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REPORT OF THE PLASMA PHYSICS AND ENVIRONMENTAL  
PERTURBATION LABORATORY (PPEPL)  
WORKING GROUPS

Volume III – Magnetospheric Experiments Working Group

Compiled by Program Development

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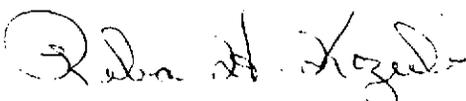
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*George C. Marshall Space Flight Center  
Marshall Space Flight Center, Alabama*

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| 16. ABSTRACT<br><br><p>A number of general studies that have been proposed for the PPEPL-Shuttle program are considered in qualitative detail from both the theoretical and practical points of view. The selection of experimental programs was restricted to those which may be considered active as opposed to refinements of the passive observational programs done previously. It is concluded that, while these new studies were scientifically worthwhile and could be performed in principle, in most cases insufficient attention had been paid to the practical details of the experiments. Several specific areas of study, stressing in particular the practical feasibility of the proposed experiments, are recommended. In addition, recommendations are made for further theoretical study, where appropriate.</p> |  |  |                       |
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## PREFACE

In December 1971, OSS/MSFC initiated a study to determine the feasibility of carrying out active (perturbation) experimental studies of the ionospheric/magnetospheric plasmas as well as laboratory plasma studies from a manned orbiting laboratory facility housed in a Spacelab module and carried into orbit by the Space Shuttle. This proposed facility has subsequently become known as the Plasma Physics and Environmental Perturbation Laboratory (PPEPL). The scientific community responded to this idea in a number of different areas, and it became apparent that the general study, being carried out by TRW Systems, Inc. and an associated science advisory board, could not address all of the aspects of each individual area. For this purpose working groups were organized in the three general areas of plasma probes, wakes, and sheaths; wave experiments; and magnetospheric studies. The specific purpose of the Working Group on Magnetospheric Studies was to analyze a representative set of experiments that might be performed on the PPEPL in the areas of magnetospheric and ionospheric modification, tracers, and energetic particle beams. An additional objective was the identification of instrumentation requirements which would impact the conceptual designs and capabilities of the PPEPL.

In addition to the contributions of individual working group members, other sources of information used by the working group on magnetospheric studies were the TRW compilation of experiment concepts, the University of Maryland study on environmental modifications experiments in space, and later contributions from members of the scientific community.

The reports from each of the three working groups are printed as separate volumes. This volume is an edited version of the report written by the Magnetospheric Experiments Working Group. Volumes I and II are the reports prepared by the Plasma Probes, Wakes, and Sheaths Working Group and the Wave Experiments Working Group, respectively.

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## MAGNETOSPHERIC EXPERIMENTS WORKING GROUP MEMBERS

W. Bernstein (Chairman)  
NOAA  
Boulder, Colorado

H. Liemohn  
Battelle Northwest Lab  
Richland, Washington

J. Barfield  
NOAA  
Boulder, Colorado

B. Hultqvist  
NOAA  
Geophysical Observatory  
Kiruna, Sweden

D. S. Evans  
NOAA  
Boulder, Colorado

S. Cuperman  
NOAA  
Tel-Aviv University  
Ramat-Aviv, Israel

J. W. Wright  
NOAA  
Boulder, Colorado

T. Holzer  
NOAA  
Boulder, Colorado

M. C. Trichel  
NASA/Johnson Space Center  
Houston, Texas

B. Whalen  
National Research Council of Canada  
Ottawa, Canada

R. Johnson  
Lockheed Corporation  
Palo Alto, California

F. Perkins  
Princeton University  
Princeton, New Jersey

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## VOLUME III - MAGNETOSPHERIC EXPERIMENTS WORKING GROUP

### I. INTRODUCTION

This group was established by NASA/MSFC to study experiments that might be performed by the Plasma Physics and Environmental Perturbation Laboratory (PPEPL) in the general areas of magnetospheric and ionospheric modification experiments, tracer experiments, and energetic particle beam experiments. The group had two basic objectives:

1. The identification and qualitative analysis of a representative set of experiments that could be performed by the PPEPL and which would provide a new insight into the basic physical processes which govern the observed states of the natural plasma systems.

2. The identification of critical implementation or instrumentation requirements that would impact the conceptual designs and capabilities of the PPEPL. It is also hoped that this effort will provide a framework for the further study of the experimental program for the laboratory.

Much of the background information used in this study was obtained from References 1 and 2.

The emphasis by this working group was primarily on experiments concerning geophysical problems, although some experiments of more general astrophysical relevance were also included. A summary of the current knowledge of the terrestrial plasma system and a compilation of those scientific problems which will probably remain unresolved before the advent of the PPEPL is documented elsewhere [3]. Rather than repeat that general material here, this working group considered only specific experiments in the areas cited above and concentrated on the resolution of specific problems.

The individuals who contributed to the experiment concepts are identified in Table 1. The experiments are not a complete or recommended selection; they demonstrate the variety of experiments that could be performed by the PPEPL and identify some of the conceptual and practical problems.



## GENERAL ORGANIZATION OF THE REPORT

The report is arranged by scientific objective and, in discussing each objective, the amount of detail concerning the required instrumentation has been minimized. At the beginning of the report, the instrumentation is discussed at some length in separate sections. Hopefully, most of the unanswered questions in the experiment descriptions will be answered in these initial sections. Those areas requiring further study are pointed out in Table 2.

**TABLE 2. EXPERIMENT OBJECTIVES  
AND EXPERIMENT TECHNIQUES**

| Objective  | Technique  |
|--|--|
| Cyclotron Resonance Interactions<br>B Field Topology<br><br>E Field Distribution                                   | Releases <sup>a</sup><br>Accelerator-shaped charges<br><br>Passive <sup>b</sup><br><br>Accelerator <sup>c</sup><br>Releases <sup>a</sup><br>Passive <sup>b</sup> |
| Interaction of Energetic<br>Particles with the Atmosphere<br><br>Tracer Experiments<br><br>Beam-Plasma Interaction | Accelerator <sup>c</sup><br><br>Release <sup>a</sup><br>Passive <sup>b</sup><br><br>Accelerators <sup>c</sup>  |

- a. Includes the release of any thermal energy material at any point in space.
- b. Includes all relevant observations necessary to interpret a specific experiment.
- c. Includes all charged particle accelerators independent of current, voltage, or particle species.

The experiments considered can be divided into three general categories:

1. Controlled modification experiments in which the artificial perturbation is large enough that observable changes in the environmental characteristics result. Because of the large volume and energy content associated with the ionospheric-magnetospheric system, such controlled perturbations in the ambient plasma parameters are necessarily limited to localized regions of space. Thus the response of the system may also be localized, although it is possible that the localized response will, in turn, produce more global effects. In some instances, the localized response to one specific perturbation may even provide a method for generation of secondary perturbations required in another experiment. For example, artificially stimulated particle precipitation could produce the requisite conductivity enhancements in the E region of the ionosphere. Experiments of this type can provide direct tests of the validity of theoretical models for naturally occurring processes, or, in some instances, can provide the basic experimental data required for the formulation of new theoretical analyses. The response of the ambient system to the perturbation will depend, even in a qualitative sense, upon its particular configuration at the time the perturbation is introduced. Thus a detailed knowledge of the state of the total ambient plasma system will be required for selection of the time and place to introduce the perturbation and for interpretation of the results of the experiments. Such perturbation may eventually lead to the control and even utilization (in an applied sense) of the environmental plasma characteristics.

However, the interaction between the perturbation and ambient plasma may be complex and result in systems behaving in a manner different from that expected. For example, Alfvén [4] has described a laboratory experiment designed to study plasma jets injected along a curved magnetic field. Injected single particles follow the curved field lines. The plasma jet might be expected to:

- a. Follow the field lines similarly to single particles.
- b. Continue to move straight ahead bringing frozen field lines with it or become electrically polarized and move straight ahead without bringing field lines with it.

However, an injected plasma jet unexpectedly bent in the direction opposite to the magnetic field curvature. Alfvén does not explain this behavior. Instead he uses this as an example of the lack of understanding of plasmas and to show that the simple extrapolation of single-particle models may be invalid. Similar

unanticipated results have been observed in active experiments in the magnetosphere. Although these interaction processes represent interesting problems in plasma physics, they may not be pertinent to the basic problem under study.

2. Diagnostic experiments that increase the knowledge of the existing states of the natural plasma systems; such experiments may be either active or passive depending upon the particular technique employed. In such active, or tracer experiments, it is assumed that the resultant perturbation of the natural system is negligible; however, the observed characteristics of the tracing agent provide diagnostic data relevant to specific properties of the natural system. Similar diagnostic data sometimes can be obtained from specific passive observations of the natural medium but may not have been carried out to date because of various limitations imposed by current satellite technology. The large weight, power, and volume of the PPEPL and its associated subsatellites will provide major improvements in both active and passive diagnostic experiments.

3. Plasma physics experiments that need a plasma medium in which phenomena believed to be important in geophysical and/or astrophysical processes can be studied in detail. In these experiments, complete scaling of the natural configuration is unnecessary; rather, the experiments should be designed taking into account only the existing theoretical treatments. The major advantage offered by the space plasma environment over laboratory plasmas lies in the very large, uniform, and unbounded plasma that is available. Because of the complexity, short flight duration, and cost associated with space experiments, a demonstration of the specific need for the unique properties of the space environment should be required for inclusion of the experiment in the PPEPL program.

While this particular division of subject matter is not stressed, the proper category for specific experiments is indicated.

## II. AREAS OF EXPERIMENTAL INTEREST

### A. General Consideration of Experimental Techniques

#### 1. ENERGETIC PARTICLE BEAMS

Experiments employing energetic particle beams, both electron and ion, from accelerators on board the PPEPL present common problems in several areas.

Basically three types of experiments have been proposed using energetic particle beams:

1. Experiments that require that the beam current, velocity distribution, pitch angle and pitch angle dispersion, and radial profile be known so that those parameters existing at launch and those observed at the point of interaction or detection can be directly compared. An example would be a charged particle beam used to sense the potential difference along magnetic field lines.

2. Experiments that require beam propagation but can tolerate reasonably large and unknown modifications in the above beam characteristics during flight. An example here would be using an accelerator beam for simple magnetic conjugacy tests.

3. Experiments that are based upon the generation of collective beam plasma interactions.

a. Beam Stability Considerations. Experiments within categories 1 and 3 would appear to be mutually exclusive; i. e. , for a given beam-plasma configuration (which is determined by the accelerator characteristics, path length, and ambient plasma parameters), one cannot expect both stability and instability. Theoretically the introduction of a charged particle beam into the ambient plasma should lead to a two-stream instability with the instability growth rate determined by beam and ambient plasma parameters. Since the instability growth rates are reduced following the initial modification in beam parameters, most of the modification of the beam is likely to occur close to the PPEPL soon after the beam has left the accelerator. Also the small dimensions of an injected beam should result in instability growth rates significantly reduced from those predicted by infinite medium theory.

A few energetic electron beam injection experiments have been carried out and they indicate that it is possible to propagate a dense energetic electron beam over large distances in the magnetosphere and ionosphere [ 5, 6 ], although the evidence for modification in beam character during transit through the ambient plasma is not clear. In the first experiment of Hess et al. [ 5 ], a 0.5 A, 9 keV electron beam was injected downward into the atmosphere from an altitude of approximately 250 km. Observations of the optical emissions produced in the interaction of the beam with the atmosphere were consistent with theoretical predictions based entirely upon binary collision processes but ignoring collective effects (instabilities). However, in a second experiment<sup>1</sup>,

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1. Private communication with W. N. Hess.

the beam was injected upward along the field line (at low L value). A study of optical emissions in the conjugate hemisphere reveals inconsistencies with these theoretical predictions and suggests that the beam must have somehow been modified in transit over the long path between hemispheres.

Clearly, additional theoretical and perhaps experimental study of beam-plasma interactions is required to establish the validity of some of the proposed experiments. Such studies will determine whether a single accelerator system will be adequate for the general range of experiments (1 through 3 above) or whether it will be necessary to design different accelerators with specific and limited properties.

b. Methods for Energetic Beam and Particle Precipitation Detection. Potential particle beam experiments proposed for PPEPL require, in some degree, the following capabilities for beam detection:

1. Simple indication that some fraction of the initial beam has been propagated from point of launch to point of detection.
2. Accurate measurement of the time delay between launch and detection
3. Accurate spatial location and the radial spread of the beam at detection as compared with the location of the injection point.
4. Determination of the modifications in beam parameters occurring during flight.

Two general methods for beam detection are apparent; each has significant limitations and problems:

1. Direct measurement of beam particle characteristics with instrumentation carried by maneuverable subsatellites that can intersect the beam at selected points.
2. Use of the atmosphere as a scintillation screen with remote observations of the optical and X-ray emissions using instrumentation aboard the PPEPL and associated ground and aircraft stations.

Both methods have been successfully used in the previous energetic beam injection experiments. The direct detection method has the major disadvantage of having to predict the expected location of the beam detection subsatellite at that point. This is difficult, at best, although such prediction has been possible in certain experiments [6]. Specifically, in many of the experiments the

expected location of the beam relative to the injection point depends on electric and magnetic field parameters that are unknown; thus, either a multiplicity of subsatellites or an inefficient search operating mode would be required. Where possible, the direct detection system offers the advantage of high sensitivity and wide dynamic range plus the ability to sense modifications in beam parameters. Operation in sunlight and in the presence of natural precipitation should not prove difficult. Note, however, that the high orbital velocity of the PPEPL would, in general, preclude its use as both the beam injection and direct beam detection platform.

The atmospheric scintillation technique allows use of the PPEPL as both the injection and detection platforms. In many cases the large field of view reduces the need for a precise prediction of beam location, while the lack of absorbing atmosphere allows inaccessible regions of the emission spectrum to be observed, possibly improving the detection sensitivity. Coordinated ground and PPEPL observations would always be desirable and necessary, particularly in some conjugate point experiments. The major limitation to this method lies in the dependence of the emission intensity, spectrum, altitude, and radial profile upon the current density, velocity distribution, and pitch angle distribution of the beam at the point of interaction with the atmosphere. These dependences set a lower limit to the beam energy and current that might not be compatible with the accelerator design requirements. A second limitation occurs in those cases which call for ion beams of different species because charge exchange effects can produce additional beam modifications with resultant decreases in emission intensities. Finally, the often faint induced emissions require observations in the dark hemisphere where major difficulties will be encountered in the separation of beam-produced emissions from those produced by natural energetic particle precipitation.

