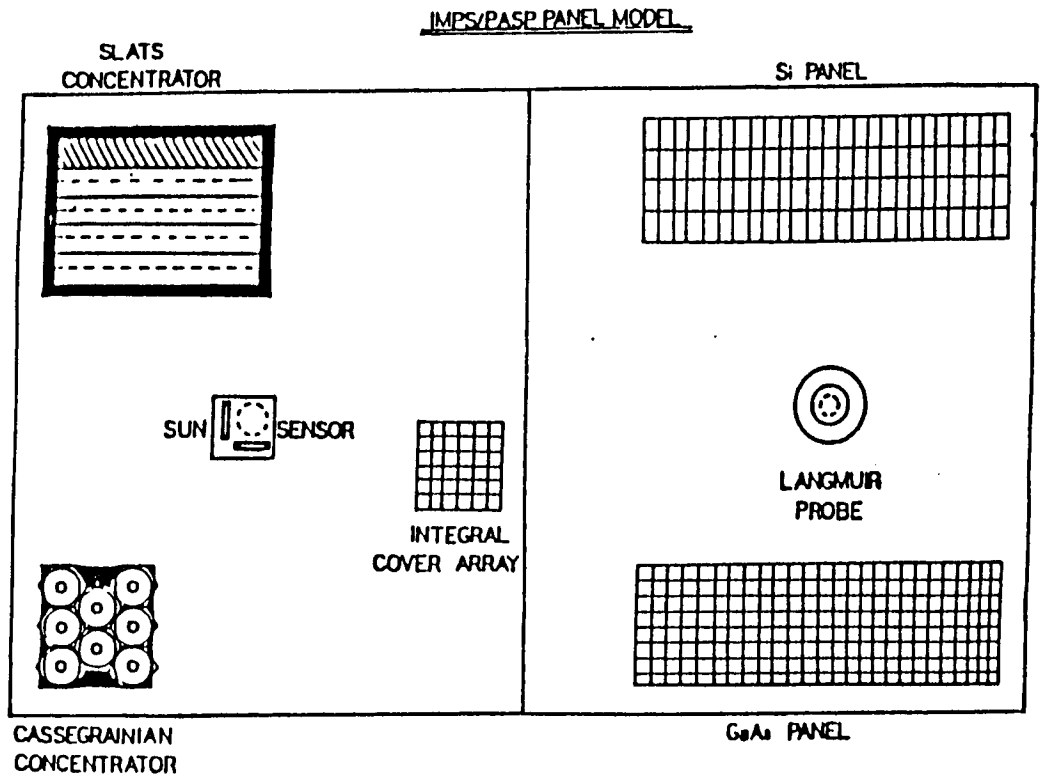
RESULTS

- ARRAY FLOATS MORE POSITIVE THAN SIMPLE MODELS PREDICT
- BORDER POTENTIAL HAS SIGNIFICANT EFFECT ON FLOATING POTENTIALS
- ARCS OBSERVED WITH TERMINAL VOLTAGES AS LOW AS 180 V

WHY SPACE EXPERIMENTS?

- GROUND ENVIRONMENT SIMULATION INCOMPLETE
  - -PLASMA ENERGY, COMPOSITION, FLOW
  - -ORBITAL $\vec{B}$
  - -NEUTRAL COMPOSITION, ENERGY, FLOW
  - -RAM/WAKE
  - -BOUNDARY CONDITIONS
- LARGE SYSTEM EFFECTS ON ENVIRONMENT NOT WELL KNOWN
- REQUIRE "SPACE TRUTH"
  - -"CALIBRATE" GROUND SIMULATION
  - -OBTAIN DATA UNDER CONDITIONS THAT CANNOT BE SIMULATED
  - -VALIDATE MODELS

PHOTOVOLTAIC ARRAY SPACE POWER (PASP) EXPERIMENT



EXISTING DATA

LABORATORY

- 0 CURRENT COLLECTION BY SHORTED, BIASED CELL STRINGS
  - SMALL AREA SEGMENTS
  - TO ± 1000 VOLTS TYPICALLY
  - PLASMA DENSITIES 10^2 TO 10^6
  - MOST DATA ON 2 X 2 CM CELLS, SOME ON 2 X 4 AND 5.9 X 5.9
- 0 ARCING ON SHORTED, BIASED CELL STRINGS
  - CONDITIONS AS ABOVE

SPACE

- 0 PIX-I (1978)
  - 100 CM^2 OF 2 X 2 CELLS, SHORTED, ±1000 VOLTS BIAS
  - 900 KM, POLAR ORBIT
  - 1 HOUR OF DATA RETURNED
- 0 PIX-II
  - FOUR SEGMENTS OF 2 X 2 CM CELLS, 500 CM^2 EACH, ±1000 VOLTS BIAS, STRINGS SHORTED
  - 900 KM POLAR ORBIT
  - FULL ORBIT COVERAGE, 16 HOURS OF DATA RETURNED

OTHER DATA USEFUL FOR PLASMA EFFECTS STUDIES

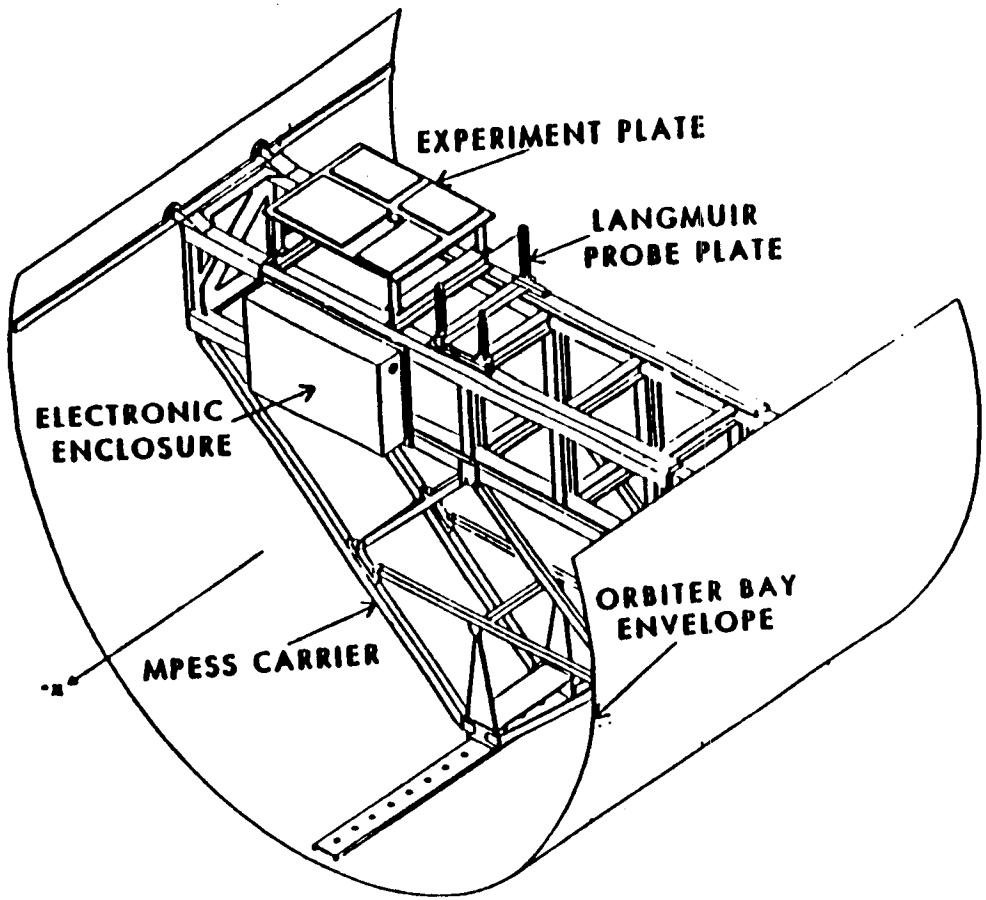
SPACE: "SCIENCE" DATA-PLASMAS, PARTICLES & FIELDS

- O STS
  - LARGE, MANNED SYSTEM EFFECTS
  - RESPONSE TO VARIOUS ACTIVE EMISSIONS
- O FREE FLYERS
  - VEHICLE & SURFACE POTENTIALS
  - PLASMA & PARTICLE EMISSION EFFECTS

GROUND

- O PLASMA TESTING OF "PIN HOLE" SAMPLES
- O WAKE STUDIES

VOLT-A CONFIGURATION



- EXPERIMENT PLATE (125 LBS)
  - 4 MODULE PLATES (S1 CELLS)
    - 5.9 X 5.9-cm (3)
    - PIX II 2 X 2-cm
  - SUN SENSOR
- LANGMUIR PROBE PLATE (25 LBS)
  - LANGMUIR PROBES
    - CYLINDRICAL
    - SPHERICAL
- ELECTRONIC ENCLOSURE (150 LBS)
  - POWER SUPPLY/CONDITIONING
  - SEQUENCER
  - VACUUM GAUGE
  - HEATERS
  - TAPE RECORDER

PLASMA INTERACTIONS TECHNOLOGY

RECOMMENDED PROGRAM

OBJECTIVE: DEVELOP MODELING AND ANALYSIS CAPABILITY TO ENABLE CORRECT INCORPORATION OF P-I EFFECTS ASSESSMENT INTO INNOVATIVE TECHNOLOGIES AND SYSTEM/SUBSYSTEM/ INSTRUMENTATION DESIGH AT ALL PHASES.

APPROACH:

- 0 DEFINE THE LOCAL ENVIRONMENT
- 0 UNDERSTAND THE PHYSICAL PHENOMENA
  - DETERMINE PHENOMENOLOGY OF INTERACTIONS
  - IDENTIFY DOMINANT INTERACTIONS MECHANISMS
  - DEVELOP AND VALIDATE MODELS
- 0 DEVELOP ANALYTICAL TOOLS AND DATA BASES

REQUIRES:

- 0 MODELING, GROUND TESTING AND FLIGHT EXPERIMENTS
- 0 CLOSE COOPERATION WITH
  - PLASMA SCIENCE
  - S/C DESIGNERS
  - RELEVANT DISCIPLINE TECHNOLOGISTS

PLASMA INTERACTIONS TECHNOLOGY

PAYOFF

SPACECRAFT

- 0 ENHANCED OPERATIONAL RELIABILITY PREDICTABILITY
- 0 ENHANCED SCIENCE RETURN

LARGE SYSTEMS

- 0 ENABLES VERY HIGH POWER SYACE SYSTEMS (INCLUDING LUNAR, MARS BASES)
- 0 ENABLES RELIABLE AUTOMATED SYSTEMS
- 0 PREDICTABLE OPERATION
- 0 ENHANCED LARGE PLATFORM BASED SCIENCE
- 0 GUIDE DEVELOPING DISCIPLINE TECHNOLOGIES

CONCLUSIONS

- O P-I IS AN ESSENTIAL BASE TECHNOLOGY
  - COMPLEMENTARY TO SPACE SCIENCE AND DISCIPLINE TECHNOLOGIES
  - REQUIRED INPUT FOR DESIGN TRADE STUDIES
- O IMPORTANCE/IMPACT INCREASES WITH
  - SYSTEM POWER, SIZE AND LIFETIME
  - AUTOMATION LEVEL
  - COMPLEXITY OF OPERATIONS
  - SENSITIVITY OF INSTRUMENTATION
- O A STRONG P-I TECHNOLOGY PROGRAM REQUIRED
  - MODELING
  - GROUND TEST
  - FLIGHT EXPERIMENTS
  - CLOSE COORDINATION WITH RELATED SCIENCE & TECHNOLOGY
  - COOPERATION WITH SYSTEM DESIGNERS

N87-20070

Some Consequences of Intense Electromagnetic Wave Injection into Space Plasmas

By

William J. Burke[1], Elena Villalon[2], Paul L. Rothwell[1], and Michael Silevitch[2]

I Introduction

The past decade has been marked by an increasing interest in performing active experiments in space. These experiments involve the artificial injections of beams, chemicals, or waves into the space environment. Properly diagnosed, these experiments can be used to validate our understanding of plasma processes, in the absence of wall effects. Sometimes they even lead to practical results. For example, the plasma-beam device on SCATHA became the prototype of an automatic device now available for controlling spacecraft charging at geostationary orbit.

In this paper we discuss the future possibility of actively testing our current understanding of how energetic particles may be accelerated in space or dumped from the radiation belts using intense electromagnetic energy from ground based antennas. The ground source of radiation is merely a convenience. A space station source for radiation that does not have to pass through the atmosphere and lower ionosphere, is an attractive alternative. The text is divided into two main sections addressing the possibilities of (1) accelerating electrons to fill selected flux tubes above the Kennel-Petscheck limit for stably trapped fluxes and (2) using an Alfven maser to cause rapid depletion of energetic protons or electrons from the radiation belts. Particle acceleration by electrostatic waves have received a great deal of attention over the last few years (Wong et al., 1981; Katsouleas and Dawson, 1983). However, much less is known about acceleration using electromagnetic waves. The work described herein is still in evolution. We only justify its presentation at this symposium based on the novelty of the ideas in the context of space plasma physics and the excitement they have generated among several groups as major new directions for research in the remaining years of this century.

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II Electron Acceleration by Electromagnetic Waves

One of the first things we were mistaught in undergraduate physics is that electromagnetic (em) waves can't accelerate charged particles. If the particle gains energy in the first half cycle, it loses it in the second half. Teachers are, of course, clever people who want graduate students. So they hold off discussing gyroresonance, in which case, all bets are off. The resonance condition is:

$$(1) \qquad \omega - k_z v_z - n \Omega_o / \gamma = 0$$

Here ω is the frequency of the driving wave, k_z the component of the wave vector along the zero order magnetic field $\underline{B}_o = \underline{B}_o \hat{z}$, v_z the particle's component of velocity along $\underline{B}_o$ and n is an integer representing an harmonic of the gyrofrequency $\Omega_o = q B_o/m$, γ is the relativistic correction $(1 - v^2/c^2)^{-1/2}$, q is the charge, and m the rest mass of the electron.

Before going into a detailed mathematical analysis it is obvious that there are going to be problems accelerating cold ionospheric electrons to high energies. Higher than first gyroharmonics will have Bessel function multipliers where the argument of the Bessel function is the perpendicular component of the wave vector and the gyroradius. For cold electrons with small gyroradii, all but the zero index Bessel function terms will be small. The second concern can be understood by considering the motion of a charged particle in a circularly polarized wave. Roberts and Buchsbaum (1964) have shown that with an electron in gyroresonance according to eq.(1) and $\underline{v}_\perp$ initially antiparallel to the wave electric field $\underline{E}$ and perpendicular to the wave magnetic field $\underline{B}$, two effects combine to drive it away from resonance. As the electric field accelerates the electron, γ increases, changing the gyrofrequency. The magnetic component of the wave changes v_z and thus, the Doppler shift term. It is only in the case of the index of refraction $\eta = ck/\omega = 1$ that unrestricted acceleration occurs. In all other cases the electron goes through cycles gaining and losing kinetic energy.

Recently, the SAIC group (Menyuk et al. 1986) has devised a conceptually simple way to understand acceleration by em waves as a stochastic process. In terms of the relativistic **moments** p_z and $p_\perp$, eq.(1) can be rewritten as

$$p_\perp^2 = (\eta^2 - 1) p_z^2 + 2 \eta_z p_z mc (n \Omega_o / \omega) + [(n \Omega_o / \omega)^2 - 1] mc^2$$

Depending on the phase velocity of the waves, equation (2) represents a family of ellipses ($\eta_z = ck_z/\omega < 1$), hyperbolae ($\eta_z > 1$) and parabolae ($\eta_z = 1$) in a $p_\perp$, p_z phase space. The zero order Hamiltonian can also be written in the form

$$(2) \qquad H_o/mc^2 = [1 + (p_z/mc)^2 + (p_\perp/mc)^2]^{1/2} - (p_z/mc)(\omega/ck_z)$$

Thus, in $p_\perp$, p_z space constant Hamiltonian surfaces represent families of hyperbolae ($\eta_z < 1$) ellipses ($\eta_z > 1$) and parabolae ($\eta_z = 1$). Hamiltonian surfaces have open topologies for indices of refraction $\eta_z \leq 1$. The case $\eta_z = 1$ in which resonance and Hamiltonian surfaces are overlying parabolae is that of unlimited acceleration studied by Roberts and Buschbaum (1964).

In the case of small amplitude waves the intersections of resonance and Hamiltonian surfaces in $p_\perp$, p_z space are very sharp. As the amplitudes of the waves grow so too do the widths of resonance. For sufficiently large amplitudes, resonance widths may extend down to low kinetic energies allowing cold electrons to be stochastically accelerated to relativistic energies.

It should be pointed out that although this model heuristically explains the main conceptual reasons for stochastic acceleration to occur, its validity extends only to small angles θ between $\underline{k}$ and $\underline{B}_o$. At large angles, it is not clear that the zero-order Hamiltonian topologies described above will still hold.

Over the past several months we have developed a rigorous extension of the analytical model of Roberts and Buchsbaum by letting $\underline{k} = k_x \hat{x} + k_z \hat{z}$ assume an arbitrary angle to $\underline{B}_o$. We begin with the Lorentz equation.

$$\frac{d\underline{p}}{dt} = q \left[\underline{E} + \underline{v} \times (\underline{B}_o + \underline{B}) \right] \tag{3}$$

The relativistic momentum and Hamiltonian are given by $\underline{p} = m \gamma \underline{v}$ and $H = mc^2 \gamma$, respectively. The magnetic field of the wave $\underline{B}$ is related to the electric $\underline{E}$ through Maxwell's equation $\underline{B} = (\underline{c}/\omega)\underline{k} \times \underline{E}$. The time rate of change of the Hamiltonian is

$$\dot{H} = q\, \underline{E} \cdot \underline{v} = qc^2\, \underline{E} \cdot \underline{p}/H \tag{4}$$

If we define $E_x = E_1 \cos\phi$, $E_y = -E_2 \sin\phi$ and $E_z = -E_3 \cos\phi$, where $\phi = k_x x + k_z z - \omega t$ then equation (4) may be rewritten in the form

$$\frac{H\dot{H}}{c^2\omega} = \frac{qE_1}{\omega} p_x \cos\phi - \frac{qE_2}{\omega} p_y \sin\phi - \frac{qE_3}{\omega} p_z \cos\phi \tag{5}$$

The Lorentz force equation can also be rewritten as

$$(6)\quad \dot{p}_x + p_y \left[\Omega + \frac{qE_2}{m\gamma} \frac{k_x}{\omega} \sin\phi \right] = \frac{qE_1}{\omega} (\omega - K_z \dot{z}) \cos\phi$$

$$(7)\quad \dot{p}_y - p_x \left[\Omega + \frac{qE_2}{m\gamma} \frac{k_x}{\omega} \sin\phi \right] = - \frac{qE_2}{\omega} (\omega - k_z \dot{z}) \sin\phi$$

$$(8)\quad \dot{p}_z - \frac{K_z}{\omega} \dot{H} + \frac{E_3}{E_1} (\dot{p}_x + \Omega p_y) = 0$$

where $K_z = k_z (1 + E_3 k_x / E_1 k_z)$. Equations (5-8) are exact. Our first simplification is to assume $E_2 k_x / \omega = B_z << B_o$, then eqs. (6-8) may be combined to give

$$(9)\quad \frac{4H\dot{H}}{c^2 \omega} = \frac{q}{\omega} (E_1 + E_2) \left[\int_0^t Q' \cos(\sigma + \phi - \sigma' + \phi') dt' + \right.$$

$$\left. + \int_0^t R' \cos(\sigma + \phi - \sigma' - \phi') dt' - 2p_\perp \sin(\sigma + \phi + \alpha) \right]$$

$$+ \frac{q}{\omega} (E_1 - E_2) \left[\int_0^t Q' \cos(\phi - \sigma + \sigma' - \phi') dt' \right.$$

$$\left. + \int_0^t R' \cos(\phi - \sigma + \phi' + \sigma') dt' + 2p_\perp \sin(\phi - \sigma - \alpha) \right]$$

$$- \frac{q}{\omega} E_3 \left\{ 4 \left(p_{zo} + \frac{K_z}{\omega} (H - H_o) \right) \cos\phi \right.$$

$$\left. - \frac{E_3}{E_1} \int_0^t (Q' + R') \left[\cos(\phi + \phi') + \cos(\phi - \phi') \right] dt' \right\}$$

where $\sigma(t) = \int_0^t \Omega(t') dt'$, $\tan\alpha = -(p_{xo}/p_{yo})$,

(the subscript o refers to the initial conditions at $t = 0$), and

$$Q = \frac{qE_1}{\omega} (\omega - K_z \dot{z}) - \frac{qE_2}{\omega} (\omega - k_z \dot{z})$$

$$R = \frac{qE_1}{\omega} (\omega - K_z \dot{z}) + \frac{qE_2}{\omega} (\omega - k_z \dot{z})$$

Primed and unprimed quantities are evaluated at times t' and t, respectively. We note that accelarations represented in Eq. (9) are related to terms multiplying electric fields in right-hand $(E_1 + E_2)$, left-hand $(E_1 - E_2)$ and parallel E_3 modes.

Our next simplification is to substitute for x and $\dot{z}$ in eq.(9) the zero order solutions (in the electric field amplitude) of eqs. (6-8). That is, we take $x = \rho \cos(\sigma + \alpha)$ where $\rho = v_\perp / \Omega$ is the electron gyroradius and

$$(10) \qquad p_z = \left[p_{zo} + \frac{K_z}{\omega} (H - H_o) \right] .$$

We note that eq.(10) reduces to eq.(2) by taking $K_z = k_z$, which is only valid for small angles between $\underline{k}$ and $\underline{B}_o$. In fact, Figure 1 shows that Hamiltonians with open (hyperbolic or parabolic) topologies in p_z, $p_\perp$ space at small angles between $\underline{k}$ and $\underline{B}_o$ become closed (elliptical) as the angle increases. **The practical implication is that cases of potentially infinite acceleration with $k \approx k_z$ become restricted to finite values at other directions of wave propagation.**

By taking $x = \rho \cos(\sigma + \alpha)$ and expanding terms with $\sin k_x x$ and $\cos k_x x$ in series of Bessel functions, eq. (9) becomes

$$(11) \qquad \frac{4H\dot{H}}{c^2 \omega} = \sum_n T_n$$

$$\begin{aligned} T_n = {} & \frac{q}{\omega} (E_1 + E_2) J_{n-1}(k_x \rho) \Big\{ \sum_m \int_o^t \Big[Q' J'_{m+1} \cos(n\theta + m\theta' + \psi + \psi') \\ & + R' J'_{m-1} \cos(n\theta - m\theta' + \psi - \psi') \Big] dt' + 2p_\perp \cos(n\theta + \psi) \Big\} \\ & + \frac{q}{\omega} (E_1 - E_2) J_{n+1}(k_x \rho) \Big\{ \sum_m \int_o^t \Big[Q' J'_{m+1} \cos(n\theta - m\theta' + \psi - \psi') \\ & + R' J'_{m-1} \cos(n\theta + m\theta' + \psi + \psi') \Big] dt' + 2p_\perp \cos(n\theta + \psi) \Big\} \\ & - \frac{qE_3}{\omega} J_n(k_x \rho) \Big\{ 4 \Big(p_{zo} + \frac{K_z}{\omega} (H - H_o) \Big) \cos(n\theta + \psi) \\ & - \frac{E_3}{E_1} \sum_m \int_o^t (Q' + R') J'_m \Big[\cos(n\theta + m\theta' + \psi + \psi') \\ & + \cos(n\theta - m\theta' + \psi - \psi') \Big] dt' \Big\} \end{aligned}$$

where $\theta = \int_o^t \Omega(t')\, dt' + \alpha + \pi/2$, $J'_\nu \equiv J_\nu(k_x \rho')$, $(\nu = m, m \pm 1)$ and $\psi = k_z z - \omega t$.

After averaging over the fast (gyroperiod) time dependencies and a good deal of tedious algebra, we obtain that, for each n, the particle energy obeys the following differential equation:

$$(12) \qquad (U + 1)^2 \left(\frac{1}{\omega} \frac{dU}{dt} \right)^2 + V_n(U) = 0$$

where $U = (H - H_o)/H_o$ and

$$V_n(U) = \frac{d_1^2}{4} U^2 \left(U + 2 r_n/d_1 \right)^2 - \psi(o)\sin\phi_n \; d_1 U \left(U + 2r_n/d_1 \right)$$

$$+ \frac{\Sigma_1 - \Sigma_2}{2} \left\{ \left(\Sigma_2 d_1 - \Sigma_1 h_1 \right) \left(G_{n+1}(U) + F_{n+1}(U) \right) + \left(\Sigma_2 d_2 - \Sigma_1 h_2 \right) F_{n+1}(U) \right\}$$

$$- \frac{\Sigma_1 + \Sigma_2}{2} \left\{ \left(\Sigma_1 h_1 + \Sigma_2 d_1 \right) \left(G_{n-1}(U) + F_{n-1}(U) \right) + \left(\Sigma_1 h_2 + \Sigma_2 d_2 \right) F_{n-1}(U) \right\}$$

$$- \Sigma_3^2 \left\{ h_1 \left(G_n(U) + F_n(U) \right) + h_2 F_n(U) \right\} - \left(\psi(O)\cos\phi_n \right)^2$$

where $\Sigma_i = -(q E_i/\omega)\, c/H_o \quad (i=1,2,3), \qquad d_1 = 1 - K_z k_z c^2/\omega^2$

$d_2 = K_z k_z c^2/\omega^2 - k_z \dot{z}_o/\omega, \qquad h_1 = 1 + K_z/k_z\,(d_1 - 1)$

$r_n = 1 - k_z \dot{z}_o/\omega - n\,\Omega_o/\omega, \qquad h_2 = K_z/k_z \; d_2$

$$\psi(O) = v_{\perp o}/2c \left[-(\Sigma_1 + \Sigma_2) J_{n-1}(k_x \rho_o) + (\Sigma_2 - \Sigma_1) J_{n+1}(k_x \rho_o) \right] + v_{zo}/c \; \Sigma_3 J_n(k_x \rho_o),$$

$$\phi_n = n\left(\alpha + \frac{\pi}{2}\right) + k_z z_o$$

and $$G_\nu(U) = \int_o^U J_\nu^2 \left[k_x \rho(U') \right] U' \, dU'$$

$$F_\nu(U) = \int_o^U J_\nu^2 \left[k_x \rho(U') \right] dU', \quad (\nu = n, n \pm 1).$$

Eq.(12) is in the form of the equations of a harmonic oscillator. Under the limit $\theta = 0$, Eq. (12) becomes the equation derived by Robert and Buchsbaum (1964). The limits of the particles excursion in energy for a given resonance n and electric field E can be found by setting the potentials $V_n(U) = 0$. At wave amplitudes where the range of potentials for different harmonics overlap, we have the onset of stochasticity.

At the present time we have just begun to explore the numerical solutions of equation (12). In Figure 2, we show some of our preliminary results. We assume that $\omega_{pe}/\Omega_o = 0.3$, the electric field amplitude is such that $\Sigma 1 = 0.1$, and the wave frequency is $\omega = 1.8\,\Omega_o$. We consider only the second cyclotron harmonic since this is the closest to satisfying the resonance condition, eq.(1), for initially cold electrons. The components of the wave electric field and the refractive index η are calculated from the cold plasma dispersion relation for electromagnetic waves at any arbitrary angle θ to B_o. It turns out that η is always smaller than, but very close to 1 ($\eta \simeq 0.97$). The maximum allowed

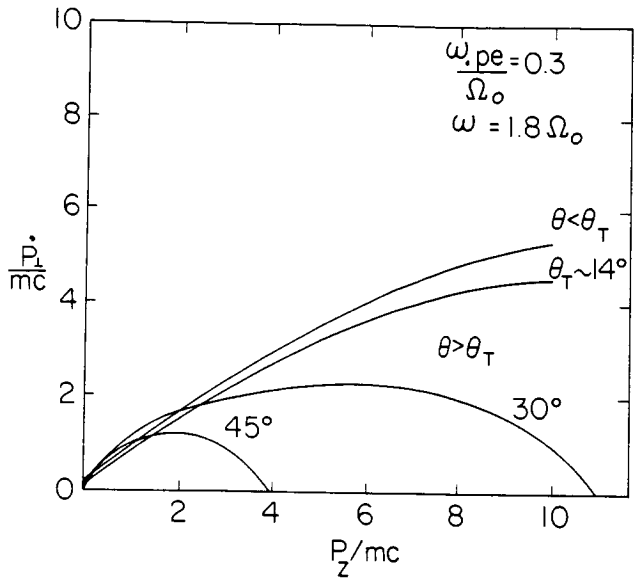

Fig. 1. Surfaces of zero order Hamiltonians with different propagation angles to magnetic field.

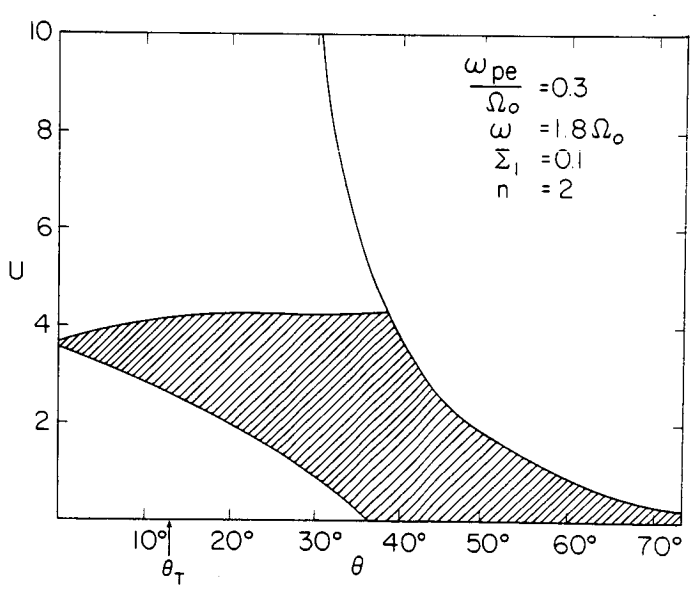

Fig. 2. Range of allowed electron energy gain (shaded) as a function of wave propagation angle to magnetic field. The solid line represents maximum energy excursion for elliptical topologies.

energy gain, as given by the zero order Hamiltonian topologies, is represented by the solid lines . The shaded region represents the actual energy gain as obtained by requiring V_n (U) $\leq$ 0. We see that for $\theta \simeq 35^o$, initially cold electrons can be accelerated to very high energies. In fact, for cold electrons we find that $U = \gamma - 1$ and that the particle can gain as much as 2.5 Mev. As θ decreases more initial kinetic energy is required for any acceleration to take place. For large θ , the elliptical hamiltonian topologies severely restrict the energy gain.

III The Alfven Maser

Active control of energetic particle fluxes in the radiation belts has maintained a continuing interest in both the United States and the Soviet Union. Electron dumping experiments concluded by the Stanford University and Lockheed groups using VLF transmissions are well known (Inan et al. 1982, Imhof et al. 1983). Perhaps less known is a theoretical paper by Trakthengerts (1983) entitled "Alfven Masers" in which he proposes a theoretical scheme for dumping both electrons and protons from the belts. The basic idea is to use RF energy to heat the ionosphere at the foot of a flux tube to raise the height integrated conductivity. The conductivity is then modulated at VLF or ELF frequencies which modulates the reflection of waves that cause pitch angle diffusion in the equatorial plane. The artifically enhanced conductivity of the ionosphere thus maintains high wave energy densities in the associated flux tube, thereby producing a masing effect.

In addition to external ionospheric perturbations particle precipitation also raises ionospheric conductivity. The masing of the VLF waves causes further precipitation which, in principle, results in an explosive instability. The purpose of this section is to establish the basic equations and to present the results of a preliminary computer simulation.

The fundamental equations derived by Trakhtengerts (1983) are based on quasilinear theory and relate only to the weak diffusion regime. It is useful to use a similar set of equations derived by Schulz (1974) based on phenomenological arguments that includes strong pitch angle diffusion. The key variables are N, the number of trapped particles per unit area on a flux tube and ε the wave intensity averaged over the flux tube. In this we assume that ε is directly proportioned to the pitch angle diffusion coefficient. The time rate of change for N is

$$(13) \qquad \frac{dN}{dt} \quad \frac{-A\ \varepsilon\ N}{1 + \varepsilon\ \tau} \quad + S.$$

where the first term represents losses due to pitch angle scattering with A a constant and S represents particle source terms in the magnetospheric equatorial plane. τ is a parameter that characterizes lifetimes against strong pitch angle diffusion. The time rate of change of ε is given by

$$(14) \qquad \frac{d\ \varepsilon}{dt} = \frac{\left(2\ \gamma\ {}^*N/N^* \right)}{1 + \ \varepsilon\tau}\ \varepsilon \ + \ \frac{Vg\ \varepsilon}{LR_e} \ln R + W$$

The first term represents wave growth near the equatorial plane, the second term gives the wave losses in and through the ionosphere and the third accounts for any wave energy sources. The terms γ^* and N^* are used to denote the weak diffusion growth rate and column density of a flux tube at the Kennel and Petschek (1966) limit for stably trapped particles. In the second term, v_g/LR_e approximates bounce frequency of waves where v_g is the group velocity of the wave LR_e the approximate length of a flux tube; R is the reflection coefficient of the ionosphere. Since $R < 1$ the second term is always negative. The $(1 + \varepsilon \tau)$ term empirically lowers growth rate due to the pitch angle distribution becoming more isotropic under strong diffusion conditions.

In our present study we have examined numerical solutions of equations (13) and (14) using non-equilibrium initial conditions. The first case is represented by Figure 3 in which we started initial wave energy densities which are a factor of 3 (top panel) and 0.1 (bottom panel) above the Kennel-Petschek limit. In both cases we ignored associated enhancements in ionospheric coupling that lead to increased reflectivity. We see that the wave energy density quickly damps to the Kennel-Petschek equilibrium represented by the solid line.

In the second level of simulation the wave energy density is initially set at a factor of three above the Kennel-Petschek equilibrium value but includes a coupling factor to the ionosphere ζ. We find that for values of $\zeta \geq 10\%$ the oscillations become spike-like. The top panel of Figure 4 represents the normalized wave energy density for $\zeta = 10\%$ after the waves have evolved into periodic spikes. The middle and bottom panels of Figure 4 represent the normalized energetic particle density (cm^{-2}) contained on a flux tube and the normalized height integrated density of the ionosphere. Attention is directed to the phase relationship between the maxima of the three curves. The maximum, energetic particle flux leads the wave term and goes through the Kennel-Petschek value as the wave growth changes from positive to negative.

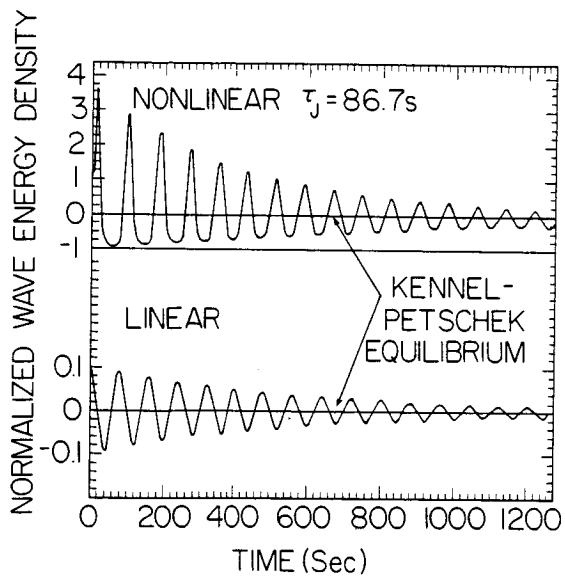

Fig. 3. Example of wave energy densities initially set at factors of 3.0 and 0.1 above Kennel Petschek equilibrium value.

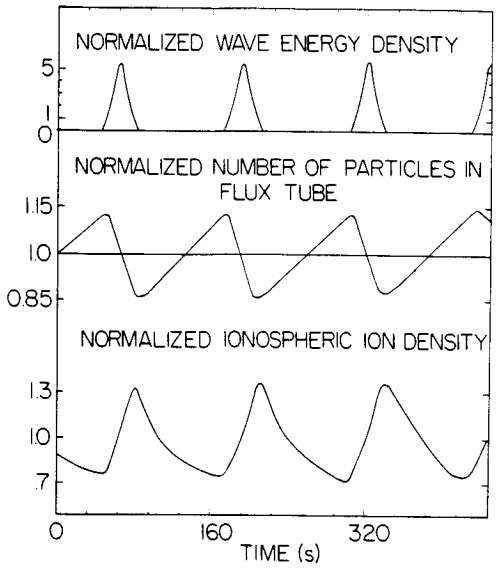

Fig. 4. Example of spike-like wave structures as well as energetic particle losses and ionospheric density changes with magnetosphere-ionosphere coupling.

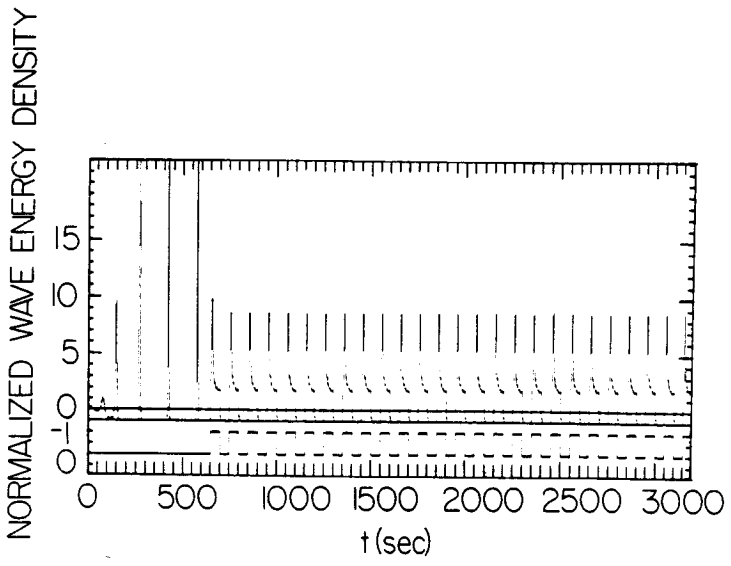

Fig. 5. Simulated, mormalized wave energy density with magnetosphere-ionosphere coupling. A VLF source is turned on at t = 650s.

The maximum ionospheric effect occurs after the wave spike maximum. Our physical interpretation of Figure 4 is as follows. A spike in the wave energy density causes a depletion of electrons trapped in the belts to levels well below the Kennel-Petschek limit. The subsequent drop of precipitating electron flux allows the ionospheric conductivity to decrease. Thus, VLF waves are less strongly reflected back into the magnetosphere. This effectively raises the Kennel-Petschek limit as higher particle fluxes are necessary to offset increased ionospheric VLF absorbtion. In the presence of equatorial sources of particles, the similations show flux levels building to 1.15 times the Kennel-Petschek limit. The enhanced fluxes in the magnetosphere, even with weak pitch angle diffusion, allows the ionospheric conductivity to rise, eventually leading to another masing spike.

Figure (5) shows the effect of an external VLF signal. The first few spikes result from the masing effect of the ionosphere due to particle precipitation. At t = 650 seconds a VLF square wave source is turned on with a 50 second duration. The spikes now are modulated at the driving frequency at a reduced amplitude. The amplitude is reduced since the fluxes are more frequently dumped with the VLF signal present than in its absence.

Iversen et al. (1984) using simultaneous ground and satellite measurements, have recently observed the modulation of precipitating electrons at pulsation frequencies. In terms of our simulations these would be close to the situation shown in Figure 4 in which natural masing occurs in a flux tube. The observed frequencies are consistent with those expected from the linear theory. Detailed comparison with experimental data necessitates knowing the efficiency with which VLF waves reach the ionosphere.

IV Conclusion

Although the work presented in this paper is still in a very preliminary stage of development it appears that significant space effects can be produced by the injection of intense electromagnetic waves into ionospheric plasmas. In the coming months we expect that as calculations mature we will grow in the ability to translate mathematical representation into physical understanding. If the results of our analyses live up to early promise then a series of ground-based wave emission experiments will be developed to measure injection effects in space. The upcoming ECHO-7 experiment presents a well instrumented target of opportunity for electron acceleration experiments with the HIPAS system. After the launch of the CRRES satellite it will be possible to make simultaneous in situ measurements of wave and particle fluxes in artificially excited Alfven Masers. Looking forward to the 1990's it appears that the WISP experiment planned for the Space Station will make an ideal source for both electron acceleration and radiation belt depletion experiments. Recently a Soviet experiment measured electrons accelerated to kilovolt energies using a low power telemetry system (Babaev et al., 1983). Just image that what could be done with the specifically designed, high power WISP!

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TECHNICAL ISSUES IN THE CONDUCT OF LARGE SPACE PLATFORM EXPERIMENTS IN PLASMA PHYSICS AND GEOPLASMA SCIENCES

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I. INTRODUCTION

Large, permanently-manned space platforms can provide exciting opportunities for discoveries in basic plasma and geoplasma sciences. The potential for these discoveries will depend very critically on the properties of the platform, its subsystems, and their abilities to fulfill a spectrum of scientific requirements. With this in mind, the planning of Space Station research initiatives and the development of attendant platform engineering should allow for the identification of critical science and technology issues that must be clarified far in advance of Space Station program implementation. An attempt is made here to contribute to that process, with a perspective that looks to the development of the Space Station as a permanently-manned "Spaceborne Ionospheric Weather Station". The development of this concept requires a synergism of science and technology which leads to several critical design issues. To explore the identification of these issues, the development of the concept of an "Ionospheric Weather Station" will necessarily touch upon a number of diverse areas, including:

1) System requirements and their hierarchy in experiment planning,
2) Ionospheric plasma physics and associated global-scale measurements and modeling,
3) Needs for tethered subsatellites,
4) Concerns with vehicle and tethered satellite interactions with the space environment, and
5) Scientific and engineering perspectives on the application of plasma contactors.

These issues, seemingly unrelated, are indeed synergistic, and bear on the planning for and application of the Space Station not only as an "Ionospheric Weather Station" but as a base for fundamental studies of plasma processes as they might be implemented by any number of active experiments (e.g., controlled injection of energetic particle beams). This overall synergism will be developed in subsequent sections, treating first the natural space station environment, the prediction and modeling of that environment, its consequences in terms of active and passive experiments, and its accessibility for comprehensive probing and attendant "Ionospheric Weather Forecasting". The treatment will establish a number of requirements, including a need for multiple-tethered subsatellites and environmental controls at the Space Station and at the location of the individual subsatellites. The requirement for environmental controls will concentrate on charge and current neutralization processes, and the applicability of plasma contactors.

II. A HIERARCHY OF ISSUES

Table 1 presents a hierarchy of technology issues that encompasses the planning of any spaceborne experiment. Issues at Level 1 address first-order requirements, including the fundamental subsystem support functions of power, thermal control, and information technology (e.g., data compression, storage, and transmission techniques). The focus here is not on these issues, but instead on "in-space operations", which at Level 2 converges on aspects of local scientific climatology, that is, on the sum total of prevailing conditions that affect the proper execution of the scientific mission. These concerns expand into Level 3 issues, with scientific attention to the availability of free-flying or tethered subsatellites, the natural, induced, and controlled space environment, and the platform's adaptability to scientific sensor requirements.

III. THE NATURAL ENVIRONMENT

With regard to the Station's natural geoplasma environment, reference is made to Figure 1, an illustration of the ionospheric plasma densities and associated phenomenological domains that would be encountered by the Station in a polar orbit at F-region altitudes. (A polar orbit is the desired configuration for an Ionospheric Weather Station.) Detailed discussions on each of the ionospheric domains can be found elsewhere (Szuszczewicz, 1986), while immediate purposes are served by a brief sketch of encountered conditions. The figure illustrates the broad range of plasma densities, including peak values near $2(10^6)$ cm^{-3} and minima near 10^4 cm^{-3}. (Minimum values can approach 10^3 cm^{-3}, depending on the altitude, season, and height of the F_2-peak.) The Figure also illustrates that the ionosphere can be substantially disturbed, with phenomena including broad-scale irregularity distributions (10's of kms to fractions of a meter) under nighttime conditions of equatorial spread-F (Singh and Szuszczewicz, 1984; Kelley et al., 1982). Similar irregularity distributions can be found at high latitudes on a nearly 24 hour-per-day basis (Singh et al., 1985; Rodriguez and Szuszczewicz, 1984; Ossakow et al., 1984). Only in the daytime hemisphere, at mid- and equatorial latitudes, can conditions be described as "quiescent".

The following points are of relevance to the Space Station and planned programs of research, engineering, and development:

1) Plasma densities can vary by three orders of magnitude on any given orbit, with the lowest density regimes of particular concern in dealing with the issue of spacecraft charging by natural energetic particle fluxes at high latitudes, by active beam injection experiments, or by $\bar{V} \times \bar{B}$ forces. (More detailed discussions on this issue will follow.)

2) The distribution of phenomenological domains offers limited periods of time for on-board experiments which require or assume near-constant ionospheric conditions. Near-constant conditions (in an orbit defined by upper F-region ephemerides) may not be available for periods extending beyond 15-20 minutes.

TABLE 1

HIERARCHY OF SPACE STATION PLASMA TECHNOLOGY ISSUES

LEVEL 1

- DYNAMICS AND CONTROL OF LARGE STRUCTURES
- FLUID MANAGEMENT
- ENERGY SYSTEMS AND THERMAL MANAGEMENT
- INFORMATION SYSTEMS
- AUTOMATION AND ROBOTICS
- IN-SPACE OPERATIONS

LEVEL 2: IN-SPACE OPERATIONS

- ADVANCED LIFE SUPPORT SYSTEMS
- ORBITAL TRANSFER VEHICLES
- PROPULSION
- MAINTENANCE AND REPAIR
- LOCAL SCIENTIFIC CLIMATOLOGY

LEVEL 3: LOCAL SCIENTIFIC CLIMATOLOGY

PREVAILING CONDITIONS AFFECTING AND/OR CONTRIBUTING TO THE SCIENTIFIC MISSION

- AVAILABILITY OF FREE-FLYING OR TETHERED SUBSATELLITES
- THE NATURAL, INDUCED, AND CONTROLLED SPACE ENVIRONMENTS
- PLATFORM ADAPTABILITY TO SENSOR REQUIREMENTS

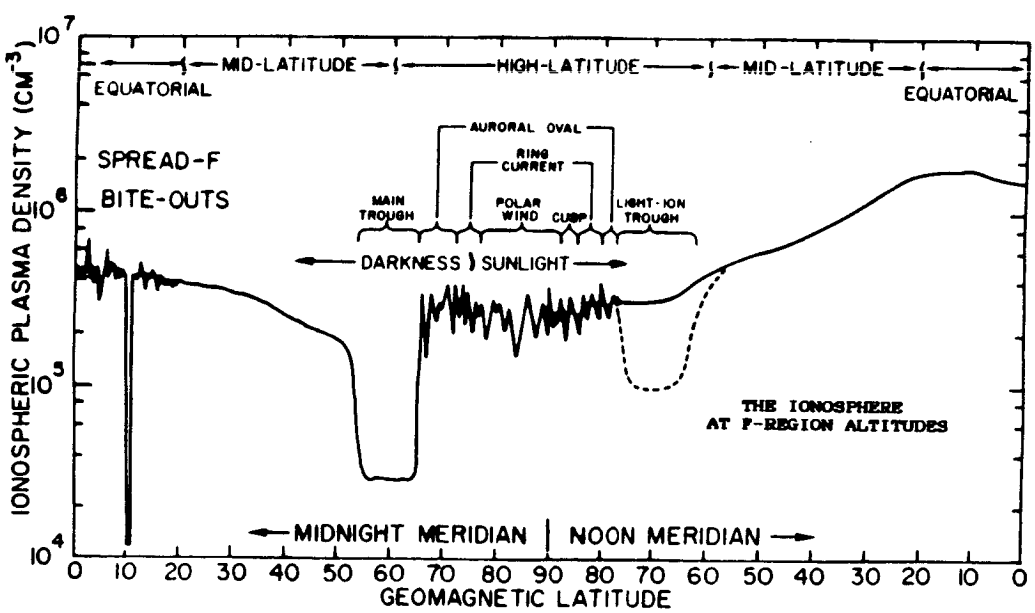

Figure 1. Phenomenological illustration of ionospheric F-region densities and irregularity domains in a noon-midnight meridian

3) The "average" F-region domain is relatively well understood, but not predictable on a day-to-day, hour-by-hour basis. For example, there is currently no genuinely predictive capability for the occurrence of equatorial spread-F, the location of the mid-latitude trough, the diffuse auroral boundary, or the specifics of particle precipitation events at high latitudes.

While the environment of the Space Station is not currently predictable in the truest sense, the Station's orbit parameters allow for its consideration as a permanently-manned solar-terrestrial monitoring system. Indeed, with certain technological accomplishments (to be discussed), the Space Station can be developed as an "Ionospheric Weather Station" with full capabilities to diagnose and predict the global-scale ionosphere. Such a capability would not only provide an important payoff in understanding the intricate role of the ionosphere in the solar-terrestrial system, but it would render a comprehensive description of the near-space environment applicable to ULF-EHF communications and remote sensing systems.

III. IONOSPHERIC PREDICTION

To predict the global-scale ionosphere means to state in advance the height profile of plasma density at any location at any time, and for any combination of solar, interplanetary, and magnetospheric conditions. In this sense, ionospheric prediction is a formidable goal, but one that the scientific community can legitimately aspire to in the year 2000 and beyond. Much work is already underway, with advances having been made in empirical and first-principles modeling. The empirical models (e.g., Rawer, 1981; Chiu, 1975) are seasonally-, monthly-, and hourly-averaged, with scientific intuition employed in the extrapolation of results to domains not covered by the available data base. Most empirical models use the sunspot number as an indicator of solar, interplanetary, and magnetospheric inputs to the overall ionospheric system, and on the average the model representation of the F_2-region (particularly peak densities) is good. This is illustrated in Figure 2 which presents a global IRI map of F_2-peak densities (that is, associated critical (plasma) frequencies) during solar maximum, near the autumnal equinox. (IRI is the empirically-derived International Reference Ionosphere of Rawer (1981)). The prescribed UT time is 0.0 hours and the month is October. The contours enclose contiguous regions of lower-limit plasma frequencies of the F_2-peak (defined as $f_oF_2=8.9(10^3)\sqrt{N_e(cm^{-3})}$. The IRI results are in agreement with averaged topside sounder measurements (Matuura, 1979; Schunk and Szuszczewicz, 1986), and included in the illustration are several intuitively satisfying features of the diurnal ionospheric behavior and its control by the geomagnetic field. These features include the sunrise enhancement of the peak density, its maximum towards the afternoon hours, and its relative position following the southward excursion of the dip equator across South America. (A brief editorial note of caution is added here to advise the reader of the inadequacies of the IRI (and other comparable global models) in its high-latitude prescription of density profiles. The averaging process tends to be dominated by photoionization, and not by particle precipitation events. Therein lies one of the more serious limitations of the IRI.)

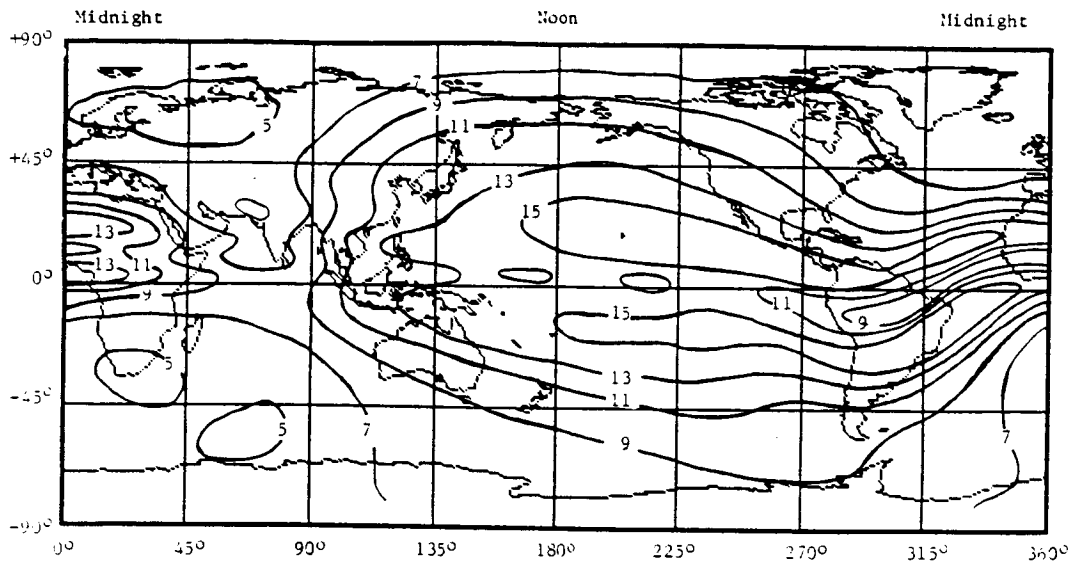

Figure 2. Boundary contours for minimum values of F_2-region critical frequencies, $f_oF_2 = 8.9(10^3)\sqrt{N_e[cm^{-3}]}$, as derived from the model International Reference Ionosphere, for sunspot maximum conditions (R=150) at UT = 0 hrs in October. The plotted units of f_oF_2 are MHz

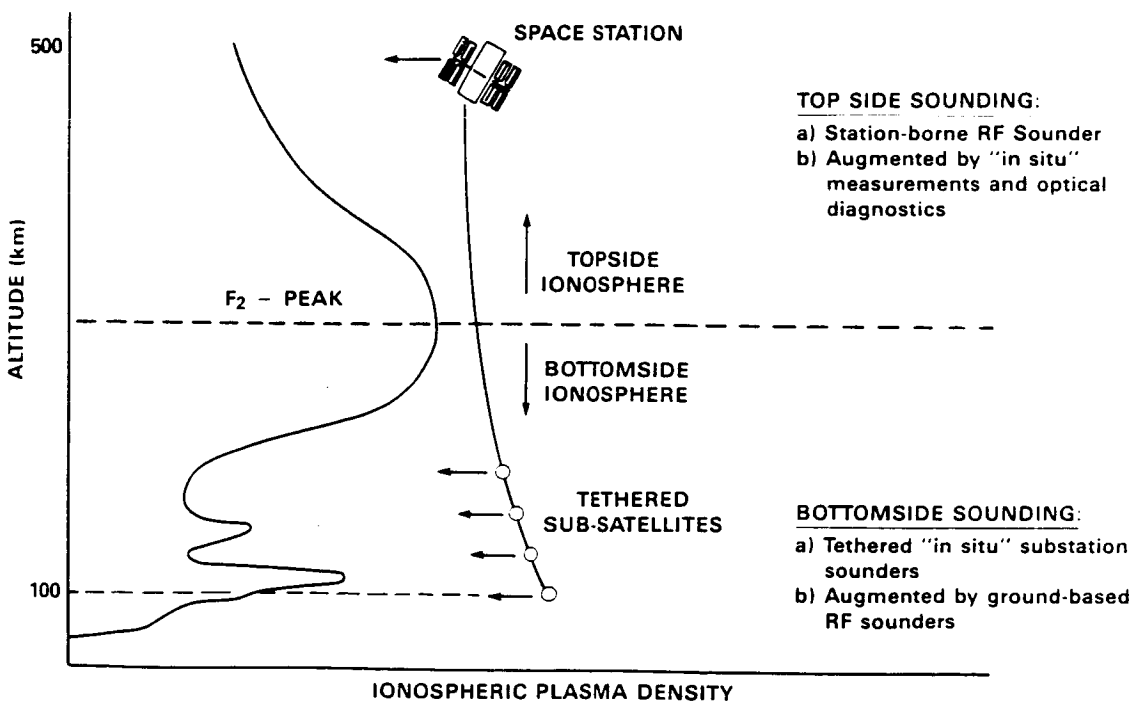

Figure 3. Concept drawing of an ionospheric weather space station (see text)

The relative success in the IRI definition of world-wide f_oF_2 profiles is not matched in the E and F_1 domains where the data base is not as complete and synoptic, and the phenomenologies still represent a complex unravelled issue (see e.g., Szuszczewicz, et al., 1978). Available E and F_1 data are generally site-specific, largely because these regions have not been routinely accessible to orbiting spacecraft and associated synoptic data basing. This deficiency in E- and F_1-region data needs to be eliminated as a fundamental requirement of programs in ionospheric physics, solar-terrestrial relations, and communication sciences; and the requirement can be fulfilled if we look to tethered satellite technology and the development of a permanently-manned space platform as an Ionospheric Weather Station.

The problem of E- and F_1-region definition is not unique to empirical models, but is shared with the approaches of first-principle and semi-empirical codes (e.g., Sojka and Schunk 1984, 1985; Anderson, et al., 1985) Often, these codes do not include the E- and F_1-regions, a testimony to the complexity of the domains and the inadequate data base. This deficiency is acknowledged and is being worked upon; and the first-principles and empirical models are expected to make important advances in the upcoming solar cycle, with their participation in concerted campaign efforts that link model predictions with coordinated real-time observational programs. Two currently active programs are the National Science Foundation efforts called GISMO and SUNDIAL.

IV. THE WEATHER STATION CONCEPT

a. An Overview

Figure 3 presents a concepts drawing of an Ionospheric Weather Station that could provide the necessary diagnostics complement for simultaneous E-, F_1-, and F_2-region definition, networked into a worldwide ionospheric prediction service. The primary platform is the Space Station, in polar orbit at an altitude near 500 km, equipped with an on-board rf sounder for topside ionospheric profile specification between the F_2-peak and the station. The concept definition also requires that the station be equipped with a complement of "in situ" and optical diagnostics... particularly for the definition of high-latitude precipitation patterns, convection electric fields, and dynamics of the auroral oval.

The E and F_1 region data requirements would be satisfied with a tethered quadra-satellite configuration draped to a low altitude limit at 100 km, with each substation separated by approximately 10 km, and equipped with on-board measurement capabilities for plasma density, and ion and neutral composition.

b. Relevant Issues Involving Local Environmental Controls

The mission concept advanced in Figure 3 presents some very pressing technological issues... not the least of which is the difficult problem of tethering a single subsatellite (i.e., a substation) to the 100 km altitude (Baracat and Butner, 1986; Penzo, 1986). In addition, there are important local environmental issues at the main platform and its substations... issues that include gaseous effluents, electrical and magnetic contamination, and uncontrolled potentials and surfaces. We focus here on the issue of

uncontrolled potentials, and explore the associated implications of $\bar{V} \times \bar{B}$ effects.

Table 2 lists several simple formulae which address the quantitative aspects of uncontrolled potentials, charging levels, currents, and sheaths.

Tethering a substation to 100 km could present some threatening consequences. The application of equation 1a with (V, B, L) = (8 km/s, .25 gauss, 400 km) points to an 80 kV $\bar{V} \times \bar{B}$ potential difference between the main station and the subsatellite. Even potentials orders of magnitude lower present problems of limited ionospheric current neutralization, unusually large sheaths, and spacecraft safety.

An indication of sheath sizes can be attained with the use of Equation 3 (Szuszczewicz, 1983) and the listing in Table 2 of related results for ionospheric conditions corresponding to 1500°K and densities at 10^3 and 10^6 cm^{-3}. The wide variation in densities is directly related to the spread expected for the space station and its tethered satellites (see e.g., Figs 1 and 2). For a spacecraft potential of only 130 volts, the sheath size can approach 7 meters in the low density limit; and at 1300 volts it approaches 21 meters. These are undesirable limits that also threaten the application of energetic particle beam injection experiments from any space platform (Winkler, 1980; Szuszczewicz, 1985; and Papadopoulos and Szuszczewicz, 1986). This can be seen through applications of Equations 1b and 2 (Linson, 1982). Equation 1b points to the fundamental limit of ionospheric current flow to a spacecraft... nominally 1 ma of current to a 1 m^2 sphere with local plasma densities at 10^5 cm^{-3}. For an on-board experiment attempting to deliver a 1 ampere electron beam from a 1 meter spacecraft, Equation 2 would point to the most severe charging rate in the range of several kv/microsecond.

There has been a continuing effort to control the development of these large potentials and maintain the spacecraft at or near the local plasma potential. Some success has resulted from improved concerns with vehicle surface conductivities and expanded areas for current collection, but the magnitude of the problem has brought about a focus on the application of high-current on-board charged-particle sources, often referred to as "plasma contactors" (e.g., Krishnan et al., 1977; Lidsky et al., 1962; and Hastings, 1986).

c. Vehicle Current and Potential Control: Plasma Contactors

One type of plasma contactor is the hollow-cathode discharge, illustrated schematically in Figure 4. A thermionic electron emitter in the presence of a relatively high neutral gas flow, such a device can produce plasma densities upwards of 10^{14} cm^{-3} near the cathode orifice (Davis et al., 1986; McCoy, 1986; Wilbur, 1986). The expansion characteristics of this plasma (and its associated "contactor" capabilities) are influenced by specific device design considerations, the ambient plasma itself, and the local geomagnetic field. The ideal contactor should provide large controllable currents of electrons and ions at minimum applied fields in the cathode-anode region. Indeed, the technology seems to be moving in that direction (J. McCoy, private communication).

