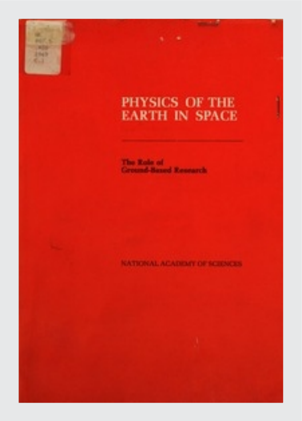


Physics of the Earth in Space: The Role of Ground-Based Research

DETAILS

159 pages | 6 x 9 | PAPERBACK
ISBN 978-0-309-01759-6 | DOI 10.17226/20605

AUTHORS

Committee on Solar-Terrestrial Research; Geophysics Research Board; National Research Council

[illegible]
10-4

PHYSICS OF THE EARTH IN SPACE

The Role of Ground-Based Research

Report of a Study by the

Committee on Solar-Terrestrial Research

of the

Geophysics Research Board

National Research Council

July 1969

NATIONAL ACADEMY OF SCIENCES
Washington, D.C.
1969

Standard Book Number 309-01759-9

Library of Congress Catalog Card Number 77-604140

Available from

Committee on Solar-Terrestrial Research
2101 Constitution Avenue
Washington, D.C. 20418

Preface

This is the report of a Study convened by the Committee on Solar-Terrestrial Research of the Geophysics Research Board to survey the present status and future directions of ground-based research in solar-terrestrial physics. It complements a 1968 Space Science Board study of research in related disciplines, using spacecraft and sounding rockets. Recommendations are based on an evaluation of new techniques now available or feasible, our state of understanding after a decade of space research, fundamental unanswered scientific questions, and current demands on our nation's resources.

The one-week Study was conducted at Snowmass-at-Aspen, Colorado, July 13-16, 1969, under the chairmanship of Herbert Friedman. The forty-six participating physical scientists were specialists in the techniques of ground-based solar-terrestrial research: solar observations, cosmic-ray and geomagnetic measurements, and electromagnetic probing of the magnetosphere, ionosphere, and upper atmosphere. The recommendations of the Study were presented to officials of interested federal agencies on the final day of the Study and were endorsed by the Committee on Solar-Terrestrial Research on September 29. The report was reviewed by the Geophysics Research Board and the Space Science Board.

The Geophysics Research Board is grateful to the participants in this Study, to William C. Bartley, secretary of the Committee on Solar-Terrestrial Research, who served as staff officer for the Study, and to Miss Ann Wagoner and Mrs. Jacqueline Boraks, for their contributions to the report's preparation. The Board acknowledges with appreciation the support of the National Science Foundation, the Air Force Cambridge Research Laboratories, the ESSA Research Laboratories, and the National Aeronautics and Space Administration, which helped to make this study possible.

Thomas F. Malone, *Chairman*
Geophysics Research Board

COMMITTEE ON SOLAR-TERRESTRIAL RESEARCH

Herbert Friedman, *Chairman*

Sidney A. Bowhill (*ex officio*)
John W. Firor
Richard M. Goody
William E. Gordon
James P. Heppner (*ex officio*)
Francis S. Johnson
Edward P. Ney
Eugene N. Parker
Juan G. Roederer (*ex officio*)
Donald J. Williams (*ex officio*)

William C. Bartley, *Secretary*

PHYSICS OF THE EARTH IN SPACE: STUDY PARTICIPANTS

Herbert Friedman, *Chairman*

Jules Aarons
Air Force Cambridge Laboratories
Syun-Ichi Akasofu
University of Alaska
Leroy R. Alldredge
Environmental Science Services Administration
Siegfried J. Bauer
National Aeronautics and Space Administration
Henry G. Booker
University of California, San Diego
Sidney A. Bowhill
University of Illinois
Neil M. Brice
Cornell University
Wallace H. Campbell
ESSA Research Laboratories
Herbert C. Carlson
Arecibo Ionospheric Observatory
Donald L. Carpenter
Stanford University ?
Paul J. Coleman
University of California, Los Angeles
T. Neil Davis
University of Alaska
Thomas M. Donahue
University of Pittsburgh
John V. Evans
Lincoln Laboratory
John W. Evans
Sacramento Peak Observatory
Richard M. Goody
Harvard University
William E. Gordon
Rice University
action Fred T. Haddock
University of Michigan
John P. Hagen
Pennsylvania State University
Robert A. Helliwell
Stanford University
Robert F. Howard
Mount Wilson and Palomar Observatories
Harold B. Liemohn
Boeing Scientific Research Laboratory
Millett G. Morgan
Dartmouth College
John P. Noxon
Harvard University
Martin A. Pomerantz ✓
Bartol Research Foundation
Juan G. Roederer
University of Denver
Alan H. Shapley
ESSA Research Laboratories
Margaret A. Shea
Air Force Cambridge Research Laboratories
Don F. Smart
Air Force Cambridge Research Laboratories
Ernest K. Smith
ESSA Research Laboratories
Masahisa Sugiura
National Aeronautics and Space Administration
William R. Webber
University of New Hampshire
Harold Zirin
Mount Wilson and Palomar Observatories

William C. Bartley, *Study Director*

Correspondents

James R. Barcus
University of Denver
Donald T. Farley
Cornell University
Anthony J. Ferraro
Pennsylvania State University
William B. Hanson
University of Texas at Dallas
Hai-Sup Lee
Pennsylvania State University

Government Agency Contributors

Albert E. Belon
National Science Foundation
Thomas D. N. Douthit
Air Force Cambridge Research Laboratories
Harold Glaser
National Aeronautics and Space Administration
F. Harold Leinbach
Environmental Science Services Administration
Frederick Reder
Department of the Army
J. William Wright
Environmental Science Services Administration

Summary of Major Recommendations

NEW PERMANENT FACILITIES

- We *recommend* a new facility, capable of fully exploiting incoherent-scatter techniques, for investigation of ionospheric and magnetospheric dynamics (Recommendation 1, p. 123).

- We *recommend* a program of controlled sounding of the magnetosphere based on a new vlf transmitter facility near 60° invariant latitude in the Antarctic and directed toward diagnostics of thermal and energetic components of the magnetospheric plasma (Recommendation 1, p. 95).

- We *recommend* relocation of the Stanford Research Institute's incoherent-scatter facility at Palo Alto, California, to the auroral zone at College, Alaska, to measure *F*-region electron density and temperature and ion temperature (Recommendation 3, p. 150; Recommendation 3, p. 124).

GREATER UTILIZATION OF EXISTING FACILITIES OR APPROACHES

- We *recommend* increased support for specific solar radio-astronomy techniques (Recommendation 1, p. 38).

- We *recommend* daily 3-mm observations of solar plages by a 36-ft telescope for a period of time sufficient to assess its effectiveness in mapping detailed variations in plages (Recommendation 1c, p. 39).

- We *recommend* continued support of existing facilities for aeronomical research at Jicamarca, Peru; Arecibo, Puerto

Rico; and Millstone Hill, Massachusetts (Recommendation 2, p. 123).

■ We *recommend* development of new ionosondes incorporating modern data-retrieval techniques for the study of ionospheric dynamics, with some to be located at aeronomic research centers (Recommendation 5, p. 125).

■ We *recommend* increased effort in laboratory aeronomic work on reaction rates associated with atmospheric optical emission (Recommendation 1, p. 150).

■ We *recommend* that Data Centers in the United States be strengthened, particularly in the fields of data digitization, rapid collection and distribution of data relevant to routine monitoring of the solar-terrestrial environment, and production of easily assimilated material such as geophysical indices (Recommendation 5, p. 78).

■ We *recommend* the implementation of problem-oriented programs of coordinated satellite and ground observations to study specific multidisciplinary questions (Interdisciplinary).

MODERNIZATION OF EXISTING FACILITIES OR TECHNIQUES

■ We *recommend* specific improvements in balloon technology (Recommendations 4 and 5, p. 58; Recommendation 9, p. 59).

■ We *recommend* acquisition of ground-based geophysical data via satellite links, possibly using a COMSAT channel (Recommendation 2, p. 76).

■ We *recommend* a study of the feasibility of replacing variometers at geomagnetic observatories with automatic, internationally standardized magnetometers and digital data-recording systems (Recommendation 3, p. 77).

■ We *recommend* implementation of multistation recording of broadband whistlers to study plasmasphere dynamics and a feasibility study of worldwide plasmapause monitoring using whistlers with standardized recording and analysis (Recommendations 3 and 4, p. 95).

■ We *recommend* simultaneous operation at the same site of partial-reflection sounding, cross-modulation, and radio-rocket probing techniques of the lower ionosphere for resolving electron-density profiles (Recommendation 1, p. 134).

■ We *recommend* comparison of radio-drift and radar-meteor techniques with rocket or gun techniques, at the same site, to select the best means of probing wind fields in the lower ionosphere (Recommendation 2, p. 134).

NEW TYPES OF INSTRUMENTATION

■ We *recommend* development of a scanning radiometer in the midcentimeter range for a "TV" picture of the sun (Recommendation 1a, p. 38).

■ We *recommend* a design study of a two-element interferometer (10-100 GHz) and utilization of existing interferometers in the centimeter band for solar active-center observations and development of broadband microwave (1-10 GHz) systems for continuous measurement of the magnetic polarization (Recommendation 1b, p. 38; Recommendation 1e, p. 39).

■ We *recommend* development of devices for measuring solar magnetic vector fields, in high resolution and short time scale, for active-region observations (Recommendation 3, p. 40).

■ We *recommend* development of a new high-counting rate (10^6 counts per hour) instrument for ground-based studies of cosmic-ray modulation and anisotropies (50-500 GeV) and development of new instruments for balloon use with large area and high charge resolution (Recommendations 4 and 6, p. 58).

NEW MOBILE STATIONS

■ We *recommend* deployment of mobile neutron detector units for specific, limited-term, cosmic-ray investigations (Recommendation 3, p. 57).

■ We *recommend* establishment of a capability of flying very large balloons in the polar-cap regions for simultaneous measurements of cosmic-ray anisotropies at conjugate points (Recommendation 5, p. 58).

■ We *recommend* development of low-cost, transportable geomagnetic observatories for study of special magnetospheric problems (Recommendation 1, p. 76).

■ We *recommend* a feasibility study of a floating incoherent-scatter facility for use in cooperative experiments with land stations, at magnetically conjugate points, or as a remote receiving station (Recommendation 4, p. 124).

