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SUMMARY OF THE SECOND MAGNETOSPHERIC WAVE-PARTICLE INTERACTION WORKSHOP HELD AT LOCKHEED PALO ALTO RESEARCH LABORATORY ON FEBRUARY 6-8, 1973

Billy M. McCormac, et al

Lockheed Missiles and Space Company, Incorporated

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held at Lockheed Palo Alto Research Laboratory

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Prepared for:

OFFICE OF NAVAL RESEARCH
UNITED STATES NAVY
800 NORTH QUINCY STREET
ARLINGTON, VIRGINIA 22217

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Artificial ULF Generation						
VLF Interaction Experiments						

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ABSTRACT

A workshop on wave-particle interactions was held at Lockheed Palo Alto Research Laboratory on February 6-8, 1973, under the sponsorship of ARPA and ONR. Wave amplification for communications were discussed. Particular attention was given to the role that wave-particle interactions play in ionospheric-magnetospheric coupling. Experimental techniques to investigate wave-particle interactions were discussed.

LIST OF ATTENDEES

The following people participated in the workshop and many of them contributed material to this report.

Dr. Peter Banks	Stanford University
Mr. L.S. Bearce	Naval Research Laboratory
Mr. William Bernstein	U.S. Department of Commerce
Dr. Paul J. Bottoms	Los Alamos Scientific Laboratory
Mr. G.B. Carpenter	Stanford Research Institute
Dr. C.R. Chappell	Lockheed Palo Alto Research Lab
Dr. John B. Cladis	Lockheed Palo Alto Research Lab
Dr. J.M. Cornwall	Aerospace Corporation
Dr. J.G. Dardis	Office of Naval Research
Dr. G.T. Davidson	Lockheed Palo Alto Research Lab
Dr. John R. Davis	Naval Research Laboratory
Dr. Jacques Denavit	Northwestern University
Dr. John E. Evans	Lockheed Palo Alto Research Lab
Dr. E.C. Field, Jr.	Pacific Sierra Research Corp.
Dr. A. Fraser-Smith	Stanford University
Dr. R. Helliwell	Stanford University
Dr. Charles Kennel	University of California at Los Angeles
Capt. D.M. LeVine	Defense Advanced Research Projects Agency
Dr. Harold B. Liemohn	Battelle Northwest
Dr. Erick L. Lindman	Los Alamos Scientific Laboratory
Dr. Billy M. McCormac	Lockheed Palo Alto Research Lab
Dr. Stephen B. Mende	Lockheed Palo Alto Research Lab
Dr. Chung Park	Stanford University
Dr. A.M. Peterson	Stanford Research Institute
Dr. W.N. Podney	Physical Dynamics, Inc.
Dr. H.M. Schulz	Aerospace Corporation
Dr. Martin Walt	Lockheed Palo Alto Research Lab
Dr. T.N.C. Wang	Stanford Research Institute
Dr. John W. Willis	Naval Research Laboratory

I. INTRODUCTION

An important objective for investigating ionospheric and magnetospheric phenomena and their interrelationship is for the design and optimization of ground based and satellite communications, navigation, detection, and surveillance systems employing ULF to UHF.

Particularly important is the need for an ionospheric model that will predict the propagation effects. Also of interest to this workshop is the amplification of manmade and natural signals at ULF and VLF.

This workshop concentrated on those aspects of ionospheric modeling and wave amplification that are related to wave-particle interactions (WPI). Wave-particle interactions were initially invoked to explain the origin of natural ELF and VLF emissions in the magnetosphere. Since then it has been shown that WPI's are responsible for

1) ULF and VLF signal amplification,
2) Modification of the distribution function of energetic particles,
3) Energy diffusion.

There are two important applications for the study of magnetospheric WPI's. First, WPI's play a very important role in the coupling between the magnetosphere and the ionosphere. Much of the energy deposited into the ionosphere above about 45° Inv. Lat., comes from the solar wind into the magnetosphere and then into the ionosphere. This energy flow into the ionosphere is very significant in modeling the ionosphere, but is currently ignored as a result of a lack of data and understanding. Second, under certain circumstances, WPI's result in large amplification of ULF and VLF waves. Better understanding of these amplification processes may lead to controlled amplification for communications.

In spite of much progress, an adequate model of the ionosphere is still wanting. In fact, the pertinent questions summarized by a National Academy of Sciences Report on the Physics of the Earth in Space 1969 still hold. These are: Is there evidence that any unrecognized photochemical processes are important in determining the electron and ion density distribution in the upper ionosphere under unusual solar-geophysical conditions? What is the relative importance of photochemistry and dynamics in explaining the anomalies and irregularities of the ionosphere? What is the origin of the electric fields that drive the electron drifts, particularly the variations that are observed and that cannot be accounted for by dynamo theory? Have all the important sources of electron heating and loss in the ionosphere been identified? What is the explanation of the changes in the E and F regions that take place during a solar flare? What are the physical processes acting on the ionosphere during magnetic storms? What causes and maintains sporadic E? How is the ionization in the polar regions distributed, and is it maintained by direct entry of solar plasma, transport effects, or by some other means? What are the roles of the ionosphere and magnetosphere in the production of aurora, and how are they mutually coupled? What can be deduced about the general and smaller-scale circulation of the high atmosphere? What can be deduced from radio and incoherent-scatter observations about the neutral high atmosphere--composition, temperature, natural chemistry, and dynamics as a function of height, geography, and time?

The International Magnetospheric Study Reports (May 1971, May 1972) list a number of problem areas that should receive high priority. Those related to WPI's are:

1) How are the different components of electric currents in the magnetosphere and ionosphere related to each other?
2) To what extent are magnetospheric processes determined by the ionosphere or affected by feedback from the latter?
3) What is the relative importance of the neutral atmosphere, the polar wind, particle precipitation, and plasma convection in

determining the behavior of the polar ionosphere and the trough region beyond the plasmapause?

4) What are the relative contributions from the various source and loss mechanisms to the radiation belts?

In Section II of this report the various aspects of ionospheric-magnetospheric coupling are discussed with particular interest on those aspects involving WPI's. A summary of an analysis of system applications of cold plasma injection is given in Section III. The physics of WPI's from a theoretical viewpoint is provided in Section IV. Section V contains a number of suggestions for experiments to measure WPI's. A summary is given in Section VI.

II. IONOSPHERIC-MAGNETOSPHERIC COUPLING

The solar wind powers all of the magnetospheric dynamics. The phenomena consist of current systems, plasma convection, energetic particle processes, electromagnetic waves, electric and magnetic fields, and various interactions between these phenomena.

The magnetosphere is coupled to the ionosphere in a complex manner such that a number of processes lead to energy deposit in the ionosphere. These energy deposits lead to a significant modification of the ionization structure and density, especially at higher latitudes. There are large temporal variations produced in the ionosphere. WPI's are important in the magnetospheric-ionospheric coupling. The details of the role of WPI's are not well understood.

At least 3 energy deposit mechanisms that deposit energy in the ionosphere involve WPI's and are important (McCormac et al., 1971b):

1) Deposit of ring current energy into the F region.
2) Joule heating and inhomogeneity production in the E region from electrojets.
3) Energetic particle precipitation into the D, E, and F regions.

In addition, the E fields imposed on the ionosphere as a result of magnetospheric-ionospheric coupling influence plasma convection and structure.

A. MAGNETOSPHERIC STRUCTURE

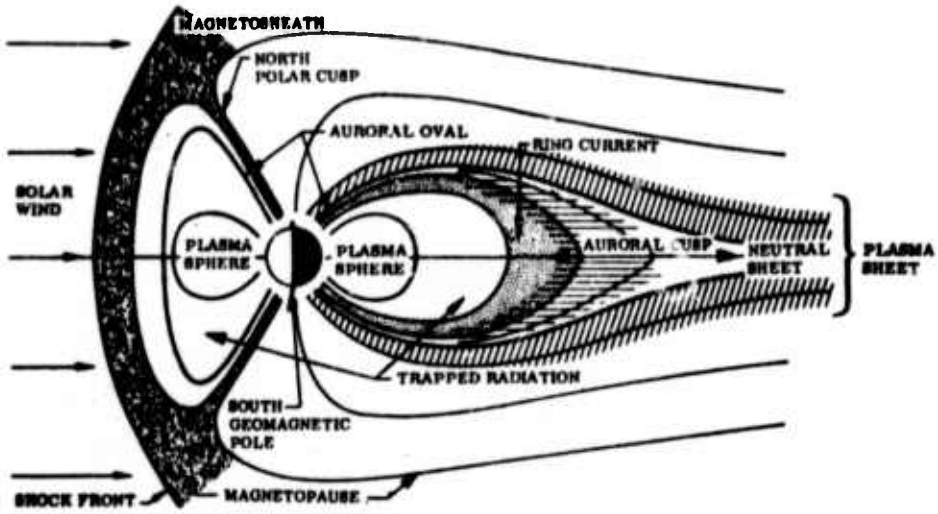
The solar wind interacts with the earth's magnetosphere to form a compressed magnetosphere in the subsolar direction and an elongated tail in the antisolar direction. A bow shock is established sunward of the earth as the solar wind plasma is retarded by the earth's increasing magnetic field intensity. Inside the bow shock a turbulent region filled with plasma, called the magnetosheath, is formed. Pressure on this region forces the plasma around the tail

or down the nearly vertical magnetic field regions called the polar cusps. The main entry of solar wind plasma into the magnetosphere is along field lines in the magnetotail which are directly connected with interplanetary field lines connected to the sun. Two neutral sheets result, one in the center of the magnetotail and another in the magnetopause. The solar wind plasma flows into the plasma sheet of the tail, builds up pressure, compresses the plasma, squeezes some down high latitude field lines to form soft (low energy particle) zone auroras. The rest is accelerated toward the earth by reconnecting field lines, is driven deeper into the equatorial region of the magnetosphere and forms the higher energy electron and proton precipitation regions. Precipitation of energetic electrons and protons is influenced by WPI's which modify the phase-space distribution causing some particles to be in the loss cone.