TABLE 2

VEHICLE CHARGING, CURRENTS AND SHEATHS

(1a) $$d\Phi[\text{volts}] = 10^2 \left(\vec{V}_{sc}[\text{km/s}] \times \vec{B}(G)\right] \cdot d\vec{L}(\text{km})$$

(1b) $$I_\infty[\text{ma}] = \left[\frac{n_\infty\,[\text{cm}^{-3}]}{10^5}\right] \left[\frac{T_e[°K]}{1600}\right]^{1/2} S[\text{m}^2]$$

(2) $$\frac{d\Phi}{dt}\left[\frac{\text{kV}}{\mu\text{s}}\right] = 9\,\frac{I[A]}{R_s[\text{m}]}$$

(3) $$(R_{sh} - R_{sc}) = \lambda_D\left[2.5 - 1.54\,\exp\left[\frac{-0.32R_{sc}}{\lambda_D}\right]\right]\left[\frac{e\phi_{sc}}{kT_e}\right]^{1/2}$$

SHEATH SIZES

	Reasonable limits of probe theory			Substantial extrapolations of model		Plasma Conditions	
$e\phi_{sc}/kT_e$	1	10	10^2	10^3	10^4	$N_e[\text{cm}^{-3}]$	$T_e[°K]$
$(R_{sh} - R_{sc})$[m]	0.21	0.67	2.1	6.7	21	10^3	1500
$(R_{sh} - R_{sc})$[m]	0.007	0.021	0.07	0.21	0.70	10^6	1500
ϕ_{sc}[volts]	0.13	1.3	13	130	1300	...	1500

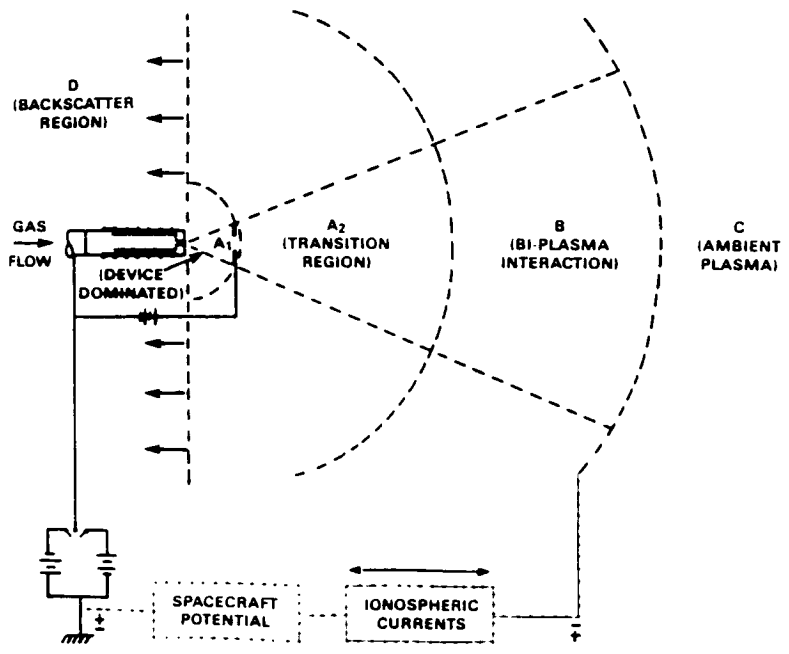

Figure 4. Phenomenological domains of hollow-cathode plasma interactions

While the bulk current-carrying characteristics of hollow-cathode contactors have been receiving attention, there is a need for the development of a detailed understanding of their intrinsic physical principles and the physics of the interactions with the local ionospheric plasma and the geomagnetic field. These interactions are critical to device performance and to the perturbations that the device are surely to introduce in the vehicle's near-space. The latter consideration bears on scientific requirements for cold-plasma-particle and wave measurements of the natural space environment. The science and technology of hollow-cathode contactor development must address this issue. Figure 4 presents a schematic view of the phenomenological domains of hollow-cathode operation in a space plasma environment. The cathode can be biased in either polarity with respect to the spacecraft ground and its outer skin (assumed a conductor in contact with the ambient geoplasma). The skin will itself be of either polarity relative to the local plasma potential, and appropriate ionospheric currents will flow across the spacecraft-associated sheath. The magnitude and polarity of this potential difference will depend on ambient plasma conditions, the spacecraft geometry and configuration, and the operation of on-board experiments (e.g. particle-beam injection). Another current path to the payload (besides that through the spacecraft sheath) is along and through the expanding hollow-cathode plasma. That expansion process, represented phenomenologically by regions A_1, A_2, B, and D, governs the current carrying capabilities of the hollow-cathode contactor.

The plasma production and expansion process begins with neutral gas flow into the cathode at relatively high pressures, typically in the range 1-100 torr. Plasma is created inside the thermionically-electron-emitting cathode and the neutral gas and plasma experience a choked flow as they pass through the cathode's exit orifice into domain A_1. In this phenomenological model, A_1 is defined as the "Device Dominated Region" because the attendant plasma processes depend crucially on the cathode characteristics and the anode-to-cathode fields. In zero order, the expansion of the neutrals in A_1 is thermal, while that of the charged particles is thermal with increasing drift velocities imparted by the applied field. The domain is collisional with orifice plasma and neutral densities quoted at 10^{15} and 10^{17} cm^{-3}, respectively (J. McCoy, private communication). The field in region A_1 can impart a relative drift velocity between the electrons and ions, with the electrons easily satisfying the Dricer field condition for the onset of collective plasma effects and the Buneman instability (see e.g., Davidson et al., 1970; Papadopoulos, 1977). This instability can turn on and off, heating the electron population, destroying all assumptions of isothermality, and affecting the plasma resistivity.

Exiting A_1, the source plasma can diminish to levels near 10^{12} cm^{-3} where it begins its exposure to a new electric field configuration resulting from the potential difference between the anode and the ambient plasma (beyond the sheath edge in region C). Region A_2 is dominated by the source plasma, which by current estimates should have a high kinetic β, excluding the ionospheric plasma and the geomagnetic field. A_2 is a transition region in which the source plasma diminishes in dominance over the domain and its kinetic β drops to unity. This is expected to occur over one-to-several meters, depending on prevailing conditions.

The processes in regions A_1 and A_2 may be considered less complex than those in region B, where counterstreaming source and ionospheric plasmas and magnetic field effects must be taken into account. In region B, the magnetic field controls the net electron emission or collection characteristics of the contactor, and it is here that the payload is truly in "contact" with the ionospheric plasma through the hollow-cathode discharge.

This discussion of plasma contactor operation is intended to expose the synergism of science and technology... for the ultimate current delivering capabilities and neutralizing effects on spacecraft potentials is dictated by the plasma expansion and counterstreaming phenomena in the varied phenomenological domains. While it appears justified to assume that hollow-cathode technology will advance to the point of large current and voltage neutralizing characteristics, the scientific requirements on any number of missions (including the Ionospheric Weather Station) will demand more from the characteristics of the hollow-cathode (or an alternate contactor design) than current or voltage neutralization. There are serious issues with the effects of the hollow-cathode on the local plasma, for the neutral gas flow is a contaminant in its own right and so will be the anticipated electrostatic noise characteristics of the device (e.g. Pirre and Berthelier, 1980). Application to beam-injection experiments is a case in point, where accumulating studies have discovered a broad spectrum of waves, ranging from 10's of Hertz to 10's of MHz. Continued studies would prefer no confusion introduced by the wave spectrum of a plasma contactor. A quality contactor (e.g. large currents and low electrostatic noise) could help immensely with continued e-beam experiments, and in the emerging era of neutral particle beams which carry their own energetic charged-particle components.

d. Contactor and Tether-Technologies, and the Ionospheric Weather Station

Should plasma contactor and tethered subsatellite technology make the appropriate advances, the Ionospheric Weather Station could become a reality. Configured as suggested in Figure 3, and adopting appropriately modified sensor techniques, the concept development would require 2 polar-orbiting space stations at an altitude of 500 km (or higher) in noon-midnight and 4 a.m. - 4 p.m. synchronous orbits. These stations would be equipped with particle and field detectors, auroral imagers, topside rf sounders, and tethered quadra-substations with "quiet" contactors and on-board measurement capabilities for plasma density and ion and neutral composition. The substation detectors would themselves require some developmental effort, in order to cope with pressure fields in the low-altitude drag regime. The comprehensive data set would then be networked into a global ionospheric prediction service which would archive the accumulating data base, test and validate first-principles and empirical codes, and extrapolate results in an ionospheric weather forecast mode.

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A Review of the Findings of the Plasma Diagnostic Package and Associated Laboratory Experiments: Implications of Large Body/Plasma Interactions for Future Space Technology

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1.0 Introduction

The purpose of this report is to review the discoveries and experiments of the Plasma Diagnostic Package (PDP) on the OSS 1 and Spacelab 2 missions, to compare these results with those of other space and laboratory experiments, and to discuss the implications for the understanding of large body interactions in a LEO plasma environment. The paper is logically divided into three sections. First a brief review of the PDP investigation, its instrumentation and experiments is presented. Next a summary of PDP results along with a comparison of those results with similar space or laboratory experiments is given. Last of all the implications of these results in terms of understanding fundamental physical processes that take place with large bodies in LEO is discussed and experiments to deal with these vital questions are suggested.

2.0 PDP instrumentation and experiments

The PDP is a small cylindrical satellite with a complement of instruments designed to measure plasma density and temperature, give ion composition, temperature and flow direction, provide complete electron and ion distribution functions, and measure electron flux from electron beams. In addition to these comprehensive particle measurements the PDP contains instrumentation to provide a complete set of single axis wave and field measurements. Waves (both electric and magnetic) are measured from approximately 10^1 to 10^5 hz and electric fields are measured both at DC and from 10^1 to 10^7 hz. A complete description of the PDP instrumentation is available in Shawhan 1984c.

The PDP was designed not only as a satellite, but because it was to be flown and deployed from the Orbiter; it was also capable of measuring the plasma environment in and around the orbiter bay by being maneuvered through various positions on the Shuttle Remote Manipulator System (RMS) arm. The initial experiments and measurements made by the PDP on the OSS-1 (STS-3) Mission were all made either in the payload bay on a pallet or within approximately 10 meters of the bay on the RMS. As will be seen in the next section these early shuttle experiments helped provide insight into the shuttle orbiter environment, conducted the first orbiter-based active plasma experiments, and provided some of the first insights in large body interactions at LEO. In addition, the OSS-1 experiments provided the baseline from which many of the future detailed interaction issues could be addressed. Spacelab 2, which repeated (with some modifications) some of the OSS-1 experiments and extended the range of interaction studies to nearly a kilometer from the orbiter, benefited greatly from the earlier OSS-1 experience. The PDP investigation was initiated by Prof. Stanley D. Shawhan (who is now at NASA Headquarters) and is currently under the leadership of Prof. Louis A. Frank at the University of Iowa. Other members of the PDP team

include Donald A. Gurnett and Nicola D'Angelo (U. of Iowa), Nobie H. Stone, David L. Reasoner (NASA/MSFC) and Joseph M. Grebowsky (NASA/GSFC). Numerous other scientists and engineers both at the U. of Iowa and NASA have played a major role in the program since its inception in 1978.

3.0 The early results

Early papers from the OSS-1/PDP program focused on defining the environment of the shuttle orbiter. This environment was a critical question mark in the eyes of many future users of the shuttle particularly in the areas of contamination, plasma, and electromagnetic environment.

3.1 The neutral environment

Early measurements of the neutral pressure environment of the orbiter revealed that the ambient pressure at orbital altitudes was only obtainable in the near wake of the vehicle and then only after a long period of outgassing. Even after seven days in orbit, pressure averaged at least an order of magnitude greater than ambient (Shawhan, 1984c). Not until Spacelab-2 analysis was available would the probable source of such a large vapor cloud be revealed.

More detailed investigation of the source of large pressure enhancements led to the study of thruster operations. It was reported that the thrusters (in particular Primary RCS and to a much less degree Vernier RCS) introduce major changes in plasma density, ion composition, neutral density, electric fields, and electrostatic plasma waves (Shawhan, 1984c; Murphy, 1983; Pickett, 1985). Other investigators have since reported similar results noting neutral density increase of up to $10^{18}/m^3$ inside the payload bay ($\sim 7 \times 10^{-5}$ Torr) with NO a major component of the enhancement (Wulf, 1986).

3.2 The plasma environment

The plasma density and apparent DC electric field shifts observed near the orbiter are not yet totally understood but may be related to interactions of the neutral constituent of the gas plume with the ambient plasma or to the plasma component per se.

Grebowsky et al. (1983) reported the surprising result that H_2O^+ is a major constituent of the plasma near the orbiter sometimes even dominating the ambient O^+ ionosphere. The source of these water ions is believed to be in charge exchange reactions between the ambient O^+ ions and a cloud of H_2O molecules generated by outgassing around the orbiter. This H_2O cloud may indeed be a major contributor to the enhanced neutral pressure environment.

The plasma environment near the orbiter not only has an altered ion composition but reveals the influence of a large body moving supersonically through its medium. Stone et al. (1986) observe the ions streaming by the orbiter and study in detail the structure of the wake behind the vehicle. They took particular note of multiple "beams" of ions with different apparent source directions and theorize that this is consistent with not only an additional source of ions close to the orbiter but may imply an E-field sheath associated with a boundary between the ion source region and the undisturbed plasma. It could in fact be that this additional source region is consistent

with observations of Grebowsky (1983) on the production of H_2O^+ near the orbiter.

Reasoner et al. (1986) have underscored the problem of making reliable ambient ionospheric density/temperature measurements near the orbiter. Combinations of contaminant ions, plasma turbulence generating heating, and ram/wake effects make it imperative to move well away from the orbiter before relying on an RPA to reliably characterize the ionosphere. This observation is of course consistent with all previously discussed results.

Electron densities and temperatures near the orbiter are reported by Murphy et al. (1986). To first order, electron densities are dominated by the ram/wake effects associated with large bodies. The orbiter is not only large compared to the debye length (10^3–10^4 λ_D) but also large compared to the electron and ion gyroradius. This size results in the investigation of a unique and unexplored region in parameter space and creates perhaps more questions than it answers. Murphy et al. (1986) report density depletions of as much as 5 orders of magnitude in the near wake of the orbiter (within the payload bay) and less dramatic though significant depletions of 1-2 orders of magnitudes at distances reachable by the RMS. Moreover, apparent temperature enhancements of $\gtrsim$ factors of 5 are observed in the wake transition region. This transition region is also characterized by plasma "turbulence" with $\Delta N/N$ values of typically several per cent. Secondary effects controlling the electron density spacial variation involve: 1.) the possible enhancement of electron density in ram (compared to ambient), Shawhan (1984c), Raitt (1984); 2.) the effect of the neutral cloud around the vehicle and the photoionization of that cloud, Pickett (1985); 3.) the role of the magnetic field both in the filling in of the wake and the production of $V \times B$ potentials in the orbiter reference frame.

3.3 Electromagnetic environment

The AC and DC electric and magnetic fields on and near the orbiter are driven by two sources: 1.) orbiter EMI associated with the hardware per se; 2.) fields associated with the interaction between the orbiter and its environment.

The orbiter EMI under JSC's leadership and Rockwell's cooperation proved to be much more benign than the original ICD specifications would indicate. Shawhan (1984b) and Murphy (1984b) reported in detail the measurement of that environment. By using the PDP's sensitive plasma wave receivers and various RMS maneuvering sequences a "map" of orbiter EMI revealed that the environment was dominated not by orbiter generated noise but by plasma interaction noise. This Broadband Orbiter Generated Electrostatic (BOGES) noise (Shawhan, 1984b) seemed to be associated with plasma turbulence around the orbiter and had field strengths as great as .1 v/m with a relatively flat spectrum up to ~ 10 khz. Although the exact mechanism was not understood, Murphy et al. (1984a), suspecting that it was similar to the turbulence observed by the Langmuir probe, indicated that it was noise of relatively short wavelength ($\lesssim$ 1 m). This noise was observed to be enhanced by any sort of gas release (thruster, water dump, etc.) implicating the gas cloud as a production mechanism. Theoretical work by Papadopolous (1984) suggested that the gas

cloud may provide the "fuel" for enhanced plasma densities by the critical ionization velocity phenomenon and may be intimately involved in the production of this BOGES noise.

Thus we see that the understanding and characterization of the orbiter environment requires detailed investigation of the inter-reactions between the orbiter body, its contaminant cloud, and the ionospheric plasma.

For purposes of completeness it should also be emphasized that a large part of both the OSS-1 and Spacelab-2 missions were devoted to detailed study of the behavior and interactions of an electron beam propagating in the ionosphere. These studies were conducted jointly with the Vehicle Charging and Potential (VCAP) experiment (Banks, 1986). The OSS-1 results are reviewed by Banks (1986) and Shawhan (1984a). Since another paper in this proceedings describes the VCAP/PDP results in detail no further discussion will be given here.

4.0 Spacelab 2, laboratory results, and the emerging picture

Many of the results discussed above began to be published after the Spacelab-2 mission which was launched in July 1985 but early results had a significant influence on the science objectives and experiment planning of Spacelab-2. The landmark nature of the plasma experiments of Spacelab-2 will gradually emerge over the next several years and, in particular, the importance of the PDP free-flight activity, described briefly below, in understanding large vehicle interactions, will become quite obvious. This is especially true in light of the hiatus of Spacelab type missions in the coming years.

After performing about 12 hours worth of experiments on the RMS which consisted of wake studies, EMI surveys, and joint experiments with VCAP, the PDP was prepped for release as a sub-satellite of the orbiter. The PDP free-flight scenario consisted of approximately 6 hours of complex maneuvers by the shuttle orbiter which controlled, in a carefully planned sequence, the relative positions of the PDP and orbiter.

First, a release and back-away maneuver moved the PDP down the "throat" of the orbiter wake to a distance of ~ 100 meters. After several station-keeping experiments the orbiter began a "fly-around" of the PDP. Part of the fly-around was executed in plane so the PDP would transit the orbiter wake at distances from 40 to 200 meters. The other part of the fly-around was out of plane moving the orbiter above and behind the PDP and targeting two flux-tube-connections (FTC's) per orbit. These FTC's were planned so that they occurred out of the orbiter's wake with one in the daytime ionosphere and one at night. The FTC's were quite successful in placing the PDP and the orbiter on the same magnetic field line at a relative distance of ~ 200 meters. These FTC's were believed to be accurate to within several meters at best to a little more than 10 meters at worst. After two "fly-arounds" and several wake transits were completed the orbiter approached and captured the PDP along the velocity vector, again allowing the PDP to examine the near wake. Dealing with topics as a continuation and refinement of the OSS-1 results we first discuss the neutral environment.

4.1 Neutral environment and the contaminant gas cloud

Further measurements by the PDP neutral pressure gauge taken during pallet operations verified the high pressure environment due to early on-orbit outgassing. Analysis of vernier thruster operations verified that only the aft down pointing verniers affected pressure in the bay (Pickett, 1986). No further observations of primaries are possible because of an instrument malfunction. A strong point to be made from Pickett's observations are that large instruments which vent gases can also have dramatic effects of the payload bay environment, raising pressure to as high as 10^{-5} Torr. The orbiter's outgassing is now known to have a major effect on the local environment.

The contaminant ion gas cloud observations were extended to ~ .5 km from the orbiter. Grebowsky, 1986 observed contaminant H_2O^+ ions in all directions around the orbiter. The presence of contaminant NO and O_2^+ ions was also reported. It is important to note that the dominant ion in the wake of the shuttle appeared to be H_2O^+ instead of ambient O^+.

If these ions are created by change exchange with O^+ analysis of their distribution function would indicate a ring in velocity space. Reports by Paterson, 1985 provide evidence that this is indeed the case and an attempt to model the outgassing and chemical reactions associated with it is currently under way. Observations of the Infrared telescope on Spacelab-2 may provide additional data on outgassing rates and the structure of the water cloud which appears to surround the vehicle.

4.2 Further studies of the orbiter wake

Investigation of the structure and dynamics of the orbiter wake both on the RMS and as a free flyer are being continued. More detailed examination of the wake turbulence indicate that the magnetic field orientation may affect the structure of the turbulent zone (Tribble, 1986). Comparisons of the electron density observed in the wake are being made with predictions of the NASA POLAR code (Katz et al., 1984) and early results indicate the code may be quite accurate at predicting at least the first order effects on electron density. The details associated with magnetic field effects, the role of the plasma turbulence and pick up ions, and processes which produce the heated electrons (Murphy, 1986) still must be investigated. Although a detailed review of wake investigations conducted both in the laboratory and in space is presented elsewhere in the proceedings it is relevant to discuss briefly some laboratory results which complement the Spacelab studies.

4.3 Complementary laboratory investigations

In addition to observing the wake region behind large objects as they pass through the near earth plasma, it is found profitable to perform laboratory experiments in order to gain some insight into the plasma-wake environment. Although the parameters may not scale directly to the plasma that has been examined above, such experiments suggest new avenues for the spacelab investigations of the future. Herein, we shall review a few recent experiments performed in laboratory plasma environments whose volume is of the order one cubic meter, possessing plasma numbers of $n_e = n_i \approx 10^6 - 10^8$ electrons/cm^3; $T_e \approx$ 1-3 eV and $T_i < T_e/10$.

Alikhanov et al. (1971) studied the flow into the wake region created by a flowing plasma passing a rectangular plate that was at floating potential. In an extended study, Eselevich and Fainshtein (1980) noted that the expansion of the plasma from the undisturbed region into the wake could be modeled with a self similar description. This can be understood from the governing fluid equations of continuity

$$v_b \delta n/\delta z + \delta(nv)/\delta x = 0$$

and motion

$$v_b \delta/\delta z + v\delta v/\delta x = -c_s^2 \delta(\ln n)/\delta x$$

where the quasineutral plasma has been assumed to be moving as a beam in the z direction with a velocity of v_b. The ion acoustic velocity is c_s. These equations are identical to the problem of a neutral gas or a quasineutral plasma expanding into a vacuum and solutions in terms of the self similar variable $\zeta = x/(z/v_b)$ can be obtained. The POLAR model discussed previously uses such a quasineutral approximation. Similar results concerning the self similar expansion into the wake region behind a grounded metal plate were reported by Wright et al. (1985). In the very near wake region where quasineutrality would be violated, it was found that the potential would be the important self similar dependent variable by Diebold et al. (1986). In this case, the dependent self similar variable becomes $\zeta = x/(z/v_b)^2$ as shown by Lonngren and Hershkowitz (1979).

As the wake region has a lower density than the ambient flowing plasma, one might conjecture that the electrons due to their higher mobility would rapidly enter the wake, creating an electric field which would accelerate the ions to velocities greater than the ion acoustic velocity. The accelerated ions have been noted in the experiments of Wright et al. (1985), (1986) and Raychaudhuri et al. (1986). The potential well that would result from such a space charge was observed in the orbiter wake by Murphy et al. (1986). That the electrons can speed ahead of the ions was recently detected by Chan et al. (1986). Ions could also enter the wake region by being deflected around the perturbing objects as was recently noted by D'Angelo and Merlino (1986a), (1986b) in an experiment performed in a plasma in a weak magnetic field oriented in the direction of the plasma flow. These experiments show results reminiscent of those by Stone 1986 where streams of converging ions were observed behind the orbiter. Finally, a series of experiments designed to examine the flow of plasma around magnetized objects has been described by Hill et al. (1986). These would be related to the TERRELLA type of experiments except that the present experiments were performed in a very low β plasma environment ($\beta \approx 10^{-4}$). A general characteristic of the observations in this experiment was that the magnetic object "appeared" to be larger for the electrons than the ions since the electron wake had dimensions that were larger than the ion wake.

Hence, we see that the laboratory experiment provides a controllable environment in which to suggest future paths for space experiments or to explain certain space observations. Future work needs to better define the role of the magnetic field and the charge on the object in question. It should be noted however that it is difficult to simulate in the laboratory conditions similar to the orbiter where the magnetic field can be perpendicular to the flow vector and where gas cloud interactions modify the

observations.

4.4 Electromagnetic environment and active experiments

Further definition of the electromagnetic environment has shown that the BOGES noise extends as far from the orbiter as the PDP observed, and was strongest along field lines connecting to the orbiter and in the turbulent wake zone (Gurnett, 1986a). Gurnett has also verified that the noise is electrostatic in nature and has very short wavelength. Considerable theoretical efforts are currently under way to determine the fundamental process creating such noise.

Of further interest may be a series of joint experiments with VCAP where, during two flux tube connection experiments, dramatic comparisons to the physics of whistler mode radiation in auroral arcs has been discovered (Gurnett, 1986b).

Further active experiments conducted by using the orbiter OMS engines to produce a cloud of water vapor and deplete the ionosphere (Mendillo, 1981; Mendillo et al., 1978) showed significant plasma depletion, as measured in the orbiter payload bay, recovering on the timescale of seconds after engine shutdown (Tribble et al. 1985). Tribble also reported a high level of plasma "turbulence" which lasted tens of seconds indicating the presence of instabilities. This phenomenon may be similar to that observed by RCS ignition and reported by Murphy et al., 1984a, and Shawhan et al., 1984b.

5.0 Summary

It is important, with such a wide range of data, to put together an emerging picture of the Shuttle orbiter interactions and then systematically address the experiments which need to be conducted in order to further the science/technology of large body interactions.

Although laboratory and small satellite observations can shed light on details of wake structures, and the electric fields associated with them, large bodies such as the orbiter pose some unique problems. Is the orbiter a comet? In many respects, there are similarities. It definitely carries its own gas cloud and understanding how large objects such as the orbiter, platforms, or space station interact with the plasma depends on more than a scaling of laboratory experiments.

Part of the interactions around large objects are due to the "scale size" effect while others are distinctly interrelated to outgassed products and the change in the balance of the ambient chemical equilibrium. As described by Grebowsky et al., 1986, the instrumentation required to completely disgrace the ionospheric chemistry and simultaneously determine all key plasma parameters requires careful consideration of the specific problems the spacecraft must study. The PDP is only a first generation experiment with instrumentation that was not optimized for studies such as "comet" problems.

Future experiments must be designed both for space and in complementary laboratory setting which can, if not solve the following problems, at least determine by appropriate empirical means their impact on future technologies. These problems include:

1. What is the effect of gas clouds associated with large objects on their interaction with the neutral atmosphere and plasma?

   a. How does the cloud affect the wake fill process?

   b. Is the orbiter cloud large enough to create a pick-up current of such magnitude that it partially screens the motional electric field? (Pickett, et al., 1985; Goertz, 1980; Katz et al., 1984).

   c. For large objects such as space station, could the energy dissipation associated with such a cloud create significant anomalous drag?

   d. How does the cloud affect the charge neutralization process and current loops associated with tethers, or particle beams?

   e. What is the effect of such a cloud on the operation of a plasma contactor?

2. The interactions of large structures with the ionosphere through electromotive forces associated with differential charging, absolute charging, and closed current loops are not well understood.

3. The phenomena of vehicle glow, its relationship with the plasma, the neutral cloud and the interacting surface have given rise to conflicting theories with insufficient data to resolve the issue. (Green, 1985)

4. Understanding of the total picture associated with large body wakes involves more than models of electron and ion density. Wave particle interactions, atmospheric chemistry, vehicle charge, and magnetic fields must be included in the analysis.

5. Joint particle beam experiments such as those between PDP and VCAP have raised many questions about the propagation of beams from structures like the orbiter. This is an immature experiment because until SL-2 no experiments (other than short sounding rocket flights) have provided remote diagnostics on such beams. (See the paper by Banks et al. in this proceedings for more detail.)

6.0 Recommendations

The Challenger accident has dealt a severe setback to the space experiments associated with large body/plasma interactions. It is unfortunate that the space station is set to proceed on course with little opportunity in the next 6 years for detailed study of the technical issues that should be resolved before it proceeds.

Studying such problems requires a commitment by NASA to a program which must involve the development of instrumentation adequate to measure the appropriate parameters, flights of opportunity within the next five to six years for such instruments, support of working groups consisting of experimentalists who may have relevant data from past missions and theorists attempting to model the phenomena and, last of all, well designed and executed laboratory experiments.

Last of all it is of paramount importance that those scientists and engineers involved with the state of the art of large body interactions, gas cloud dynamics, high voltage effects, etc. have effective knowledge transfer to those individuals and organizations making the design decisions of the future.

Acknowledgements

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LABORATORY PLASMA INTERACTIONS EXPERIMENTS - RESULTS AND IMPLICATIONS TO FUTURE SPACE SYSTEMS

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I. INTRODUCTION

Space system plasma interactions have long been recognized as limiting factors in the reliability of space systems. Plasma interactions (PI) not only produce effects that may adversely affect the operation of space systems, (e.g., the occurrence of electrostatic discharges), but may also induce significant modifications in the ambient environment. The PI enhanced environment may in turn modify the interaction processes, compounding the adverse effects.

The reliable prediction of the space system PI processes would require the use of an extremely large and complex computer code. Fortunately, an alternate approach, which combines test/analytical techniques, has proven to be a viable process. In this approach, the important interaction mechanisms are identified by laboratory simulation tests, and the experimental data are then used to analytically predict the effect of PI on space systems. This approach was used on the Galileo electrostatic discharge (ESD) program[1]. Laboratory simulation tests have distinct advantages over that of in situ flight tests. They:

(1) are relatively inexpensive,
(2) offer virtually unlimited operation time, and
(3) provide diagnostic instruments that are generally more complete.

Therefore, laboratory simulation experiments provide more quantitative and detailed data on the PI phenomenon. Inevitably, laboratory simulation results need to be validated by flight experiments. The design of flight experiments will be more precise if a comprehensive data base of laboratory test results is readily available. Therefore, in the PI arena, the role of laboratory simulation testing is crucial.

This paper presents results from several selected laboratory PI experiments. The important physical processes identified by these

results and the implications to future space systems are discussed. These experiments are:

(1) ESD - high voltage solar array interaction
(2) ESD - dielectric charging
(3) Spacecraft charging and multibody interaction
(4) Electron beam injection

II. RESULTS FROM SELECTED PLASMA INTERACTION EXPERIMENTS

A. ESD Generated by High-Voltage Solar Array Plasma Interactions

The deployment of high-voltage solar arrays is necessary to satisfy the power requirements of spacecraft of the next century[2]. However, there is a concern that ESD events caused by the interaction of exposed high-voltage surfaces with the plasma environment may interfere with future missions. At the Jet Propulsion Laboratory, experiments were performed to investigate the environmental conditions under which solar arrays will discharge and to characterize the electromagnetic interference (EMI) generated by typical ESD events. Figure 1 shows the experimental setup for this investigation.

Two types of solar cells were used to fabricate the solar arrays used for this investigation, 2 cm by 2 cm "PIX" cells and 5.9 cm by 5.9 cm "VOLT" solar cells.[3] For the same surface area, the PIX array had a much larger area of exposed conductors than the VOLT array. Since discharges usually take place at the exposed conductors, the difference in the exposed surface area accounts for the main difference in the observed discharge phenomenon.

In this series of experiments, the high voltage array was simulated by applying a high negative voltage bias to the metallic interconnects of the arrays. Figure 2 shows the dependence of the discharge rate on the plasma density. This set of data was obtained when the biased high voltage was at a potential of -626 V with respect to the facility ground. At a low plasma density ($<10^4/cm^3$), a discharge may not occur, whereas at a high plasma density ($>10^6/cm^3$), the discharge rate may be as high as 10/sec. Therefore, the operation of high-voltage solar arrays will be less susceptible to discharge at high altitudes (where the density is lower).

As expected, the radio frequency (rf) radiation generated during a discharge event scales with the applied voltage.[3] Figure 3 shows the rf spectrum caused by the discharge of a PIX array when biased at a potential of 1000 V. The same diagram also shows the existing allowable wideband emission specifications on the shuttle.[4]

The rf radiation generated by the discharge of a simulated high voltage array was higher than the allowable specifications. The

operation of the shuttle or future space systems may not be affected by this level of rf radiation, but the science measurements and the detection of electromagnetic waves in particular would definitely experience the interference caused by the inadvertent ESD events. Discussions have been held that indicate space station science experiments would require EMI specifications more stringent than those for the shuttle[5]. In view of the data displayed in Figures 2 and 3, it is obvious that high-voltage array ESD needs to be controlled. The recommended methods are:

(1) Operate the high voltage array at a low potential (below the threshold potential) so that ESD cannnot occur.

(2) Cover exposed conductors with an insulator.

B. ESD Generated by Dielectric Material Charging

Many experiments have been performed at various institutions on dielectric charging and discharging.[6,7,8] These experiments have usually focused on:

(1) Enhanced environments,
(2) EMI generation.

Measurements[6] have indicated that during an ESD event, the ambient environment was significantly modified (Figure 4), with resulting increases in:

(1) local plasma density,
(2) EMI level,
(3) optical emission, and
(4) neutral gas pressure.

In a typical discharge, the plasma generated at the discharge region may have a density as high as $10^{11}/cm^3$. Since the typical plasma density in the ionosphere is $10^6/cm^3$ or less, even after taking into account diffusion of the discharge generated plasma, the ambient density 1 meter away from the discharge region may be an order of magnitude higher than the ambient plasma. The discharge rate and the threshold voltage of a high-voltage solar array depend strongly on the ambient plasma density. If an ESD event occurs in the vicinity of a high-voltage solar array, it may cause unexpected arcing of the high-voltage array. Discussions were held that noted an accurate prediction of the natural space environment was needed to enhance the reliability of future space systems.[9] This paper shows that a precise estimate of the ESD-enhanced plasma environment is an absolute necessity to insure the survivability of future space systems.

Results of charging/discharging experiments of common dielectric materials have indicated that the magnitude of ESD-generated EMI will increase with the area of the test sample. That is, the EMI effect could be very severe for large space systems. During a discharge, charges stored on the surface of the dielectric material were

released. The collapse of the corresponding image charge induces a current in the structure of the spacecraft. This current became the source of the conducted emission. Figure 5 shows the experimental data on the scaling of this discharge current as a function of the surface area.[6] In this figure, the test level generated by a MIL-STD 1541 sparker[10] (the existing ESD susceptibility test standard for space systems) is indicated by the shaded area. The data show that an improved test technique/fixture is needed for testing large space structures.

C. Charging and Multibody Interaction

For an equipotential spacecraft, charging by itself will not cause the occurrence of ESD events. Only when a potential difference exists between different parts of the spacecraft can ESD occur, as in the case of dielectric charging, or when a potential difference exists between two different spacecraft. In this section, the latter case will be considered. The occurrence of ESD due to the contact of two or more spacecraft at different potentials is also known as multibody interaction. This phenomenon may occur when a free flyer, such as an astronaut and his/her extravehicular activity (EVA) equipment, is subjected to charging by auroral electrons in the wake of a large spacecraft (Figure 6a). Under this condition, the potential of the large spacecraft will be at or near the space potential, whereas the potential of the free flyer will be at a high negative potential with respect to space. When the free flyer comes into contact with the large spacecraft, ESD may occur if the potential difference is sufficiently large. An experiment was performed to investigate this phenomenon. Figure 6 shows the experimental setup. In this experiment, a piece of spacesuit material was irradiated by an electron beam of energy of 15 keV. The resulting surface potential was observed to be 10 kV. When a grounded probe approached this surface, an ESD event occurred before any physical contact was made.[11] Figure 7 shows the transient current pulse detected with a 50 ohm load resistor. The peak voltage was observed to be 50 V. If this signal appeared on the input of a sensitive circuit, significant damage to the IC could occur.

In this experiment the spacesuit material and the probe simulated the free flyer and the large space structure, respectively. The electron beam provided the current source for the charging of the capacitor formed by the free flyer and the large spacecraft. This current helped maintain the potential of the free flyer during its approach to the large spacecraft. Similar conditions may occur if the EVA equipment is accidentally irradiated by particle beams.

In the next century, frequent EVA is expeceted for the servicing space system. The control of the adverse effects generated by multibody interaction is a must to insure the survivability of these space systems. Several techniques may be employed, two of which are:

(1) Impose restrictions onthe docking of freeflyers during the occurrence of an aurora and during beam injection experiments.

(2) Use a plasma neutralizer to reduce the differential charging before docking a free flyer.

D. Injection of Electron Beams into the Ionosphere

Beam injection in space is expected to be more common in the next decade.[12] Several applications will require beam injection. They include active beam injection experiments, communications, and charge neutralization. Although electron beam injection experiments have taken place during the last twenty years, the basic mechanisms of beam plasma/space vehicle interaction are not well understood. Laboratory experiments have been performed to simulate beam injection into the ionosphere. In these experiments, an electron beam was injected into a vacuum region which has a finite neutral pressure, usually in the range of 10^{-5} torr.[13,14] The flow of the beam current depended critically on the ionization of the residual neutral gas pressure. The results of a beam injection experiment performed in a double plasma device indicated that the space charge of the electron current initially created a negative virtual cathode potential well which limited the flow of electrons.[14] This self-consistent potential profile also decelerated the injected electrons, and the resulting electron distribution resembled a half Maxwellian distribution. As the beam current was increased, a double layer (DL) structure was formed (Figures 8 and 9). The formation of this double layer allowed the injected electrons to reappear as beam electrons in the high potential regions. These beam electrons ionized the neutral gas producing a low energy background plasma. The resulting electron distribution was a bump-on-tail distribution function. As the injected beam current density was further increased, the amount of ionization increased to such an extent that the negative virtual cathode type potential well collapsed, and the flow of injected electrons was no longer inhibited by space charge effects. This caused a further increase in the ionization rate, resulting in the ignition of the beam plasma discharge (BPD) phenomenon.

The effects described above were similar to the injection of an electron beam from a spacecraft (Figure 8). In the flight experiment of Winckler et al.[15], at a low current density, the potential of the spacecraft was raised to a high positive potential. This was due to the fact that there was insufficient ambient plasma to provide for the return current. Consequently, the spacecraft potential was raised to a higher voltage to provide a larger collection area for the return current. The Winckler experiment indicated that at a high beam current density, the ambient plasma density increased by more than an order of magnitude. This was attributed to the ignition of BPD. Since the ambient density was high, there was sufficient return current and the spacecraft potential was observed to be approximately near the space potential. Another phenomenon of beam injection in space was the large amplitude fluctuations in the plasma density in the vicinity of the spacecraft. This phenomenon resembles that of the

moving double layer (sheath) phenomenon observed in the laboratory.[16]

In a beam injection experiment, electrostatic and electromagnetic turbulence are generated by beam plasma interactions.[14] Depending on the plasma and beam parameters, turbulence at electron plasma, ion acoustics, ion cyclotron, and whistler modes may be generated. The power levels of these beam-generated turbulences depend on the power of the electron beam. Multimegawatt beam injection experiments have been proposed for spacecraft of the next decade. The electromagnetic compatibility (EMC) aspects of these beam injection systems need to be considered in detail for future space systems.

III. SUMMARY

The experimental results discussed in this paper show the significance of the effects caused by spacecraft plasma interactions, in particular the generation of EMI. As the experimental results show, the magnitude of the adverse effects induced by PI will be more significant for spacecraft of the next century. Therefore, research is needed to control possible adverse effects. Several techniques to control the selected PI effects were discussed. Tests, in the form of flight experiments, are needed to validate these proposed ideas.

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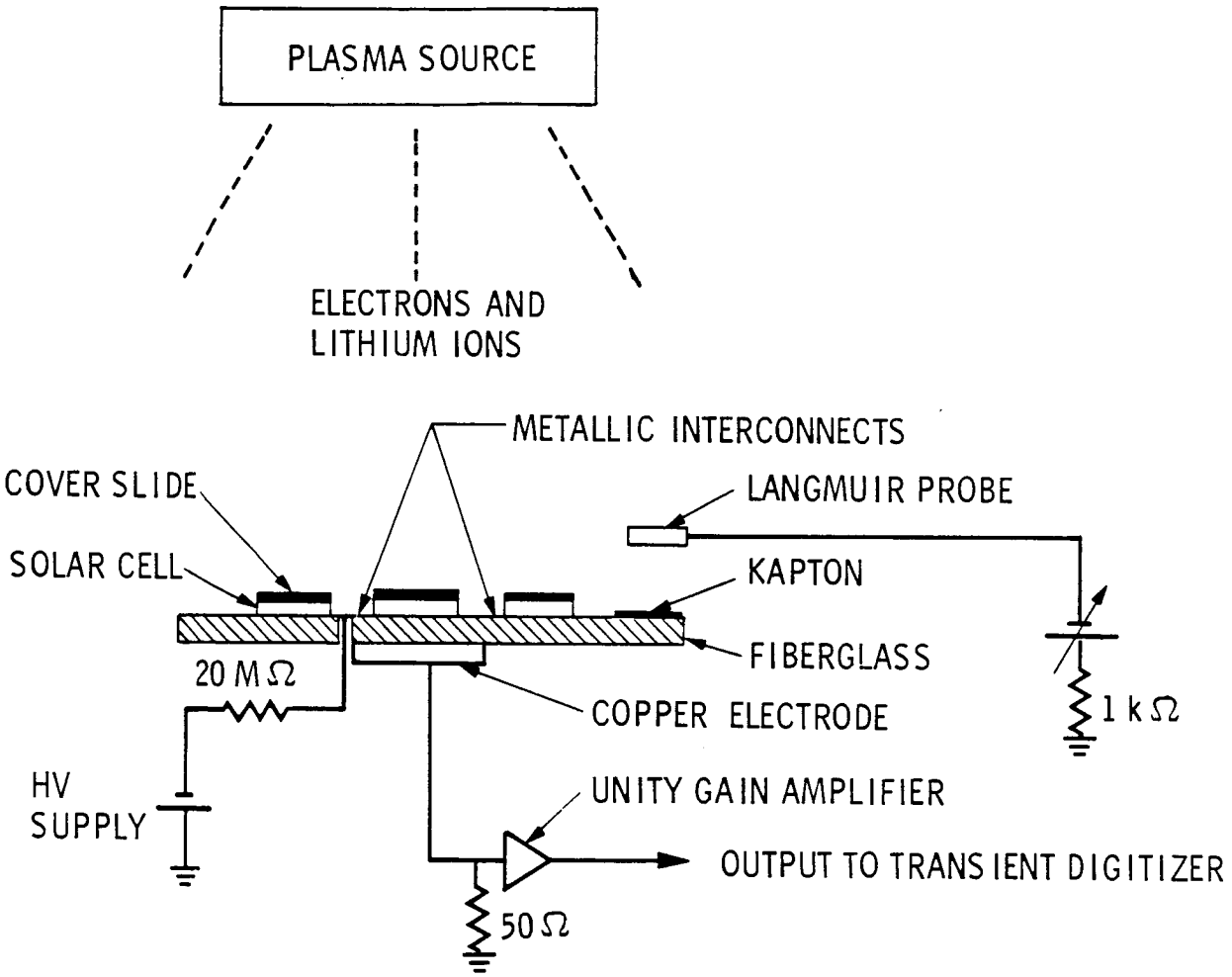

Figure 1. Schematic of the experimental setup for the investigation of high-voltage solar array plasma interaction.

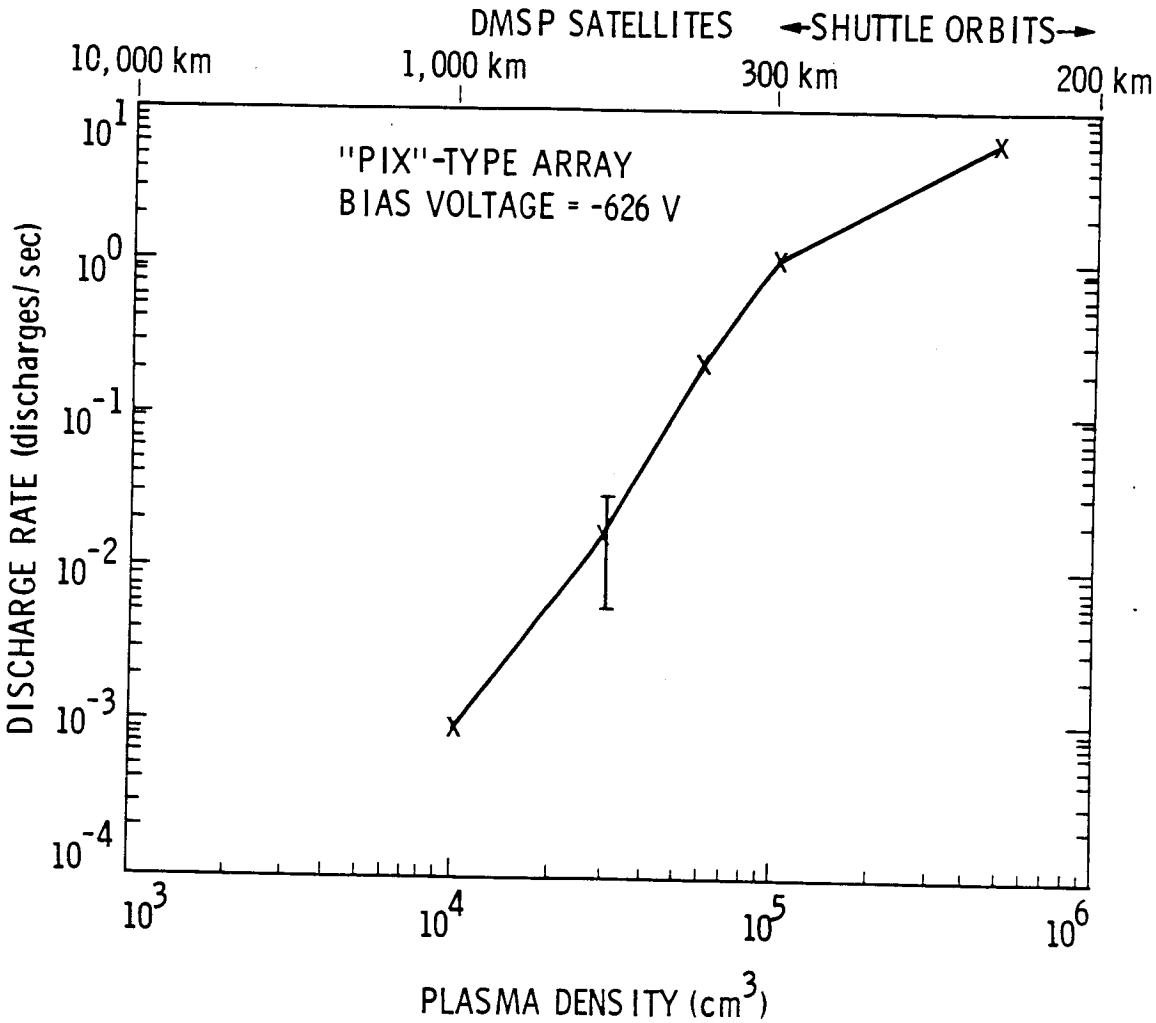

Figure 2. The observed discharge rate as a function of ambient plasma density.

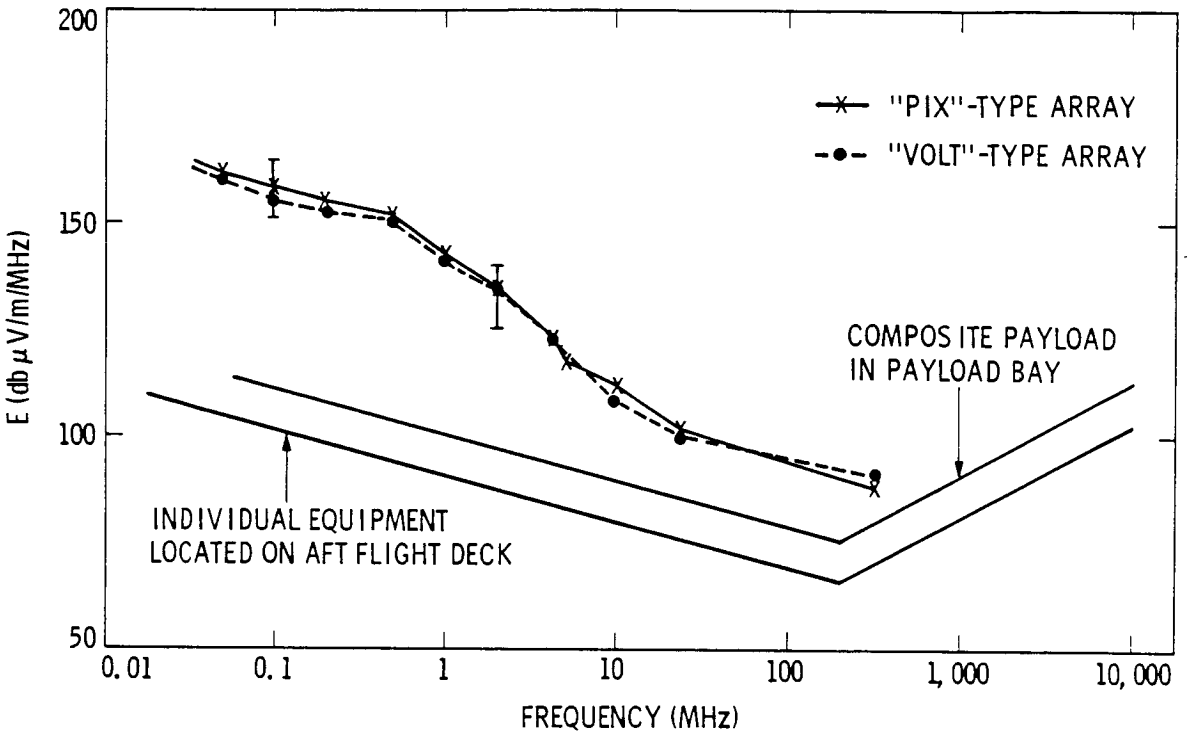

Figure 3. Rf Spectra generated by the discharge of solar arrays, the arrays were biased at 1000 volts.

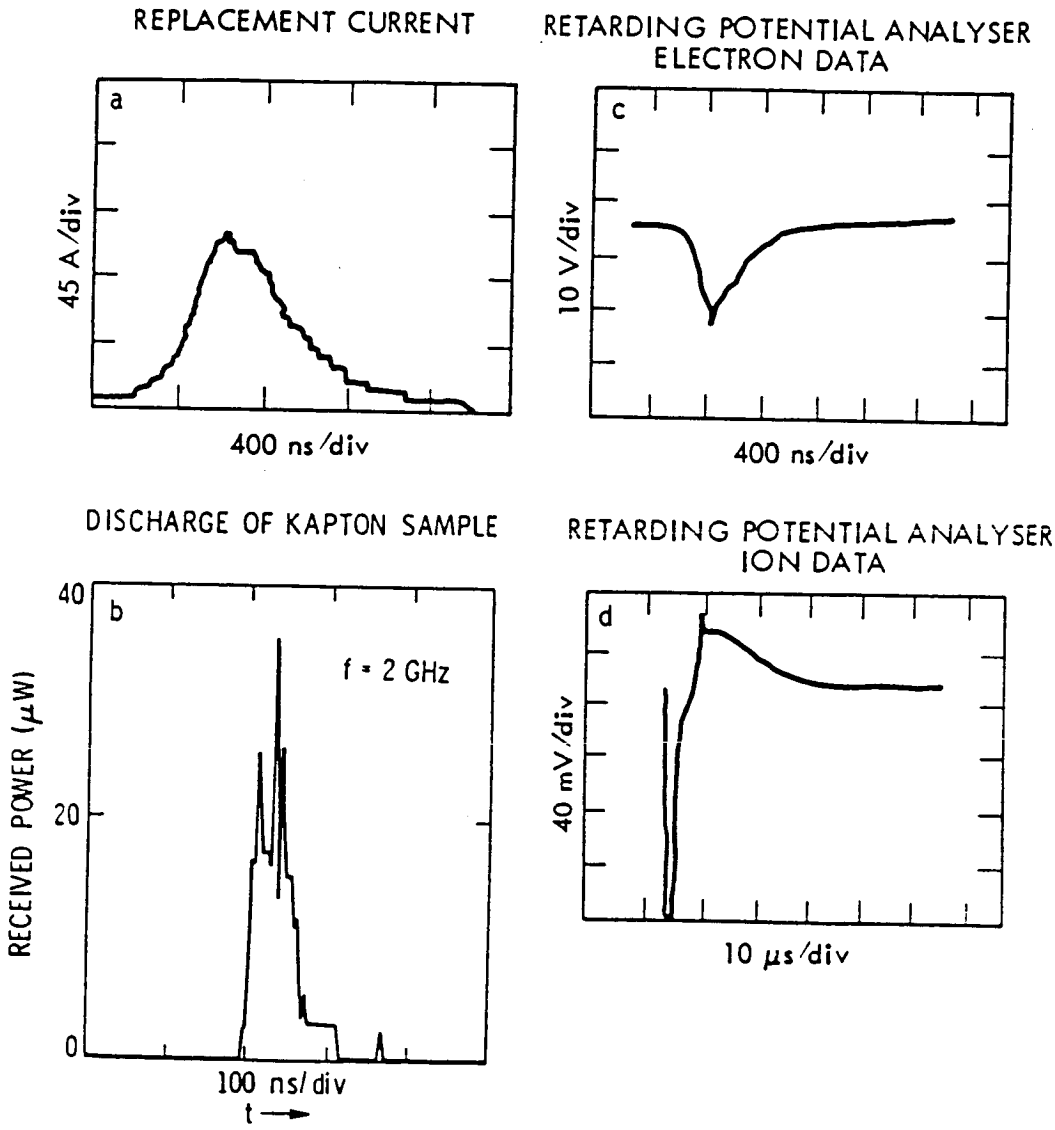

Figure 4. The enhanced environment created by a dielectric discharge. (a) discharge current, (b) rf radiation, (c) electrons, (d) ions

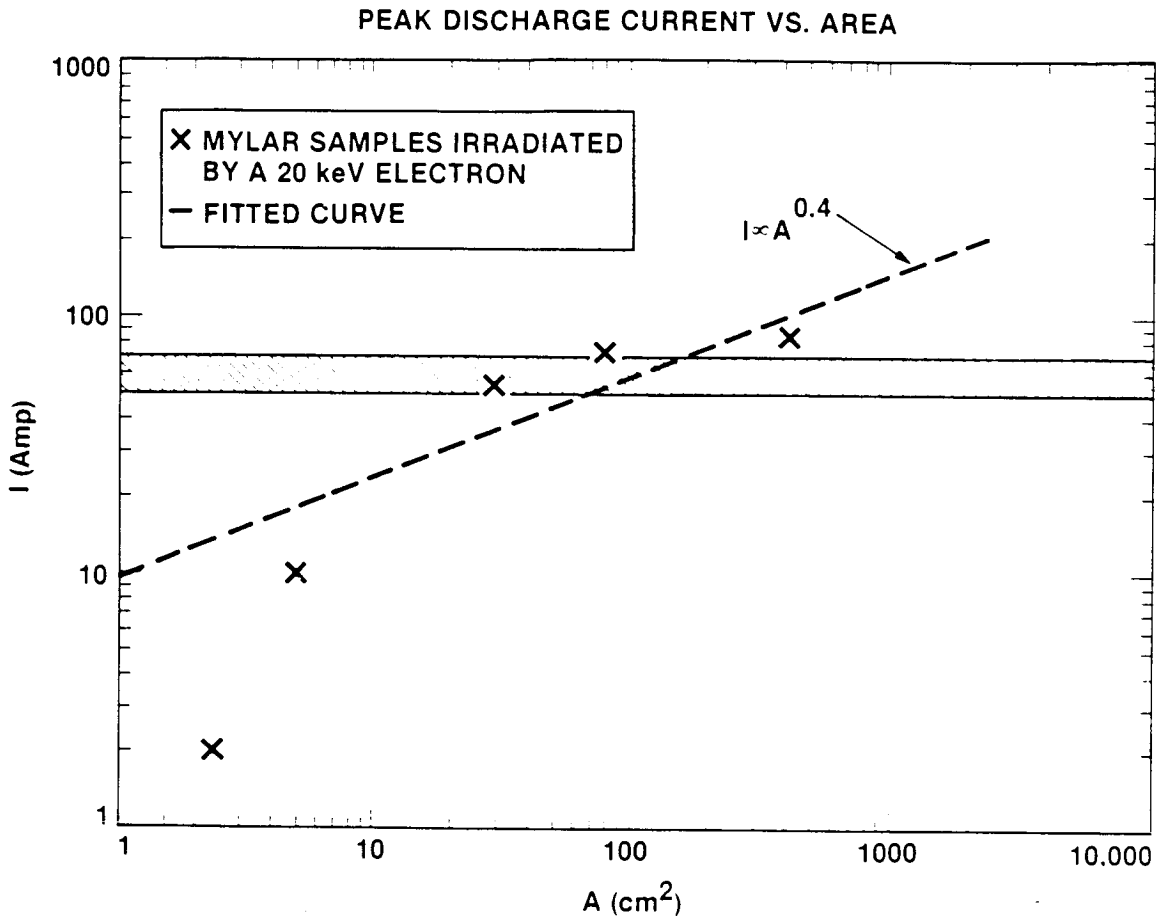

Figure 5. The observed peak discharge current as a function of the area of the Mylar samples

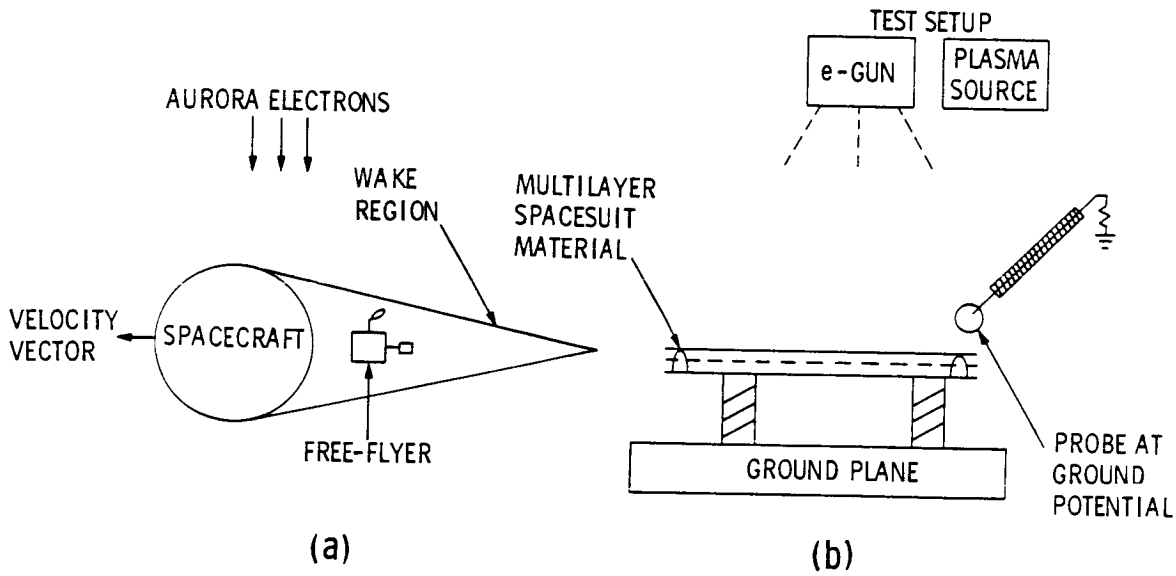

Figure 6(a) Charging of a free-flyer in the wake region of a large space structure
(b) Experimental setup for the investigation of multibody interactions

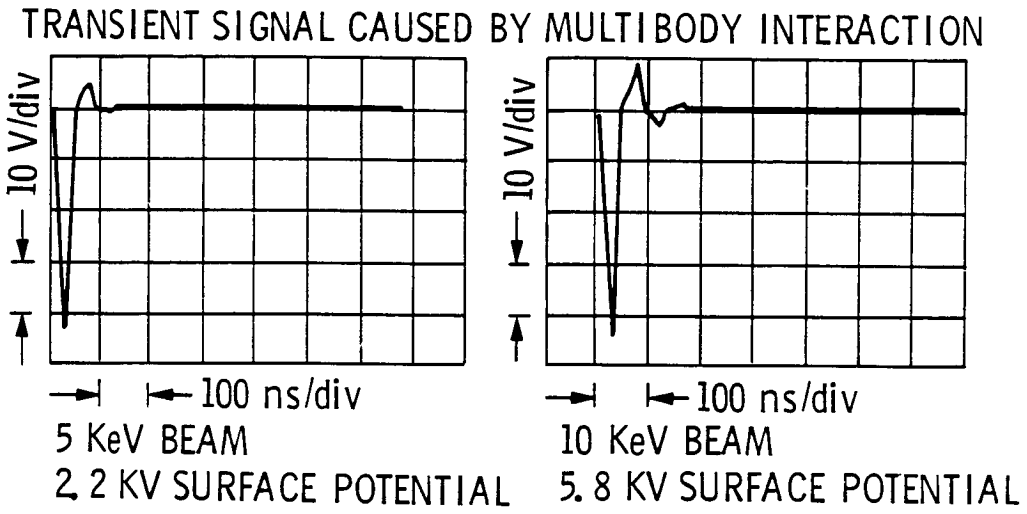

Figure 7. Transient signals generated by ESD events as a result of multibody interaction.

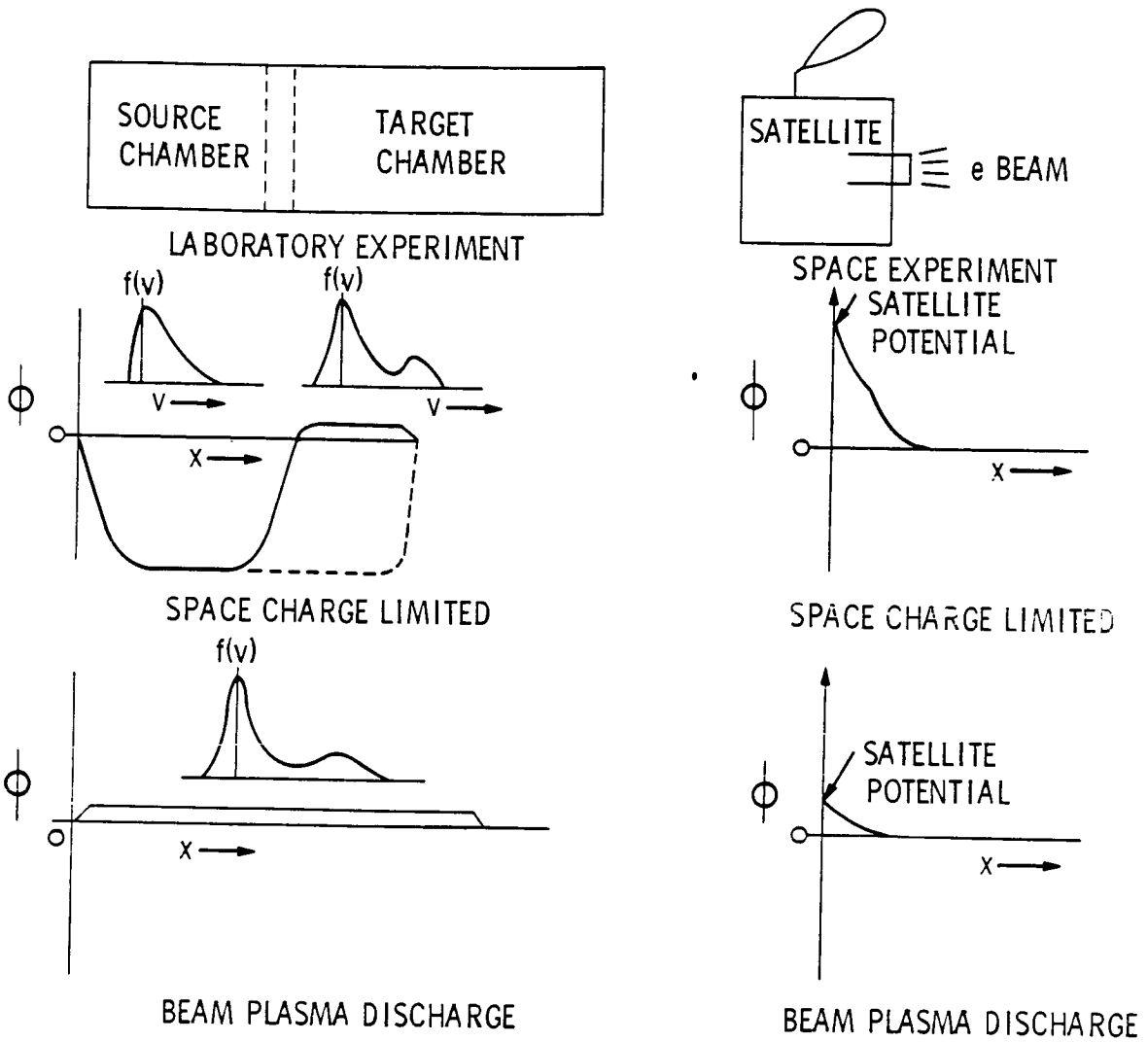

Figure 8. Comparison of Laboratory beam injection experiment with space-based beam injection experiments; the potential profile for each case is plotted. f(v) represents the distribution function of electrons.