1 Perspectives

INTRODUCTION

This study was convened by the Committee on Solar-Terrestrial Research of the National Academy of Sciences Geophysics Research Board to examine the present status of ground-based solar-terrestrial research and to recommend directions for future research over the next 5 to 10 years. Major scientific questions concerning solar-terrestrial physics that remain to be answered after a decade of space research were identified in the Space Science Board's 1968 Woods Hole Study, *Physics of the Earth in Space--A Program of Research: 1968-1975*. In that study it was concluded that a coordinated program of ground-based, balloon, aircraft, rocket, satellite, and space-probe measurements is needed to answer these questions. As a first step toward formulating such a program, *in situ* space techniques were examined and a specific program for satellite and space-probe research through 1975 was recommended. Fundamental questions which can be approached most directly through rocket techniques are discussed in a 1969 Space Science Board report, *Sounding Rockets: Their Role in Space Research*.

An equally urgent task remained, namely, to examine in detail the future of ground-based solar-terrestrial research. The present study group was asked to consider the broad aspects of ground-based techniques (understood to include aircraft and balloons) and to provide guidance to the National Science Foundation, ESSA Research Laboratories, the National Aeronautics and Space Administration, and research activities within the Department of Defense in planning the most desirable over-all program.

This report may be considered as Volume 2 of *Physics of the Earth in Space*, of which the 1968 Woods Hole report was Volume 1. Much of the background material covered in the earlier report is equally relevant to the present study and is therefore not repeated here. The report consists of eight chapters. Chapters 2 through 8 discuss seven categories of ground-based solar-terrestrial measurements--solar, geomagnetic, cosmic-ray, whistler and other wave phenomena, incoherent scatter and radio probing of the upper and lower ionosphere, and optical aeronomy. These chapters were prepared by individual groups of participants, with joint sessions and interchange of members as subject matter dictated. Background papers were prepared and circulated in advance of the study as a point of departure for working group discussions. Based on the working group findings, the study group as a whole agreed on the priorities and recommendations set forth in the Summary of Major Recommendations.

PERSPECTIVES

Natural science has a history as old as civilization. Through the Chinese and Korean chronicles of auroral events we can trace solar cycles back as far as 1000 B.C. In recent times, solar-terrestrial research has moved forward with great strides: most notably in the growth of geomagnetic observations during the nineteenth century and the development of radio science in the early twentieth century. The global nature of geophysical research has always been its distinguishing characteristic, and it was entirely natural that geophysicists should initiate the great multination scientific efforts of the two International Polar Years, the International Geophysical Year, and the International Years of the Quiet Sun. Apart from the intellectual and applied values of geophysical science itself, the intrinsic values of such international cooperation could justify our continuing concern for the future health of solar-terrestrial research.

Scientific satellites in earth orbit, surveying circumterrestrial space with a global eye, have elevated solar-terrestrial research to an entirely new perspective. When the IGY combined the power of space technology with the widespread international resources for ground-based geophysics, our understanding of the sun-earth system achieved remarkable progress.

The spectacular discoveries of space research during the past decade have tended to overshadow the role of ground-based studies. But we must recognize that, in the same period, ground-based research has responded to the challenges of space discoveries with a quiet revolution of its own. The mature development of the broad field of solar-terrestrial physics requires the most intimate coordination of ground-based and space-based scientific programs. If the future efforts are properly joined, the total scientific yield will be enormously increased.

The Sun-Earth System

We begin with a discussion of the sun, tracing its influence through the interplanetary medium to near-earth space over the entire electromagnetic spectrum (the power emitted by the sun is $\sim 4 \times 10^{33}$ ergs sec^{-1}, of which $\sim 5 \times 10^{24}$ ergs sec^{-1}, or 5 million horsepower per sq mile, irradiates the atmosphere of the earth). Ionizing x rays and ultraviolet radiation, which constitute only $\sim 10^{-5}$ percent of the solar flux ($\sim 5 \times 10^{19}$ ergs sec^{-1}) are absorbed in the outer atmosphere to produce the ionosphere. A considerably greater amount of energy, $\sim 10^{20}$ ergs sec^{-1}, arrives at the magnetosphere in the form of solar-wind plasma, even under solar-quiet conditions. When the sun is intensely active, the energy delivered in ionizing radiations, both electromagnetic and corpuscular, can increase by orders of magnitude. No comparable energy supplies are available elsewhere in the sun-earth system. The earth itself has a store of 10^{37} ergs in kinetic energy of rotation, the energy content of the outer geomagnetic field is about 10^{25} ergs, and the reservoir of energetic particles in the Van Allen belts holds less than 10^{22} ergs. But only a tiny fraction of the kinetic energy of rotation can be dissipated in the magnetosphere, and all the energy in the radiation belts is far from sufficient to account for the luminosity of a typical aurora. Only the sun is capable of activating the entire environment of space and generating the vast complex of geomagnetic and ionospheric storm responses of near-earth space.

A great flare on the sun can release $\sim 10^{32}$ ergs in x-ray ultraviolet and energetic-particle radiation. Every link in the system from sun to earth reacts to such a catastrophic event. After interacting with the interplanetary medium, the magnetosphere, and the upper atmosphere, the last residue of energy from the sun's explosive gift to earth is a faint red airglow that suffuses all the sky from north pole to south pole. Although the glow is composed only of the single, characteristic emission line of oxygen at 6300 A, following a great flare the full sky may radiate 10^{23} ergs of this monochromatic energy. This aeronomic "death rattle" of the violent solar explosion is equivalent of the energy of dozens of megaton H-bombs. Such is the power of solar influence on terrestrial events.

The goal of ground-based solar-terrestrial research is to trace all the links in this chain from our distant point of view. Radiant signals from remote processes can be observed only in the limited ranges of the optical spectrum, in radio waves and energetic particles that can penetrate the atmosphere, and in the geomagnetic field. Yet the information transmitted through these "windows" is vast, and the variety of natural test sources and tracers in space offer fine diagnostic capabilities. Cosmic-ray investigators regard the earth itself as a giant spacecraft--an interplanetary monitoring probe. The earth's magnetic field and atmosphere are ideal for analyzing high-energy (>500-MeV) solar-particle radiations which are beyond the instrumental sensitivity of present space probes.

The Interplanetary Medium

A brief look at some of the developments leading to our present understanding of the solar wind can provide interesting examples of the interplay of ground-based and space-based investigations. In theory the solar wind is a direct consequence of coronal heating. In the development of the theory all the varied solar observations that contribute to our knowledge of the coronal temperature profile were invoked. The wind carries away from the corona ten times as much energy as is radiated in electromagnetic waves; it effectively provides the thermostatic control that regulates the coronal temperature in the million-degree range. At the orbit of the earth, the wind is traveling at supersonic speed. Eventually it must terminate at some great distance (10 to 100 AU), where the dwindling ram pressure of the wind is finally matched by the opposing pressure of interstellar gas and magnetic fields. Closer to home, where the wind encounters the earth's magnetic field, a bow shock envelops the magnetosphere. Inside this geomagnetic trap are confined all the vast variety of physical processes that are identified with the new field of magnetospheric physics. Let us confine our attention here to the origin of the solar wind and its behavior in interplanetary space. The scientific questions concern the fine structure of the wind, the variation of flow as a function of heliographic longitude and latitude, nonradial motions, microscopic effects characteristic of collision-free plasma, anisotropy in the particle pressure distribution, and deviations from typical solar composition. Some of these characteristics, for example, ion composition, can be determined only by space-probe instruments; some, such as the variation of flow with heliographic latitude, are best detected by ground-based methods; but much of our understanding is derived from both space and ground-based data combined.

Classical methods of studying interplanetary plasma were largely confined to observing the deflection of comet tails, geomagnetic storms in the wake of solar flares, the solar-cycle modulation of cosmic rays, and the degree of polarization of zodiacal light. Systematic studies of comet tails were begun about a quarter century ago. The tail stretches away from the sun and typically lags by a few degrees from the comet-sun line. Within the comet tail itself, fine knots are accelerated away from the comet head up to speeds as great as 100 km sec^{-1}. Bierman, as early as 1951, attributed the lag effect and the internal acceleration to the pressure of a radial flow of solar protons which now has come to be known as the solar wind. Subsequent observations made it possible to identify activity in cometary tails with geomagnetic storms. We recognize now that comets offer unique possibilities for exploring the solar wind in regions inaccessible to space probes. Many comet orbits are highly inclined to the ecliptic plane and thus serve as probes of the wind at high heliographic latitudes and over a wide range of heliocentric distances. The comet Humason has provided a measure of the wind at 3 to 5 AU, much farther out than any spacecraft has yet traveled. From cometary data alone it is possible to conclude that the average solar wind speed is approximately 500 km sec^{-1} between the sun and earth, and that it varies in phase with geomagnetic activity but never falls below a minimum of approximately 150 km sec^{-1}. At 1 AU it exhibits a tangential velocity component of approximately 5 to 10 km sec^{-1}. All these results are consistent with direct observations from satellites and deep space probes.

The aurora phenomena and geomagnetic disturbances long ago provided important clues to the solar wind. From the time delay between a solar flare and the occurrence of an aurora and geomagnetic storm, solar-wind velocities of 1000 to 2000 km sec^{-1} had been inferred. When correlations are made between lesser forms of solar activity and geomagnetic disturbances that recur with the 27-day periodicity of the sun's rotation, we derive "quiet time" wind speeds of approximately 250 to 500 km sec^{-1}. Furthermore, it is even possible to infer fine structure in the wind that would suggest a tangling of fast and slow streams.

How large is the "heliosphere," the volume of space around the sun which is filled with plasma borne by solar wind? For one possible answer, we can turn to observations of the variation of cosmic-ray intensity near the earth. According to theory, galactic cosmic rays should be modulated by the solar wind; when the wind speed is high, the modulation region should be large, and cosmic rays should be more effectively excluded from the region near the earth. Modulation studies were an important component of the IGY program more than a decade ago. An 11-year cyclic modulation of cosmic rays was recognized, similar to the 11-year sunspot cycle, but the cosmic-ray modulation lagged behind the solar index, whether sunspot number or geomagnetic activity, by several months to a year. Since the solar activity indices correlate with speed of the solar wind, the cosmic-ray lag may be attributed to the time of buildup or filling of the modulation region by the solar wind. If the wind flows with a speed of 500 km sec^{-1}, a one-year lag implies a scattering volume of the order of 100 AU.