Figure II-1a shows a meridian section of the magnetosphere with notations showing the various regions of confined plasma and the paths available to the charged particles. Figure II-1b shows an equatorial section of the magnetosphere in the same condition as that shown in Figure II-1a. An east-west electric field is generated across the neutral sheet near the cusp region which may accentuate the differences of L shells along which the protons and electrons drift and precipitate into the upper atmosphere. The protons drift into the elongated plasmasphere on the dusk side of the earth and cause ionospheric heating, and in case of major solar storms, often result in mid-latitude red arcs.

B. STORM EFFECTS

The time variations of the plasma sheet play a key role in the response of magnetospheric phenomena to changes in dynamic pressure of the solar wind and to magnetospheric substorm phenomena. Substorms occur every few hours in quiet times; their main effects occurring in the vicinity of local midnight



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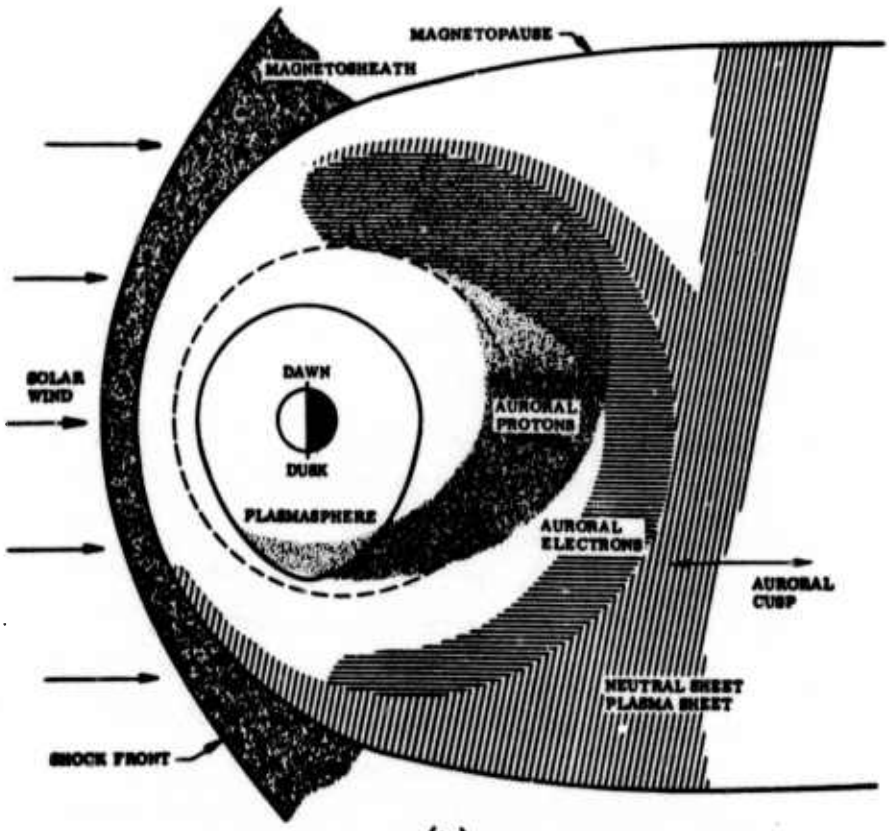

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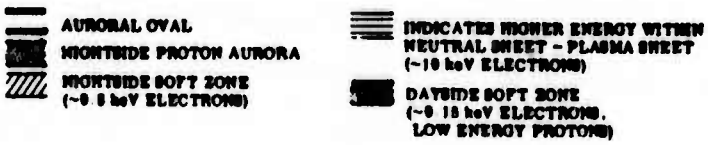

Figure II-1 Noon-midnight meridian (a) and equatorial (b) views of the earth's magnetosphere showing the distribution of plasmas and particles and their precipitation regions.

at any observing station near the auroral region. The plasma sheet is filled with particles following field lines connecting interplanetary space to the magnetosphere. A reconnection or merging of field lines in the neutral sheet drives a volume of the plasma earthward. This process enhances trapping and auroral particle precipitation. A negative bay or decrease in the horizontal component of the earth's magnetic field in the auroral region develops. During the initial growth phase of the substorm the plasma sheet is thinned by the increased external pressure on the tail. Subsequently, during the expansion phase of the substorm the plasma sheet thickens again as the magnetic field configuration of the tail returns closer to a dipole configuration.

The plasma sheet is inflated to higher pressures when conditions favor field line merging, leading to an increase in frequency and intensity of substorms.

C. CURRENT SYSTEMS

A substorm results in the production of a westward electrojet and an asymmetric ring current. The westward directed electrojet is a current of $\lesssim 10^6$ amperes flowing near invariant latitude $\Lambda \sim 65^\circ$ in the 2300 to 600 hours sector of the polar ionosphere. The asymmetric ring current has about the same current flow and is in the equatorial region of the magnetosphere where the L value is about 6. It is most intense in the afternoon sector. The westward electrojet and the asymmetric ring current are believed to be connected by field aligned (Birkeland) currents to form the current system shown in Figure II-2. The connecting Birkeland currents flow upward from the E-region of the ionosphere in the late evening sector and downward into the ionosphere in the dawn sector. Figure II-2 shows how the normal symmetric ring current is modified when the conductivity of the ionosphere is greatly increased by large particle energy deposits during magnetospheric substorms and a substorm circulation system with Birkeland currents is established.

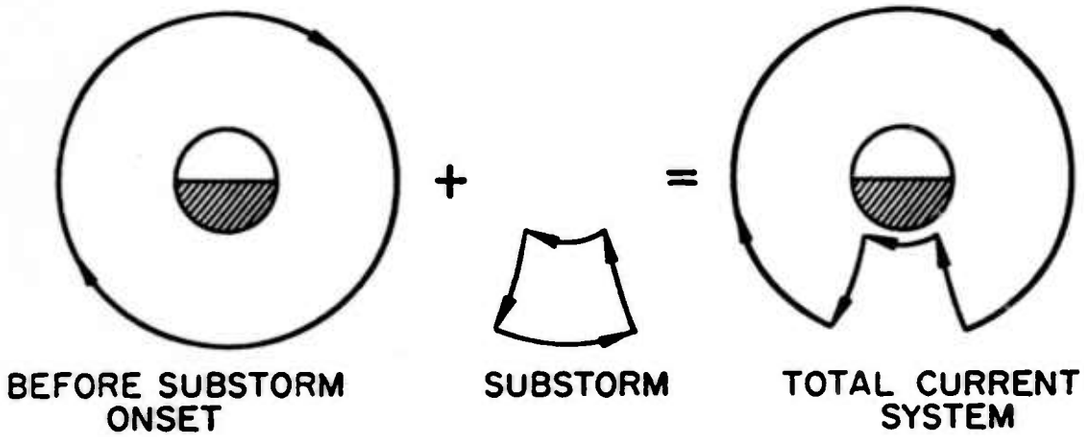

Figure II-2 Boström current system model showing modification of the ring current and the establishment of the westward electrojet by a substorm current system.

Figure II-3 shows some detail for the establishment of a substorm current loop (Figure II-2) involving the westward flowing auroral electrojet. Energetic particle precipitation increases the conductivity of the E-region of the ionosphere so that the E-fields generated by magnetospheric action can drive the current around the loop. The conductivity along the almost vertical magnetic field lines from the electrojet is large and a large cross sectional area is available for the high altitude distributed current flow. $E_{\perp}$ fields in the ionosphere have been measured to be directed across the electrojet and toward the equator. Electron flow is in an eastward direction along the electrojet and constitutes a Hall current.

In the dawn sector of the electrojet electrons flow upward along the field lines and some protons from the ring current flow downwards. In the midnight sector these directions are reversed. It is assumed that most of the $\sim 10^6$ amps consists of electron Hall current flow and rather than proceeding to flow completely around the auroral oval it follows the path having higher conductivity up the field lines in the dawn sector, across the ring current region as a widely distributed current and down into the ionosphere in the midnight sector of the auroral electrojet as Birkeland or field aligned currents. For completeness the eastward electrojet, which has a strength of about 10^3 amperes, is shown on Figure II-3. This electrojet is part of the ionosphere current system and is not related to the substorm current system.

D. PLASMASPHERE

The plasmasphere or inner region of the magnetosphere plays an important role in the disposition of the plasma coming into the inner magnetosphere and the distribution of its energy. The plasmasphere boundary occurs at L values from 3 to 8 and is characterized by a rapid fall off of ion density from $\sim 10^2 \text{ cm}^{-3}$ to 1 cm^{-3} at larger radii. Figure II-1a shows the noon-midnight meridian cross section of the plasmasphere at times of medium activity. When the proton ring current runs into the bulge of the plasmasphere in the dusk sector, WPI's cause the protons to lose their energy and heat the plasma. In large storms this heated plasma is conducted down to the ionosphere and red arcs occur at L values near 3. This is the source of energy for producing the high F region temperatures observed.