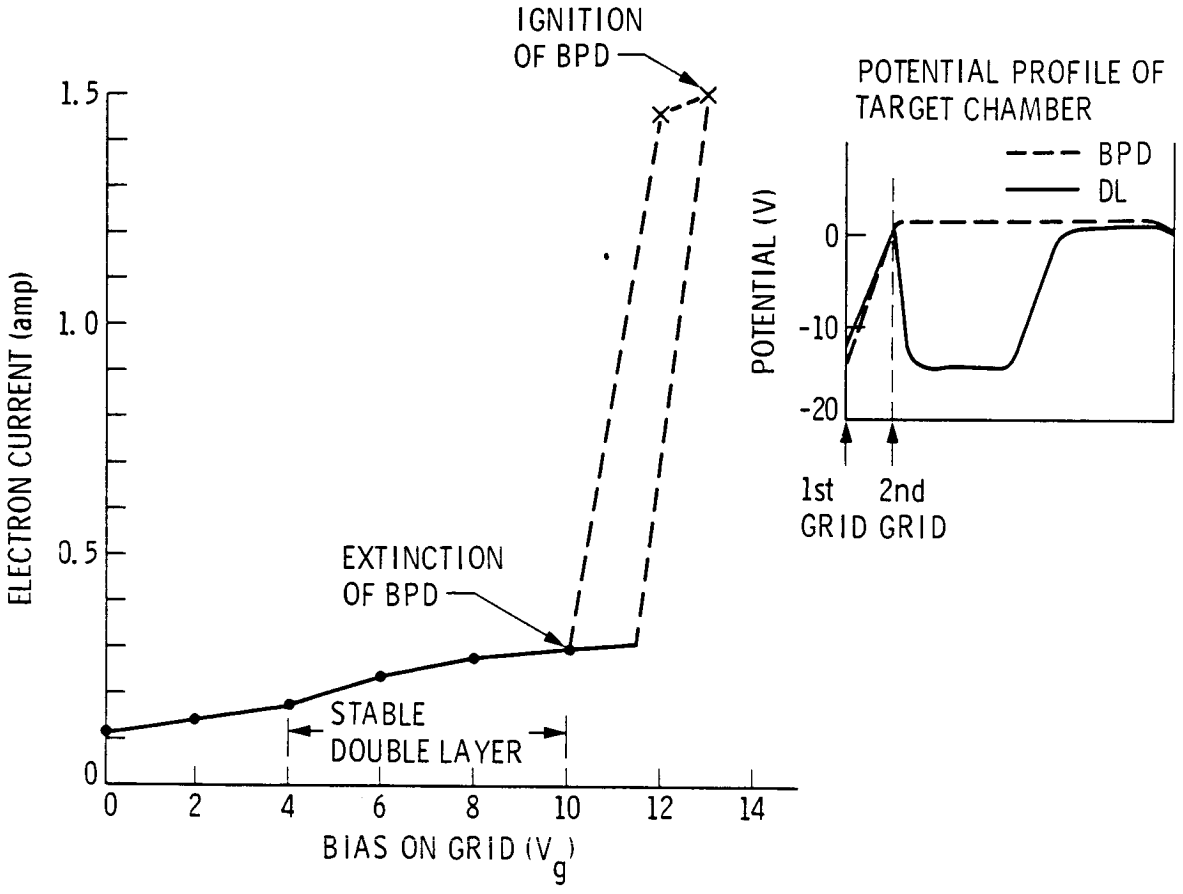

Figure 9. Different regimes of a beam injection experiment.

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Plasma Issues Associated with the Use of Electrodynamic Tethers

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Abstract

The use of an electrodynamic tether to generate power or thrust on the Space Station raises important plasma issues associated with the current flow. In addition to the issue of current closure through the Space Station, high power tethers ($\geq$ tens of kilowatts) require the use of plasma contactors to enhance the current flow. They will generate large amounts of electrostatic turbulence in the vicinity of the Space Station. This is because the contactors work best when a large amount of current driven turbulence is excited. Current work is reviewed and future directions suggested.

1 Introduction

Electrodynamic tethers have been studied as a means of providing electrical power and thrust for the Space Station. Typically such tethers would be 20-100 km in length and have power levels of 25 kw to 100 kw. The use of an electrodynamic tether offers the significant advantage of a device which is reversible in that it can produce both power (kinetic energy of the Station $\longrightarrow$ electrical energy) and thrust (electrical energy $\longrightarrow$ kinetic energy of the Station). Furthermore in the power generation mode, the tether - drag compensation system produces electrical energy more efficiently than direct conversion of the chemical energy in the rocket fuel used for drag make-up. However since the electrodynamic tether by its very nature works by its interaction with the plasma environment, the space technology plasma issues associated with its use are of critical importance.

In this paper some of the plasma issues currently under investigation are reviewed and several important plasma issues for the future are identified . The outline of the paper is as follows: in section II, work on current induced radiation from the Station is reviewed, in section III, a simple theory of plasma contactors is presented, in section IV, the role of turbulence induced transport is outlined and in section V, the implications for the future of this work are discussed.

2 Current induced radiation from the Space Station

The combination of an electrodynamic tether with the Space Station may look like the configuration in Fig. 1. Whatever the final configuration is like, one of the effects of the tether will be to draw a current through parts of the Station Structure. Of course, since the Station is itself a large conducting object in low earth orbit, it will see a motionally induced potential along its structure and a current flow even without an electrodynamic tether. The current through the system will

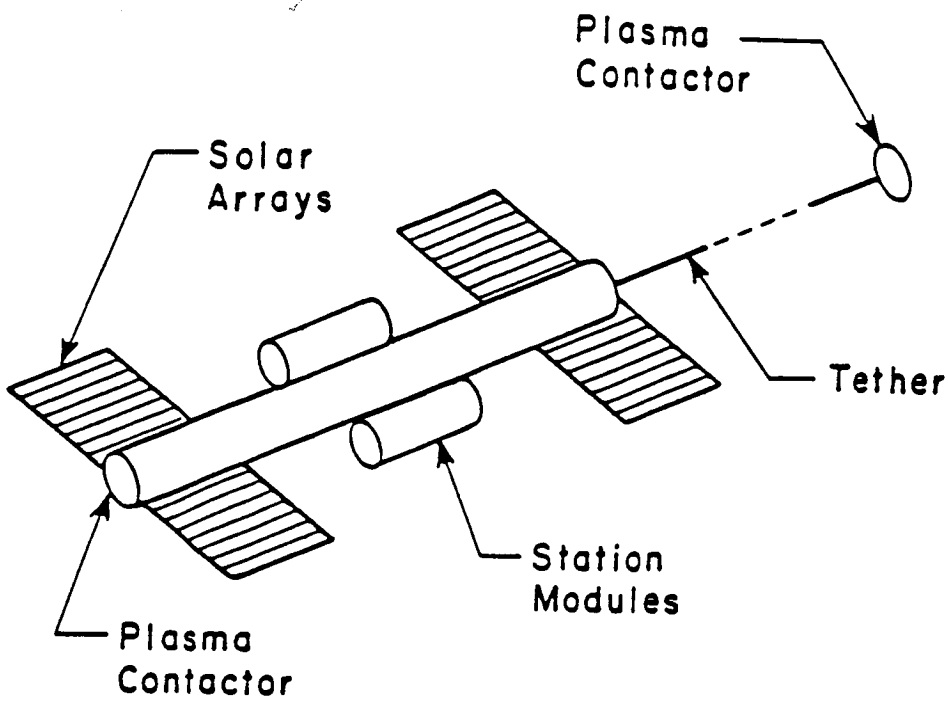

Figure 1: Space Station - Tether combination

cause the irreversible loss of power which will be emitted as electromagnetic radiation into the surrounding ionosphere. We assume that the current density flowing through the tether-station combination varies as $cos(\omega^* t)$ where $\omega^* \neq 0$ takes into account that the tether current may have an AC variation impressed on it. This can occur for two possible reasons, firstly because the power distribution system on the Station will probably be AC and there could be some inductive coupling between this current and the current in the power distribution system. Secondly, another possible use for the tether is as an antenna [M.D. Grossi, private communication, 1986] in which case the current in the system would necessarily be AC. With this assumption for a source current, Maxwell's equations for the emission into a magnetoactive medium can be solved and it can be shown that the average radiated power ($\bar{P}_{rad}$)can be written as

$$\bar{P}_{rad} = I^2 Z \tag{1}$$

where I is the current flowing through the tether-station combination and Z is the radiation impedance given by[1]

$$Z = Z_o \pi^2 \int_{Bands} d\omega \frac{1}{\sqrt{S}(\omega)} (\frac{c}{V_o c_A}) \int_{-\infty}^{\infty} dk_2 (\frac{j_{s2}}{I})^2 \frac{k_2^2}{k_\perp^2} (1 - \frac{c^2 k_\perp^2}{\omega^2 P(\omega)})^{1/2} \tag{2}$$

In (2), $Z_o = 2c_A/c^2$ in gaussian units, c_A is the Alfven velocity in the ionosphere, V_o is the orbital velocity of the system, j_{s2} is the (Fourier tranformed) current density flowing in the Station, $k_\perp^2 = k_1^2 + k_2^2$ and $k_1 = (\omega - \omega^*)/V_o$. The functions $S(\omega)$ and P(ω) are the well known perpendicular and parallel diagonal elements of the dielectric tensor[2] characterizing the ionosphere around the system. In the frequency integral in (2), the integration is only over the allowed bands of emission in the cold ionosphere. There are two possible bands, the Alfven band ($O < \omega < \Omega_i$. the ion

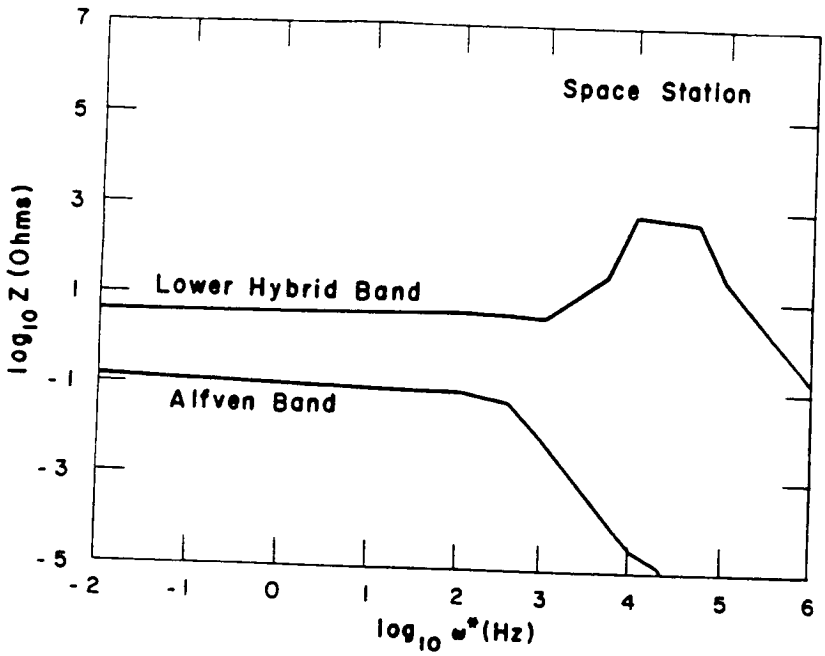

Figure 2: Radiation impedance Z against AC frequency of the current

cyclotron frequency) and the lower hybrid band ($\omega_{lh} < \omega < \Omega_e$, with $\omega_{lh} \simeq \sqrt{\Omega_e \Omega_i}$ and Ω_e being the electron cyclotron frequency). In fig. 2 we present a typical calculation of $Z(\omega^*)$ for probable Space Station parameters. For low AC frequencies ($\omega^* \leq 10^2$Hz) the irreversible radiation loss occurs in both the Alfven band and the lower hybrid band and for a typical current of 10 Amps is approximately 420 w. For higher AC frequencies ($\omega_* \approx 10^4$Hz) most of the radiated power is in the lower hybrid band and for a 10 Amp current, 7.5 kw of power is radiated. For very high AC frequencies the amount of power radiated in either band is negligible.

These calculations suggest a number of interesting conclusions. First, that radiative loss of power from the tether-station system may be important and secondly, that electromagnetic noise will be found around the Space Station even for very small AC frequencies. This may explain the observation of solar array hiss. [C. Purvis, private communication, 1986].

3 Theory of Plasma Contactors

The electrodynamic tether works by using the ionosphere as a source of electrons to make up the current flow. The random electron current density in the ionosphere at Station altitudes is very low ($\simeq 10^{-3} A/m^2$) and so to collect even 1 A of current would require a collection area of 1000 m^2. This has motivated research into plasma contactors where a plasma source surrounds the current collector with a plasma cloud which then provides a much larger effective collection area than the physical area of the collector. This works as long as electrons which stream along the geomagnetic field and enter the cloud can be diverted towards the anode at the end of the tether. A sufficient condition for this to occur is that

$$\nu_e > \Omega_e \tag{3}$$

where ν_e is the effective electron momentum scattering frequency and Ω_e is the electron cyclotron frequency. This condition states that in the cloud electrons will scatter before they complete their gyro-orbits. Hence they will not be bound to the field lines and can be collected at the anode. This condition is not necessary since to collect electrons all that is required is that electrons can undergo a random walk across the magnetic field at a rate sufficient to give the desired current. However use of this condition leads to a particularly simple analysis and enables us to place bounds on the current-voltage characteristics of the contactor[3]. With this sufficiency condition we can model the contactor cloud as a spherical expansion from some initial radius r_o to some critical radius r_c where $\nu_e/\Omega_e = 1$. The cloud is then described by the equations

$$\frac{\partial \Phi}{\partial r} = \frac{1}{en_e}[\frac{\partial p_e}{\partial r} - \frac{m_e \nu_e}{e}(\frac{I}{4\pi r^2})] \tag{4}$$

$$\frac{1}{r^2}\frac{\partial}{\partial r}(r^2 n_i v_i) = 0 \tag{5}$$

$$n_e = n_i \tag{6}$$

$$\frac{1}{2}m_i v_i^2 + e\Phi = \frac{1}{2}m_i v_i^2(r_o) + e\Phi(r_o), \tag{7}$$

$$I_{total} = I_i + I_e, \tag{8}$$

with boundary conditions

$$v_i(r_o) = c_s, \tag{9}$$

where c_s is the ion acoustic velocity

$$\Phi(r_o) = \Phi_o, \tag{10}$$

$$n_i(r_o) = I_i/(4\pi r_o^2 e c_s) \tag{11}$$

In these equations, subscript i means ions and e means electrons and the rest of the notation is standard.

The total current I_{total} consists of outgoing ions and incoming electrons. The ions are taken as freely falling under the influence of the potential. The equations (4) - (8) are the statement that the ions are repelled by the anode at r_o while the electrons are collected. The plasma cloud stays quasineutral and the potential drop is determined from the self-consistent force balance in the radial direction. To complete this simple model a prescription for the electron scattering rate is needed as a function of density. We take the scattering as

$$\nu_e = \nu_{ei} + \nu_{en} + \nu_{eff} \tag{12}$$

where ν_{ei} is Coulomb scattering, ν_{en} is electron-neutral scattering and ν_{eff} is turbulent scattering. It is easy to show that for most contactor plasmas ($n_e \leq 10^{12} cm^{-3}, n_n(neutral) \leq 10^{12} cm^{-3}, T_e \sim 5eV$), $\nu_{ei} + \nu_{en} \leq \Omega_e$ hence turbulent scattering is essential for current collection. The turbulent scattering is modelled as

$$\nu_{eff} \simeq \alpha \omega_{pe} \tag{13}$$

where $\alpha \simeq < \delta E_k^2 > /8\pi/nT_e$ is the fraction of energy in the electrostatic turbulence relative to the thermal energy; ω_{pe} is the electro plasma frequency. We note that for saturated ion acoustic turbulence $\alpha \simeq 10^{-3} - 10^{-2}$. These one dimensional equations for the spherical cloud have been solved for an argon plasma and the results are presented in figs 3 and 4. In fig. 3 the potential drop is shown against the total current for different ion currents. In order to obtain significant currents it was found to be necessary to assume high turbulence levels ($\alpha \simeq 0.2 - 0.4$). For each contactor ion current (I_c) it was shown that the total current was limited. This is because as the total current is increased, the potential drop increases which causes the ions to gain an increasing amount of energy as they fall down the potential hill. This has the effect of making the plasma cloud contract and at some current the total current exceeds the sum of the saturation electron current and the ion current. For total currents larger than this value, a very large potential drop ($\simeq$kV) is required. From fig. 3 we see that increasing the turbulence level does increase the potential drop as expected but a far more important effect is the increase of the cloud size with turbulence level and hence the increase in the maximum total current which can be obtained. Note that in all calculations the total potential drop is relatively small ($\leq 10^3 V$). This illustrates the power of plasma contactors in that large currents ($\simeq 10' sA$) can be pulled for small potential drops.

In figure 4 we see that the gain (I_{total}/I_{ion}) decreases with increasing ion current. This is due to the cloud contraction mentioned previously. For small contactors ($I_i \simeq 10^{-3} A$) it can be as high as 15 but for the bigger contactors that would be used on the Space Station a gain of 6 is more typical. This suggests that use of several small contactors may be more efficient (in terms of the mass of gas needed for the contactor) than using one big contactor. This is shown by the following calculation. Four amperes of total current can be obtained with 1 contactor emitting an ion current of 2 A and with a gain of 2, or it can be obtained by using 4 contactors emitting an ion current of 0.2 A each with a gain of 5 each. The total ion current in this case is 0.8 A. Hence by using a number of smaller contactors the total mass flow rate is less than half that needed by using one bigger contactor.

This simple model suggests that plasma contactors can work as advertised, in being low impedance current collection devices. However they will require the generation of large plasma clouds and electrostatic turbulence. Both of these may have an impact on Space Station.

A more sophisticated analysis suggests that there might still be a region of spherical expansion even when the condition $\nu_e > \Omega_e$ is not required. We can see this as follows:

The plasma cloud emitted from a contactor used in the ionosphere bears an important resemblence to barium releases in the magnetosphere. In both cases the initial energy density in the cloud

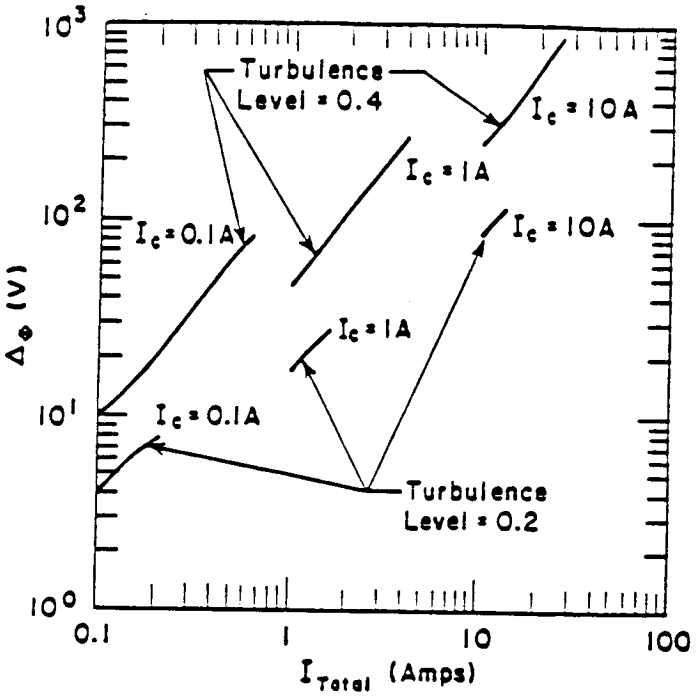

Figure 3: Potential drop through contactor cloud against total current flowing

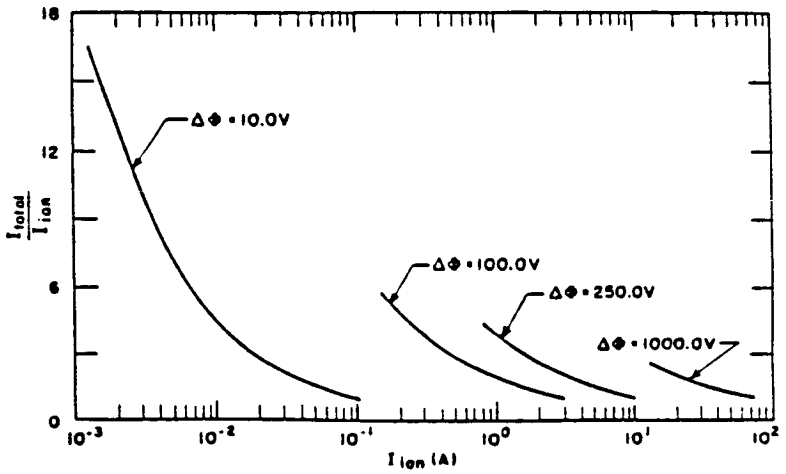

Figure 4: Gain I_{total}/I_i against ion current I_i for several potential drops

exceeds the energy density stored in the ambient magnetic field. This is conventionally measured by the plasma β defined as

$$\beta = \frac{n(T_e + T_i)}{B^2/8\pi} \tag{14}$$

where the electron temperature T_e and the ion temperature T_i are in energy units. The magnetic energy density is $B^2/8\pi$. When $\beta \geq 1$ then the plasma has more thermal energy than magnetic energy. For a contactor which emits a density n $\simeq 10^{12} cm^{-3}$ with $T_e \simeq 5$ eV and $T_i \simeq 0.1$ eV and for B = 0.45 Gauss we obtain $\beta \simeq 9.9 \times 10^2 \gg 1$. When $\beta > 1$ then the plasma will shield out magnetic fields as well as electric fields. That is, the self-consistent magnetic field in the plasma cloud will dominate the response of the cloud to magnetic fields and the effect of the ambient field will be insignificant. This suggests an explanation for the fact that ground based experiments have seen no dependance on the earth's magnetic field in the current characteristics of the cloud.

A simple model would suggest that since the ambient field is not important in the cloud then the cloud will expand spherically until we have $\beta \simeq 1$. For a release which scales as $1/r^2$ and is isothermal then

$$\frac{B^2}{8\pi} \simeq \frac{n_o r_o^2}{r_s^2}(T_e + T_i) \tag{15}$$

If the initial density is $10^{12} cm^{-3}$ and r_o is 10cm (which are the conditions of our previous contactor study) then we obtain r_s = radius of high β spherical expansion = 3.15 m. At the point at which this is reached we have $n(r_s) = 1.01 \times 10^9 cm^{-3}$. This high β core will essentially provide a collector volume which is much larger than the physical collector volume. This is because any electron that enters this region is very likely to be pulled into the center as a result of the bias on the collector. However, this expanded region will still not be enough to collect the ampere level currents necessary for viable operation of a system. Therefore the collisional enhancement we have discussed previously may still be necessary. The plasma cloud therefore will probably look as in fig. 5.

The distorted outer region of the cloud will play an important role in communicating information about the collector along the field lines. This is because with no cloud the physical collector will emit Alfven wings which will carry information about it down the field lines and accelerate electrons toward it. Hence the distance down the field that the moving collector can collect from is given by

$$\ell \simeq v_A(\frac{r_o}{V_o}) \tag{16}$$

where V_A is the Alfven velocity, and r_o/V_o is the transit time of the collector across a field line. Hence even with turbulent scattering the maximum current that can be collected is

$$2j_{th}[\pi r_o^2 + 2\pi r_o \ell] \simeq 2\pi j_{th} r_o^2[1 + 2\frac{v_A}{V_o}] \tag{17}$$

where j_{th} is the random electron current in the ionosphere. Since $v_A \gg 1$, we find that for a physical collector with no cloud (and with no ionization) the upper bound on collected current is

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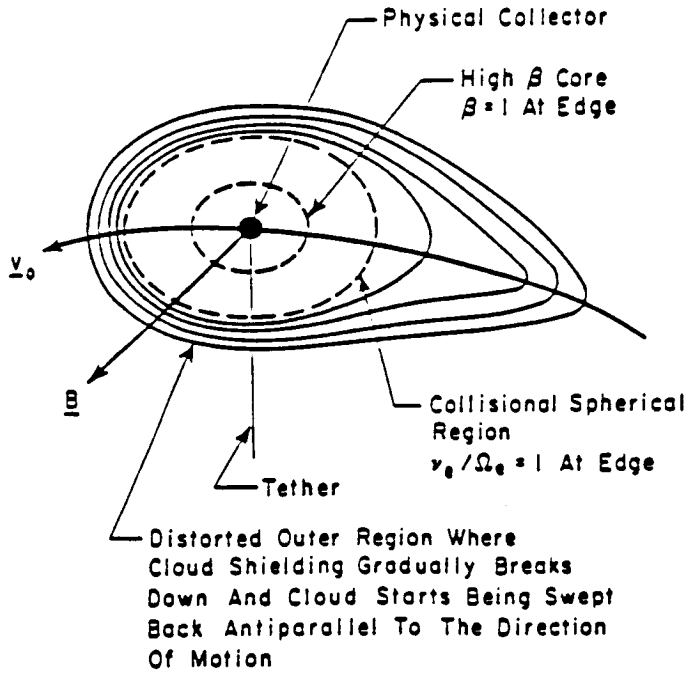

Figure 5: Cloud shape around the anodic end of the tether

approximately $2\pi r_o^2 j_{th}(2v_A/V_o)$. With a cloud which extends a distance $r_{c\ell}$ in front of the collector then the collection distance is

$$\ell \simeq v_A(\frac{r_{c\ell}}{V_o}) \tag{18}$$

The upper bound on the collected current is then $\simeq 2\pi j_{th} r_o^2 (2v_A/V_o)(r_c r_{c\ell})/r_o^2$ where r_c is the radius at which $\nu_e/\Omega_e = 1$. Since $r_c r_{c\ell}/r_c^2 \gg 1$ we see that the contactor cloud will allow a much larger bound on the collected current to a moving collector.

4 Plasma turbulence excited by contactor current flow

We have shown that plasma contactors need to generate electrostatic turbulence so that enhanced scattering of electrons takes place. Ground based tests of current collection through a contactor cloud have indicated large amounts of turbulence associated with the operation of contactors [P. Wilbur, private communication, 1986]. This may provide another explanation for the observation that the current flow does not seem to be affected by the imposed magnetic field.

Plasma turbulence occurs because the plasma becomes linearly unstable to some plasma oscillation, this linear instability then grows and saturates due to some nonlinear mechanism. The nonlinear saturated state is what causes the enhanced scattering. It is well known that currents in plasmas can drive instabilities and give rise to enhanced resistivity. Instabilities such as the ion acoustic instability and the Bunemann instability are well studied examples of such instabilities and will occur in the contactor clouds. However these instabilities propogate mainly along the magnetic field and so give rise to enhanced resisitivity but not very much perpendicular scattering.

Since the contactor requires that the electrons be scattered across the magnetic field this will most effectively be done by waves which have $\lambda_\perp \simeq \rho_e$ where $\lambda_\perp$ is the perpendicular wavelength and ρ_e is the electron cyclotron radius. With this in mind we model the ion distribution function as the sum of two Maxwellians (corresponding to the contactor ions and ambient ions). The electron distribution function is taken to be a drifting Maxwellian. A kinetic linear instability analysis indicates that it is possible to find an instability with

$$\omega_r = b_e^{1/2}\left(\frac{k}{k_\perp}\sqrt{\Omega}_e\left(\Omega_{i1}\frac{n_{i_1}}{n_e} + \Omega_{i2}\frac{n_{i_2}}{n_e}\right)\right) \tag{19}$$

where ω_r is the oscillation frequency of the instability, $b_e = k_\perp^2\rho_e^2/2$, k $= \sqrt{k_\perp^2 + k_\parallel^2}$ and Ω_{i1}, Ω_{i2} are the ion cyclotron frequencies of the two ion species. For $b_e \sim$ O(1), k $\simeq k_\perp$ this is the lower hybrid frequency. The growth rate is given by

$$\begin{aligned}\gamma \;=\; & -\sqrt{\pi}\Big[\frac{\omega_r - k_\parallel v_D}{k_\parallel v_{the}}\Gamma_o(b_e)\exp^{-\left(\frac{\omega_r - k_\parallel v_D}{k_\parallel v_{the}}\right)^2} \\ & + \frac{n_{i1}T_e}{n_eT_{i1}}\frac{\omega_r}{kv_{thi1}}\exp^{-(\omega_r/kv_{thi1})^2} + \frac{n_{i2}T_e}{n_eT_{i2}}\frac{\omega_r}{kv_{thi2}}\exp^{-(\omega_r/kv_{thi2})^2}\Big] \\ & \frac{\omega_r^3}{k^2}\frac{1}{\left[\frac{n_{i1}T_e}{n_eT_{i1}}v_{thi1}^2 + \frac{n_{i2}T_e}{n_eT_{i2}}v_{thi2}^2\right]}\end{aligned} \tag{20}$$

where $\Gamma(b_e) = e^{-b_e}I_o(b_e), I_o$ is the Bessel function of imaginary argument and the current density is j = $-en_ev_D$. This growth rate is maximised for

$$k_\parallel/k \simeq ((m_e/m_{i1})n_{i1}/n_e + (m_e/m_{i2})n_{i2}/n_e)^{1/2} \tag{21}$$

and for $b_e = O(1)$. This instability is called the current driven lower hybrid instability, is driven by inverse Landau damping from the electrons and is damped by ion Landau damping. In fig. 6, the marginal stability curves (in terms of current density) are shown against electron density. We see that instability will exist for an intermediate density range (5 x 10^6 ¡ n_e ¡ $10^8 cm^{-3}$) if we consider current densities of 1 A/m^2 at the collector.

This suggests that the turbulent region of the plasma cloud will be a shell or band at some distance from the plasma source. Furthermore we see that for $n_e \geq 10^6$cm^{-3}, the marginal stability curves all have minima. This indicates that the contactors will need to pull a minimum current to work effectively. Below a critical current no instability will be excited and no turbulent scattering will occur. From fig. 6 we can deduce a consistency condition for the current density versus electron density profile. If the current density for $n_e \simeq 10^5 cm^{-3}$ (ambient) is the random current density ($\simeq 10^{-3} A/m^2$) and at the collector ($n_e \simeq 10^{12} cm^{-3}$) is 1A/$m^2$ then the profile must be more like curve C rather than A or B. For curve A there is no turbulent scattering anywhere and therefore no possibility of enhancement. For curve B the only unstable region occurs for a small density range and for $T_e/T_i \simeq 10$. If the contactor is emitting a nonequilibrium plasma with $T_e/T_i \simeq 10$ at the collector then far out in the cloud we would expect $T_e/T_i \ll 10$, and so only for C the possibility of turbulent enhancement. This supports the idea of a turbulent shell around the collector.

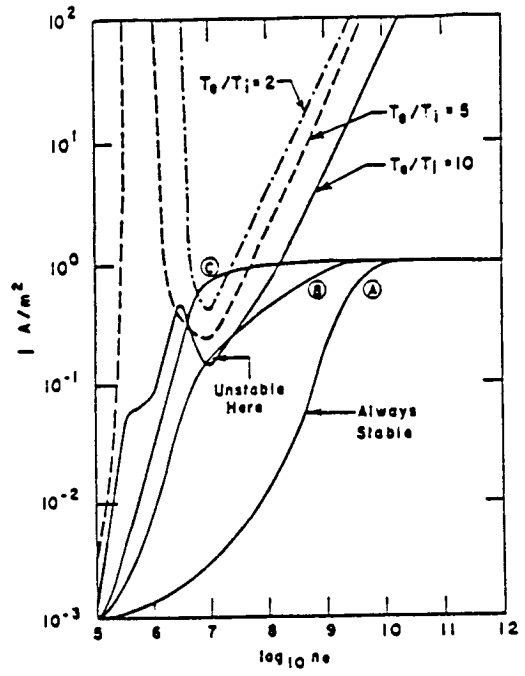

Figure 6: Marginal stability curves for lower hybrid instability.

5 Discussion

It has been shown that use of high power electrodynamic tethers involves large current flows, emission of radiation as well as hot plasma and generation of large amounts of electrostatic turbulence. All of these may impact the Space Station. In light of these we can identify some of the issues that need to be addressed by future research.

One of the most important issues is the nature of the current flows around large conductive objects close in the far field e.g. down in the E-region of the ionosphere or is current closure local? If current closure is a local phenomena then does this raise safety concerns? The issue of current closure is intimately related to the question of radiation from the Space Station and tether. We see that it is possible to lose significant amounts of power through radiation into the whistler frequency range. This would probably deposit into the local ionosphere and cause large scale changes (heating, ionization). If nothing else, this suggests a large signature to the tether/station combination. This also suggests that we need to consider whether any approaching vehicles would be affected by the radiation coming from the Station. If there were some coupling between the radiation field and the electronics of an approaching vehicle then some damage would result.

We have seen that the use of a high power tether will involve plasma contactors. These will emit hot plasma into the ionosphere. Since this will be occuring continously we need to consider what will happen to all this foreign material in the ionosphere. Will it accumulate in the orbit of the Station? Will it deposit on Space Station surfaces with possible deleterious effects? Will there be long term changes to the ionosphere as a result of this emission? Even if these things are not issues, the plasma clouds will have an affect on communications. Since the plasma density is so much higher than ambient, they will block microwave frequencies and will also generate noise over a large frequency range. This suggests that communications will have to be designed with these

issues in mind.

6 Conclusions

We have reviewed some current work on the plasma issues associated with the use of high power electrodynamic tethers. All the current work suggests that the tether will have a significant impact on the ionosphere. This will occur both by deposition of electromagnetic radiation and by deposition of plasma into the ionosphere. Both types of deposition will cause possible large scale changes to the ionosphere and may have long term effects. These will be the subject of future research.

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N87-20075

Radiation of Plasma Waves by a Conducting Body Moving Through a Magnetized Plasma†

by

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ABSTRACT

An understanding of the interaction between a moving conductor and a plasma is very important for the design of large structures in space, such as a space station or the tethered satellite system. It is well known that very large conducting objects which move slowly across magnetic field lines radiate low frequency (Alfvén) waves. In this paper we formulate the problem in such a way that the radiation in all frequency bands can be computed. We then quote results of detailed calculations for spheres and cylinders of various sizes in the cold plasma approximation. In general, we find that in a plasma for which $\omega_p^2 >> \omega_e^2$ and $V^2 << c_A^2 << c^2$, there is radiation in three frequency bands: $\omega < \Omega_i$, $\omega_{lh} < \omega < \Omega_e$, $\omega_p < \omega < \omega_{uh}$, where V is the speed of the body, c_A is the Alfvén speed, c is the speed of light in vacuum, ω is the frequency of the radiation, and Ω_i, ω_{lh}, Ω_e, ω_p, and ω_{uh} are the ion cyclotron, lower hybrid, electron cyclotron, plasma, and upper hybrid frequencies, respectively.

1. Statement of the problem

We consider the problem of a conductor moving nonrelativistically through a magnetized plasma with velocity $\mathbf{V} = V\,\mathbf{e}_x$. We call the rest frame of the plasma Σ and the rest frame of the conductor Σ'. We assume that in Σ far from the conductor the plasma is uniform and isotropic and has a magnetic field

$$\mathbf{B}_0 = B_0\,\mathbf{e}_z \tag{1}$$

and an electric field

$$\mathbf{E}_0 = 0 \tag{2}$$

In Σ' the fields far from the body are given by

$$\mathbf{B}'_0 = B_0\,\mathbf{e}_z \tag{3}$$

and

$$\mathbf{E}' = \frac{\mathbf{V} \times \mathbf{B}_0}{c} = -\frac{VB_0}{c}\,\mathbf{e}_y \tag{4}$$

Inside the conductor, the electric field $\mathbf{E}'$ and the conduction current density $\mathbf{J}'_c$ are related by

† This paper is a shortened version of the paper of the same name that appeared in the Journal of Geophysical Research, Vol 91, No A9, pages 10, 117-10, 135, September 1, 1986.

$$\mathbf{J}'_c = \sigma \mathbf{E}' \tag{5}$$

In Σ, Eq (5) takes the form

$$\mathbf{E} = -\frac{\mathbf{V}\times\mathbf{B}_0}{c} + \frac{\mathbf{J}_c}{\sigma} \tag{6}$$

We consider here the special case where $\mathbf{V}$ is perpendicular to $\mathbf{B}_0$. Our formulation can be easily modified to include the general case. The coordinate system that we use is shown in Fig. 1.

A conductor placed in an electric field in vacuum becomes polarized so as to shield out the external field. The equipotential surfaces for a prolate spheroid embedded in an external electric field directed along its axis is shown in Fig. 2. The field has azimuthal symmetry about the axis of the spheroid.

If the conductor is embedded in a plasma, the above solution cannot apply, since the component of the electric field parallel to the magnetic field will drive currents in the plasma. In particular, for an object is much longer in the direction of the external field than in the direction perpendicular to the field, such as the prolate spheroid shown in Fig. 2, the fields near the tips are much stronger than the field at infinity.

Let L be a characteristic size of the body and c_A the Alfvén speed. If the body is large enough and is moving slowly enough ($V << c_A$ and $V/L\Omega_i << 1$), then the MHD approximation is applicable. The MHD model of the interaction between a moving conductor and a magnetized is based on the work of Drell, Foley and Ruderman (1965), who used it to explain the anomolously fast decay of the orbit of the Echo I weather satellite. The model did not gain wide acceptance until it was confirmed by in situ observations by Voyager I of the Alfvén wing generated by the jovian satellite Io. Further theoretical work was done by Neubauer, and good agreement to the model was obtained in analysis of the magnetic field data by Acuna et al (1981) and of the plasma data by Barnett (1986). In this limit, the conductor radiates Alfvén waves. Viewed in Σ', there is a standing wave pattern consisting of two Alfvén "wings" attached to the body. The wings have a cross-section determined by the shape of the body, and they extend in the direction of the Alfvén characteristics, $\mathbf{V}_A^{\pm}$, defined by

$$\mathbf{V}_A^{\pm} = \mathbf{V} \pm \frac{\mathbf{B}_0}{\sqrt{4\pi\rho}} \tag{7}$$

where ρ is the plasma mass density. A side view of the Alfvén wing for a perfectly conducting sphere is shown in Fig. 3. The electric field $\mathbf{E}'$ is zero inside the Alfvén wings, while outside them the electric field resembles the field that surrounds a conducting infinite cylinder emersed in a uniform electric field perpendicular to its axis. The external electric field is shielded out by charges on the surface of the wing. In addition, electric current flows along $\mathbf{B}$ on the surface of the wing. The current flows toward the sphere on the side of the wing that is negatively charged, crosses the magnetic field through the sphere, and flows away from the sphere on the side of the wing that is positively charged. A front view of the Alfvén wing, showing schematically the charge and current density, is shown in Fig. 4. The electric field in a plane perpendicular to $\mathbf{B}$ through the center of the sphere is shown in Fig. 5. The plasma bulk velocity $\mathbf{V}'$ resembles the flow of an incompressible fluid around and infinite cylinder.

The streamlines in a plane perpendicular to **B** are shown in Fig. 6. An interesting property of the Alfvén wing system is that a three dimensional problem has effectively become a two dimensional one. Instead of flowing around a spherical obstacle, the plasma must flow around a cylindrical one.

Also shown in Figs. 3 and 4 is the direction of the Poynting vector **S**. Viewed in Σ, the conductor loses energy due to radiation. This radiation is analogous to classical Cherenkov radiation, which occurs whenever a particle moves through a dielectric faster than the phase speed of light in the dielectric. In the case of the Alfvén wing, the conductor is moving accross the magnetic field faster than the Alfvén waves can propagate in that direction (the phase velocity of Alfvén waves perpendicular to **B** is zero). If the velocity of the conductor were greater than the Alfvén speed, a shock would form instead of the Alfvén wing.

The question remains, are the MHD waves predicted by Drell et al the only waves generated by a conductor moving through a plasma, or are there waves of higher frequencies? If other waves are possible, how does one compute the amount of energy radiated?

2. Mathematical Formulation

We now proceed to the formulation of the problem without the MHD frequency constraint. We solve the problem using Fourier transforms. Our method incorporates the boundary conditions in an integral equation. We start by writing

$$\nabla \times (\nabla \times \mathbf{E}) + \frac{1}{c^2}\frac{\partial^2 \mathbf{E}}{\partial t^2} = -\frac{4\pi}{c^2}\frac{\partial \mathbf{J}}{\partial t} \tag{8}$$

We now write **J** as a sum of two terms

$$\mathbf{J} = \mathbf{J}_p(1-H) + \mathbf{J}_c H \tag{9}$$

or

$$\mathbf{J} = \mathbf{J}_c - \mathbf{J}_s \tag{10}$$

where

$$\mathbf{J}_s(\mathbf{x},t) = (\mathbf{J}_c(\mathbf{x},t) - \mathbf{J}_p(\mathbf{x},t))H(\mathbf{x},t) \tag{11}$$

and

$$H(\mathbf{x},t) = \begin{cases} 1 & \text{inside the conductor} \\ 0 & \text{elsewhere} \end{cases} \tag{12}$$

$\mathbf{J}_p$ is the current density in the plasma,while $\mathbf{J}_c$ is the current density in the conductor. We now define the fourier transform $f(\mathbf{k},\omega)$ of the function $f(\mathbf{x},t)$ by

$$f(\mathbf{k},\omega) = \mathfrak{f}\left\{f(\mathbf{x},t)\right\} = \frac{1}{(2pi)^2}\int f(\mathbf{x},t)\, e^{i(\mathbf{k}\cdot\mathbf{x} - \omega t)} d^3x\, dt \tag{13}$$

$\mathbf{J}_p(\mathbf{k},\omega)$ is related to $\mathbf{E}(\mathbf{k},\omega)$ through the dielectric tensor **K** by the relation

$$\mathbf{J}_p(\mathbf{k},\omega) = \frac{i\omega}{4\pi}\left[\mathbf{K}(\mathbf{k},\omega) - \mathbf{I}\right]\cdot\mathbf{E}(\mathbf{k},\omega) \tag{14}$$

where **I** is the identity matrix, and **K** is the dielectric tensor of the plasma. Although the

computations that we quote at the end of this paper were performed using the cold plasma dielectric tensor, which is derived from the linearized equztions of motion, any plasma model can be used. Using (9) through (14), we can write the Fourier transform of (8) as

$$\mathbf{T}(\mathbf{k},\omega) \cdot \mathbf{E}(\mathbf{k},\omega) = -\frac{4\pi i\omega}{c^2}\mathbf{J}_s(\mathbf{k},\omega) \tag{15}$$

where $\mathbf{T}$ is the so-called dispersion tensor, defined by

$$\mathbf{T} = -k^2\mathbf{I} + \mathbf{kk} + \frac{\omega^2}{c^2}\mathbf{K} \tag{16}$$

Eq. (16) can be inverted to solve for $\mathbf{E}$ in terms of $\mathbf{J}_s$

$$\mathbf{E}(\mathbf{k},\omega) = -\frac{4\pi i\omega}{c^2}\mathbf{T}^{-1}(\mathbf{k},\omega)\cdot\mathbf{J}_s(\mathbf{k},\omega) \tag{17}$$

Once $\mathbf{E}(\mathbf{k},\omega)$ is known, the magnetic field perturbation $\mathbf{B}$, the plasma current density $\mathbf{J}_p$, and the electric charge density ρ can easily be found from the Fourier transforms of Maxwell's equations. We seek an equation for $\mathbf{J}_s$. To derive it, we multiply Eq. (6) by $H(\mathbf{x},t)$ and use Eq. (11) to eliminate $\mathbf{J}_c$. The result is in the linlearized approximation
$\mathbf{V} \times \mathbf{B} \simeq \mathbf{V} \times \mathbf{B}_0$ is

$$\mathbf{J}_s(\mathbf{x},t) = \left[\sigma\left[\mathbf{E}(\mathbf{x},t) + \frac{\mathbf{V}\times\mathbf{B}_0}{c}\right] - \mathbf{J}_p(\mathbf{x},t) + \rho_c(\mathbf{x},t)\mathbf{V}\right]H(\mathbf{x},t) \tag{18}$$

where we have linearized by writing $\mathbf{B}_0$ instead of $\mathbf{B}$. We note that the Fourier transforms of the fields on the right side of Eq. (18) can be written in terms of the Fourier transform of $\mathbf{J}_s$. The result is the desired integral equation for $\mathbf{J}_s$.

$$\mathcal{f}^{-1}\left\{\mathbf{J}_s(\mathbf{k},\omega)\right\} = 0 \quad \text{for } \mathbf{x} \text{ in the plasma} \tag{19a}$$

$$\mathcal{f}^{-1}\left\{\mathbf{W}\cdot\mathbf{J}_s\right\} = \frac{\mathbf{V}\times\mathbf{B}_0}{c} \quad \text{for } \mathbf{x} \text{ in the conductor} \tag{19b}$$

where the tensor $\mathbf{W}$ is defined by

$$\mathbf{W} = \frac{4\pi i\omega}{c^2}\mathbf{T}^{-1} + \frac{1}{\sigma}\left[(\mathbf{k}^2 - \frac{\omega^2}{c^2})\mathbf{I} - \mathbf{kk}\right] \cdot \mathbf{T}^{-1} \tag{20}$$

We are led to an integral equation by the facts that the relation between $\mathbf{E}$ and $\mathbf{J}_s$ is an algebraic relation in $(\mathbf{k},\omega)$ space, while the location of the conductor, as expressed by $H(\mathbf{x},t)$, is simple in ordinary $(\mathbf{x},t)$ space. Notice that the boundary conditions are automatically included in our formulation.

3. Properties of the solutions

The solution to (19) and (20) contains a complete description of the fields surrounding a conductor moving through a magnetized plasma. Unfortunately, this integral equation is difficult to solve. To obtain numerical estimates, we therefore take the alternate approach of trying to study the properties of the solutions. If we assume that we know the source current

$\mathbf{J}_s$, the electric field is given by the Fourier transform of (17). When one uses a complex contour integration to evaluate the integral, the only contributions come from the poles of the integrand, which occur at the zeros of the equation

$$\det \mathbf{T}^{-1} = 0 \tag{21}$$

Equation (21) is the familiar dispersion relation for the plasma. In the present case, we seek a solution which is independent of time in Σ', which implies that in Σ,

$$\omega = \mathbf{k}\cdot\mathbf{V} \tag{22}$$

For the geometry described in (1) - (4), (22) takes the form

$$\omega = k_x V \tag{23}$$

Furthermore, since we are primarily interested in the power radiated, we need to study the behavior of the solutions far from the origin. In particular, we are interested only in those modes for which $\mathbf{k}$ and ω are both real, since only these modes can transport energy to infinity. In low Earth equatorial orbit, the plasma and the orbital velocity obey the following inequalities

$$\omega_p^2 >> \Omega_e^2 \tag{24}$$

and

$$V^2 << c_A^2 << c^2 \tag{25}$$

For such conditions, (21) and (23) have solutions for real $\mathbf{k}$ and ω in only three frequency bands

$$\begin{array}{ll} \omega < \Omega_i & \text{Band I} \\ \omega_{lh} < \omega < \Omega_e & \text{Band II} \\ \omega_p < \omega < \omega_{uh} & \text{Band III} \end{array} \tag{26}$$

Band I is the MHD band discussed by Drell et al; bands II and III are new. This radiation is analogous to classical Cherenkov radiation. We have already pointed out that a conductor moving through a magnetized plasma only radiates plasma waves whose phase speed in some direction is slower than the speed of the body. For a body that moves slowly compared to the Alfvén speed, this occurs only in the frequency bands described by (26). A polar plot of the phase speed versus the angle between $\mathbf{k}$ and $\mathbf{B}_0$ for the mode that is excited in each of these three bands is shown in Figs. 7-9. Note that the phase velocity vanishes in some direction for each of these three cases.

4. Calculation of radiated power

Having identified the frequency bands within which power is radiated, we now have to estimate the amount of power that will be radiated into each band. To do this, we guess the spatial dependence of the source current distribution and use Poynting's theorem to compute its magnitude. Poynting's theorem can be written as follows

$$P_{rad} = -W - \frac{\partial U_{EM}}{\partial t} \tag{27}$$

where

$$P_{rad} = \frac{c}{4\pi} \int \mathbf{E} \times \mathbf{B} \cdot d\mathbf{a} \tag{28}$$

$$W = \int \mathbf{E} \cdot \mathbf{J}\, d\mathbf{x} \tag{29}$$

$$U_{EM} = \frac{1}{8\pi} \int (E^2 + B^2)\, d\mathbf{x} \tag{30}$$

where P_{rad} is the power radiated, U_{EM} is the electro-magnetic energy, and W is the mechanical work done by the fields. We choose for our volume of integration a large rectangular prism with the conductor at its center, and we perform all of the calculations in frame Σ. If we make the box large enough, the term $\frac{\partial U_{EM}}{\partial t}$ can be neglected, due to the fact that the solution we seek is independent of time in frame Σ'. To evaluate the remaining integrals, we use the following ansatz; assume that the source current can be written as

$$\mathbf{J}_s(\mathbf{x}) = -I\, f(\mathbf{x})\, \mathbf{e}_y \tag{31}$$

where $f(\mathbf{x})$ is a known function, the form of which one guesses from the geometry of the conductor. Now consider (28). Since both $\mathbf{E}$ and $\mathbf{B}$ are linear functions of $\mathbf{J}_s$, P_{rad} is proportional to I^2. To evaluate (29), we use Ohm's law (6) for $\mathbf{E}$. Since $\mathbf{J}_c$ is proportional to $\mathbf{J}_s$, (29) results in two terms, one proportional to I and one proportional to I^2. We can therefore write (27)-(29) as

$$I^2 Z_{rad} = I\, (\phi - I^2 R) \tag{32}$$

where ϕ has dimensions of electric potential, and we have assumed that $\mathbf{J}_s \simeq \mathbf{J}_c$. Z_{rad}, R, and ϕ can be computed using (31),(17),(13),(28) and (29). Equation (32) can be interpreted as an electrical circuit analog, where ϕ is the voltage, I is the current, and Z_{rad} and R are the resistences of two resistors in series. The problem of computing the radiated power thus reduces to evaluating Z_{rad}, given by

$$Z_{rad} = \frac{c}{4\pi I^2} \int (\mathbf{E} \times \mathbf{B}) \cdot d\mathbf{a} \tag{33}$$

with $\mathbf{E}$ and $\mathbf{B}$ given by

$$\mathbf{E}(\mathbf{x},t) = \mathfrak{f}^{-1} \left\{ -\frac{4\pi i\omega}{c^2}\, \mathbf{T}^{-1} \cdot f(\mathbf{k})\mathbf{e}_x \right\} I \tag{34}$$

and

$$\mathbf{B} = \mathfrak{f}^{-1} \left\{ \frac{c}{\omega} \mathbf{k} \times \mathbf{E} \right\} \tag{35}$$

where $f(\mathbf{k})$ is the Fourier transform of $f(\mathbf{x})$ defined in (31). We have evaluated (33) explicitly for two different geometries. The first case is a sphere of radius a. The second is a cylinder of radius b and length L whose axis points in the $\mathbf{e}_y$ direction. In both cases we have assumed a current density of the form given in (31), with $f(\mathbf{x})$ a constant inside the object and zero outside it. In both cases Z_{rad} can be expressed as a sum of three terms

$$Z_{rad} = Z_I + Z_{II} + Z_{III} \tag{36}$$

where Z_I, Z_{II}, and Z_{II} are the contributions from bands I, II, and III, respectively. Analytic expressions for Z as a function of a and of b and L can be found for several limiting cases. These cases are summarized in Table 1. The results of numerical calculations of Z_I, Z_{II}, Z_{II}, and P_{rad} are shown in Figs. 10-13, and the plasma parameters used in the calculations are given in Table 2. Of considerable interest are the results for a long, thin wire, since this might have applications to tethered satellite systems. If one wants to estimate the power that can be generated using a TSS, one can simply consider R to be the load resistence. Due to the contributions from band II, the impedence is much higher than expected in this case. A cylinder with $L = 10km$ and $b = 1cm$ has a radiation impedence of nearly 10^5 ohms! These results suggest that previous power estimates for passive TSS systems might be much too high. One must use care when applying these results to the TSS, however. In particular, effects due to the size of the subsatellite and local plasma clouds from "plasma contactors" can be mocked up by using an "effective" b.

Our formulation can also be used to estimate the radiated power for active systems. One must then consider I in (31) as a known source strength Some calculations of that sort are discussed in the article by Hastings et al.

5. Summary

We have considered the problem of the interaction between a moving conductor and a magnetized plasma. We have shown that steady state solutions exist for which the body is surrounded by a system of standing waves. Wave modes are excited for which the phase speed in some direction is less than the speed of the conductor. The process is analogous to Cherenkov radiation, or to the formation of a shock wave surrounding a body in supersonic motion through a gas. We have extimated the power radiated for spherical and cylindrical bodies moving perpendicular to the background magnetic field. Our results suggest that, due to the high radiation impedence in band II, a passive electrodynamic tethered satellite system will not draw large currents.

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TABLE 1. Radiation Impedence of Conductors Moving Through a Plasma Perpendicular to the Magnetic Field

	Size	Impedence
	Sphere of Radius a	
Region I	$a \gg \frac{V}{\Omega_i}$	$Z_I = \frac{2c_A}{c^2} \equiv Z_0$
	$a \ll \frac{V}{\Omega_i}$	$Z_I = \frac{4\pi a \Omega_i}{15V} Z_0$
Region II	$a \gg \frac{V}{\omega_{LH}}$	$Z_{II} = \frac{4\eta V c_A}{3\Omega_i^2 a^2} Z_0$
	$\frac{V}{\Omega_e} \ll a \ll \frac{V}{\omega_{LH}}$	$Z_{II} \cong \frac{2\pi c_A}{3\eta a \omega_{LH}} Z_0$
	$a \ll \frac{V}{\Omega_e}$	$Z_{II} = \frac{3c_A}{4\eta^2 V} Z_0$
Region III	$a \gg \frac{V c_A}{\omega_{LH} c}$	$Z_{III} = \frac{4V c_A}{15 a^2 \omega_{LH}^2} Z_0$
	Cylinder of Length L and Radius b With Axis Perpendicular to Both V *and* B_0	
Region I	$b \ll \frac{V}{\Omega_i}$ $L \ll \frac{V}{\Omega_i}$	$Z_I = \frac{\pi L \Omega_i}{4V} Z_0$
	$b \ll \frac{V}{\Omega_i}$ $L \gg \frac{V}{\Omega_i}$	$Z_I = \left[\ln\left(\frac{L\Omega_i}{V}\right) + 0.27\right] Z_0$
Region II	$L \gg \frac{V}{\Omega_e}$ $b \ll \frac{V}{\Omega_e}$	$Z_{II} = \frac{2c_A}{\eta^2 V}\left[\ln\left(\frac{V}{b\Omega_e}\right) + 1.06\right] Z_0$
Region III	$L \gg \frac{V}{\omega_p}$ $b \gg \frac{V}{\omega_p}$	$Z_{III} = \frac{V^2 c_A^2}{c(b\omega_{LH})^3} Z_0$

We have expressed the impedence in terms of $Z_0 \equiv 2c_A/c^2$ in Gaussian units. For conditions typical of low earth orbit, $Z_0 = 6.7 \times 10^{-14}$ s/cm = 0.06Ω. If $\eta = (m_e/m_i)^{1/2} = 1/172$ (oxygen plasma). $c_A = 300$ km/s and $B_0 = 0.33$ G.

TABLE 2. Plasma Parameters Used in Numerical Calculations

Parameter	Value
B	0.33 G
n_e	3.6×10^5 cm^{-3}
η	1/172
V_s	7.3 km/s
c_A	300 km/s
M_A	0.024
ω_p	3.4×10^7 s^{-1}
Ω_e	5.9×10^6 s^{-1}
ω_{LH}	3.5×10^4 s^{-1}
Ω_i	2.0×10^2 s^{-1}
$1/k_e$	1.2 mm
$1/k_{LH}$	21 cm
$1/k_i$	36 m

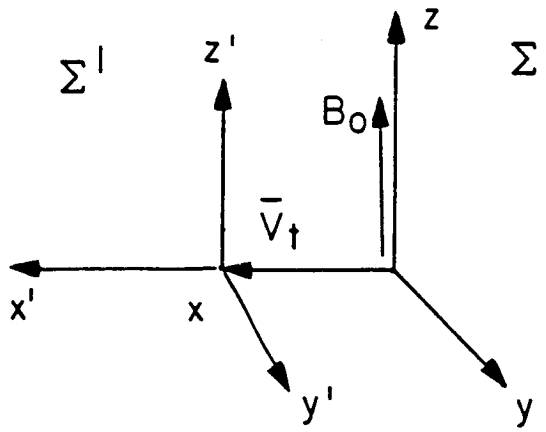

Fig. 1. Coordinate System

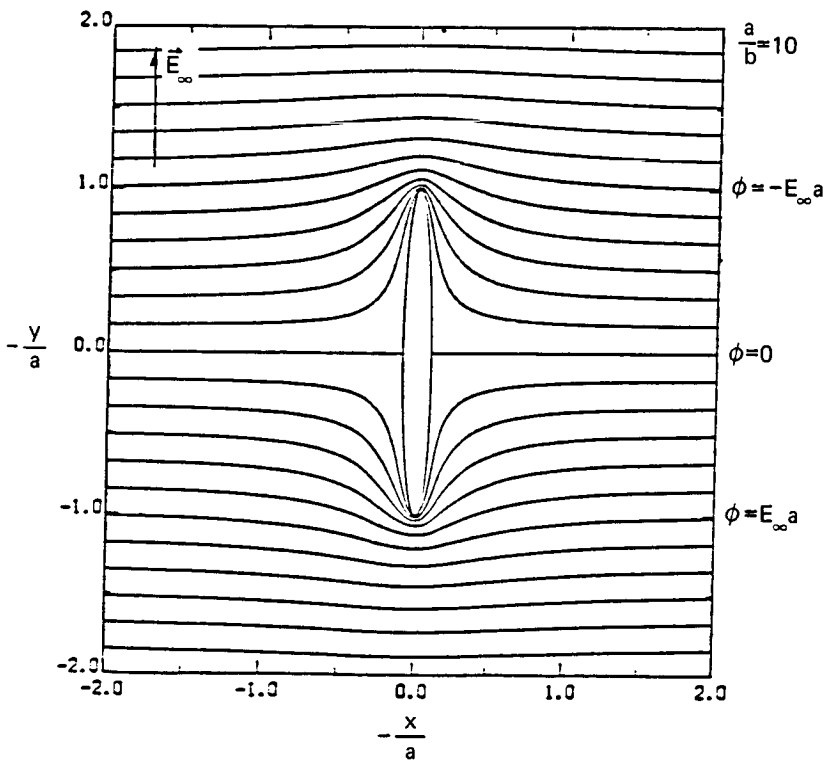

Fig. 2. Equipotential surfaces for prolate spheroid

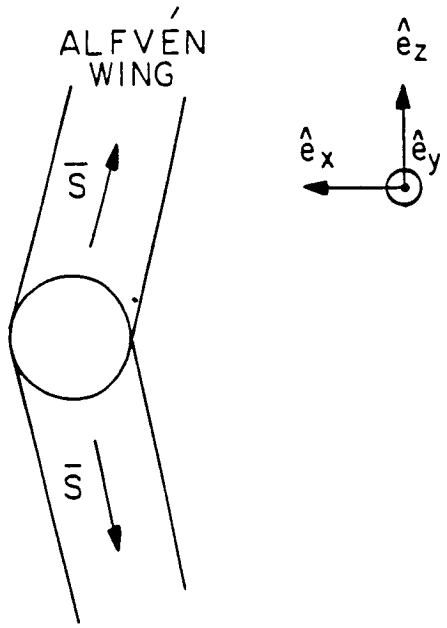

Fig. 3. Alfven wing for perfectly conducting sphere-side view

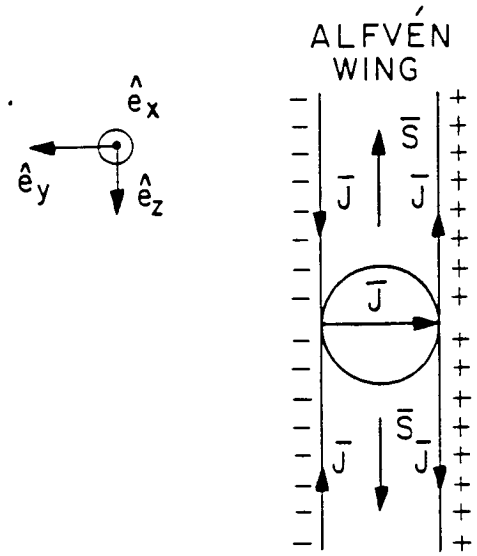

Fig. 4. Alfven wing for perfectly conducting sphere-front view

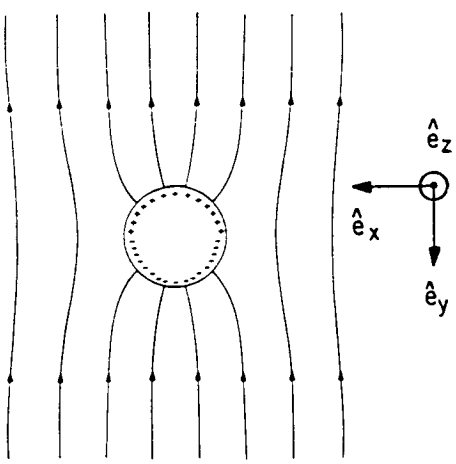

Fig. 5. Electric field lines in equatorial plane for perfectly conducting sphere

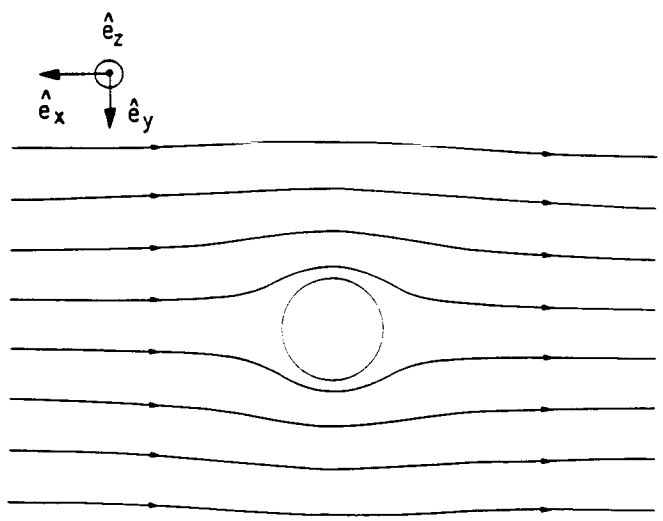

Fig. 6. Stream lines in equatorial plane for flow around perfectly conducting sphere

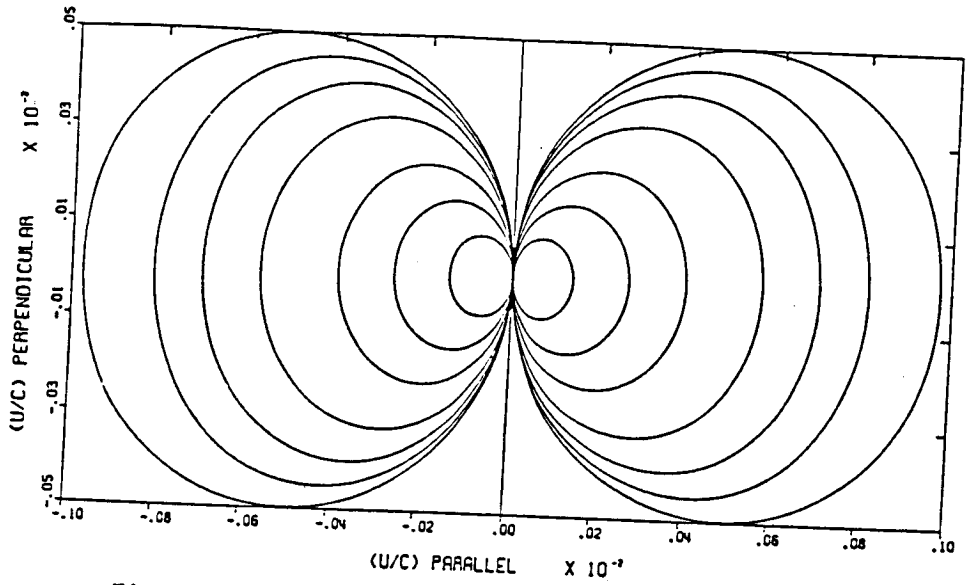

Fig. 7. Phase velocity vs. angle for 7 different frequencies in Band I

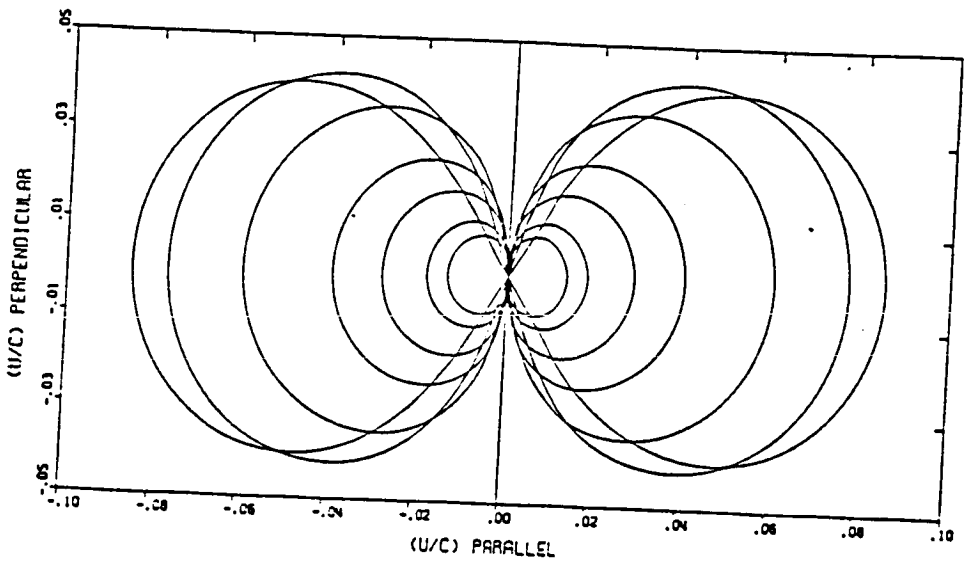

Fig. 8. Phase velocity vs. angle for 7 different frequencies in Band II.