Over the past decade, ground-based radio observations have been a very fruitful source of evidence concerning the properties of interplanetary plasma. Somewhat analogous to the twinkling of stars seen through the atmosphere is the scintillation of small-diameter radio sources, such as the distant quasars, when observed through the interplanetary medium. Small-scale density fluctuations in the solar wind produce scintillations at rates up to ten per second. Sources can be selected at large angles from the sun, and scintillation has been observed even in the antisolar direction. The interplanetary medium not only causes scintillation of galactic and extragalactic radio sources but even produces similar effects on the radio emissions from Jupiter. A typical scale size of interplanetary plasma irregularities, as derived from scintillation analysis, is of the order of 100 km; the average electron density is inversely proportional to distance out as far as the earth's orbit and fluctuates ~ 2 percent about the mean value. Spaced radio receivers on the ground still show correlations in density fluctuations when the distances between stations are as large as 50 km, but when the distance is increased to the order of a few hundred kilometers, the correlations vanish. Thus we learn that electron-density fluctuations have a lifetime of the order of 0.1 sec and are not transported intact by the solar wind; what is more likely is that the fluctuations are a wave phenomenon. Further deductions from spaced receiver measurements are that average wind speeds are 300 to 500 km sec^{-1} and essentially radial and that the wind speed increases with heliographic latitudes--an observation consistent with deductions from cometary observations. Because such observations refer to regions inaccessible to rocket probes, they have especial value.

When cosmic radio sources are observed through the extended solar corona, they appear larger because the radio waves are scattered by refractive irregularities associated with electron-density variations. From the anisotropy of the scattering we can deduce filamentary shapes to the electron clouds. Furthermore, the orientation of the filaments identifies the magnetic-field direction and thus the solar-wind direction. Scattering measurements have been successful in probing the interplanetary space to half the distance from sun to earth. Typical of the results deduced is an upper limit of 5000 km to the filamentary length; scattering is strongest near the solar equatorial plane and is dependent on the solar cycle.

To obtain evidence of disturbances in the solar-wind flow close to the source, we have powerful techniques of solar radio astronomy. Solar flares produce large ejecta of plasma which are accompanied by blast waves that travel with speeds as great as 1000 km sec^{-1} and plasma oscillations that propagate through the outer corona at nearly the speed of light. Radio-frequency drift observations can be used to gauge the run of solar-wind density with radial distance out to approximately 5 solar radii. A limitation of ground-based observations is that 10 MHz is about the lowest frequency that can penetrate the ionosphere. Similar measurements have been made to frequencies as low as 0.9 MHz from satellites and deep-space probes and thus have extended the technique to heliocentric distances as great as 20 solar radii.

Radar reflections from the corona give cruder results but offer the hope of much further refinement. Signals reflected from coronal irregularities have indicated outward speeds of 200 km sec^{-1}. The observed Doppler broadening and wavelength shifts are indicative of an average outward flow of wind. Radar reflections from the moon could in principle provide information about the intervening plasma, but the evidence is strongly masked by the much larger effects of the ionosphere. However, when the radar is shifted to planetary targets, the integrated electron content beyond the earth's magnetosphere may be one or two orders of magnitude greater than within the magnetosphere.

The spectacular success of space probes in directly measuring solar-wind parameters has tended to overshadow the role of ground-based studies. In the above paragraphs examples have been offered to indicate how solar-wind diagnosis is attainable through studies of cometary tails, geomagnetic storms in relation to solar activity, cosmic-ray modulation, radio scintillations, radio scattering, solar radio noise bursts, and radar reflections. It should be abundantly clear how inherently powerful these methods are, particularly when combined with appropriate spot checks *in situ* by space probes to calibrate the continuously applicable ground-based techniques.

The Magnetosphere

The magnetosphere is the region of near-earth space threaded by magnetic field lines linked to the earth. It contains charged particles with a wide range of energies, from thermal energy to hundreds of millions of electron volts. This huge bag of plasma and energetic particles swells and contracts under the influence of the solar wind. Continuous pressure of the solar wind squashes the sunward side and combs the lines of force downwind into a long, stretched-out tail. Furthermore, like a bowl of jelly, it oscillates with characteristic time constants. The quasi-periodic recurrence of perturbations called "magnetospheric substorms" suggests that the geomagnetic cavity is constantly storing up energy until some fundamental instability causes an explosive release of this energy into the atmosphere. Large sudden changes in the solar-wind characteristics (for instance the arrival of a blast wave emitted by a large solar flare) cause sudden compressions of the magnetosphere, followed by an almost catastrophic shakeup and rearrangement of a large fraction of the particle population inside. Down on earth, this shakeup is seen as a spectacular succession of such geophysical events as polar lights or auroras, magnetic storms, and ionospheric storms. Historically, the systematic ground-based study of magnetic storms gave the first hint of the emission of plasma by the sun, and the study of auroras led to the first ideas about energetic-particle motion and energization in the earth's magnetic environment--well before the advent of the space age.

In general, almost every important perturbation at the surface of the magnetosphere or inside transmits characteristic magnetic signatures to the surface of the earth. Some types of geomagnetic measurements have been carried on for generations, often guided by an almost religious, ritualistic devotion to care of measurement and systematic archiving. Today we are grateful for these accurate records of a hundred years of geophysical history, because the revelations of space research now give clear meaning to such data. However, while the early instruments were adequate to respond to the slow magnetic variations in the development of global magnetic storms, they were much too slow to register the rapid oscillations called micropulsations. More and more magnetospheric wave phenomena are being recognized through these micropulsation signals with characteristic frequency bands, amplitude variations, and dispersion properties.

Information on surface magnetic field variations gathered on a worldwide basis is processed at various internationally operated centers and condensed into the values of so-called "magnetic indices." Among these magnetic indices, now compiled more or less routinely, are the following: Sq and L for dynamo currents induced by solar radiation heating of the upper atmosphere and by lunar tides, respectively; Kp for 3-h values representing planetary magnetic activity linked to solar-wind agitation and its effects on the magnetospheric boundary; AE for polar magnetic substorms indirectly measuring the intensity of the polar electrojet; and Dst relating to the magnetospheric ring current that intensifies during a geomagnetic storm. In general terms, geomagnetic observations give information on the most important electric current systems in the magnetosphere and, thus, indirectly on the driving electric fields and/or distributions of drifting charged particles. For example, perturbations in these various indices can be related to Chapman-Ferraro currents at 10 earth radii induced by pressure of the solar wind on the magnetospheric boundary, to tail currents that flow at 80 earth radii, to equatorial electrojets, to polar electrojets, and to various other current systems. The surface magnetic field, with the aid of physical models based on space measurements, can therefore be used to monitor a number of physical processes occurring in space during quiet and disturbed times.

The philosophy behind proposals to monitor magnetospheric behavior from the ground is to "calibrate" the ground observations with sufficient rocket and satellite measurements to establish the independent usefulness of surface data. Once the total complex of surface magnetic signatures is understood, the great versatility, continuity, mobility, and relative inexpensiveness of ground networks can be efficiently exploited.

Whistlers and the Plasmapause

Lightning flashes generate radio noise in the form of "whistlers," which propagate from one hemisphere of earth to the conjugate hemisphere along geomagnetic field lines that arch through the magnetosphere. The whistler is a dispersion phenomenon which depends on the electron density along the ducting path in which the wave is trapped. Sometimes, the whistler can be heard by simply connecting an antenna through an audio amplifier to a loud speaker. The name derives from the audio tone which glides from high to low frequencies.

Since the basic whistler phenomenon was first explained by Storey in 1953, there has been increasing recognition of many diversified forms of whistlers. The "knee" whistler, for example, identifies with a sharp decrease in electron density at about 4 earth radii. This boundary between high- and low-density plasma is called the "plasmapause" and encloses the "plasmasphere." Essentially all the atmosphere of the plasmasphere above approximately 1000 km is predominantly hydrogen. The volume is bounded approximately by the surface formed by revolving a geomagnetic field line that has an equatorial radius of about 4 earth radii about the geomagnetic axis. The actual equatorial radius of this very sharp boundary varies significantly with local time and solar activity. Ground-based whistler observations have been uniquely successful in tracing the variations of equatorial radius. At the same time, spacecraft observations of electron and proton densities have demonstrated that the plasmapause follows a field-line surface, or *L*-shell, down to lower altitudes at increasing latitudes. In fact, the plasmapause comes right down to the topside ionosphere.

As the equatorial radius of the plasmapause varies with local time and solar-terrestrial disturbances, so also does the latitude vary at which the plasmapause comes down into the topside ionosphere. Identifying this latitude continuously as a function of universal and local time and describing the plasmapause in the topside ionosphere is a problem of considerable challenge. Polar-orbiting satellites can see the boundary as they cross it; but because of their motion they are not suited to following the movements of the boundary. A ground-based incoherent backscatter radar can obtain electron and proton profiles of the topside ionosphere and can detect the latitudinal transit of the plasmapause; but to do the job completely, several north-south chains of these relatively expensive stations would be required in middle geomagnetic latitudes. The possibility does exist of detecting the plasmapause from the bottomside ionosphere by interpretation of electron-density profiles and airglow. Electric fields associated with the movement of plasma across the magnetic field lines can be measured in the neutral atmosphere, just below the ionosphere, by means of rockets and balloons, but these techniques are not suited to provide continuous information. It is important, therefore, that efforts be made to develop inexpensive, fixed-station, ground-based techniques to observe the plasmapause in the ionosphere and thus provide an important supplement and extension to the whistler technique, which serves well to define the plasmapause at great heights in the equatorial plane.

The Ionosphere

Our understanding of ionospheric structure and dynamics has advanced remarkably in the past two decades. Primitive models treated the ionosphere as a succession of simple stratified layers of ionization, each controlled by certain monochromatic fluxes of solar ultraviolet radiations. Largely with the aid of direct measurements from rockets and satellites, we now recognize the role of the entire spectrum of solar x rays and ultraviolet in producing a continuum of ionization from the base of *D* region to the upper range of *F* region. Loss processes involve complex ion chemistry, and trace constituents can have influence far out of proportion to their concentration. While the processes of a static ionosphere are now rather well understood above 90 km, it has become increasingly evident that local conditions are influenced as much by winds, drifts, and waves as by photoionization and recombination processes. Wavelike ionospheric motions detected from the ground include so-called "very large traveling disturbances," which follow magnetic storms; moderate-scale disturbances, which are much more common from day to day; acoustic waves related to severe weather near ground; and, finally, gravity waves, which propagate upward from the troposphere. Ionospheric weather is thus far more disturbed than would be predicted by any simple model of a static atmosphere under the diurnal control of the sun.