The foregoing requirements for ascertaining the properties of artificial particle beams are identical to the requirements for determining similar properties of natural or artificially induced precipitation. Thus, the subsequent discussion of charged particle observations also applies to direct observation of accelerator beams. The critical properties include occurrence of precipitation; identification of species, flux, and energy spectrum; pitch angle distribution; spatial extent and location; and duration of the beam pulse.

c. Vehicle Neutralization. The emission of either ion or electron beams from an isolated space vehicle generates a potential difference between the spacecraft and ambient plasma that would modify and inhibit beam emission if there were no compensation. Several possible methods exist for neutralizing the emitted charge, but the adequacy of each method for the particular PPEPL configuration has not been studied. The methods are:

1. Collection by the vehicle, from the ambient medium, of a current equal to the emitted current. For a given ambient plasma environment, the total collected current is dependent upon the collecting area. The deployment of large area collecting surfaces and the emission of high current neutral plasma jets have been used to provide neutralization for the rocket-borne electron beam experiments.

2. Emission from the vehicle of an equal current of opposite charge. This technique is more suitable for the emission of energetic ion beams where emission of an equal electron current would provide vehicle neutralization. However, because of the high charged particle densities associated with modest energy ion beams, neutralization of the space charge associated with the beam itself is required to prevent beam blowup. Such beams must be neutralized by electron injection directly into the beam; in effect producing a neutral plasma jet.

The rocket accelerator experiments have shown that vehicles can be successfully neutralized during periods of energetic electron emission by either an increase in collection area or by plasma jet emission. Ion engine tests have demonstrated that vehicle neutralization during emission of high current electron neutralized ion beams can be achieved. However, in all the electron beam experiments, measurements of the return neutralizing flux to the vehicle indicate that these ambient particles had been significantly energized. It is not known whether this heating was produced in the neutralization process, collective beam-plasma interactions heating the local plasma, or whether the return electron flux was generated at low altitudes by collisional beam-atmosphere interactions.

## 2. GENERAL PROBLEMS ASSOCIATED WITH THE INJECTION OF LARGE VOLUMES OF PLASMA

This discussion is generally limited to plasma releases at large geocentric distances in spite of the additional experimental requirements for the release of plasma from the PPEPL at ionospheric altitudes. This is because of the unique problems of delivery of the plasma and of performing the necessary diagnostic observations associated with such experiments when they are in regions inaccessible to the Shuttle vehicle itself.

a. Injection. Several of the proposed experiments require the distribution of large amounts of cold plasma ( $10^{24}$  to  $10^{28}$  ion pairs) over large regions of space in distant regions of the magnetosphere (cusp, tail, equatorial plane beyond the plasmopause) and even into the undisturbed solar wind. It is generally accepted that photoionization by solar radiation of atoms, volatilized

by means of stored chemical energy, represents the simplest method of generating a volume of cold plasma. In general, this process restricts one to the use of alkali and alkaline earth metals. Lithium offers several advantages over barium including (1) the larger number of ion pairs per unit weight of release; (2) the slower rate of photoionization of lithium that permits a larger volume of space to be filled with cold plasma, thereby minimizing effects associated with transient  $\beta > 1$  conditions; and (3) the atomic mass of  $\text{Li}^+$  more nearly approximates that of the naturally occurring hydrogen plasma, thus minimizing possible effects of this parameter.

The most important consideration in these experiments is the method for delivery and injection of the plasma at the desired location. Several possible methods can be considered:

1. Direct delivery of the material to the desired location by an associated powered vehicle, such as a tug, with volatilization accomplished by a thermite (evaporative) reaction.
2. Direct delivery of the material by a separate vehicle launched from the PPEPL or from the ground, such as a Scout, and again using the thermite reaction. The recent Ba release at a distance of approximately 6 earth radii used this method.
3. Injection of jets of neutral alkali atoms at low altitudes ( $\approx 500$  km) using shaped charge releases from ground-launched rockets or the PPEPL. If a rapidly photoionizing material such as Ba were used, the jet of neutral material would quickly transform to an ion jet. If the release direction were aligned upward along the magnetic field and the jet velocity were sufficient, the geomagnetic field would guide the ion cloud to the desired location. The use of the more slowly ionizing Li in a shaped charge would allow the material to be jettied across magnetic field lines to the desired location but would require a vastly greater amount of material since very large volumes will be filled with Li plasma.

Several such Ba shaped charge releases have been carried out [7] and demonstrate the feasibility of the technique. Still unexplained is the observed breakup of the  $\text{Ba}^+$  plasma jet into several smaller, discrete jets. It is not at all clear that the shaped charge configurations presently used ( $< 1$  kg of Ba) can be extrapolated to the very large amounts of material ( $> 100$  kg) required in the transverse field Li releases; further studies are required to establish the adequacy of this injection method.

4. Another possible high altitude injection method is based upon a low altitude evaporative (thermite) release from either the PPEPL or an associated ground-based rocket into regions of the magnetosphere where natural processes (e.g., the polar wind) would convey the resultant ion cloud to high altitude. Important considerations include: (1) the injected ion mass must be compatible with the transport process, (2) the total injected mass should not be sufficient to modify the flow pattern, and (3) the injection of a new ion species should not modify plasma stability characteristics and, possibly, plasma flow patterns. None of these areas has been investigated in any detail.

b. Ion and Neutral Cloud Measurements. Procedures for acquiring the overall characteristics of such plasma clouds are not established. Even placing a diagnostic vehicle within the cloud will only provide limited local data. The quantities that must be determined include (1) spatial extent of the cloud, (2) average density and gross density irregularities and, (3) drift and spatial evolution of the cloud. Remote optical observation of the cloud provides the best source of information. Since the  $\text{Li}^+$  resonance line ( $\lambda = 199 \text{ \AA}$ ) requires that optical observations be made from above the atmosphere, the PPEPL is adequate because it provides a good platform, although its orbit prevents continuous observations. The  $\text{Ba}^+$  primary emission is in the visible band and is detectable from ground observations.

## B. Mission-Oriented Experiments

### 1. MAGNETOSPHERIC WAVE-PARTICLE INTERACTIONS

The interaction between waves and particles in the magnetosphere is believed to be one of the dominant processes that maintains its dynamic equilibrium. As such, it is essential that one understands the nature of the various mechanisms by which waves and particles exchange energy and has quantitative models of this process. Several experiments have been suggested to improve the understanding of wave-particle interactions.

Most studies of the wave-particle interaction have centered around the cyclotron resonance interaction as the chief mechanism for energy transfer. In this process, the helical wave fields interact with electrons at VLF frequencies and protons at ULF frequencies. The particles in the interaction are only those within a narrow band of parallel velocities because of the Doppler frequency criterion that must be satisfied. As energy is transferred from the particles to the waves, the pitch angles of the interacting particles are driven toward the loss cone and, thus, these particles may precipitate into the upper atmosphere.

The combined precipitation and signal amplification make this process easily detectable. Several possible experiments to study this process have been proposed; they all basically center about cold plasma seeding in the equatorial plane beyond the plasmopause.

Both Brice and Lucas [ 8 ] and Cornwall et al. [ 9 ] have pointed out that naturally occurring enhancements in cold plasma density in the magnetosphere may play a dominant role in the loss processes that partially determine the temporal and spatial behavior of energetic particle fluxes. They both have suggested that when very low ambient plasma densities exist, the stably trapped energetic particle flux can exceed the limiting fluxes derived by Kennel and Petschek [ 10 ]. When the cold plasma densities are increased, modifications in electron and ion electromagnetic cyclotron (EMC) instability characteristics occur which theoretically result in the pitch angle scattering and precipitation of these previously stably trapped particles, and amplification of the electromagnetic waves. Experimental evidence supporting the occurrence of the proton EMC instability at the ring current-plasmopause boundary has been given by Williams et al. [ 11 ] and Cornwall [ 12 ].

These theoretical treatments of the EMC instabilities are limited basically to the linear regime with the inclusion of effects arising from the partial reflection of wave energy at the system boundaries. Analytical methods have not been developed for treatment of the nonlinear behavior. These, however, can be treated in computer simulation experiments<sup>2</sup> and extension of these to more realistic magnetosphere conditions is suggested.

Young et al. [ 13 ] suggest that an electrostatic instability, also dependent on cold plasma density, rather than the EMC instabilities may provide the dominant loss process for magnetospheric energetic particles. Experimental evidence supporting this model has been given by Mozer and Bogott [ 14 ].

Brice [ 15 ] and Cornwall [ 12 ] noted that the required local enhancements in cold plasma density for stimulation of the EMC instabilities could be achieved artificially, i. e., by injecting or producing cold plasma clouds in the appropriate location. Stimulation of the electron instability requires only an increase in electron density; a light ion density enhancement is required for the proton instability. The use of a  $\text{Li}^+$  plasma cloud conveniently satisfies

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2. Cuper, S. et al.: A Computer Simulation of Cold Plasma Effects on the Whistler Instability for Geostationary Orbit Plasma Parameters. Submitted for publication in J. Geophys. Res., 1973.

both requirements; Cornwall and Schulz [16] have shown that a heavy ion cold plasma actually stabilizes the proton cyclotron process. In a series of detailed studies, Williams [17], Williams and Cessna [18], and Bernstein and Cessna [19] have developed several feasible configurations for the cold plasma seeding experiment using current satellite and subsatellite technology.

Basically, this experiment attempts to modify the natural energetic particle distribution through the injection of cold plasma. An alternate and more complex version of the experiment would attempt to increase the trapped energetic particle flux and perhaps increase its anisotropy. Injection of an anisotropic energetic particle population from a satellite-borne accelerator into a natural ambient cold plasma would thus produce particle pitch angle diffusion and wave amplification. This particular experiment has not been considered in detail but, if feasible, would perhaps eliminate the requirement for direct access to the distant equatorial plane inherent in cold plasma seeding.

The injection of plasma should be done when the natural cold plasma density is low enough that the stably trapped, anisotropic, energetic particle fluxes exceed the theoretical limiting flux intensities and, also, where increases in the ambient cold plasma density (from typically  $< 0.1/\text{cm}^3$  to  $\approx 5/\text{cm}^3$ ) significantly modify the instability growth rate. Such conditions are most often found in the distant equatorial plane beyond the plasmapause. Cornwall [12] has pointed out that the ring current proton fluxes almost always satisfy the required conditions at synchronous altitude. However, the naturally occurring energetic electron fluxes show far greater variability [20] and often do not satisfy the required conditions. Reasonable criteria (in the absence of in situ measurements) must be developed to select the proper ambient conditions.

Approximately 1 kg of ionized Li will fill a volume of several hundred kilometers radius to a density of  $\approx 3/\text{cm}^3$ . Since the overall mass efficiency for generating an ionized Li cloud by a thermite release is approximately 6 percent, some 20 kg of Li material would be required. Similar ionization efficiencies exist for other release mechanisms. Such volumes and densities are estimated to be large enough to result in measurable environmental effects (particle equatorial precipitation and enhanced electromagnetic radiation).

The basic objectives of such an experiment include:

1. Positive evidence that stimulated particle precipitation is associated with cold plasma injection by remote observation of the precipitation.
2. The identification of electromagnetic radiation near the equatorial cyclotron frequencies (and energetic particle precipitation) associated with

cold plasma injection which would establish the role of the EMC instabilities. This also can be accomplished by remote observations.

3. A detailed study of the wave-particle relationship (amplitude, frequency, pitch angle distribution, etc.). Such measurements must be done within cold plasma cloud itself.

Some experimental efforts that might have stimulated the EMC instabilities by cold plasma injection have been carried out. These include the thermite Ba release at  $L = 5.2$  for which measurements of particle precipitation have been described by Mozer [21] and several high  $L$  value Ba shaped charge releases [7]. Because Ba releases were employed, only electrons would have been affected. Even so, apparently no significant effects on particle precipitation or enhanced wave generation were observed. However, the shaped charge program is continuing, and the use of Li is anticipated.

The problems of a cold plasma release at a specific high altitude have been discussed previously (see Section II. A. 2. a). The PPEPL will probably be used as the low altitude diagnostic platform. Unless very large area releases are employed, direct measurements of precipitation would be difficult and remote observations of particles and waves would be required. Optical instrumentation aboard the PPEPL would also be used for observation and measurement of the cold plasma cloud.

The time required from the start of the experiment to the formation of a plasma cloud in the equatorial plane ranges from approximately 0.5 hour for a shaped charge technique to approximately 4 hours for the material to be carried to the equatorial plane by rocket. In addition, the plasma cloud should not be expected to last longer than 1 hour because of diffusion of plasma along the magnetic field as well as convection away from the region of interest. Thus, the position of the PPEPL or other observation platform must be carefully synchronized with the creation of the plasma cloud for observations from the PPEPL.

Critical PPEPL design considerations include:

1. The means for the injection of the required amounts of cold plasma into the distant equatorial plane.

2. Instrumentation for remote observation of the ionized and neutral injected material. (Optical instrumentation to observe Ba,  $Ba^+$ , and Li emissions exist and no problems are anticipated since the relevant emissions are visible. Comparable instruments for the detection of  $Li^+$  at  $\lambda = 199 \text{ \AA}$  remain to be identified.)

3. Both particle detectors (for direct measurement) and optical and X-ray detectors (remote) are needed aboard PPEPL to characterize precipitation.  $H\beta$  and  $Ly\alpha$  detectors will be required for situations involving proton precipitation.

4. VLF and ULF detectors are needed to detect and characterize any enhanced electromagnetic radiation.

5. Real-time measurements of the total particle distribution in the vicinity of the injection will be useful, if not necessary, for the selection of release conditions.

A second approach to the stimulation of plasma instabilities, which lead to the precipitation of energetic particles, is the use of VLF and ULF radiation from PPEPL-borne transmitters with the expectation that this radiation will couple to the particles of interest. These experiments are discussed in detail by the wave-particle working group (see Volume II of this report).

## 2. MAGNETIC FIELD TOPOLOGY

Many aspects of the topology of the geomagnetic field and its dependence upon geophysical activity remain unresolved. With the advent of the PPEPL and its capabilities, several straight-forward experiments can provide needed experimental answers. Implicit in the experiments are certain characteristics of the reflection of energetic particle, both by the mirror magnetic field configuration and backscattering by the atmosphere. Such measurements are intended to produce a more complete knowledge of the existing magnetosphere configuration.

a. Conjugate Point Location. If an energetic particle beam is launched upward along closed field lines from an accelerator on the PPEPL, observation of where the beam strikes the atmosphere in the conjugate hemisphere will locate the conjugate point for comparison with calculated models of the geomagnetic field. Beam detection in the conjugate hemisphere can be accomplished by direct detection of the particles from an associated satellite or by optical observations from ground or aircraft instrumentation of the emissions produced in the interaction between the beam and atmosphere. The modifications produced in the beam trajectory by  $\nabla B$  drift, curvature drift, and convective electric field drift can be evaluated through the use of beams of different velocities. In general, it is preferable to use electron beams since the low velocities of ion beams result in much larger convective drift effects. Obviously, if the field

line is not closed, or is sufficiently distorted that the beam can no longer complete a transit between hemispheres, conjugate effects will not be observed. Both electron beam<sup>3</sup> and shaped charge Ba releases [7] have been employed for conjugate point mapping but only at low L value.