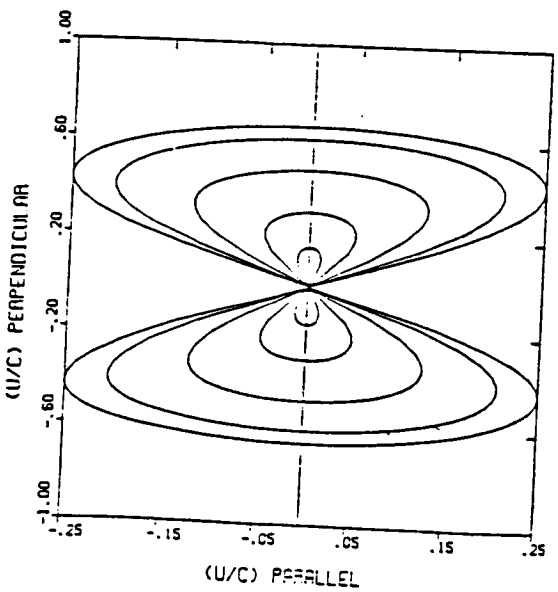

Fig. 9. Phase velocity vs. angle for 5 different frequencies in Band III.

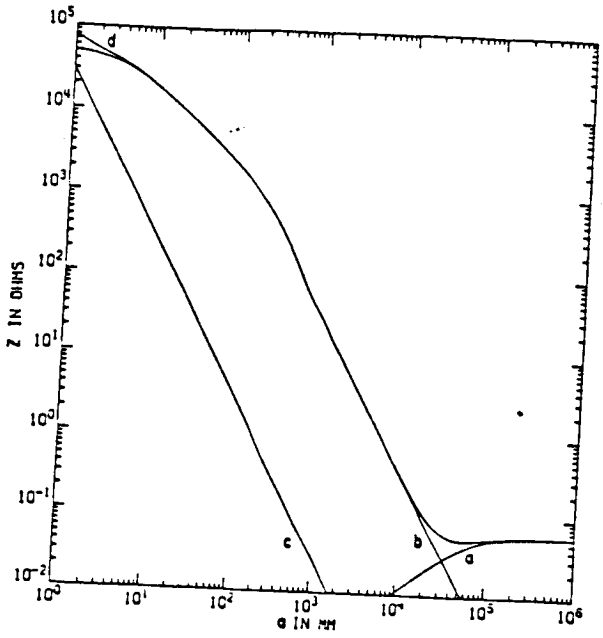

Fig. 10. Impedence vs. radius for a sphere. The lines labelled a, b, c, and d are the contributions from bands I, II, III, and total, respectively. Plasma parameters are given in Table 2.

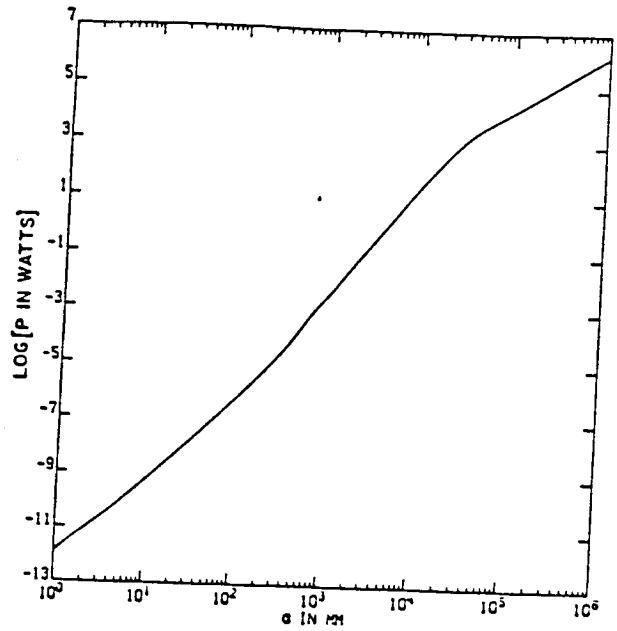

Fig. 11. Power radiated vs. radius for a sphere. Plasma parameters used are given in Table 2.

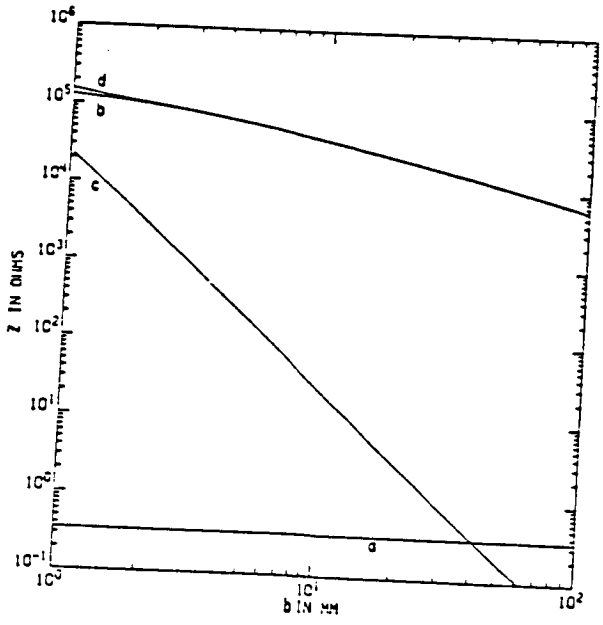

Fig. 12. Impedence vs. radius for a 10 km long cylinder. The lines labelled a,b,c, and d are the contributions from bands I, II, III and total, respectively. Plasma parameters are given in Table 2.

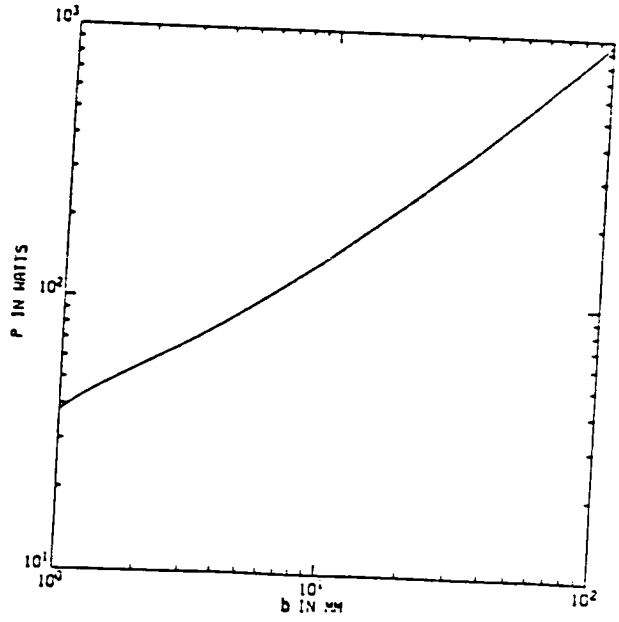

Fig. 13. Power radiated vs. radius for a 10 km long cylinder. Plasma parameters used are given in Table 2.

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HIGH CURRENT/HIGH POWER BEAM EXPERIMENTS FROM THE SPACE STATION

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1-INTRODUCTION

In this over-view on the possible uses of high power beams aboard the Space Station I will consider the advantages of the Space Station as compared to previous space vehicles, the kind of intense beams that could be generated, the possible scientific uses of these beams and associated problems. I have chosen this order deliberately to emphasize that the "means", that is, the high power particle ejection devices, will lead towards the possible "ends", scientific measurements in the Earth's upper atmosphere using large fluxes of energetic particles.

2-THE SPACE STATION PLATFORM

The availability of the Space Station as a platform should markedly relieve some of the limits that have constrained the use of energetic particle ejection sources on sounding rockets, satellites and the Space Shuttle. Because the Space Station and its auxiliary structures provide a large platform, several emission systems and sensing devices can be placed, oriented and operated simultaneously. The components can be separated by distances required for the use of high voltages. The astronaut-crew will be able to start, stop or modify experiments at a safe distance from high power devices. Energy storage devices, rechargable by the power generation systems, can supply pulsed power. One benefit of the Space Station is that it will allow the use of oxide-coated cathodes for thermionic electron emission in devices required for the generation of both electron and ion beams. The result will be an enormous gain in efficiency of power use. Oxide coated cathodes aboard space vehicles are difficult to use because low work function surfaces are poisoned by water vapor coming from the outgassing of other surfaces. The Space Station could provide a relatively water vapor free environment (water vapor partial pressure less than 10-6 torr) which would allow the use of low work function cathodes. One new problem on the Space Station will be the effects of the impact of ambient atomic oxygen over long periods on the cathodes. A suggested solution to this problem is the reconditioning and manual or robotical replacement of oxide-coated cathodes without displacing main ejector optics. The availability of long (~100 m) structures, would allow the stacking of linear accelerator drift tube sections. These sections could be tuned and positioned in a vibration-free environment. The availability of large rectangular structures, (100 m by 50 m) would allow the use of cyclotron type devices. Larger dimensions for all types of accelerators would become available by constructing and launching free flyers from the Space Station. To avoid radiation effects on personnel during and after the operation of accelerators, the accelerators would be controlled and serviced at a safe distance by the Space Station crew.

One of the major problems in using space vehicles has been the choice of proper ground or low altitude sites for measurements of beam effects . Having a platform from which repetitive ejections can be made will permit iterative measurements and repositioning of sensing instrumentation. It will also allow the repositioning of instrument bearing balloons and aircraft and the timely launching of instrumented sounding rockets. We could patiently await the proper but rare combinations of solar, magnetic and atmospheric conditions. Solar eclipse, magnetic index values, or ionospheric plasma concentrations could be used as separate control conditions for the start of measurements.

The zero or near-zero g forces on accelerators aboard the platform will probably not influence the particles ejected from the plasma sources; however, they could affect the energy storage and transfer systems. Investigations of these effects will be an important part of the research on the use of high power particle ejection devices on orbiting platforms.

3-BEAMS

About 50 kilowatts will be available from the active power sources on the Space Station, not much better than what has been available up to now from stored energy sources on space vehicles. The power sources can be used to continuously eject ampere beams of keV electrons. However, by using the mass and volume available for energy storage devices, and by using these energy storage devices for pulsed power, a new capability for the use of intense beams in space could be achieved. One ton of energy storage devices on the Space Station, a modest assumption, could easily store one megajoule of energy. Unloading this energy in one millisecond will make a megawatt of power available for cathode heating and beam generation, and for the ejection of kiloampere beams of keV electrons.

How often could such a large power pulse be produced? Only 10 kilowatts of the real time power devoted to charging the energy storage, could produce one pulse per day. Increased energy storage per mass unit and an increased orbited mass could provide high power for beams emitted in short pulses. Space charge limitations would obviously play a large role in limiting the current ejected from a single gun. However there are proven techniques of using positive ion and neutrals to decrease the effects of space charge and thereby increase the beam current per gun. Of great importance is the consideration that the Space Station would also allow a large number of guns to be used concurrently; each could deliver a large current per pulse. The use of a large number of ejection devices at one time greatly increases the importance of using low work function emissive cathode devices.

High energy (megavolt) and high current (kiloampere) electron emission devices require more space than their low energy analogues. Large volumes (cubic meters) are required for the cathodes and associated power-processing devices; these dimensions would be available on the Space Station.

As with electrons, the ejection of high currents of keV ions or neutrals will require a large number of elements that draw on the high power available from the energy storage devices. Because mass will not be a prime

consideration, the ion sources can be used to accelerate large quantities of gases with atomic weights starting at one, hydrogen atoms, to large molecules. For the keV regimes biased sources will provide adequate accelerations. However, high energy ion emission, as for very high energy electron emission, will require linear or curved accelerators. A great deal of effort is being expended to miniaturize the elements of such systems for possible space use, but the Space Station may give us the opportunity of using elements such as massive Cockrot-Walton sources, now used very successfully on the ground.

4-USES

Projected uses of high power beams on the Space Station can be considered in one of two categories: previous uses now extended by the Space Station characteristics, and new uses not previously feasible because of beam, power, or platform limitations. The factors that extend the previous uses include: use of more intense beams to increase the signal-to-noise ratio at detectors; use of an extended network of detectors over a large distance, areas, or volume to work independently or as a phased array; the availability of time to allow for modulated and phase sensitive filters; the ability to simultaneously use multiple beams with different energy electrons to induce desired excitation of ionization levels; and the ability to change directional response of detectors.

One of the earliest uses of electron beams on sounding rockets was in the in-situ measurement of the atmosphere. Characteristics such as ambient composition, neutral particle density, and temperature were sought. The measured signals included scattered electrons as well as the visible, ultraviolet, x-ray, and infrared emissions induced by electron beam excitation of the atmospheric gases. The major problem, especially at low altitudes, has been to measure the normal ambient in the presence of gases coming from the platform itself. For example, the ram wake effect has been utilized to distinguish atmospheric nitrogen from outgassed nitrogen. However, for some constituents, e.g., atomic oxygen, such a technique is not feasible because the atoms cannot be concentrated by the use of normal enclosures. In addition to the improvements already noted it is hoped that the Space Station will be able to provide places of measurements at some distance from contaminants. The ability to make measurements as a function of distance away from surfaces should make possible the extrapolation to normal ambient conditions. This use of electron beams will allow for in-situ measurements of temporal changes of ambient conditions.

Intense beams of high energy electrons will allow for probing of the atmosphere at some distance from the platforms. Measurements of atmospheric properties, especially density will be possible from 100 km down to perhaps 50 km or below. The measurements will be made by having the range of the energetic particles correspond to the altitude regime to be measured while using detectors on spacecraft and on the ground to look at emission signals. It is exciting to contemplate having ground-based spectrometers and cameras focused on a region or volume of space at a specific altitude, having signals from that region every ninety minutes and being able to anticipate and change beam intensity, particle energy and even the type of excitation particle.

Of course the other side of the coin to measuring the normal ambient has been the ability to significantly modify the atmosphere; to choose specific altitudes, and look at the modification parameters such as the total energy, energy distribution, and pulse lengths that are required for heating a region to a new state. Kilowatt beams have already been used to induce atmospheric effects which can be measured from the ground; more intense beams will allow for more accurate as well as a new range of measurements.

One of the earliest uses of electron beams from sounding rockets was the creation of artificial auroras with the purpose of understanding natural auroras. With the new platforms beams of particles with the same energy and flux distribution as the natural beams can be ejected into the atmosphere. Ground based instrumentation could then be used at optimum sites for measurements. We probably are a long way from creating reactions in large regions similar to those in which natural beams occur, but it may be possible with smaller sized beams to duplicate most of the interesting features of high energy particle penetration into the atmosphere.

The idea of using impacting electron beams on a free flying object to create spacecraft charging, to measure the charging, return currents, and ambient effects during beam impact, and to measure the rate and characteristics of discharging after beam cessation,has been around for some time. We know that the phenomena would be characteristic of low Earth orbit, and would not be directly applicable to geosynchronous orbit satellites. However, for low Earth orbit objects information could be obtained on questions that have remained after two decades of spacecraft charging measurements at even low Earth orbit. Investigations could be made of the relationship between spacecraft charging and such variables as object size and shape, orientation of the object to the magnetic field, plasma density, neutral particle density, object speed and orientation, surface characteristics and material distribution. From charging experiments the next steps are the study of discharging and the prevention of charge buildup. The ability to impact the free flying object with a wide range of currents, single particle energies and multiple energy spectra, will allow for basic understanding but also will provide the opportunity for the design and testing of active and passive discharging, and charging techniques.

Beam plasma interactions including the transfer of energy forms of beams of charged particles to wave energy in the plasma have been studied in some rocket and Space Shuttle experiments. The large dynamic range in beam energies and fluxes should allow for the investigation of these phenomena in regimes of beam and plasma properties not previously used either on the ground or in space. It will also be possible to compare laboratory results where walls of vacuum chambers are present to the new boundary conditions in space. An additional important aspect will be the comparison of the effects of single and multiple beams with the same total energies.

It will be possible to produce ionized layers on command. Beams of proper energy will now be available to efficiently increase the plasma density at various altitudes. The duration, extent, and effects of

these artificial ionospheres as a function of beam parameters will be important experiments for both scientific and commercial interests.

The use of the Space Station will allow much more ambitious experiments than previously attempted on space vehicles. Examples are the new ability to produce beam currents in space with energy densities larger than the Earth's magnetic field, and to produce beams with currents and energies that create pinch effects on the beams themselves. Quasi-neutral plasma beams could be produced with energies large enough to flow across field lines; therefore experiments with astrophysical implications that previously could be done only in numerical form or in very limiting ground chambers will now be possible on a repetitive basis in the conditions of Space Station altitudes.

5-PROBLEMS

We know from the use of particle ejection sources on sounding rockets and satellites, that these sources can introduce problems and sometimes actual dangers to the space vehicle platform as well as to other payloads. The identification of these problems and the solutions will be critical aspects of the use of high power beams on the Space Station. Criteria must be established for determining and testing the limiting effects of high voltage components on space vehicles in the ionosphere. The need for enclosed containers and the types of such containers for high voltage components and systems must be determined. The trade-off between pressurized containers and other ways of using high voltages in the plasma conditions of the Space Station must be studied, tested, and carefully verified. In addition to the problem of exposing materials to normal ambient conditions which can cause a slow deterioration to insulating characteristics, there will be the problem of the changed ambient: the new density, temperature, and flux of high energy particles may cause a rapid change not yet predicted by the much different ground conditions. On the positive side the Space Station may allow the use of large quantities of heavy insulating materials, such as oil now regularly used on the ground but not yet used on space vehicles.

Of course there is the problem of spacecraft charging. Whether it will be solved actively by hollow cathodes, plasma sources, automatic plasma emitters, or passively, by grounding wires, or large areas for return currents, is yet to be determined. As emitted beam fluxes used increase, even the return flux of low energy particles to compensate for the high energy emissions will start to change the ambient around the grounded portion of the platforms. The return of high energy particles due to the Earth's magnetic field or simply by scattering will also be important. The emitted beams, the return fluxes and the activities of the high density energy storage devices used in short pulses, may influence the ability to emit signals (telemetry) or to send signals internally (commands) and will have to be carefully studied.

6-CONCLUSION

The Space Station will provide a good platform for the use of high energy high power beam emission devices. The use of massive energy storage systems will play a key role in allowing for the emissions of power beams. It will provide opportunities for a large number of interesting experiments in space. There are however significant problems which must be solved.

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PLASMA HEATING, PLASMA FLOW AND WAVE PRODUCTION AROUND AN ELECTRON BEAM INJECTED INTO THE IONOSPHERE

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Abstract. A brief historical summary of the Minnesota ECHO series and other relevant electron beam experiments is given. The primary purpose of the ECHO experiments is the use of conjugate echoes as probes of the magnetosphere, but beam-plasma and wave studies have also been made. The measurement of quasi-DC electric fields and ion streaming during the ECHO 6 experiment has given a pattern for the plasma flow in the hot plasma region extending to 60m radius about the ECHO 6 electron beam. The sheath and potential well caused by ion orbits is discussed with the aid of a model which fits the observations. ELF wave production in the plasma sheath around the beam is briefly discussed. The new ECHO 7 mission to be launched from the Poker Flat range in November 1987 is described.

Introduction

This paper will be concerned mostly with results from the ECHO 6 electron beam sounding rocket experiment in which studies were made of the hot plasma regions, plasma flow and ELF wave production in the vicinity of the injected electron beam. The ECHO 6 mission is the latest in a coordinated series of electron beam experiments carried by large sounding rockets at ionospheric heights. The primary purpose of the experiments, beginning with the first launch in August 1970 from the NASA Wallops Island range in Virginia, has been to inject powerful pulses of electrons which travel in the outer magnetosphere, reflect from the magnetic conjugate region and return near the point of origin where under proper conditions they may be detected and analyzed. The original science objective, which was successfully carried out during the ECHO 1, 3, and 4 experiments has been to use these electron echoes as probes of the distant magnetosphere to study the dynamic morphology of the magnetic field in the nighttime sector by measuring bounce times and field line lengths, thus determining the degree of "inflation" of the magnetosphere during substorms and during the action of the tail current systems. Another objective has been to study the pitch angle diffusion and acceleration of the electrons to increase the understanding of the injection and acceleration of natural particles. Electron beams as probes are discussed by Winckler (1982). The geometry in space from the Poker Flat range in Alaska is shown schematically in Figure 1.

Electron beam experiments, a type of "active" experiment in the magnetosphere, have been carried out by a number of investigators. The Franco-Soviet ARAKS experiment (Cambou et.al., 1980), the Davis Kauai experiment (Davis et.al., 1980) and the ECHO series have been concerned with conjugate phenomena. Most other such experiments have had as their objective the study of the beam-plasma interaction in the ionosphere either for comparison with laboratory measurements of the beam plasma discharge or for studies of vehicle potentials and plasma wave production caused by the beam interaction. The ECHO series remains unique among electron beam experiments in retaining as the primary objective the study of conjugate echoes as outlined above. Following the original Hess Artificial Aurora experiment (Hess et.al., 1971), the ECHO series has emphasized optical and photometry measurements including low light level TV measurements of the artificial auroral streaks in the ionosphere, the luminosity around beam-emitting payloads, and the search for unstable luminosities around the beams (the beam plasma discharge) for which no adequate optical evidence has been obtained in space. The ECHO series has been successful also in studies of ELF frequency range wave spectra including ion resonances produced by the electron beam injections because of the high quality orthogonal electric field experiments carried by the ECHO 6

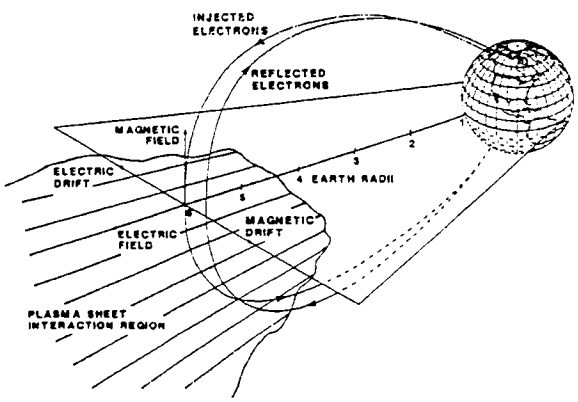

Figure 1. Magnetic field line geometry for nominal magnetic conditions from Alaska for conjugate echo trajectories.

mission. It is notable that electron beams can excite strong ion resonances and that this is a unique result from the sounding rocket type experiment and will probably not be accessible to orbiting plasma laboratories because of the high orbital speed through the plasma medium. An analysis of the ECHO 6 ELF waves and their possible sources is contained in the Ph.D. thesis of Yasuyuki Abe (Minnesota, 1986) and also in Winckler et.al. (1985). Electron beam experiments through 1979 have been reviewed by Winckler (1980).

Electron beam experiments have now been conducted on a number of flights of the Space Shuttle. A major experiment called SEPAC was carried on Spacelab-1 STS 9 and evolved essentially in the format suggested by the AMPS Study Group (Obayashi et.al., 1984). Other Shuttle-based electron beam experiments are reported by Shawhan et.al. (1983). These experiments will be discussed in detail elsewhere in this symposium. Orbiting plasma laboratories have in certain respects a high potential but are at the same time limited by their high speed through the ionospheric plasma and other factors in their ability to investigate natural phenomena in the magnetosphere.

ECHO 6 Plasma Studies

Experiment Details

We will be concerned with measurements of the perturbed plasma region in a cylindrical volume around an electron beam injected upwards from a rocket in the magnetosphere at 200 km altitude. The ECHO 6 mission included a Plasma Diagnostics Package (PDP) which was separated from the accelerator or main payload while the two sections were rotating about an axis inclined 20 degrees towards magnetic north from the local field vector. The PDP thus moved away from the main payload spinning at 0.5 rps as shown in Figure 2. The separation speed of 1.5 m/sec along the line of the PDP axis produced a slow increase in the radial distance of the PDP from the field line containing the beam. The accelerators were activated when the perpendicular radial distance was about 34m and continued to more than 100m. The accelerators were programmed in many modes, but we shall be concerned here mostly with beam injections at a pitch angle of 100 degrees, i.e. 10 degrees upwards from perpendicular, and also with injections at 180 degrees upwards parallel to B and downwards at 15 degree pitch angle. Data will be analyzed only in 50ms or 100ms intervals when only Gun 1 was operating, which produced discrete energy pulses from 20 KeV to a maximum of 36 KeV at 240 mA. The accelerator system is described elsewhere (Winckler et.al., 1984b). Two types of measurements will be analyzed; firstly, those obtained with the PDP orthogonal electric field probes shown in Figure 2. The two pairs were sampled in differential, and also individually, with respect to the payload body each 0.4 msec, which permitted us to construct the instantaneous electric vector in a plane perpendicular to the magnetic field with 0.4 msec resolution and a Nyquist frequency of 1250 Hz; secondly, measurements were also made of the thermal ion spectra with the PDP electrostatic spectrometers which rotated with the PDP but viewed several different inclinations including the direction perpendicular to the PDP spin axis. The experiment included many other features which are described in several publications (Winckler et.al., 1984a; Winckler et.al., 1984b; Winckler et.al., 1985; Winckler et.al., 1986).

Hot Plasma

The heating of a plasma by an electron beam is a well recognized phenomenon and has been much discussed (see for example Grandal, Ed., 1982). The beam plasma interaction results in the electron beam kinetic energy being converted

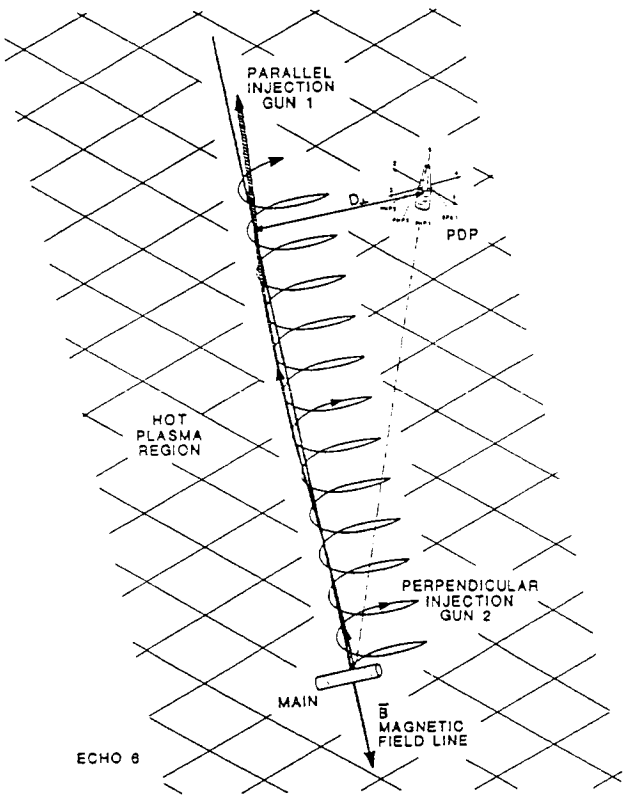

Figure 2. Geometry of the Plasma Diagnostics Package shown moving away from the main payload along its spin axis inclined 20 degrees to the magnetic field.

through basically the two-stream instability into turbulent electric fields similar to an RF discharge. These fields may be capable of accelerating the electrons in the ambient plasma to produce a discharge. This "beam plasma discharge" has been studied extensively in laboratory vacuum tanks and probably occurrs in space if the neutral density is sufficiently high (Galeev et.al., 1976; Hallinan et.al., 1984). Laboratory experiments, as well as the theoretical treatments of this subject, deal with the region close to the beam or even the region within the Larmor spiral of the beam itself. However, the ECHO 6 measurements clearly show that a much larger plasma region is heated and perturbed out to distances of 60m for the ECHO 6 beam which corresponds to 6 gyro radii from the beam center. This plasma region is heated very quickly, within 1 msec of beam turn-on, by a mechanism which must be an extension of the central beam plasma interaction but which certainly is not well understood. This hot plasma region contains strong electric fields generated by the beam as we shall discuss here in detail and also produces plasma and electromagnetic waves from the low ion gyro frequencies near 20 Hz up to very high frequencies probably up to the upper hybrid frequencies. Unfortunately, direct measurements of the plasma electron spectra or of the plasma parameters during beam injection were not obtained on the ECHO 6 experiment due to the failure of its electron spectrometer system and because the Langmuir probe was blocked by large floating potential changes of the PDP payload. Nevertheless, these floating potential changes, in themselves, provide a valuable measure of the hot plasma environment. They were observed by the probe-payload single potential differences and also could be observed by the shift in the low or cutoff energy of the ionospheric thermal ion spectra measured by the ion spectrometer. These two methods gave essentially the same result, but the minimum energy of the ions is a very convincing measure of the negative floating potential of the PDP with respect to plasma potential because the ions are accelerated through this potential difference from the ambient medium in order to reach the spectrometer. The use of this method has been developed by Arnoldy at the University of New Hampshire (Arnoldy and Winckler 1981) and others. That paper also presents good spectra of the hot electron plasma near the ECHO 3 beam-emitting rocket payload which may well be typical of the present ECHO 6 situation as well (see also Figure 7 in this paper). Electron and ion heating and acceleration by electron beams are discussed also in Arnoldy et.al. (1985) and by Winckler et.al. (1986). We show in Figure 3, in the lower panel; the PDP floating potentials as a function of flight time (bottom of figure) or perpendicular distance (top of figure) derived from the low energy cutoff of the thermal ion spectra, and in the upper panels, the magnetic north and east components of the quasi-DC electric field measured by the PDP probes. The curves correspond to a "down" injection at 15 degrees, as well as the 100 degree "out" and 180 degree "up" directions. The largest effects are produced by "out" injections in which the beam spirals with a gyro radius of 10m and produces electric field and floating potential effects out to 50m. It is difficult to assign an electron temperature to the plasma on the basis of the floating potential measurements, but spectra previously obtained have characteristic temperatures of several eV and a continuously falling spectra reaching

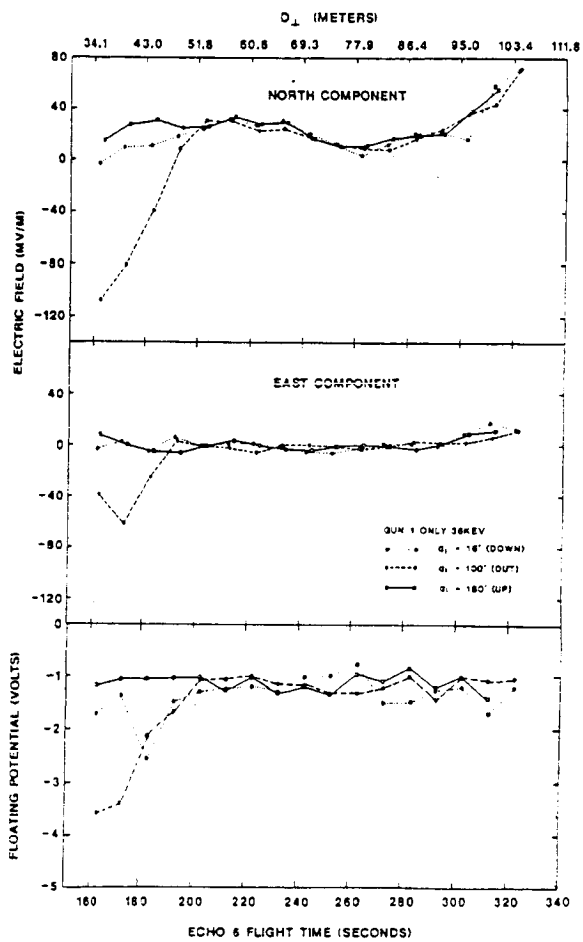

Figure 3. Electric field components in the earth reference frame showing the correlation of strong beam sector directed electric fields with the hot plasma region (lower panel floating potential). Perpendicular distance of the PDP from beam shown at top of figure.

nearly to the beam energy which in this case was 36 KeV.

Electric Fields

The quasi-DC electric field values shown in Figure 3 are averages over 50 msec intervals and represent the effects of the beam and the magnetospheric convection background in the earth reference frame but with wave frequencies higher than about 20Hz averaged out. These wave fields may be quite dramatic as shown by the example in Figure 4. This figure includes the effects of both accelerators and shows a strong low frequency rotating electric vector at 50 Hz (O+) and higher frequency components. The quasi-DC average field vector which has been subtracted is also shown and is typical of data used in constructing Figure 3. The north and east components of these average fields are negative, which means that the electric vector perpendicular to the magnetic field in the hot plasma region was directed inward but with a direction westward of the beam, while in the region outside the hot plasma beyond 50m, the fields showed only the predominately northward magnetospheric convection component. It is instructive to display these quasi-DC beam produced vector fields in the plane perpendicular to the magnetic field each 10s as the PDP moved away from the beam. To simplify the interpretation of the observed fields, the remaining vector field and flow patterns will be shown in the payload reference frame where the payload and the injected beam are at rest, and the observed field E' is given by E'= E + VXB where E is the total field in the earth reference frame and V is the rocket velocity perpendicular to B. Three such vector average E-field surveys are shown in Figure 5 corresponding to gun 1 only injecting down, out and up at 36 keV and 240 mA. The down injection passes by the PDP only after reflecting and scattering from the atmosphere 100 km below and produces little effect. The up injection is field aligned and passes the PDP which saw almost no effect in the range of radial distances surveyed beyond 40m. The large effects are produced by out injections spiralling almost perpendicular to the magnetic field. We note that as the flight progresses northward and descends, V decreases. When the PDP emerges from the hot plasma region near 60m (Figure 5, panel B) the strong inward fields disappear and the field vector E' rotates to an average northwesterly direction in the payload frame. This ionospheric field dominates the surveys in Figure 5 between 60m and the end of the data at 120m but in itself contains certain fluctuations characteristic of the ionosphere in the presence of an auroral arc. The ECHO 6 system did interact with an aurora, and we have discussed this in a previous publication (Winckler et.al., 1985).

At the beginning of data at accelerator turn-on, the PDP was about 34m radial distance from the beam and was 117m above the accelerator payload. It appears that very little effect was discerned of the positive potential of the main payload as shown by the lack of beam effect in Figure 5 panels A and C. but that the electric field patterns are those associated with the presence of the negative electron beam and the hot plasma surrounding it. Generally, the accelerator payload would be expected to have a potential of several hundred volts positive associated with the injection of the beam and the balance of the return currents from the ionospheric plasma. No direct payload potential

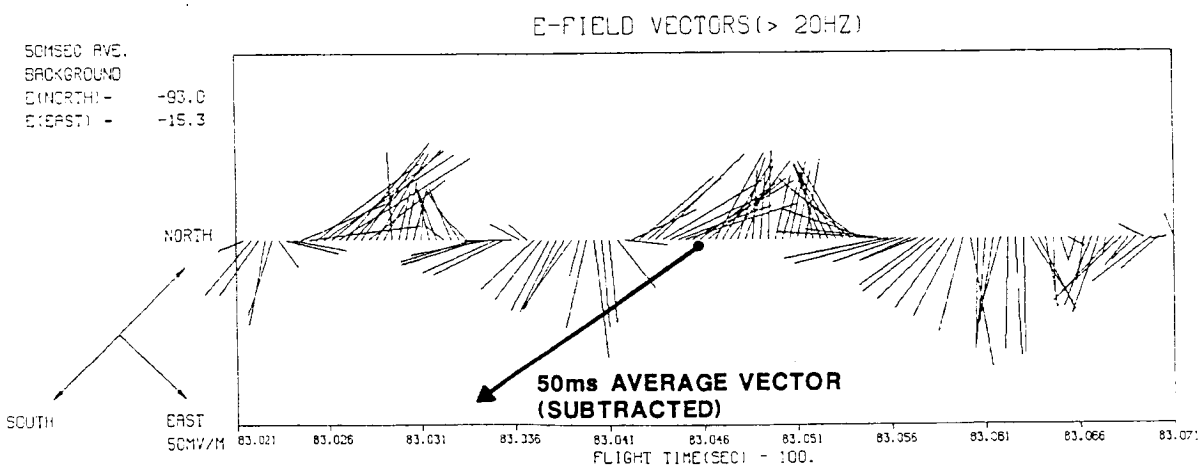

Figure 4. Maximum resolution data showing an electric field vector each 0.4 ms with the 50 ms average vector shown on the figure substracted. Earth reference frame. The rotational mode wave is probably an O+ gyro resonance.

measurements were made during the ECHO 6 experiment. Rocket payload potentials in the ionosphere have now been studied using deployable tethered subpayloads which give values in the range of several hundred volts and constitute the most reliable method to measure this potential (Raitt et.al., 1986). Figure 6 has been constructed to show not only the electric fields and flow directions corresponding to the gun 1 out injection but also a suggested hot plasma region, the beam geometry and reference dimensions. The unique plasma field with the ionospheric field in the rocket reference system subtracted is also shown as a dotted arrow. It is seen that none of the strong fields associated with the hot plasma are directed towards the beam. The question is "Why is this so?" and "What is the exact significance of these fields?" We must consider that the electron beam carries a negative space charge of significant proportions. This will be discussed somewhat later, but if the plasma fields were due to this space charge alone, one would expect symmetry around the beam gyro axis. There is also the problem that the PDP scan line in the magnetic perpendicular plane surveys only one radial region around the beam. Also, the measurements begin only at 34m radius which was the location of the PDP when the accelerator was turned on for the first time.

Plasma Flow

With a little imagination it is possible to construct a potential field and flow lines along the equipotentials which correspond to the hydro-dynamical case of a single vortex located in a uniform stream. Such a diagram is shown in Figure 7. The field has been constructed by assuming an axisymmetrical potential around the beam and a uniform flow corresponding to E+VxB. Since the external flow field is known, it is possible to construct the flow lines based on an average over the region exterior to the hot plasma when only the ionospheric effects were present. The flow pattern is brought around the beam in such a way as to correspond to the electric vectors measured inside 60m radius, and then the interior is merely a series of circles. The exact negative potential of the circulating beam is not known. However, in the diagram shown, one can construct a potential well, and this has been done along the line X-X and is shown in Figure 8. For the case shown, the potential dips to about -5 volts as given by the "observed" line. The classic vacuum potential of a line charge, which more or less fits the right side of this potential, is given by the dotted

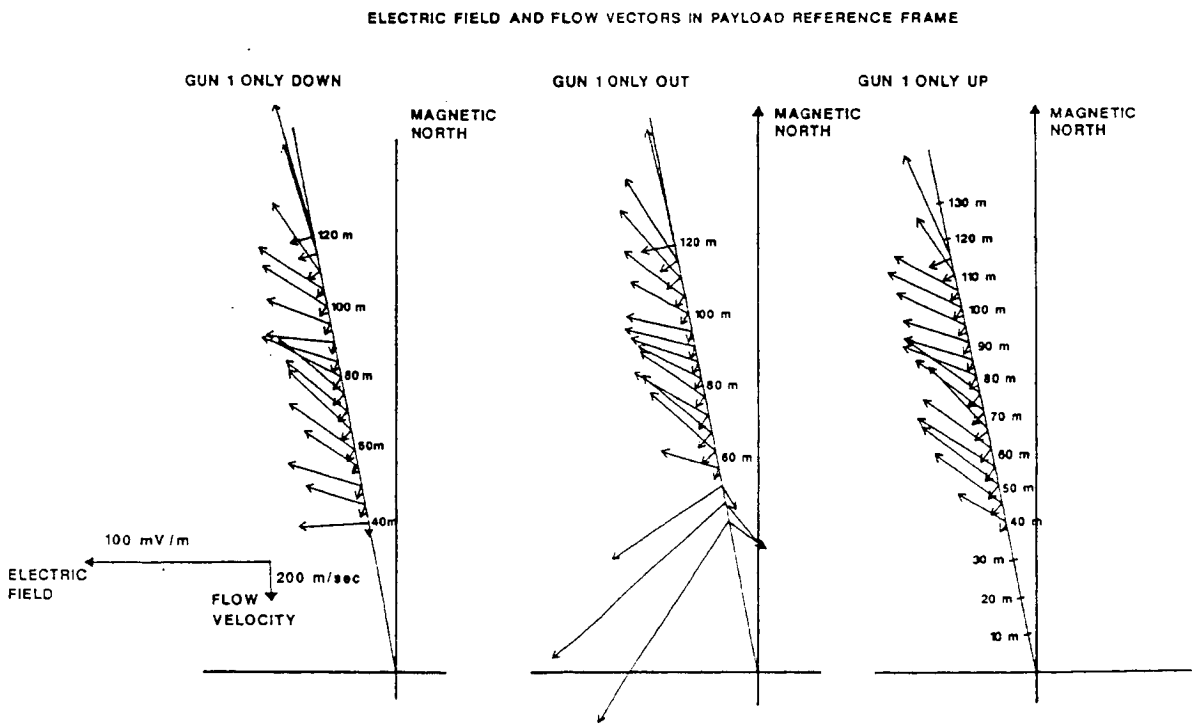

Figure 5. The electric fileds and flow vectors in a plane perpendicular to B in the payload references frame. These are 30 ms averages for times when only Gun 1 was injecting at 36 KeV and 240 mA in the down, out, and up pitch angle configuration.

curve, and the constants are included. Of course, the radial potential profile is not simply that of a line charge even close to the beam because of the plasma sheath which forms around it. Also, the pattern is asymetrical due to the external flow influence. Nevertheless, the basic origins of the flow pattern shown in Figure 7 cannot be very different from that discussed here.

We have checked the flow by a completely independent method; namely, to observe the streaming or ram direction of ionospheric thermal ions with the ion spectrometer. Some scan data are shown in Figure 9. These have been ordered in ten-second blocks corresponding to the program for the two accelerators shown at the bottom. Of

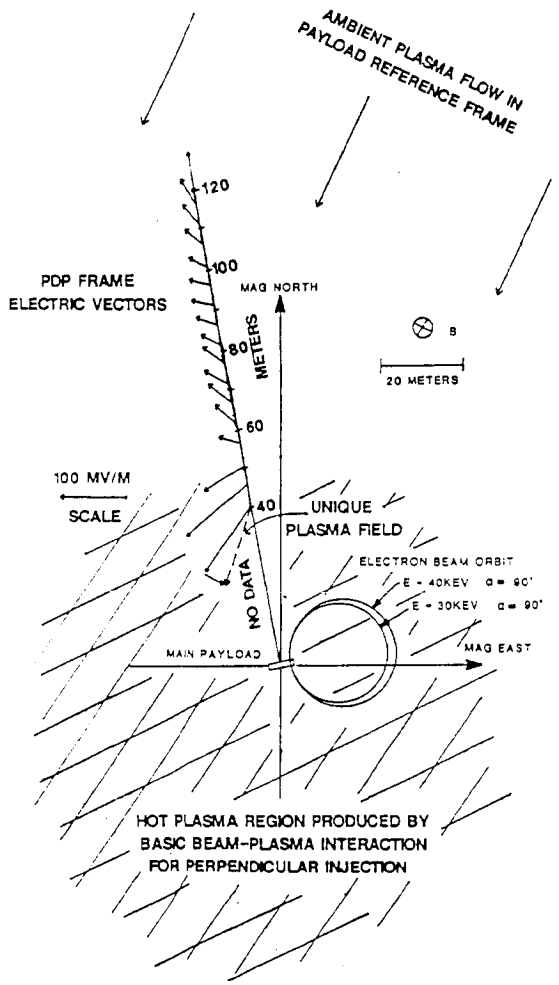

Figure 6. Summary of electric field and flow vectors in the payload references frame showing the beam and hot plasma region dimensions. Note the dotted arrow showing the unique plasma field with the ionospheric field subtracted.

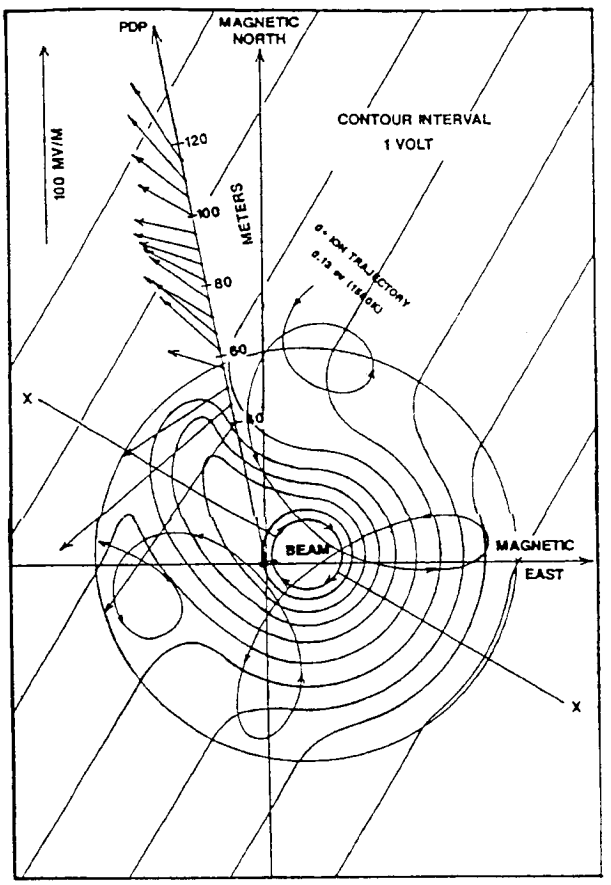

Figure 7. Flow patterns fitted to the observed electric fields for the out gun configuration. The circle shows the boundary of the hot plasma and beam associated electric field region. Contours within this region are very qualitative. A typical thermal ion trajectory is also shown. For the potential distribution along the line XX, see Figure 8.

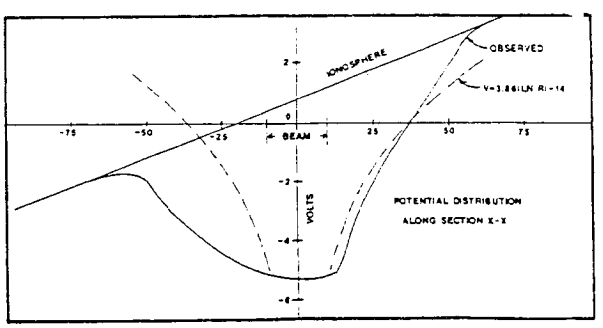

Figure 8. Transverse potential distribution along section XX in Figure 7. The electric field of a negative line charge in vacuum at the beam location is shown by the dashed curve.

particular interest is the down, the out and up configuration of Gun 1. The out configuration shown by the black bar corresponds to observing the thermal ions from a completely different direction than that characteristic of the background ionosphere traced out by the two outside parallel lines. At the top of the figure, the direction of observation is shown by a diagram. The center line corresponds to a direction nearly 150 degrees counterclockwise than normal. After the 170 second scan, the out configuration of the gun no longer coincides with the time at which the ion spectrometer could observe the ram direction of the thermal ions, and so a peak is not observed but only the systematic peaks on either side due to the "normal" ionosphere. However, even up to the 190 or 200 second traces, one can observe structure due to diversion of ions out of the normal pattern leaving gaps or irregularities caused by the turning on of the accelerator in blocks of time shown along the bottom line. We find that the ion measurements are in complete accord with the electric field boom measurements as regards the large shift in flow direction in the outer part of the hot plasma region. One must note that due to the superposed beam-produced wave activity, the ions are further perturbed with short time structures which are extremely complex and which have not been analyzed in detail up to this time.

The Beam as a Cylindrical Charge

The generation of a sheath around the beam comes from the action of the coulombic negative potential of the beam plus the space charge produced by the orbiting ions and the presence of the plasma electrons. It has been possible to uncover a dependence of these plasma fields on the linear charge density of the beam, because during a portion of the gun program, the beam was stepped through a series of pitch angles around 90 degrees, thus altering the parallel velocity of the beam from downward to upward and slowly changing the pitch of the spiral and the linear charge density associated with it. In Figure 10, we show that effect in a series of scans over pitch angle at each of a number of radial

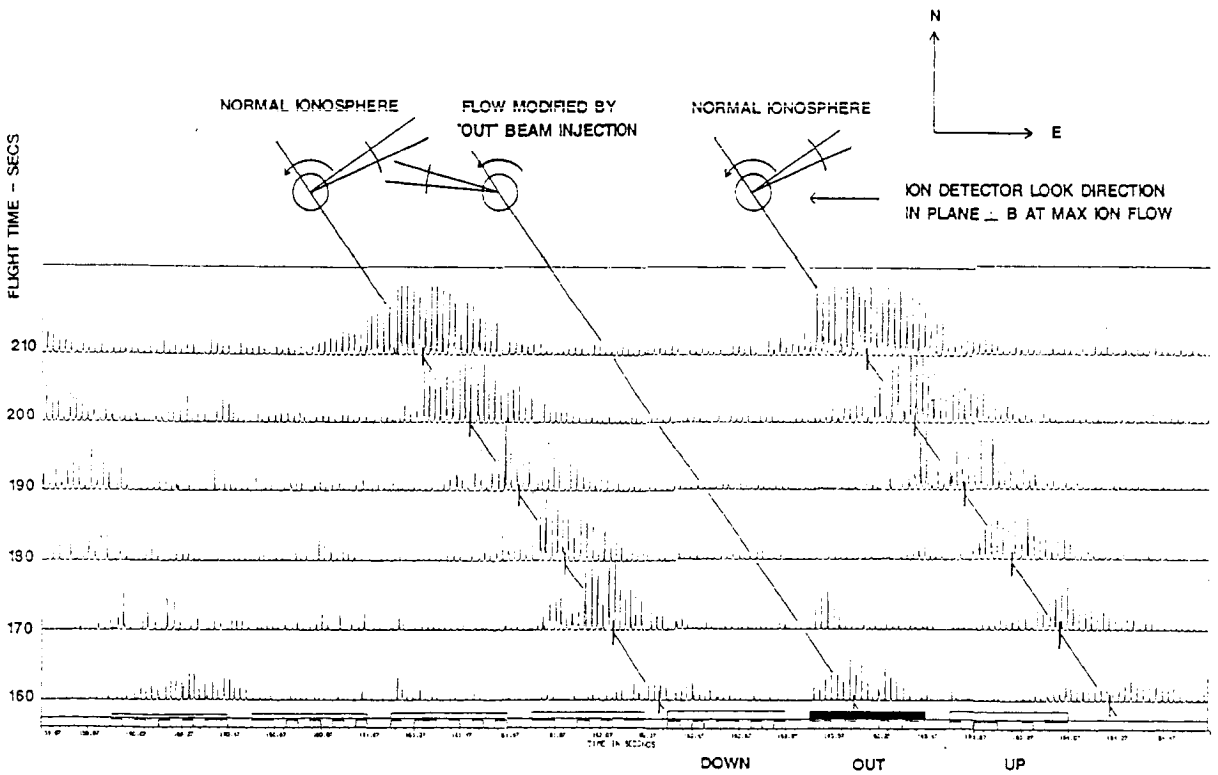

Figure 9. Ion drift detector (IDD) responses as the PDP rotated with a 2 second period. The data is organized by accelerator program times, so the times at which the ionospheric ion "ram" was seen lie on the indicated slant lines (ion look directions at top). During several accelerator "out" pulses, the ion "ram" direction is found approximately 140 degrees from the background flow direction, showing the effect of the accelerator-produced electric fields.

distances labelled on the curves in meters. It can be seen that downward injections at 88 degrees gave the smallest fields and that most of the curves maximize in the upward range between 90 degrees and 94 degrees, with a peak at 92 degrees. This is exactly what one would expect if we consider the divergence angle of the beam of about 2 degrees with the result that at 92 degrees all of the beam moves upward. The drop of the measured fields as the pitch angle increases can be caused by the decrease in linear density as the parallel velocity of the beam increases. Figure 10 was constructed when Gun 1 was injecting alone at a 15 KeV energy and a current of about 57 mA. The electric fields obtained with the full power of 36 KeV, 240 mA and a pitch angle of 100 degrees (called "out" injections) are actually similar to the peak values shown in Figure 10.

The equivalent cylindrical (or line) charge of the beam is given by L(C/m) = I/((1.88x10*7) K*1/2 cos a) where I is the beam current in amperes, K the energy in keV and a the pitch angle in degrees. Application of Gauss's law gives the electric field at distance R(m) as E(mV/m) = 1.8x10*13 L/R in a vacuum. Thus one obtains 9900 mV/m at 40m distance from a 15 keV 57mA beam at 92 degrees pitch angle in vacuum. This is about 100 times the observed range of values, a difference attributable to the neutralization of the beam charge by ions forming a sheath in the hot plasma region around the beam.

It is thus quite certain that we are observing the negative coulombic charge of the beam with its accompanying circulating flow imbedded in the

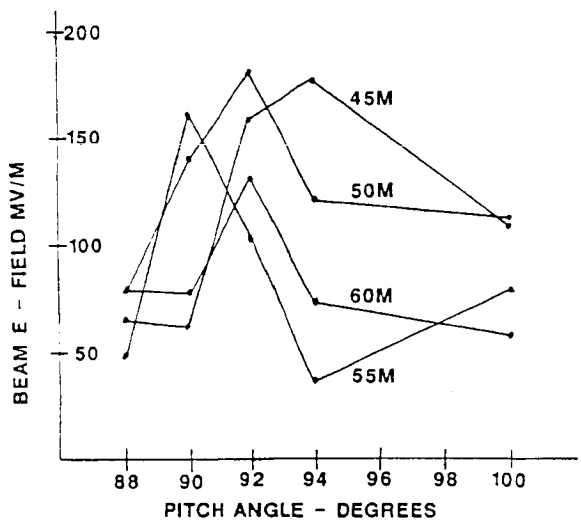

Figure 10. Average electric field in the payload reference system at various distances along the PDP survey line as a function of beam pitch angle near the perpendicular direction. Gun 1 only at 15 KeV, 57 mA.

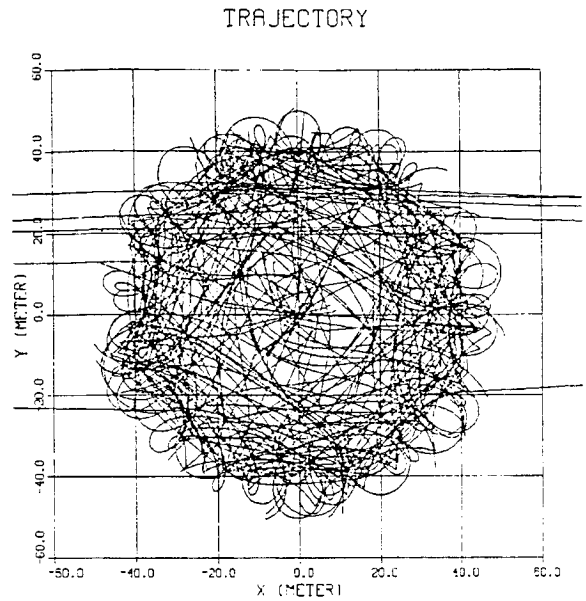

Figure 11. Some typical thermal ion trajectories in a negative axisymmetric potential well. Courtesy of Y. Abe.

external uniform flow field of the ionosphere. It is in this framework that the various wave phenomena observed can arise. To derive theoretically a more exact potential for comparison with observations, one would have to do a self-consistent computation of the ion orbits in the classical vacuum potential of the beam and iterate the charge density in the sheath a number of times to converge on a final steady state solution for the sheath potential. We show in Figure 11, a figure constructed by Y. Abe to illustrate the first step in such a calculation. We have also shown in Figure 7 more or less to scale an orbit of an oxygen ion of 0.13 eV (1500 k) energy. This ion is drifting and precessing in the direction of the external flow lines, falls through the potential of the beam, accelerates and gyrates a few times before escaping. This trajectory is only for illustration and is not exact except in the external region.