E. IONOSPHERIC COUPLING

Recent advances in theory, together with observational data, show that accurate models of ionospheric and magnetospheric behavior imply the existence of important couplings between three fundamentally different regions:

1) The cool-plasma of the ionosphere and magnetosphere
2) The neutral atmosphere above 100 km altitude, and
3) The waves and energetic plasma of the magnetosphere.

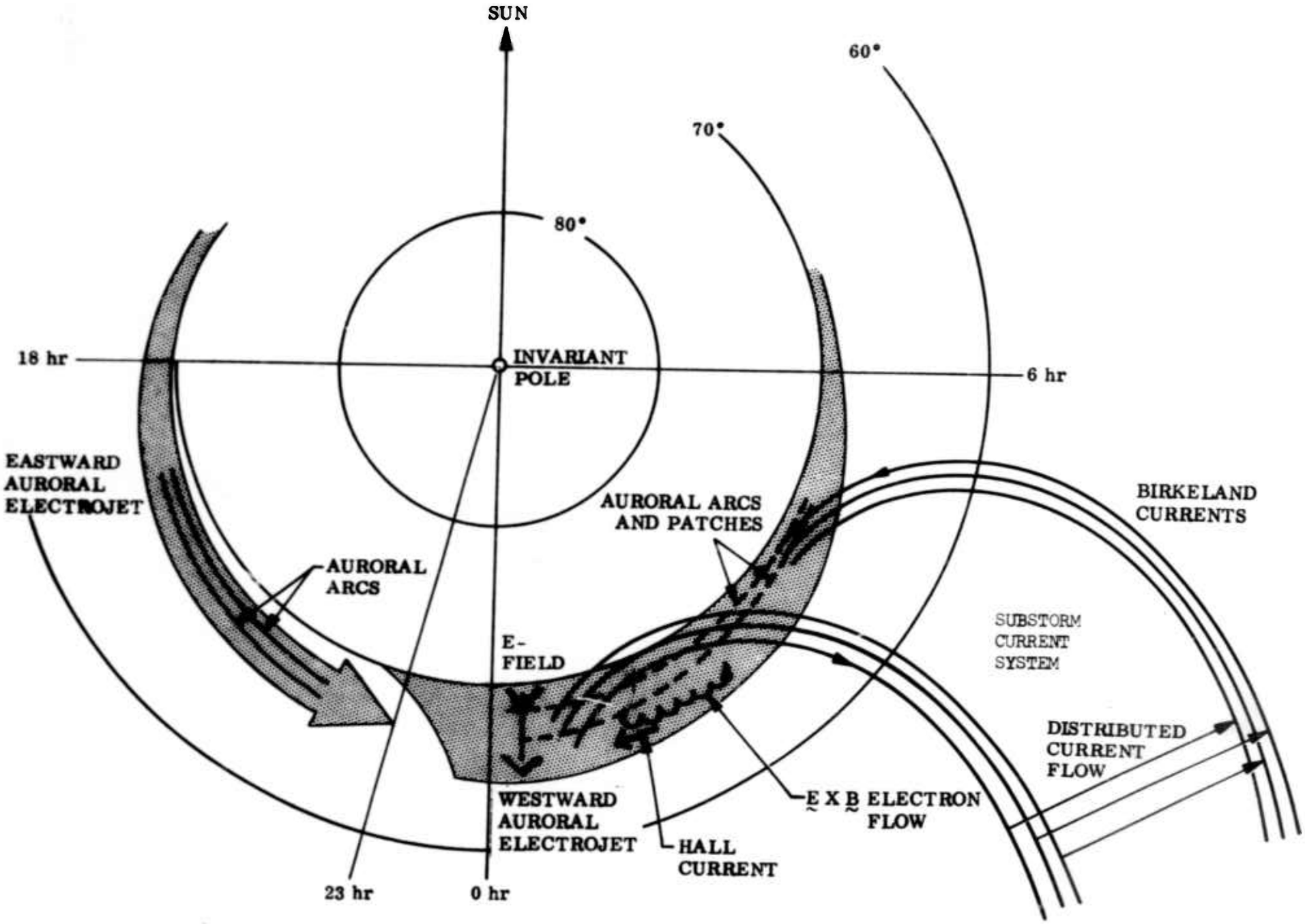

Figure II-3 The auroral electrojets and the substorm current system.

The main source of cool plasma in the ionosphere is photoionization which, via various reaction chains, leads to the ions O_2^+, NO^+, O^+, and H^+ in order of altitude dominance. During the past eight years there has been an increasing appreciation of the strong coupling existence between these ions and neutral atmosphere, not just in terms of the neutral composition effects, but including the influences of global wind patterns in moving F_2-region ionization up or down magnetic field lines. Since the global winds in the F-region are not known, computational models based on solar heating or horizontal atmospheric pressure gradients have been used to predict ionospheric effects.

More recently, the striking influence of electric fields has been recognized, both at high latitudes where magnetospheric convection is present and at lower latitudes inside the plasmasphere where substorm effects can dramatically alter ionospheric heights and densities. Analysis of conventional ionosonde data has shown that the mid-latitude nighttime ionosphere reacts rapidly to substorms with large eastward electric fields being found in the pre-midnight sector and westward fields afterwards. The complete global morphology of electric fields is not known and even the magnetospheric origin is poorly understood. The determination of the behavior of electric fields in space and time is one of the crucial problems facing the development of accurate models of the ionospheric and magnetospheric plasma.

Recent studies have also shown that the electric fields observed in the ionosphere and magnetosphere are not simply a result of external processes associated with the solar wind/magnetosphere interaction. At low latitudes, for example, it is known that neutral winds established through solar heating create a dynamo electric field (through neutral gas/ion collisions) which causes important ionization drifts within the plasmasphere. At high latitudes, large (100-500 m/sec) winds in the thermosphere are created by convection electric fields driving auroral zone and polar cap plasma through the neutral gases. To some unknown extent the neutral atmosphere then acts as a dynamo of large inertia which provides a flywheel feedback effect upon the total

electric field. During the onset of rapid plasma convection, energy is dissipated in the neutral atmosphere, both through Joule heating and in setting the neutral gas into motion. Later, this neutral gas kinetic energy is available to drive dynamic electric fields even in the absence of an external (magnetospheric) source.

Perhaps more perplexing are electric fields seen inside the plasmasphere associated with substorms. Analysis of conventional ionosonde data has shown that the mid-latitude nighttime ionosphere reacts rapidly to substorms with large eastward electric fields being found in the pre-midnight sector and westward fields afterwards. Since eastward substorm fields are not normally seen within the nighttime auroral zone, it would seem that some important basic polarization process must be acting.

It is also clear that important couplings exist between the cool and energetic particle plasma environments. The wave-particle interactions which lead to the precipitation of energetic particles depend upon the thermal plasma density. Likewise, the upward flow of cool plasma depends strongly upon the presence of possible parallel electric fields and currents which may be an intrinsic part of the energetic proton ring current. In addition, it is known that there are associated heating processes which produce, via thermal conduction, many important ionospheric effects. In fact, the magnitude of the field aligned currents themselves may depend upon the degree of ionization induced by the precipitating particles.

In summary, it is no longer possible to arbitrarily separate the magnetosphere, ionosphere and neutral atmosphere. There are many important processes which are intimately linked by effects associated with each of these regions and progress towards comprehensive models must take these couplings into account.

F. IONOSPHERIC MODEL REQUIREMENTS

A large number of military systems depend upon the transmission and reception of radio waves and often system performance is critically influenced by the interaction of the waves with the ionosphere. The ionosphere acts as a reflector of radio waves at frequencies up to and including HF, permitting them to propagate to great distances around the earth. Communication, navigation and over-the-horizon detection (OHD) systems normally utilize the HF band (3 to 30 MHz). Systems employing frequencies of a few tens of kilohertz are also used regularly and systems which will employ frequencies as low as a few tens of hertz are being developed. The ionosphere is usually transparent to radio waves of Very High Frequency (VHF) (30 to 300 MHz) and above. However, even radio waves that pass through the ionosphere are modified by the traversal; the extent of modification diminishes as frequency increases. Communication, navigation and detection via satellites are carried out at VHF. Radars responsible for tracking satellites and rocket bodies in trajectory also employ VHF and higher frequencies.

Evaluation of such systems prior to their deployment requires representation of the ionosphere in terms of a comprehensive model. An ionospheric model intended for radio-system application must first specify whether a propagation path exists between source and receiver, i.e., whether the frequency of interest will reflect or penetrate the ionosphere at suitable incidence angles to establish a ray path connecting the two end points. Basically, such a specification at least requires knowledge of the maximum electron density and its height. Enumeration of the different paths that can exist between end points requires some knowledge of the electron-density profile details. Determination of the coherent bandwidth for a particular path generally increases the need for detailed profile information, although the integrated electron density between source and receiver provides a first-order description of the dispersion for ground-to-satellite paths at sufficiently high frequencies. Determination of propagation attenuation also requires some knowledge of electron-density and collision-rates profiles in the lower ionosphere (D and E regions).