A less obvious method of conjugate point mapping has been suggested by Linson<sup>4</sup>. Evidence shows that the ionospheric conductivity of the conjugate hemisphere may play an important role in the behavior of large, low altitude, Ba releases at moderate and low L values. If this hypothesis is valid, spatial perturbations in the conjugate ionosphere electron density distribution should be produced by a release, and these density perturbations may be detected optically or by ionosonde techniques.

b. Field Line Length Measurements. Measurements of the transit time required for an energetic particle beam to propagate between hemispheres (as described in Section a. above) or to propagate to the conjugate hemisphere and reflect back to the launch hemisphere show field line length and, consequently, is a measure of its distortion relative to the assumed dipole configuration. In the bounce technique, which has been described by Hendrickson et al. [6], particles were injected at a high pitch angle and reflected by collisions with the conjugate atmosphere (for alternative geomagnetic field geometries, magnetic mirroring above the atmosphere would be the dominant particle reflection process). In Hendrickson's experiment, the reflected particles were measured directly, since it was possible to locate the detection system at the predicted return point after correction for various particle drifts. This first experiment was carried out successfully at  $L = 2.5$ , but a high L injection was performed recently with, as yet, uncertain results. Beam injection parallel to the magnetic field is most advantageous for the production of conjugate point effects (i. e., a conjugate auroral emission), while high pitch angle injection is required for the reflection mode. Once again, electron beams are preferable to ion beams and several different energies should be employed. Neither technique is applicable if the field line is not closed.

c. Closed or Open Field Line Configuration. At present, the high latitude boundary of energetic ( $> 40$  keV) electron fluxes, which have a trapped-particle pitch angle distribution, is used to denote the boundary between a closed

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3. *ibid.*

4. Private communications with L. M. Linson.

or open (cannot sustain a trapped particle distribution) magnetic field line configuration. Both energetic particle beam experiments described previously probably cannot provide additional information relative to the field line configuration. As a routine diagnostic for magnetospheric conditions, measurements of the natural trapped particle distribution may provide the simplest method for determining the transition from closed to open geometries.

If the field lines are open in the sense that they cannot maintain a trapped particle distribution or constrain the trajectory of an injected beam, measurements at the ends of the field lines are no longer sufficient even to define qualitatively the field line configuration. In such cases, almost point-by-point measurements of the beam trajectory or magnetic field configuration are required to determine the geometry. The fluorescence of ion beams under sunlight provides a method of painting field lines so that they can be observed remotely.  $Ba^+$  fluorescence is, of course, used in conventional plasma cloud releases. While  $Ba$  shaped charge releases provide a proven method for production of medium velocity (10 to 20 km/sec) dense  $Ba^+$  jets, Hones [22] has suggested that use of an ion engine converted to operate on  $Ba$ , would provide a higher velocity ion beam with the added advantage that the system would allow the releases to be repeated at will. Both Hones [22] and Wescott et al. [7] have restricted themselves to use of ground-based observations to track the ion cloud which, in turn, requires that the ion fluorescent radiation appear in the visible region of the spectrum. With the observation system on the PPEPL, problems with atmospheric absorption are no longer important, and the use of other ions becomes possible. The use of lower mass ions is desirable because their higher velocities minimize trajectory corrections due to convective drift. The particular questions associated with the technique are: (1) are the beam particle densities required for optical observation of the beam so large that the magnetic field strength will be insufficient to constrain the beam in the equatorial plane? and (2) are the beam densities anticipated from the PPEPL accelerator system commensurate with those required for optical detection?

### 3. ELECTRIC FIELD DISTRIBUTION IN THE MAGNETOSPHERE AND IONOSPHERE

The electric field configuration in the magnetosphere and ionosphere has been extensively studied in the past few years. The relevance of electric field measurements to geophysical processes has been discussed in an associated report [3].

Mozer [23] has summarized existing methods for studying electric fields in the ionosphere with vehicle-borne instrumentation and ground-based techniques; each method has its advantages and disadvantages. Obviously, one or more of the vehicle-borne systems will be incorporated into the PPEPL and associated subsatellite payloads. Adapting some of the ground-based techniques

for use on the PPEPL must be considered. The number of incoherent back-scatter facilities is increasing and coordination with these stations is essential.

a. E Perpendicular to B ( $E_{\perp} B$ ). The use of small Ba releases to study the  $E_{\perp} B$  field configuration is an established technique. At the present time, the Ba canisters are boosted to the desired altitude by rockets and the resultant cloud motion is observed from ground stations. Thus observations are usually limited to a specific place and time. Obviously, many release canisters can be carried by the PPEPL with planned releases at selected latitudes during an orbit. The motion of the clouds can be observed from the PPEPL itself and, because of its rapid but known orbital motion, the triangulation required for determining the cloud velocity and direction may be possible from the PPEPL, as well. Some correlated observation from ground stations should be possible. Although the clouds must be viewed against a dark sky, the cloud itself must be at a sunlit altitude. This does not present a problem for releases at or above PPEPL altitudes. However, for releases below PPEPL altitude, as with observations from the ground, the requirement of a dark atmosphere and sunlit release altitudes restricts release times to near local dawn and dusk. Small shaped charge releases, a technique that appears entirely feasible, will permit measurement of both the B field topology and  $E_{\perp} B$  configuration at relatively high altitudes. Low altitude releases may acquire an additional velocity because of neutral winds, so accompanying releases of TMA or other neutral fluorescent materials are necessary to permit an assessment of neutral wind effects.

b. E Parallel to B ( $E_{\parallel} B$ ). Energetic particle beams may be particularly useful in the study of parallel electric fields, although the existence of such fields remains in doubt. Kelley et al. [24] suggest that such fields of magnitude approximately 10 to 20 mV/m exist at low altitudes ( $< 250$  km), but their results have not been confirmed by other investigators. Observations of field aligned particle fluxes, sometimes exhibiting very peaked energy distributions as well, suggest that regions of  $E_{\parallel} B$  do exist at upper ionospheric altitudes and higher. Since these features have been observed in both electron and proton precipitation (not simultaneously), either polarity of field seems to exist. The particle measurements indicate that a total potential drop of a few kilovolts is typical. In some instances, it has been suggested that the potential drop occurs over a relatively short distance (double layer), while other models predict a greater length to the region of  $E_{\parallel} B$  sustained by turbulent plasma instabilities. The beam technique may permit the remote determination of the magnitude of the total potential drop and its location along a field line, but it is less likely that the local electric field strengths could be accurately determined.

The use of particle beams to probe remote potential distributions is based on the assumption that the interaction between the beam and field is limited to the macroscopic electric field and that the interactions with the turbulent microscopic fields, which are necessary to provide the required anomalous resistivity, can be neglected. Furthermore, it is assumed that the injected beam does not modify the region of potential drop. The general condition that either polarity field can exist implies the use of both ion and electron beams. Several physical situations are possible:

1. An  $E_{\parallel} B$  to Decelerate the Charged Particles in the Beam — Information about both reflection and transmission of the beam is of interest. In the reflection mode, beams with parallel energy less than the total potential drop will be reflected by the potential barrier. A measurement of the energy at which a charged particle is no longer reflected will indicate the magnitude of the potential drop. In the transmission mode, only beams with parallel energy greater than the potential drop can surmount the barrier. Measurement of the energy at which transmission just occurs shows the total potential drop. Of course, the basic difference here is simply on which side of the potential barrier the charged particles are detected.

2. Field Polarity Accelerates Selected Beam Species — Only transmission experiments are possible in this configuration; a measurement of the increase in charged particle energy in passing through the region of  $E_{\parallel} B$  indicates the potential drop.

For measurements of  $E_{\parallel} B$  in the ionosphere (altitudes below the PPEPL), all the above configurations appear feasible; moreover, because the reflected and transmitted beam locations can be specified, both remote optical and direct subsatellite detection techniques could be employed to sense the effect on the beam. For regions of  $E_{\parallel} B$  at unknown altitudes above the PPEPL, only the reflection mode appears to provide a feasible method of sensing electric fields, and probably only optical sensing of the atmospheric emissions will test whether a beam is reflected or not. If the occurrence of such regions of  $E_{\parallel} B$  is associated with discrete, narrow regions of enhanced particle precipitation, severe problems will occur in the application of this technique since the behavior of the artificial beam may be masked by the natural precipitation.

Particle beams may also be employed to study magnetospheric and ionospheric  $E_{\perp} B$  fields. As noted in the experiments for studying B field topology, corrections for convective drift are required to determine the true B field configuration. Estimates of  $E_{\perp} B$  integrated over the total path of the beam can

possibly be derived from these and similar measurements, particularly if the fields are large and the beam transit time is long (heavy ion beam). It is not feasible to direct a charged particle beam downward from the PPEPL to measure ionospheric level  $E_{\perp} B$  fields because the spatial displacement of the beam caused by  $\vec{E} \times \vec{B}$  effects would be small. For example, for a total path length of 300 km and  $E_{\perp} B$  of 20 mV/m, the displacement of a 3 keV proton beam would only be approximately 300 meters.

#### 4. INTERACTION OF ENERGETIC PARTICLE BEAMS WITH THE ATMOSPHERE

The interaction of auroral energetic particles, both electrons and protons, with the atmosphere has been studied intensively. Particular emphasis has been placed on reconstructing the complex particle distribution function from observations of the optical and X-ray emissions generated in the particle-atmosphere interaction. Factors considered were altitude profile, spectrum, intensity ratios of selected lines, line widths, particularly  $H\beta$  and  $H\alpha$ , etc. Of equal interest have been the observed optical emission spectra. Accelerators on the PPEPL to produce beams of known current density and energy can provide quantitative data that can serve as a calibration for various optical measurements of natural phenomena. Because of the high orbital velocity associated with the PPEPL and the small beam area, the beam-atmosphere interaction will be transient. Therefore, the quasi-equilibrium conditions produced by auroral precipitation will not be achieved with this experiment, and direct comparison with the natural case will be difficult.

In these experiments the charged particle beam is directed downward at the atmosphere. If parallel electric fields exist along the beam trajectory, the beam will be altered in transit which, in turn, will compromise the interpretation of any optical observations. On the other hand, this working group feels that the rather short paths between the Shuttle and the atmosphere (particularly at high latitudes where the magnetic field lines are nearly vertical) will cause a minimal modifying effect due to beam-plasma instabilities.

Two major areas of scientific interests are considered in the following subsections.

a. Range-Energy Measurements. Detailed Monte Carlo calculations of the interaction between monoenergetic electron beams of various pitch angle distributions with a selected model atmosphere have been carried out [25]. Reasonable agreement was found between these theoretical predictions and the results of the first rocket-borne electron accelerator experiment [5, 26];

however, this experiment was limited to a single energy ( $\approx 9.0$  keV) 0.5 A, 1 sec duration beam with a fixed, but poorly known, pitch angle distribution. The extension of this experiment to cover the complete energy (1 to 50 keV), current density, and pitch angle ranges is necessary for the complete study of this problem. Similar experiments should also be performed for proton beams, where the charge exchange process [27] introduces an additional radial spreading (dependent on pitch angle) of the incident beam.

The experimental parameters that must be determined include:

1. The radial extent of the optical emission region.
2. The altitude of the lower border of the emission region.
3. The altitude profile of selected emission lines.
4. The emission intensity of selected lines corrected to the zenith.
5. The characteristics of the charged particle flux backscattered from the atmosphere.

The determination of altitude profiles requires a triangulation technique. At any given location, the beam-atmosphere interaction region will always occur in a fixed spatial location relative to the accelerator; thus, optical equipment aboard the PPEPL will be restricted to viewing the emissions from a specific and fixed aspect. Because of the latitude dependence of the declination angle and curvature of the magnetic field lines, a range in aspect angles will occur during an entire orbit. However, the neutral atmosphere characteristics and the beam path length also vary with latitude; therefore, this method of varying the aspect angle, and hence triangulation, does not appear quantitative enough. Rather, it is suggested that optical instrumentation be included on an associated subsatellite or, to achieve the desired triangulation, the experiment be associated with ground- or aircraft-based observation sites.

An associated subsatellite may not be required for measuring the backscattered flux. The PPEPL instrumentation may be adequate for this since at high L values the beam path lengths and particle transit times are short. If the total transit time required for the beam to travel to the atmosphere and for the backscattered flux to return to PPEPL altitude is not greater than the time required for the PPEPL to traverse the spot diameter, such direct measurements appear feasible.

The radial extent of the light emissions and total emission intensities can be measured from the PPEPL itself with correction for aspect angle. Finally, supplemental measurements of atmospheric density in the 100 to 200 km altitude range are necessary to provide a quantitative measurement of range-energy relationships.

Existing photometric and TV optical detection techniques appear adequate.

b. Atmospheric Emissions. Energetic particle beams can provide a known input source for the excitation of optical emissions. Observations of the emissions from the PPEPL eliminates atmospheric absorption effects and allows the spectral range to be extended into the UV and IR regions. These experiments and those described in the preceding subsection are similar. In that case, however, the optical measurements were primarily intended to measure the rate of loss of beam energy and collisional effects on beam geometry. The atmospheric emissions experiments, on the other hand, are directed toward studying the atmospheric emission spectrum's dependence upon the character of the incident charged particles; therefore, they require far more detailed spectroscopic information. In addition, it may be possible to obtain direct measurements of the dependence of the Ly $\alpha$ , H $\beta$ , and H $\alpha$  yields per proton incident upon the atmosphere on proton energy and pitch angle. Since the sensitivity of spectroscopic instrumentation is far less than typical filter photometers and the accelerators will be operated in a pulsed mode, the accelerators and spectographs will probably be synchronized to achieve adequate signal-to-background ratio for weak emissions.

## 5. MEASUREMENTS OF THE EFFECTIVE RECOMBINATION COEFFICIENT IN THE NIGHTTIME E REGION

Bombardment of the atmosphere with energetic particle beams may provide a method for the transient production of localized regions of enhanced electron density in the nighttime ionosphere similar to those found in meteor trails. The altitude of the density enhancement can be modified by variation of beam energy and species (protons or electrons) and the resultant ionization density by variation of beam current. For this discussion, the authors assume that the density enhancements will extend several kilometers in the vertical direction and that the radial extent will correspond to that measured by Davis et al. [26]: 140 meters for an approximately 9 keV, 10.5 A electron beam. It was assumed that any proton beam will be highly field aligned to minimize spreading associated with charge exchange. For the 9 keV, 0.5 A electron beam, the ionization production rate at 105 km is approximately  $2 \times 10^7$  electrons/cm<sup>3</sup>/sec<sup>1</sup> over 140 meters; for an irradiation period of  $2 \times 10^{-2}$  sec,

the final density achieved will be approximately  $4 \times 10^5/\text{cm}^3$  within the enhanced density volume. This density is significantly higher than that occurring naturally in the temperate latitude or quiet auroral latitude nighttime ionosphere; therefore, it is reasonable to assume that the ionization production caused by energetic particle precipitation and chemical processes would normally be small after beam cutoff. These enhanced density regions may also be a useful tool for the study of ionospheric characteristics.