ELF Wave Production

Finally, we comment on the ELF wave effects actually observed in the flow pattern shown here. The wave production depends strongly on the conditions of the observed beam injection such as the pitch angle, the type of beam with the discrete or the continuous energy spread from either Gun 1 or Gun 2 and also on the radial distance. The matrix-montage shown in Figure 12 was obtained from three configurations of Gun 1

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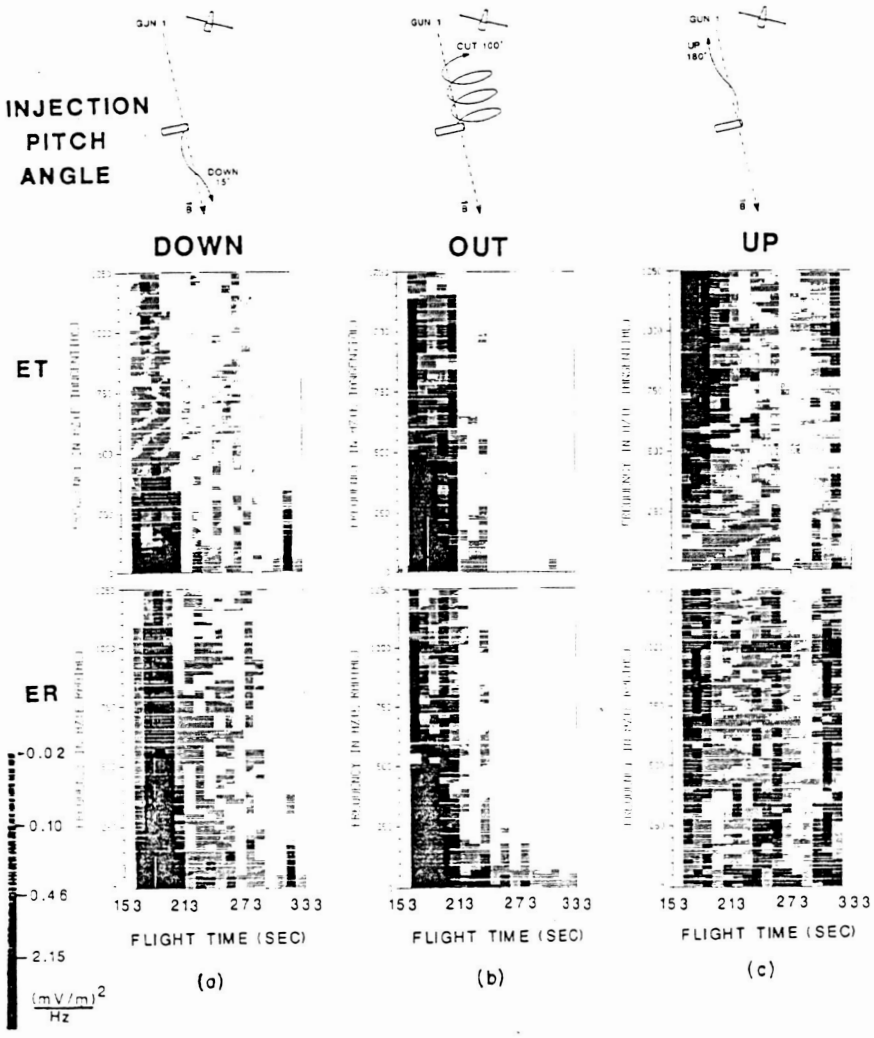

Figure 12. ELF wave spectrograms sorted according to down, out and up injections of Gun 1 only in the transverse and radial polarization components. Note that the up injection concentrates the wave energy towards the lower hybrid range above the 1250 Hz Nyquist frequency, but out and down injections are concentrated below 500 Hz. Intense wave activity is mainly in the hot plasma region (see lower panels). Wave activity dropped near 80 m when the system passed through auroral field lines.

at full power of 36 KeV and 240 mA when injected down, out or up and the wave spectrograms have been constructed for the transverse polarization and the radial polarization as a function of distance from the beam. We comment here only on the very striking fact that the downward and outward orientations produce large power at very low frequencies up to a radial distance corresponding closely to the hot plasma region. The upward injections, on the other hand, produce power largely in the transverse mode and reaching a maximum beyond our Nyquist frequency of 1250 Hz with low power below 200 Hz. It is in this configuration that a strong proton-gyro resonance has been observed as discussed in a previous publication (Winckler et.al., 1984). It has been suggested by Professor Paul Kellogg that low frequency waves generated in the hot plasma region may be due to a Buneman type instability caused by the rotating electron plasma passing through the randomized ion sheath (see also, Kellogg et.al., 1982).

The New ECHO 7 Mission

We are implementing a new ECHO mission which may be the last in the series and will be launched in November 1987 from the Poker Flat range in Alaska. This mission combines all of the experiences with the previous six flights to optimize both the conjugate echo and magnetospheric studies and the beam plasma physics. To guarantee the interception of echoes, ECHO 7 will be launched on a magnetically eastward trajectory like ECHOS 1, 2, 3, and 4. This will result in the interception of echoes during a limited portion of the flight. However, there will be four separate sections of the payload which are deployed, and all will be capable of echo detection. Two of these, a PDP like that used in the ECHO 6 mission described above and a second similar section called the Energetic Particle Package (EPP), will carry more sophisticated echo detectors in the form of large aperture electrostatic analyzers using microchannel plate detectors and amplifier systems. These energy spectrometers will be backed up by scintillation counters on all of the payloads and directed over a range of pitch angles. Since three of the subpayloads will be separated from the accelerator payload, the blanking of echo signals by the presence of the injected beam on the accelerator payload, as was encountered with the earlier ECHO flights, will be avoided. Also, the payloads will spread out in a certain region around the beam injecting field line as shown in Figure 13, which will increase the echo detection time during the flight. It is planned to launch the Terrier-Black Brandt (Black Brandt 9) eastward just to the south of a stable, discrete auroral arc in the presence of northerly magnetospheric convection electric fields in the evening sector of the magnetosphere. The experiment will thus be conducted in the diffuse auroral region, and it will probably not be possible to cross the aurora as was accomplished with ECHO 6.

The mission includes extensive beam plasma studies. The nose cone will be equipped by the Kellogg group at Minnesota with a plasma waves analysis system and includes a Langmuir probe and a scintillation counter to detect beam energy particles. The nose cone experiment will be launched upward parallel to the magnetic field and will thus remain near the injected beam (reference Figure 13). The PDP will be injected to the south at a 10 degree angle to the magnetic field and will contain orthogonal electric booms, as in ECHO 6, for studying the ELF range up to 2500 Hz. It will also contain ion and electron spectrometers and an imaging ion spectrometer for searching for perpendicular ion acceleration near the beam. This payload will contain a television camera which will view the beam injecting payload continuously during the flight to study the

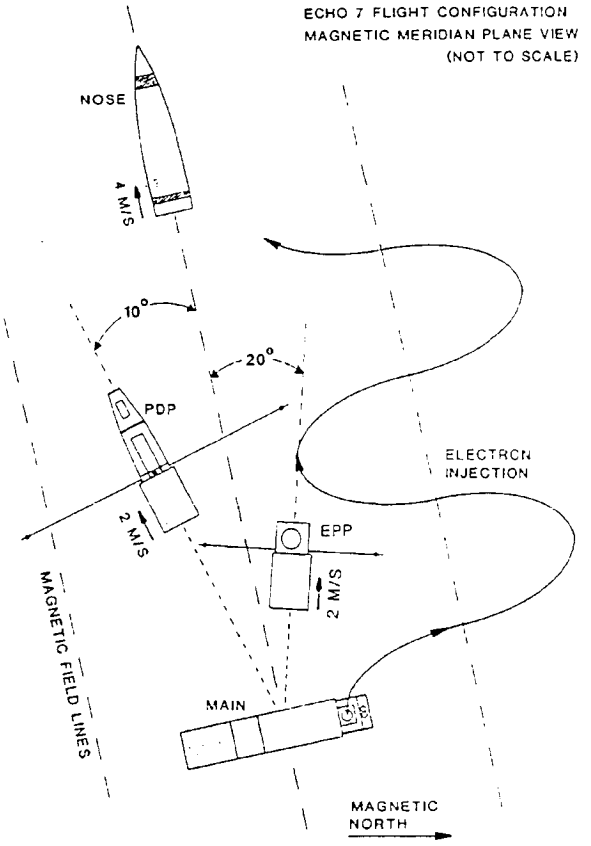

Figure 13. The ECHO 7 payload disposition in flight. Three deployable payload sections will carry wave and particle instrumentation, search for conjugate echoes and study plasma and electromagnetic radiation from the main accelerator payload.

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distribution of luminosity in the hot plasma region. It will also contain arrays of photometers and the major echo detecting system described above. The EPP will contain a major plasma and electromagnetic wave detection system furnished by the Ernstmeyer group at the Air Force Geophysics Laboratory and will also include an orthogonal boom system in the ELF electric field range up to 1250 Hz. Both EPP and PDP will also carry magnetic antennas for wave studies. The main payload will contain a single accelerator of the type flown on ECHO 6, capable of 40 KeV maximum at 250 mA. This payload will be implemented in its entirety by the Malcolm group at the Air Force Geophysics Laboratory. It will have a magnetically controlled pitch angle system, and the payload will contain some photometric and particle detectors. This payload will also deploy a small tethered subflyer which will extend to several hundred meters distance and study the beam-emitting payload potentials with respect to the undisturbed plasma medium. The experiment is aimed at a comprehensive probing of the distant magnetosphere and also to extend the studies of the electric fields and plasma flow discussed in this paper with two-point measurements simultaneously in the flow pattern. It is also hoped to explore the origin of the hot plasma region and to investigate basic mechanisms of wave production by the electron beam over a very wide frequency range essentially from DC to above the upper hybrid frequency.

Acknowledgements

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POSTER ABSTRACTS

N87-20078

Large manned systems/environment interactions in low earth orbit (LEO)

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With the advent of the NASA Space Transportation System, regular flights of a large manned spacecraft, the Space Shuttle Orbiter, became a reality. From the earliest mission containing space science instruments as a payload on the third flight of the Orbiter (STS-3), it became apparent that the disturbance caused by the interaction of this orbiting system with the low earth orbit (LEO) environment resulted in adverse conditions for the performance of scientific observations of the Orbiter natural environment and for certain high sensitivity optical observations.

The interaction of the Space Shuttle Orbiter system can be divided into two parts, the structure-environment interaction, and the outgas cloud-environment interaction. The structure interaction in the generation of neutral and plasma wakes, and the induced **V x B** electric fields were expected and have been clearly observed by several workers (Shawhan et al., 1984; Raitt et al. 1984; Murphy et al., 1986; Siskind et al., 1984). However, the degree of the outgas cloud interaction was unexpected. It has now been established that the Orbiter carries up a large quantity of water adsorbed to its surfaces and absorbed in the porous thermal control tiles. This water outgasses during the flight and interacts with the ambient environment to generate an area of turbulent ionospheric plasma around the vehicle serving as a possible source for the generation of contaminant ion species (Carignan and Miller, 1983; Wulf and von Zahn, 1986; Pickett et al., 1985; Raitt et al., 1984). The energetics of the formation of contaminant ions could result in the presence of excited species which would result in an increase in the background light level for instruments viewing through the cloud produced (Torr et al., 1985). If we allow that the outgas cloud extends to adsorbed material on the surface, then another major effect is the visible - near IR glow observed on the ram-side Orbiter surfaces (Banks et al., 1983; Swenson et al., 1985, 1986; Slanger, 1986). Measurements undertaken to date on several Space Shuttle Orbiter flights have shed some light on the properties and results of the various interactions, however the studies have left much to be investigated to be able to approach an understanding of the phenomena, and to thereby enable predictions to be made on the interaction of an even larger manned system with the environment when the Space Station becomes a reality.

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N87-20079

CONTROLLING AND MONITORING THE SPACE-STATION/PLASMA INTERACTION

--- A BASELINE FOR PERFORMING PLASMA EXPERIMENTS AND USING ADVANCED TECHNOLOGY

by

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ABSTRACT

1. The size, complexity, and motion of Space Station through the earth's environmental plasma means that there will be a large, complicated interaction region, involving a sheath, wake, charging of surfaces, induced electric fields, secondary emission, outgassing with ionization, etc.

2. This interaction will necessarily be a factor in carrying out and interpreting plasma experiments and in the use of certain technologies.

3. Attention should be given ahead of time to:

(1) Monitoring this interaction so that it is well described: A diagnostics module for measuring both the environmental plasma and the spacecraft induced plasma effects should be placed in several locations on the spacecraft. It should measure both neutral and charged particle distribution functions including composition, magnetic and electric fields, and the spacecraft potential and surface differential potentials.

(2) Simplifying the interaction by appropriate design and construction of the spacecraft and by appropriate planning of technology use: This could be done, for example, by electrically separating different parts of the spacecraft and biasing them at different potentials, and by using conductive films and special coatings with selected secondary and photoemission properties on the spacecraft surfaces.

(3) Controlling the interaction by both active and passive means: Plasma emitters for modifying and controlling the spacecraft charge should be placed in several locations. Portable electrostatic shields could be deployed around noisy sections of the spacecraft in order to carry out sensitive experiments. A particle "umbrella" could be raised to deflect the ram ions and neutrals in order to provide a controlled environment.

N87-20080

SPACECRAFT CHARGING IN THE AURORAL PLASMA: PROGRESS TOWARD UNDERSTANDING THE PHYSICAL EFFECTS INVOLVED

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ABSTRACT

The work presented here is in four parts. In the first, we review the main differences between the plasma environments in geostationary orbit and low polar orbit with regard to high-voltage charging situations. We next present results from a calculation of secondary-electron escape currents from negatively-charged spacecraft surfaces having various orientations relative to the local magnetic-field direction. We show that for finite ranges of combinations of electric and magnetic field directions, secondary-electron escape is completely suppressed and therefore cannot help to discharge the spacecraft. In such circumstances, secondary electrons may travel distances many times their gyroradii before reimpacting, and this may produce greatly increased secondary-electron surface currents. Thirdly, we develop a simple rough estimate of the required conditions for high-voltage auroral-zone charging. The results suggest that for any given spacecraft, surface potentials are likely to depend more strongly on the ratio of ambient flux of high-energy electrons to that of all ions, than on any other environmental parameter. Finally, we present preliminary results of numerical simulation work directed towards testing this hypothesis. Numerical instabilities encountered in doing this simulation work probably are closely related to physical sensitivities inherent in the physics of the ion wake behind the spacecraft, and especially to beam-like constituents of the ion population in the wake.

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N87-20081

Electrostatic Charging of Electrically Active Spacecraft

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ABSTRACT

A model is presented which predicts the temporal behavior of the ionospheric charging of spacecraft which eject energetic positive ions. The dynamic interaction of the spacecraft with the space-plasma environment is modelled as an equivalent electrical circuit consisting of a variable capacitor in parallel with two current sources. The spacecraft/space-plasma sheath is modelled as a variable capacitor containing positive-ion space charge. The ejection of energetic positive ions from the spacecraft represents a current source which charges the capacitor. Return current collected from the space-plasma sheath to the spacecraft is modelled as a variable current source which discharges the capacitor. The model can predict the temporal behavior of sheath movement, spacecraft potential, and space-plasma return current for a wide range of altitude, duty cycle, and ejected positive-ion current. Experimentally measured charging results, obtained for the Satellite Positive Ion Beam System (SPIBS) rocket flight, are accurately predicted by the model. Anticipated vehicle charging levels are presented for neutral-particle-beam platforms operating with a net, unneutralized, positive-ion-current component present in the emitted neutral-particle beam.

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N87-20082

Vehicle Charging of the Shuttle Orbiter During Electron Beam Emission

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The Vehicle Charging And Potential (VCAP) experiment has flown as part of shuttle missions STS-3/OSS-1 in March 1982 and STS-51F/Spacelab-2 in July/August 1985. During these missions, a 1 keV electron beam was emitted with currents of 50, 100 and 150 mA. The Orbiter response to electron beam emission was measured by a charge and current probe located in the payload bay. Examination of these vehicle charging and return current signatures has revealed a variety of unanticipated signatures in addition to several expected results.

Principle results include (1) enhanced vehicle charging when the engine nozzles are in the wake, due to the reduced access of the ambient electrons to conducting surfaces on the Orbiter, (2) return current density measurements which range between zero and 7.5 mA/m^2, consistent with the collection of all incident thermal electrons in certain attitudes, and (3) thruster firing events during electron beam emission with plumes which limit return current to conducting surfaces on the Orbiter, thereby requiring the Orbiter to assume a more positive potential. Current probe measurements during these events may record either a reduced return current if the thruster plume covers the current probe, or an enhanced current due to the increased vehicle potential if the probe is located away from the thruster plume.

Several features of the data are not adequately explained and are still under investigation. These include (1) large decay time events in which return currents require several seconds to decay to quiescent levels after beam emission terminates, (2) large rise time events in which return currents require several seconds to achieve an equilibrium during beam emission, (3) widely varying amounts of turbulence on return current signature. In one case, this turbulence reaches a maximum as the angle between the magnetic field and the electron beam passes through zero.

N87-20083

GROUND TESTING IN A SIMULATED AURORAL ENVIRONMENT

by

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Shuttle polar orbit missions are being planned in which astronaut extravehicular activities (EVA) will eventually include external operations or repair and refurbishment of satellites. Recent satellite data and model calculations show that significant spacecraft charging and differential charging occurs in that environment and could endanger equipment and personnel involved in the EVA. These spacecraft charging events take place in response to an intense flux of high energy electrons accompanied by a large drop in the ambient plasma density.

The purpose of this paper is to determine the extent to which the auroral environment can be simulated in a large vacuum chamber so that conditions which lead to significant charging and discharging may be observed and controlled. A large chamber, such as the Chamber A facility at the Johnson Space Center or the Mark I facility at AEDC in Tullahoma, would be required in order to simulate the effects of an aurora-like, large cross-section, energetic electron precipitation on a target system the size of an astronaut with a life support system. The precipitating electrons can be simulated with an array of multipactor sources and the background ionization produced by the beam can be limited to the range of the auroral density if the chamber pressure is not significantly above 1×10^{-6} Torr. Some small chamber work has shown that the plasma in the beam will diffuse radially at a rate determined by the Bohm diffusion coefficient.

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N87-20084

COMPUTER MODELS OF THE SPACECRAFT WAKE

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Abstract

Until recently, computations of space plasma flow over a spacecraft have been unstable for ratios of spacecraft dimension to Debye length typical of the low earth orbit environment. We present calculations of the spacecraft/environment interaction based on two computer codes, MACH and POLAR.

We have developed MACH, an inside-out particle tracking code, for the purpose of validating the physics of POLAR in regimes where there are no comprehensive theoretical or experimental results. While the spacecraft which can be treated by MACH are restricted to simple geometries, the methodology is more fundamental than POLAR. MACH generates self-consistent solutions within the context of quasisteady Vlasov plasma flow and achieves Debye ratios previously unobtainable.

POLAR uses a three-dimensional finite-element representation of the vehicle in a staggered mesh. The plasma sheath is modeled by outside-in particle tracking. Solutions for the plasma flow, wake and vehicle charging are obtained by Vlasov-Poisson iteration; charge stabilization techniques make the results virtually insensitive to the Debye ratio. POLAR reproduces the Laframboise static plasma solutions for spherical probes and fits the Makita-Kuriki probe data for spheres in a flowing plasma in regions where comparisons are valid.

POLAR and MACH solutions for the particle and electrostatic potential structure of the wake of a charged disk in a low-altitude flow are shown for Mach numbers 4, 5, and 8. New features of the solutions include ion focussing in the wake and a definitive determination of the sheath edge in the wake which shows that the sheath is not an equipotential.

N87-20085

A Plasma Generator Utilizing the High Intensity ASTROMAG Magnets

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The magnet configuration for the proposed particle astrophysics magnet facility (ASTROMAG) on the Space Station includes a cusp magnetic field with an intensity of a few tesla. With these large magnets (or others) located in the outer ionosphere, many quite interesting and unique plasma physics experiments become possible. First, there are studies utilizing the magnet alone to examine the super-sonic, sub-Alfvenic interaction with the ambient medium; the scale length for the magnet perturbation is ≈ 20 m. The magnetic field geometry when combined with the Earth's and their relative motion will give rise to a host of plasma phenomena: ring nulls, x-points, ion-acoustic and lower-hybrid shocks, electron heating (possible shuttle glow without a surface), launching of Alfven waves, etc. Second, active experiments are possible for a controlled study of fundamental plasma phenomena. A controlled variable species plasma can be made by using an RF ion source; use of two soft iron rings placed about the line cusp would give an adequate resonance zone (ECH or ICH) and a confining volume suitable for gas efficiency. The emanating plasma can be used to study free expansion of plasma along and across field lines (polar wind), plasma flows around the space platform, turbulent mixing in the wake region, long wavelength spectrum of convecting modes, plasma-dust interactions, etc.

APPENDIX A

ADDITIONAL PAPERS

This appendix contains three papers contributed by Professors Hannes Alfvén and Carl-Gunne Fälthammar discussing the relation of studies of solar system plasmas to laboratory and astrophysical plasmas.

N87-20086

MAGNETOSPHERE-IONOSPHERE INTERACTIONS - NEAR EARTH MANIFESTATIONS OF THE PLASMA UNIVERSE

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Abstract

As the universe consists almost entirely of plasma, the understanding of astrophysical phenomena must depend critically on our understanding of how matter behaves in the plasma state. *In situ* observations in the near Earth cosmical plasma offer an excellent opportunity of gaining such understanding. The near Earth cosmical plasma not only covers vast ranges of density and temperature, but is the site of a rich variety of complex plasma physical processes which are activated as a result of the interactions between the magnetosphere and the ionosphere.

The geomagnetic field connects the ionosphere, tied by friction to the Earth, and the magnetosphere, dynamically coupled to the solar wind. This causes an exchange of energy and momentum between the two regions. The exchange is executed by magnetic-field-aligned electric currents, the so-called Birkeland currents. Both directly and indirectly (through instabilities and particle acceleration) these also lead to an exchange of plasma, which is selective and therefore causes chemical separation. Another essential aspect of the coupling is the role of electric fields, especially magnetic field aligned ("parallel") electric fields, which have important consequences both for the dynamics of the coupling and, especially, for energization of charged particles.

1. INTRODUCTION

Ionized matter - plasma - is the overwhelmingly dominating constituent of the universe as a whole. Matter in the plasma state is characterized by a complexity that vastly exceeds that exhibited in the solid, liquid and gaseous states. Correspondingly, the understanding of the physical, and especially the electrodynamical, properties of the plasma are still far from well understood.

These properties are still subject to basic research, and many fundamental questions remain to be answered. However, important progress has been made recently as a result of experiments in the laboratory and in those regions of space accessible to in situ observations and experimentation.

While it is universally acknowledged that our universe is a plasma universe, it seems to be far from fully realized that the physical understanding of this universe depends critically on our understanding of matter in the plasma state, In fact, the recent progress in plasma physics should provide a much improved foundation for understanding astrophysical processes in the universe of the present - as well as cosmogonic processes of the past. So far the increasing insight into the behaviour of matter in the plasma state has not been widely applied to astrophysics. To make full use of this insight should be a very important step toward a better understanding of our plasma universe.

A brief look at the evolution of plasma physics is useful in establishing an appropriate perspective.

Early plasma experiments were limited essentially to cool and/or weakly ionized plasmas. They formed the limited empirical basis on which the classical plasma theory was built. This theory was developed into a high degree of mathematical sophistication and was believed to have general validity. One of the predictions based on it was that magnetic confinement of plasma should be rather easy, and thermonuclear fusion possible within 15 years.

When the thermonuclear effort made it possible to produce and study hot and higly ionized plasma in the laboratory, it was found that the plasma exhibited many kinds of unpredicted, "anomalous" behaviour. The "thermonuclear crisis" that resulted led to the start of a new epoch in thermonuclear research, characterized by a close interplay between experimental and theoretical research. This has led to impressive progress in solving plasma physical problems that are vastly more complex than envisaged by classical plasma theory.

Similarly, in space research it was widely believed that the cosmical plasma would have negligible resistivity, as predicted by classical formulas, and behave essentially as an ideal MHD medium. If so, the electric field would be a secondary parameter of little importance, and magnetic-field-aligned ("parallel") electric fields out of the question. As a consequence, the electric field and especially the magnetic-field-aligned electric field, which we now know to be of crucial importance, were long disregarded. Even to this day, only very few attempts have been made at directly measuring electric fields in the outer magnetospere.

The magnetosphere was universally assumed to be populated by a hydrogen plasma from the solar wind, whereas we now know that it is sometimes dominated by oxygen plasma originating in the Earth's own atmosphere. As a result of generally accepted theories, one did not even do the appropriate measurements until recently of outflowing ions and of magnetospheric plasma composition. Much of this delay could have been avoided, if results already known from laboratory plasma experiments had been applied to the space plasma. (In fact, on this basis Hannes Alfvén proposed parallel electric fields as an accelerating mechanism for auroral primaries already in 1958, but the idea was almost universally refuted as contrary to classical theory.)

It is a sobering fact that even after hundreds of satellites had circled the Earth, the generally accepted picture of our space environment was still fundamentally wrong in aspects as basic as the existence and role of electric fields and even the origin and chemical composition of the near Earth plasma itself. In the light of this, how can we believe in detailed theoretical models of distant astrophysical objects, until we have learned - and applied to astrophysics - the lessons of how the real plasma behaves in the Earth's own magnetosphere.

2. THE MAGNETOSPHERE - IONOSPHERE SYSTEM

The Earth's ionosphere and magnetopshere constitute a cosmical plasma system that is readily available for extensive and detailed *in situ* observation and even active experimentation. Its usefulness as a source of understanding of cosmical plasmas is enhanced by the fact that it contains a rich variety of plasma populations with densites ranging from more than 10^{12} m^{-3} to less than 10^4 m^{-3} and temperatures from about 10^3 K to more than 10^7 K (equivalent temperature). Even more importantly, this neighbourhood cosmical plasma is the site of numerous and complex plasma physical processes which for example lead to particle acceleration and element separation. The understanding of these processes should be essential also to the understanding of remotely observed astrophysical phenomena that take place in plasmas that will remain out of reach of *in situ* observation (Fälthammar *et al*. 1978; Haerendel 1980, 1981; Fälthammar 1985). For example, one of the outstanding characteristics of cosmical plasmas is their ability to efficiently accelerate charged particles. Many kinds of particle acceleration take place in the near Earth plasmas, and this allows us to study in detail the mechanisms responsible.

A basic reason why the near-Earth plasmas are so active in terms of plasma physical processes is the coupling that the geomagnetic field imposes between the hot thin magnetospheric plasma, which is dynamically coupled to the solar wind and the

cool, dense inospheric plasma, which is tied by friction to the Earth (Vasyliunas 1972; Greenwald 1982).

This situation causes an exchange of momentum and energy between the two regions. The exchange is executed through electric currents - the Birkeland currents - flowing between them. Both directly and indirectly (through the instabilities and acceleration that they cause) the Birkeland currents also lead to an exchange of matter between the magnetosphere and the ionosphere. The exchange of matter is selective, so that the chemical composition of the ionospheric plasma that populates the magnetosphere is very different from that of its source. The very efficient element separation that hs unexpectedly been discovered in the near-Earth plasma, and is accessible to *in situ* investigation there, should also be of considerable astrophysical interest.

The present paper will concentrate on some crucial aspects of the magnetosphere-ionosphere system, namely the electric fields and currents and their role in particle acceleration, plasma transport and chemical separation.

3 BIRKELAND CURRENTS

A phenomenon of paramount importance for the coupling between the magnetosphere and the ionosphere is that of Birkeland currents. In addition to being prime agents for exchange of *momentum* and *energy* between the two regions they also play an important role in redistributing *matter* between them. The energy coupling between the magnetosphere and ionosphere by means of the Birkeland currents was recently discussed by Sugiura (1984).

A reason why the Birkeland currents are particularly interesting is that, in the plasma forced to carry them, they cause a number of plasma physical processes to occur (waves, instabilities, fine structure formation). These in turn lead to consequences such as acceleration of charged particles, both positive and

negative, and chemical separtion (such as the preferential ejection of oxygen ions). Both these classes of phenomena should have a general astrophysical interest far beyond that of understanding the space environment of our own Earth.

3.1 The distribution of Birkeland currents

Although predicted by pioneers like Birkeland and Alfvén the existence of electric currents connecting the magnetosphere and ionosphere apparently came as a surprise to many. In fact the first measurements revealing the magnetic effects of what we now call Birkeland currents were initially interpreted as standing Alfvén waves above the auroral zone (see Dessler 1984).

Since then the Birkeland currents have been investigated by means of many satellites. Their general large scale distribution at low altitude (Fig. 1) is well established and described in an extensive literature. Much of the knowledge as of 1983 is summarized in the AGU Geophysical Monograph 28 edited by Potemra (1984). A concise review of field aligned as well as ionospheric current systems was given by Baumjohann (1983). Recent papers on the distribution of Birkeland currents are those of Potemra et al. (1984), Zanetti et al. (1984), Araki et al. (1984), Iijima et al. (1984), Potemra and Zanetti (1985) and Hruska 1986. A new Birkeland current system, flowing in and out of the polar cap and intensifying during periods of northward interplanetary magnetic field has recently been described by Iijima et al. (1984). It is referred to as the NBZ system (for Northward B_z). Birkeland currents in the polar cusp have a pronounced dependence on the y-component of the interplanetary magnetic field. These currents may reflect the most direct coupling between the solar wind generator into the ionsophere (Potemra et al. 1984; Potemra and Zanetti 1985; Clauer et al. 1984; Clauer and Kamide 1985; Zanetti and Potemra 1985).

Very recently the dependence of Birkeland currents and plasma convection patterns on B_y have been investigated by means of Dynamics Explorer data both for southward and northward B_z (Burch et al. 1985; Reiff and Burch 1985).

In recent theoretical studies Kan et al. (1984) and Marklund et al. (1985) have investigated the role of partical blocking of secondary Birkeland currents in causing the rotation of the ionospheric electric field pattern observed during substorms. The degree of closure of secondary Birkeland currents (associated with gradients in the height integrated ionospheric Pedersen conductivity) also plays a key role in a new model of the westward travelling surge developed by Rothwell et al. (1984).

Within the large scale Birkeland currents there exist fine structures in the form of thin current sheets with extreme current densities. A case reported by Burke et al. (1983) and Burke (1984) is shown in Fig. 2. The sharp downward and upward slopes of the narrow dip in the magnetic field component B_y correpond to a pair of thin upward and downward Birkeland current sheets. The upward current sheet had a latitudinal extent of less than 2 km and an average current density of $135 \cdot 10^{-6}$ A m^{-2}. In the downward current sheet of the same event the current density was $15 \cdot 10^{-6}$ Am^{-2}. The authors note that the upward currents were carried by electrons that appeared to have fallen through a potential drop of a few kV. Also, the observed electron population, the relation between current density and accelerating voltage nearly (but not quite) agreed with adiabatic motion in the mirror field. (The voltage or the source plasma density or both would need to be a little higher than estimated.) The measured electron temperature, about 200 eV, did not indicate any substantial heating, which would be expected if anomalous resistivity played a major role. For the downward currents, which could readily be carried by upflowing cold ionospheric electrons, conditions at the 1000 km satellite altitude are close to the limit for ion cyclotron instability.

Recently Bythrow et al. (1984) have reported very high current densities - up to $94 \cdot 10^{-6}$ Am^{-2} - also in earthward currents (measured by HILAT). From the current to the plates of the ion drift meter the authors estimated an ion number density of $2 \cdot 10^{10}$ m^{-3} and hence a magnetic-field aligned drift velocity of 30 km/s for the electrons carrying the Birkeland current. They concluded that this should be enough to destabilize electrostatic ion acoustic waves as well as electrostatic ion cyclotron waves. Simultaneous measurements of electron fluxes indicated that 2 - 4 km equatorward of this Birkeland current the height-integrated Pedersen conductivity had a sharp gradient (2 ohm^{-1} km^{-1}), which in combination with a prevailing nortward electric field could be the cause of the observed Birkeland current.

Small scale current structures have been observed not only near the ionosphere but even in the equatorial region Thus it has been shown by Robert et al. (1984) that most of the SIP's (short irregular pulsations) observed at GEOS-2 are in fact the magnetic signatures of localized current structures passing by the spacecraft at a high velocity. The structures are estimated to have a current density of $6 \cdot 10^{-9}$-$3 \cdot 10^{-7}$ Am^{-2}, a size of 20 - 900 km and to move at a velocity of 15 - 170 km/s. They are associated with large electric field spikes (3 - 25 mV/m).

3.2 Driving electromotive forces

One may distinguish between two kinds of electromotive forces that can drive Birkeland current. One is the MHD dynamo action of the bulk motion of plasma in the solar wind, plasma sheath and outer magnetosphere. The other is due to charge separation generated by differential drift of charged particles (gradient and curvature drift). This kind of generators draws on the kinetic or thermal energy of individual particles and may be characterized as thermoelectric. Both these kinds of generators are likely to be important in the magnetosphere (see e. g. Block 1984 and Vasyliunas 1984).

An internal source of MHD dynamo action is the forced rotation of the ionosphere. (To this average contribution is added the dynamo action of ionospheric winds.) The corotational dynamo has an e.m.f. of nearly 100 kV (the equator being negative and both poles positive). However, most of this e.m.f. connects to low- and mid-latitude plasmas. These have a low ohmic resistance and a small enough moment of inertia that they are easily forced to corotate. Thus the net e.m.f. of the circuit, and hence the Birkeland currents, stay nearly zero.

The high latitude part, from the auroral ovals to the poles, still accounts for about 10 kV of the corotational e.m.f. This is small, but not negligible, compared to the externally applied polar cap potential.

Although in the case of the Earth the internal dynamo plays a minor role, the situation can be different in other magnetospheres (for a review see e.g. Hill 1984). Thus Jupiter's magnetospheric processes seem to be dominantly powered by the rotation of the planet. In this case the Jovian satellite Io and its plasma torus are important as an external load (Shawhan 1976, Eviatar and Siscoe 1980). Rotational dynamo action has also been proposed to be important at Uranus (Hill et al. 1983).

Of external sources there are both (1) MHD-type dynamos (the solar wind, the plasma sheet and regions of the magnetosphere where convection field is externally enforced e. g. by a viscous-like interaction) and (2) thermoelectric generators (regions where the gradient and curvature drifts produce charge separation, see e.g. Block 1984, Atkinson 1984a, Vasyliunas 1984).

It is outside the scope of the present paper to discuss the dynamos themselves. These are well described in the literature and for recent reviews the reader is referred to e. g. Stern (1983, 1984). Only one aspect will be briefly discussed, namely the possible role of spatially small-scale dynamo regions and corresponding fine-structure in the ionosphere magnetosphere

coupling.

It has been suggested by Heikkila (1982), Lemaire (1977) and Lemaire et al. (1979) that plasma from the magnetosheath is injected in the form of clouds into the magnetosphere. Until they lose their momentum these clouds would form localized and temporary MHD-dynamo regions on closed field lines. In addition they would create regions where, due to curvature and gradient drifts, the plasma would contain both protons of solar wind origin and magnetospheric O^+ ions. It has been suggested by Lundin (1984) and Lundin and Dubinin (1985) that such clouds would form dynamo regions by polarization due to the differential motions of the different types of ions.

A general expression for the differential flow vector of two ion species has been derived by Hultqvist (1984). From measured values of particles and fields he estimated that terms containing pressure gradients and transverse electric currents could easily reach values of some hundreds of km/sec, and that also inertia terms and the magnetic gradient terms could approach 100 km/sec with quite resonable assumptions about characteristic times and characteristic lengths.

Thus determination of electric field from particle fluxes could be uncertain by tens of mV/m even if local particle distribution functions were known exactly (but not their gradients or whether variations were temporal or spatial).

The concept of intruding plasma clouds as localized generator regions for auroral arc structures has been further elaborated by Stasiewics (1984a, 1985). As the localized cloud dynamo drives Birkeland currents to the ionosphere and back magnetic field aligned potential drops may develop in the upward current branch. As a necessary but not sufficient condition for this to happen Stasiewics (1984a) concludes that the scale has to be so small that the characteristic dimension is less than $3(B_i/B_m)r_{ge}$, where B_i/B_m is the ionospheric to equatorial magnetic field strength ratio and r_{ge} is the electron gyro

radius in the equatorial plane. These considerations are applied also to nightside plasma ion clouds such as have been known for a long time (de Forest and McIlwain, 1971).

4. REDISTRIBUTION OF PLASMA

We know know that ionospheric ions contribute significantly to populating many regions of the magnetosphere (in addiin to the obvious one, the plasmasphere). They are also present in all energy ranges from thermal to high energy. It started with the discovery by Shelley et al. (1972) of precipitating O^+ with energies up to 12 keV and was later followed by the first direct observations of the O^+ ions leaving the ionosphere (Shelley et al. 1976). Consequences for magnetosphere ionosphere coupling were discussed by Sharp and Shelley (1981). Reviews of the ionosphere as a source of magnetospheric ions was given by Shelley et al. (1982), Horwitz (1982), Sharp et al. (1985) and Yau et al. (1985). For recent results related to this topic see e. g. Lennartsson et al. (1985), Stokholm et al. (1985), Ipavich (1985), Baker (1985), Waite et al. (1985). Only recently has the composition of the bulk of the storm time ring current been measured (Gloeckler et al. 1985). Then, too, it is found that injection of ionospheric ions is important.

The presence of ionospheric ions in the magetospheric plasma has of course important consequences both macroscopically (e g. by local-dynamo effects, as mentioned above) and microscopically (by their influence on wave propagation, instabilities and wave particle interaction). Heavy ions of ionospheric origin may also influence the localization and initiation of plasma sheet instabilities during substorms (Baker et al. 1985b).

A comprehensive collection of papers on the distribution of hot energetic ions in the magnetosphere are found in a recent book edited by Johnson (1983), see also Hultqvist (1983a,b, 1984). Even very energetic (112-157 keV) O^+ ions have recently been observed in the plasma sheet (Ipavich et al. 1984). In a review

Hultqvist (1985) emphasizes that present knowledge of low energy plasma in the magnetosphere is very far from complete and improving this knowledge is greatly needed. We may note that in the auroral acceleration region the incomplete knowledge of the low energy plasma introduces a considerable uncertainty in stability analyses, as discussed for example in the recent review by Kaufmann (1984). See also Lennartsson et al. (1985). A schematic overview of sources, transport and acceleration of plasma in the magnetosphere according to Collin et al. (1984) is shown in Fig. 3.

At low and middle latitudes storm-time depletion of the plasmasphere are followed by a diffusive refilling process that takes 7-22 hours (Horwitz et al. 1984).

On polar cap field lines a supersonic streaming of ionospheric plasma - the polar wind - has long been predicted for theoretical reasons. These were initially discussed by Hanson and Pattersson (1963) and Dessler and Michel (1966), later formalized by Axford (1968), Banks and Holzer (1968) and others; for a review see Cowley (1980). The polar wind has been observed by the Dynamics Explorer spacecraft (Gurgioli and Burch 1982, 1985; Nagai et al. 1984; Waite et al. 1985). In addition to the theoretically expected cold polar wind there are also substantial fluxes of suprathermal (above 100 eV) field-aligned O^+ ions that seem to have been subject to some other acceleration processes. Persoon et al. (1983) have compared polar cap electron density profiles determined by the DE-1 plasma wave experiment and earlier, lower altitude observations. They conclude that in addition to a subsonic to supersonic transition at about 1000 km altitude there is a transition from collision dominated to collision free outflow at about 1.5 - 2 R_E. Over the polar cap, DE-1 observations recently reported by Waite et al. (1985) show outward flow of suprathermal low energy (less than 10 eV) O^+ ions with fluxes exceeding $2 \cdot 10^{12}$ m^{-2} s^{-1}, mainly from a region near the dayside polar cap boundary. The integrated source strength is estimated to be $7 \cdot 10^{24}$ s^{-1} for quiet (K_p less than 3) and $2 \cdot 10^{25}$ s^{-1}. The distinction between

classical polar wind outflow and O^+ enhanced suprathermal flow has recently been analysed by Moore et al. (1985).

The extraction of ionospheric ions is related to the Birkeland currents both directly through exchange of charge carriers and indirectly by parallel and perpendicular ion acceleration mechanisms driven by the Birkeland currents.

Observations of upflowing ions from the auroral zone and polar cap were recently reviewed by Yau et al. (1984). The total outflow of ionopsheric ions into the magnetosphere, according to Collin et al. (1984) from S3-3 data, are given in Table 1. Locally, upward oxygen ion fluxes exceeding 10^{14} m^{-2} have been observed with DE-2 at 900 km altitude and account for a substantial fraction of the simultaneously observed Birkeland currents (Heelis et al. 1984)

A direct effect of Birkeland currents is due to the fact that the closed-loop current, of which the Birkeland currents are a part, is carried by different particle species in different parts of the loop.

Possible consequences at ionospheric levels were discussed by Block and Fälthammar (1968, 1969) who showed that this effect can modify the F-region density distribution and contribute to the formation of F-region troughs. As the density depletions are associated with loss of ionospheric ions to the magnetosphere, it was also suggested that "the ionosphere and magnetosphere might form a more or less closed loop for the plasma" (Block and Fälthammar 1969). Recent computations by Cladis and Francis (1985) indicate that oxygen ions in the storm-time ring current may go through such a closed loop.

At the magnetospheric end the consequences of the transition of current carriers has been analyzed in a series of papers by Atkinson (see Atkinson 1984a and references therein). If Birkeland currents carried predominantly by electrons connect to transverse magnetospheric currents carried largely by ions,

depletions or enhancements should occur depending on the direction of the Birkeland currents. Thus, inward Birkeland currents would cause enhancements of magnetospheric plasma and outward currents would cause depletions. Another example: if part of the cross-tail electric current is deviated through the ionosphere, plasma accumulates in the morning side and evacuates in the evening side of the magnetosphere. According to Atkinson (1984b) the distribution of Birkeland currents at ionospheric altitudes can thus be used to diagnose plasma redistribution in the outer magnetosphere. A steady state model developed on this basis has recently been further extended to include thick adjacent current sheets mapping to the whole plasma sheet (Atkinson 1984c).

A particularly interesting exchange of mass between the ionosphere and the magnetosphere is the outflow of heavy ionospheric ions in the form of "beams" and "conics" (see e.g. Gorney et al. 1981), both because of the acceleration mechanisms of which they bear witness and because they show that very effective chemical separation can take place in a cosmical plasma. The latter could have important consequences in the context of astrophysical abundance considerations.

In the beams the distribution function has its maximum along the magnetic field. However, considering the limits set by instrument resolution some of them may be post-accelerated conics masquerading as beams. They appear to be accelerated by an electric field, and contain information about the potential drop between their source and the observation point. However, they do not give a simple quantitative measure of this potential, because it is obvious that they have also been subject to non-adiabatic processes. For example, their energy spread (50-150 eV) is much greater than would be expected (0.2 eV) if ionospheric O^+ had only fallen adiabatically through a potential drop. It is also well established (Kintner et al. 1979; Cattell 1981; Kaufmann and Kintner 1982, 1984) that there is very close correlation between ion beams and electrostatic hydrogen cyclotron waves. As described in the recent review by

Kaufmann (1984) the typical observed distribution functions of the ion beams may be explained if it is assumed that these waves are the result of the instability of the beams. The typical beam temperatures of 50-150 eV are approximately such that the beams should be marginally stable to generation of hydrogen cyclotron waves. As the ascent through the mirror field tends to narrow the distribution, the beams would, in this scenario, be kept near the limit of instability. This would also mean that at high altitude the beams would have such a width as to efficiently prevent them from reaching the opposite hemispehre. Hence the non-observation of downgoing beams.

The conics have a maximum in their distribution function at a non-zero value of transverse to parallel velocity ratio and are apparently the result of a transverse acceleration followed by expulsion by the magnetic mirror force. Two main explanations of the transverse acceleration have been proposed. One main explanation invokes waves, either electrostatic ion cyclotron waves (Ungstrup et al. 1979; Lysak et al. 1980; Papadopoulos et al. 1980; Ashour-Abdalla et al. 1981; Singh et al. 1981, 1983; Dusenberry and Lyons 1981; Okuda and Ashour-Abdalla 1981, 1983; Ashour-Abdalla and Okuda 1983, 1984; Okuda 1984; Gurnett et al. 1984;) or lower hybrid waves (Chang and Coppi 1981; Retterer et al 1983; Singh and Schunk 1984). In a two-component plasma of stationary hydrogen and oxygen ions and drifting electrons preferential heating of either hydrogen or oxygen can take place depending on the ratio of electron drift speed and the ratio of hydrogen to oxygen concentration (Ashour-Abdalla and Okuda 1983). For a given critical drift the maximum perpendicular heating is generally larger for the oxygen ions than for the hydrogen ions (Ashour- Abdalla and Okuda 1984). Both theoretical analysis and numerical simulation were used and gave results in good agreement. Recently Nishikawa et al. (1985) studied ion heating by hydrogen cyclotron waves, such as are often observed on auroral field lines, using analytical methods as well as numerical simulations. Much stronger heating resulted for oxygen ions than for hydrogen ions. As pointed out by Horwitz (1984) transverse acceleration of O^+ ions is also favoured by the fact

that due to greater inertia they have a longer residence time in the acceleration region. Recent results reported by Gorney et al (1985) indicate that the residence time and hence the heating of upflowing ions may be much enhanced by downward pointing parallel electric fields.

Kintner and Gorney (1984) searching the S3-3 data found only one case of perpendicular ion acceleration and broadband plasma waves at the satellite. The wave mode could not be identified, but the electric field of the waves was, in all cases, smaller than required by present theories.

Several authors (Mozer et al. 1980; Lennartsson 1980; Kletzig et al. 1983; Yang and Kan 1983; Greenspan 1984; Borowski 1984) have considered electrostatic shocks or similar electrostatic structures as an alternative or complementary explanation of the transverse acceleration. In this case, too, it is found that the heavier ion species are preferentially accelerated and tend to become less field-aligned. Whereas Yang and Kan (1983) consider this an auxiliary mechanism (to cyclotron heating), Borovsky (1984) finds in his simulations that the particles become more field-aligned as the ion cyclotron waves grow and therefore suggests that the ion conics produce the waves rather than vice versa.

According to Cattell (1984) the S3-3 data indicate that both electrostatic ion cyclotron waves and electric field gradients contribute to the energizing of the ions but that neither is sufficient to account for the observed energy.

A major difficulty in clarifying the processes leading to formation of beams and conics is the limited knowledge of cold background electrons and ions (Kaufman 1984). The present state observational knowledge of low energy plasma outside the plasmapause has recently been reviewed by Hultqvist (1985). Cf. also Stokholm et al. (1985).

5. MAGNETIC-FIELD ALIGNED ELECTRIC FIELDS

One of the crucial questions in magnetosphere-ionosphere coupling is the ability of the plasma to support magnetic-field aligned ("parallel") electric potential drops and thus electrically and dynamically decouple the two regions. This property is also intimately related to the ability to carry Birkeland currents and to energize charged particles.

There has now for some time been an almost complete consensus that such electric fields do exist and that they play an important role in energizing auroral particles. It is, however, also clear that parallel electric fields alone cannot account for all the observed features of the accelerated particle populations. A recent review of parallel electric fields, with extensive references to the literature, has been given by Fälthammar (1983). The present discussion will be limited to general outlines and comments on some recent developments.

5.1 Possible types of parallel fields

A central problem concerning parallel electric fields is what forces are responsible for balancing the dc electric force on the charged particles. On the basis of the kind of force involved, the parallel electric fields can be divided into three categories (Fälthammar 1977, 1978). The three forces are:

1. The net force from wave fields. In the magnetosphere only the electric part of the wave field, and only its component parallel to the magnetic field, can contribute apppreciably to the momentum balance. The prime example of this case is that of anomalous resistivity. The collisionless thermoelectric effect proposed by Hultqvist (1971) would also belong to this category.

2. The magnetic mirror force. Magnetic mirror supported parallel fields have been extensively invoked in explaining observed particle distributions above the auroral zone.

3. Inertia forces. A final possibility is that the force from the electric field is balanced by the inertia of the charged particles themselves. This is the situation in electric double layers. Such are well known from the laboratory and are often considered to be important in space, too.

It is very likely that these categories occur in combinations. E.g. in the presence of a parallel field supported by the magnetic mirror force, strong wave activity may still substantially change particle distributions. Or, numerous weak electric double layers may appear and disappear at random with a result very much resembling a state of anomalous resistivity (Block 1972, 1981).

Each of these categories of electric fields has its own peculiarities. A couple of these will be mentioned here.

Anomalous resistivity requires that the wave electric field along the magnetic field (and a fortiori the total wave field) has an rms value well exceeding (probably by a factor of 10 or more) the d.c. field that it supports: $E_{rms} >> E_{dc}$ (Shawhan et al. 1978). Although the existing wave fields are not known in enough detail for an accurate evaluation, it can be estimated that anomalous resistivity might account for parallel d.c. fields of the order of mV/m. This could still be enough for supporting several kilovolts, but the potential drop would have to be distributed over distances of the order of one or more Earth radii.

Another feature of the anomalous resistivity is that the power is dissipated locally. For the current densities known to prevail above the aurora, any appreciable parallel field supported by anomalous resistivity would imply extremely rapid heating of the local plasma of the order of eV/sec (Block and

Fälthammar 1976; Block 1984).

In a plasma with two ion species, anomalous resistivity may also lead to selective ion acceleration. A numerical simulation by Mitchell and Palmadesso (1984) showed that the momentum transferred from the waves mainly affected one ion species (H^+) leaving the other (O^+) to be freely accelerated in the d.c. electric field. From numerical simulations Rowland and Palmadesso (1983) concluded that low frequency ion cyclotron turbulence can limit the high velocity runaways via pitch angle scattering. From comparisons between simulations and DE observations electron precipitation bursts Lin and Rowland (1985) suggest that anomalous resistivity does play an important role in connection with particle acceleration.

Parallel electric fields supported by the magnetic mirror force could in principle exist even in the absence of a current, as suggested by Alfvén and Fälthammar (1963) and recently discussed by Serizawa and Sato (1984). Mostly however, the upward mirror force is invoked in the context of upward Birkeland currents, where the principal current carriers are impeded by the magnetic mirror force.

In this case, too, the maximum field strength that can be supported should typically be of the order of a few mV/m. Thus, any large potential drops would have to involve large distances along the magnetic field.

As shown by e. g. Knight (1973), Lemaire and Scherer (1974, 1983) and others the current voltage relation for mirror-supported fields is, under certain assumptions, linear over 2 or 3 powers of ten in voltage and current. For a mirror-supported field this is a relation between the current density and the total voltage drop, not a local relation between current density and electric field at any given part of the flux tube. Thus there does not exist a conductivity, only a conductance. For typical plasma sheet parameters this conductance is $3 \cdot 10^{-6}$ A $(mV/m)^{-1}$ (Fälthammar 1978). This holds,

however, only provided the loss cone of the source plasma is continually replenished. Otherwise the conductance can be reduced to arbitrarily low values. Furthermore, it has been shown by Yamamoto and Kan (1985) that the current density can be substantially reduced relative to that given by the Knight-Lemaire formula, if the potential drop is concentrated at altitudes as low as 4000 km.

Correspondingly, there should be a relation between energy flux and accelerating voltage such that in a certain energy range the former is proportional to the square of the accelerating voltage. Such a relation has been confirmed by Lyons et al. (1979) and Menietti and Burch (1981). A linear rather than quadratic relation was reported by Wilhelm (1980) but this seems to be explainable in terms of a spatial variation of the source plasma.

Electric double layers represent the opposite extreme in terms of spatial distribution. The thickness L of a double layer with voltage drop V in a plasma of electron temperature T_e is of the order of

$$L = C\ (eV/kT_e)^{1/2}\ {}_D \qquad (2)$$

where ${}_D$ is the Debye length and the factor C is of the range 10-100 (Shawhan et al. 1978).

An important feature of the double layer is that the power released goes into energetic particles that deposit their energy remotely and therefore there is no problem of excessive local heating.

5.2 Observational evidence

The earliest observations interpreted as evidence of parallel electric fields were those of field alignment and narrow energy peaks in precipitating electron fluxes. Gradually the evidence accumulated and now includes both observation of

(1) natural particle populations, (2) motion of artificially particles injected by measured active experiments and (3) direct measurements of electric fields. At the same time it has become abundantly clear that the situation is not simple, and that d.c. electric fields alone cannot explain all the characteristics of observed particle spectra. In the following will be given a very brief summary of observations interpreted as evidence for parallel electric fields as well as objections against this interpretation. For a more complete review and references to the original papers, see e.g Fälthammar (1983) and, for particle observations, Kaufmann (1984).

I. Observations of natural particle populations

In addition to the field alignment and narrow energy peaks already mentioned, there is a large amount of satellite data showing characteristic structures in the particle distribution functions. These include occurrence of an <u>acceleration boundary</u> in downcoming electron distributions, similar to what would be expected if the particles had been accelerated in a potential drop of a few kV. Another important feature is a <u>widened loss cone</u>, as would be expected from a potential drop below the satellite (again in the kV range). <u>Upstreaming ion beams</u>, if assumed to have passed an electrostatic accelerated ion region, indicate a potential drop below the satellite that is in rough agreement with the widened electron loss cone.

While most observations of accelerated particle populations have been made at altitudes of a few hundred to a few thousand kilometers, an inverted V event observed at 13 R_E has recently been reported (Huang <u>et al</u>. 1984) showing that at least sometimes the acceleration region can be very far away.

Low voltage (tens of V) upward pointing electric fields - perhaps analogous to the wall sheath in a laboratory plasma - have been reported by Winningham and Gurgiolo (1982). Equatorward of the morning side polar cusp the electrons that carry the downward Region 1 Birkeland currents appear to be

accelerated by potential drops of tens of V at altitudes of several thousands kilometers (Burch et al. 1983).

Although the magnitude of the potentials of parallel electric fields can be estimated from existing particle data, the determination of their spatial distribution is much more difficult. As shown by Greenspan et al. (1981) even distinguishing between double layers and smoothly distributed electric fields is difficult with existing data and would require accurate high resolution measurements of low energy electrons (around 100 eV and less). As the distribution functions often vary appreciably within a satellite spin period multiple detectors with high time resolution would be needed. To extract the information carried by the upstreaming ions a wider energy coverage would also be desirable (see e. g. Kaufmann 1984).

A number of objections were already long ago raised against the interpretation of auroral particle distributions in terms of parallel electric fields (O'Brien 1970; Whalen and McDiarmaid 1972; Whalen and Daly 1979). For example, Hall and Bryant (1974) considered that the shape of the angular distribution of electrons and of the width of the energy peak were indicative of a stochastic acceleration process. Wave particle interaction was also invoked by many authors to explain the width of the energy peak and the occurence of multiple peaks (for references see Hall et al. 1985). The velocity space features (acceleration boundary, widened loss cone) are diffuse and the velocity space region that corresponds to trapping between the electric field above and the magnetic mirror below is populated. The upcoming ion beams are much wider than could be explained by electrostatic acceleration alone. These and other difficulties with purely electrostatic acceleration were summarized by Bryant (1983). Although some of these objections can be eliminated even within adiabatic models (cf. e. g. Block 1984; Brüning and Goertz 1985; Lotko 1985) it is of course not surprising that non-adiabatic processes play a role, too (cf. par. 5.3 below).

II. Active experiments

The first active experiments to indicate the existence of parallel electric field were shaped charge Ba releases (Haerendel et al. 1976), where a clear acceleration of the Ba ions could be seen (in one case corresponding to a voltage drop of 7.4 kV at an altitude of 7500 km). This seems to be one of the most conclusive observations, of the existence of a parallel electric field. By now a total of half a dozen such experiments have been made. The main results of these have been compiled in a recent paper by Stenbaek-Nielsen et al. (1984).

Active experiments have also been made using electron beams ejected from a rocket to probe the parallel electric fields. Reflexions of the electrons were observed, which are compatible with the existence of parallel electric fields above the rocket but do not constitute a proof (Wilhelm et al. 1984, 1985). If interpreted in terms of parallel electric fields they indicate field strengths of 1 - 2 mV/m above about 2500 km and potentials of at least a few kV or more.

III. Electric field measurements

Direct electric field measurements at high and low altitudes have shown different latitude distributions that imply the existence of parallel electric fields at intermediate altidues (Mozer and Torbert 1980). The discovery by direct measurements of the so-called electrostatic shocks, i.e. regions of strong (hundreds of nV/m) over short distances (a few km) imply that electric field mapping along electrically equipotential magnetic field lines does not apply. In a static situation this would irrevocably imply the existence of parallel electric fields somewhere between the ionosphere and the satellite. However, it cannot be excluded that this lack of mapping may instead be due to the induction field of an oblique Alfvén wave as proposed by Haerendel (1983), cf. par. 5.3.

Although it was in the past often considered that strong electric double layers ($V>>kT_e/e$) would exist over the auroral zone, direct electric field measurements indicate that they are limited and rare, if they exist at all (Boehm and Mozer 1981). On the other hand occurrence of numerous weak double layers have been discovered (Temerin et al. 1982; Hudson et al. 1983) and seem to be able to account for integrated potential drops of the order of several kV.

5.3 Some recent developments

Parallel electric fields have usually been considered to be important mainly in regions of upward current flow becuase outflowing ionospheric electrons were thought to provide copious current carrying capability for downward currents. However, theoretical works by Newman (1985) has shown that also downward parallel electric fields may exist. The key to this is the existence, at the low altitude end of the field line, of an ambipolar diffusion region with an upward directed electric field of a few eV. This is found to be sufficient to exponentially reduce the densities of electrons and ions enough that a net downward electric field above would not extract excessive electron current. Very recently observations have been reported by Gorney et al. (1986), where the phase space distributions indicate acceleration by a downward pointing electric field with a potential of a few tens to a few hundreds of volts over the altitude range of 1000 - 6000 km.

In a recent Ba jet experiment Stenbaek-Nielsen et al. (1984) noticed a sudden decrease in the speed of progression of the tip of the jet as it reached 8100 km altitude. Their interpretation was that at this altitude the barium was accelerated rapidly upward to a sufficient speed that the density decreased below detectability. For this to happen through energization by wave fields and subsequent magnetic-mirror expulsion, the authors estimate that gyroresonant waves in excess of 25 mV/m would have been required. They therefore favour a d.c. electric field as the

only plausible explanation. From a detailed study of the brightness distribution they estimate a lower limit to the strength of the d.c. field. The result is that the potential must have been in excess of 1 kV. Because of the limited resolution of the TV images only an upper limit (200 km) could be set to the distance over which the potential drop occurred. Hence the field strength must have been at least 5 mV/m.

One important observation in this case was that as the Ba jet itself drifted (westward), and auroral arc segments drifted through it (from south to north), no apparent corresponding changes were seen in the behaviour of the barium. The situation persisted for at least 10 minutes. Thus the observed electric field appears to have been a large-scale horizontal structure and not associated with individual arc structures. Of course this does not exclude arc-related parallel electric fields still higher up. The simultaneously observed background luminosity at 6300 - 4278 Å corresponded to a characteristic energy of the precipitating electrons of about one keV.

Not unexpectedly, parallel electric fields alone are insufficient to account for all features of auroral particle distributions. Features that seem to require other explanations have been pointed out by several authors. These features were summarized by Bryant (1983), who favours an entirely different approach aimed at explaining the auroral acceleration entirely by wave-particle interactions without recourse to a d c electric field. Recently this approach has been expounded in a series of papers (Bingham et al. 1984, Hall et al. 1984, 1985 and references therein). The acceleration mechanism favoured by these authors is lower hybrid waves driven by ion beams streaming torward the Earth in the plasmasheet boundary. Referring to the ion beams reported e. g. by DeCoster and Frank (1979) and the wave observations of Gurnett and Frank (1977) and Mozer et al. (1979) the authors find that (1) the energy of the beams is easily sufficient to power the auroral acceleration and (2) the normalized energy density of lower hybrid waves on auroral field lines is high.

However, the electric field of these waves is very nearly transverse to the magnetic field and it is only the parallel component of the wave electric field that can contribute to the field-aligned acceleration. Therefore more detailed knowledge of the wave fields seems to be necessary to assess with certainty what effect the waves have on the particles. Furthermore, as some of the evidence of for field aligned parallel fields - such as the acceleration of artificial ions beams - remains intact, attempts to explain auroral acceleration entirely without paralle d c fields appears problematic, and a combined approach more promising.

The combined effect of (ion acoustic) wave turbulence and a dc parallel electric field has ben analyzed by Stasiewics (1984b,c), using the quasilinear Vlasov equation to estimate the runaway region in velocity space. One of the results is a new interpretation of the classical type of peaked auroral spectrum (see Fig. 4). The accelerating potential, U, is not given by the energy at the peak, but by the difference between this energy and the energy at the minimum of the spectrum. The latter energy is in typical cases about 1 keV and is related to the energy required for electron runaway in the presence of the wave field. A theoretical prediction of its value is, however, not possible without much better knowledge of the actual wave spectra in the interaction region than is now available.

For the low energy electrons, region I in Fig. 4, the spectral form E^{-1} is ascribed to the heating of the trapped electrons and not to atmospheric backscatter (Evans 1974). In this interpretation region II in Fig. 4 corresponds to runaway electrons that have fallen freely through the d c electric field of the acceleration region. Hot magnetospheric electrons with velocities exceeding the runaway velocity will pass the acceleration region unimpeded and form region III of the spectrum.

Stasiewicz (1984c) also derived a relation between the voltage and current density that is a generalization of that of Knight (1973) and a corresponding relation between energy at the spectral peak and the precipitating energy flux. When the energy at the peak is much larger than the source plasma temperature, this relation reduces to the quadratic form that applies in the adiabatic case (Lundin and Sandahl 1978).

As already mentioned the occurrence of numerous weak double layers and solitons have been known from electric field measurement at high altitude on the satellite S3-3. According to recent results reported by Boehm et al. (1984) and Kellog et al. (1984) similar structures exist even at rocket altitudes (above 200 km). In both cases the observations were made by means of double probe electric field experiments. But in neither case was the experiment designed for this unexpected discovery. Therefore the information on the size and motion of the structures is still incomplete.

In the flight reported by Kellog et al. (1984) a lower limit to the typical voltage drop of the double layer like structures was determined to be 0.4 V. In the corresponding structures observed by Boehm et al. (1984) the electric fields, mostly parallel to the magnetic field, were typically 50 mV/m and the corresponding potentials at least 0.1 V. However the lower limit of the potentials observed varied up to 2 V. No limit could be set on the size of the structures but a lower limit of their velocity was estimated to be 15 km/s. In addition closely spaced soliton-like structures were observed with electric fields greater than 1 mV/m.

Further measurements with dedicated instrumentation is necessary to clarify the nature of these phenomena.

6. CONCLUDING REMARKS

For a proper understanding of astrophysical phenomena, theoretical analysis, which by necessity must rely on simplifying assumptions, must be guided by empirical knowledge of how real plasmas behave. Laboratory experiments have an essential role to play in this context, but *in situ* observations of the magnetospheric plasma can, in some respects, provide us with an even better knowledge of plasma behaviour in natural conditions. The plasma in the magnetosphere (including the ionosphere) and the solar wind are the only cosmic plasma accessible to extensive *in situ* observations and experiments.

Observations of magnetospheric plasmas extend our empirical knowledge to a new range of plasma parameters by many powers of ten. It is also fortunate that plasmas in the Earth's neighbourhood cover such wide ranges of density and temperature and that magnetosphere-ionosphere interactions cause a rich variety of plasma processes to take place.

The truly fundamental progress in the understanding of the magnetospehre has only begun. Important observational discoveries have opened a new epoch in magnetospheric research. The knowledge already obtained, and the insights still to be gained, in magnetospheric research should be of great value in understanding astrophysical plasmas and may have important inpacts on astrophysics.