In addition to the level of detail required of an ionospheric model, consideration must also be given to the description of ionospheric variability. These variations may be regular and predictable; examples of such variations are diurnal, seasonal, solar cycle and latitudinal changes. Of greater concern, perhaps, are the transient and often unforeseen variations related to nuclear detonations, solar disturbances, and magnetic storms. An ionospheric model that embodies all of the above details and variations is highly desirable in order to provide designers and systems analysts with a means of determining system sensitivities in both design and network studies.

The ionospheric model should be based (insofar as possible) upon physical processes that occur in the atmosphere so that the full range of ionizing fluxes (ambient, naturally disturbed and artificially disturbed) and the resultant ionospheric reactions can be simulated. For the more conventional systems operating between VLF (3 to 30 kHz) and HF, the ionospheric description provided by the model must be representative of conditions that exist from the bottom of the D region up to several earth radii. Detailed electron density, ion density, and collision-frequency profiles, together with their temporal and spatial (geographic and geomagnetic) changes, covering all known variations are essential requirements of the model. Systems functioning at VHF and above also require comprehensive topside electron-density profiles to model the total electron content as it relates to dispersion, refraction, scintillation and Faraday rotation at frequencies that penetrate the ionosphere. The model should incorporate the naturally occurring irregularities (e.g., aurora) by accounting for the known physical processes that are involved. For systems designed to operate at frequencies of less than 3 kHz, an extension of the model into the stratosphere below the D region is indicated.

No single ionospheric model that embodies the physical processes and accounts realistically for temporal and spatial variations in the ionosphere now exists within the U.S.A. Several ionospheric/propagation models have been developed for predicting propagation conditions. The

development of these models has relied on either idealized electron-density profiles or upon statistical data (e.g., monthly median critical frequencies). A brief review of some of the existing ionospheric models and their characteristics is given below.

- NOAA has developed an ionospheric code for long path prediction of HF communications (Jones et al., 1966; Barghousen et al., 1966). This E and F region ionospheric model incorporates some information on temporal and spatial variations. This model is based on statistical observations and is limited to providing estimates of the E and F layer median critical-frequency and the layers' virtual heights. No attempts are made to construct a complete electron-density profile from the E and F region parameters. E and F region variations that result from solar and magnetic storms or other naturally occurring phenomena are not considered.

- WEPH V is a nuclear environment prediction code (Knapp, 1971). A fairly complete description of the altitude variation in ionospheric properties is given but no representation of seasonal, solar cycle, or latitudinal variations is contained. Two idealized profiles, one for day and one for night are used to represent the diurnal changes.

- The NUCOM code calculates HF propagation in a nuclear environment (Nielson et al., 1968). The NOAA ionospheric model for the E and F region parameters is incorporated and the electron-density profile to the F layer peak is modeled with three parabolas.

  Some estimates of the electron density above the F layer peak are made by using a Chapman layer approximation above the F layer peak. The D region is represented by the WEPH day-night idealized profile.

- First order temporal and spatial variations of D region electron-density profiles are contained in the WEDSRI code which was developed for evaluation of VLF propagation systems (Owen, 1971). Some

estimates are made of D region variations due to latitude, solar activity, time after sunset, etc., by incorporating the known ionizing fluxes and ionospheric reaction rates. The magnitude of the fluxes was adjusted to produce electron-density profiles that were consistent with measurements.

Further research into magnetosphere-ionospheric coupling is required before an entirely comprehensive ionospheric model can be developed from first principles. This research would primarily be directed at understanding the spatial and temporal ionospheric variations produced by the interaction of ionizing fluxes--particle or photon--with the ionosphere and magnetosphere.

Empirical models are being developed by Air Force Cambridge Research Laboratory (T. Elkins) and Atlantic Science Corp. (R. Bent). However, global models based on physical processes for the quiet and naturally disturbed ionosphere are wanting. Generally speaking, it is probably easier to model the disturbed ionosphere following a nuclear explosion than it is to model the quiet and naturally disturbed ionosphere.

A global theoretical ionospheric modeling project for the quiet and naturally disturbed ionosphere is underway at ARPA (STO) and includes the following contractors: NOAA, NRL, Science Applications, UCSD, Pennsylvania State University, Utah State University and Cornell University. The needs of military operational systems for ionospheric modeling are discussed in several reports (Rose et al., 1971; Rose et al., 1972; Chesnut, 1971).

III. SYSTEM APPLICATIONS

The application of cold plasma injection to stimulate WPI's for application to military long wavelength communications was analyzed (Field, 1972; Carpenter, 1973). Consideration was given to the following four applications:

- Blackout from anomalous ionization
- Jamming with amplified noise
- Controlled amplification of transmitted signals to achieve adequate margin
- Communication via amplified background signals

The results of the study are more or less negative, primarily as a result of a lack of a good data base on WPI's.

A. BLACKOUT FROM ANOMALOUS IONIZATION

This is the production of ionospheric absorption due to the precipitation of charged particles caused by a cold plasma injection. This would be less important than some natural absorption events. The deposition altitudes are too high to degrade conventional LF/VLF/ELF.

Significant degradation of nightside ULF propagation in the F layer waveguide is predicted.

B. JAMMING WITH AMPLIFIED NOISE

Here a cold plasma release would amplify the natural noise sources producing degradation. The frequency ranges are limited to 0.1 to several Hz and 10^2 to 10^4 Hz. Adequate ambient conditions are essential. The effects are limited in geographic coverage and are avoidable through frequency diversity.

C. CONTROLLED AMPLIFICATION OF TRANSMITTED SIGNALS TO ACHIEVE ADEQUATE MARGIN

The possibility of using cold plasma injection to amplify transmitted signals was investigated. Operational problems in selecting

the injection region and the times involved between deciding to inject plasma and communication make this technique impractical at this time.

D. COMMUNICATION USING AMPLIFIED NOISE

It may be possible to send a simple message by amplifying the ambient noise; however, it seems most impractical at this time. For example, the amplified signals are similar to natural signals and cannot be modulated or formatted.

IV. PHYSICS OF WAVE-PARTICLES INTERACTIONS

Wave particle interactions in the magnetosphere may:

1) Produce ULF wave amplification by interaction with protons and ions.
2) Produce VLF wave amplification by interaction with electrons.
3) Participate in the transfer of energy between the magnetosphere and the ionosphere.

Many geophysical observations have been interpreted to demonstrate that all three of these types of wave-particle interactions occur. All experiments are particularly deficient in that no single satellite or rocket payload has simultaneously measured the plasma, energetic particles, waves, and fields.

To date, empirical relationships have been advanced to relate the magnetosphere to the ionosphere. Both linear and nonlinear theoretical studies have been made. It has been obvious for some time that linear theory is not adequate to answer the important WPI questions. Now, the procedure for including nonlinear effects realistically is becoming apparent.

A. LINEAR THEORY OF EMC MODES

Most of the theoretical work has concentrated on wave-particle interactions in the electromagnetic cyclotron (EMC) mode. Current dogma holds that there are three basic requirements for effective generation of proton or electron EMC instabilities (Cornwall and Schulz, 1973).

1) The pitch-angle anisotropy A (defined through the pitch-angle distribution $(\sin \alpha)^{2A}$) should exceed a critical value $A_c = (\frac{\Omega}{\omega} - 1)^{-1}$, where Ω is the cyclotron frequency and ω the wave angular frequency.

2) The single-particle energy should exceed a critical value $E_R = \frac{B^2}{8\pi N} A_c^{-2} (1 + A_c)^{-1}$ (for protons) where N is the ambient plasma density. A similar expression holds for electrons.

3) The total particle flux exceeds a critical value (known as the stably trapped limit): $F > 2\text{-}10 \times 10^{10} L^{-4} cm^{-2} s^{-1}$.

For the ring current, criteria 1) and 3) are almost always met, but criterion 2) can only be met when the ring current is pushed up against the plasmapause, <u>or</u> when artificial plasma is injected outside the plasmasphere. According to theory, when the proton EMC instability does occur, it will produce ULF waves in the 0.1 - 5 Hz range and precipitate protons.

Linear theory predicts single-pass gains of 10-40 dB in ULF, and much higher in VLF, in both sufficiently dense natural plasma (i.e., the plasmasphere) and in artificial (e.g., lithium) plasmas clouds outside the plasmasphere. These gains are upper limits and may be in error by many orders of magnitude.

Many geomagnetic substorm phenomena have been interpreted in terms of the EMC instability. The critical lack of simultaneous plasma, particle, wave and field data make it impossible to draw any positive conclusions about the theoretical relation between plasma density and

generation of unstable EMC modes (see criterion 2). Some experimental inferences can be drawn concerning other theoretical predictions; it is observed that much of the energy of the storm-time ring current is actually dissipated in the ionosphere (mid-latitude SAR-arcs, ionospheric heating), but it has not been possible to account for the direct deposition of much energy as particle precipitation. This suggests that energy diffusion is quite significant, with most energy going into waves and then into plasma heating, and relatively little into direct precipitation of ring current protons.

A study was based on the linear theory for the cyclotron-resonance interaction to select suitable experiments (Liemohn, 1972). Since some of the linearity assumptions are not valid in the injection region the quantitative results are open to question. Nevertheless, the linear results are believed to provide a reasonable basis for selecting injection methods that appear to be effective for stimulating amplification. A thorough nonlinear study of promising cases is recommended.