The study of the ionosphere has involved a constant interplay of ground-based and space-based research. Every individual form of probing has had its limitations. Classical ground-based ionosondes are necessarily bottomside sounders, and satellite sounders are necessarily topside sounders. Rockets can successfully tie the bottomside and topside measurements together, but only over the confining domain of a rocket range. Similarly, radar backscatter sounders can probe the electron density and determine ion, electron, and neutral gas temperatures continuously from approximately 100 km to several thousand kilometers but are limited in their utility to the vicinity of the antenna.

There appears to be considerable promise for laser soundings of the upper atmosphere. Produced with rather modest equipment, these soundings have demonstrated the feasibility of measuring atmospheric density up to heights of 100 km, and it is likely that a well-conceived program could extend these measurements to 120 km or perhaps somewhat higher. The ability to define the lower boundary of the thermosphere would be extremely useful for developing realistic models of the upper atmosphere. The time resolution would also be such that many wave phenomena (i.e., internal gravity waves) could also be studied from the ground. Other aspects of such a program might include measurement of aerosol concentrations up to 30 km, determination of upper-atmospheric winds by measuring Doppler shift with a bistatic system, and measurement of trace constituents at high altitudes by resonance scattering using a tunable laser.

Even in thermal equilibrium and in the absence of turbulence, the ionospheric plasma contains irregularities due to statistical density fluctuations which lead to "incoherent scattering" of radio waves. Radar pulses returned from these irregularities contain such a great variety of information about the ionosphere that the incoherent scatter technique as employed at Arecibo, Puerto Rico; Millstone Hill, Massachusetts; Jicamarca, Peru; and several observatories abroad has become the most powerful new technique for ionospheric probing from the ground. Theory shows that the electron concentration can be deduced from total scattered power and that the spectrum of scattered waves is determined by the ion and electron temperatures, ionic composition, and plasma drift. Two broad maxima occur whose sharpness increases with the difference between electron and ion temperatures. The influence of the geomagnetic field component perpendicular to the radar beam introduces sharp spikes in the scattered spectrum at multiples of the electron or ion gyrofrequencies. It thus becomes possible to determine the ionic mass spectrum. Continuing improvement in instrumentation and extensions of theory make possible the determination of drift velocities associated with motions of electrons, ions, and plasma. With the power available at the larger radar facilities now in operation, the ionosphere can be surveyed from roughly 90 to a few thousand kilometers.

Although every range of the ionosphere has its share of challenging problems, the greatest uncertainties in our understanding now relate to the *D* region. The entire *D*-region situation is so complex and difficult to learn about, even by direct rocket probing, that we cannot even clearly pose the questions we need to answer. To make progress toward better understanding, every promising technique of probing from the ground and from space has to be carefully explored.

D-region behavior can be profoundly affected by minor atmospheric constituents, including H_2O, CO_2, CH_4, N_2O, CO, NO_2, O_3, H_2O_2, HO_2, OH, NO, and CO. These molecules also account for most of the infrared emission of the airglow. Although the infrared airglow may interfere with ground-based, airborne, and balloon-borne infrared astronomy measurements, it contains a wealth of aeronomical information which thus far has barely been tapped.

Water vapor and its dissociation products have a pervading influence on *D*-region chemistry. They control the neutral concentrations of O and O_3 through rapid reactions which are accompanied by strong OH infrared emissions. The existence of hydrated ions and conglomerate ions has only recently been recognized. Oxonium (H_3O^+) and hydronium ($H_3O^+H_2O$) are major *D*-region ions. Laboratory measurements suggest that O_4^+, $O_2^+(H_2O)$, $H_3O^+(OH)$, $H_3O^+(OH)(O_2)$, $H_3O^+(OH)(H_2O)$, and $H_3O^+(H_2O)_n$ may all play significant roles.

Negative ion reactions studied in the laboratory have pointed to a host of possible ionospheric processes involving complex reaction chains. Whereas earlier theory was confined to consideration of the behavior of O_2^-, we now are concerned with the conversion of O_2^- to O_3^- to NO_3^- and O_3^- to CO_3^- to NO_2^-. We also need to consider their importance relative to charged ice and dust particles.

The *D* region has been referred to as the "chemical kitchen" of the ionosphere. With so many variables at play, no single observational approach is likely to provide most of the desired answers. Only by closely matched observations of airglow, electron density, ion density, composition, diurnal and seasonal changes, and transport effects can the important variables be identified.

Now that we have almost full-time solar observational capabilities with satellites carrying x-ray flux measuring instruments and ultraviolet spectrometers, individual solar flare events can be traced in great spectral detail from space and simultaneously by means of all the ionospheric disturbances and radio-noise emissions that are observable at ground level.

As the number and refinement of observations increases, it becomes impressively clear that there is no single, simple flare model but rather a large spectrum of flare events which we can only crudely characterize by our conventional categories of class 1, 2, 3, faint, normal, and bright or by proton, hard x-ray, soft x-ray, white-light, and uv-continuum emissions or by "fast burst," "gradual rise," "fluctuating," and other phenomenological features. Many long-held and presumably firmly established concepts of ionospheric behavior have become open to question as a result of improved observational powers both in space and on the ground.

It used to be that ionospheric disturbance phenomena were studied as a means of estimating solar-flare x-ray and uv fluxes. But flares have now become diagnostic probes for ionospheric processes because the flare spectrum is directly measurable from space and the aeronomic cross sections for ion production processes are becoming known with considerable accuracy. Flares produce a variety of sudden ionospheric disturbances (SID), which can be resolved in height from the base of the *D* region to lower portions of the *F* region. Timing differences on a scale of a minute or less in the initiation of disturbances and in the rise to peak of the event can be highly diagnostic of the nature of the ionospheric production and loss processes when comparable data for ionizing fluxes are available directly from satellites.

Processes specific to the 60- to 75-km height range are:

1. Sudden phase anomalies (SPA), where the sky wave changes phase with respect to the ground wave as a result of an effective lowering of the reflection ceiling near the base of the *D* region, sometimes by as much as 16 km.
2. Sudden enhancement of atmospherics (SEA), manifested in improved reflection of very long radio waves (about 10,000 m) from the bottom of the *D* region. Distant tropical thunderstorms provide a steady background on a frequency of approximately 27 kHz, and signal strength may increase 100 percent during a large flare.
3. Sudden field-strength anomalies (SFA), observed as interference effects over medium distances between sky wave and ground wave when both are of nearly equal intensity. As the reflecting ceiling drops, the two waves vary in and out of phase, thus giving large variations in field strength at receiver.

In the 75- to 90-km range there occur sudden ionization increases which lead to:

4. Shortwave (5 to 20 MHz) radio fadeout (SWF), which is attributable to *D*-region absorption. The phenomenon is prompt to within a minute of flare outbreak.

5. Increased absorption of cosmic radio noise from outer space observed by riometers at approximately 19 MHz (SCNA).

To explore the ionosphere above 90 km we can observe sudden frequency deviations (SFD). An SFD is an abrupt increase in the frequency of a high-frequency radio wave reflected from the *F* region followed by a slower decay to the transmitted frequency. The frequency deviation characteristically may exhibit several peaks near maximum and may even show negative deviations during the decay phase. In contrast with the *D*-region effects that accompany 1- to 10-A x rays, the SFD's are highly impulsive--the rise to maximum is roughly a minute, and the source radiation is probably in the euv region from 10 to 1030 A, most likely dominated by enhancement of the Lyman continuum radiation of hydrogen.

Observations of SFD in radio transmissions via the *E* and lower *F* regions have shown surprisingly fine temporal structure resolvable on a scale of only a few seconds. Without knowledge of the solar radiation flux, SFD's could serve as fast-resolving, broadband detectors of explosive flare outbursts. When combined with satellite flare measurements the SFD data can provide unique evidence of electron production rates and recombination coefficients. Recently it has become possible to record x-ray bursts with fine structure similar to SFD's, and it is remarkable that the SFD and directly measured flux patterns are comparably sharp and can be matched to within 1 or 2 sec. From such comparisons it is possible to derive the concurrent solar euv continuum emission and to infer ionospheric reaction times far shorter than previously suspected.

Auroras

Auroral phenomena are fascinating for their evanescent beauty and for the baffling complexity of the physical processes at their source. Few natural phenomena have stimulated so many theoretical explanations with no fully accepted theory. Yet it is unfair to imply that the mystery is as deep as ever. Largely with the aid of space research, many previous theories have been laid to rest, and the remaining candidates focus on newly defined characteristics of the "doughnut and tail" model of the magnetosphere. Earlier ideas of direct bombardment of the auroral zone by solar particles, and the speculation that auroral particles are dumped from the store of trapped particles in the radiation belts have been contradicted. It is still unknown whether the particles causing the auroral phenomena are magnetospheric in immediate origin or freshly injected in bulk from the solar wind into the magnetosphere; but in either case these particles are energized in the magnetosphere or in its tail by some acceleration mechanism. It is puzzling that the solar-wind parameters vary so little compared with the geomagnetic disturbances and auroras. The reasons must be associated with the acceleration mechanisms, and direct spacecraft measurements may soon provide the answers.

For the ground-based observer, the correlation of optical data, radio data, and magnetic-storm perturbations is the route to understand the terminal processes in auroral morphology. Auroras seem to fall into three general classifications: electron auroras, proton auroras, and diffuse glows.

The general pattern of auroral activity outlines an oval centered on the geomagnetic pole and touching the circle of maximum frequency of occurrence at the southern edge near midnight. With increasing activity, the oval grows in width and shifts farther south. Starting with the form of a single drapery, transitions may follow rapidly to spiral forms and multiple draperies stacked one behind the other. Veils may appear in the evening, begin to break up by midnight, and terminate by early morning in unstructured patches. The most spectacular aspects of auroras are the rapid motion and sharp transitions from one shimmering structure to another. A bright red aurora may switch on in a matter of seconds from a dark sky only to vanish completely after a few minutes. Many forms show complex incoherent movement. Substorms are accompanied by explosive expansions of auroral forms with rapid poleward motion followed by southward drift.

Optical studies of auroral forms have absorbed the efforts of many observers for decades. During the IGY, efforts were made to establish more than one-hundred all-sky camera stations and also to organize amateur observers as objective reporters who filled out standardized descriptive forms and mailed them to Data Centers. From such efforts to present developments in image orthicon TV photography is a great step. These modern TV systems reveal movements so rapid that they escape the human eye and are totally undetectable by conventional high-speed photography. Four image orthicon cameras are used to obtain as many as 60 auroral images per second. Often a subvisual auroral glow will increase sharply in intensity for a period of tens of minutes to hours and develop a rayed structure. The rays align with the magnetic field and are very sharp. Although rockets have identified auroral rays with the influx of 10- to 20-keV electrons, we need to explain why the electrons are funneled into the rayed forms and not diffused widely over the sky. In discrete forms, the brightness may be two to three orders of magnitude greater than in diffuse glows. Furthermore, the thinner the rays, the shorter their lifetimes--in some cases less than a few tenths of a second. It is such rapid phenomena that can be revealed in a new light by high-speed recording systems.