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CAPTIONS

Fig.1 Schematic Birkeland current patterns according to Reiff and Burch (1985) for various orientations of the interplanetary magnetic field. The upper row is for strongly northward B_z and B_y going from postitive (A) through zero (B) to negative (C). The lower rows are for B_z weakly northward (middle row) and southward (bottom row). Patterns to the left are for positive B_y and to the right for negative B_y.

Fig.2 Magnetic field signature of a pair of thin, high-density current sheets within the evening Region 1, Birkeland current (Burke 1984). The steep gradients on either side of the narrow dip beginning at 11.48.16 UT correspond to outward and inward Birkeland current sheets of $135 \cdot 10^{-6}$ A m^{-2} and $15 \cdot 10^{-6}$ A m^{-2} respectively.

Fig.3 Schematic overview of sources, transport and acceleration of plasma in the magnetosphere according to Collin *et al.* (1984).

Fig.4 New interpretation of inverted-V electron spectra according to Stasiewics (1984c). The acceleration voltage v is now related to the difference of the energies E_p at the peak and E_r at the minimum.

TABLE 1. The Estimated Terrestrial Ion Outflow in the Energy Range 0.5 to 16 keV for O^+ and H^+ During Magnetic Storms and Quiet Times

	Range	Mean
Quiet Time		
H+	$0.7–1.4 \times 10^{25}\ s^{-1}$	$1.1 \times 10^{25}\ s^{-1}$
O+	$0.15–0.4 \times 10^{25}\ s^{-1}$	$0.27 \times 10^{25}\ s^{-1}$
Total	$0.85–1.8 \times 10^{25}\ s^{-1}$	$1.3 \times 10^{25}\ s^{-1}$
O+/H+	0.1–0.4	0.25
Storms Time		
H+	$1.5–4.5 \times 10^{25}\ s^{-1}$	$3.0 \times 10^{25}\ s^{-1}$
O+	$3.5–5.0 \times 10^{25}\ s^{-1}$	$4.2 \times 10^{25}\ s^{-1}$
Total	$5.0–9.5 \times 10^{25}\ s^{-1}$	$7.2 \times 10^{25}\ s^{-1}$
O+/H+	0.7–2.1	1.4

The range indicates the uncertainty of the estimate resulting from both counting statistics and uncertainties in the identification of the newly outflowing ions.

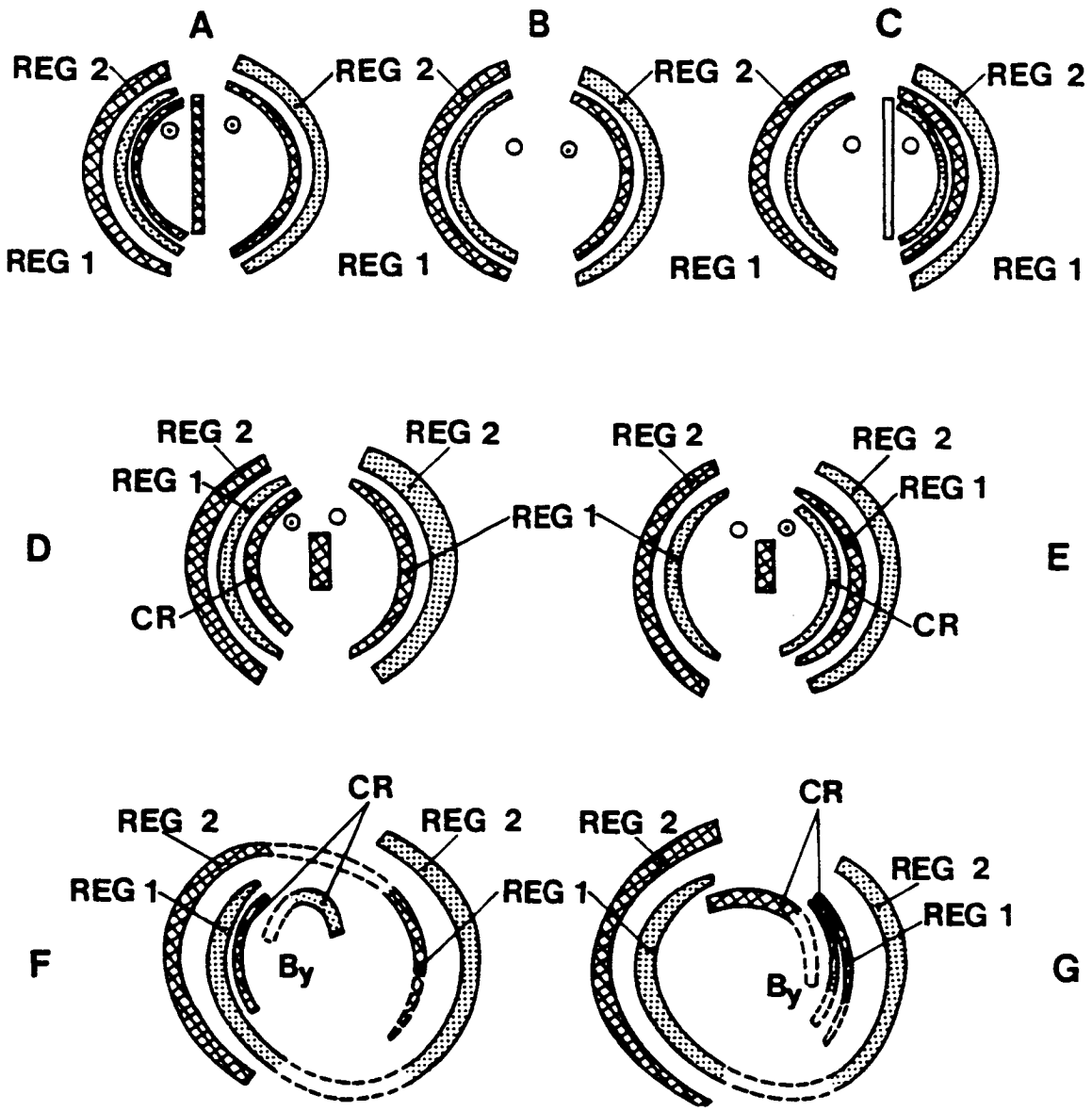
A
B
C
REG 2
REG 1
REG 2
REG 1
REG 2
REG 1
REG 2
REG 1
D
REG 2
REG 1
CR
REG 2
REG 1
E
REG 2
REG 1
CR
REG 2
F
CR
REG 2
REG 1
By
REG 2
REG 1
G
CR
REG 2
REG 1
By

Fig. 1

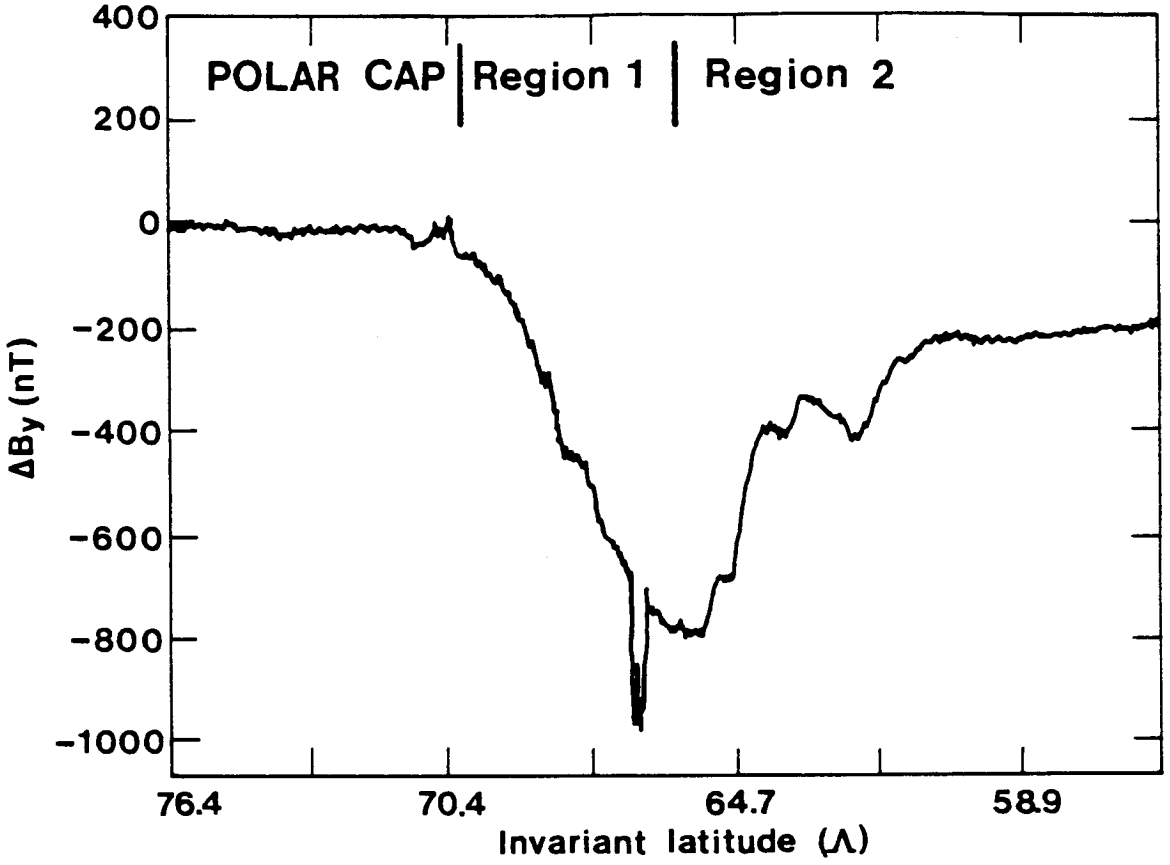
POLAR CAP
Region 1
Region 2
400
200
0
-200
-400
-600
-800
-1000
ΔBy (nT)
76.4
70.4
64.7
58.9
Invariant latitude (Λ)

Fig. 2

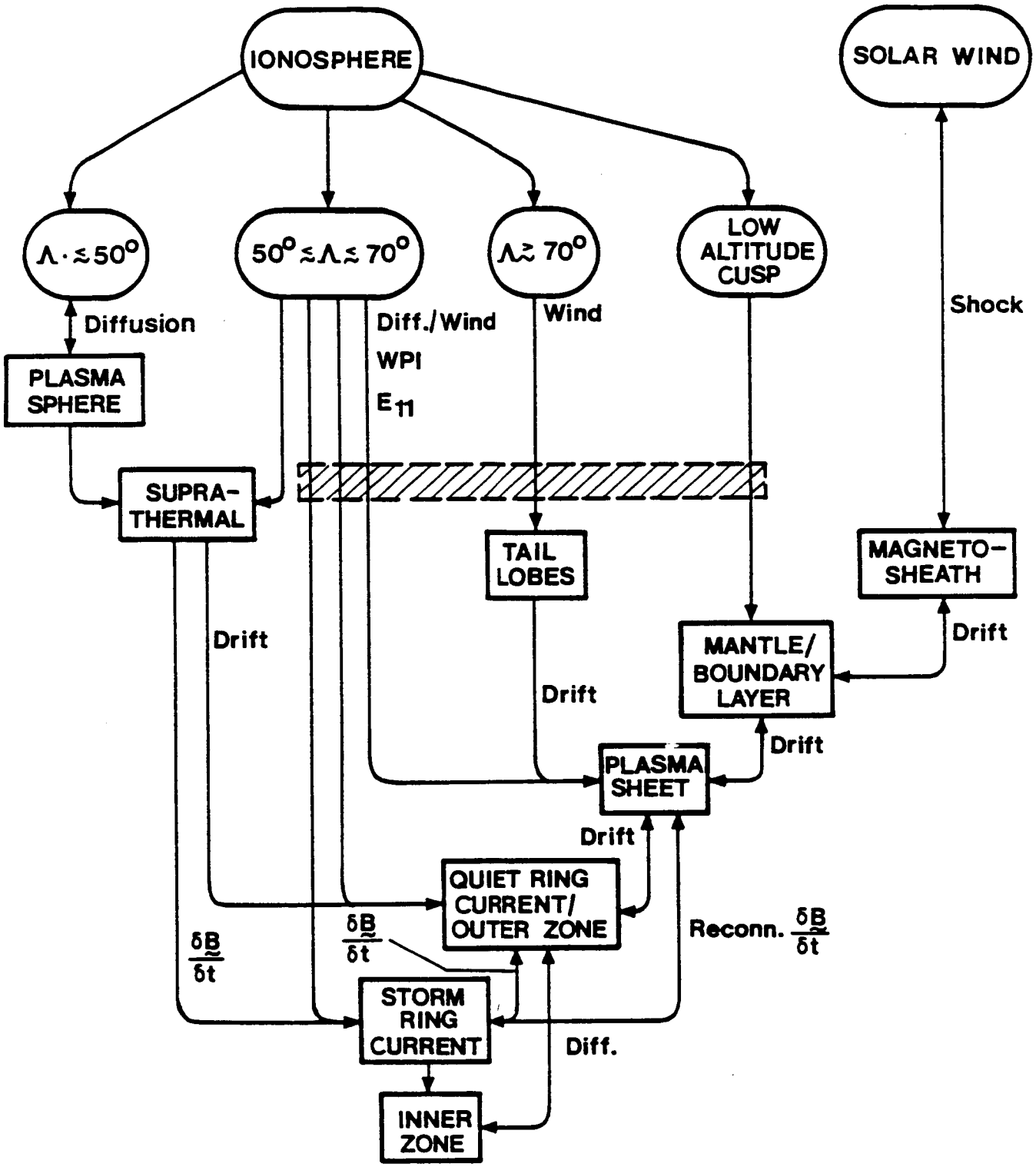
IONOSPHERE
SOLAR WIND
Λ ≲ 50°
50° ≲ Λ ≲ 70°
Λ ≳ 70°
LOW ALTITUDE CUSP
Diffusion
Diff./Wind
WPI
E11
Wind
Shock
PLASMA SPHERE
SUPRA-THERMAL
TAIL LOBES
MAGNETO-SHEATH
Drift
MANTLE/ BOUNDARY LAYER
Drift
Drift
Drift
PLASMA SHEET
Drift
QUIET RING CURRENT/ OUTER ZONE
δB/δt
δB/δt
Reconn. δB/δt
STORM RING CURRENT
Diff.
INNER ZONE

Fig. 3

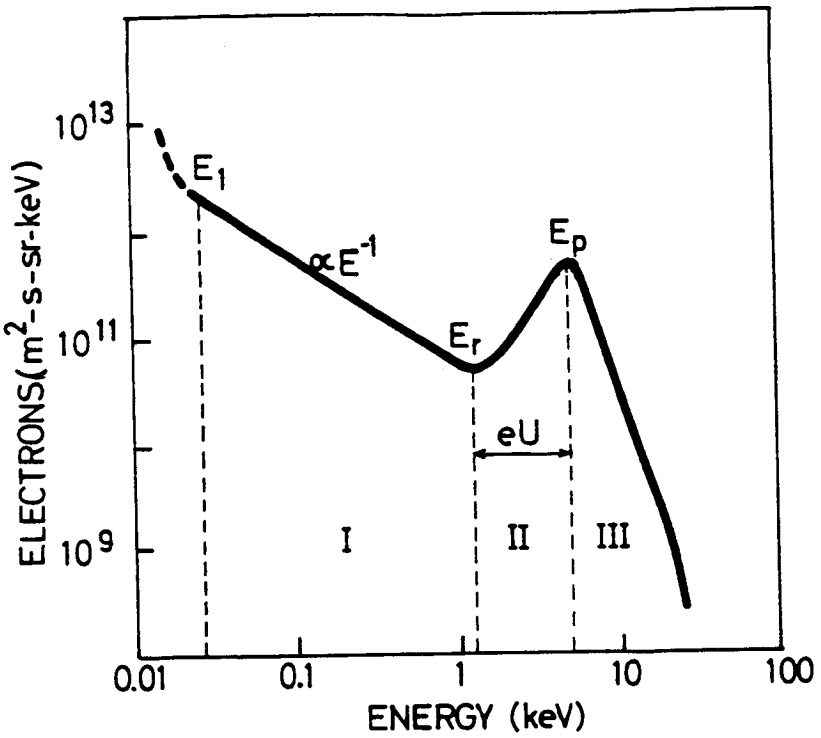
ELECTRONS(m²-s-sr-keV)
10¹³
10¹¹
10⁹
E₁
∝E⁻¹
Eₚ
Eᵣ
eU
I
II
III
0.01
0.1
1
10
100
ENERGY (keV)

Fig. 4

PLASMA UNIVERSE

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Abstract

Traditionally the views on our cosmic environment have been based on observations in the visual octave of the electromagnetic spectrum, during the last half-century supplemented by infrared and radio observations.

Space research has opened the full spectrum. Of special importance are the X-ray-γ-ray regions, in which a number of unexpected phenomena have been discovered. Radiations in these regions are likely to originate mainly from magnetised cosmic plasmas. Such a medium may also emit synchrotron radiation which is observable in the radio region.

If we try to base a model of the universe on the plasma phenomena mentioned we find that the plasma universe is drastically different from the traditional visual universe.

Information about the plasma universe can also be obtained by extrapolation of laboratory experiments and magnetospheric in situ measurements of plasmas. This approach is possible because it is likely that the basic properties of plasmas are the same everywhere.

In order to test the usefulness of the plasma universe model we apply it to cosmogony. Such an approach seems to be rather successful. For example, the complicated structure of the Saturnian C ring can be accounted for. It is possible to reconstruct certain phenomena 4-5 billions years ago with an accuracy of better than 1%.

I SPACE RESEARCH AND THE PLASMA UNIVERSE

1. Impact of space research on cosmic physics. Terminology

For centuries or millennia our knowledge of the universe has been based on information received in the visual octave 0.4-0.8 μ (see Fig.1). During the last half-century the visual light astronomy has been supplemented by infrared and radio astronomy. During the last decade space research has opened the whole electromagnetic spectrum. This means that we now also receive information in the whole infrared region and the ultra-violet-X-ray-γ-ray region.

In this paper we shall concentrate our attention on the X-ray and γ-ray regions. Most of the emissions in these wavelengths are likely to be produced by electrons with energies in excess of some hundred eV. We know that processes in magnetized plasmas, especially in connection with double layers and other magnetic field aligned electric fields, accelerate auroral electrons to some 10^3 eV. Further in solar flares basically similar plasma processes produce energies of 10^9-10^{10} eV (C.P. III)*. Carlqvist's theory of relativistic double layers demonstrates that under cosmic conditions even much higher energies may be generated in magnetized cosmic plasmas (Carlqvist, 1986).

Hence with some confidence we can assume that the X-γ-rays we observe derive mainly from magnetized plasmas with electron energies in excess of some hundred eV. This means that it seems legitimate to call the picture we get from these wavelengths "the high energy plasma universe".

As we shall see this picture is often drastically different from the traditional picture of the visual universe which is based on observations in visual light. This light derives from solid bodies (e.g. planets) but to a much larger extent from stellar photospheres which usually are in a state of low energy

* C.P. = Alfvén, H., Cosmic Plasma, Astrophys. Space Sci. Libr. 82, D.Reidel Publ. Co., Dordrecht, Holland, 1981.

plasmas ($\lesssim$10 eV). Hence visual universe is not far from a synonym to low energy plasma universe, but for the sake of convenience we shall use the term visual universe. We shall compare this with the high energy plasma universe, a term which we shall shorten to plasma universe.

High energy magnetized plasmas do not only emit X-rays-γ-rays but also synchrotron radiation which often falls in the radio bands. Hence radio astronomy also gives us information about the plasma universe.

2. Difference between plasma universe and visual universe

The following figures show a few typical differences. Fig. 2 shows that the sun seen in X-rays is shockingly different from our visual picture of it.

The general time scales of the visual and the plasma universe are also often different. Whereas our night sky gives an impression of calmn - the moon moves with a time period of one month, planets with periods of years or centuries - γ-ray bursts which are the most energetic events in the gamma ray region (Fig.3) change their output by orders of magnitude in seconds or milliseconds; i.e., ten orders of magnitude more rapidly.

Also, those radio waves which derive from synchrotron radiation in a plasma give us a picture of the plasma universe which does not resemble the visual night sky very much (Fig.4).

3. Relations between the visual and the plasma universe

The relation between the visual and the plasma universe is somewhat analogous to the relation between a visual and an X-ray picture of a man. The visual picture is - literally - superficial: you see his skin and not very much more. The X-ray

picture reveals the structure of his whole body, it shows the skeleton and intestines, and gives us a better understanding of how his body works.

Similarly, the visual picture of our solar system gives us information about thin surface layers of the celestial bodies, whereas plasma investigations tell us the structure of the interplanetary space, and - by extrapolation - how once the solar system was formed out of a dusty plasma (see 6). Similarly, as most of the universe is likely to be in the state of a dusty plasma, the plasma universe is more basic than the visual universe. Further, the X-ray γ-ray regions cover 10 times more octaves and $>>1000$ times more band width than the visual light, and when receivers in these wavelength regions have been adequately developed we can expect to obtain more observational data from them than from the single visual light octave.

There is still another good reason for concentrating our attention on the plasma universe: our views of the universe are traditionally based on visual observation and in order to compensate for the "generally accepted" but distorted views of the structure of the universe and how it has developed it is healthy to put much emphasis on the plasma universe.

4. Model of the plasma universe

There is another, and perhaps even more important approach to the study of the plasma universe. There are good reasons to suppose that the basic properties of plasmas are the same everywhere (C.P. I.2 and Bg 2*). Hence plasma experiments in the laboratory or in the magnetospheres (including solar magnetosphere ≡ heliosphere ≡ solar wind region) are relevant also for the understanding of distant astrophysical regions. Similarly, passive in situ measurements from spacecraft in the magnetospheres give us important information about galactic, cosmogonic, and cosmological conditions. Fig. 5. shows different plasma regions and the transfer of knowledge between them.

* Bg (2) menas Background material n:o (2).

The same material as in Fig. 5 is used in Fig. 6 for constructing a picture of the plasma universe (in an essentially logarithmic scale).

We can depict the extrapolation mentioned above as a "knowledge expansion" which started from laboratory research. With the advent of the space age, which made possible in situ measurements in the magnetospheres the "knowledge expansion" increased in strength and is now on its way to reach out as far as spacecraft go.

It is very important that it proceed further out. Indeed, astrophysics will be changed very much when (sooner or later) the knowledge expansion reaches interstellar and intergalactic regions (Bg 2 and Alfvén 1986).

Extrapolation of laboratory and magnetospheric research demonstrates that the plasma universe has properties which differ from those of the traditional visual universe in many respects. A survey of these is given in C.P., and briefly summarized in Bg (2). Important results are:

5. Electric currents in interplanetary interstellar, and intergalactic space

Space is divided by current sheaths into compartments. On the two sides of a current layer magnetisation, density, temperature and chemical composition may differ. Examples: the magnetopause which separates the solar wind and our magnetosphere, and similar phenomena around other planets. In interstellar and intergalactic space also the kind of matter may differ (koinomatter on one side, antimatter on the other, see C.P.VI).

Space is penetrated by a network of filamentary currents. Examples: Birkeland currents (magnetic field aligned electric currents) currents producing the filamentary structure of the corona, and similar currents in hydromagnetic "shock fronts".

The filaments are usually produced by the pinch effect. They transfer energy and momentum over large distances. The currents often produce electric double layers (C.P. II.6), in which charged particles may be accelerated to high, even very high, energies.

Such current layers and pinches may scatter radiation. Whether such effects are large enough to isotropize the 3 K radiation is an open question.

II APPLICATIONS

6. Application to Cosmogony

One of the many problems that will appear in a new light is the cosmogonic problem. We shall here discuss the application of the plasma universe model to cosmogony (HAGA* and Bg9).

In these publications the sun is supposed to be formed from a dusty interstellar cloud by processes which we shall not discuss here. It has a certain mass, spin and magnetization. Residuals from the cloud form cloudlets which fall in towards the sun and according to the plasma cosmogony they are emplaced in those regions where they reach the "critical velocity". (When the relative velocity between a non-ionized gas and a magnetized has reached the "critical velocity" the kinetic energy of the relative velocity equals the ionisation energy (C.P. IV.6.). An unexpectedly strong interaction occurs. Angular momentum is transferred from the sun. These processes are governed by plasma effects, of course in combination with mechanical effects. The result is a state of partial corotation (see Fig. 7 (table)).

The next process is when the plasma becomes deionized and forms planetesimals. This plasma-planetesimal transition (PPT) is as-

* HAGA means two monographs by H. Alfvén and G. Arrhenius 1975 and 1976 (see Bg3)

sociated with a contraction by a factor Γ, which should be approximately $\Gamma = 2:3$, but some secondary effects should reduce this value by a few percent.

The planetesimals aggregate to planets. Around some planets the same processes are repeated in miniature, which leads to the formation of satellite systems. The cosmogony of these is similar to the cosmogony of the planetary system. We shall here study the formation of the Saturnian system, especially the rings. The results we obtain are applicable to the formation of planets (see HAGA).

6.1 Structure of Saturnian Rings

The present structure of this is seen in Fig. 8. Fig. 9 shows the basic mechanism of the contraction at the PPT (HAGA 17.2 and Bg 4,5, and 9).

Before the PPT a plasma element (or charged grain) is acted upon by the gravitation pull F_g from the central body and the centrifugal force F_c. Moreover, because the plasma preferentially moves along the magnetic field lines, there is also an electromagnetic force F_E. In a dipole field we have for geometrical reasons $F_c = 2/3\ F_g$; $F_E = 1/3\ F_g$ (HAGA and Fig.9). At the PPT, F_E is cancelled. As F_c alone cannot compensate F_g, the result is a contraction by a factor $\Gamma \approx 2/3$ (a small correction decreases Γ to about 0.63-0.65). Fig. 10 demonstrates that if Mimas and Janus have swept the plasma close to their orbits, the PPT contraction displaces these empty regions to smaller Saturnocentric distances, thus producing what we call "cosmogonic shadows". If the Saturnocentric distances of satellites Mimas and Janus are scaled down by a factor $\Gamma = 0.64$, the regions which they have swept before the PPT coincide with the Cassini division and a pronounced minimum in the inner B ring. Before the spacecraft missions to Saturn, confirmation of the cosmogonic shadow effect has already been found in four cases, so that the bulk structure of the Saturnian rings could be explained by these cosmogonic effects. (Similar confirmation of the 2:3 fall down

is found in the asteroidal belt; see Bg 7). Two of these cases are demonstrated in Fig. 10.

Fig. 11 shows the diagrams of the A, B, and C rings; more detailed diagrams are depicted in Figs. 11A. 11B, and 11C.

A remarkable discovery of the Voyager missions was that the Cassini division was not empty. There are two ringlets near its center. Holberg pointed out that in the density minimum at the inner part of the B ring there is a similar doublet.

Preliminary attempts to understand this led to the conclusion that the primary cosmogony shadow of a satellite should be identified with the density minimum between the two ringlets of the doublet. However, the density gradient caused by the shadow and associated electric fields produce one secondary shadow on each side of the primary shadow by changing the fall-down ratio. This means that the total result may be as depicted in Fig. 12. It seems to give a first approximation of the general structures of the Cassini division and the Holberg minimum.

6.2 The C ring

With this as a background we shall now analyse the detailed pattern of the C ring. The C ring consists of a number of ringlets separated by almost void regions. This makes it of special interest. The A and B rings are sometimes approximated as uniform discs. This cannot possibly be done with the C ring.

The diagram shows that some of the ringlets are sharp peaks (marked R) which have been identified as caused by gravitational resonances with some of the satellites (see Fig.11). Besides there are a number of ringlets with drastically different structures. The density maxima are rather flat and they are much broader than the resonances. It is reasonable to assume that these might have been caused by the same mechanisms as produced the shadows of Mimas and Janus. If we do this we find that all these maxima can be identified with cosmogonic shadows caused by the shadow producers which are shown at the upper scale (Bg 9).

There seems to be a third kind of maxima which are very wide and low, as shown at 1.358 and 1.375 (Fig.11C). Some of the photographs show very faint ringlets deriving from these.

The cosmogonic shadows can be regarded as signatures of the processes we have summarized. Table 1 shows how the Γ values agree within less than one percent. Fig. 13 is a picture of the Saturnian rings which shows the identifications.

There has been much discussion about gravity waves in the rings. It seems reasonable to approximate both the A ring and B ring as homogeneous discs in which such waves may proceed (but there is no convincing proofs that they affect the ring structure). However, the C ring concists of a number of distinct ringlets separated from each other by almost void regions. It seems unlikely that gravity waves are of any importance in the C ring.

6.3 Conclusions. Accurate reconstruction of cosmogonic events

1. With the model of the plasma universe as a background, it is possible to understand much of the complicated structure of the Saturnian C ring.
2. Fig. 11C and Table 1 demonstrate that it is possible to reconstruct certain cosmogonic events with an accuracy of better than 1%. This makes possible a new approach to the evolutionary history of the solar system.
3. As cosmogony is a key problem in astrophysics, planetology, geology, paleobiology, etc., the results will be relevant to a number of sciences.

7. Other applications of the plasma universe model

A large number of other applications of the plasma universe model have been made, many of them before the term plasma universe was coined. Many of these are described in the "Background material". Of special interest are:

7.1 Circuits

Up to recently practically all descriptions of electromagnetic conditions in space have been based on pictures of magnetic fields. Electric currents have been accounted for as curl B. As has been clarified especially at the Symposium on Magnetospheric Currents (Potemra 1984) and the Double Layer in Astrophysics Symposium (A. Williams 1986), this is erroneous, because there are a number of essentially electrostatic phenomena which require that electric currents and the circuits in which they flow are explicitely introduced (see 5).

Basically the same circuit can be used to account for the electromagnetic conditions in the auroral region, in the heliosphere, and in intergalactic space (C.P. III). The formation of the two giant plasma clouds in Fig. 4 are explained by a transfer of energy from the rotation of the central galaxy by means of the same circuit as transfers energy from plasma clouds in the magnetosphere to electric double layers in which it is accelerating charged particles to high or very high energies (C.P. Fig.III.8).

7.2 Magnetosphere-ionosphere interactions - as a manifestation of the Plasma Universe

As the universe almost entirely consists of plasma, the understanding of astrophysical phenomena must depend critically on our understanding of how matter behaves in the plasma state. In situ observations in near earth cosmical plasmas offer an excellent opportunity of gaining such an understanding (Fälthammar 1986). The near earth plasma not only covers vast ranges of density and temperature but also a rich variety of complex plasma physical processes.

Hence an application of the plasma universe models makes it easier to understand the near earth processes. Vice versa, the study of near-earth processes gives us important information which can be applied to a better understanding of interstellar and intergalactic plasma phenomena.

7.3 Cosmology

In the plasma universe the big bang hypothesis will meet serious difficulties. (See C.P. VI).

8. Conclusions

The transition from the geocentric to the heliocentric cosmology is usually attributed to the Copernican theory. This is only partially correct. Galileo's introduction of the telescope was probably more important, because it gave a large quantity of new observational material. In fact the heliocentric cosmology had been proposed 2000 years earlier by Aristarcus, but without telescope he could not prove it.

Spacecraft has given us an enormous wealth of new information. The purpose of this paper is to give a sketch of possible consequences of this for our views of our cosmic environment. It will require much work before we can construct a new picture of the universe which incorporates our new knowledge.

This paper is a summary of the publications which are quoted in the reference list. Further references are found in them.

Figure Captions

Fig.1 As we now can eliminate atmospheric absorption we can observe our cosmic environment also in X-rays and γ-rays, wavelengths which are mainly produced by plasma phenomena.
Traditionally all our knowledge of the universe was derived from observations in the visual octave, later supplemented by radio observations and some infrared observations. Space age has made it possible to see not only this "visual universe" but also the "plasma universe".

Fig.2 The sun seen in X-rays looks drastically different from the visual sun. The large dark regions are "coronal holes".

Fig.3 A majestic calmness characterizes the visual night sky. The planets move with periods of years, if not centuries. (Only the moon has a period of one month.) But the plasma universe as observed in X-rays and γ-rays shows variations by orders of magnitude, with time constants of seconds, if not milliseconds.

Fig.4 A double radio source is a very strong emitter of synchrotron radiations produced in giant magnetized plasma clouds. Nothing is seen in visual light at the place of the clouds, but there is usually a galaxy halfway between them.

Fig.5 Transfer of knowledge between different plasma regions. The linear dimensions of plasma vary by 10^{27} in three jumps of 10^9

from laboratory plasmas	- 0.1 m
to magnetospheric plasmas	- 10^8 m
to interstellar clouds	- 10^{17} m
Hubble distance	10^{26} m

Including laser fusion experiments brings us up to 10^{32} orders of magnitude.
New results in laboratory plasma physics and in situ measurements by spacecraft in the magnetospheres (including the heliosphere) make sophisticated plasma diagnostics possible out to the reach of spacecraft (10^{13} m). Plasmas at larger distances should to a considerable extent be investigated by extrapolation. This is possible because of our increased knowledge of how to translate results from one region to another. See C.P. and Ref. (2).
The figure shows us an example of how cosmogony (formation of the solar system) can be studied by extrapolation from magnetospheric and laboratory results, supplemented by our knowledge about interstellar clouds.

Fig.6 Plasma universe. Contains essentially the same information as Fig. 5. Plasma research has been based on highly idealized models, which did not give an acceptable model of the observed plasma. The necessary "paradigm transition" leads to theories based on experiments and observations. It started in the laboratory about 20 years ago. In situ measurements in the magnetospheres caused a similar paradigm transition there. This can be depicted as a "knowledge expansion", which so far has stopped at the reach of spacecraft. The results of laboratory and magnetospheric research should be extrapolated further out. When this knowledge is combined with direct observations of interstellar and intergalactic plasma phenomena, we can predict that a new era in astrophysics is beginning, largely based on the plasma universe model (see C.P. and (2)).

Fig.7 Application of the plasma universe model to plasma cosmogony. According to HAGA (Bg 3) the main processes were those listed here. According to the "hetegonic principle" satellites and planets were formed by basically

the same processes. Hence, we can study essential features of planetary formation through a study of the Saturnian satellite system. This is convenient because of the remarkably accurate observations of this satellite system by the Voyager results (Bg (4,5,6,8,9,10)).

Fig.8 Saturnian rings and the innermost satellites.

Fig.9 Partially corotating plasma. The gravitation of the central body on a plasma cloud or grain is balanced to 2:3 by the centrifugal force and to 1:3 by electromagnetic forces. When at the PPT the latter disappear, the partially corotating medium contracts by a factor Γ = 2:3 (a small correction brings down the Γ-value to 0.63-0.65) (see HAGA).

Fig.10 Mimas and Janus (or the jetstreams out of which they are formed) sweep the regions in which they move so that they are free from plasma. At the PPT contraction these empty regions are scaled down by the factor Γ. This explains why there is a void region called the Cassini division , and a similar low density region at 1.60. The Saturnocentric distances of these correspond to Γ = 0.65.

Fig.11 Opacity of the A, B, and C rings. Below "photographic recording".

Fig.11A The A ring and Cassini's division. It has been believed for a long time that the outer limit of the A ring is given by the Roche limit, which probably is correct. It is limited inwards by the Cassini division which has a double ringlet in its interior. A tentative explanation is given in Fig. 12. The primary shadow of Mimas should be the void at 1.993 between the two ringlets. In the region 2.00 to 2.02 there is a void which we identify with outer secondary shadow in Fig. 13, outside which

there should be a region of increased density which we identify with the 2.02-2.05 maximum. Inside the primary maximum there is a secondary shadow 1.95-1.99 and further inwards a maximum. However, the Mimas 2:1 gravitational resonance at 1.94 and the beginning of the dense B ring make the structure somewqhat ambigous.
The Encke division at 2.21 and the Keeler division at 2.26 are difficult to explain either by resonances or cosmogonic shadow effects. A suggestion by Cuzzi that Encke is produced by a tiny satellite seems attractive, but a similar explanation is necessary for the Keeler division.

Fig.11B The B ring. The densest ring. The primary shadow of Janus produces a void at 1.59, surrounded by a double ringlet at 1.58 and 1.60. Outside the doublet there is a secondary shadow at 1.60-1.64 followed by a maximum at 1.65. Inside there is a secondary shadow 1.56-1.58 and still further inside a maximum at 1.55. All this agrees reasonably well with the idealized Fig. 12. Most of the ring is characterized by large fluctuations which probably are not due to cosmogonic effects. There are no satellites which should give shadows in this region.

Fig.11C The C ring. There are three sharp maxima which are identified as gravitational resonances (cf. Fig.11) and two other similar sharp maxima (at 1.31 and 1.36) which because of their sharpness are likely to be still unidentified resonances. In the region 1.35-1.40 there are some not very well structured density variations (but they show up in some strongly contrast-enhanced photographs like Fig.13). All the rest of the structure of the C ring seems to be explicable as produced by a superposition of cosmogonic shadow effect of the Shepherds and the A rings according to Fig. 12 (see Ref. 9).

Fig.12 Cosmogonic shadows. The primary shadow is supplemented by one secondary shadow inside and one outside the primary shadow. These are presumably produced by changes in the contraction ratio due to the density gradient caused by the primary shadow. A similar effect makes "antishadows" also double.

Fig.13 Photograph (contrast-enhanced) of the Saturnian rings. Should be studied in detail in combination with Fig. 11 and Fig. 11C. In the C ring there are sharp gravitational resonances, which are shown by lines downwards on the photograph and are located at 1.290, 1.470 and 1.494. a (at 1.312) is unidentified but its sharpness indicates that it is a gravitational resonance. According to Fig. 11C the density varies only slowly between a and the inner Encke shadow at 1.405, but because of the contrast enhancement the small variations show up as weak diffuse ringlets at b and c.
All other markings in the C ring can be identified as cosmogonic shadows. The outer components of the doublet from leaky region and Keeler are very small according to Fig. 11C - presumably because of closeness to Roche - and are not visible in the photograph.

Background material (Referred to as Bg)

1. Cosmic Plasma, Astrophysics and Space Science Library, 82, D.Reidel Publ. Co., Dordrecht, Holland, 1981. Referred to as C.P.

   An analysis of the drastic revision of cosmic plasma physics produced by in situ measurements in the magnetosphere.

2. "Paradigm Transition in Cosmic Plasma Physics", Introductory lecture at the Conference on Plasma Physics, June, 1982, Gothenburg, Physica Scripta, T2/1, 10-19, 1982.

   A brief summary of Cosmic Plasma and a list of ten different fields of cosmic plasma physics were space research is producing a "paradigm transition", see also Geophys. Res. Letters 10, 487-488, 1983.

3. Structure and Evolutionary History of the Solar System, with G. Arrhenius, D. Reidel Publ. Co., Dordrecht, Holland, 1975.

   Evolution of the Solar System, with G. Arrhenius, NASA Scientific Publication 345, US Government Printing Office, Washington, D.C., 1976.

   Two monographs which demonstrate the basic importance of plasma phenomena in the evolutionary history of the solar system. The latter is much more detailed. Referred to as HAGA.

4. The Voyager I Saturn Encounter and the Cosmogonic Shadow Effect. Astrophys. Space Sci. 79, 491, 1981. See also ESA SP-161.

5. Solar System History as Recorded in the Saturnian Ring Structure, Astrophys. Space Sci. 97, 79-94, 1983.

   These two papers demonstrate that the Voyager measurements of the Saturnian ring confirm the 2:3 contraction at the plasma-planetesimal transition (which is predicted in 3).The agreement is better than a few percent.

6. Cosmogony as an Extrapolation of Magnetospheric Research, Space Sci. Rev.. 39, 65-90, 1984.

   Demonstrates that the advance in space research has made it possible to approach certain parts of cosmogony by an extrapolation of magnetospheric results.

7. "Origin, Evolution and Present Structure of the Asteroid Region", Lecture at the meeting, Asteroids, Comets, Meteors, Uppsala, June 20-22, 1983, in Asteroids, Comets, Meteors: Exploration and Theoretical Modelling, Eds., C.-I. Lagerkvist and H. Rickman, Astronomical Observatory, Box 515, S-751 28 Upsala, Sweden.

8. "Space Research and the New Approach to the Mechanics of Fluid Media in Cosmos", with F. Cech, Opening lecture at the XVIth International Congress of Theoretical and Applied Mechanics at Lyngby, Denmark, August 19-25, 1984, Theoretical and Applied Mechanics, F.I. Niordson and N. Olhoff, Elsevier Science Publishers B.V., North-Holland, IUTAM, 1985. Also presented as Opening lecture at Plasma Astrophysics Course and Workshop at Varenna, Italy, August 28-September 7, 1984, European Space Agency Scientific Publication 207, Nov. 1984, 8-10 rue Mario-Nikis, 757 38 Paris-Cedex, France.

9. "Voyager Saturnian Ring Measurements and the Early History of the Solar System", with I. Axnäs, N. Brenning, P.-A. Lindqvist, Report TRITA-EPP-85-07, Dept of Plasma Physics, The Royal Institute of Technology, S-100 44 Stockholm, Sweden, 1985, Planet. Space Sci. 34, 145, 1986.

A demonstration that practically the whole complicated pattern of the Saturnian C ring and essential features of the A and B ring can be accounted for with an accuracy of better than 1%.

This starts a transfer of cosmogony from speculation to real science.

10. Cosmogonic Scenario with G. Arrhenius, Preprint Dept of EE & CS and GRD, Univ. of California, San Diego, La Jolla, CA 92093, USA, 1985.
Report TRITA-EPP-85-04, Dept of Plasma Physics, The Royal Institute of Technology, S-100 44 Stockholm, Sweden, 1985.

An attempt to outline the basic processes in cosmogony. To some extent a systematic update of 3.

References to these are given as Bg (2) meaning paper 2 in this list.

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Carlqvist, P. 1986, On the Acceleration of Cosmic Particles by Electrostatic Double Layers, submitted to IEEE Transactions on Plasma Science, Special issue on plasma and cosmic plasma.

Fälthammar, C.-G. 1986, Magnetosphere-Ionosphere Interactions - Near Earth Manifestations of the Plasma Universe, IEEE Tansactions on Plasma Science, Special issue on plasma and cosmic plasma (in print).

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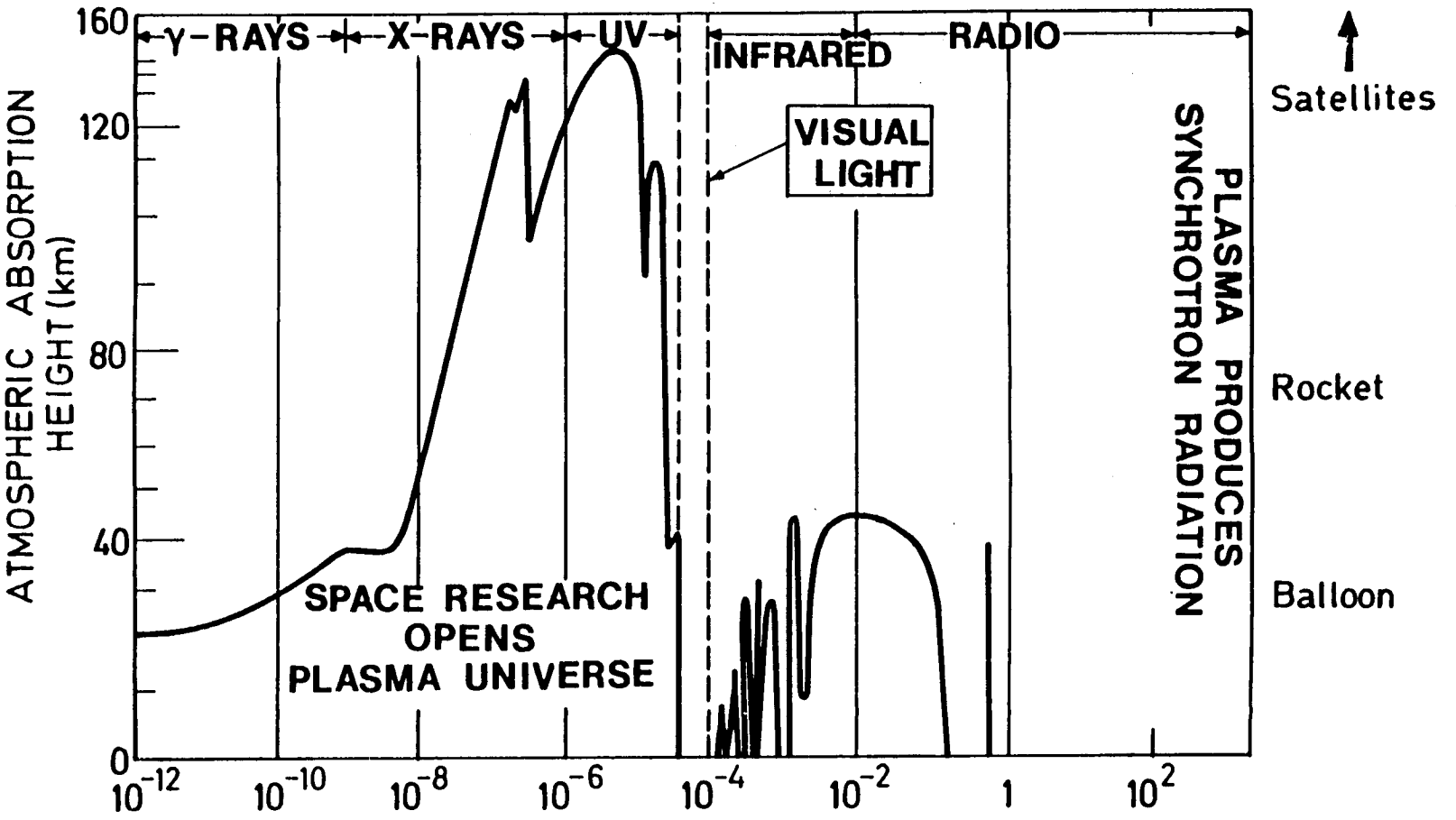


ATMOSPHERIC ABSORPTION GIVEN IN HEIGHT TO WHICH RADIATION PENETRATES

Fig. 1

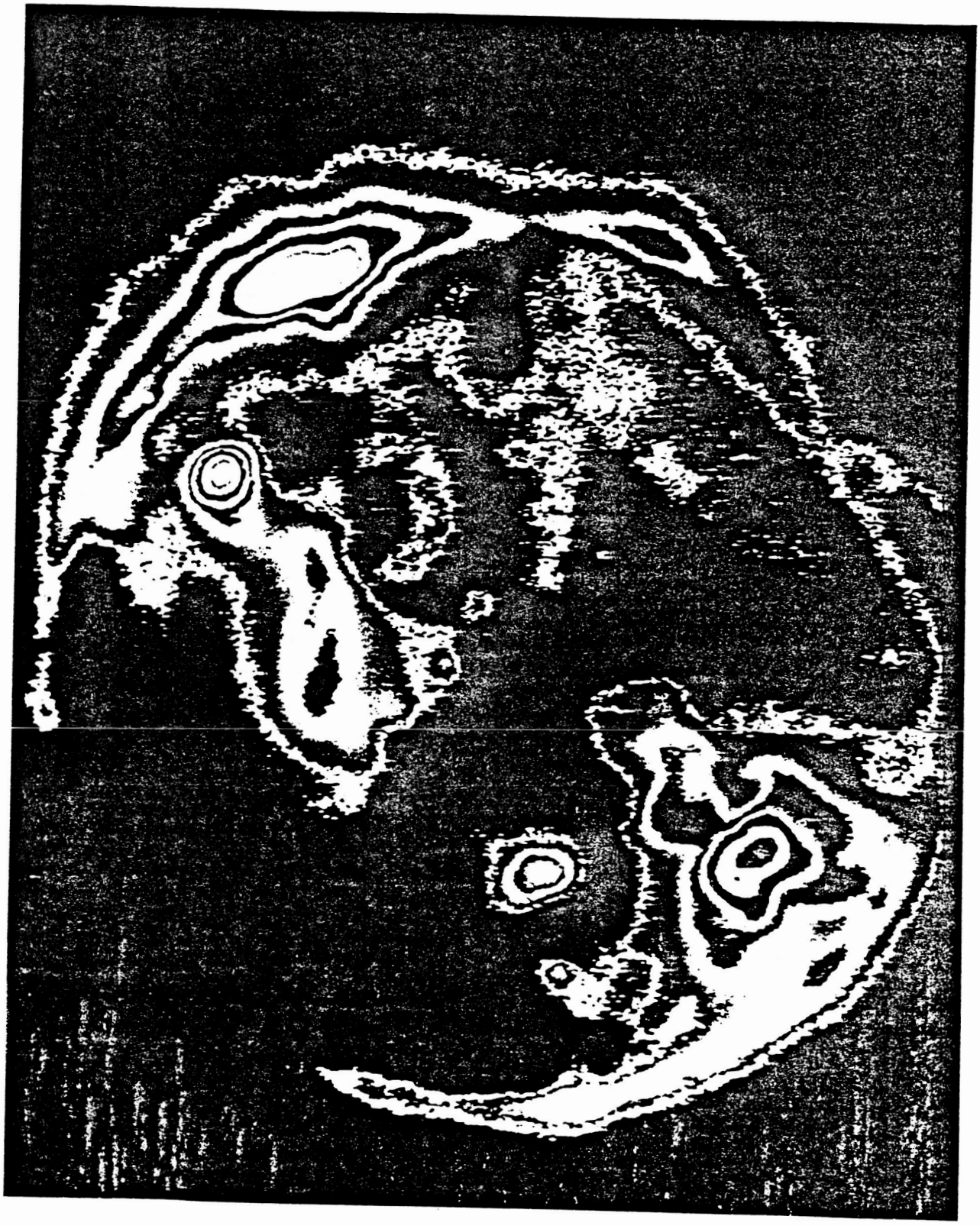


Fig. 2

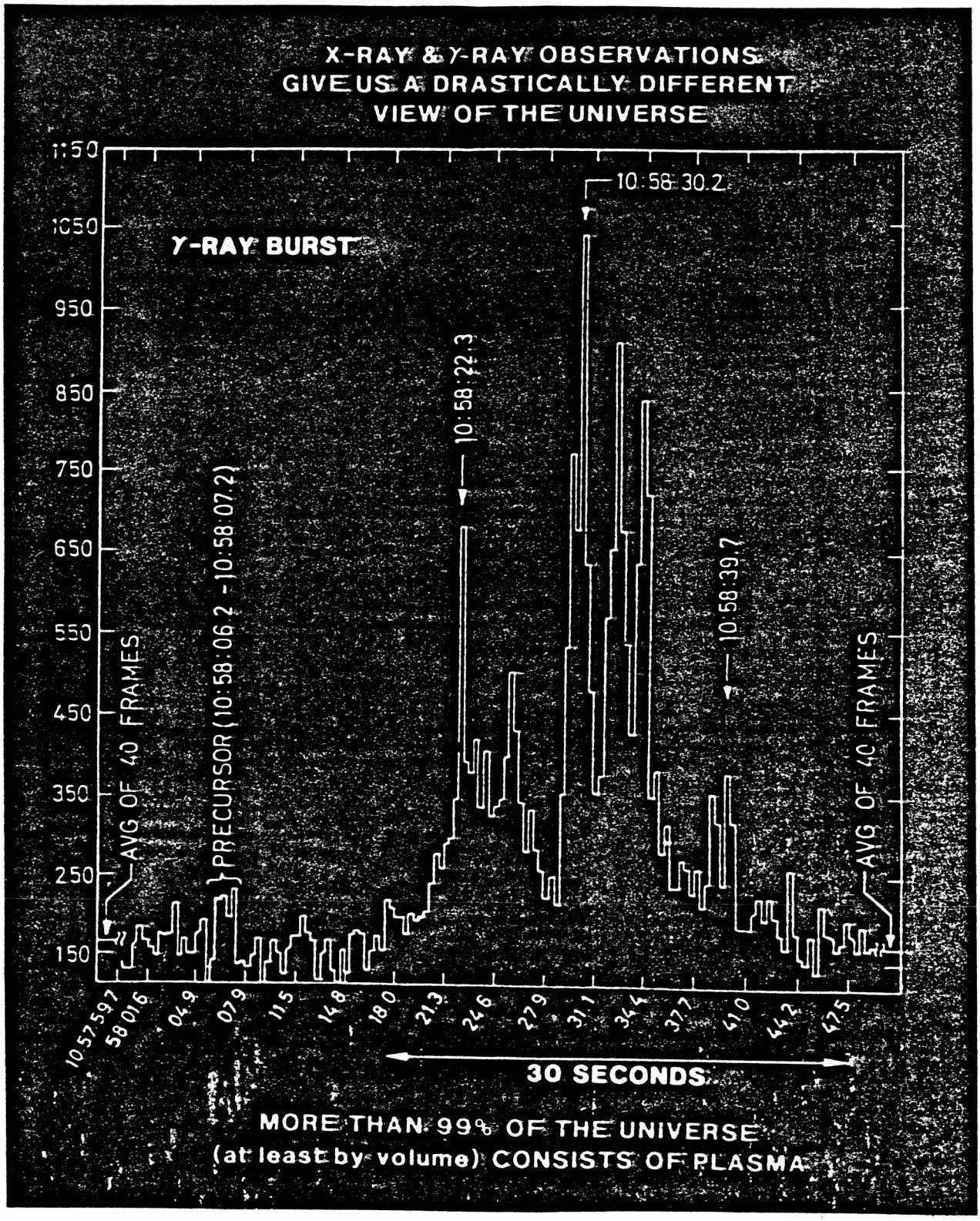


Fig 3

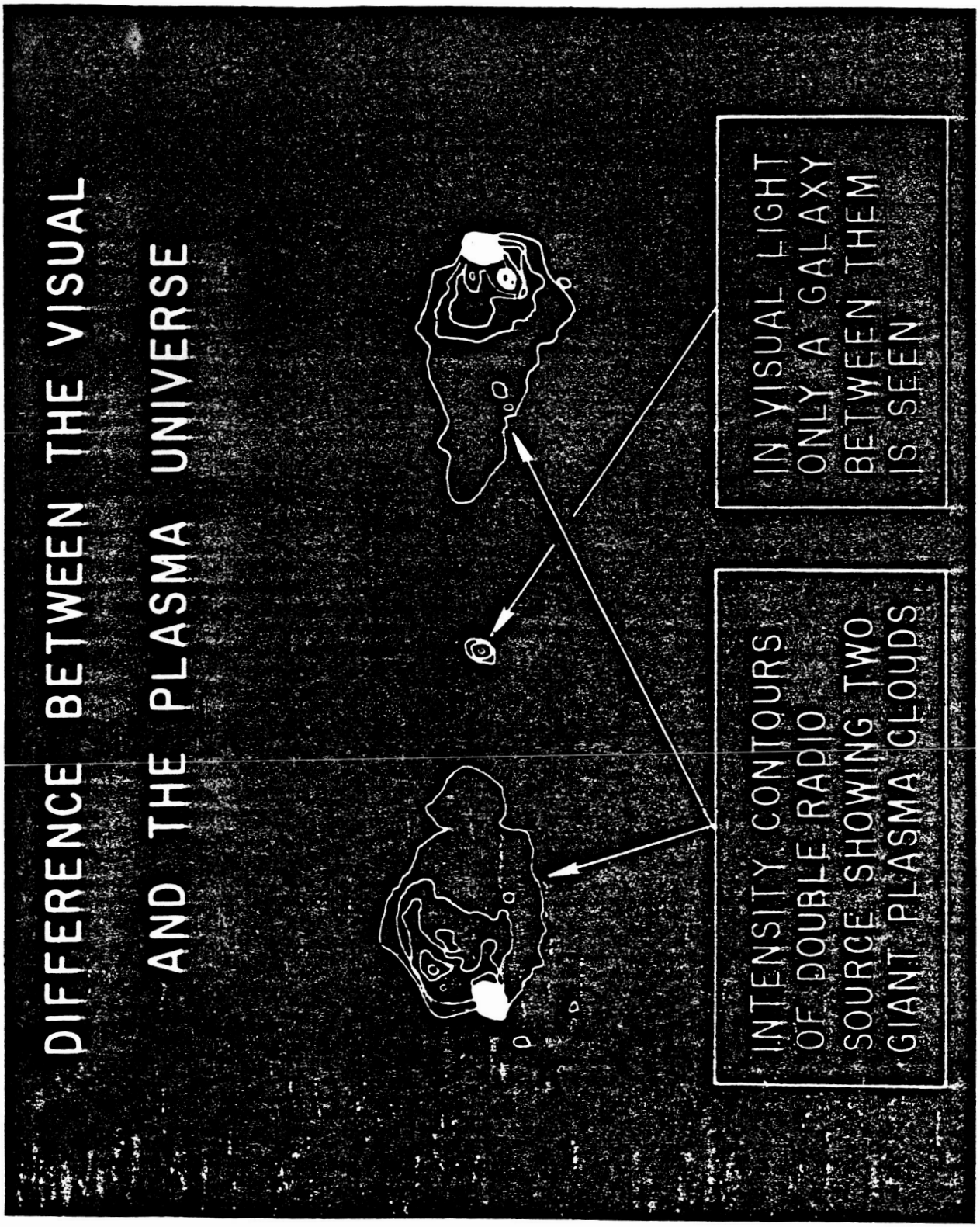


Fig. 4

TRANSFER OF KNOWLEDGE BETWEEN DIFFERENT PLASMA REGIONS

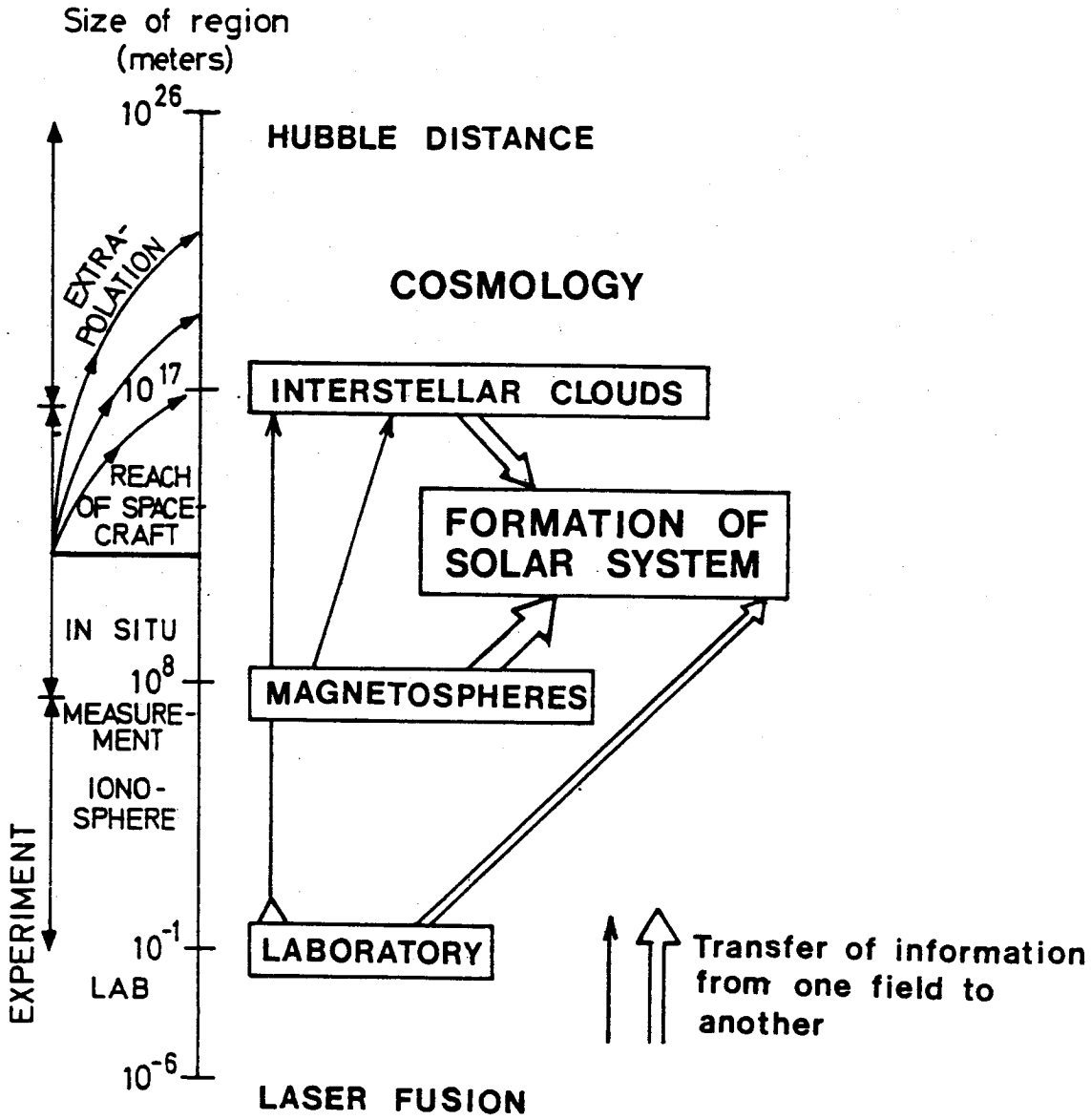


Fig. 5

PLASMA UNIVERSE

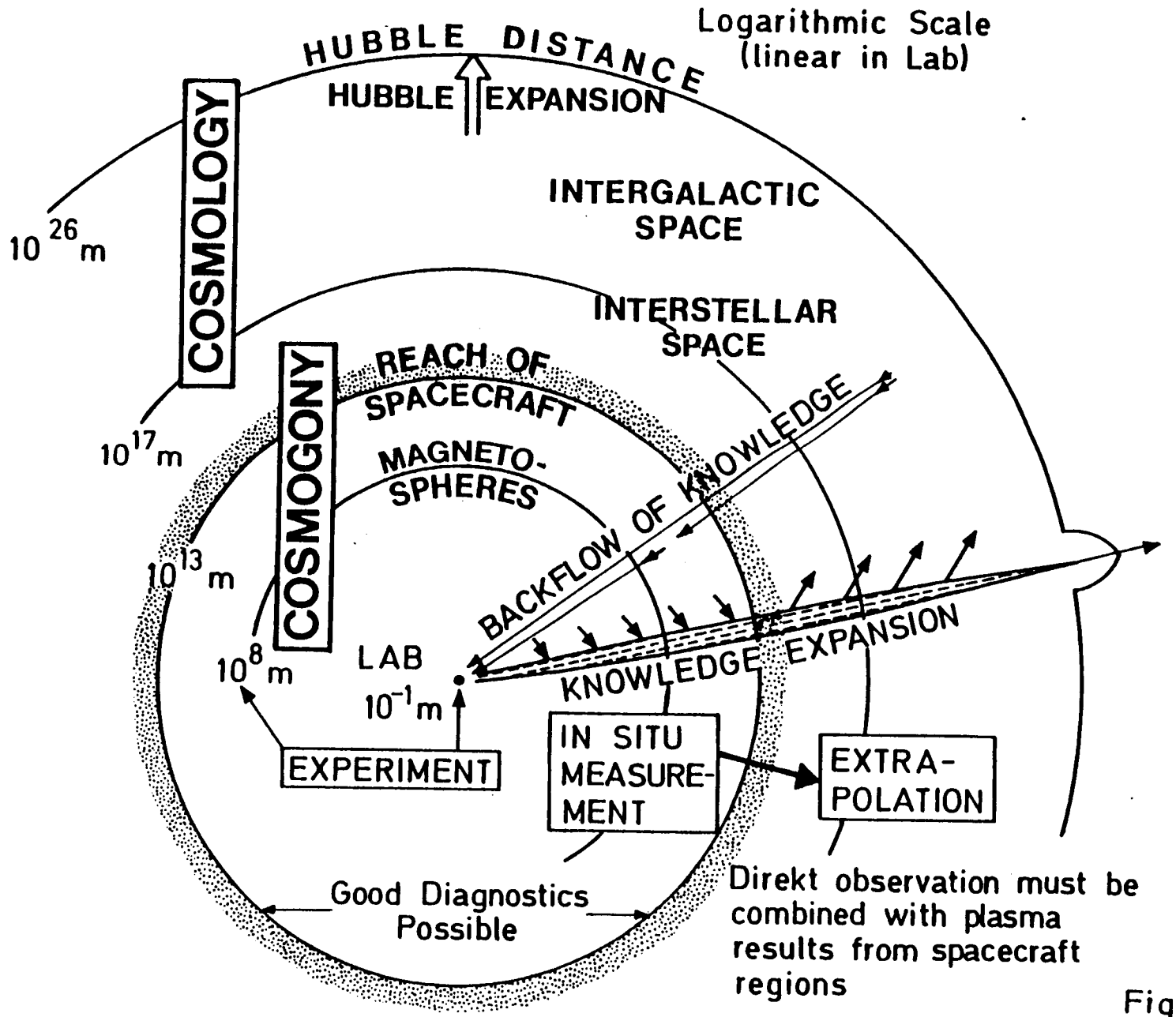


Fig. 6

PLASMA COSMOGONY

FORMATION OF SUN FROM INTERSTELLAR CLOUD

RESIDUALS FALL IN

FIRST PROCESSES GOVERNED BY PLASMA PROCESSES

- EMPLACEMENT OF PLANETARY MATTER
- TRANSFER OF ORBITAL MOMENTUM

PLASMA PLANETESIMAL TRANSITION (PPT)

- ASSOCIATED WITH CONTRACTION 2:3

LAST PROCESSES GOVERNED BY MECHANICAL PROCESSES

- ACCRETION OF PLANETESIMALS TO PLANETS

SATELLITE FORMATION BY REPETITION OF SAME PROCESS

- IN MINIATURE

Fig. 7

SATURN WITH MASSIVE RINGS AND INNERMOST SATELLITES.