Several conclusions can be drawn from the study. Amplifications of 40-60 dB are calculated for several cases of interest. Such enhancements of VLF or ULF noise levels are easily detectable with ground or satellite receivers located along the injection field lines. One of the most promising cases is lithium injection at geosynchronous altitude where broad regions at the surface of the earth would be illuminated by ULF noise in the band 0.4 - 0.5 Hz. At VLF the low-energy cesium-electron beam works well as an amplifier and also provides a fluxtube waveguide for the electromagnetic energy. Although the electron and proton beams appear to generate amplification, the interaction region is severely limited in size with present particle gun technology and the total energy transferred to the waves is quite small. Plasma injections into the more dense inner magnetosphere are relatively ineffective due to the local propagation characteristics and the wave amplification is small.

B. NONLINEAR THEORY

Linear theory represents only a first step in the treatment of magnetospheric wave-particle interactions. Essential nonlinearities enter at an early stage. For example, if the particle flux in some region of the magnetosphere suddenly exceeds the limit of stable trapping, the consequence is a growth of wave energy and a precipitation of the excess particle flux.

Especially in VLF amplification processes it is possible to achieve saturations of linear growth on a single pass. Linear theory breaks down, and nonlinear aspects of wave-particle interactions must be considered. Another nonlinearity is associated with quasi-linear diffusion of particles. While this theory is well understood in principle, it is extremely hard to apply in the magnetosphere without some carefully chosen simplifications.

At present, there is a considerable amount of effort applied to computer simulation which might throw more light on the subject of wave-particle interactions in the magnetosphere. R. Helliwell and J. Denavit have attempted to model the interaction of magnetospheric electrons with packets of waves in the VLF frequency range. Helliwell's work has been aimed at the understanding of whistlers; it is therefore particularly relevant because the inhomogeneous magnetic field has been explicitly included. Important results were a rather good model for the prediction of amplification of an input signal, and some computed wave saturation levels. Denavit has explored the details of the wave packet interaction.

The nonlinear evolution of electron whistler wave packets depends on the transit time to trapping time ratio, $\tau_{transit}/\tau_{trapping}$. For a wave packet of length ℓ, the transit time of resonant particles is given by:

$$\tau_{transit} = \frac{\ell}{|v_r - v_g|}$$

where $v_r = (\omega - \Omega)/k$ is the resonant particle velocity, ω is the frequency, Ω the cyclotron frequency, k the wave number, and v_g is the group velocity. The trapping time is the period of oscillations of electrons trapped in the wave given by:

$$\tau_{trapping} = \frac{2\pi}{\sqrt{\Omega_w v_\perp k}}$$

where $\Omega_w = (B_w/B_o)\,\Omega$ is the cyclotron frequency corresponding to the wave magnetic field, B_w, and $v_\perp$ is the perpendicular velocity of the trapped electron. Note that nonlinear effects thus depend on the length of the wave packet as well as its amplitude.

1) For $\tau_{transit}/\tau_{trapping} \leq \frac{1}{2}$ resonant electrons are not trapped during their transit through the wave packet and linear theory is applicable. The wave packet may be damped or amplified by cyclotron resonance, but its length and shape are unchanged.

2) For $\frac{1}{2} \leq \tau_{transit}/\tau_{trapping} \leq 4$ resonant electrons are trapped. As they travel through the wave packet they alternatively take energy away from the waves during a half period and return some of this energy during the following half period. This results in a transport of energy from the front to the rear of the wave packet. The wave packet is elongated and the length of the newly emitted wave train may be several times the length of the triggering wave train.

3) For $\tau_{transit}/\tau_{trapping} \gg 4$, the energy exchange mechanism described above is applicable only to the head of the wave train after which the electrons acquire a steady-state phase correlation antiparallel to B_w. This results in a sideband instability described by the dispersion relation.

$$1 - \frac{\omega^2}{k^2c^2}\left[1 + \frac{\omega_p^2}{(\Omega - \omega)\omega}\right] = \frac{\frac{1}{2}\ \omega_R^2 < v_\perp^2 >/c^2}{\omega_\tau^2 - (\omega - kv_r - \Omega)^2}$$

where ω_p is the plasma frequency, $\omega_R = \left(\frac{4\pi\ e^2 n_c}{m}\right)^{1/2}$ is the plasma frequency of the correlated particles and ω_τ is the trapping frequency. The effect of this instability is to generate sidebands to the triggering wave whose amplitude can grow as large or larger than the main wave amplitude.

From these efforts and some other work at various laboratories (such as NOAA and NRL), we can begin to see how to guide the analytical approach to the wave particle interaction. Particularly, it appears that while the generated waves approach saturation they grow exponentially at a rate very near to that derived by purely linear plasma theory. The saturation might also be predicted heuristically on the basis of simulation results; for an infinite wave train, saturation seems to occur when the trapping time of particles interacting with the wave approaches the growth time. For a realistic magnetosphere model, the saturation limit is probably determined by the length of the interaction region and the transit time as described above.

Computer simulation has been useful as an aid to intuition and to verify certain theoretical results, but it has some severe limitations as an analytic tool. The pertinent results which have been presented have generally been obtained with large programs which often take an hour or more of time on a CDC 7600 (or equivalent) computer for a single run (many runs might be required for any problem). A special limitation on most existing programs is that they are unable to accommodate wave trains with a length of several thousand wavelengths as occurs in VLF propagation. Thus, in order to simulate cyclotron resonance and trapping effects with short wave trains, it becomes necessary to increase the wave amplitude and the energetic particle density by several orders of magnitude. It should be noted that this limitation would not be so severe in the simulation of ULF propagation which appears to be feasible with realistic parameters. Another limitation of present numerical simulation is that they do not take into

account two-dimensional effects such as line curvature or coupling with modes perpendicular to the magnetic field, and the simulation of these effects will have to await the development of two-dimensional codes.

The relevant processes can be simulated by a pair of coupled linear transport equations only in the limit of weak diffusion, i.e., only if the particle excess is slight. However, if the excess is a factor of two or more (as would generally happen in an artificial modification of the radiation environment), strong diffusion is likely to set in and produce a nonlinear modification of both the wave growth rate and the particle loss rate. It develops that this common nonlinearity is readily represented by simple analytic expressions, and that a quantitative phenomenological description of the transient state is near at hand.

A more difficult nonlinearity enters if the bounce-averaged treatment fails because the wave amplitude becomes too large on a single pass. For example, if the initial wave spectrum consists of a finite-amplitude signal transmitted from the ground, the signal may be (or become) of sufficient amplitude that it physically traps the resonant particles in its periodic potential well. This is a serious nonlinearity only if the amplitude-dependent oscillation frequency of a resonant particle exceeds the growth rate of the wave. In this case, the wave amplitude is found to saturate, and further growth is quenched. The foregoing conclusion is based on the theory of an infinite wave train in a homogeneous plasma. There is an open question as to whether this type of saturation would occur for a finite wave train, or for the case of an interaction region of finite length. In both of these latter situations, a continuous supply of fresh particles (unprocessed by the finite-amplitude wave) is entering the interaction at any given time. It seems clear that the duration of the wave train and the length of the interaction region must somehow affect the saturation process, but the nature of the modifications that ensue is a matter of open controversy, deserving of further study by analytical and numerical simulation.

C. RING-CURRENT-IONOSPHERIC COUPLING

It is commonly thought that electric convection fields drive the ring current up against the plasmapause, where its energy is dissipated. However, this simple view cannot be correct for electric fields varying slowly (time scales $\gtrsim$ hours) (Cornwall, 1972). The ring current itself is of such high density that (as a perfect conduction) it is capable of shielding itself, and the region interior to it, from these convection fields. However, fluctuating fields (time scales $\lesssim$ hours) can readily penetrate the ring current.

These circumstances must lead to a profound modification of the older, simple view of formation of the plasmapause, ion trough dynamics, ionospheric heating by particle precipitation, field-aligned currents, and other magnetosphere-ionosphere couplings. Much theoretical effort is required here. It appears that solar dynamo winds, carried by the neutral atmosphere to mid-latitudes where plasma flows are generated by frictional drag upon the ionosphere, must be important in maintaining the plasmapause (which otherwise would expand to meet the ring current). The role of fluctuating electric fields in plasmaspheric dynamics is surely important (e.g., in forcing us to distinguish the plasmapause, as an ion density discontinuity, from the corotation boundary, or last closed EXB drift orbit), but as yet ill-understood. The entire area of ionosphere-magnetosphere coupling will be obscure until the coupling (or better, decoupling) of magnetospheric convection and the ring current are elucidated.

D. FUTURE REQUIREMENTS FOR THEORY

1. Advances in theory depend upon experiment. Satellite payloads of the following type are essential: energetic particle (electrons, 0 to 100 keV; protons, 0 to 100 keV); fields (electric, DC and 10 Hz to 100 kHz; magnetic, DC and 0.1 to 10 Hz plus higher frequencies if possible); and thermal ion measurements (density, temperature, composition). The magnetic field sensitivity on the spacecraft should be 10 mγ at 0.1 Hz. The orbit should either pass through the plasmapause (e.g., S^3) or at least occasionally intersects it (e.g. synchronous).

2. Nonlinear theoretical calculations are needed. Linear amplifications of ~ 1000 dB in VLF are meaningless, and even 40 dB in ULF must be interpreted with due attention to saturation effects. While nonlinear work is in progress on this problem for VLF, little has been done in ULF. This field should be pursued. Better, more complete numerical and analytical modeling is required, supported by the results of nonlinear theory and computer simulation.

3. Effort should be expended on the specific problem of ring current - convection field coupling, which influences nearly every area of our understanding of magnetosphere-ionosphere coupling.