After the particle bombardment over a specific area ceases, the enhanced electron densities will decay because of recombination and diffusion of ionization. The history of this decay can be studied in an approximate fashion by ground-based radar and ionosondes. The density decay caused by diffusive processes can be estimated separately from correlated studies of the ionization trails produced by micrometeorites. This is because the ions in a meteor trail are often atomic and recombine very slowly by radiative processes. Thus, the dissipation of such trails is usually dominated by diffusion of the ionization.

Once the contribution of diffusion to the decay of the artificially stimulated ionization anomaly is removed, the recombination rates of the ambient molecular ions can be quantitatively measured. The ability to generate the density enhancements over an altitude range will permit a study of dependence of the recombination coefficients on temperature and on the particular chemical constitution of the medium.

This particular experiment requires ground-based radar and/or ionosonde diagnostics. Some simplification will be realized because the regions of enhanced density will be produced at a precise location relative to the detection system. Supplemental data, such as altitude, spatial extent, location, etc., can be derived from optical measurements performed from the PPEPL and the ground.

It is possible that other experiments can be identified that will use the enhanced columns of ionization. Analogy may be drawn from the fact that meteorite trails have been used to study E region neutral winds at lower latitudes and electric fields at higher ones.

## 6. PERTURBATIONS OF THE ELECTRICAL CONDUCTIVITY OF THE IONOSPHERE

A general class of experiments considered for the PPEPL involves the perturbation (either an increase or a decrease) of the electrical conductivity of the ionosphere. At the higher L shells, such experiments are directed toward understanding the electrical coupling between the ionosphere and

magnetosphere and at the lower L shells toward modification of the ionospheric dynamo current system. In designing these experiments, two fundamental specifications are imperative: (1) the nature of the perturbation (i. e., its magnitude, spatial and temporal extent, and spatial and temporal locations) and (2) the means to be used in detecting the consequences of the perturbation.

a. Magnetosphere-Ionosphere Coupling. Various observations (for example see Reference 28) indicate that dc electric fields always exist perpendicular to the magnetic field in the ionosphere. The magnitude of these fields appears to be largest in the high latitude and equatorial regions; though they are certainly not negligible at midlatitudes. The presence of such fields in the ionosphere are necessarily associated with ionospheric current flow. The existence of a steady electric field in a magnetized plasma implies a bulk plasma motion in the  $\vec{E} \times \vec{B}$  direction. However, if the electric field is nonzero in the rest frame of the neutral atmosphere, the  $\vec{E} \times \vec{B}$  motion is opposed by a frictional force arising from ion-neutral drag. Thus to maintain a steady motion, the drag force must be balanced by  $\vec{J} \times \vec{B}$  force arising from a current driven in the  $\vec{E}$  direction (i. e., a Pedersen current). The ion-neutral drag also produces a current flowing antiparallel to  $\vec{E} \times \vec{B}$ , since the ion motion in the  $\vec{E} \times \vec{B}$  direction is retarded much more by neutral drag than is the electron motion (the Hall current). Therefore, the nature of the ionospheric currents flowing in response to an electric field perpendicular to  $\vec{B}$  depend on the nature of the drag force exerted on the ionospheric plasma by the neutral atmosphere; this force, in turn, depends upon the ionosphere and neutral atmosphere density and composition. Consequently, the ionospheric current system associated with a particular electric field depends upon longitude, latitude, altitude, and time. If the Hall and Pedersen currents are proportional to the electric field magnitude, then the proportionality factors,  $\sigma_H$  or  $\sigma_P$ , (the respective conductivities) are functions of longitude, latitude, and time.

In the absence of field aligned currents, a local region of enhanced conductivity will simply be polarized in a manner to satisfy the current continuity equation. The nature of this polarization depends on the size and shape of the perturbed region and the background values of the  $\sigma_P$  and  $\sigma_H$  as compared with the enhanced ones.

In a real situation, field aligned currents will flow and the polarization currents will try to close through Pedersen currents at higher and lower altitudes in the ionosphere, or through magnetic field aligned currents together with magnetospheric polarization currents, and/or Pedersen currents in the conjugate ionosphere. Once field aligned currents are taken into account, the consequences of the perturbation are exceptionally complex. This problem has

been considered in varying degrees of sophistication (for example see References 29 through 31 and footnotes 5 and 6) and with particular emphasis on auroral arc formation and the initiation of substorms. Each of these authors has considered a very special case and their relevance to any possible experiment remains questionable.

Even at the present level of understanding, it is clear that several major experimental constraints must be satisfied.

(1) **Magnitude of Conductivity Enhancements.** Bostrom [29] has modeled the ionosphere in and above an auroral arc and has estimated that the enhanced (produced by energetic particle precipitation) height integrated  $\sigma_H$  and  $\sigma_P$  were approximately 50 mho, which may be compared with conductivities of not greater than 1 mho in the undisturbed nighttime ionosphere. Linson and Petschek [32] suggest that conductivity enhancements of approximately 5 mho would be an acceptable experimental objective. The simplest method of enhancing the conductivities is increasing the local ionization density. Because of the dependence of the conductivities upon collision frequencies, the required density will be markedly dependent on the altitude of the enhancements. A given density enhancement produces maximum effects on the Pedersen conductivity at 130 to 140 km altitude and on the Hall conductivity at approximately 110 to 120 km.

(2) **Spatial Extent of the Region of Enhanced Density.** Linson and Petschek [32] suggest that the radius of the enhanced density region exceed a few kilometers. If the analogy to the auroral arc configuration can be accepted, then a long (100 km), narrow (1 km) strip oriented east-west would be desirable. If the experimental objective were to inhibit the convective flow pattern, a 100 km by 1 km strip oriented north-south might be preferable.

(3) **Duration of the Conductivity Enhancements.** Linson and Petschek [32] suggest that the duration of the conductivity enhancement should exceed the time required for an Alfvén wave to propagate from the ionosphere to the equatorial plane, approximately 60 sec.

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5. Sato, T. and Holzer, T. E.: Quiet Auroral Arcs and Electrodynamics Coupling Between the Ionosphere and the Magnetosphere. Submitted for publication in J. Geophys. Res., 1973.

6. Holzer, T. E. and Sato, T.: Quiet Auroral Arcs and Electrodynamics Coupling Between the Ionosphere and Magnetosphere, II. Submitted for publication in J. Geophys Res., 1973.

Several experimental methods are available for producing these conductivity enhancements:

1. Large Ba Clouds Released from PPEPL — Large (10's of kg) Ba releases at altitudes greater than 175 km have produced the desired Pedersen conductivity enhancements. Releases at lower altitudes are not as efficient because of rapid oxidation of released Ba and collisional effects on cloud expansion. Multiple releases could produce desired strip configurations. Large releases have been carried out at high latitudes without any observable magnetospheric effects. However, they all have been done near local dusk because of requirements for ground-based optical observation of the releases. Local midnight would appear to be a more desirable time to expect magnetospheric results.

2. Use of Fast Moving Gas Clouds Launched from PPEPL — Evans (see the appendix) has suggested that releasing a gas cloud from a vehicle moving at hypersonic velocity would produce a relatively high ionization density both from collisional ionization of the released gas with the ambient atmosphere and from local heating. It is a particularly attractive method for producing localized high density strips at 140 km altitude and is also attractive because the gas cloud derives its high velocity partially from the orbital velocity of the PPEPL. Evans emphasizes that the recombination (loss) process for the enhanced density region could be primarily radiative rather than disassociative since much of the ionization is in the form of atomic ions characteristic of the release material, thus the lifetime of the regions will exceed the required sec. He points out that his estimates of density enhancements from a release at 10 km/sec are at best qualitative and require further theoretical and experimental study.

3. Use of Ion and Electron Accelerators — The use of particle beams produced by the accelerators on the PPEPL to produce the density enhancements does not seem practical: (a) the high orbital velocity implies the use of high instantaneous power levels and (b) disassociative recombination will mean a short lifetime for the density enhancements.

It is difficult to speculate upon the possible consequences to be observed in such experiments. At least a modification in the ionospheric electric field distribution, perhaps also occurring in the conjugate hemisphere, might be expected. An auroral arc, manifested in field aligned electron precipitation, might be formed, or, if carried out under the right conditions, a substorm might be triggered. The interpretation of the results of such experiments will require a complete knowledge of the state of the magnetosphere prior to and during the experiment. In fact, it may even be desirable to select specific conditions as a

requirement for the experiment. Such knowledge of the magnetosphere will require that observational data from ground sites and associated satellites in the magnetosphere and interplanetary medium be available in real-time data displays.

The Pedersen currents are ion currents, whereas the Hall currents are electron currents. Thus the Hall conductivity could be substantially reduced by adding (at altitudes between 100 and 140 km) electronegative gases, such as SF<sub>6</sub> or fluorocarbons, which would attach to electrons to form heavy negative ions. The effects of adding such a gas to the E region when the auroral electrojet (Hall current) is intense could produce interesting results relevant to the ionosphere-magnetosphere coupling.

b. Modifications of Midlatitude Ionospheric Current System. Davis et al. [33] have described a series of experiments in which they have attempted to modify the ionospheric dynamo current system at midlatitude by introducing conductivity anomalies at the 100 to 140 km altitude range. They have used explosive Cs releases to produce a rapid increase in ion density; the ionization is produced in the explosion itself; photoionization is not required. The resultant modification in conductivity and, therefore, in the current systems is expected to generate a magnetic signal containing frequency components in the ULF range. If it is possible to produce such waves, their use in other experiments (e.g., propagation and penetration) should be considered, particularly in view of the difficulty anticipated with ULF transmitters. The PPEPL may prove to be an excellent launch platform for such experiments. Typical weight of explosive and Cs used in rockets is approximately 100 kg.

An alternate method for rapidly producing a large area density enhancement in the E region (100 to 140 km) is based on the interaction of micro-meteorites with the atmosphere. In this case, it may be possible to use a shaped charge configuration to accelerate small solid particles (Fe, Si, etc.) of several microns radius downward into the atmosphere. If velocities slightly greater than those of the current Ba configurations (20 to 30 km/sec) could be achieved, the interaction of approximately 1 kg of these pellets with the atmosphere will create ionization densities of approximately 10<sup>5</sup> to 10<sup>6</sup>/cm<sup>3</sup> over a volume of approximately 100 km<sup>3</sup> in the desired altitude range. The enhanced ionization will be relatively long-lived because the ions will be the atomic ion (characteristic of the pellet material) rather than the molecular ions characteristic of the atmosphere.

The main difficulty with such a technique is in determining whether it will be possible to accelerate a large mass of small pellets to the desired velocity by a shaped charge without complete volatilization of the pellets. If this occurs, it will be impossible to achieve the localized density enhancement at the desired low altitudes.

## 7. EXPERIMENTS OF GENERAL ASTROPHYSICAL INTEREST

As noted in the introduction, the PPEPL capabilities and the local ionospheric plasma can provide an excellent configuration for the basic experiments, not only of geophysical significance but also of more general astrophysical interest. These are discussed in the following subsections.

a. Beam-Plasma Interactions (Two-Stream Instability). The general beam-plasma configuration, where the beam-directed velocity greatly exceeds its thermal spread or the thermal spread of the ambient plasma, occurs frequently in geophysical and astrophysical processes. This interaction is generally assumed to lead to an instability that rearranges the particle distribution function; it provides one of the important mechanisms for the emission of radio waves from the sun, planets, and astrophysical bodies in general.

One particularly important aspect of the problem is the linear growth and nonlinear stabilization of the longitudinal wave electrostatic instability which, in the linearized approximation in the infinite medium geometry, has an extremely rapid growth rate [34]. These factors are important in all experiments in which energetic particle beams are used as tracers. Both the apparent stability observed for injected electron beams and also sometimes observed in auroral precipitation require further explanation. Perkins [35] has suggested that such an instability can occur for sufficiently intense auroral precipitation and that stochastic electrostatic acceleration of some particles to high energies is possible. Indeed, this mechanism is predicted to occur in the ionosphere at Shuttle altitudes.

Another factor to be considered is the mechanism by which electrostatic plasma waves of frequency  $\omega_p$  are converted into electromagnetic waves of frequency  $\omega_p + 2\omega_p$ , as well as the efficiency of this conversion process. It is generally agreed that some observed radio emissions, such as Type III solar radio bursts, are consistent with the occurrence of the two-stream instability that initially produces electrostatic waves. Subsequently a fraction of the electrostatic wave energy is converted to electromagnetic wave energy in the scattering of the electrostatic waves by ambient plasma irregularities [36]. Since the solar particle beams propagate over many solar radii, the energy loss from the particle beam driving the instability must be small.

The controlled experimental study of these processes may be possible with the PPEPL particle accelerators; the unbounded, uniform, ambient plasma offers major advantages over laboratory configurations where wall effects

control the instability characteristics. However, the finite, small beam size attainable with the accelerators, may tend to stabilize the two-stream instability and, together with the very low temperature of the ambient ionospheric plasma, may invalidate any direct measurement of the electrostatic-mode/electromagnetic-mode coupling process. This experiment requires intense theoretical study before its validity can be established.

The electromagnetic wave's frequency and power spectrum can be determined by instrumentation placed near the beam. Accurate measurement of the electrostatic waves and the beam particle distribution will require that an instrumented subsatellite penetrate the beam.

b. Anomalous Resistivity Produced by Current Instabilities. Recently Kindel and Kennel [37] have shown theoretically that certain regions of the ionosphere are unstable to the growth of microscopic plasma turbulence when field aligned currents,  $J_c$ , exceed certain critical thresholds. The nonlinear development of such instabilities leads to regions of anomalous resistivity which can sustain potential drops parallel to the magnetic field. The existence of such electric fields is suggested by observations of energetic particle energy and pitch angle distributions. A possible experiment from the PPEPL involves artificially generating such regions of anomalous resistivity. This would provide measurements of the dependence of the instability upon current density and would permit a study of the resultant plasma turbulence.

As noted previously, one method for vehicle neutralization during electron beam emission is through the collection, to the vehicle from the ambient plasma, of a return current equal to the emitted current. The maximum return current density is  $J_{sat} = (N_e v_{th})/4$ ; the total maximum return current (assuming no potential difference between the PPEPL and the ambient plasma) is  $J_{sat} A$  where A is the collecting area. To insure vehicle neutralization, A is chosen so that  $I_{emit} = J_{ret} A \ll J_{sat} A$ . However, it is possible to select conditions where  $J_{sat} > J_c < J_{ret}$  where  $J_c$  is the critical instability current density threshold of Kindel and Kennel ( $1.6 \times 10^{-7}$  A/cm<sup>2</sup>). Typically for a collecting area of 2000 m<sup>2</sup>, an emitted current of 5 A would be required to yield a return current density  $\geq J_c$ , and an extended (as opposed to a sheath) potential distribution surrounding the vehicle should result. If electrons are collected from directions transverse to the magnetic field, the instability criteria will need to be modified.