CONCLUDING REMARKS

The past decade has seen great progress in every aspect of solar-terrestrial research, and the broad outlines of the physics of the earth's environment have been well defined. But improved observational capabilities have also uncovered far deeper scientific questions than were previously apparent. The preceding pages offer a sampling of current scientific questions and concepts drawn from the broad field of solar-terrestrial relations. Many of these are discussed in depth in the various chapters of the study. Others are touched on in the previous study. What is abundantly clear from the survey is the great diagnostic power that can be achieved by organizing a proper synthesis of the new potentials of ground-based and space research. The study group recommends ways and means to achieve the desired balance in our national program.

2 Solar Measurements

As the energizer for all the phenomena of interplanetary space, the magnetosphere, and the ionosphere, the sun has an important place in the study of solar-terrestrial effects. An understanding of solar physics will define the initial physical characteristics of x-ray, radio, and particle radiations from the sun. Observations from near the earth and in the ionosphere define the state of these radiations after traversing 1 AU of the interplanetary medium and the reactions of the magnetosphere and ionosphere to them. The comparison of these initial and terminal conditions is a powerful tool for unraveling the physics of the intervening space and the terrestrial responses to the solar radiations.

The solar atmosphere is divided for observational reasons into several overlying levels above the opaque white granulation surface. In order of increasing height and decreasing density, they are the photosphere (~300 km), chromosphere (2-3000 km), and corona (directly observable out to 6 solar radii). The temperature falls through the photosphere and lower chromosphere from 6000 K to a minimum of about 4500 K. It then rises rapidly to 100,000 K at the chromosphere-corona interface, where it jumps abruptly to the coronal temperature of ~ 1,500,000 K. This interface is a region of special interest in solar physics.

The solar flares are by far the most important source of the photon and particle emissions that produce interplanetary and geophysical reactions. They are active center phenomena extending from the low chromosphere into the corona, although the magnetic fields which drive them reach down through the photosphere to some depth probably below the white surface of the sun. Flares are the most energetic and catastrophic of the several features of solar activity. Intense x-ray and fast-particle emissions originate in and above the interface level, frequently rising in a second or two from zero to a peak intensity corresponding to a temperature of 10^8 K. At lower levels the flares are spectacularly visible by their emission of the hydrogen Balmer lines and the H and K lines of ionized calcium.

Magnetic fields appear to play a fundamental role in the flares and all other forms of solar activity. The fields observed in the photosphere appear to penetrate to very high levels. The solar wind, which originates in the corona, reflects the large-scale photospheric magnetic pattern in the observed sector pattern of alternating magnetic polarities in interplanetary space.

The last 20 years have seen notable strides in solar research. This is the result of the introduction of solar radio observations, ultraviolet and very soft x-ray (xuv) observations from spacecraft, and advances in ground-based optical methods and technology, such as the invention of the magnetograph and improvements in diffraction gratings. Each of the three techniques elucidates certain features of the sun. The xuv radiations, which are completely absorbed by the terrestrial atmosphere, show the hottest and most active high-level portions of the flares and other superthermal features. The millimeter and centimeter radio waves show the associated fast particles. Their outbursts could define the most energetic phases of large flares and some indication of their magnetic character if the currently available spatial resolution and polarization analysis were upgraded. Longer waves originate at higher levels and show the corona out to several solar radii. And the optical ground-based observations show the lower solar atmosphere up to the middle chromosphere just below the interface level. These define the configurations and magnetic fields of the flare bases with far better spatial resolution and precision than are presently achieved by the xuv and radio techniques.

SCIENTIFIC PROBLEMS

The problems of solar physics of particular interest to solar-terrestrial studies can be classified in terms of magnetic fields, the solar cycle, and the physics of flare phenomena and other rapidly varying features. These problems are fundamental to the understanding of the physics of the earth in space because they deal with the major aspects of the sun's domination of the interplanetry medium in which the earth is immersed and its irradiation of the geomagnetic envelope and the terrestrial atmosphere. The following are some of the important problems.

Magnetic Fields

The study of magnetic fields ranks first in importance because these fields appear to be the energy source for solar activity. The site of the active features is the strong magnetic field region enveloping a sunspot group, and there is a well-established connection between flares and such magnetic anomalies as inverted polarities, complex magnetic structures, and steep field gradients. We cannot exclude the possibility of other unknown causes of solar activity, but if we must choose a point of attack, the magnetic character of active centers is unquestionably the most promising. Ignoring for the present the question of the origin of these fields, the primary problem is how magnetic energy can be converted into thermal energy, energetic particles, and photons on the observed time scales, and what observable phenomena should result. The observational description of active-center phenomena is still inadequate to solve this problem.

The Solar Cycle

What solar mechanism can account for the existence of a quasi-periodic variation of all forms of solar activity? Why do the amplitudes, periods, and magnetic polarities vary from one cycle to the next? What effect has the nonuniform rotation of the sun, and does it interact with deep-lying magnetic fields? On a global scale, the magnetic fields appear to rotate uniformly, while the sunspots drift through the fields at rates that vary with latitude.

Sunspots are the most conspicuous indicators of the strongest magnetic fields. What, in detail, is the structure of a sunspot in terms of magnetic field, temperature, and density? What accounts for such structures as the fine details of penumbrae, the umbral grains, and the *K*-line umbral flashes?

Physics of the Flare Phenomenon and Other Rapidly Varying Features

Is the optical flare the true locus of the most energetic processes, or is it merely a relatively superficial accomplishment? Why do magnetic anomalies often lead to flares? Does the impact of infalling material from ascending prominences account for any substantial portion of the flare energy? How are loop prominences formed inside the barrier of the active center magnetic fields, and what is the origin of their suprathermal internal mass velocities? What processes produce surges? What processes in the flare produce the electrons that generate x rays? What is the relation of these to the radio bursts? Where and by what processes do the particles of energies > 1 MeV originate?

A complete solution of any of these problems is not possible. However, the research of the last decade has set the stage for rapid and important advances, attainable through the full use of ground-based and space observations to guide the necessary theoretical research.

GROUND-BASED OPTICAL OBSERVATIONS

Magnetic Fields

The measurement of the magnetic field in and around the solar active centers is the most important observational problem--and the most difficult. Ideally, one would wish to obtain a quantitative determination of the magnetic vector at every point in a three-dimensional volume, with sufficient spatial resolution to define the smallest distances separating significantly different vector fields and sufficient time resolution to follow major evolutionary changes in the fields. This is a very large order indeed, and one which we do not expect to meet fully, but we may anticipate that even approximate achievement can lead to a very solid advance.

Optical measurement of solar magnetic vectors depends on the Zeeman effect as modified by the radiation transfer properties of the solar atmosphere. Complete observational data for a single element of area of the solar surface comprise the profiles of the Stokes parameters (which specify brightness and polarization) across one or more sensitive lines in the solar spectrum. Each of the observable Stokes profiles (i.e., the profiles of the lines in the Stokes parameters) is a complicated average of the effects throughout an element of volume in the solar atmosphere, defined in height by the contribution function on the line observed (which varies across the profile) and transversely by the area of the resolved surface element. In a field where the magnetic gradients are steep, this volume element will doubtless not represent a "point" in the solar atmosphere very satisfactorily. The volume elements contributing to different lines will generally be at different heights but will have a generous overlap. However, an exceedingly useful set of observational data would be an array of the Stokes profiles in several lines measured over a raster pattern on the surface of the sun, with (x, y) intervals corresponding to the best attainable spatial resolution. The corresponding magnetic vectors could then be calculated (with some useful redundancy) from the Unno relations (or the somewhat more general modification derived by Beckers).

As a practical matter, the relatively few photons emitted from single resolution elements in very narrow spectral bands severely limit the speed of data acquisition. It is thus impossible to measure the Stokes profiles, one surface element at a time, with useful angular and temporal resolutions over a useful area of the solar surface (including, say, 1000 elements of area). The development for solar-terrestrial research of a Stokes polarigraph which would collect data for many surface elements simultaneously is thus most important.

Beginnings have been made. The Leighton adaption of the spectroheliograph measures the circular polarization (and could perhaps be adapted to measure the two-plane polarization parameters) in a single narrow wavelength band of a line profile along a line on the solar surface. By scanning the line across the sun, it records the distribution of circular polarization over an area of the solar surface. The output signal consists in variations in optical density on a photographic plate which can be interpreted fairly unambiguously in terms of longitudinal field strength. Several promising experiments are under way to achieve the same result by television methods. Success here will be the first step toward the considerably more sophisticated devices required for even the minimum of data necessary to determine the surface distribution of the magnetic vector. The principal limitations of present video systems are their noise and restricted dynamic range.

When we can map the magnetic fields in detail, it will be possible to determine empirically their influence on the visible structure of the solar atmosphere. This will be an important test for deducing chromospheric fields from the observed morphology. Meanwhile, very useful measurements of the sightline components of magnetic fields in the photosphere and in prominences are being obtained with magnetographs (circular polarimeters) of the Babcock type and, in sunspots, from photographic spectrograms in polarized light. The present observations, even though they do not define the complete magnetic vector, yield information of the greatest significance for our understanding of solar activity and its influence on the earth. Unfortunately, only a few instruments are operated by only a few people, and the coverage of all active centers is fragmentary. An increase in the flow of magnetic data by a factor of 5 from instruments well distributed in longitude would be extremely useful for solar-terrestrial research. A rough estimate calls for two or three additional observing stations and added support for existing groups to enable them to approach continuous observation of the active centers. This would provide a reasonably continuous patrol of active center fields of the kind needed for correlations with geophysical events and would automatically provide magnetic data for studying the physics of solar activity.

Solar Features

Magnetic-field observations are important because they may help to define the processes by which the fields produce sunspots, plages, prominences, coronal activity, and flares. To attain better understanding we also need more complete descriptions of these phenomena in terms of spatial configurations, densities, temperatures, and mass motions. The determination of these characteristics is not a new problem in solar physics. Past research has made a promising beginning on some of the simpler features like coronal condensations. It is safe to say, however, that there is not a single feature for which our knowledge is adequate to trace the physical processes back to the magnetic sources of energy.