V. WAVE-PARTICLE INTERACTION EXPERIMENTS

These experiments are input-output type. The environment and the input must be simultaneously measured with the output.

To measure the relationship of WPI in the magnetosphere and ionsopheric modeling several types of data are needed.

1) Output: The output includes the characteristics of the ionosphere, T_i, T_e, N_e, N_i, structure, and dynamics. Except for emphasis on a new tool, the Chatanika radar in Alaska, no attention was given to this problem during the workshop. Many other sensors are needed as shown in several analyses of this problem (McCormac, et al., 1971a). The Chatanika radar samples a limited space-time domain of interest in WPI's.
2) Input: In this WPI problem area it is difficult to separate input from some supporting data requirements. At least the ULF and VLF waves in the interaction region are the input. The supporting data or if you like, input include the energetic particle, plasma, and fields at the location of the WPI. The input includes any artificial plasma injection.
3) Supporting Data: It is a long step from a WPI in the equatorial region of the outer magnetosphere and an ionospheric effect. One must determine how the energy gets to the ionosphere, such as by energetic particles, currents, energy diffusion, etc. Required are such data as (none of these can be measured at synchronous orbit and not adequately if at all by the Chatanika radar):

    Precipitating electrons and protons
    Location, strength, and structure of the electrojet
    Field aligned currents
    Heat conduction from the magnetosphere.

A. EXISTING WPI DATA IN THE MAGNETOSPHERE

Plasma may be injected into the outer magnetosphere by artificial or natural means. The barium release in 1971 provides some information of the behavior of a plasma cloud. No VLF emissions following this release were observed. OGO-5 data provide some insight into natural plasma injection; however, OGO-5 did not measure all of the proper energetic particle energies and did not measure ULF waves of 0.1 to 5 Hz.

1. Barium Release on 21 September 1971

The study of the magnetospheric barium release of the 21st of September 1971 near synchronous altitude provides some significant insights into magnetospheric ionospheric coupling processes (Mende, 1972).

The barium test plasma cloud was sufficiently weak to be essentially non-diamagnetic and thus was a good simulation of natural cold plasma clouds. The morphology, the dynamic behavior and the instabilities associated with this cloud are characteristic of the natural magnetospheric cold plasma. Since the magnetospheric cold plasma largely controls the mid latitude energetic particle precipitation through wave particle interaction, cold plasma morphology is of extreme interest for ionospheric modeling.

The relevant results of the many studies connected with this release can be summarized as follows:

a) The barium cloud 5 minutes after release became sufficiently weak that it had to be non-diamagnetic, otherwise the electron temperature had to be unreasonably high. The absolute calibration of the Lockheed data confirms this.

b) The cloud continued to be very narrow in width perpendicular to the magnetic field after it became non-diamagnetic. Striation formation still continued. Thus, striation generation cannot be ruled out from non-diamagnetic diffuse releases such as the proposed lithium release.

c) The slow deceleration of the striations is evidence that the weak plasma striations do not couple to the ambient plasma as fast as expected. Therefore, the magnetospheric electric fields did not control the motion of the barium plasma.

It is very important to produce a theoretical model for the magnetospheric striation instability. Natural detached cold plasma obervations should be evaluated by considering the possibility that they are highly structured.

The implications of the barium cloud results on future artificial chemical (possibly lithium) ion releases should be looked at quantitatively because such ion releases are an important tool in controlled magnetospheric experiments.

2. <u>OGO-5 Data</u>

The initial phase of the study of detached high density plasma regions in the earth's magnetosphere has shown that in the few cases that have been studied it has been found that there is wave generation directly correlated with the detached plasma regions and this wave generation is found only inside the regions where the cold plasma density exceeds several particles cm^{-3}. These preliminary results give some indication that the injection of sufficient densities of cold plasma (protons and electrons) into a region of energetic electrons whose fluxes are near the stable trapping limit will result in the generation of ELF (40 to 120 Hz) waves.

In particular, the correlated studies of the Lockheed light ion mass spectrometer, the UCLA search-coil magnetometer (ELF), the UCLA energetic particle detector, and the UCLA fluxgate magnetometer (ULF) data in the enhanced density regions have given the following information:

1) When the satellite entered regions of enhanced cold plasma density, ELF waves of frequencies 40 - 120 Hz are found.

2) When the observed waves are at frequencies which are resonant with the > 50 KeV electrons (as measured by the UCLA experiment), these observed electrons are found to have fluxes which exceed the stable trapping limit as predicted by theory. In cases where the > 50 KeV electrons are resonant, and their fluxes do not exceed the stable trapping limit no ELF waves are observed.

3) The frequencies of the ELF waves are the expected frequencies which result from the Doppler-shifted electron cyclotron resonance interactions.

4) The ELF waves were right-hand polarized and were normally propagating within 30° of the magnetic field direction indicating that they may well be trapped (or ducted) in the enhanced plasma regions.

5) The peak power in the ELF waves is approximately $10^{-4}\ \gamma^{2}\ Hz^{-1}$.

6) There were no noticeable effects on the distribution of the energetic (> 50 KeV) electrons in the detached plasma regions. This is to be expected since the drift time of the electrons through the cold plasma regions is of the order of a few minutes and the effective pitch angle diffusion time is of the order of an hour. We should point out that because of incomplete particle measurements we cannot exclude the possibility of enhanced particle precipitation among the lower energy protons and electrons which would certainly affect E and F region ionospheric modeling studies.

7) ULF waves of period 20 seconds were occasionally present. Their generation may be caused by the more energetic (> 100 keV) protons present in the trough region.

Of the cases studied there have been no observations of ULF waves of a few second period that are expected to be generated by the ring current protons. However, none of the cases studied have been equatorial measurements, and the few second period waves which are expected to be generated at the equator may not propagate to the higher latitudes of the satellite.

The study has been limited to "a few good cases" which have given interesting results. Further studies of this correlated data could give statistical information on the occurrence probability of ELF wave generation and amplification and on the effects of the varying widths of the enhanced density regions (or ducts) on the effective trapping and subsequent amplification of the waves. Further studies of these data can also give direct information on the power that can be generated in these naturally occurring waves.

B. MAGNETOSPHERIC WAVE-PARTICLE EXPERIMENTS USING VLF WAVE INJECTION

A magnetospheric wave-particle experiment is to be carried out at Siple Station, Antarctica, by R. Helliwell. Very low frequency radio waves are to be injected into the magnetosphere at L = 4 for the purpose of stimulating emissions and causing precipitation of energetic electrons. A 100 kw transmitter operating in the 4 to 30 kHz range will drive a 13-mile long horizontal electric dipole located about 15 feet above the snow surface. The first experiments will be performed at 6 kHz, which is one-half the minimum gyrofrequency on the field line through Siple, Antarctica. The conjugate station at Roberval, Quebec, will observe the whistler-mode signals and triggered emissions. Observations of particle precipitation will be made at Siple, using various conventional methods, such as balloon-borne x-ray detectors, riometers, VLF propagation, auroral photometers, etc. Satellites will observe the triggering of nonducted VLF emissions and the modification of the pitch angle distribution of energetic electrons interacting with the injected waves.

The purpose of this experiment is to advance our understanding of the mechanism by which coherent waves interact with energetic electrons. Current theories of wave-particle interactions have not been able to explain many of the observed results. Improved experiments are needed to show quantitatively how the medium responds to known input waves. The planned experiments should lead to more realistic theories of wave-particle interactions. They should define more clearly the conditions under which amplification and attenuation of VLF waves may occur in the magnetosphere. They should also produce new information on the amount of pitch angle scattering of electrons under different conditions.

A novel feature of the wave injection experiment is the possibility for control of the precipitation of particles into the ionosphere. Specific experiments on the transient response of the ionospheric layers to known particle inputs can then be performed. Electron energies

from 1-200 kev should be readily accessible to VLF waves. Already it has been found that whistlers appear to dump 50-100 kev electrons into the nighttime D region at mid-latitudes. These events cause perturbations in VLF propagation lasting 30 seconds or so. Another experiment has shown that whistler-triggered rising emissions produce bursts of Bremsstrahlung x-rays at 30 km altitude. It may be possible in the new controlled experiment to find related effects in the E region and possible the F region.

Another objective of the experiment is to vary the precipitation rate so as to modulate the conductivity of the D region, thereby exciting micropulsations. If this could be accomplished, we would then have a new tool for the study of hydromagnetic emissions.

There are many types of measurements which will be of interest in studying wave-particle interactions using VLF wave injection. Any method which is capable of producing high time resolution data on properties of the ionosphere would be useful in this experiment. This includes radio, particle and optical measurements. Examples are detection of propagation disturbances from LF to HF, measurement by ionosonde of the fluctuations in ionospheric layers, measurement of the electron density and other ionization parameters using incoherent scatter. Riometers, magnetometers, etc., will be useful. All-sky cameras, auroral photometers can be used to search for optical emissions connected with the precipitation of energetic particles. Of great importance is the use of satellites for monitoring the energetic particle distribution and for detecting the VLF waves created in the magnetosphere. An important point is the difference between the properties of ducted and nonducted VLF waves. Ducted waves reach the ground and can be monitored best by receivers on the ground. Nonducted signals seldom if ever are detectable on the ground, but are readily seen by satellites. It is expected that the injected VLF waves will interact strongly with electrons in both the ducted and nonducted propagation modes. Since only the ducted signals can be observed on the ground our picture would be incomplete without simultaneous observations of the ducted waves.