The motion of the PPEPL across magnetic field lines presents a problem. It is assumed that the return current is collected over the entire extended surface area of the vehicle. If the PPEPL is 100 m long and travels at 7 km/sec, then a single field line will be part of the current path for approximately 10 msec. If the disturbance (return current demand) propagates along the field at the local Alfvén velocity, anomalous effects should be observable up to 10 km. The beam energy is not critical in this experiment; 5 to 10 A at 100 V should be adequate.

Probing the region of anomalous resistance for its potential distribution and wave characteristics will probably require penetration of the region by an appropriately instrumented subsatellite. Measurements of the energy spectrum of the return collected current will also provide evidence for anomalous energization.

## 8. TRACER EXPERIMENTS

Among the remaining unsolved problems in magnetospheric physics are:

1. The origin of the energetic particle population within the magnetosphere and of those particles associated with the visual aurora.
2. The nature of those processes that accelerate charged particles, and the location in space.
3. The various transport and loss processes that determine the spatial and temporal character of the charged particle distribution within the magnetosphere.

These questions could be answered effectively if one had the ability to follow the behavior of individual charged particles during their interactions with natural magnetospheric processes.

The first steps toward such a capability have already been taken (e.g., barium ion clouds to map electric field patterns). In a further effort to answer some of the above questions, a somewhat different approach, that of examining the species, isotopic number, and charge state of naturally occurring energetic ions, has also been used recently. Because there are systematic differences in these parameters between solar wind plasma and plasma of terrestrial origin (i.e., the ionosphere), such measurements may reveal the origin of the ions in question.

Whalen and McDiarmid [38] have measured the abundance of  $\text{He}^{++}$  relative to  $\text{He}^+$  and  $\text{H}^+$  during a proton aurora. The absence of significant fluxes of  $\text{He}^+$  together with an observed  $\text{He}^{++}/\text{H}^+$  ratio of about 0.05 led them to conclude that the ions associated with this aurora originated in the solar wind.

Axford et al. [39], using a collection foil technique, measured the  $\text{He}^3/\text{He}^4$  ratio in the ion fluxes associated with a proton aurora. The observed ratio was inconsistent with the terrestrial abundance of helium isotopes but did agree with similar measurements of the solar wind isotopic composition.

On the other hand, Shelley et al. [40] have reported large fluxes of kilo electron volt energy, heavy ions ( $\text{N}^+$ ,  $\text{O}^+$ ) precipitating into the atmosphere during geomagnetic storms. The absence of significant numbers of these ions in the solar wind led them to conclude that the ions must have originated from the ionsphere.

The PPEPL will permit major improvements in experiments using both the foil collection and mass-spectrometer techniques. Because of the large volume and weight carrying capability of this vehicle, mass spectrometers having a factor of 100 greater sensitivity can be used. Similarly, the foil collection experiments can be extended with mechanical shutters to govern the specific regions of space and time when data are desired.

A sophisticated extension of those experiments which use naturally present ions as tracers are those that actively release easily identifiable ions which themselves become tracers. Such an approach has an obvious advantage in that the introduced ions are subject to well-defined and known boundary conditions. Lithium is probably the most suitable ion species to use, not only because it has a very low natural abundance but also because its low mass suggests that its behavior in the magnetosphere will be similar to protons. Several different geometries for the release of  $\text{Li}^+$  have been suggested; they are discussed in the following subsections.

a. Injection of Li into the Solar Wind at the Subsolar Point. In this configuration, one hopes to study the overall injection, acceleration, and transport processes. If a Li cloud is released in the interplanetary medium, in approximately 1 hour it will be ionized by solar photons and charge exchange reactions with solar wind protons. The resultant ions will be picked up by the magnetic field and accelerated to solar wind velocities; it is assumed that the dimensions of the  $\text{Li}^+$  plasma cloud exceed those of the magnetosphere. When incident upon the magnetosphere, some fraction of the accelerated contaminant ions will enter through the dayside cusps and tail and may subsequently be

transported and accelerated to constitute part of the auroral ion precipitation and ring current. Properly instrumented and located subsatellites can measure the evolution and spatial distribution of the contaminant ions within the magnetosphere.

The required amounts of material depend upon the assumed injection efficiency, the distribution of particles throughout the magnetosphere, and the achievable detection sensitivity. Very crude, but optimistic, estimates assume (1) 10 percent by weight efficiency in Li release, (2) a probability of  $10^{-3}$  for injection into the magnetosphere, (3) volume filled  $2 \times 10^{29}/\text{cm}^3$ , and (4) sensitivity of detector  $10^{-4}$  ions/ $\text{cm}^3$ , and yield a required injection of approximately  $10^3$  kg. The implications of such a release on solar wind flow patterns and consequently on the solar wind-magnetosphere interaction and entry efficiency have not been examined.

b. Injection of  $\text{Li}^+$  into the Tail and Dayside Cusps. It is also possible to consider more localized injections into the tail and dayside cusp regions to examine the entry and acceleration of particles. The amounts of material required will be significantly reduced since the inefficiency of the solar wind entry process will be eliminated. On the other hand, the tracer ions introduced in these locations will have energies corresponding only to those of the release rather than to that of the solar wind ions. In this respect, their eventual behavior will be similar to that of local terrestrial ions rather than solar wind ions.

Clearly, each of these experiments implies delivery of the cold plasma to high altitudes. Injection into the solar wind necessitates use of a high altitude vehicle; shaped charge releases from low altitude may prove useful for magnetospheric injection in general and perhaps natural transport processes, such as the polar wind, can be exploited to inject contaminant material into the tail. In all cases, diagnostic instrumentation on high altitude satellites will be required for tracing the contaminant material.

c. Ionospheric Injections. The use of gaseous releases to investigate the ionosphere as a source of energetic magnetospheric ions may be desirable and feasible. The recent observations of high intensities of energetic (keV) oxygen ions in the magnetosphere, which have been inferred to be of ionospheric origin [40], provide evidence that the ionosphere can be an important source of energetic magnetospheric ions. Furthermore, this particularly raises the question of whether some part of the energetic ions, such as the ring current ions, might also be of ionospheric origin. At present, the location (altitude, latitude, longitude, and local time) of the oxygen ion source in the ionosphere and the acceleration, transport, and loss processes are unknown. Since oxygen is the dominant ion in the ionosphere in the high ( $\lambda > 60$  deg) magnetic latitudes

and below about 3000 km, the acceleration process may be at relatively low altitudes; therefore, gaseous releases of tracer ions for studies of the source location and acceleration processes for the ionospheric ions may be feasible. The role of a polar-orbiting PPEPL should be studied further, particularly after additional data on the energetic oxygen ion morphology are available.

### III. CONCLUSIONS AND RECOMMENDATIONS

#### A. Further Study Program

In these descriptions, the authors have attempted to point out some apparent problems that require further study. Basically these problems can be divided into two general categories: (1) those associated with the implementation and performance of a particular experiment and (2) those associated with the lack of understanding of the basic physics and the consequent lack of definition of experimental constraints and conditions. Although only a few of the possible experiments have been considered, the identification of such problems in almost all the experiments indicates that a continuing study program is essential for defining a valid research program for the PPEPL. These problems are summarized as follows:

##### 1. Implementation and Performance

a. How can large cold plasma clouds be injected at selected locations in the distant magnetosphere and beyond? Is low altitude release with subsequent transport a feasible method? If a natural transport process is used, what are the required limitations on the total and ion masses of the injected material?

b. How can ionospheric releases be injected at specified locations (longitude, latitude, and altitude) from the PPEPL? If injected from PPEPL, will the high velocity perpendicular to  $B$  at high latitudes modify the expected plasma configuration? Will these alterations preclude the use of such clouds for  $E_1$ ,  $B$  and  $B$  field topology experiments? What type of rocket launch facility must be incorporated into the PPEPL? How many rockets could be launched per mission?

- c. Will the development of density nonuniformities in cold plasma clouds (striations) introduce unanticipated modifications in their effects? Does the observed breakup in shaped charge  $Ba^+$  plasma jets prevent their use in field line mapping experiments?
- d. Can the important properties (spatial extent, density, density non-uniformities, etc.) of distant  $Li^+$  plasma clouds be determined by optical techniques?
- e. How do possible modifications in the properties of energetic beams (velocity, pitch angle, spatial extent) influence their use in studies of B field topology and E field distribution? Do such modifications introduce difficulties in beam detection, particularly by remote optical techniques?
- f. Is it possible to detect low energy (1 keV) particle beams by the atmospheric scintillation technique? Will charge exchange reactions cause greater problems for low energy ion beams than for electrons? Can the characteristic radiation of the beam ions be used to increase the usable signal background ratio?
- g. What accelerator capabilities are required to permit beam detection in the presence of intense natural particle precipitation? Can UV emissions be used for sunlit hemisphere optical observations?
- h. What modifications are imposed in beam characteristics in transit of a turbulent medium? Are the assumptions of specular reflection by a potential barrier maintained by turbulence valid? Is this interaction pitch angle dependent?
- i. Will the time of release of low altitude  $Ba^+$  clouds still be limited to dawn and dusk even when clouds are observed from the PPEPL? Are there more suitable materials than Ba that have not been used because of atmospheric absorption of the radiation? Is the PPEPL itself a suitable observation platform to determine cloud motion, or will supplementary sites be required?
- j. Are the use of shaped charge (high explosive) and evaporative (thermite) releases or rocket launches from the PPEPL consistent with safety requirements?
- k. What is the ionization efficiency of a high velocity (10 to 15 km/sec) neutral gas cloud interacting with the neutral atmosphere at approximately 140 km? What are the radial diffusion characteristics of such an ionized region? What is its lifetime? Can the ionization enhancement be accurately determined?

1. Can the presence of electrostatic turbulence in a local region (e. g., within an energetic particle beam) be determined remotely?

m. Do any of the large injection experiments lead to general long term environmental modifications? Will environmental impact statements be required?

n. Will a sufficient distribution of interplanetary and magnetospheric spacecraft be available in the 1980's to permit an adequate determination of the state of the entire plasma system when a specific experiment is performed? Will such data be available in a real-time format to permit selection of desired conditions? Will the capability exist for repeating the experiment under different conditions?

o. Will the general perturbed region surrounding the PPEPL preclude its use for certain desirable diagnostics?

## 2. Problems in Basic Physics

a. Can whistler and ULF wave amplitudes observed at PPEPL altitudes in the ionosphere be quantitatively related to equatorial plane amplitudes? Can a study of natural whistlers provide a measure of the amplification associated with the EMC instabilities?

b. What collective beam-plasma instabilities occur in the finite-beam/infinite-plasma configurations? What are the instability growth rates and how are they modified by the variable beam-ambient plasma characteristics encountered in the magnetosphere?

c. Will a simulation of Type III radio bursts be possible in the ionospheric plasma? What efficiency for the mode-mode coupling process could be predicted for this plasma configuration?

d. Under what conditions should ionospheric conductivity enhancements be performed? Can theoretical treatments of the magnetosphere-ionosphere coupling be developed to prescribe the required experimental geometry, spatial extent, degree of conductivity enhancement, altitude, etc., as well as the predicted consequences? What should be the magnetospheric consequences of the transient decrease in the Hall conductivity when the auroral electrojet is relatively intense?

e. How does the transient nature of the energetic beam-atmosphere interaction modify the emitted optical spectrum from that observed in the aurora?

f. What are the specific conditions for a valid tracer experiment? What criteria must be established to insure that only a negligible perturbation of the natural system results from injecting the tracer material? Do such criteria invalidate certain aspects of a given experiment while maintaining validity for other aspects?

## B. Instrumentation and Development

### 1. PASSIVE DIAGNOSTIC ON PPEPL

The passive diagnostic capabilities to be included in the PPEPL facilities are identified in Table 3; the particular instrument techniques and configurations are not specified.

This tabulation differs little from that included in the TRW [1] passive diagnostic list for the PPEPL. However, specification by generic name alone is basically insufficient and more detailed instrument requirements, particularly with respect to sensitivity and both spatial and temporal resolution, should be included. For example:

1. The moderate and low energetic particle detectors should be able to provide a meaningful measurement of the flux, energy spectrum, and pitch angle distribution of precipitating particles (either natural or stimulated) in approximately  $10^{-1}$  sec, the time taken by the PPEPL to cross small scale auroral features.
2. The geometrical factors of the 40 keV particle detectors should be large enough to ensure acceptable counting rates at high latitudes for use as field line tracing devices.
3. The energetic particle mass spectrometer should have a geometrical factor large enough to make statistically significant observations of minor constituents in ion precipitation (energetic,  $\text{He}^+$ ,  $\text{He}^{++}$ , etc.) without restriction to rare intense events.
4. Adaptation of the spectroscopic systems to the pulsed mode operation of the beam accelerators is probably necessary to achieve an adequate signal-to-background ratio. Also the viewing angle and range between PPEPL and the excited emissions are latitude dependent.
5. The imaging system must be capable of providing an accurate measurement of cloud or beam spot location.

TABLE 3. PASSIVE DIAGNOSTIC CAPABILITIES

| Diagnostic Area  | Energy or Frequency<br>(Wave Length) Bands   |
|--|--|
| Geomagnetic Field  | Steady Component <sup>a</sup><br>Waves 0.001 - 20 Hz   |
| Energetic Particle Detectors<br>(Flux, Energy Spectrum, Pitch<br>Angle Distribution) | Cosmic Rays <sup>a</sup> $\geq 10^7$ eV<br>Energetic $10^5 - 10^7$ eV<br>Moderate $10^3 - 10^5$ eV<br>Low $10 - 10^3$ eV   |
| Local Plasma Sensors<br>(Density, Temperature)                                       | Photoelectrons <sup>a</sup> 1 - 50 eV<br>Thermal $\geq 10$ eV  |
| Electromagnetic Fields<br>(Amplitude, Frequency)                                     | LF <sup>a</sup> and above<br>10 Hz - 50 kHz<br>10 Hz - 1000 kHz<br>$10^3$ kHz - $10^5$ kHz   |
| Electric Fields<br>(3-Axis)  | dc<br>ac   |
| Mass Spectrometers<br>(Neutral + Ionized)  | Thermal $1 \leq \text{amu} \leq 50$<br>Energetic $> 100$ eV<br>$1 \leq \text{amu} \leq 150$  |
| Optical Spectrum   | X-rays <sup>a</sup> $\leq 10 \text{ \AA}$<br>UV $10 \text{ \AA} - 4000 \text{ \AA}$<br>Visible $4000 \text{ \AA} - 7000 \text{ \AA}$<br>IR $7000 \text{ \AA} - 10\,000 \text{ \AA}$<br>Far IR $\geq 10\,000 \text{ \AA}$ |
| Optical Imaging  | Visible <sup>a</sup> $4000 \text{ \AA} - 7000 \text{ \AA}$<br>UV $10 \text{ \AA} - 4000 \text{ \AA}$   |
| Backscatter Radar  | -  |

- a. These measurements are cataloged in differing energy and frequency bands because there is generally unique instrumentation associated with each band

## 2. ACTIVE CAPABILITIES FROM PPEPL

The PPEPL capabilities required for active experiments are listed in Table 4.