The first requirement is a quantitative description of the active features in terms of the observational data. Ideally, all the optical information available would be included in a data array of the Stokes parameters as functions of the (x, y) position on the solar disk, wavelength, and time. In the foreseeable future, however, we must content ourselves with well-chosen fractions of these four enormous four-dimensional matrices.

Ground-based optical observations can make useful contributions through sequential monochromatic and white-light photography (which permits detailed studies of morphological development of active centers), measurements with high spatial resolution of sightline (Doppler) velocities, measurements of spectroscopic line intensities and reliable line profiles, and in some cases, determinations of polarization. Such observations are within the capability of existing observational equipment, but the spatial and temporal resolution are as a rule insufficient. Every improvement in spatial resolution, as in Stratoscope balloon observations and spectrograms showing the "wiggly" lines, has resulted in new information of first importance. The need for sharper images has resulted in a very successful upgrading of methods and existing telescopes, and several new instruments have been built specifically for the purpose with refinements such as evacuated optical systems to eliminate internal convection turbulence. With better spatial resolution should go better time resolution. Experience confirms the natural expectation that small objects change more rapidly than large ones, and a capability for 10-sec resolution is none too good. Another problem is the sheer volume of data needed, relative to which progress by the existing observatories, most of which are exemplars of scientific industriousness, is painfully slow.

Matters can be improved by two fairly obvious measures: the establishment of more solar observatories at good seeing sites and the development of new equipment capable of much more rapid acquisition of data, in a form digestible by computers, from resolution-limited elements of area on the sun. The construction of new solar observatories, while desirable, should be considered within the framework of a larger effort to upgrade the national or global solar-observing capabilities as a whole. In this context, the critical element is the available number of highly qualified solar physicists. Existing solar observatories generally have fewer than the optimal number of high-level scientists for their observing facilities, largely because of a shortage of qualified people and, to a lesser extent, because of budget limitations. Clearly a more pressing need is the training of more good solar physicists to make optimum use of available facilities.

Flare Patrol

The energetic photons and particles which excite terrestrial responses originate in, or are associated with, the rapidly changing phenomena of the active centers surrounding sunspots.

The development of these centers, from the appearance of the first detectable magnetic field or plages to a maximum level of activity and through the following decline, is still imperfectly known, and at present, the onset of flares cannot be predicted with any great confidence. For several years, a worldwide network of H-α patrol stations, some of which are operated by the National Aeronautics and Space Administration and the Environmental Science Services Administration and some by the Air Weather Service, have kept a very complete record of solar optical activity. The typical station has a 6-in. telescope, equipped with H-α birefringent filter and 35-mm camera, which records a 15-mm image of the sun at intervals of 10 to 60 sec whenever the sun is observable. Cooperation among the stations is excellent, and all data on flares and other observed activity are transmitted simultaneously to the patrol headquarters of both groups. The purpose of these partrol programs is to provide data for warnings to various agencies whose operations can be affected by sun-induced disturbances, and the observational data are well suited to this purpose. The 15-mm image is too small, however, for a satisfactory study of the significant evolutionary details of active centers. The patrol data could be made far more useful, for both their original purpose and research purposes, at a comparatively trivial cost by simply increasing the image size to 24 mm and sacrificing the solar polar zones in the photographed images. This is an insignificant loss, since most of the interesting activity occurs at latitudes of less than 45°. We urge that all the patrol instruments be modified to give the larger image, and that the film strips be made readily available for research use.

New Techniques

We do not attempt to list here all the technological advances that are needed. We believe, however, that this is the area to which the major portion of support funds should be directed. Several items are of outstanding importance for optical solar astronomy. They appear to be within the reach of determined and well-financed development efforts and most would have a substantial impact on research areas other than solar astronomy. We list them here with a brief discussion of the solar research application of each.

1. Video systems: Development of high-quality video systems is important to all forms of astronomical imagery, and

particularly to the space program. A good video system will serve the same function as photographic film but should generate an electrical output signal accurately proportional to light intensity on the receiving camera tube. To be useful, the signal must have a photometric accuracy better than that of photographic film, and the system must receive and utilize photons continuously and simultaneously over the whole sensitive area, although the readout may be point by point as in ordinary television. The system should have a digital output which can be utilized by a modern computer. A most important application of such a video system in solar research is in measuring the Stokes parameters as a function of position over an extended area in the solar image. These measurements always involve taking the difference at every point between the image brightness in two modes of polarization. The Leighton spectroheliomagnetograph performs this operation by taking two photographs and subtracting by superposing a negative of one on the positive of the other. This is a most laborious process which could be avoided by a real-time system that differentiates the signals in the video images.

2. Optical filters with passband in the 0.1-A range, rapidly tunable over a few angstroms: There are several possible approaches to this problem. The most promising are variants of Fabry-Perot interferometers, birefringent filters, and, possibly, of image-transmitting resonance-scattering filters. Narrow-band filters are required to obtain solar images in the light from a discrete wavelength on the profile of a line in the spectrum. Combined with a video system, such a filter could record a line profile at every point in a solar image by recording for each point the intensity at successive wavelength settings. There also is a serious need for simple multilayer filters of 3 A or so bandpass with good optical quality and long-term stability.

3. A Stokes line-profile polarigraph capable of measuring magnetic vectors simultaneously over extended areas of the sun: This system would consist of the video system and narrow-band filter described above, with a complex polarization analyzer. Its importance for the study of the structure and evolution of magnetic fields in active centers, particularly during flares, has been discussed above.

4. Large diffraction gratings: The improvement of diffraction gratings, with better resolving power and efficiency and freedom from scattered light, is of fundamental importance. Interferometric control of the ruling, developed by Harrison of MIT, has brought an enormous advance, but the best gratings

still fall appreciably short of the perfection of other optical elements and are limited in length to 25 or 30 cm. Continuation of Harrison's project, which is primarily for the exploration of new ruling techniques, is of the utmost importance and should not be terminated unless a comparable new ruling facility is established. Optical research on the sun is only one of the many scientific fields in which larger and more perfect gratings are a vital requirement.

5. Specialized telescopes for best possible resolution: Even under the most favorable atmospheric conditions, resolution is limited to about 500 km on the sun. Although it is usually assumed that this limit is set purely by the atmosphere outside the telescope, the cumulative effect of the many elements in a complicated optical system, and the effects of internal convection in very long telescopes do contribute to image degradation. Experiments using a simple, old-fashioned refractor of 20 or more inches in aperture would be useful to determine whether such instruments could yield a significantly sharper image.

GROUND-BASED RADIO OBSERVATIONS

Except for a thin layer at the top of the photosphere, the sun is composed entirely of a highly ionized magnetic plasma. No electromagnetic techniques can observe the plasma inside this layer, but outside the photosphere in the chromosphere and corona, the plasma is highly accessible to observation by radio techniques since its optical depth is high and is a strong function of wavelength, being less for the shorter wavelengths. We recognize two categories of experiments, designed to clarify different aspects of the corona and chromosphere: active observations, based on high-powered radar and sensitive angle of arrival effects; and passive observations, upgraded toward higher spatial, spectral, and time resolution, with polarization measurements.

Characteristics of the Radio Solar Spectrum

The study of the sun by the techniques of radio astronomy covers the frequency range of 22 octaves, from high-altitude ground-based measurements at 406 GHz (0.74 mm) to measurements carried out in space at 100 kHz (3km). Because of this wide frequency range, the techniques that are used are quite different in each

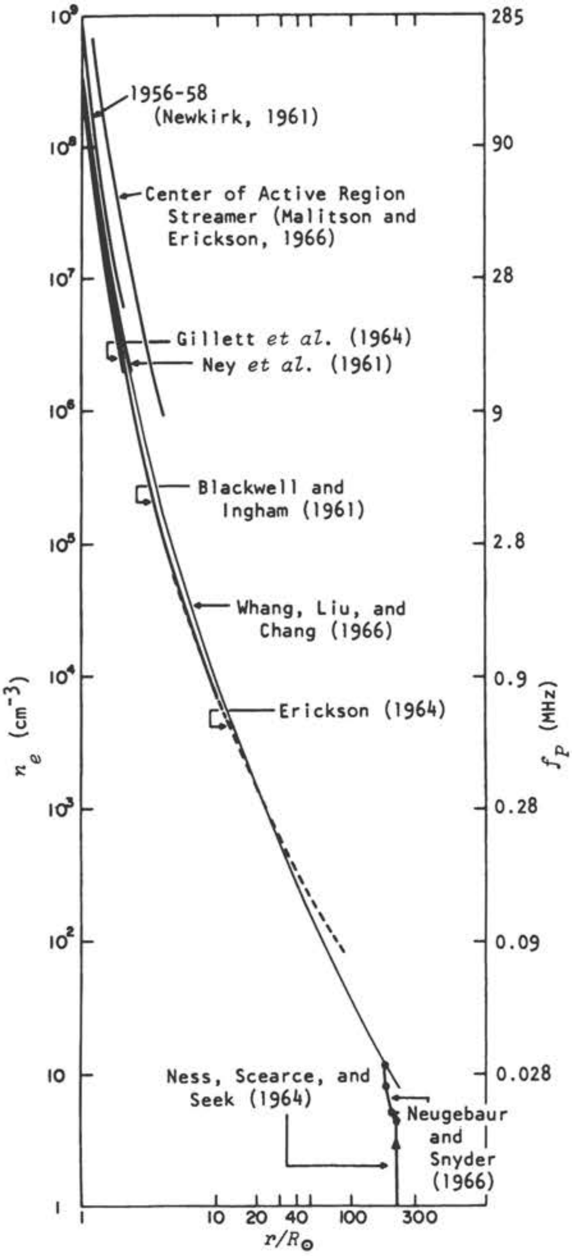


FIGURE 1 Measurements of electron density in the solar corona.

six or eight octaves of the frequency range. The transparency of the terrestrial atmosphere is a function of wavelength effectively limiting ground-based observation to the region approximately bounded by 3 mm and 50 m.

In general, the sun at a given wavelength has a "quiet" thermal component and a variable nonthermal component. The latter is principally associated with solar flares which are nonthermal processes and are frequently accompanied by x-ray and solar-particle emission. The nonthermal component is of particular interest because it arises both from regions of magnetically trapped relativistic gas and from regions of shock waves and coherent plasma oscillations. The radiation emitted from these two regions are, respectively, gyro and synchrotron radiation and scattering from electric fields in plasma oscillations. It has been possible to observe solar radio emission from these regions in the corona over a range of heights from 1.003 to 50 solar radii (R_s).