Although a special transmitter is being employed in the current experiments, it is well to keep in mind that existing VLF transmitters can be used in a limited way in this type of work. Signals from Station NAA, NSS, NWC, the Omega network, and various other transmitters can be used. However, their use is generally limited to only a few modulation functions and fixed frequency and power.

Wave-particle experiments using only ground-based transmitters are significantly limited in two ways. First, the maximum injected wave field is limited to perhaps 1-10 mγ in the equatorial plane for practical transmitters of the 1 Megawatt class. A second, and more fundamental, limitation is the narrow range of injected wave normal directions that can be excited from the ground. This limitation is a direct result of Snell's law and the high refractive index of the ionosphere at VLF. Both limitations can be removed by injecting the waves from a satellite VLF transmitter. Dipoles or loops (superconducting loops may be feasible) can be used with transmitter powers of 100-1000 watts to conduct a wide range of wave-particle and propagation experiments. A satellite VLF transmitting experiment is a natural and necessary second phase in a VLF wave injection program.

The wave injection experiments outlined above would also be useful for the support of experiments on the effects of cold plasma injection. Thus, when a cold plasma injection is made it is necessary to determine the kind of wave-particle interactions that can occur. In proposals for this experiment it has been assumed that spontaneous emissions will occur and their properties will then be used to check the theory. However, it is well known that a plasma may remain quiescent until an external signal is introduced. Therefore, it is essential that the cold plasma injection experiments be carried on under conditions where a signal can be injected for the purpose of exciting latent instabilities.

Relating to this Siple Station experiment is one by Aerospace from Alaska. A balloon borne VLF antenna will be used to transmit to the conjugate point in New Zealand.

C. ARTIFICIAL ULF GENERATION

Several techniques have been tried or are being designed to generate ULF waves. The feasibility of generating micropulsations is not yet established.

1. Ground-Based ULF Generator

A means of artificially producing geomagnetic micropulsations by using a large horizontal current loop on the ground has been designed (Fraser-Smith et al., 1972). Most natural micropulsations appear to be produced by MHD waves propagating in the ionosphere or magnetosphere.

The loop would generate MHD waves in the E region of the ionosphere which would radiate micropulsations of 10 to 100 $m\gamma$ amplitude. Placing a large loop of about 100 km diameter in a region of very low conductivity should yield a magnetic moment of 7×10^{13} A m^2. Pulsing the loop current at about 1 Hz should produce the micropulsations in the E region.

The problem of coupling the ULF waves out of the ionospheric duct must be calculated much better.

The cost of such an installation is estimated to be $1,000,000 to $10,000,000 depending on the degree of sophistication.

2. NRL Experiments

NRL has in two different experiments attempted to produce ULF waves by means of perturbing the ionospheric dynamo current system. The first method attempted to apply a large transient stimulus to the lower ionosphere currents through the explosive release of ionized cesium clouds at 100 to 140 km altitude. Calculations had indicated that under the existing geophysical conditions (dawn period, equinox) only a small

perturbation of about 10^{-2} γ should have been observed on the ground in the vicinity of the release. In one release, a disturbance of this magnitude may have occurred. No propagating ULF waves were detected; however, it must be noted that both the release timing and magnetometer sensitivity were less than optimum for these initial attempts. The second approach involved RF heating the E layer at Boulder, with the ionospheric heater modulated at ULF frequencies. Analysis of the data from this experiment indicates that the received signals are down by a factor of 10 from the predicted values, and it is not certain that they result from the suggested mechanism. Both experiments are likely to be repeated in the near future.

D. PIGGYBACK SATELLITE PLASMA INTERACTION EXPERIMENT

To investigate WPI's one must simultaneously measure the energetic particles, plasma, waves, and fields. The data requirements are summarized in Section IV.

The details of the payload which has been proposed for making WPI measurements near synchronous orbit (the Plasma Interaction Experiment) are shown in Table I. The proposed payload consists of flight spare experiments that have been flown previously on the NASA ATS-5 satellite, the NASA OGO-5 satellite, and the STP 71-2 satellite. The estimated budget to cover modification, refurbishing, calibration of the instruments and to cover experimenter participation in integration of the payload is estimated to be $368,000 if NASA Goddard fully funds the instrumentation listed for them in Table I. The remainder of the costs associated with the integration, spacecraft, and launch are expected to be paid for through the Space Test Program of the Air Force.

The payload proposed in Table I does not contain ULF magnetic field detectors which are considered to be essential. More detail is needed on the sensitivity and adequacy of instruments proposed for measurement of the fields and waves. The cost will be somewhat higher when a complete set of instrumentation is included.

The presently proposed synchronous satellite will form a measurement base around which many coordinated experiments pertinent to ionospheric modeling and wave amplifications through WPI processes can be studied. The following is a list of fundamental scientific problems which can be studied both by the satellite alone and by correlated measurements with other experimental bases.

A fully instrumented satellite payload at synchronous orbit is particularly useful for simultaneously measuring the particle, plasma,

Table I

PLASMA INTERACTION EXPERIMENT

Instrumentation:

3DLE (UCSD) - Measures 50 eV - 50 KeV protons and electrons using 4 different sensors.

ODME (UCSD) - Measures 300 KeV to 5 MeV electrons and > 12 MeV protons.

3DME (UCB) - Measures > 30 KeV electrons and 30 KeV to 250 KeV protons with three sensors directed parallel and perpendicular to B.

TDMS (LPARL) - Measures composition, density, temperature, and bulk flow velocity of the cold plasma (0 → 100 eV). Uses 4 sensor heads directed parallel and perpendicular to B.

HI (LPARL) - Measures energetic ions in the range 100 eV → 12 KeV and electrons in the range 500 eV → 50 KeV.

Electric Field (NASA Goddard) - 2-axis measurement of E-field from DC - 10 Khz. (4-130 ft booms).

Solar Radio Burst (NASA Goddard) - Uses E-field booms to measure E-field frequencies from 50 Khz - 4 Mhz.

Magnetometer (NASA Goddard) - 3-axis Fluxgate magnetometer DC → 20 hz.

Total Weight For Instrumentation	75 pounds
Total Power	36 watts
Telemetry	6 kbits/sec

Planned Orbit - Near Synchronous with satellite located near the Chatanika field line for at least a three month period preferably in the fall and winter.

Anticipated Launch Date - Late '75 → '78.

and field environment along with waves. This will be useful for both artificial releases of lithium or barium and for natural proton plasmas.

Observations in the ionosphere on the field lines through the synchronous satellite combined with the satellite data can provide data on energy deposit in the ionosphere in a limited latitudinal band on the ground. The Chatanika radar in Alaska will fulfill these conditions on occasion. A VLF transmitter may be set up on the field lines to stimulate WPI's and precipitation. At these latitudes, the energy deposit will at least involve precipitation particles. Scanning photometers can cover a very large region of the ionosphere in a short period of time for correlation with the satellite for example.

If the Chatanika radar is on the same field line as the satellite, a measurement of $E_{\perp}$ at the satellite and a calculation of $E_{\perp}$ based on plasma flow observations at the radar may give a measure of anomalous resistivity along the field line and the effects of neutral wind on the ionospheric plasma distribution. Plasmasphere-ionosphere coupling may be measured by comparing the flow along the field line at synchronous orbit with the height distribution of ionization measured simultaneously at the foot of the field line at Chatanika.

Two closely spaced satellites at synchronous orbit are required to separate temporal and spatial effects. This satellite might be placed near to GEOS, for example to separate spatial and temporal effects. It is important to remember that a single satellite cannot tell where particles, plasma, and waves are going after detection or where they have come from.

E. A TENTATIVE PLAN FOR A VLF THREE-WAVE INTERACTION EXPERIMENT

1. Introduction

Under certain circumstances, it may be possible for electromagnetic energy to be coupled between waves of different types in the magnetosphere. For example, a three-wave interaction could involve two VLF waves (which might be considered analogous to the "pump" and "idler" waves in a laser or parametric amplifier) interacting to yield a wave at the difference frequency (the "signal") which might fall in the ULF band (nominally 0.5 to 5.0 Hz). Such an interaction would require very high pump wave field strengths in the interaction region, and it is precisely for this reason that VLF pump and idler waves are proposed.

The virtue of employing a VLF pump and idler is that the magnetospheric trapped electron belt causes amplification to VLF waves in a manner directly analogous to that in which it is believed trapped protons (or ions) can amplify ULF waves. Indeed, the amplification limits for VLF waves may exceed the limit of 30 dB or so calculated for ULF waves. It should be possible to transmit VLF pump and idler waves from below the ionosphere into field-aligned ducts, which will direct them into the region of the magnetosphere where they can be amplified by electron cyclotron interactions with trapped electrons. The amplified VLF waves may then exceed the threshold for commencement of a three-wave process whose product will be the desired ULF signal. This signal, which may undergo further amplification due to cyclotron interaction with the resident protons, can then descend through a series of interactions analogous to those which are appropriate to Pc 1 micropulsations and be detected by earth-based sensors. Because the VLF transmitter is controlled, coherent integration may be used for signal processing, with a predetection bandwidth narrowed about the modulation spectral peak (the difference frequency between pump and idler) to as narrow a passband as the propagation medium and operational considerations will allow. Bandwidths of hundredths of Hertz would

seem to be allowed in view of the fact that VLF magnetospheric ducts normally have lifetimes of tens of minutes.