TABLE 4. CAPABILITIES REQUIRED FOR ACTIVE EXPERIMENTS

| Perturbation Technique                            | Capability Required   |
|---|---|
| Energetic Particle Beams                          | Electrons $\approx 100 \text{ eV} \leq 10 \text{ A}$<br>Electrons $1 - 50 \text{ keV} \leq 10 \text{ A} (\pm 5 \text{ deg})$<br>Protons $1 - 50 \text{ keV} \leq 10 \text{ A} (\pm 5 \text{ deg})$<br>Other Ions $1 - 50 \text{ keV} \leq 10 \text{ A}$ |
| Cold Plasma Releases<br>(Shaped Charge, Thermite) | Ba $< 1 \text{ kg}$<br>$> 10 \text{ kg}$<br>Li $> 10 \text{ kg}$<br>Cs $> 100 \text{ kg}$   |
| Hypersonic Gas Releases                           | Gas $\approx 50 \text{ kg}$   |
| Other Injections                                  | Artificial Meteors<br>Metal Chaff<br>Electronegative Gases<br>Trimethylamine (TMA)  |
| Radio and Other Sounders                          | LF and above<br>VLF<br>ELF<br>Lasers  |

Here again the authors differ little from the capabilities included in the TRW report [1] in the generic sense. As with the passive diagnostics, this identification is basically insufficient, for example:

1. In almost all the experiments that use low altitude releases, the latitude and altitude, and sometimes the time of the release, are specified here. In general, the altitude will not be the same as the PPEPL altitude. This suggests that rather large incremental (km/sec) velocities must be imparted to the release canisters, if they are to be released from the PPEPL, to permit their delivery to the required locations at the specified time.

2. The consequences of many of the active experiments are uncertain for a variety of reasons. Therefore, the authors require that they be performed several times under varying conditions.

### 3. CORRELATIONS

The experiments will require coordination with a variety of other observations (Table 5).

TABLE 5. COORDINATION WITH OTHER OBSERVATION SITES

| Observation Site                             | Observation Type   |
|--|--|
| Ground-Based Sensors                         | Rockets<br>Balloons<br>Ionosondes<br>Optical Sensors<br>Electromagnetic Fields<br>Radar<br>Magnetometers |
| Satellite<br>(Independent and Subsattelites) | Ionosphere<br>Magnetosphere<br>Solar Wind  |

## APPENDIX – OUTLINE OF A GAS RELEASE TECHNIQUE FOR ALTERING IONOSPHERIC CONDUCTIVITIES\*

The proposal outlined here describes a technique for increasing the electron and ion density of the E region ionosphere over large enough an area so that the ionospheric level portion of the magnetospheric current system will undergo a significant increase in conductivity. The purposes of performing such a perturbation are summarized here.

### I. Purposes for Creating Ionospheric Conductivity Anomalies

#### A. Producing a Possible Shunt Path for the Magnetotail Sheet Current, thus Initiating a Substorm

The conventional view of the growth and expansion phases of a substorm describes the process in terms of reconnection. The growth phase is associated with the erosion of magnetic flux from the nose of the magnetosphere (by reconnection with the interplanetary field). This flux is carried in the antisolar direction by the solar wind and is piled up in the north and south lobes of the geomagnetic tail. In this fashion, the magnetosphere achieves the elongated and stressed geometry that is observed before a substorm. The expansion phase of the substorm is associated with the enhanced reconnection, across the magnetotail neutral sheet, of the stored magnetic flux. The magnetosphere thus relaxes from a high potential energy geometry to a more bipolar geometry.

An alternate way to visualize this process, followed by Bostrom [41], is to realize that the magnetotail achieves its stressed geometry because of a physical current of approximately  $10^6$  A, flowing from dawn to dusk across the neutral sheet. This current is presumed to close by flowing along the magnetosheath so that both the north and south lobes of the magnetotail are enclosed by these current loops. The increase in tail flux can then be viewed as caused by an increase in the current flowing around these inductive loops. Indeed, Bostrom went so far as to compute the equivalent inductance of this circuit, obtaining a value of 100 henries for each lobe.

In this circuit model, the expansion phase of the substorm is associated with the disruption of the loop current and the collapse of the induced magnetic field, similar to what happens when the current in an electromagnet is interrupted. Two modes of interruption come immediately to mind. The first is the onset of an instability somewhere in the current loop which would increase

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\*This appendix was written by D. S. Evans.

the resistance in the circuit and reduce the current. The second mode is the shunting of the loop current through some lower resistance path in the magnetosphere. It has been suggested [41, 42] that, in fact, an enhancement in high latitude ionospheric conductivity could provide such an alternate current path.

This model has many attractive features. Once a sufficiently intense auroral arc exists — presumably increasing the ionospheric conductivity to a sufficient degree — current is diverted from the magnetotail loop current along the magnetic field lines (such field aligned currents have been observed) and into the ionosphere. The collapse of the magnetotail geometry associated with the current reduction energizes and precipitates the resident plasma, thereby further increasing the ionospheric conductivity. Thus a process with a great deal of positive feedback can be visualized to account for the expansive phase of a substorm.

An experiment that would artificially increase the ionospheric conductivity strip of an auroral arc could be used to test this model of a substorm.

B. To Induce Field Alignment Currents to Flow and, thus, Test for the Stability of These Currents in the Topside Ionosphere

Coronti and Kennel [31] have discussed a model of auroral arcs in which the enhanced conductivity along the arc provides an alternate path for currents ordinarily flowing in the outer magnetosphere. In this model, however, the field aligned currents flowing into the ionosphere are unstable at altitudes greater than or equal to 1000 km [37]. The instability is such that the field aligned current is limited by the development of a parallel electric field (or, alternatively, one may think in terms of anomalous resistivity). In this situation, the high conductivity portion of the ionosphere is isolated from the outer magnetosphere by the field aligned resistance and, therefore, the ionosphere will probably not provide a suitable path for the magnetotail current.

However, the appearance of a field aligned electric field will provide a mechanism for accelerating charged particles downward into the ionosphere. This, in turn, will sustain the conductivity anomaly that had initiated the whole process. In a sense, the current discharge process outlined above is replaced in this model by an energy discharge into the ionosphere.

The model may be investigated by examining the topside ionosphere above a conductivity anomaly in search of an  $E_{\parallel} B$  and also by searching for energetic particle influxes subsequent to the creation of a conductivity anomaly in the ionosphere.

### C. The Creation of a Natural Aurora by Introducing Conductivity Anomalies

Linson and Petschek [32] have outlined a model in which conductivity anomalies in the auroral ionosphere inhibited the convective flow pattern in the outer magnetosphere, thus, provoking, in some unspecified manner, instabilities that would result in the enhanced precipitation of auroral particles. This precipitation would maintain the high conductivity. While Linson and Petschek are rather unspecific about the exact nature of the induced instabilities, models of this sort, in which the ionospheric conductivity triggers and sustains particle precipitation, appear time and again in the literature. There exists, therefore, a vague but substantial motivation to introduce, in a controlled fashion, conductivity anomalies in the high latitude ionosphere in conjunction with observations of the local energetic particle precipitation.

### D. A Study of the Distortion of the Ionospheric Level Electric Field Geometry in and Near a Conductivity Anomaly

Barium ion releases near auroral forms and probe observations above auroral forms have indicated that the ionospheric electric field is depressed in regions of high ionospheric conductivity [43, 44]. The general explanation for this is that the electric field is shorted or that the high conductivity strip has inhibited convective flow. The exact consequences of such a short circuit, or, in fact, whether the aforementioned observations have been properly interpreted, can easily be investigated using  $Ba^+$  releases in conjunction with the controlled creation of a conductivity anomaly.

The four experiments just described have the common purpose of attempting to investigate magnetospheric processes using an approach very much like one an engineer would use to probe an electrical circuit of unknown behavior, that is, by varying one or more of the circuit elements and observing in what fashion the circuit reacts.

### E. A Possible Test of Magnetic Conjugacy

As opposed to the previous four experiments, which perturb the environment in an active way, the possibility exists of using a conductivity perturbation in the more passive role of determining the geomagnetic field geometry, in particular, conjugacy.

If one assumes that a geomagnetic line of force is an equipotential, then a distortion of the ionospheric electric field pattern, induced by a conductivity anomaly, will map upward along the line of force. If the particular

line of force is closed, an electric field distortion produced in one hemisphere will map to the conjugate point even though the conductivity anomaly is present in only one hemisphere. A distorted electric field imposed upon the quiet unperturbed conjugate hemisphere will produce an altered ionospheric current flow which, in turn, may be sensed by ground-based magnetometers. Thus, if a correlation can be established between magnetic disturbances in one hemisphere and the creation of conductivity anomalies in the conjugate ionosphere, a strong argument in favor of magnetic conjugacy could be made.

It is not possible to compute the degree of magnetic perturbation that would be observed because the effect of E fields or the degree of distortion in E caused by a conductivity anomaly has yet to be measured.

It is noted that this particular test for conjugacy may have a considerable advantage over electron beam or tracer experiments. This is because the magnetic signature of conjugacy may be observed over a considerable area and on cloudy nights; whereas, a test that relies upon a beam exciting the atmosphere requires that optical equipment be sighted at the excitation point without much room for error. (This might be justification enough for placing magnetometer arrays in the Southern Hemisphere during the large AEC Ba<sup>+</sup> releases over Alaska.)

## II. Discussion of Spatial and Temporal Scales and of the Magnitude for Ionization Perturbations

The length of time that a conductivity must be present before the magnetosphere as a whole is able to react is a factor in performing the experiments outlined above. Linson and Petschek [32] have estimated that it would require some 60 sec after a conductivity anomaly is introduced in the ionosphere before the convection pattern in the outer magnetosphere would be disrupted. This estimate is based upon assuming that the low altitude perturbation propagates upward along field lines with the Alfvén speed.

Estimates by Bostrom [41] of the time scale for an electric field distortion in the ionosphere to propagate upward yield values in the same range, i. e., several 10's of seconds.

Thus it should be assumed that even if a conductivity anomaly was able to enhance precipitation, a time constant of approximately 100 sec may be required to successfully perturb the magnetosphere using a conductivity anomaly.

Linson and Petschek [32] have also estimated the area of perturbation that might be required before significant distortion of the outer magnetospheric convection pattern. The criterion was that the perturbed area, at ionospheric levels, map to an area in the equatorial plane extending over one or more low energy proton gyroradii (assumed energy is approximately 1 keV). On this basis, a minimum perturbation scale length greater than or equal to 3 km was estimated.

It seems that the experiments with  $Ba^+$  releases, with the possible exception of the results reported by Stoffregen [45], have not produced the effects, such as enhancing precipitation or triggering substorms, that have been discussed. Hence, one must conclude that if conductivity anomalies do play a role in magnetospheric dynamics, the anomaly must extend over areas greater than the typical  $Ba^+$  release, i. e., greater than 1 km<sup>2</sup>.

Perhaps the best guide to the appropriate area of conductivity anomaly is that given by the visual aurora itself. Typically the discrete arc form is 1 to 10 km wide (north-south extent) and 100 to 1000 km long (east-west extent). The north-south dimension is somewhat less than the minimum needed according to the Linson-Petschek criterion.

Thus one assumes that if a conductivity anomaly is to have any dramatic effect upon the magnetosphere, the north-south width should be greater than or equal to 1 km and the east-west extent no less than 100 km.

When one judges the degree of conductivity enhancement required in such experiments, it is probably wisest to again use the aurora itself as a guide. Bostrom [29] has modeled the ionosphere in and above an auroral arc and computed that the enhanced height integrated Pedersen and Hall conductivities were both approximately 50 mho. This may be compared with the conductivities of the undisturbed nighttime ionosphere that are not greater than 1 mho. The conductivity enhancement produced by a perturbation enhancement, therefore, should be approximately 50 mho.

Figure A-1 plots the specific conductivities  $\sigma_H$  and  $\sigma_P$  (this is the conductivity in mho/m for a plasma density of one ion-electron pair per cubic meter) as a function of altitude for a wintertime model atmosphere. This figure shows that the most advantageous altitude to produce ionization, insofar as influencing conductivity, is about 130 km where both the specific Hall and Pedersen conductivities are approximately  $1.5 \times 10^{-15}$  mho/m/ion-electron pair.

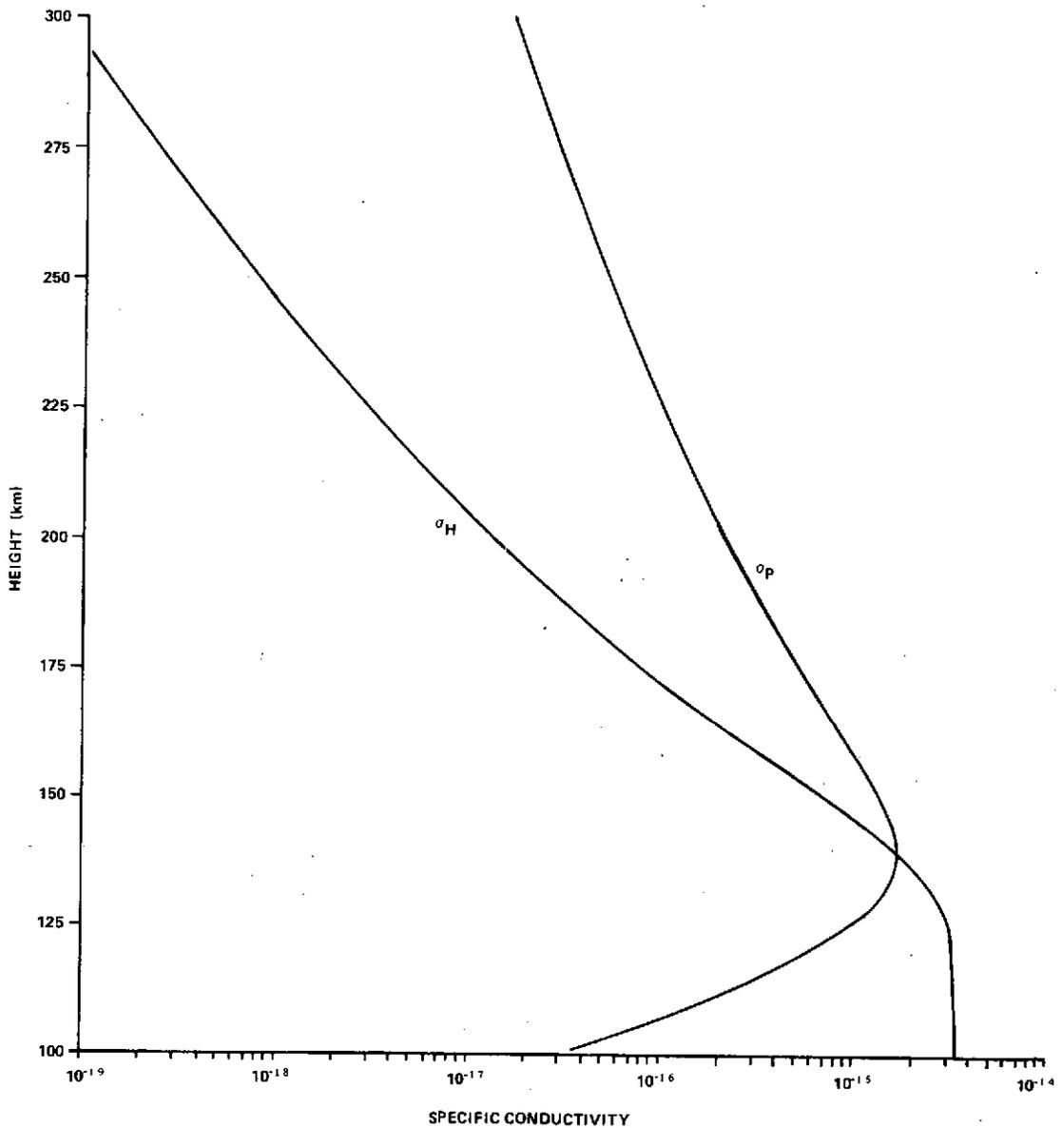


Figure A-1. Specific conductivity as a function of altitude (wintertime model atmosphere).