The coronal plasma generally limits the propagation of radio waves to frequencies above the local plasma frequency. Observations at successively lower frequencies originate from the corona at greater and greater radial distances. Figure 1 illustrates the relationship with distance from the sun's center between electron density N_e in the solar corona and the corresponding plasma resonance frequency. Observations in the centimeter and millimeter bands are appropriate for studying the chromosphere and lower corona, and observations in the meter and decameter bands apply to the outer corona and solar wind. Ground-based radio observations are limited by the ionosphere to the study of the sun out to approximately $3R_s$.

Solar Radio Bursts

It is clear that a better understanding of the physics of the flare mechanism may be obtained by making detailed observations of radio events prior to and during the progress of the chromospheric flare. These observations should be made at millimeter and centimeter wavelengths because the escaping radio energy at these wavelengths originates in the chromosphere between 6000 and 12,000 km above the photosphere, depending on the wavelength. The radio measurements should include intensity, position, and polarization, as a function of time. They should aim toward spatial resolution of 1 sec of arc. These measurements should be compared with photographs taken simultaneously in H-α and at wavelengths up to 4 or 5 A from H-α.

To attain these objectives, several types of related studies should be pursued. Ground-based observations should be correlated with x-ray and xuv observations from space vehicles, looking for time-development similarities. Negative correlations, i.e., flares without radio bursts and bursts without flares, must be studied to search for the physical mechanisms involved. Interdisciplinary studies involving bursts and solar-proton emission should be expanded. To ensure that all significant events are captured, the radio equipment should be operated on a patrol basis with provision made, where applicable, for more detailed measurements when a flare or a radio burst appears. Further, efforts to map the sun at millimeter wavelengths should be intensified; reliable equipment already exists to permit observations at 8- and 3-mm wavelengths.

Since in the centimeter and decimeter regions, plage areas radiate more intensely than the solar disk background, it is possible and important to construct maps of the sun at 8- and 3-mm wavelengths. These data on the plage region can be correlated with other measurements, especially x-ray. Also, spectra of these plage areas in the radio region should be obtained. Routine monitoring of intensity and polarization is needed as well. It should be noted that recent measurements show that plage regions which grow in brightness and have steep gradients as seen by millimeter radio maps will produce bursts.

The spectra of bursts have been studied at two observatories (Air Force Cambridge Research Laboratories and Pennsylvania State University), utilizing peak flux density at discrete frequencies in the meter to centimeter range. In general, the spectra fall into three classifications: increasing flux with increasing frequency, decreasing flux with increasing frequency, and bursts that have a distinctive peak usually in the decimeter range. Each activity center appears to generate predominantly one type of burst. The next step is to study the optical and magnetic characteristics of the centers that have characteristic burst types. The mechanisms of individual events having particular spectra should be studied to determine the physical processes responsible for radio emission. Various aspects of spectral study should be expanded, such as variation of spectrum as a function of time (with time resolution on the order of 1 min), studies of the spectrum of total energy from the burst, and rapid variations in burst development.

To maintain a history of radio-burst events from a center of activity, consistent monitoring of the sun is necessary, preferably on a 24-hour-a-day basis. This involves developing international standardized calibration and reporting techniques, as well as improving networks for the exhange of solar data.

The utility of studying burst spectra has been demonstrated by using spectra in the meter-to-centimeter range to derive short-term predictions of polar cap events. Such work should be pursued with the aim of bridging the gap between radio and optical wavelengths.

Solar Flares

As noted above, evidence is mounting that magnetic fields are the key factor in the development of the active region and of the flare itself. Fields in the higher region of the chromosphere cannot be measured optically. These magnetic fields affect the intensity and polarization of radio waves generated in the presence of the field through the interaction of energetic electrons with the field, and give rise to gyro and synchrotron radiation. The transfer of the emitted radiation through the overlying magnetoionic corona modifies the intensity and polarization characteristics. We therefore suggest that polarization measurements at millimeter and centimeter wavelength may provide a measure of the intensity and direction of the fields in an active region. Measurements at several wavelengths will be needed to determine the spatial variations and the variations during a burst. Polarization measurements made with the multifrequency patrol radiometers which do not resolve the sun are certainly useful, but the real need is for polarization radiometers in larger antennas which can resolve an active region.

Interferometer techniques should be used to measure the size and location of the radio emission in an active region. Much could be done with antennas 6 to 10 ft in diameter used as an interferometer to measure the size of the source, but the problem would remain of identifying in which of the many fringes on the sun, or even where in an active region, the source was located. A preferable arrangement would use an existing, large, precision paraboloid, such as the 140-ft antenna at the National Radio Astronomy Observatory, as one element of the interferometer. In this case, the envelope of the fringe pattern would be much smaller. For example, if the measurement were made at a wavelength of 1 cm, the field of view would be less than 1 min of arc and could contain only four or five fringes. It would be logical to make complete polarization measurements at the same time.

An instrument long needed in solar research is a high-resolution, rapid-scan device that could provide a "television" image of the sun at least once a minute, with a resolution of at least 1 min of arc and operating at a wavelength short of 10 cm. Such an instrument, designed for work at a much longer wavelength (near 4 m), is operating in Australia. It has given new and exciting insight into dynamic activity in the outer corona. At centimeter wavelengths, which would probe the middle chromosphere--the seat of the suprathermal activity in solar flares--a feasible arrangement would be an array of 10-ft-diameter paraboloids, with rapid phase shifts to provide the fast scans. This instrument could identify and map active regions during the course of a flare.

Studies should be made on the feasibility of extending the "television" technique, either in the array form of a cross or of a circle, to dimensions of several kilometers in order to provide a resolution of 5 sec of arc. This high resolution is desirable for precise mapping of the nonthermal radio-emission regions and their polarization characteristics and would make possible the measurement of any transverse component in the velocity of the emitting source.

Interpretation of the flare event as seen at radio wavelengths has been vastly oversimplified. Measurements with the instruments described will improve our ability to relate the events to physical processes and thus enhance our ability to understand the nonthermal properties of the flare process.

It is believed that most cosmic rays of solar origin are produced during flare events. Hence solar cosmic-ray studies and their correlation to the other flare manifestations are important to solar physics. Details of these studies are treated in the next chapter.

The Outer Solar Atmosphere

The middle and outer parts of the corona can be investigated by radio means. Studies of this region have revealed new information about the dynamical properties and structure of the corona and given insights into the mechanisms responsible for the solar wind and the onset of the flare blast wave.

Radar studies made at low frequency (~38 MHz) and with low spatial resolution have demonstrated that usable echoes from moving plasma regions can be obtained. It would be desirable to increase the antenna directivity of the radar to allow detection of echoes from smaller discontinuities and to measure the velocities and positions of these discontinuities with more precision.

Coronal scintillation studies using a radio signal from a Pioneer space probe and the natural signals of discrete radio sources have been used to deduce the size, density, distribution, and velocity of plasma clouds in the outer corona. Faraday rotation and Doppler studies have also been made with Pioneer 6. Both man-made and natural signals are valuable tools in these researches. The Pioneer-type experiments are advantageous in that the low signal amplitude of natural sources requires radiometers having very large antenna apertures. Nevertheless, using natural sources, the movement of the plasma clouds can be followed far from the sun and to high celestial latitudes which are not now easily accessible to space probes. Furthermore, the numerous natural discrete sources are well scattered over the sky and are permanently available for study. Consequently, such experiments should be continued and the sensitivity improved through the use of even larger antennas. If a sufficiently powerful beacon with a high-gain antenna directed toward the earth could be placed on a Pioneer spacecraft, even better measurements of the scintillations could be made (limited, however, to the plane of the ecliptic). The proposed Sunblazer experiment was a step in this direction. It was to radiate at two frequencies so that differential delay could be used (the Seddon-Jackson ionosphere experiment) to measure total electron content in the line of sight, as well as radio scintillations.

Eclipse measurements at many radio frequencies have made it possible to determine the temperature, density, and spatial distribution of the upper chromosphere and the lower corona. Further eclipse work from millimeter to centimeter wavelengths is needed to study the structure of the middle chromosphere where optical depth unity for these wavelengths occurs. Even at these short wavelengths, sufficient resolution to determine the radial brightness distribution of the sun can be obtained only at eclipses. The spectra of discrete active centers are obtainable at present only through the eclipse observations, since no other method achieves the necessary spatial resolution.

Since emission of radio waves in the meter-to-kilometer wavelength range is the last detectable evidence of solar energy moving into interplanetary space, observations in these long wavelengths are of importance. The relationships between solar-wind modulation and the physical processes responsible for the great radio bursts have only been qualitatively established. Additional correlation studies between long-wave radio emission and parameters measured by space vehicles are needed. Sweep-frequency monitoring should be continued, with a vigorous effort to standardize burst classification and to provide users of the data with information to normalize or equate the sweep-frequency equipment in use.

RECOMMENDATIONS

1. To achieve an appropriate balance between radio and optical solar research, and to take advantage of the research tools now available in this area, we *recommend* that support for solar radio astronomy be increased. Specifically:

a. Hydrogen-alpha and radio observations indicate that the base of the flares is normally in the lower to middle chromosphere. Radio observation at centimeter and millimeter wavelengths which penetrate to the middle chromosphere have revealed preflare heating of the plasma in, or coming up through, the plage region prior to the onset of radio bursts. It is important to an understanding of the physics of the flare mechanism to observe with greater spatial resolution than is now feasible the development of the plage region prior to the flare, the subsequent growth in intensity of the burst, and the transverse motions of the emitting regions as the flare progresses. The strong magnetic fields always present in the flare region indicate the desirability of making polarization measurements as well to provide more information about the fields at the height of the flare. To this end, *we give high priority* to the development of a scanning radiometer to measure intensity and polarization in the midcentimeter range with a spatial resolution of 1 min of arc or better, and capable of producing a "television" picture of the whole sun at least once a minute, and of a restricted flare region every 5 to 10 sec.

b. We believe that a most direct and powerful attack can be made on the problem of the flare and its concomitant nonthermal processes which generate energetic particles, x rays, and radio outbursts, by means of simultaneous x-ray mapping of the flare region from spacecraft and by broad spectral coverage, from the ground, of intensity and polarization parameters over the centimeter and millimeter wavelength bands. These dynamic pictures of the active centers require simultaneous hydrogen-alpha and optical magnetographic maps to show the magnetic-field configurations below the flare and the morphology of the region visibly heated by the rapidly accelerated electrons and protons.

The ideal radio instrument would consist of a large broad-band array of antennas producing complete pictures of solar-active centers several times a minute with a spatial resolution of about 1 sec of arc and over the whole millimeter and centimeter bands (frequencies from 1 to 100 GHz). The four Stokes parameters specifying the state polarization at these frequencies would be shown in separate pictures.