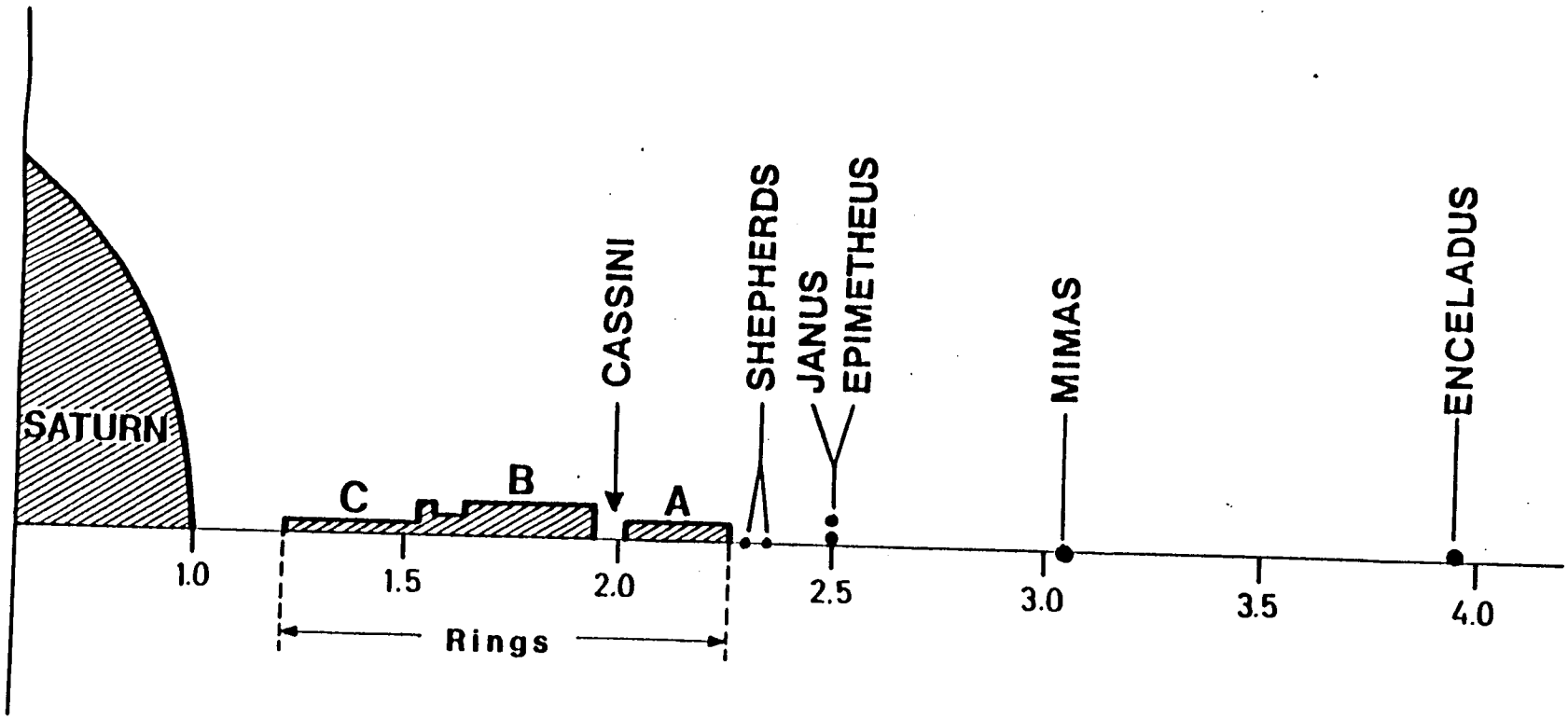


Fig. 8

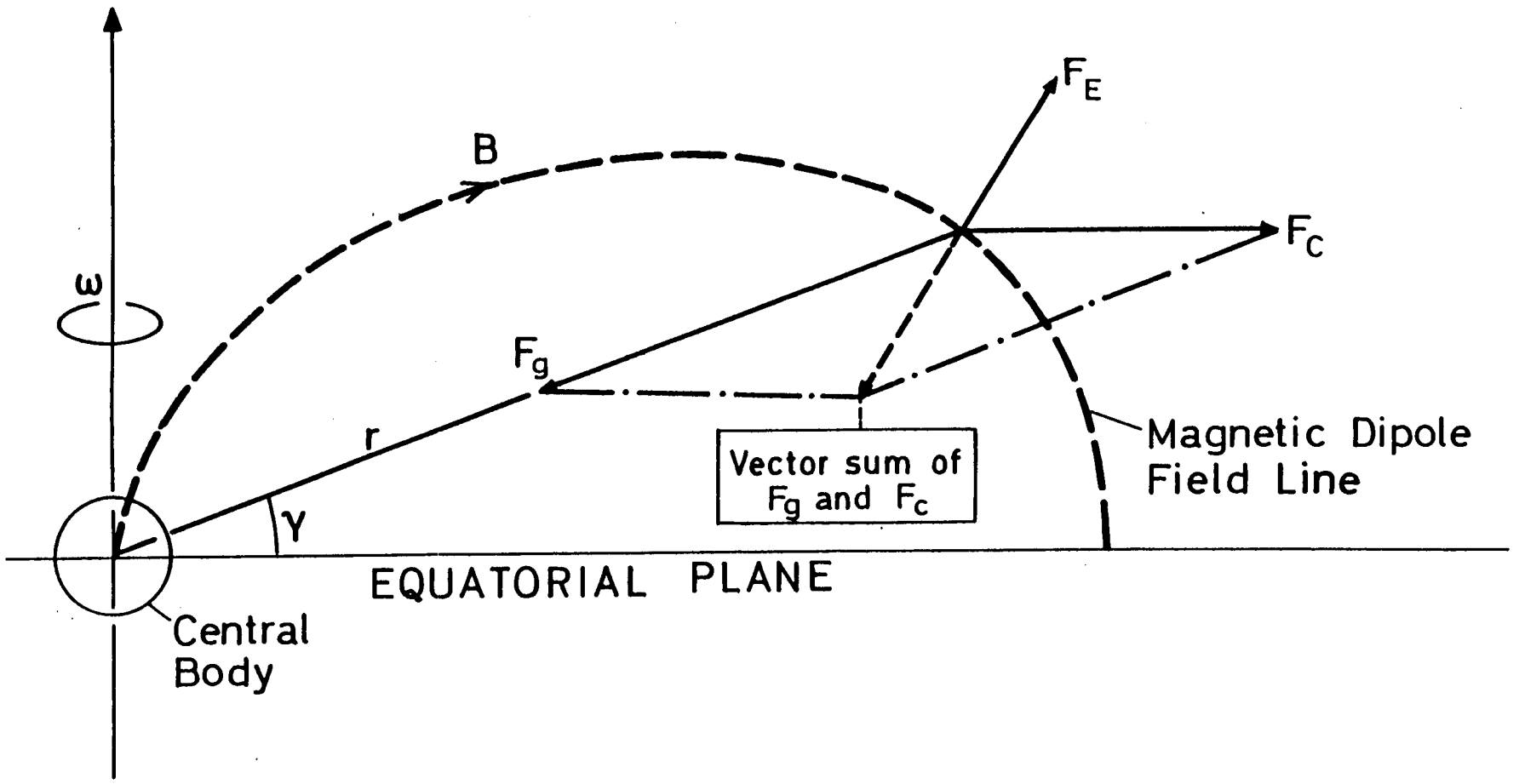

F_E
B
F_C
ω
F_g
r
γ
Vector sum of F_g and F_c
Magnetic Dipole Field Line
EQUATORIAL PLANE
Central Body

Fig. 9

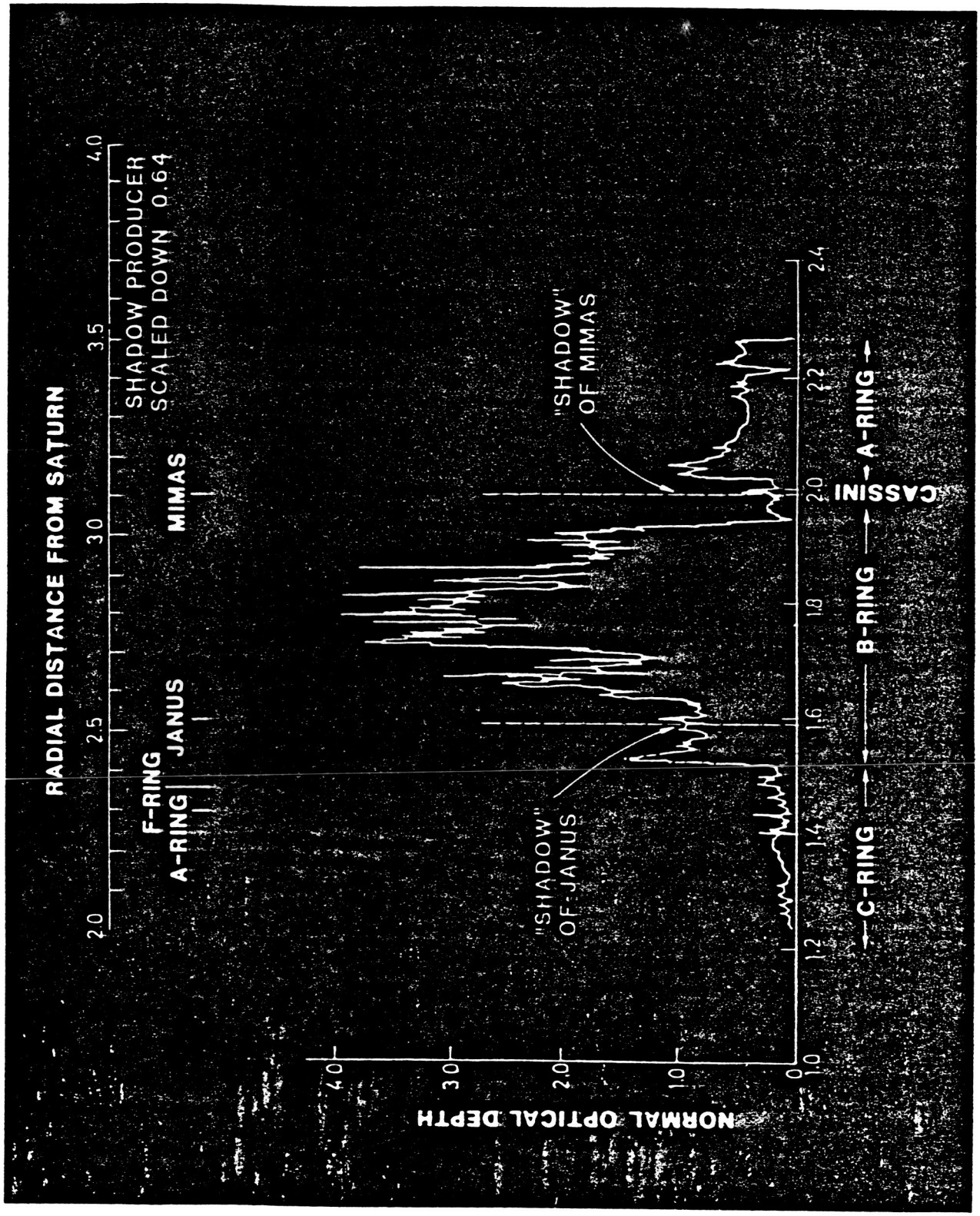


Fig. 10

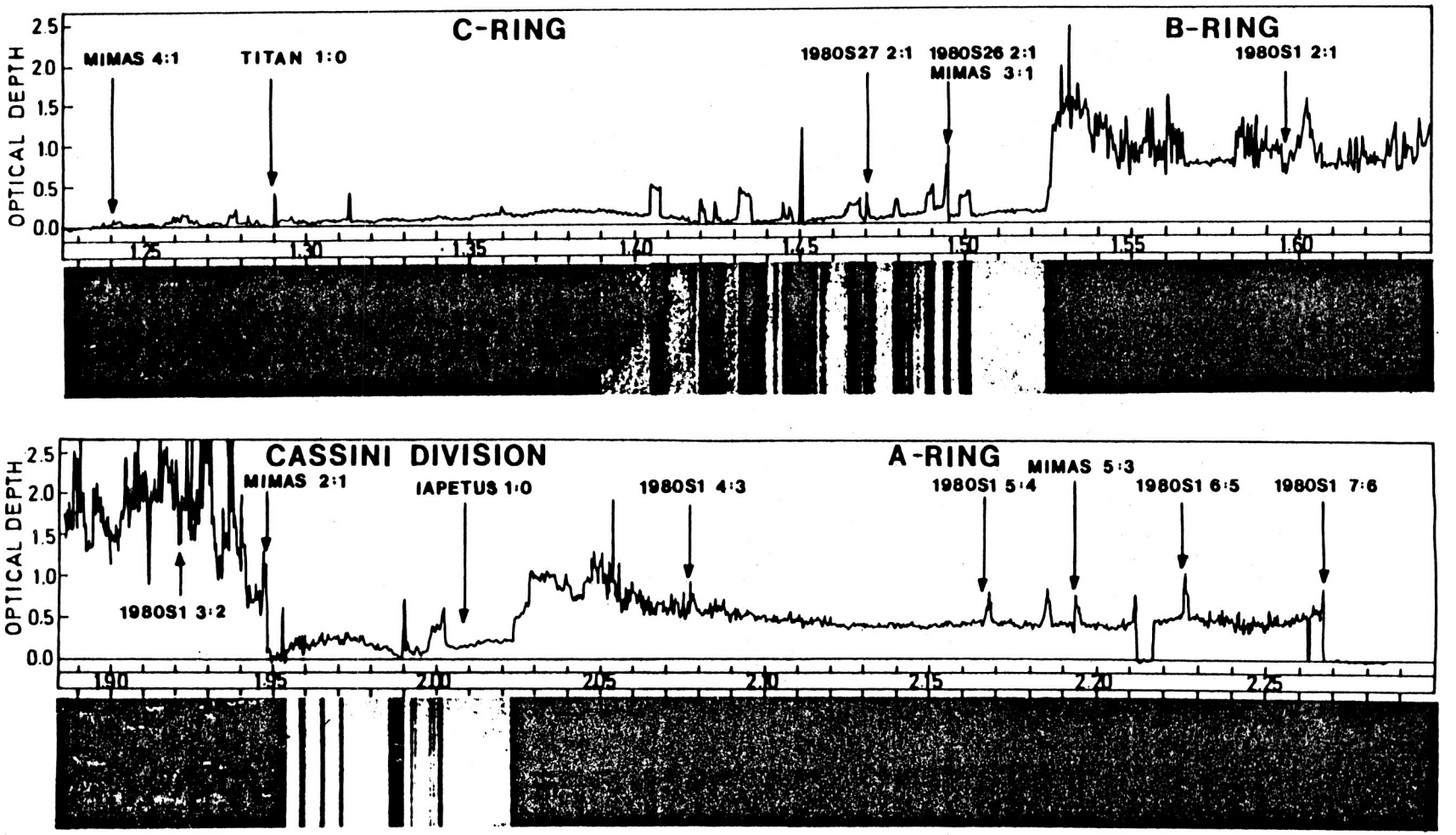


Fig. 11

CASSINI A-RING

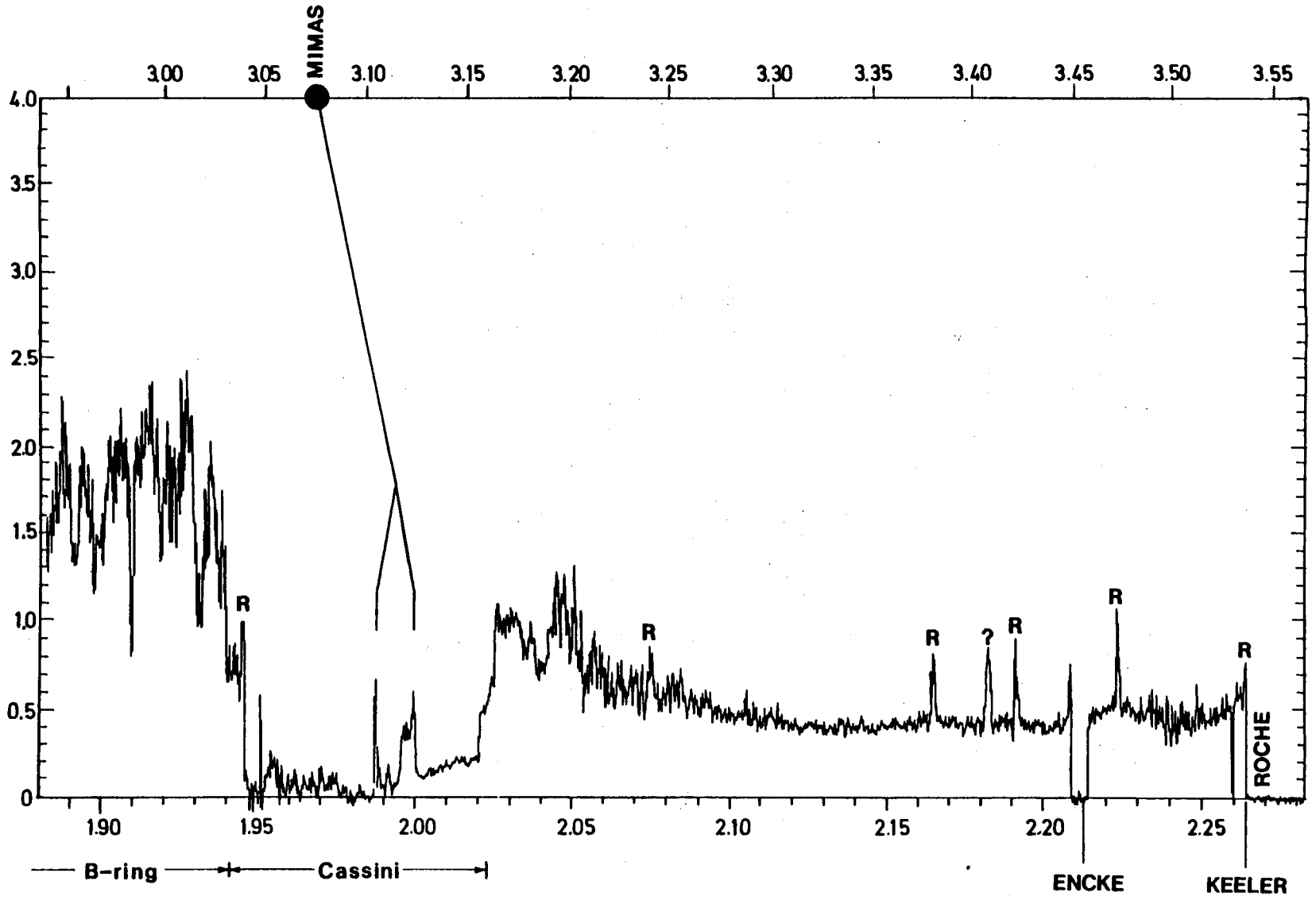


Fig. 11 A

B-RING

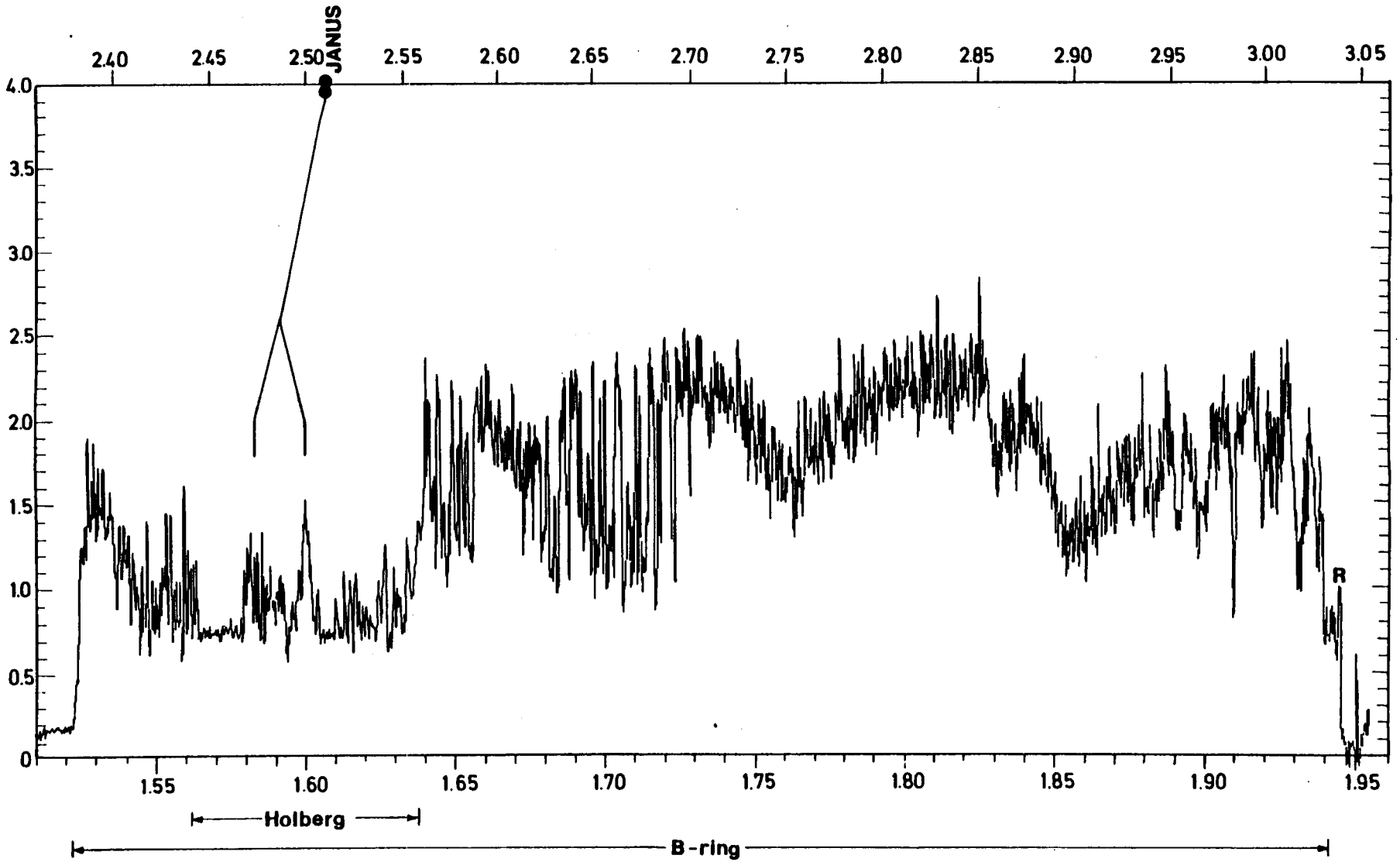


Fig. 11 B

C-RING

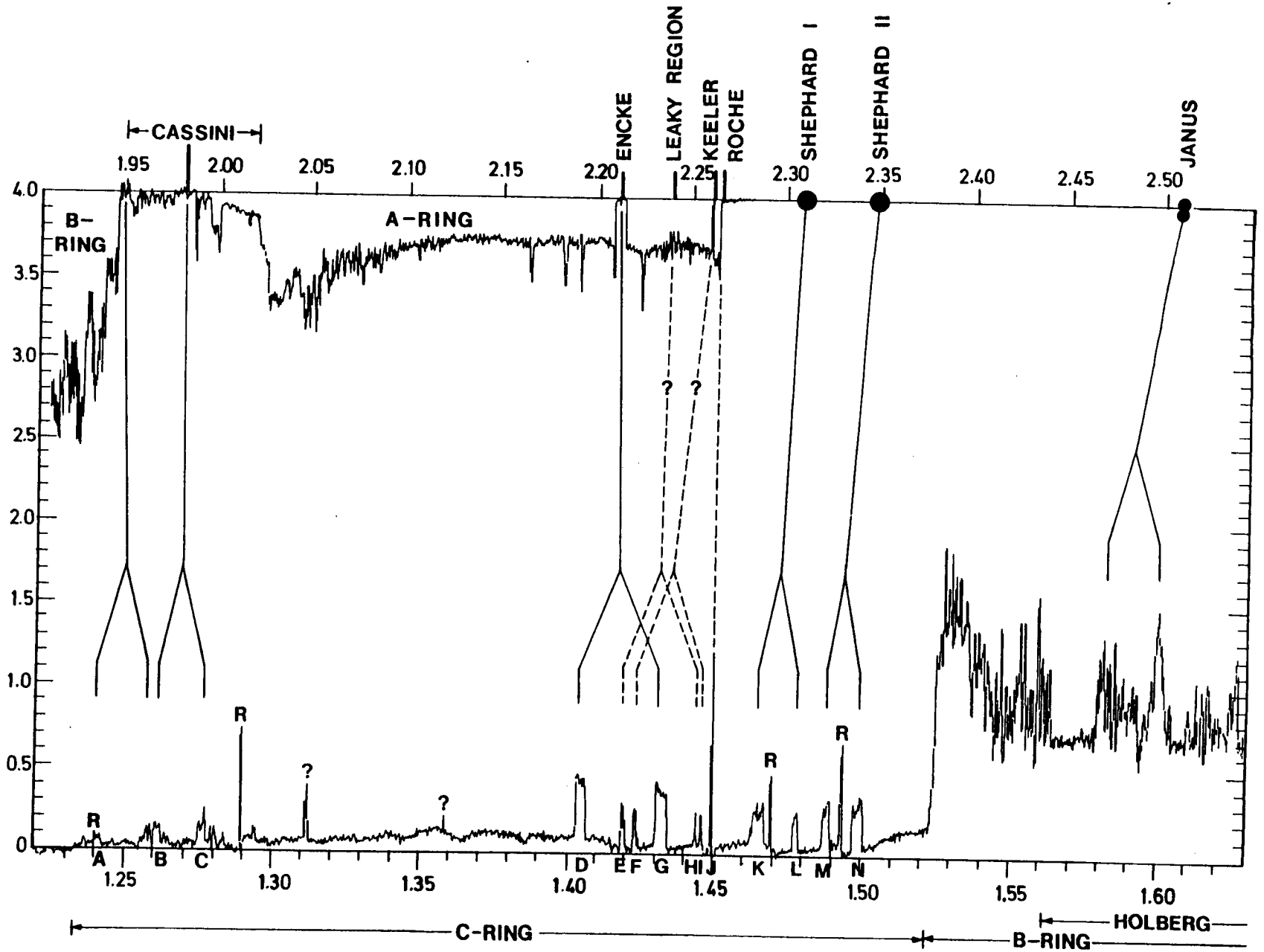
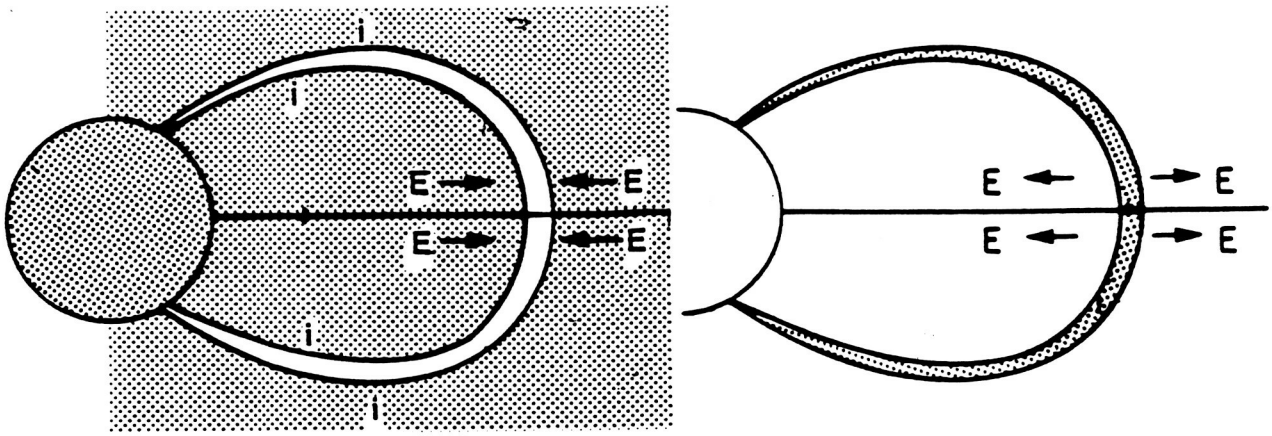


Fig. 11 C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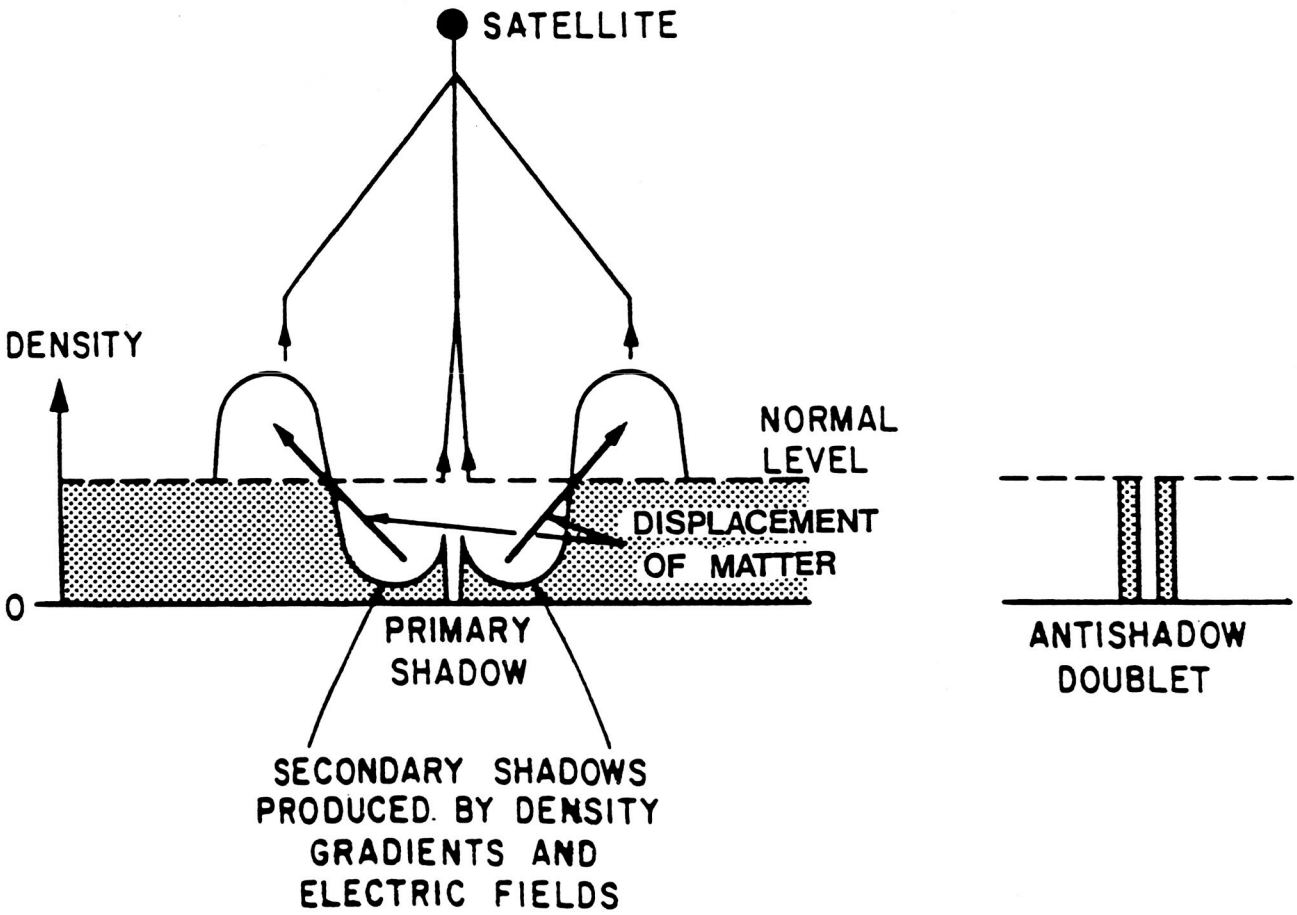
SATELLITE
DENSITY
NORMAL LEVEL
DISPLACEMENT OF MATTER
0
PRIMARY SHADOW
SECONDARY SHADOWS PRODUCED BY DENSITY GRADIENTS AND ELECTRIC FIELDS
ANTISHADOW DOUBLET

Fig. 12

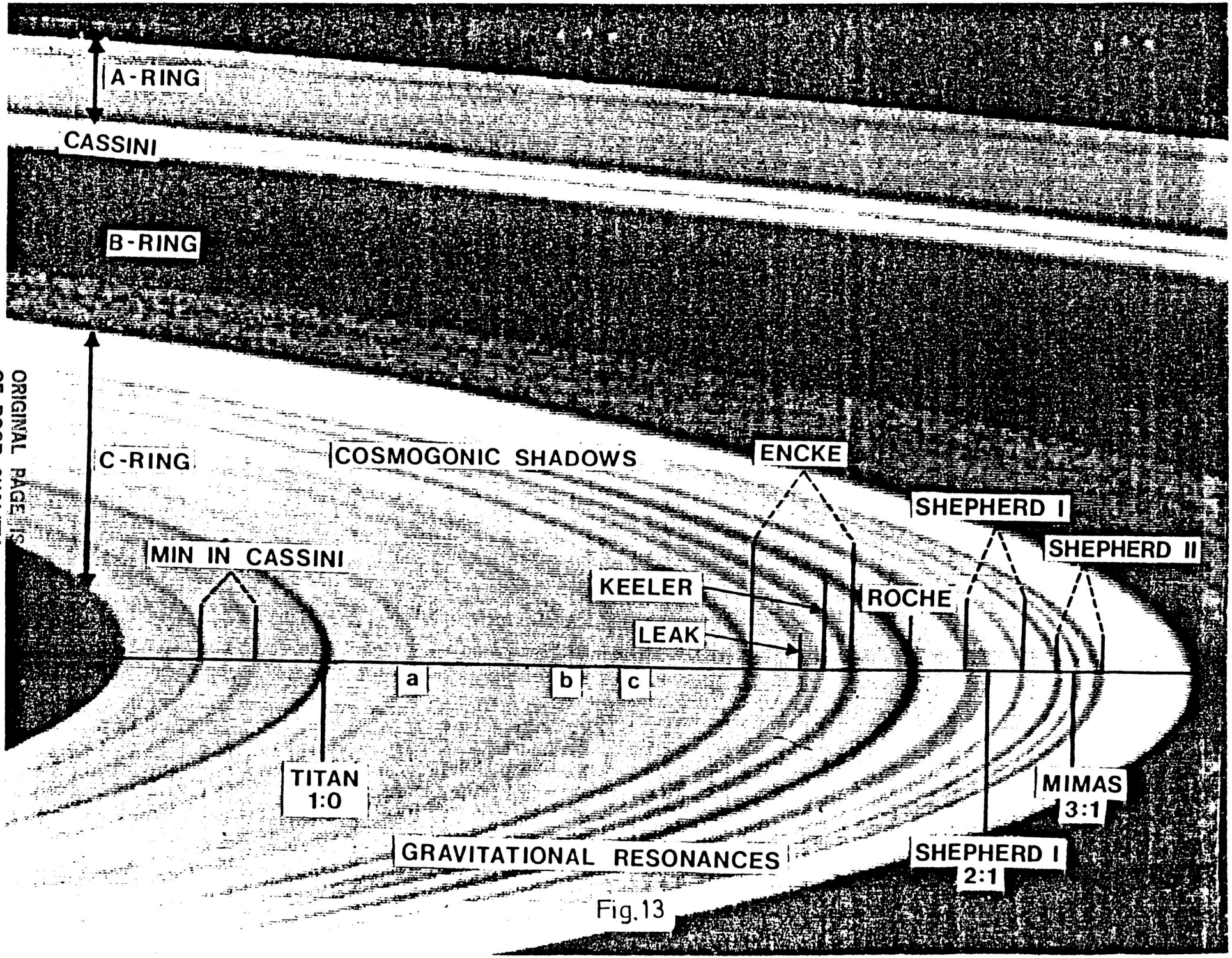

Fig.13

DOUBLE LAYERS AND CIRCUITS IN ASTROPHYSICS

N87-20088

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Abstract

As the rate of energy release in a double layer with voltage ΔV is $P \approx I\Delta V$, a double layer must be treated as a part of a circuit which delivers the current I. As neither double layer nor circuit can be derived from magnetofluid models of a plasma, such models are useless for treating energy transfer by menas of double layers. They must be replaced by particle models and circuit theory.

A simple circuit is suggested which is applied to the energizing of auroral particles, to solar flares, and to intergalactic double radio sources. Application to the heliospheric current systems leads to the prediction of two double layers on the sun's axis which may give radiations detectable from earth.

Double layers in space should be classified as a new type of celestial object (one example is the double radio sources). It is tentatively suggested in X-ray and γ-ray bursts may be due to exploding double layers (although annihilation is an alternative energy source).

A study of how a number of the most used textbooks in astrophysics treat important concepts like double layers, critical velocity, pinch effects and circuits is made. It is found that students using these textbooks remain essentially ignorant of even the existence of these, in spite of the fact that some of them have been well known for half a century (e.g., double layers, Langmuir, 1929: pinch effect, Bennet, 1934). The con-

clusion is that astrophysics is too important to be left in the hands of those astrophysicist who have got their main knowledge from these textbooks. Earth bound and space telescope data must be treated by scientists who are familiar with laboratory and magnetospheric physics and circuit theory, and of course with modern plasma theory. It should be remembered that at least by volume the universe consists to more than 99% of plasma, and that electromagnetic forces are 10^{39} time stronger than gravitation.

I GENERAL PROPERTIES OF DOUBLE LAYERS

A. Double Layers as a Surface Phenomenon in Plasmas

Since the time of Langmuir, we know that a double layer is a plasma formation by which a plasma - in the physical meaning of this word - protects itself from the environment. It is analogous to a cell wall by which a plasma - in the biological meaning of this word - protects itself from the environment.

If an electric discharge is produced between a cathode and an anode (Fig. 1) there is a double layer, called a cathode sheath, produced near the cathode, which accelerates electrons which carry a current through the plasma. Similarly, a double layer is set up near the anode, protecting the plasma from this electrode. Again, a space charge constitutes the border between the double layer and the plasma. All these double layers carry electric currents.

The lateral limitation of the plasma is also produced by double layers, which reduce and slow down the escape of the rapid electrons and accelerates the positive ions outwards so that an ambipolar diffusion is established (no net currents). If the plasma is enclosed in a vessel, its walls get a negative charge and a positive space charge is set up which - again - is the border between the double layer and the plasma. If the discharge constricts itself the walls can be taken away (without removing the space charge they carry). In these double layers the net electric current is zero.

If the cathode itself emits electrons, e.g., if it is a thermionic or photoelectric emitter, the sign of the cathode fall may be reversed, so that the double layer is limited by a negative space charge which acts as a "virtual cathode". The anode fall may also be reversed.

The lateral double layers may also change sign. This occurs in a dusty plasma if the dust is negatively charged (e.g., by absorbing most of the electrons). in this case we have a "reversed plasma" in which the ions form the lighter component. A magnetized plasma in which the Larmor radius of the ions is much larger than that of the electrons may also be a reversed plasma.

If a plasma is inhomogeneous so that the chemical composition, density, and/or electron temperature differs in different parts of the plasma, the plasma may set up double layers which split the plasma into two or more regions, each of which becomes more homogeneous (Schönhuber, 1968). For example, a Birkeland current flowing between the ionosphere and the magnetosphere may produce one or more double layers in this way, when it flows through regions with different densities.

There are innumerable variations and complications of the simple case we have discussed, in the same way as biological cell walls show innumerable variations. If we try to increase the current by increasing the applied voltage, the plasma may produce a double layer (see Fig. 1) which takes up part of the voltage so that the plasma current density does not exceed a certain value. Hence the plasma divides itself into two cells, analogous to what a biological cell does when it gets a large energy input.

The voltage difference ΔV over a double layer is usually of the order 5-10 times the equivalent of the temperature energy kT_e/e (Torvén and Andersson, 1979). However, if there are two independent plasmas produced by different sources, the double layer which is set up at the border between them may be 100 or 1000 kT_e/e or even larger (Sato et al., 1981; Torvén, 1982).

B. Noise in Double Layers

There is one property of a double layer which often is neglected: a double layer very often - perhaps always - produces noise and fluctuations. By this we mean irregular rapid variations within a broad band of frequencies. Lindberg (1982) studied the noise in a stationary fluctuating double layer and demonstrated that it broadens the energy spectrum of the electrons. The plasma may expand perpendicular to the magnetic field. The electrons in the beam which is produced in the double layer are scattered much more by the noise than by collisions. (Some people claim that noise is essential for the formation and sustenance of a double layer. This is actually a chicken-egg problem.)

An analogy to this is that the "critical velocity" phenomenon also seems to be associated with noise. Noise production is often associated with strong currents through plasmas. Langmuir (1927) proposed that random impulses strongly scatter electrons in gas discharges, an early example of the importance of noise in determining the behaviour of a plasma.

The noise - often incorrectly called "turbulence" - is such an important property of plasmas that theories which do not take it into consideration run some risk of being irrelevant. In additions, computer simulations that do not produce noisy double layers should be regarded with some scepticism.

The development of three-dimensional electromagnetic computer simulations (Buneman *et al.*, 1980) will allow a much more realistic treatment of plasma behaviour. Peratt *et al.* (1980) have thus been able to simulate in detail experiments on the interaction of two plasma filaments produced by exploding wires. Both electrostatic and electromagnetic fluctuations are implicitly included.

C. Theoretical and Experimental Approaches

Since thermonuclear research started with Zeta, Tokamaks, Stellarators - not to forget the Perhapsastron - plasma theories have absorbed a large part of the energies of the best physicists of our time. The progress which has been achieved is much less than was originally expected. The reason may be that from the point of view of the traditional theoretical physicist, a plasma looks immensely complicated. We may express this by saying that when, by an immense number of vectors and tensors and integral equations, theoreticians have prescribed what a plasma must do, the plasma - like a naughty child - refues to obey. The reason is either that the plasma is so silly that it does not understand the sophisticated mathematics, or it is that the plasma is so clever that it finds other ways of behaving, ways which the theoreticians were not clever enough to anticipate. Perhaps the noise generation is one of the nasty tricks the plasma uses in its IQ competition with the theoretical physicists.

One way out of this difficulty is to ask the plasma itself to integrate the equations; in other words, to make plasma experiments. Confining ourselves to cosmic plasmas, nowadays there are two different ways of doing this.

1. By performing scale model experiments in the laboratory. This requires a sophisticated technique, which in part we can borrow from the thermonuclear plasma physicists. It also requires methods to "translate" laboratory results to cosmic situations. (See CP, I.2 *)). Great progress has been made in this respect, but much remains to be done.

2. By using space as a laboratory and performing the experiments in space. This is a fascinating new technology which is most promising - but somewhat more expensive. We shall shortly discuss the laboratory experiments in later sections. There are a number of good surveys on the program of this meeting.

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*) CP stands for H. Alfvén, 1981.

D. Field and Particle Aspects of Plasmas

Space measurements of magnetic fields are relatively easy, whereas direct measurements of electric currents are very difficult - in many cases impossible. (Roy Torbert (1985) is now developing a technique which makes direct measurements of space currents possible). Hence, it is natural to present the results of space exploration (from spacecraft and from astrophysical observations) with pictures of the magnetic field configuration. Furhtermore, in magnetihydrodynamic theories it is convenient to elminate the current (i = current density) by ∇X B. This method is acceptable in the treatment of a number of phenomena (see Fig.2).

However, there are also a number of phenomena which cannot be treated in this way, but which require an approach in which the electric current is taken account of explicitly. The translation between the magnetic field description and the electric current description is made with the help of Mazwell's first equation

$$\nabla \times B = \mu_o \left(i + \frac{\delta D}{\delta t}\right) \qquad (1)$$

in which the displacement current can usually be neglected. (However, it is sometimes convenient to account for the kinetic energy of a magnetized plasma by introducing the permittivity $\varepsilon = \varepsilon[1 + (c/V_{MH})^2]$. where c and V_{MH} are the velocities of light and of hydromagnetic waves (see Alfvén and Fälthammar, 1963, Cosmical Electrodynamics 3.4.4, hereafter referred to as CE. If this formalism is used, the displacement current is often large).

Phenomena which cannot be understood without explicitly accounting for the current are:

1) Formation of double layers.

2) The occurrence of explosive events such as solar flares, magnetic substorms, possibly also "internal ionization" phenomena in comets (Wurm, 1963; Mendis, 1978) and stellar flares.
3) Double layer violation of the Ferraro corotation. Establishing "partial corotation" is essential for the understanding of some cosmogonic processes (H. Alfvén and G. Arrhenius, 1975 and 1976).
4) Formation of filaments in the solar atmosphere, in the ionosphere of Venus and in the tails of comets and in interstellar nebulae.
5) Formation of current sheets which may give space a "cellular structure".

Exploration of those plasma properties which can be described by the magnetic field concept have in general been successful. However, this is not the case for those phenomena which cannot be understood by this approach.

E. Recent Advances

There is a rapidly growing literature concerning double layers and their importance for different cosmic situations. Of special interest is the work of Knorr and Goertz (1974), Block (1978) and Sato and Okuda (1980, 1981). A balanced review of these achievements is given by Smith (1983).

As indicated by the title of the present lecture, I will concentrate my attention on the astrophysical applications of double layer theory. The development of the theory of double layers, including numerical simulation, is covered by a number of other papers at this meeting.

II. LABORATORY EXPERIMENTS

A. Electrical Discharges in Gases

Towards the end of the nineteenth century electric discharges in gases began to attract increased interest. They were studied in Germany and in England. As there were few international conferences, the Germans and the English made the same discoveries independently. Later, a strong group in Russia was also active. The best survey of the early development is Engel--Steenbeck, Elektrische Gasentladungen (1932). See also Cobine (1958). Some modern textbooks are those by Loeb (1961), Papoular (1963), and Cherrington (1974).

B. Birkeland

At the turn of the century geophysicists began to be interested in electrical discharges, because it seemed possible that the aurora was an electrical discharge. Anyone who is familiar with electrical discharges in the laboratory and observes a really beautiful aurora cannot avoid noting the similarity between the multi-colored flickering light in the sky and in the laboratory. Birkeland was the most prominent pioneer. He made his famous terrella experiment in order to investigate this possibility (Birkeland, 1908). Based on his experiments, and on extensive observations of aurora in the auroral region he proposed a current system which is basically the same as is generally accepted today. However, the theory of electric discharges was still in a very primitive state.

When Sydney Chapman began his investigations on magnetic storms and aurora one or two decades later, he proposed a current system (the Chapman and Vestine system (Chapman and Vestine, 1938)) which was located entirely in the ionosphere. His most important argument against Birkeland's current system was that above the atmosphere there was a vacuum, and hence there could be no electrons or ions which could carry any currents.

(The relation between Chapman and Birkeland is analyzed by Dessler (1983).)

C. Langmuir and Plasma

The interest in double layers made a great leap forward when Langmuir began his investigations. He introduced the term plasma in this paper "Oscillations in Ionized Gases" (Langmuir, 1928; see also Langmuir and Tonks, 1929a and b). Curiously enough, he does not give any motivation for choosing this word, which was probably borrowed from medical terminology. He just states: "We shall use the name "plasma" to describe this region containing balanced charges of ions and electrons". His biographers do not give any explanation either. Langmuir also made the first detailed analyses of double layers.

Irving Langmuir was probably the most fascinating man of the plasma pioneers. As his biographers describe him, he was far from being a narrow-minded specialist. His curiosity was all--embracing, his enthusiasm indiscriminate. He liked whatever he looked upon, and he looked everywhere. Indeed he was not far from the ideal which Roederer, in a recent paper (1985), contrasts with the isolated specialists that dominate science today (see Section VIII).

Langmuir once wrote, "Perhaps my most deeply rooted hobby is to understand the mechanism of simple and familiar phenomena" and the phenomena might be anything from molecules to mountains. One of his friends said, "Langmuir is a regular thinking machine: put in facts and you get out a theory". And the facts his always active brain combined were anything from electrical discharges and plasmas to biological and geophysical phenomena. Science as fun was one of his cardinal tenets.

From this one gets the impression that he was very superficial. This is not correct. He got a Nobel prize in chemistry because he was recognized as the father of surface chemistry. He knew

enough of biology to borrow the term plasma from this science, and the mechanism of double layers from surface chemistry. Langmuir's probes were of decisive value for the early exploration of plasmas and double layers, and they are still valuable tools.

All magnetospheric physicists must regret that as far as is known, he probably never saw a full-scale auroral display. Schenectady, where he spent most of his life is rather far from the auroral zone, and he seems never to have travelled to the auroral zone. If he had, his passion for combining phenomena in different fields might very well have made him realize that the beautiful flickering multi-colored phenomena in the sky must be connected with the beautiful flickering multi-colored phenomena he had observed so many times in his discharge tubes. At a time when Birkeland was dead he might have saved magnetospheric physics from half a century when it was a credo that the road to magnetic storms and aurorae should go through a jungle of misleading mathematical formulae where trees and trees prevented you from seeing the wood - but you can never reconstruct history.

In 1950 I published a monograph, Cosmical Electrodynamics (Alfvén, 1950) in which Chapter III deals with electrical discharges in gases. Essential parts of this is devoted to plasma physics, I mention Langmuir only in passing because a quarter of a century after his break-through the results were considered as "classical": all experimental physicists were familiar with his works on plasmas, double layers, probes, etc. However, many theoreticians were not; they had no knowledge of Langmuir's work. They do not mention the word "plasma" and had no idea that experiments in close contact with theory had shown that plasmas were drastically different from their "ionized gases". I tried to draw attention to this by pointing out: "What is urgently needed is not a refined mathematical treatment (referring to Chapman-Cowling) but a rough analysis of the basic phenomena (referring to the general knowledge of plasmas).

Today, 60 years after Langmuir most astrophysicists still have no knowledge of his work. The velocity of the spread of relevant knowledge to astrophysics seems to be much below the velocity of light (compare Section VIII).

D. The Energy Situation in Sweden and Exploding Double Layers

In Sweden the waterpower is located in the north, and the industry in the south. The transfer of power between these regions over a distance of about 1000 km was first done with a.c. When it was realized that d.c. transmission would be cheaper and that this also could be used in underwater cables, mercury rectifiers were developed. It turned out that such a system normally worked well, but it happened now and then that the rectifiers produced enormous overvoltages, so that fat electric sparks filled the rectifying station and did considerable harm. In order to get rid of this a collaboration started between the rectifier constructors and some plasma physicists at the Royal Institute of Technology in Stockholm.

An arc rectifier must have a very low pressure of mercury vapor in order to stand the high back voltages during half of the a.c. cycle. On the other hand, it must be able to carry large currents during the other half-cycle. It turned out that these two requirements were conflicting, because at a very low pressure the plasma could not carry enough current. If the current density is too hign, an exploding double layer may be formed. This means that in the plasma an evacuated region is produced: the plasma refuses to carry any current at all. At the sudden interruption a some 100 or 1000 km inductance produces enourmous over-voltages, which may be destructive.

In order to clarify this phenomenon a series of laboratory experiments was made, in close contact with theoretical work on the same phenomenon. Nicolai Herlofson was the leader of this activity.

At low current densities a drift motion $v_d < v_T$ is superimposed on the thermal velocity v_T of the electrons in the plasma. If the current density increases so that $v_d > v_T$ the motion becomes more similar to a beam, and an instability sets in which is related to the two-stream instability. This produces a double layer which may be relatively stable (although it often is noisy and may move along the tube). If the voltage over the tube is increased in order to increase the current, the higher voltage is taken up by the double layer and the current is not increased. However, under certain conditions the double layer may "explode".

A simple mechanism of explosion is the following: the double layer can be considered as a diode for electrons combined with a reverse diode for ions, limited by a slab of plasma on the cathode side and another slab on the anode side. Electrons starting from the cathode get accelerated in the diode and impinge upon the anode slab with a considerable momentum which they transfer to the plasma. Similarly, accelerated ions transfer momentum to the cathode slab. When more energy is supplied from the outer circuit the result is that the anode and cathode plasma columns are pushed away from each other. When the distance betweeen the electrons in the diodes becomes larger the drop in voltage increases. This run-away phenomenon leads to an explosion.

Nowadays the mercury arc rectifiers are replaced by semiconductors, but our work with them led to an interesting spin-off in cosmic physics. We had since long been interested in solar physics and had interpreted solar prominences as caused by pinching electric currents. With this as background, Jacobsen and Carlquist (1964) suggested that the violent explosions called solar flares were produced by the same basic mechanism as made the mercury arc rectifiers explode. It drew attention to the fact that <u>every inductive circuit carrying a current is intrinsically explosive</u>.

Further consequences were:

1. The obvious connection between laboratory and space plasma led to a long series of plasma experiments planned to clarify cosmic phenomena.
2. It inspired Carlqvist to work out a detailed theory of solar flares, and later to develop a theory of relativistic DL's.
3. It inspired Boström (1976) to develop a theory of magnetic substorms, which in important respects is similar to Akasofu's theory (Akasofu, 1977).

In general, the connection between a technical difficulty and an astrophysical phenomenon led to what Roederer (1985) calls an "interdisciplinarification", which turned out to be very fruitful.

E. Extrapolation to Relativistic Double Layers

In most of the DL's in the magnetospheres and those studied so far in the laboratory the electrons and ions have such low energies that relativistic effects are usually not very important. However, in solar flares DL's with voltages of 10^9 V or even more may occur, and in galactic phenomena we may have voltages which are several orders of magnitude larger.

Carlqvist (1969, 1982a,c) finds that in a relativistic double layer the distribution of charges $Zn_+(x)$ and $n_-(x)$ can be divided into three regions: two density spikes near the electrodes and one intermediate region with almost constant charge density. In a later paper Carlqvist gives examples of possible galactic DL voltage differences of 10^{14} V. This means that by a straightforward extrapolation of what we know from our cosmic neighborhood, we can derive acceleration mechanisms which bring us up in the energy region of Cosmic Radiation.

III DOUBLE LAYERS AND FROZEN-IN MAGNETIC FIELD LINES

A. Frozen-in Field Lines - A Pseudo-Pedagogical Concept

In Cosmical Electrodynamics I tried to give a survey of a field in which I had been active for about two decades. In one of the chapters I treated magnetohydrodynamic waves. I pointed out that in an infinitely conductive magnetized fluid the magnetic field lines could be considered as "frozen" into the medium - under certain conditions - and this concept made it possible to treat the waves as oscillations of frozen-in strings.

The "frozen-in" picture of magnetic field lines differs from Maxwell's views. He defined a magnetic field line as a line which everywhere is parallel to the magnetic field. If the current system which produce the field changes, the magnetic field changes and field lines can merge or reconnect. However, if the current system is constant the magnetic field is also constant. To speak of magnetic field lines moving perpendicular to the field makes no sense. They are not material.

In a detailed analysis of the motion of magnetic lines of force Newcomb (1958) has demonstrated that "it is permissible to ascribe a velocity v to the line of force if and only if $\nabla \times (E + v \times B)$ vanishes identically".

I thought that the frozen-in concept was very good from a pedagogical point of view, and indeed it became very popular. In reality, however, it was not a good pedagogical concept but a dangerous "pseudo-pedagogical concept" By "pseudo-pedagogical" I mean a concept which makes you believe that you understand a phenomenon whereas in reality you have drastically misunderstood it.

I never believed in it 100% myself. This is evident from the chapter on "magnetic storms and aurora" in the same monograph. I followed the Birkeland-Störmer general approach but in order

to make that applicable to the motion of low-energy particles in what is now called the magnetosphere it was necessary to introduce an approximate treatment (the "guiding-centre" method) of the motion of charged particles. (As I have pointed out in CP III.1, I still believe that this is a very good method for obtaining an approximate survey of many situations and that it is a pity that it is not more generally used.) The conductivity of a plasma in the magnetosphere was not relevant.

Some years later criticism by Cowling made me realize that there was a serious difficulty here. According to Spitzer's formula for conductivity, the conductivity in the magnetosphere was very high. Hence the frozen-in concept should be applicable and the magnetic field lines connecting the auroral zone with the equatorial zone should be frozen-in. At that time (-1950) we already knew enough to understand that a frozen-in treatment of the magnetosphere was absurd. But I did not understand why the frozen-in concept was not applicable. It gave me a headache for some years.

In 1963 Carl-Gunne Fälthammar and I published the second edition of Cosmical Electrodynamics together. He gave a much higher standard to the book and new results were introduced. One of them was that a non-isotropic plasma in a magnetic mirror field could produce a parallel electric field $E_{\parallel}$. We analyzed the consequences of this in some detail, and demonstrated with a number of examples that in the presence of an $E_{\parallel}$ the frozen-in model broke down. On p. 191 we wrote:

> "In low density plasmas the concept of frozen-in lines of force is questionable. The concept of frozen-in lines of force may be useful in solar physics where we have to do with high- and medium-density plasmas, but may be grossly misleading if applied to the magnetosphere of the earth. To plasma in interstellar space it should be applied with some care."

B. Magnetic Merging - A Pseudo-Science

Since then I have stressed in a large number of papers the danger of using the frozen-in concept. For example, in a paper "Electric current structure of the magnetosphere" (Alfvén, 1975) I made a table showing the difference between the real plasma and "a fictitious medium" called "the pseudo-plasma", the latter having frozen-in magnetic field lines moving with the plasma. The most important criticism of the "merging" mechanism of energy transfer is due to Heikkila (1973) who with increasing strength has demonstrated that it is wrong. In spite of all this, we have witnessed at the same time an enormously voluminous formalism building up based on this obviously erroneous concept. Indeed, we have been burdened with a gigantic pseudo-science which penetrates large parts of cosmic plasma physics. The monograph CP treats the field-line reconnection (merging) concept in I.3, II.3 and II.5. We may conclude that anyone who uses the merging concepts states by implication that no double layers exist.

A new epoch in magnetospheric physics was inaugurated by L. Lyons and D. Williams' monograph (1985). They treat magnetospheric phenomena systematically by the particle approach and demonstrate that the fluid dynamic approach gives erroneous results. The error of the latter approach is of a basic character. Of course there can be no magnetic merging energy transfer.

I was naive enough to believe that such a pseudo-science would die by itself in the scientific community, and I concentrated my work on more pleasant problems. To my great surprise the opposite has occurred: the "merging" pseudo-science seems to be increasingly powerful. Magnetospheric physics and solar wind physics today are no doubt in a chaotic state, and a major reason for this is that part of the publsihed papers are science and part pseudo-science, perhaps even with a majority for the latter group.

In those parts of solar physics which do not deal with the interior of the sun and the dense phosphere region (fields where the frozen-in concept may be valid) the state is even worse. It is difficult to find theoretical papers on the low density regions which are correct. The present state of plasma astrophysics seems to be almost completely isolated from the new concepts of plasma which the in situ measurements on space plasma have made necessary (see Section VII).

I sincerely hope that the increased interest in the study of double layers - which is fatal to this pseudo-science - will change the situation. Whenever we find a double layer (or any other $E_{\parallel} \neq 0$) we hammer a nail into the coffin of the "merging" pseudo-science.