If ionization were to be produced over a limited height range centered at 130 km, it is simple to compute the required height integrated density to produce 50 mho height integrated conductivity, i.e.,

$$N \times 1.5 \times 10^{-15} = 50 \text{ mho}$$

$$N \approx 3 \times 10^{16} \text{ electrons/m}^2 \text{ column}$$

If the ionization were confined to a layer 1000 meters thick, then the ionization number density would be approximately  $3 \times 10^{13}/\text{m}^3$ . This required density is about 30 times larger than normally found in the aurorally excited E layer but is distributed over a much more limited altitude interval.

Linson and Petschek [32] have estimated that the height integrated density of approximately  $4 \times 10^{15}$  electrons/ $\text{m}^2$  column is the minimum required to produce a useful perturbation in ionospheric conductivity (specifically, approximately 5 mho).

### III. Methods of Producing Conductivity Anomalies As Suggested in the Past

#### A. Alkali Metal Vapor

Release of alkali metal vapor clouds (most often barium, but also cesium and lithium) has become a well-established technique for producing ionization perturbations in the ionosphere. In principle, similar techniques might be used to produce properly scaled conductivity anomalies. Such releases do have serious disadvantages for this purpose, however.

The release of such metal vapors is usually accomplished either by a very rapid thermite reaction or by vaporizing the metal in a shaped charge detonation. Although the initial vaporization process immediately provides some ionization of the material, the technique relies primarily upon photoionization of the vapor by sunlight. The time constants required to produce the cloud of ions via photoionization ranges from approximately 10 sec in the case of barium to more than 1000 sec for lithium. This leads to at least three difficulties insofar as producing the large-scale conductivity anomaly is concerned:

1. It is very difficult, except by using multiple releases, to obtain enhancements in ionization over large horizontal areas but still confined in vertical extent to the proper altitude.

2. The requirement for sunlight to ionize the vapor means that such perturbations must be performed in the already highly conducting sunlit ionosphere.

3. The chemical reaction, either explosive or thermite, is a rather inefficient means of vaporizing the metal. Generally only about 10 percent of the available metal is vaporized. Thus to supply the more than  $10^{24}$  ions required for perturbation, Linson and Petschek estimate that a total payload (Ba, explosives, etc.) of more than 1000 kg mass would be required.

The first objection, that of a lack of control over the volume that is to be perturbed, may be overcome to a certain extent by using a high temperature boiler rather than an explosive chemical reaction to vaporize the metal. A low altitude satellite can then trail the vapor and, thus, perturb a large volume. For the conductivity experiment described here, the satellite must release vapor over a path length of approximately 100 km (approximately 10 sec of satellite travel time). To achieve the densities that seem to be required for suitable conductivity changes, about  $3 \times 10^{19}$  atoms must be vaporized each meter of travel, or, for a 100 km trail,  $3 \times 10^{24}$  atoms (approximately 5 g moles). The heat of vaporization for barium is about 1100 joules/g; thus, about  $7.5 \times 10^5$  joules are required to vaporize the 5 g moles. If this is to be done in 10 sec, the average power required is 75 kW.

Quite apart from the power requirement, the necessity remains for sunlight to ionize the barium vapor; therefore, the perturbation can still be performed only in the sunlit ionosphere.

#### B. Creating Ionization by Means of Charged Particle Beams

It has been suggested that a charged particle accelerator placed on rockets or satellites could direct a beam downward into the atmosphere and produce conductivity anomalies in the same manner as the naturally occurring aurora does. It is worthwhile to compute the power required.

The criterion adopted here for a significant perturbation is the creation of a height integrated ionization density of  $3 \times 10^{16}/\text{m}^2$  column over an area of 1000 by 100 000 meters. This is a total population of  $3 \times 10^{24}$  electrons. It requires on the average approximately 30 eV of energy to ionize an ambient atmospheric constituent, with a particle beam, so that an energy input of approximately  $9 \times 10^{25}$  eV or  $1.4 \times 10^7$  joules of energy would be needed to produce the desired population. If this is to be done over approximately 14 sec (the time for a satellite to move 100 km) an average power of 1 MW is required. This seems prohibitively large.

There is perhaps a more serious objection to this technique, however; it involves the persistence of ionization. The production of ionization by an artificially charged particle beam is very much the same as by natural auroral

precipitation. For the aurora, the predominant ionization produced seems to be in molecular ions. The dominant loss mechanism in the atmosphere for this sort of ion population is disassociative recombination, i. e.,



This process has a large rate coefficient, and observations in the auroral ionosphere indicate an effective recombination coefficient  $\alpha \approx 10^{-7}$  sec. Thus, in the absence of an ionization production, the electron density decays as  $dN_e/dt = -\alpha N_e^2$ , which for  $\alpha \approx 10^{-7}$  results in a time constant for the decay of the ionization of less than 10 sec. Apparently the conductivity anomaly produced by a charged particle beam from a satellite will decay before significant effects from the perturbation are observed.

#### IV. The Use of Fast Moving Neutral Gas Clouds to Create Conductivity Anomalies

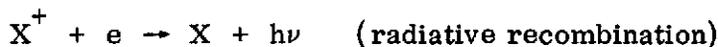
The technique that is proposed is to use the inherent kinetic/energy molecule in a gas release from a vehicle moving at hypersonic velocities to produce the ionization required to create conductivity anomaly. Because the physics of the release has much similarity to that of meteor trails, it is useful to discuss meteor-generated ionization trails by way of introduction.

##### A. Meteor Ionization Trails

A micrometeorite passing through the upper atmosphere has speeds ranging from approximately 11 km/sec to approximately 110 km/sec. At altitudes beginning at approximately 110 km, such meteors began to experience atmospheric drag and aerodynamic heating. Because the typical micrometeorite is so small (approximately 0.1 mm diameter), the effects of drag are usually not treated from an aerodynamic point of view but are treated as a particle-particle interaction [46, 47]. In this view, when a meteor impacts an atmospheric molecule, the molecule is totally absorbed by the meteor with 10 to 100 eV of energy. This amount of energy is more than that binding the individual meteor atoms to the meteor itself. Thus in the process of slowing down, a considerable number of individual meteor atoms (Fe, Si, Ca, etc.) are released to the ambient atmosphere as a tenuous gas moving with the meteor velocity. The rate of evaporation increases as the atmospheric density increases; however, even for meteors weighing only  $10^{-2}$  g, the rate of evaporation can exceed  $10^{19}$  atoms/sec at 115 km [48].

The evaporated atoms, moving at meteoric speed, have kinetic energies (relative to the stationary atmosphere) ranging from approximately 50 eV to more than 1 keV. In treating the collision between the evaporated atom and an atmospheric constituent (O,N), however, the energy in the center of mass system is appropriate. In this coordinate system, the energy available for transfer between a fast Fe atom and a stationary N atom ranges from approximately 6.0 eV at 10 km/sec to approximately 700 eV at 100 km/sec. It is seen that collisions between iron atoms and nitrogen atoms occurring at relative velocities greater than approximately 14 km/sec have the potential of ionizing one atom or the other. In fact such ionization does occur with a probability per atom greater than 0.1 for typical meteor speeds. Indeed, the electron production rate at 115 km from a modest meteor is  $10^{17}$  electrons/sec [48].

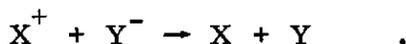
It should be noted that the ionization trail produced by a meteor often persists for more than 100 sec (unlike auroral ionization). Indeed, radar studies suggest that the trail dissipates because of diffusion of the ionization rather than any attachment or neutralization process. The accepted explanation for this is that the majority of ions in the trail are atomic ( $\text{Fe}^+$ ,  $\text{Ca}^+$ , etc.). The recombination of these ions are dominated by the two processes



and



followed by



Both of these processes have rate coefficients far lower than the disassociative recombination which dominates the auroral ionosphere.

## B. Hypersonic Gas Releases as an Ionization Source

In this discussion, the technique is described for a standard set of conditions. The effects that are derived scale more or less with the amount of gas released, release velocity, etc.

Consider a canister of gas similar to a commercial cylinder that contains about 280 moles of gas, or approximately  $1.7 \times 10^{26}$  molecules. This canister may be launched (for example, from a Shuttle vehicle) on a trajectory that brings it to a perigee of approximately 130 km with a velocity of 10 km/sec. These parameters specify a closed orbit about the earth (neglecting drag) having an eccentricity about 0.65. The interesting feature of this orbit is that the canister would remain in the altitude range of 130 to 140 km for over 1000 km of horizontal travel. Thus the potential exists for performing direct perturbations on the ionosphere at the most advantageous altitudes and over significant dimensions.

The Shuttle vehicle at 400 km altitude has an orbital speed of about 7.66 km/sec. Thus if the canister is to be launched from the Shuttle, a speed increment of approximately 2.5 km/sec is required from a rocket motor. For the mass of gas discussed here, this would require a rocket motor of slightly more total impulse than that provided by the X-248 fourth stage of the Javelin.

Table A-1 lists many of the parameters appropriate to the release of a variety of gases into the atmosphere from a canister moving at 10 km/sec. Note that gases such as  $\text{SiF}_4$ ,  $\text{WF}_6$ , and  $\text{MoF}_6$  can simulate the evaporated atoms from stony or metal meteors.

Consider that the canister releases the total of  $1.7 \times 10^{26}$  molecules in 10 sec or over a 100 km path. The release density is then about  $1.7 \times 10^{19}$  molecules/cm of trajectory. The first question is: Over what volume of the atmosphere is this gas stopped by collisions with the atmosphere?

For a meteor, Opik [46] calculated that individual meteor atoms of roughly the same velocities and masses as the gases in Table A-1 will stop in the atmosphere within about 20 gas kinetic mean free paths or, because the mean free path at 130 km is approximately equal to 10 meters, the atom will come to rest within about 200 m. Opik also estimated that the range transverse to the path of the meteor for these atoms will be about 100 meters. On the basis of this calculation, the released gas would be expected to come to a stop within a horizontal cylinder 100 km long and 100 meters in radius. Opik's computations, however, are for evaporated meteor atoms, which represent a very small perturbation in terms of mass or energy addition to the ambient atmosphere. This is not true for the gas release described here.

TABLE A-1. PERTINENT PARAMETERS FOR SEVERAL GASES

| Gas              | Parameter <sup>a</sup> |           |           |           |           |                        |
|------------------|------------------------|-----------|-----------|-----------|-----------|------------------------|
|                  | A<br>(eV)              | B<br>(eV) | C<br>(eV) | D<br>(eV) | E<br>(kg) | F<br>(j)               |
| O <sub>2</sub>   | 16.6                   | 8.3       | 4.15      | 13.50     | 8.96      | 4.48 × 10 <sup>8</sup> |
| SF <sub>6</sub>  | 75.9                   | S 16.7    | S 5.54    | S 10.30   | 40.90     | 2.04 × 10 <sup>9</sup> |
|                  |                        | F 9.9     | F 4.52    | F 17.30   |           |                        |
| SiF <sub>4</sub> | 54.1                   | Si 14.6   | Si 5.29   | Si 8.12   | 29.10     | 1.45 × 10 <sup>9</sup> |
| WF <sub>6</sub>  | 154.9                  | W 96.0    | 7.65      | W 8.10    | 83.40     | 4.17 × 10 <sup>9</sup> |
| MoF <sub>6</sub> | 109.0                  | Mo 49.9   | 7.13      | Mo 7.35   | 58.70     | 2.93 × 10 <sup>9</sup> |

a. The parameters are defined as:

- A — The kinetic energy of the released atom relative to the stationary atmosphere.
- B — The kinetic energy of the released atomic species relative to the atmosphere.
- C — The kinetic energy of the released and disassociated gas atoms in center of mass coordinates in a collision with an ambient O atom.
- D — The ionization potential of the released atoms.
- E — Total mass of 280 moles of gas.
- F — Total kinetic energy associated with this mass.

Consequently, an alternate criterion may be invoked — the released gas stops in a volume of atmosphere that corresponds to an ambient mass about 20 times the released mass of gas. This criterion tends to take into account the fact that the ambient atmosphere begins to move under the impact of the very significant momentum associated with the released gas. It is unlikely that the horizontal extent of the perturbation will be very much greater than the 100 km determined by the trajectory of the canister and the main effect of this criterion will be to increase the radius of the cylindrical perturbation region. For the WF<sub>6</sub>, some 85 kg of gas will be released. Thus

$$\pi 10^7 r^2 \rho \approx 20 \times 85\,000$$

The mass density  $\rho$  of the atmosphere at 130 km is approximately  $1.2 \times 10^{-11}$  gm/cm<sup>3</sup>. Solving for  $r$  yields

$$r = 67\,000 \text{ cm} = 670 \text{ m} .$$

Thus, as a first approximation, the authors assumed that the gas release will perturb the atmosphere over a volume  $10^7$  cm long and approximately  $5 \times 10^4$  cm in radius centered at 130 km altitude. The total volume of this region is about  $8 \times 10^{16}$  cm<sup>3</sup>.

At this point the magnitude of the perturbation introduced by the release of 85 kg of WF<sub>6</sub> gas can be estimated.