To properly assess the possibility that a three-wave process involving VLF pump and idler waves and a ULF signal wave can take place in the magnetosphere, it is necessary to consider the three-wave interaction problem in a plasma in which both electrons and ions are active participants. There is evidence, albeit slim, that three-wave interactions may occur naturally. Fraser-Smith has suggested that atmospheric discharges may be a cause for Pc 1 micropulsations and if so, a three-wave interaction could be the coupling mechanism.

In order to bring about magnetospheric amplification of VLF pump and idler waves, so that the relatively weak fields of earth-bound transmitters may be increased to the magnitude which is necessary to trigger the interaction, it is necessary to consider the typical frequency ranges in which such amplification is observed naturally and investigate the sites of available VLF transmitters. VLF whistlers are most commonly observed at between three-tenths and five-tenths of the equatorial electron gyrofrequency along a similarly defined magnetic field line. Considering the latitudes, available tuning ranges, and normal transmitting frequencies of three U.S. Navy VLF Stations (NPG, NAA and NSS) it was determined that NAA may be used to create ULF waves at a frequency below 5 Hz.

2. Planned Experiment

The VLF Station NAA (Cutler, Maine) is geographically best suited of all Navy VLF transmitters for conduct of a three-wave interaction experiment. The use of NAA requires a transmitting frequency near the 14.0 kHz lower tuning extreme of that transmitter to be employed. The allocated frequency of 14.7 kHz will be acceptable. In order to conduct a thorough investigation of the phenomena of interest, it will be necessary to repeat the basic experiment several times over a period of a few weeks. Because the most desirable conditions for ULF wave

reception at earth-based terminals exist in the midnight-to-dawn hours, it is proposed that the experiment be conducted nightly during the hours of midnight to 0800 local standard time at the transmitter.

It is suggested that mid-fall (October and November) will permit acceptable performance for VLF communications at 14.7 kHz. The month of October is desirable from the standpoint of field logistics in transporting, emplacing, and manning the ULF experimental receiving apparatus. It is suggested that the transmitter be shared equally between experimental and routine operations. Commencing at 0000 each night, the transmitter will be devoted to routine traffic for one half-hour, followed by one half-hour of experimental operation, in which one complete "basic" experiment will be performed. The basic experiment will consist of transmission in a balanced-modulated format with a sidetone separation of 5 to 20 Hz for twenty minutes. This period will be followed by two minutes of one-quarter Hertz, 50% duty cycle square wave modulation (2 seconds on, 2 seconds off), and by eight minutes of quiet. Parameters will not be changed during the half-hour period of a basic experiment, but changes of modulation bandwidth (i.e., sidetone separation) or pulse repetition frequency in the square wave mode, may be made between experimental cycles.

The ULF receiving apparatus will be located at one or two sites several tens of kilometers from the transmitter. Telephone communications will be necessary between all three sites on an intermittent basis.

F. GEOS

The ESRO geostationary satellite, GEOS, is to be launched in July 1976 to make integrated scientific studies of the distribution of thermal plasma, energetic particles, fields, and waves. It will be placed on the magnetic field lines through Iceland part of the time and on the field lines through Kiruna part of the time.

The satellite will be very well instrumented to investigate WPI's. The instrumentation includes: energetic protons, energetic electrons, ion composition, electron density, dc magnetic fields, electric fields (dc to 77 kHz), and ac magnetic fields. Three search coils will be used to measure 0.1 to 300 Hz with a sensitivity of 10^{-4} mγ Hz$^{-1/2}$ at 1 Hz and 3 coils for VLF at 0.3 to 10 kHz with a sensitivity of 10^{-6} mγ Hz$^{-1/2}$ at 1 kHz.

Transmission experiments are also carried on GEOS.

1) Pulse: Duration 3.3 ms, amplitude -50 Vrms, applied to a dipole antenna 40 m tip-to-tip, transmitted frequency stepped from 450 Hz to 74 kHz with a frequency step of 300 Hz. The frequency stepping may be performed either automatically or on manual command from the ground. Therefore, it is possible to sweep the whole frequency range in 30 s or to transmit only on any one of the listed frequencies.

2) CW: 1 V peak from 14 to 457 Hz with a frequency step of 4.7 Hz or from 450 Hz to 75 kHz with a frequency step of 300 Hz. This voltage is applied between two meshed spheres located 1.4 m apart and 3 m from the spaceship.

Cooperative experiments with GEOS will be carried out from ground stations, with balloons and rockets. In addition, it was felt that if a well instrumented geostationary satellite were moved to

within about 100 km of GEOS, then space-time uncertainties could be minimized. The potential use of lithium and barium plasma injection is viewed with caution by the GEOS experimenters until it can be proven that such releases will not harm the experiments.

G. ARAKS

The French and Soviets are preparing for a cooperative conjugate experiment between Kergulen Island and Soyza. Two rockets will be launched in January 1975 from Kergulen carrying an electron gun to ~ 350 km altitude. A 0.5 to 1A beam of 15 keV electrons will be fired at different angles to the magnetic field to measure backscattering and coulomb scattering. An instrument package will be separated from the rocket to make ULF (0.1 to 5 Hz) and VLF (20 Hz to 100 kHz) observations.

H. AEC PLANS

The AEC (Los Alamos Scientific Laboratory) plans to detonate lithium and barium liner shaped charges up the magnetic field lines from Alaska in late 1973 or later. These artificial releases could provide ULF or VLF amplification which might be observable.

VI. SUMMARY

A. IMPORTANCE OF WPI

Wave-particle interactions play an important role in the transfer of energy from the magnetosphere to the ionosphere. The transfer of energy is in several forms: heat, energetic particles, and currents. The deposit of this energy significantly affects the ionization, temperature, structure and dynamics of the high latitude ($> 45^\circ$ Inv Lat) D, E, and F regions of the ionosphere. Current ionospheric models do not include the effects of these energy sources.

WPI's play a crucial role in the amplification of ULF and VLF waves. The applications of using wave amplification for communications or blackout do not look very promising; however, the data base on which to evaluate systems applications is extremely limited.

B. IONOSPHERIC MODELING

The ionospheric effects measurements must be an integral part of any experiment pertaining to ionospheric-magnetospheric coupling. The various ionospheric observations should be delineated.

Some data are available and would be useful for studying ionospheric-magnetospheric coupling and ionospheric modeling. Particularly useful for energy diffusion and ionospheric effects are the optical, plasma and particle data from the ISIS satelite.

C. SYSTEM APPLICATIONS

The results of the analyses to investigate cold plasma injection to stimulate WPI's for application to military long wavelength communications are more or less negative, primarily as a result of a lack of a good data base on WPI's.

D. THEORY

More complete and accurate modeling (analytical and numerical) of magnetospheric WPI's is needed with important nonlinear effects explicitly included. While some nonlinear work is in progress for VLF, little has been done for ULF.

Theory requires more experimental data in order to make much progress. A satellite payload must have a set of instruments to measure the particles, plasma, fields, and waves with sufficient sensitivity to be of any value for theoretical efforts.

E. EXPERIMENTS

Analysis of the magnetospheric barium release data provides information on plasma behavior of use for planning WPI experiments on artificial releases. The currently funded effort should be sufficient.

Analysis of OGO 5 data is limited to WPI studies for energetic electrons > 50 keV and waves in the ELF (40 to 120 Hz). No search coil magnetometers were carried to measure ULF in the 0.1 to 5 Hz range. The ULF fluxgate magnetometer is too insensitive for WPI investigations. It is doubtful if OGO 5 data can be extrapolated into the ULF region for input to theoretical studies. Some of the results from OGO 5 may be applied to the VLF region of interest (400 to 1500 Hz), although the effects of electrons < 50 keV are not included. Analysis of OGO 5 data would give information on the probability of natural occurrence of ELF associated WPI's at synchronous orbit.

The Siple Station VLF experiment will provide much useful data for L = 4. The interpretation of these data should lead to much improvement in the theory which also will be applicable to higher L shells. The Aerospace VLF experiment in Alaska will be quite useful for improving the data base on VLF.

The experiments to investigate the production of ULF waves by cesium releases in the E region or the Boulder RF heater do not look very promising as long as the ULF waves are looked for on the ground.

The ground based loop ULF generator appears feasible but will cost $1,000,000 or more. It should probably be located at high L shells.

Artificial releases of lithium to investigate ULF wave amplification and barium for VLF wave amplification still appear feasible. The AEC will probably develop suitable release packages. The damage to satellite instruments used in WPI experiments from Li deposit requires study.

The French and Soviets are maintaining much research in VLF and ULF waves, amplification, and conjugate region experiments.

The ESRO satellite GEOS will be the only carefully designed WPI experiment in orbit (launch July 1976), containing a full complement of particle, plasma, field, and wave measuring instruments with careful attention given to magnetic cleanliness. The experimenters are interested in cooperative experiments such as artificial releases and a nearby satellite.

The proposed ARPA/ONR Piggyback Satellite at synchronous orbit will be particularly useful for simultaneously measuring particles, plasma fields, and waves in the natural magnetosphere or from lithium and barium releases. More careful attention needs to be given to the wave and field instruments for this satellite payload. The costing needs to be more carefully estimated. After a proper payload is selected, fixed price proposals should be obtained from all experimenters, since this concept is only modification of spares. This will allow exact costing. The intent of NASA Goddard to participate and Space Test Program to pay for all other costs must be verified.

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