IV DOUBLE LAYER AS A MECHANISM FOR ENERGY RELEASE

A. Double Layer as a Circuit Element

It is a truism to state that a DL which releases a power $P \approx I\Delta V$ is part of a circuit in which a current I flows. We shall investigate the properties of such a circuit by starting with a conventional simple circuit and step by step adopt it to cosmical conditions.

Fig. 3 depicts a simple circuit containing a double layer, which following Carlqvist is depicted by a D and L written together with the L pointing in the direction of the current. Besides the double layer DL the circuit contains an inductance in which is stored an energy ("circuit energy").

$$W_L = \frac{1}{2} LI^2 = \frac{1}{2\mu_o} \int B_I^2 \, d\tau \qquad \text{(IV.1)}$$

where B_I is the magnetic field produced by the current I and $d\tau$ is a volume element.

If a magnetized plasma (field B_o) moves with velocity v in relation to the circuit it produces an e.m.f. in the circuit

$$\varepsilon = \int v \times B_o \cdot ds \qquad \text{(IV.2)}$$

where ds is a line element in the direction of I.

If $\varepsilon > 0$ we have a <u>generator</u> transferring plasma power εI into the circuit; if $\varepsilon < 0$ we have a <u>motor</u> transferring circuit energy into kinetic energy of the plasma. In Fig. 3 we have introduced a symbol ⊕ with the arrow parallel to I to represent a generator and a similar one, but with the arrow antiparallel to I, to represent a motor. Finally, the circuit may contain a resistance R which dissipates power RI^2 into heat, etc.

An electrotechnical circuit like Fig. 3 consists essentially of metal wires. Is it realistic to use this for cosmic plasma problems? Apparently not. There are no metal wires in space. Further, if we want to use the circuit in connection with cosmic problems, most or all the circuit elements are <u>distributed</u> over cosmic distances. There have been many detailed studies made concerning the relations between kinetic energy of a plasma and currents, which give a deeper understanding of these processes than our circuit approach.

However, our purpose is <u>not</u> to study the detailed problems but to get a <u>general survey</u> of energy transport in cosmical physics. Is the circuit approach useful as a first approximation to such problems? Maybe.

A map of a city is useful in spite of the fact that it does not describe all the houses. Or rather because it does not attempt to do so. For calculating the motion of charged particles the guiding centre method is often preferable to the Störmer method even if it does not give the exact position of a particle at a certain moment. Or rather because it does not.

In space charged particles move more easily parallel to B than perpendicular, and parallel currents are often pinched to filaments. A wire is not too bad an approximation to a pinched fi-

lament. Moreover, the generators-motors as well as the double layer are often confined to relatively small volume.

Hence, with all these reservations in mind we are going to apply the simple circuit of Fig. 3 to a number of cosmical problems in Section VI.

However, the circuit representation could - and must - be developed in many respects. For example when a current flows in large regions the simple inductance L should be replaced by a transmission line. See Fig. 4.

We should also observe that a theory of certain phenomena need not necessarily be expressed in the traditional language of differential equations etc. It could also be expressed as an equivalent circuit. The pioneer in the field is Boström who (1974) summarized his theory of magnetic substorms in the circuit shown in Fig. 5. If this method is developed it is quite possible that it will be recognized as the best way to represent energy transfer in cosmic plasmas.

B. Properties of the Circuit

Every circuit which contains an inductance L is intrinsically explosive (cf. II.D). The inductive energy $W_I = 1/2\ LI^2$ can be tapped at any point of the circuit. If we try to interrupt the current I the inductance tends to supply its energy to the point of interruption, where the power $P = I\Delta V$ is delivered (ΔV = voltage over the point of interruption and I the current at this point) This means that most of the circuit energy may be released in a double layer and if large it cause an explosion of the DL. In a laboratory plasma (Fig. 4b) this occurs due to a region of "negative resistance" in the current-voltage characteristic of the double layer (Carpenter et al., 1984; Torvén et al., 1985). (If the inductance is distributed over a considerable region, there are transient phenomena during which I is not necessarily the same over the whole circuit.)

In electro-technical literature in general, the resistors and inductances in the circuit may often be non-linear and sometimes distributed over larger volumes. Similarly, the DL symbol may mean one double layer but also a multiple double layer. We should also allow this circuit element to represent other types of $E_{\parallel}$; for example, mirror-produced fields. Hasegawa and Uberoi (1982) have shown that under certain conditions a hydromagnetic wave produces a magnetic field-aligned electric field, which also should be included as DL. This means that DL stands for any electric field parallel to the magnetic field.

C. Local Versus Global Plasma Theories

Consider a long. homogeneously magnetized uniform plasma. It is confined laterally by tube walls or by a magnetic field. It carries no longitudinal current. Information/energy is transmitted in a time T from one end to the other by sound waves or hydromagnetic waves or by diffusion. Phenomena with a time constant << T can be treated by local theories (because one end does not know what happens in the other). The Chapman-Cowling theory may be valid. However, if a longitudinal current I flows through the plasma and returns through an outer wire (or circuit) the situation is different. Except for rapid transients the current must be the same in the whole tube and in the wire. If the current is modulated in one end this information is rapidly transferred to the other end and to the wire. The current may produce double layers which accelerate electrons (and ions) to kV, MV, GV, etc. It may pinch the plasma, producing filaments. These effects also produce coupling between the two ends of the plasma column and reduce the coupling to its local environment.

Electrons accelerated in a DL in the plasma column may travel very rapidly from one end of the plasma column to the other.

Hence, if there is a current through a plasma we must use global theories, taking account of all the regions through which

the current through the plasma column flows. Local theories are not valid (except in special cases).

A global theory must also be used to describe the influence of a DL on the motions in the plasma column.

In a one-dimensional model the voltage drop is ΔV but in a two-dimensional cylindrical model it is a maximum ΔV at the axis but decreases to zero at a certain outer limit. Hence we have

$$P = \alpha I \Delta V$$

with $0 < \alpha < 1$. It is also required that there are radial electric fields in the surrounding plasma. These together with the magnetic field produce drift motions in the plasma column (Carlqvist, 1979; Raadu, 1984).

The theoretical treatment of a current-carrying plasma must start with locating the whole region in which the current flows. It is convenient to draw <u>the circuit</u> and determine the resistances, the inductances, and the generators and DL's. These elements are usually distributed and non-linear, and the circuit theory may be rather complicated.

The return current need not flow through a wire. it could very well flow through another plasma column. An example of this is the auroral current system. As pointed out in VI.A the energy is transferred from the cloud C to DL <u>not</u> by high energy particles <u>nor</u> by waves (and of course not by mangetic reconnection!). It is a property of the circuit. A <u>global</u> theory is necessary which takes account not only of the plasma cloud near the equatorial plane but also of the ionosphere and double layers which may be found in the lower magnetosphere. Another still more striking example is given in VI.C.

V. TRANSFER OF KNOWLEDGE BETWEEN DIFFERENT PLASMA REGIONS

In CP (Alfvén, 1981) it is pointed out that the basic properties of a plasma are likely to be the same in different regions of cosmic plasmas. This is represented by Fig. 6, called the Cosmic Triple Jump.

The linear dimensions of plasma vary by 10^{27} in three jumps of 10^9

from laboratory plasmas	- 0.1 m
to magnetospheric plasmas	- 10^8 m
to interstellar plasmas	- 10^{17} m
up to the Hubble distance	- 10^{26} m

Including laser fusion experiments brings us up to 10^{32} orders of magnitude. New results in laboratory plasma physics and in situ measurements by spacecraft in the mangetospheres (including the heliosphere) make sophisticated plasma diagnosis possible out to the reach of spacecraft (- 10^{13} m). Plasmas at larger distances should to a large extent be investigated by extrapolation. This is possible because of our increased knowledge of how to translate results from one region to another.

Fig. 6 shows us an example of how cosmogony (formation of the solar system) can be studied by extrapolation from magnetospheric and laboratory results, supplemented by our knowledge about interstellar clouds. When better instruments for observing the plasma universe in X-rays and γ-rays are developed we may get more information from these than from visual observations. (See Alfvén, 1986b.)

Fig. 7 contains essentially the same information as Fig. 6. It demonstrates that plasma research has been based on highly idealized models, which did not give an acceptable model of the observed plasma. The necessary "paradigm transition" leads to theories based on experiments and observations. it started in the laboratory about 20 years ago. In situ measurements in the

magnetospheres caused a similar paradigm transition there. This can be depicted as a "knowledge expansion", which so far has stopped at the reach of spacecraft. The results of laboratory and magnetospheric research should be extrapolated further out. When this knowledge is combined with direct observations of interstellar and intergalactic plasma phenomena, we can predict that a new era in astrophysics is beginning, largely based on the plasma universe model.

VI. EXAMPLES OF COSMIC DOUBLE LAYERS

In order to demonstrate the usefulness of the equivalent circuit methods we shall here apply it to a variety of different cosmical problems.

A. Auroral Circuit

The auroral circuit is by far the best known. It is derived from a large number of measurements in the magnetosphere and in the ionosphere which were pioneered by the Applied Physics Laboratory at Johns Hopkins University.

Zmuda and Armstrong (1974) observed that the average magnetic field in the magnetosphere had superimposed on it transverse field which they interpreted as due to hydromagnetic waves. Inspired by discussions with Fälthammar, Dessler suggested that the transverse field components instead indicated electric currents essentially parallel to the magnetic field lines (Cummings and Dessler, 1967).

This means that it was Dessler who discovered the electric currents which Birkeland had predicted. Dessler called them "Birkeland currents", a term which is now generally accepted and sometimes generalized to mean all currents parallel to the magnetic fields. I think that it is such a great achievement by Dessler to have interpreted the magnetospheric data in what we

now know is the correct way that the currents should be called Birkeland-Dessler currents.

In the auroral current system the central body (Earth and Ionosphere) maintains a dipole field (Fig. 8). B_1 and B_2 are magnetic field lines from the body. C is a plasma cloud near the equatorial plane moving in the sunward direction (out of the figure) producing an electromotive force

$$\varepsilon = \int_{c_2}^{c_1} (\vec{v} \times \vec{B})\, d\vec{s}$$

which gives rise to a current in the circuit c_1, a_1, a_2, c_2. The circuit may contain a double layer DL with the voltage ΔV_D which essentially is used for accelerating auroral electrons. The energy is transferred from C to DL not magnetic merging or field reconnection. It is a property of the electric circuit (and can also be described by the Poynting vector (see Fig. 8).

B. Heliospheric Current

In a way which is described in CP II.4.2, we go from the auroral circuit to the heliospheric circuit (Fig. 9).

The sun acts as a unipolar inductor (A) (cf. Fig. 4a) producing a current which during odd solar cycles goes outward along the axes in both directions and inward in the equatorial plane. The current closes at large distances (B_3), but we do not know where. The equatorial current layer is often very inhomogeneous. Further, it moves up and down like the skirt of a ballerina. In even solar cycles the direction of the current is reversed.

By analogy with the magnetospheric circuit we may expect the heliospheric circuit to have double layers. They should be located at the axis of symmetry, but perhaps preferentially in those solar cycles when the axial current is directed away from

the sun.

No one has yet tried to predict how far from the sun they should be located. They should produce high energy electrons and synchrotron radiation from these should make them observable as radio sources. Further, they should produce noise. They may be observable from the ground, but so far no one has cared to look for such objects.

C. Double Radio Sources

If in the heliospheric circuit we replace the rotating magnetized sun by a galaxy, which is also magnetized and rotating, we should expect a similar current system, but magnified by about 9 orders of magnitude (Fig. 10 and CP II.4). This seems to be a very large extrapolaation, but in fact a number of successful extrapolations from the laboratory to the magnetosphere are by almost the same ratio. (Of course all theories of plasma phenomena in regions which cannot be investigated by in situ measurements are by definition speculative!)

The e.m.f. is given by Eq.(IV.2), taken from the galactic center out to a distance where the current leaves the galaxy, which may be the outer edge. Inside the galaxy the currrent may flow in the plane of symmetry similar to the current sheet in the equatorial plane of the sun, but whether the intergalactic picture is correct or not is not really important to our discussion here. The e.m.f. which derives from the galactic rotation is applied to two circuits in parallel, one to the "north" and one to the "south" (see Fig. 10). As galaxies often are highly north-south symmetric it is reasonable that the two circuits are similar. Hence we expect a high degree of symmetry in the current system (at least under idealized conditions).

In the magnetosphere, the current flowing out from the ionosphere produces double layers (or magnetic mirror induced

fields) at some distance from the earth. Because of the similarity of the plasma configuration, we may expect double layers at the axis of a galaxy, and a large release of energy in them. It has been suggested that the occurrence of such double layers is the basic phenomenon producing the double radio sources. For the details of this theory see CP.

In the galactic circuit, the e.m.f. is produced by the rotating magnetized galaxy acting as a homopolar inductor, which implies that the energy is drained from the galactic rotation, but from the interstellar medium, not from the stars. By the same mechanisms as in the auroral circuit, it is transferred first into circuit energy and then to the double layers where in each the power $P = I\Delta V$ is released. In a single DL or a series of DL's on each side of the galaxy, an acceleration of charged particles takes place. From the magnetosphere we know that layers are produced when the current flows outwards. (Whether double layers can be formed when the current flows inwards is still an open question.) If the same is true in the galactic case, there is a flow of thermal electrons to the layer from the outside and when passing a series of double layers the electrons are accelerated to very high energies. Hence, a beam of very high energy electrons is emitted from the double layer along the axis towards the central galaxy. This process is the same as the one which produces auroral electrons, only scaled up enormously both in size and energy. In analogy with the current in the magnetotail, the current in the equatorial plane of a galaxy may also produce double layers, which may be associated with large releases of energy.

Fig. 10a shows a radio astronomy picture of a double radio source. The DL's produced by the current system (Fig. 10b) should be located at the outer edges of the strong radio source. When electrons conducting the currents outside the double layer reach the double layer, they are accelerated to very high energies. Similarly, ions reaching the double layer on their outward motion from the central galaxy will be accele-

rated outwards when passing the double layers. The strong axial current produces a magnetic field, which pinches the plasma, confining it to a cylinder close to the axis.

Although the electrons are primarily accelerated in the direction of the magnetic field, they will be scattered by magnetic inhomogeneities and spiral in such a way that they emit synchrotron radiation. The accelerated electrons will be more like an extremely hot gas than a beam. With increasing distance from the double layer the electrons will spread and their energy and hence their synchrotron emission will decrrease. This is in agreement with observations. It is possible that some of them will reach the central galaxy and produce radio emission there. It is also possible that the observed radio emission from the central galaxy is due to some other effect produced by the current (there are several mechanisms possible). Such phenomena in the central galaxy will not be discussed here.

The ions passing the double layer in the outward direction will be accelerated to the same energy as the electrons. Because of their larger rest mass, they will not emit much synchrotron radiation.

It should be stressed again that, just as in the magnetosphere and in the laboratory, <u>the energy released in the double layer derives from circuit energy and is transferred to it by electric currents which essentially consist of relatively low energy particles</u>. There is no need for a beam of high energy particles (or plasmons) to be shot out from the central galaxy. On the contrary, the central galaxy may be bombarded by high energy electrons which have obtained their energy from the double layer.

An attempt to a semi-quantitative analysis of the double radio galaxies is given in <u>CP</u>. It is likely that modifications are needed.

D. Solar Prominence Circuit. Solar Flares

The circuit consists of a magnetic flux tube above the photosphere and part of photosphere (see Fig. 11). the generator is in the photosphere and is due to a whirl motion in sunspot magnetic field.

Generator output increases the circuit energy which can be dissipated in two different ways: 1. When current density surpasses critcal value an exploding DL is produced in which most of the circuit energy is released. This causes a solar flare (Alfvén and Carlqvist, 1967; Carlqvist, 1969). Hénoux (1985) has recently given an interesting study of solar flares and concludes that a current disruption by DL's is an appealing explanation of solar flares. 2. Under certain circumstances the electromagnetic pressure of the current loop may produce a motor which gives rise to a rising prominence.

E. Magnetic Substorms

According to Boström (1974) and Akasofu (1977), an explosion of the transverse current in the magnetotail gives an attractive mechanism for the production of magnetic substorms (see Fig. 5). Boström has shown that an equivalent magnetic substorm circuit is a way of presenting the substorm model. The onset of a substorm is due to the formation of a double layer, which interrupts the cross-tail current so that it is redirected to the ionosphere.

F. Currents and Double Layers in Interstellar Space

As it is relatively easy to measure magnetic fields, it is natural that the first description of the electromagnetic state of interstellar and intergalactic space is based on a magnetic field description. However, as no one claims - at least not explicitly - that the magnetic fields are curl-free, we must have a network of currents. As investigations of DL's (and quite a

few other phenomena) require explicit pictures of electric currents, it is essential to apply these pictures (cf. Fig.2).

Filamentary structures were quite generally observed already long ago, and may be observed everywhere where sufficient accurate observations can be made. There are a number of processes by which they are generated. For example, the heliospheric current system must close at large distances (cf. Fig. 9) and it is possible - perhaps likely - that this is done by a network of filamentary currents. Many such filaments may produce DL's and some of these may explode.

G. Double Layers as a New Class of Celestial Objects

The general structure and evolution of such a network of currents, including their production of DL's, has not yet been investigated. it is possible that under certain circumstances the final destiny of a set of currents is DL's, perhaps exploding DL's. DL's may be considered as a new class of celestial objects. We have already given an example of this in the interpretation of double radio sources as DL's.

H. X-ray and γ-ray Bursts

When a number of explosions are observed, such as γ-ray and X-ray bursts, one may try to explain them as exploding DL's.

However, another possible source of energy is annihilation (CP, VI.3). There is also a possibility that they may be due to double layers in a baryon symmetric universe.

I. Double Layers as a Source of Cosmic Radiation

As pointed out in II.E, relativistic DL's in interstellar space may accelerate ions up to cosmic ray energies (see Carlqvist (1986)).

VII. DOUBLE LAYERS IN TEXTBOOKS

As has been pointed out many times (see e.g. CP I Alfvén, 1982) in situ measurements in the magnetospheres and progress in laboratory plasma physics have caused a "paradigm transition" which means that a number of old concepts have to be abandoned and a number of new phenomena must be taken into account. M. Azar (1986) has made a search through some of the most generally used textbooks in astrophysics, in which of these the new concepts have been presented to the students in astrophysics. His results are listed in Table I.

The table gives the surprising and depressing result that the students in astrophysics still are kept ignorant of what has happened in plasma physics.

Double layers were analyzed in detail by Langmuir (1929a). The development described in III.A demonstrated that there must be "double layers" in a generalized sense (= magnetic field aligned electric field) so the first decisive evidence for their existence in the magnetosphere dates from 1962. The real discovery of double layers in the magnetosphere is due to Gurnett (1972). But still there are only 2 out of 17 textbooks which even mention that anything like that could exist.

The use of "equivalent circuits" is discussed in Alfvén and Fälthammar (1963) and further in a number of papers. Boström (1974) has given the most interesting account of their use. Still, Akasofu is the only one in the list who has understood the value of this in cosmic physics.

That parallel currents attract each other was known already at the times of Ampere. It is easy to understand that in a plasma currents should have a tendency to collect to filaments. In 1934 it was explicitly stated by Bennett that this should lead to the formation of a pinch. The problem which led him to the discovery was that the magnetic storm producing medium (solar wind with present terminology) was not flowing out uniformly

from the sun. Hence it was a problem in cosmic physics which led to the introduction of the pinch effect.

Today everybody who works in fusion research is familiar with pinches. Indeed, several thermonuclear projects are based on pinches. Pinches in cosmical physical are discussed in detail in Alfvén and Fälthammar (1963), and futher in a large number of papers; see CP II,4, But to most astrophysicists it is an unknown phenomenon. Indeed, important fields of research, e.g., the treatment of the state in interstellar regions, including the formation of stars, are still based on a neglect of Bennett's discovery more than half a century ago. As shown in the table, present day students in astrophysics hear nothing about it. In a recent survey article in Science M.M. Waldrop (1985) described some "mysterious" threads which were claimed to be different from anything earlier discovered. Published photographs indicated that these phenomena are likely to be common filamentary structures; indeed, have been well-known since 1934 (Alfvén, 1986a).

In conclusion, it seems that astrophysics is too important to be left in the hands of theoretical astrophysicists who have got their education from the listed textbooks. The space data from astronomical telescopes should be treated by scientists who are familiar with laboratory and magnetospheric physics, circuit theory, and of course modern plasma physics. More than 99% of the universe consists of plasma, and the ratio between electromagnetic and gravitational forces is 10^{39}.

VIII. ROEDERER'S INTERDISCIPLINARIFICATION

A. The Roederer Syndrome

In his article "Tearing Down Disciplinary Barriers" (EOS, Oct. 1, 1985, p. 681) Juan G. Roederer points out the conflict between the demand for "increased specialization on one hand and

the pursuit of an increasingly interdisciplinary approach on the other".

This is important. Indeed, in the present state of science specialization is favored to such an extent that science is plit up into a number of increasingly small specialties. We lack the global view. This is evident from the preceding section.

We should remember that there once was a discipline which was called "Natural Philosophy" ("reine Naturwissenschaft"). Unfortunately this discipline seems not to exist today. It has been renamed "science" but science of today is in danger of loosing much of the Natural Philosophy aspect.

Roederer further discusses the phychological and structural causes for the loss of the global view, and points out that one syndrome of causes is the "territorial dominance, greed, and fear of the unknown". Scientists tend to "resist interdisciplinary inquiries into their own territory... In many instances, such parochialism is founded on the fear that intrusion from other disciplines would compete unfairly for limited financial resources and thus diminish their own opportunities for research".

B. Microscale Example

All this agrees with my own experience. When running a lab I found that one of my most important activities was to go from room to room and discuss in depth the problems which a certain scientist or a group of scientists was trying to understand. It often happened that one group reported that in their field they had a special problem which they could not possibly understand. I told them that if they cared to open the door to the next room - it was not locked! - just this special problem had been solved half a year ago, and if they injected the solution itno their own field, this would take a great leap forward. Often they were not at all happy for this suggestion, probably

because of the syndrome which Roederer has discussed, but when faced with "tearing down the disciplinary barriers" within the laboratory they realized how important such action is for progress (cf. II.D). This may be considered a mild case of the Roederer syndrome.

Such an example from the microscale structure of science supports Roederer's general views, but examples from the macroscale structure are much more important. Large parts of this lecture have been a series of examples of the malady which Roederer describes.

The lack of contact between Birkeland's and Langmuir's experimental-theoretical approach on the one hand and the Chapman--Cowling mathematical-theoretical approach on the other has delayed progress in cosmic plasma physics by perhaps half a century. The many new concepts which came with the space age begin to be understood by magnetospheric physicists but have not yet reached the textbooks in astrophysics, a delay of one or two decades, often more, as seen in the preceeding section. Very few if any deny that (at least by volume) more than 99% of the universe consists of plasma but students in astrophysics are kept ignorant even of the existence of important plasma phenomena like those listed in Table I.

Dr Roederer's prescription for curing this serious disease is "tearing down disciplinary barriers", indeed "interdisciplinarification" of science. This seems to be wise. However, we must suspect that to many astrophysicists this is bitter medicine. Can we find ways to sweeten it?

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FIGURE CAPTIONS

Fig. 1 Plasma produced by an electric discharge. In case the plasma is inhomogeneous, either because its cross section varies or its chemical composition or its density varies, one or more double layers may be produced between the electrodes (cf. Torvén and Lindberg, 1980).

Fig. 2 Dualism in plasma physics (cf. CP I.3).

Fig. 3 Example of a simple electric circuit where the double layer symbol suggested by Carlqvist (1982) is used. The double layer is connected in series with a voltage source V, an inductance L, and a resistance, R. A current I flows in the circuit.
The usual symbol for an e.m.f. (which is derived from a galvanic element) is replaced by the suggested symbol for a "generator". The arrow points in the direction of the current I. The same symbol with the arrow antiparallel to I represents a "motor" in which circuit energy is used to accelerate the plasma.

Fig. 4a (Upper) In certain cases, e.g., if the circuit has large dimensions, the simple inductance L should be replaced by a transmission line. (Lower) A rotating magnetized celestial body often acts as a homopolar inductor.

Fig. 4b Current-voltage characteristic of a laboratory double layer showing a region of negative resistance (Carpenter et al. 1984).

Fig. 5 Boström (1974) has given a summary of his theory of magnetic substorms in the form of a circuit. Solar wind energy produces a cross-tail current in the neutral sheet. The arrow indicates that this current can give rise to a very large voltage. (In our terminology it

should be replaced by the DL symbol.) This causes the circuit energy to be discharged over the ionosphere, where it is observed as a magnetic substorm. At substorm onset, the resistance of the neutral sheet increases because a DL is produced and the tail current is redirected to the ionosphere.

Fig. 6 Cosmic Triple Jump.

The linear dimensions of plasma vary by 10^{27} in three jumpts of 10^{9}:

from laboratory plasma	- 0.1 m
to magnetospheric plasmas	- 10^{8} m
to interstellar plasmas	- 10^{17} m
up to the Hubble distance	- 10^{26} m

including laser fusion experiments brings up to 10^{32} orders of mangitude.

New results in laboratory plasma physics and from in situ measurements by spacecraft in the magnetospheres (including the heliosphere) make sophisticated plasma diagnosis possible out to the reach of spacecraft (- 10^{13} m). Plasma at larger distances should to a large extent be investigated by extrapolation. To some extent this is possible because of our increased knowledge of how to translate results from one region to another.

As an example, cosmogony (formation of the solar system) can be studied by extrapolation from magnetopsheric and laboratory results, supplemented by our knowledge about interstellar clouds.

Fig. 7 Plasma research has been based on highly idealized models, which did not give an acceptable model of the observed plasma. The necessary "paradigm transition" leads to theories based on experiments and observations. It started in the laboratory about 20 years ago. In situ measurements in the magnetospheres caused a similar paradigm transition there.

This can be depicted as a "knowledge expansion", which unfortunately seems to have stopped at the reach of spacecraft. The results of laboratory and magnetospheric research should be extrapolated further out. When this knowledge is combined with direct observations of interstellar and intergalactic plasma phenomena, we can predict that a new era in astrophysics is beginning, largely based on the plasma universe model.

Fig. 8 Auroral circuit (seen from the sun) (cf. CP, Fig. II:17). The central body (earth and ionosphere) maintains a dipole field. B_1 and B_2 are magnetic field lines from the body. C is a plasma cloud near the equatorial plane moving in the sunward direction (out of the figure) producing a generator with

$$V = \int_{c_2}^{c_1} (\vec{v} \times \vec{B})\, d\vec{s}$$

which gives rise to a current in the circuit on c_1, a_1, a_2, c_2 and c_1. In a double layer DL with the voltage ΔV, the current releases energy at the rate $P \approx I\Delta V$, which essentially is used for accelerating auroral electrons. The energy is transferred from C to DL not by high energy y particles or waves, and not by magnetic merging or field reconnection. It is a property of the electric circuit (and can also be described by the Poynting vector).

Fig. 9 Heliospheric circuit. The sun acts as a unipolar inductor (A) producing a current which goes outward along both the axes and inward in the equatorial plane and along the magnetic field lines B_1. The current must close at large distance (B_3), either as a homogeneous current layer, or - more likely - as a pinched current.

Analogous to the auroral circuit, there may be double layers which should be located symmetrically at the sun's axes. Such double layers have not yet been discovered.

Fig. 10 Galactic circuit.

(a) Observed radio emission of Cygnus A (by Hargrave and Ryle 1974).

(b) the heliospheric circuit is scaled up by a factor 10^9 and the sun replaced by a galaxy located almost exactly between the radio sources (cf. CP, III.4.4). The radio emission is attributed to synchrotron emission by electrons accelerated in the double layers.

Fig. 11 Prominence-Solar Flare Circuit.

Whirling motions in the photosphere act as a generator, feeding energy into the circuit (which is similar to Fig. 3). The circuit energy can be released either as a solar flare produced by an exploding double layer and/or as kinetic energy in a rising prominence.

Table 1.

	DL	CV	PE	Circ.
Astrophysical Concepts M. Harwit, 1973 (New York: John Wiley and Sons)				
Theoretical Astrophysics Ambartsumian, 1958 (New York: Pergamon Press)				
Astrophysics: The Atmospheres of the Sun and Stars L. H. Aller, 1963 (New York: Ronald Press)				
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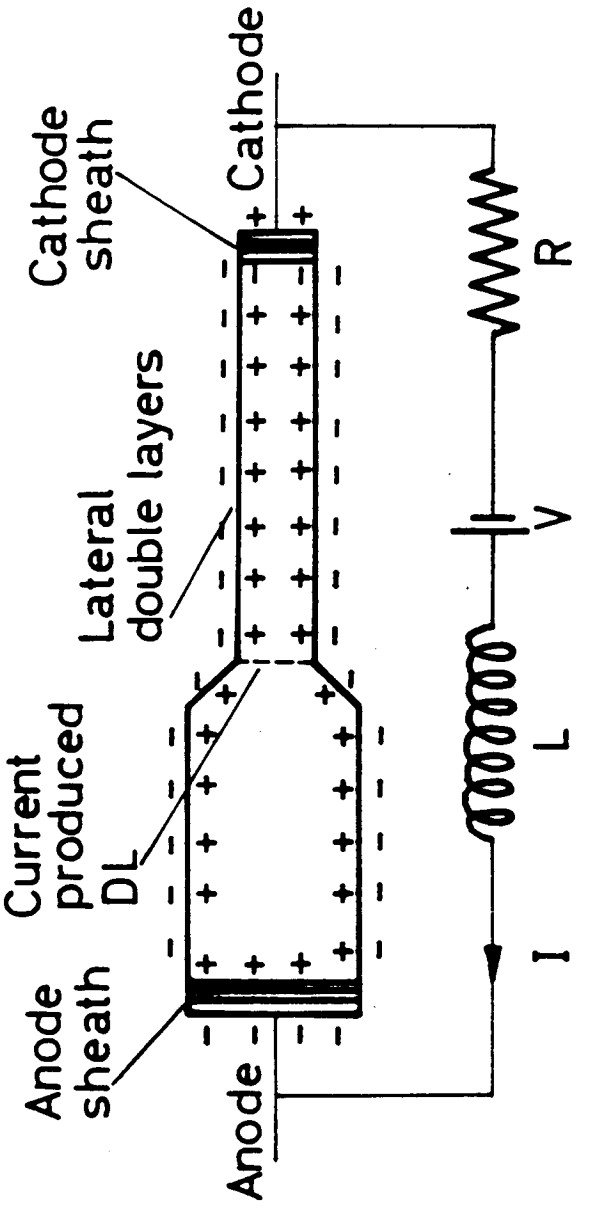
Physics of Magnetospheric Substorms, S. I. Akasofu, 1977 (Dordrecht, Holland: D. Reidel Publishing Co.)	X			X

X means that the field of research is at least mentioned. Blanks mean that the student is kept ignorant of the fact that such a field exists.

3/3/86

Fig.1


Cathode sheath
Cathode
Lateral double layers
Current produced DL
Anode sheath
Anode
R
V
L
I

TRANSLATION FORMULA

$$\nabla \times \vec{B} = \mu_0 \vec{i}$$

MAGNETIC FIELD DESCRIPTION

MAGNETIC FIELDS ARE:

- Measured rather easily
- Basic for plasma anisotropy including high energy particle motion
- Gives a good description of some waves in plasmas

ELECTRIC CURRENT DESCRIPTION

ELECTRIC CURRENTS ARE DIFFICULT TO MEASURE DIRECTLY BUT ESSENTIAL FOR UNDERSTANDING:

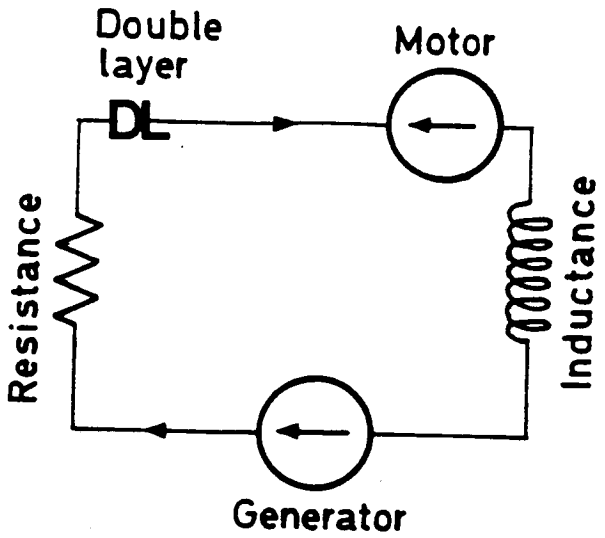
- Double layers
- Transfer of energy from one region to another
- Current sheet discontinuities
- Cellular structure of space
- Magnetic substorms, solar flares

The plasma dualism is somewhat analogous to the general particle field dualism in physics. The current description requires a new formalism with double layer and electric circuits as important ingredients.

Fig. 2

Fig. 3

SIMPLE CIRCUIT



Circuit energy $W_C = LI^2/2$

Generator voltage $V_G = \int_{GEN} \vec{v} \times \vec{B_0} \cdot \vec{ds} > 0$

Motor voltage $V_M = \int_{MOT} \vec{v} \times \vec{B_0} \cdot \vec{ds} < 0$

Generator power $P_G = IV_G$

Motor power $P_M = IV_M$

Double layer voltage ΔV

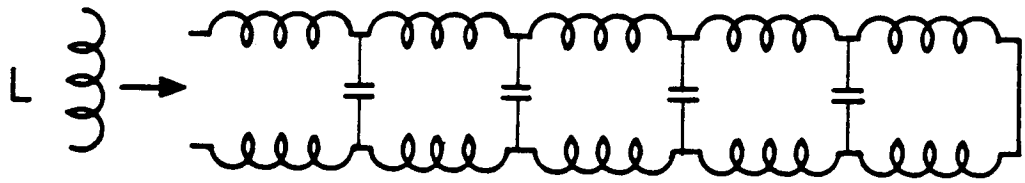
Power delivered to particles by DL $P_X \approx I\Delta V$

Power losses in resistances etc. $P_R = RI^2$

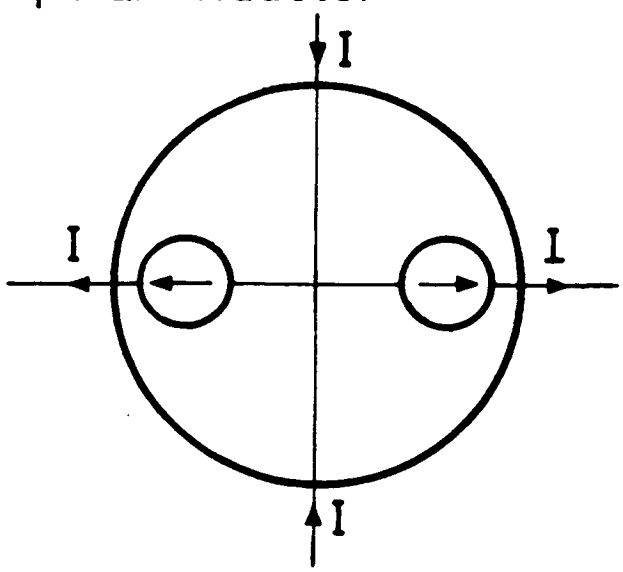
Fig. 4a

OTHER SYMBOLS

If inductance is distributed L should be replaced by transmission line

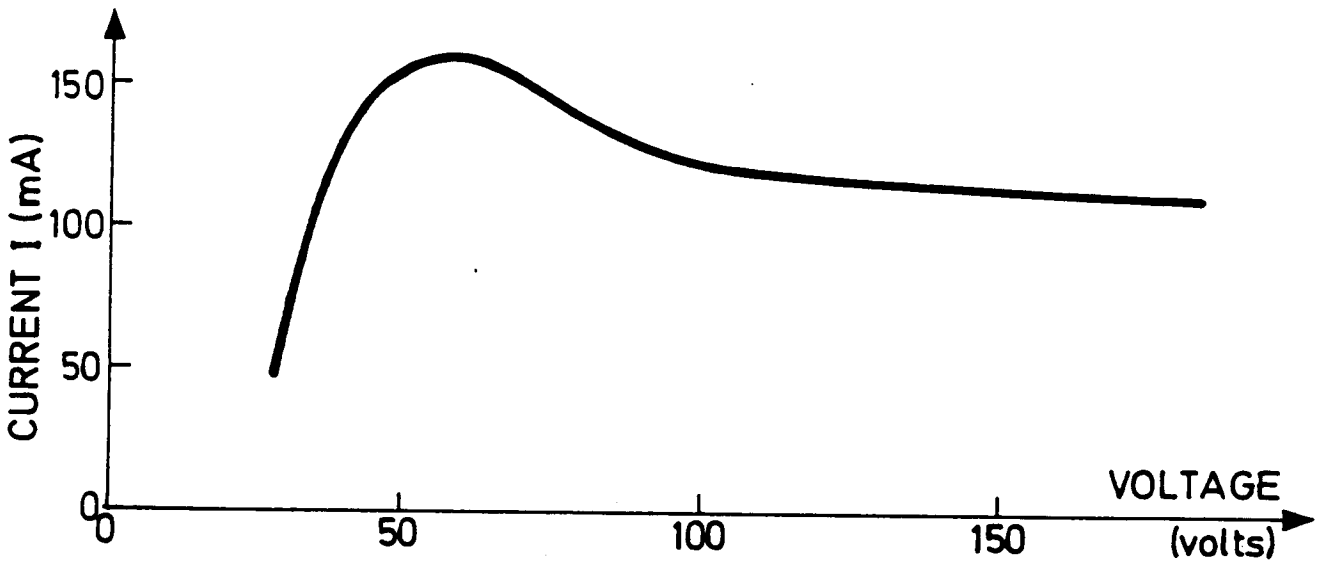


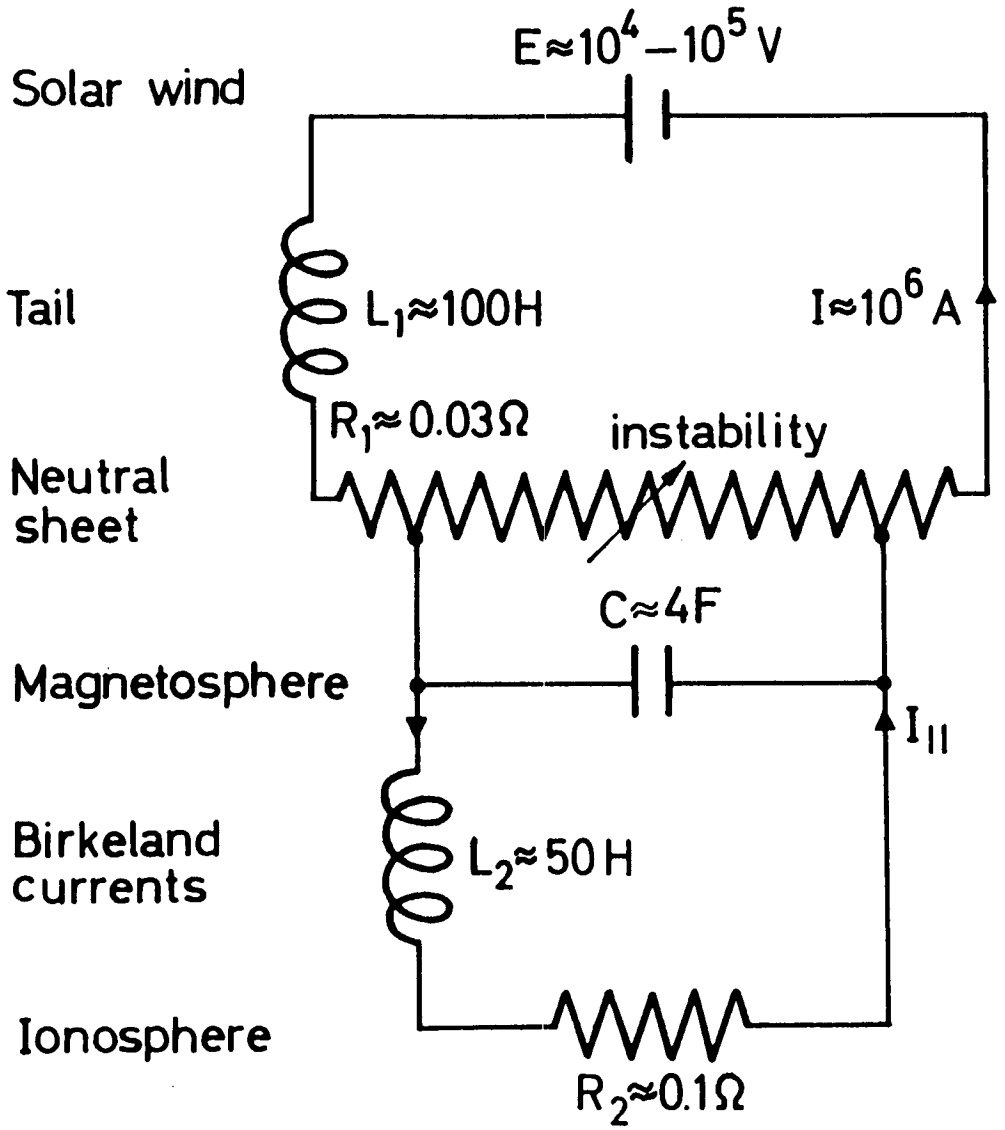
Magnetized celestial body acting as homopolar inductor



C-6

Fig. 4b





$\frac{1}{2} L_1 I^2 \approx 5 \times 10^{13}$ J

$\tau_1 = L_1/R_1 \approx 50$ min

$\frac{1}{2} CV^2 \approx 2 \times 10^9$ J

$\tau = R_2 C \approx 0.4$ sec

$\tau_2 = L_2/R_2 \approx 8$ min

Fig. 5

Fig. 6

TRANSFER OF KNOWLEDGE BETWEEN DIFFERENT PLASMA REGION

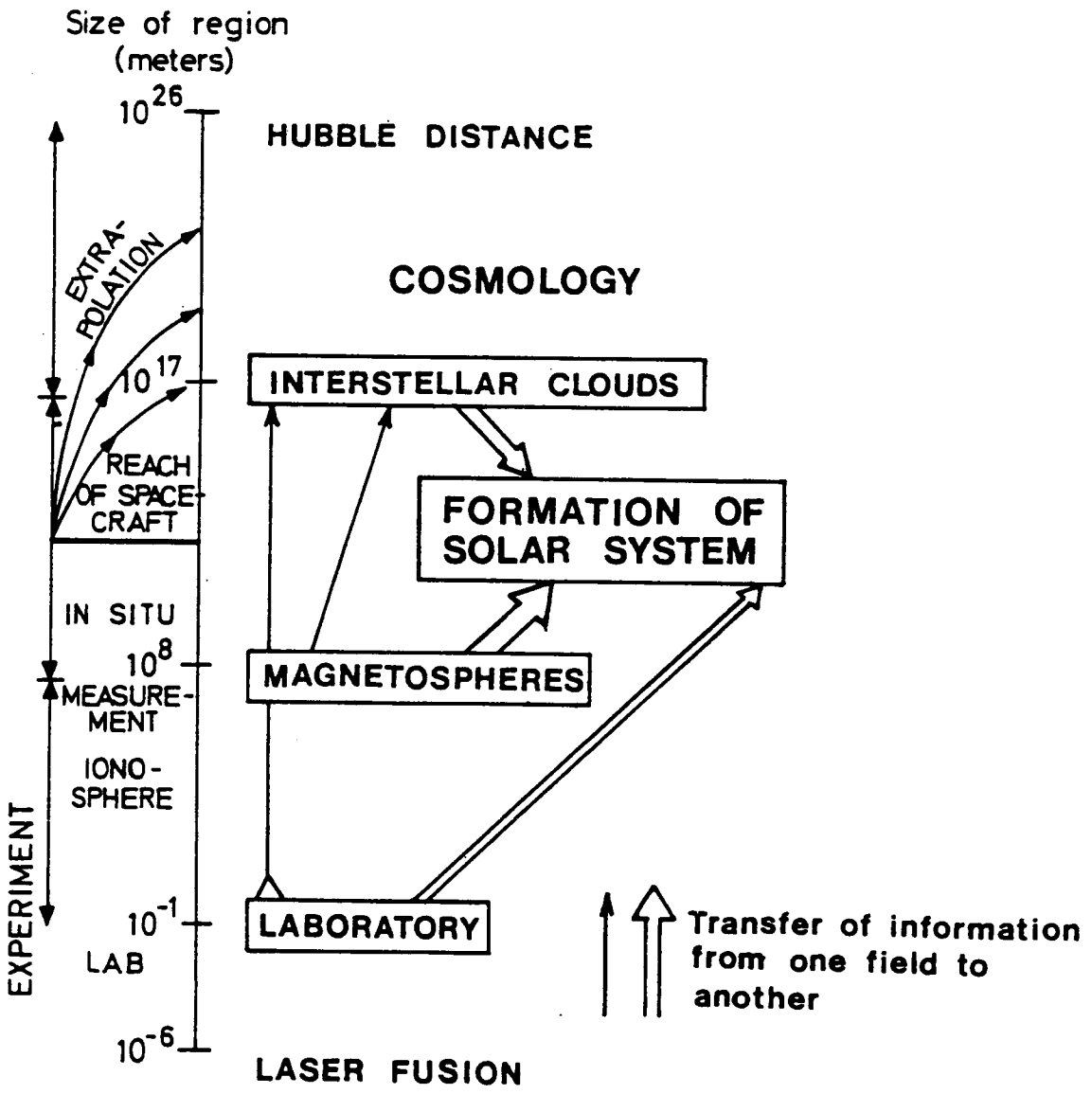


Fig. 7

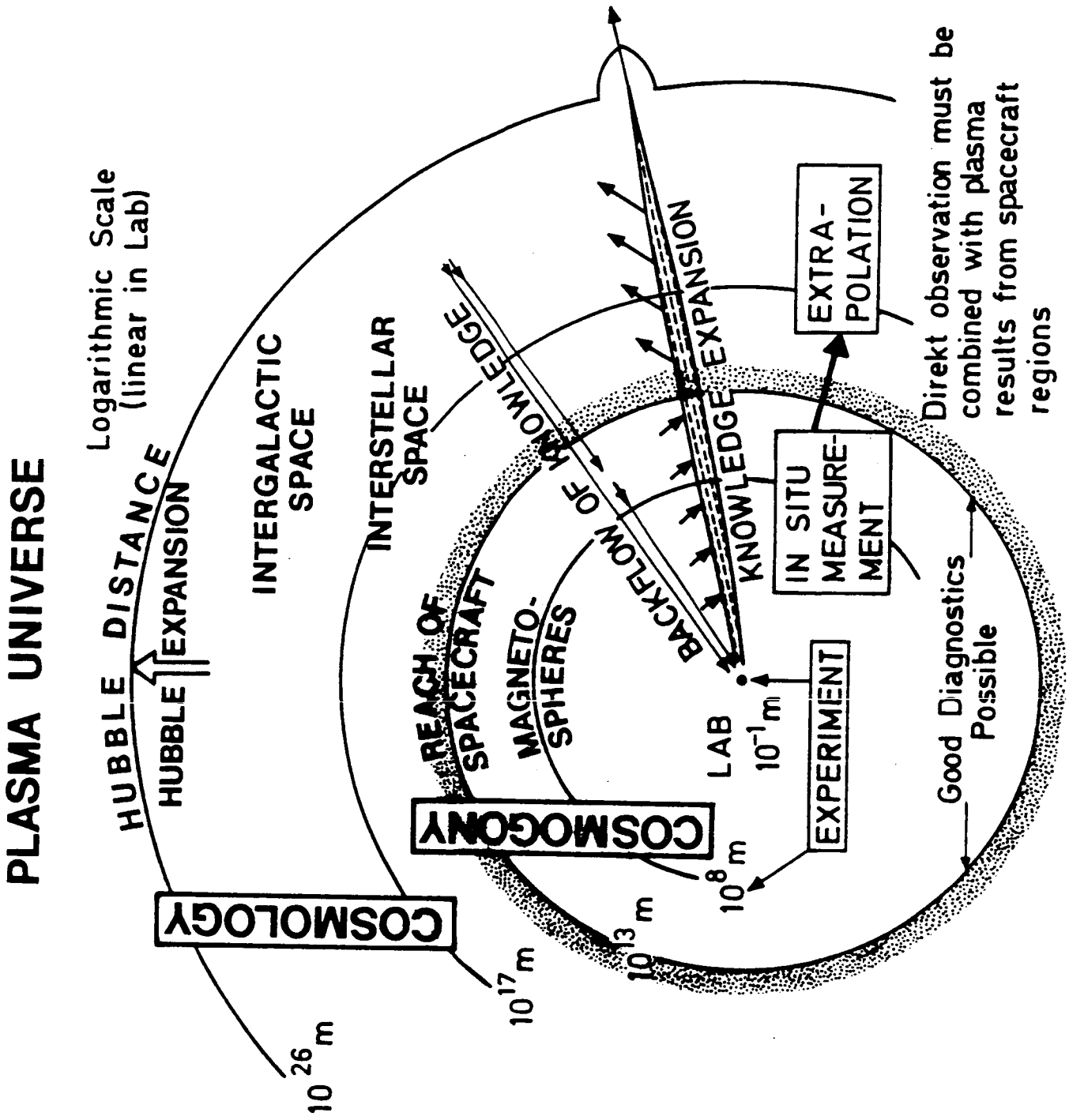


Fig. 8

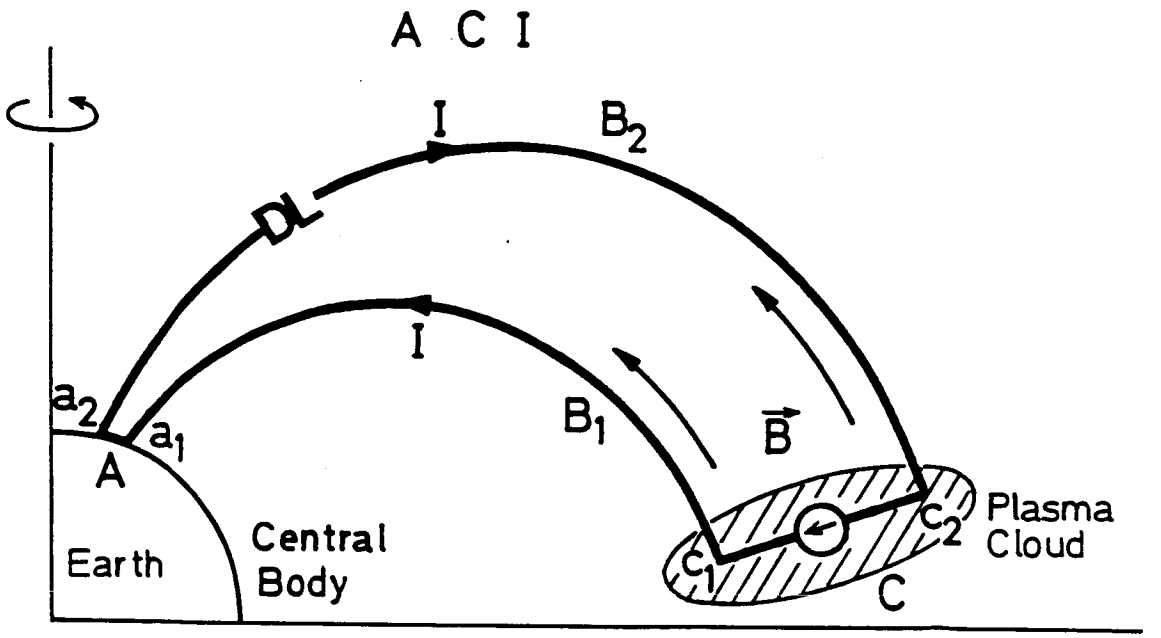


Fig. 9

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OF POOR QUALITY

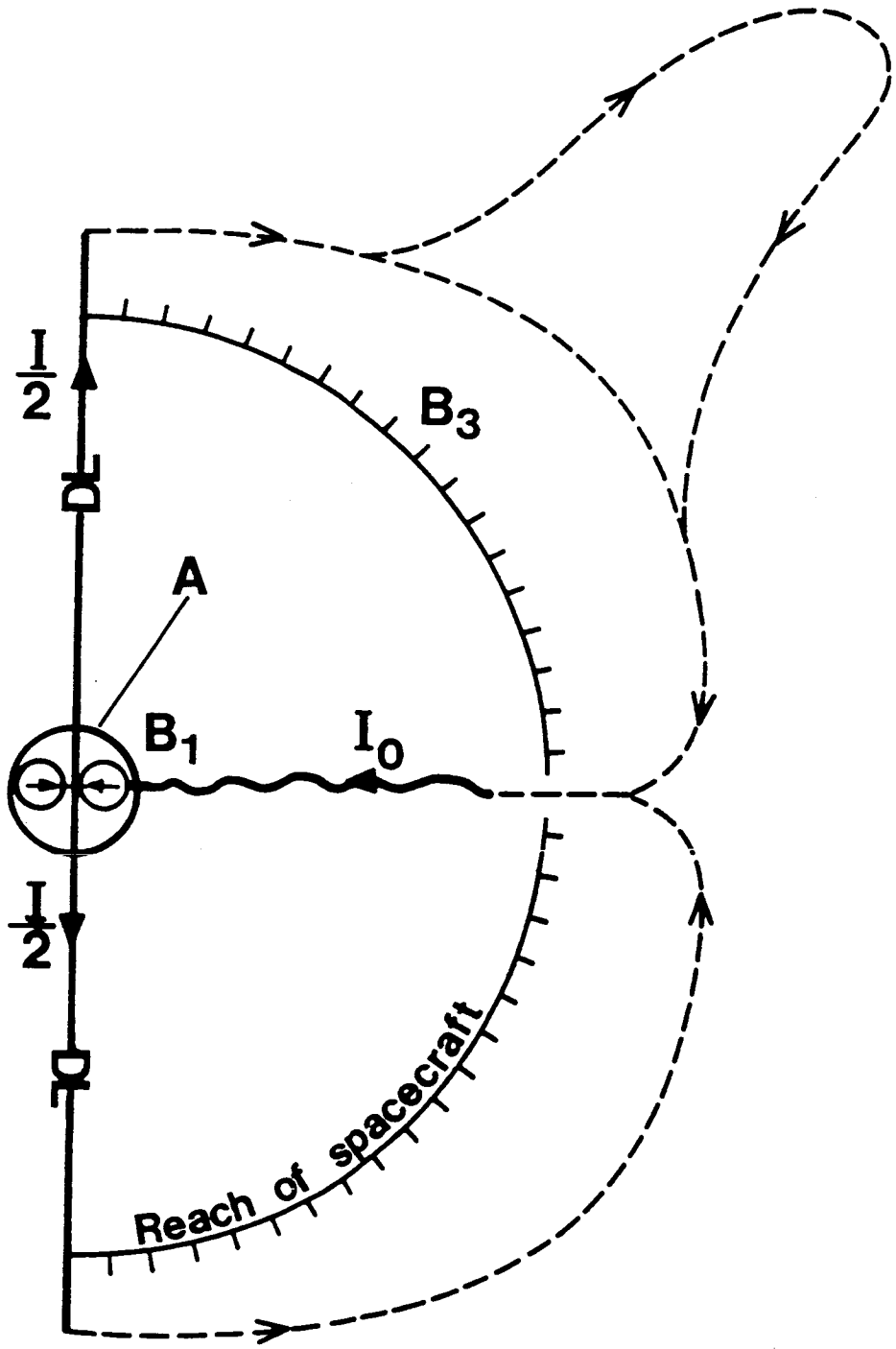


Fig. 10

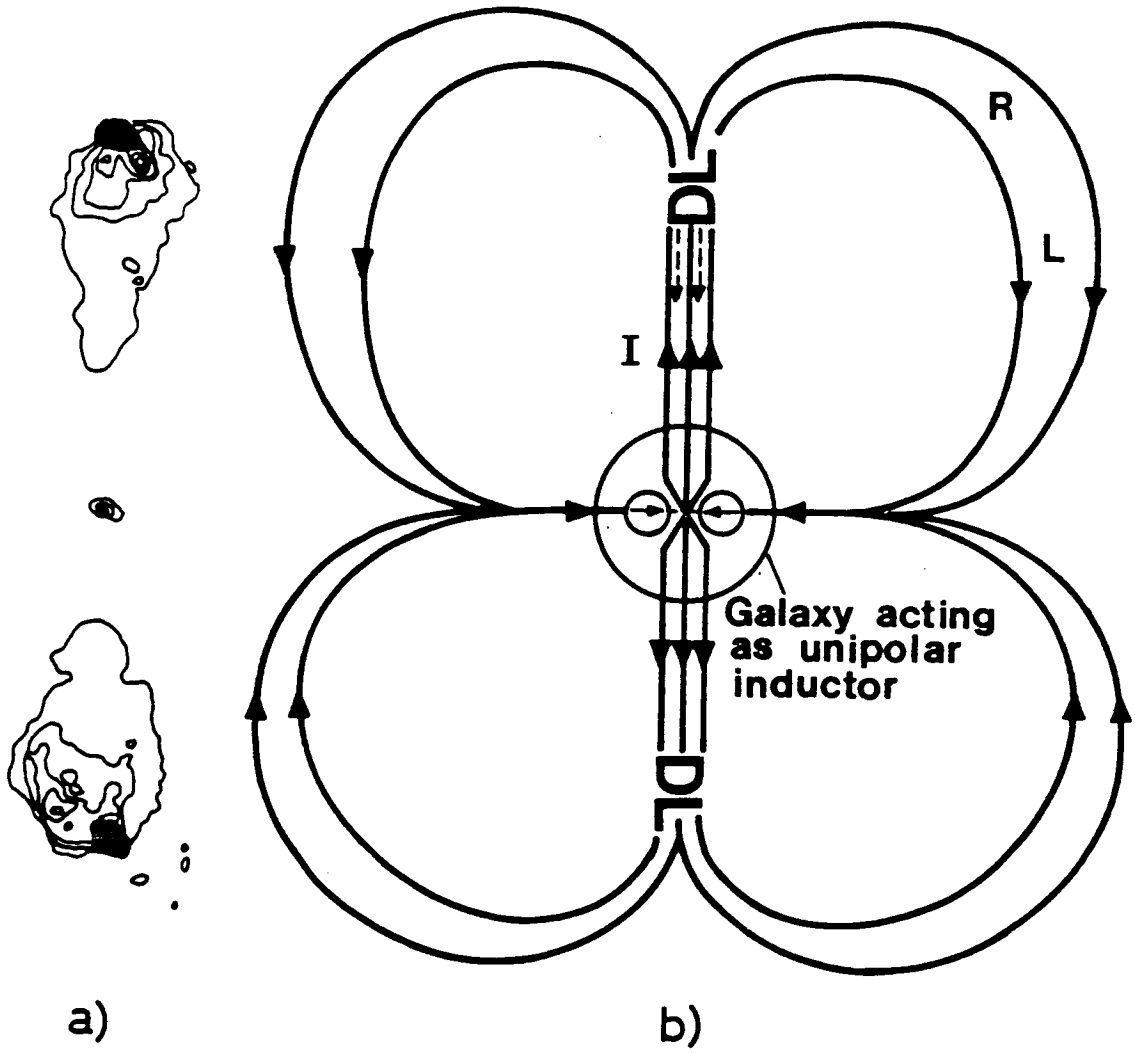
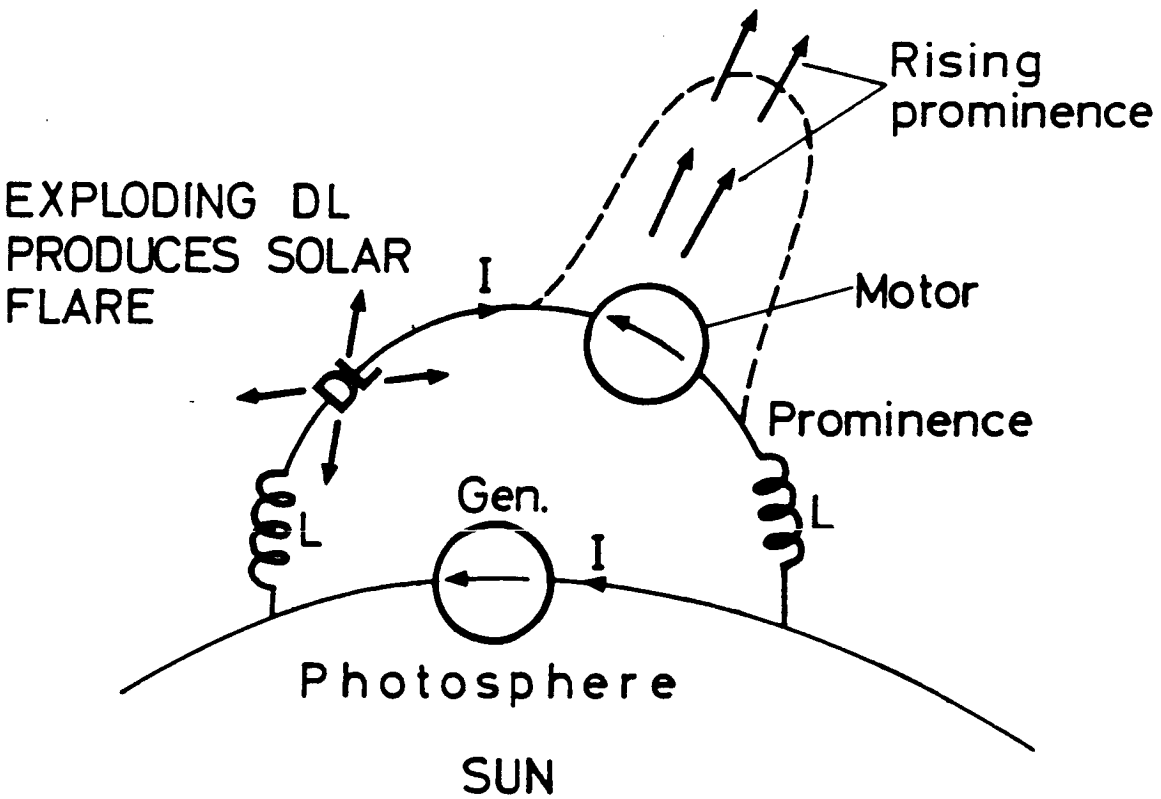


Fig. 11


Rising
prominence
EXPLODING DL
PRODUCES SOLAR
FLARE
I
Motor
Prominence
Gen.
L
L
I
Photosphere
SUN

APPENDIX B

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