### 1. Injected Energy Density

This is obtained by dividing the net available kinetic energy of the gas by the volume to yield

$$\text{energy density} \approx 3 \times 10^{11} \text{ eV/cm}^3 .$$

If this energy appeared as ionization, an electron density approximately equal to  $10^{10}$ /cm<sup>3</sup> might be expected. If the energy appeared as heating of the ambient gas and thermodynamic equilibrium were attained (which is unlikely), the gas temperature rise greater than  $10\,000^\circ\text{K}$  might be expected.

### 2. Injected Number Density

If the gas molecule disassociated (a point more fully discussed below), then the following number density perturbations are to be expected: tungsten atoms of approximately  $2 \times 10^9$ /cm<sup>3</sup> and fluorine approximately  $1.2 \times 10^{10}$ /cm<sup>3</sup>. The ambient number density at 130 km is approximately  $3 \times 10^{11}$ /cm<sup>3</sup>, so that the gas release represents a perturbation on the order of 1 to 10 percent of the ambient.

The question of whether or not the released gas molecule disassociated is an important one. The available energy in center of mass collisions between O<sub>2</sub> and WF<sub>6</sub> (for a 10 km/sec relative speed) is about 15 eV. The binding energy of O<sub>2</sub> is about 5 eV (for N<sub>2</sub> the energy is 9.8 eV) so that the ambient

atmospheric molecules are likely to be disassociated very quickly. The binding energy of  $WF_6$ , however, is probably quite high (the available data for the gaseous fluorine compounds show binding energies of approximately 15 eV), and there is some doubt whether this molecule will be totally disassociated in a single collision. However, the disassociation of the molecule could take place in steps, one atom at a time, without a single expenditure of 15 eV. Therefore, the authors tacitly assume that there is considerable disassociation of both atmosphere molecules ( $N_2$ ,  $O_2$ ) and the injected gas takes place during the stopping of the cloud. As is described below, this may not be a critical assumption.

The second important question is that of ionization. As was pointed out above, the magnitude of energy injection carries the potential of producing considerable ionization. However, computations in center of mass coordinates show that the energy available for transfer from one atom to another in a collision is generally insufficient for ionization. For example, consider that  $W \rightarrow O$  has 7.65 eV available, while the ionization potential of W is 8.1 eV and of O is 13.55 eV. Alternatively, consider that  $W \rightarrow N$  has 6.76 eV available, while the ionization potential of N is 14.48 eV.

However, while single collision ionization seems to be an impossible accomplishment from the ground state of these atoms, the possibility exists for ionization from excited atomic states, a process that would require less energy transfer for each collision. Indeed, if the gas temperature is nearly as high as the energy balance suggests it may be, the atoms will be highly excited and considerable collisional ionization of tungsten atoms is expected

For computing conductivities, it is arbitrarily assumed that  $10^{-3}$  of the W atoms released in the cloud become singly ionized. This would result in a density of approximately  $2 \times 10^6$  ions/cm<sup>3</sup>. The amount of energy diverted to this ionization is approximately equal to  $1.6 \times 10^7$  erg/cm<sup>3</sup>, which is less than  $10^{-4}$  of that energy available. On this basis, the assumption seems reasonable.

The ionization density of  $2 \times 10^{12}/m^3$  created at 130 km may be folded into the specific conductivities in Figure A-1 to yield conductivity values for both  $\sigma_H$  and  $\sigma_P$  of about  $3 \times 10^{-3}$  mho/m. Finally, assuming that the ionization perturbation extends over a height, integrated conductivity of approximately 3 mho is obtained.

This value is about 10 times the conductivity of the undisturbed ionosphere but only 10 percent of the conductivities associated with an auroral arc. The argument that the ionization production is  $10^{-3}$  of all tungsten atoms

released is rather vague and, possibly, weak. In support of the argument, however, analogy may be made between this experiment and laboratory shock tube experiments. The release of gas from a canister moving at 10 km/sec may generate a shock wave that propagates at least at the initial velocity of the gas cloud, i. e., a velocity of about Mach 25 with respect to the ambient atmosphere. Similar physical situations in laboratory shock tube experiments have resulted in gas temperatures so high that a considerable portion (greater than 10 percent) of the gas is ionized [49].

If, however, the arguments presented here are incorrect, and little ionization will be produced in this gas release, there is one further step to be taken to improve the situation.

### C. Dual Gas Releases

The primary uncertainty in producing ionization by a single gas release as described above was that the energy, in center of mass coordinates, available in a single collision between tungsten and an atmospheric constituent was insufficient to ionize either atom. From a kinematic point of view, a much more favorable situation would be collisions between fast tungsten atoms and stationary tungsten atoms.

As was pointed out above, the individual atoms or molecules in the released cloud come to rest with respect to the atmosphere within a kilometer or so after release (the required time is about 0.15 sec). At that point, the ambient atmosphere has about 1 percent admixture of massive atoms or molecules.

If at this point a second gas canister, identical to the first, were to pass through this volume of space releasing additional  $WF_6$ , these gas molecules, in the process of stopping, will have a very high probability of colliding with a massive but stationary contaminant atom.

This sort of collision has a high probability of ionization of one or both of the participants. The energy available in a collision between two tungsten atoms with 10 km/sec relative velocity is approximately 48 eV or 6 times the ionization potential. A similar collision between molecules of  $WF_6$  would have available 77 eV, or about 5 times the energy required for total disassociation.

In a situation with similar kinematics, 30 km/sec Fe atoms striking N, Opik [46] estimates that 7.5 percent of the Fe becomes ionized together with a significant number of target atmospheric constituents. Thus, it is estimated

that for the dual gas release, where a net number density of tungsten atoms of approximately  $4 \times 10^8/\text{cm}^3$  are injected into the ambient atmosphere, about 5 percent of these metal atoms will become ionized. This would result in ionization density of approximately  $2 \times 10^8$  ion-electron pairs/cc, which in turn would produce Hall and Pedersen conductivities of  $\sigma_{H,P} \sim 3 \times 10^{-1}$  mho/m. Again, for a perturbation height of  $10^3$  meters, the net height integrated conductivities could be

$$\sum \sigma_{H,P} = 300 \text{ mho} ,$$

or considerably more than those associated with auroral forms.

To implement this version of the gas release experiment, two identical canisters would have to follow one another along the same trajectory separated by approximately 1.5 km (0.15 sec). This would be easy to accomplish using a separation technique after the burnout of the injection rocket motor.

## V. Summary

The experiment described here can produce perturbations with the following characteristics:

1. Long-lived enhancements in ionization of densities ranging from less than  $10^6/\text{cm}^3$  to greater than  $10^8/\text{cm}^3$  in a controlled fashion.
2. The enhancements may be created at arbitrary altitudes ranging from 110 to 200 km.
3. Depending on the altitude, the transverse scale size of the perturbation may range from 200 meters to more than 5 km.
4. The longitudinal extent of the enhancement can range to greater than 100 km.
5. The perturbation in the height integrated ionospheric conductivities can be controlled over the range from approximately 1 mho to greater than 300 mho.
6. By proper choice of release altitude either the Hall or Pedersen conductivities can be selectively enhanced.

## REFERENCES

1. TRW Systems, Inc.: Candidate Experiment Synopses for the Plasma Physics and Environmental Perturbation Laboratory. Report No. 21390-6003-R0-00, July 1972.
2. University of Maryland: Environmental Modification Experiments in Space. Ad Hoc Committee Report to NASA, 1968.
3. National Aeronautics and Space Administration: Final Report of the Space Shuttle Payload Working Groups, Atmospheric and Space Physics. Goddard Space Flight Center, Greenbelt, Md., 1973.
4. Alfvén, H.: Cosmic Plasma Physics. K. Schindler, Ed., Plenum Press, New York, 1972, pp. 1-14.
5. Hess, W. N. et al.: Artificial Aurora Experiment: Experiment and Principal Results. *J. Geophys. Res.*, vol. 76, 1971, p. 6067.
6. Hendrickson, R.A.; McEntire, R.W.; and Winckler, J.R.: The Electron Echo Experiment: A New Magnetospheric Probe. *Nature*, vol. 230, 1971, p. 564.
7. Wescott, E.M. et al.: Results of Five Successful Magnetospheric Probing with Ba Shaped-Charge Generated Plasma Jets. *EOS*, vol. 54, 1973, p. 435.
8. Brice, N. and Lucas, C.: Influence of Magnetospheric Convection and Polar Wind on Loss of Electrons From the Outer Radiation Belt. *J. Geophys. Res.*, vol. 76, 1971, p. 900.
9. Cornwall, J.M.; Coroniti, F.V.; and Thorne, R.M.: Turbulent Loss of Ring Current Protons. *J. Geophys. Res.*, vol. 75, 1970, p. 4699.
10. Kennel, C.F. and Petschek, H.E.: Limit on Stably Trapped Particle Fluxes. *J. Geophys. Res.*, vol. 71, 1966, p. 1.
11. Williams, D.J.; Fritz, T.A.; and Knoradi, A.: Observations of Proton Spectra ( $1.0 \leq E_p \leq 300$  keV) and Fluxes at the Plasmopause. *J. Geophys. Res.*, vol. 78, 1973, p. 4751.

## REFERENCES (Continued)

22. Hones, E.: Study of Magnetospheric Electric and Magnetic Fields by Tracer Techniques. Report of Ad Hoc Committee on Environmental Modification Experiments in Space to NASA, University of Maryland, 1968.
23. Mozer, F.S.: Analysis of Techniques for Measuring dc and ac Electric Fields in the Magnetosphere. *Space Sc. Rev.*, vol. 14, 1973, p. 272.
24. Kelley, M.C.; Mozer, F.S.; and Fahleson, V.V.: Electric Fields in the Nighttime and Daytime Auroral Zone. *J. Geophys. Res.*, vol. 76, 1971, p. 6054.
25. Berger, M.J.; Seltzer, S.M.; and Maeda, K.: Energy Deposited by Auroral Electrons in the Atmosphere. *J. Atmos. Terr. Phys.*, vol. 32, 1970, p. 1015.
26. Davis, T.N. et al.: Artificial Aurora Experiment: Ground-Based Optical Observations. *J. Geophys. Res.*, vol. 76, 1971, p. 6082.
27. Davidson, G.T.: Expected Spatial Distribution of Low-Energy Protons Precipitated in the Auroral Zones. *J. Geophys. Res.*, vol. 70, 1965, p. 1061.
28. Maynard, N.C.: Magnetosphere-Ionosphere Interactions. K. Folkstad, Ed., University of Orlogset, Oslo, Norway, 1972., pp. 155-168.
29. Bostrom, R.: A Model of the Auroral Electrojets. *J. Geophys. Res.*, vol. 69, 1964, p. 4983.
30. Atkinson, G.: Auroral Arcs: Results of the Interaction of a Dynamic Magnetosphere with the Ionosphere. *J. Geophys. Res.*, vol. 75, 1970, p. 4746.
31. Coroniti, F.V. and Kennel, C.F.: Polarization of the Auroral Electrojet. *J. Geophys. Res.*, vol. 77, 1972, p. 2835.
32. Linson, L.M. and Petschek, H.E.: Triggering an Aurora. Report of Ad Hoc Committee On Environmental Modification Experiments in Space to NASA, University of Maryland, 1968.

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## REFERENCES (Continued)

33. Davis, J.R. ; Willis, J.W. ; and Althouse, E.L. : Investigations of Artificial Stimulation of VLF Waves in the Ionosphere and Magnetosphere. Report 7552, Naval Research Laboratory, Washington, D.C., 1973.
34. Briggs, R.J. : Advances in Plasma Physics. A. Simon and W. B. Thompson, Ed., Interscience Publishers, Inc., New York, 1971, pp. 43-78.
35. Perkins, F.W. : Plasma-Wave Instabilities in the Ionosphere Over the Aurora. *J. Geophys. Res.*, vol. 73, 1968, p. 6631.
36. Zheleznyakov, V.V. : Radio Emission of the Sun and Planets. Pergamon Press, London, 1970, pp. 589-609.
37. Kindel, J.M. and Kennel, C.F. : Topside Current Instabilities. *J. Geophys. Res.*, vol. 76, 1971, p. 3055.
38. Whalen, B.A. and McDiarmid, I.B. : Further Low Energy Auroral-Ion Composition Measurements. *J. Geophys. Res.*, vol. 77, 1972, p. 1306.
39. Axford, W.E., et al. : Auroral Helium Precipitation. *J. Geophys. Res.*, vol. 77, 1972, p. 6724.
40. Shelley, E. G. ; Johnson, R.G. ; and Sharp, R.D. : Satellite Observations of Energetic Heavy Ions During a Geomagnetic Storm. *J. Geophys. Res.*, vol. 77, 1972, p. 6104.
41. Bostrom, R. : Magnetosphere-Ionosphere Coupling; Critical Problems of Magnetospheric Physics. E. R. Dyer, Ed., National Academy of Sciences, Washington, 1972.
42. Atkinson, G. : An Approximate Flow Equation for Geomagnetic Flux Tubes and Its Application to Polar Substorms. *J. Geophys. Res.*, vol. 72, 1967, p. 5373.
43. Wescott, E.M. ; Stolarik, J.D. ; Heppner, J.P. : Electric Fields in the Vicinity of Auroral Forms from Motions of Barium Vapor Releases. *J. Geophys. Res.*, vol. 74, 1969, p. 3469.

## REFERENCES (Concluded)

44. Aggson, T.: Atmospheric Emissions. B.M. McCormac and A. Omholt, Ed., Van Norstrand Reinhold Co., New York, 1969, p. 305.
45. Stoffregen, W.: Electron Density Variations Observed in the E-Layer Below and Artificial Barium Cloud. *J. Atmos. Terr. Phys.*, vol. 32, 1970, p. 171.
46. Opik, E.J.: Physics of Meteor Flight in the Atmosphere. Interscience Publishers, Inc., New York, 1958.
47. Greenhow, J.S. and Lovell, A.C.B.: The Upper Atmosphere and Meteors; Physics of the Upper Atmosphere. J. A. Ratcliffe, Ed., Academic Press, New York, 1960.
48. Dubin, M.: Meteor Ionization in the E-Region; Meteors. T. R. Kaiser, Ed., Pergamon Press, London, 1955.
49. Wright, J.K.: Shock Tubes. John Wiley and Sone, New York, 1961.

# APPROVAL

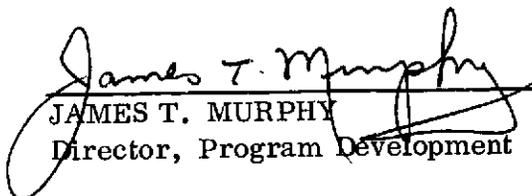
## VOLUME III – MAGNETOSPHERIC EXPERIMENTS WORKING GROUP

Compiled by Program Development

The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

This document has also been reviewed and approved for technical accuracy.

  
\_\_\_\_\_  
HERMAN P. GIEROW  
Director, Mission and Payload Planning Office

  
\_\_\_\_\_  
JAMES T. MURPHY  
Director, Program Development