For a ground facility, this will be very costly and complex. Its scientific usefulness should be explored by means of less elaborate instruments which can give observations of great value, although short of the complete information desired. Therefore, we *recommend* that a study be funded to provide a design of a two-element interferometer, using presently available antennas, to measure the Stokes parameters over an 8 to 1 range in frequency between 1 and 10 GHz and, similarly, between 10 and 100 GHz (λ = 30 to 3 mm). We *further recommend* that present high-resolution interferometers operating in the centimeter band be used to study solar-active centers and flares to determine the size scale of the smallest features observable.

c. Maps of solar intensity and polarization at wavelengths of 3 and 8 mm with a resolution of 1 min of arc or better are urgently needed now on a daily basis. Because of their excellent resolution, the National Radio Astronomy Observatory's 36-ft and 140-ft radio telescopes should be available for solar studies. We *recommend* that the 36-ft telescope be used to make daily 3-mm maps of the sun for a period of several months to assess the effectiveness of these observations in studying detailed variations of the solar plages.

d. Even when observing the integrated radiation from the whole sun, we can often identify radio bursts with the active centers on the disk, particularly when a flare occurs. Much valuable information is presently missed because polarization is neglected. It is known that the sense of circularly polarized microwave bursts often changes with frequency in a given burst. We therefore *recommend* that polarization analysis of burst radiation be added to the intensity measurements now being made on a routine basis. Radio monitoring of intensity and polarization of solar radiation should be carried out at a number of well-spaced frequencies to obtain dynamic spectra and the frequency dependence of the degree, ellipticity, and sense of polarization.

e. We *recommend* support for the development of a broadband microwave feed and circuitry system capable of measuring the four Stokes parameters continuously at chosen frequencies over the 1- to 10-GHz range.

2. The scientific productiveness of optical observers is often hampered by limited and outdated equipment. To enable

them to work more effectively, we *recommend* that funds be provided for the improvement of existing facilities. The construction of new observing facilities in favorable longitudes and climates should also be considered. It is particularly desirable to establish and operate two or three new magnetograph stations and to provide for digital recording of quantitative solar data of all kinds in a form compatible with electronic computers.

3. There is every reason to believe that the tremendous localized source of energy for the flare is the magnetic field of the active region. Anomalous behavior in this complex magnetic field precedes the development of the flare. Most existing magnetographs observe only one component of the field, in one element of area at a time. We *strongly recommend* that a program to develop an instrument capable of measuring the vector field in high resolution and on a short time scale (i.e., in many elements simultaneously) be supported. This program will require the development of the following devices: (a) a signal-generating video system capable of 7- or 8-bit photometric accuracy, with digital recording for a raster of at least 10^5 elements of area; (b) sharp band filters with tunable bandpasses 0.1 A wide or less; (c) a Stokes line-profile polarigraph capable of measuring magnetic vectors simultaneously over extended areas of the solar surface with high spatial and temporal resolution; and (d) larger diffraction gratings with path differences of 35 cm or more, having improved resolution, efficiency, and freedom from scattered light.

4. The operation of existing flare-patrol networks should continue but should be upgraded to provide more significant data for research purposes besides providing data for predictive purposes. We *recommend* that a working-level advisory group on observational techniques and calibration be formed to aid the operating agencies in effecting improvements and in maintaining the high quality of the data.

5. Despite much success in upgrading optical solar telescopes by improved spatial resolution and the incorporation in newer instruments of devices of proven capability such as evacuated optical systems there is still no assurance that any telescope existing or being built has the best resolution now achievable from a ground location. In view of the crucial importance of image sharpness, we *recommend* that further experiments aimed at the achievement of the highest possible optical resolution be supported.

6. We *recommend* greater support for exchanging optical, radio, magnetic, extreme ultraviolet, and x-ray data obtained

on the many different aspects of solar phenomena at many different sites. These exchanges involve costs for travel, communications, and reproduction of data. The active ground-based observatories are usually in isolated locations at a considerable distance from the nearest universities. While this is a problem that must be solved by the efforts of the solar astronomers themselves, we *urge* that funding be available for such measures as providing for working visits of graduate students to solar optical and radio observatories, opportunities to make observations at such observatories for thesis projects, postdoctoral fellowships at such observatories, and one-year courses by solar astronomers at good graduate astronomy departments that lack this specialty.

3 Cosmic-Ray Measurements

Cosmic rays are electrically charged atomic nuclei of many elements, energetic electrons, or gamma rays having energies ranging from a few MeV to at least 10^{12} GeV. The cosmic-ray flux is composed principally of protons. The abundance of alpha particles, the next most abundant species, appreciably exceeds that of the remainder of the cosmic-ray population. Galactic cosmic rays are those that arrive from far beyond the solar system, as distinguished from solar cosmic rays which are emitted by the sun. Prior to interaction with the earth's atmosphere, cosmic rays are referred to as primaries; all their progeny are designated as secondaries.

The importance in solar-terrestrial research of the study of all the properties of solar cosmic rays is self-evident. Less obvious is the equally high relevance of galactic cosmic rays to this field, because of the interactions of the electrically charged particles with interplanetary magnetic fields. As a consequence of particle-field interactions, cosmic rays having magnetic rigidities (momentum per unit charge) up to several hundred GV serve effectively as probes of the solar-controlled electromagnetic conditions in space.

Modulations of the primary cosmic radiation are studied directly, with a variety of balloon-borne instruments, and via their secondaries that propagate through the atmosphere, with continuously recording neutron and meson detectors located on or below the earth's surface as indicated in Table 1. The effects of the interplanetary magnetic field on protons, heavy nuclei, and electrons differ markedly. Therefore, observations of charge, mass, and energy discrimination of the low-energy cosmic rays with balloon-borne instruments provide an exceedingly sensitive means for testing theoretical models of this field. In the case of the surface measurements,

TABLE 1 Important Techniques for Ground-Based Cosmic-Ray Studies

Technique (Instruments)	Energies Covered[a]	Primary Species
Neutron monitor, fixed or mobile (including multiplicity monitor)	1-50 GeV; mean 10 GeV; 100 GeV	Principally protons
Balloon flights (various instruments)	50 MeV; 2 GeV; 15 GeV	Protons, helium, and heavier charges
	20 keV; 20 MeV; 15 GeV	Electrons
	20 keV and above	X rays
	30 MeV and above	Neutrons
Riometers and ionospheric forward-scatter circuits	5-50 MeV	Principally protons
Meson detectors (new configuration, underground)	5-100 GeV; mean 50 GeV; 200 GeV	Principally protons

[a] Atmospheric limit; instrument limitation; upper magnetic cutoff.

the atmosphere is a blackbox which provides a coupling between the incident primaries and the detector. The combination of the earth's magnetic field, the atmosphere (and any further superposed absorber as in the case of underground detectors), and the detector make up a multicomponent optical system. Thus the earth itself may be considered analogous to a spin-stabilized spacecraft carrying multiple detector arrays. Spatial anisotropies are studied by relating time (such as diurnal) variations in the intensity observed at a number of stations distributed over the earth's surface to their asymptotic directions of viewing in space.

There are unique advantages in obtaining measurements with instruments located on or below the earth's surface. (1) The study of anisotropies requiring observations of exceedingly high precision (extending to $\sigma = \pm 0.20$ percent per day) continuously, simultaneously, and sometimes over long periods of time, at a number of points around the globe, can only be carried out with ground-based instruments. (2) Ground-based instruments provide the only means of studying the intensity variations of particles with energies exceeding about 500 MeV, because spacecraft-borne instruments are generally not capable of energy discrimination above that level. (3) The energy range attainable by inclined and underground telescopes utilizing the geomagnetic field as an energy spectrometer encompasses all cosmic rays with energies above the atmospheric cutoff that are subject to solar modulation. (4) Measurements of particles that have arrival directions appreciably inclined to the ecliptic plane, and hence that serve as probes of regions of space not likely to be accessible to spacecraft for some time to come, can be carried out only by ground-based instruments located in the polar regions.

It is noteworthy that the ground-based studies discussed in this chapter not only are valuable in advancing our knowledge about the earth's environment, the interplanetary medium, and the sun, but they also effectively complement *in situ* experiments carried out with space vehicles. In particular, it will become apparent in the following discussion that they provide data germane to space research that cannot otherwise be obtained. In this essential respect, balloon-borne experiments are properly construed as being included in the ground-based category and are therefore considered here in detail.

Ground-based cosmic-ray research, despite its long history, has only recently emerged from the era of exploration. A high degree of sophistication in ground instruments, data analysis, and theoretical interpretation is now required. Routine methods of data-gathering and treatment no longer suffice for resolving the subtle and sometimes extremely minute effects that may hold the key to understanding significant physical mechanisms. On the other hand, the rewards of ground-based cosmic-ray experiments continue to be substantial because of the newly attained possibilities for designing experiments, including those affording long-term observations at groups of stations.

SOLAR COSMIC RAYS

The basic objectives of solar cosmic-ray studies are (1) to understand the mechanisms whereby solar cosmic rays are given their high energies and (2) to study their motions in the interplanetary medium. The processes of particle acceleration as an energy release in solar flares are of basic physical significance and are poorly understood. Likewise, knowledge of the subsequent interaction of these particles with the interplanetary magnetic fields is incomplete; for example, we still are unable to assess the relative importance of diffusive and energy-loss processes in this interaction.

It is generally believed that a majority of the solar cosmic rays are accelerated in a very short time interval during a solar flare. The arrival of the solar-flare particles at the earth is spread out in time because of propagation effects. The highly relativistic particles can arrive within 10 min as manifested by their ground-level effects. For these high energies, the entire event may last for only a few hours. However, at energies of approximately 100 MeV or less, observable by balloons or satellites, the particle flux may rise to a maximum in a period anywhere from several hours to days and decay over a period of time lasting many days. These low-energy solar particles perturb the polar ionosphere and thereby affect radio communications.

An important consideration is the energy, or magnetic rigidity spectrum, of the solar cosmic rays. This spectrum is generally observed to be exponential but sometimes may be fitted by a power-law relation. Because of the steepness of these spectra, the occurrence of ground-level effects observed with neutron monitors is rather infrequent--perhaps once or twice a year near the solar activity maximum. At energies observable at balloon altitude, many more events can be detected and studied. At still lower energies (a few MeV), detectable by ground-based radio-propagation techniques and by instruments aboard spacecraft, a nearly continuous emission of solar particles may be observed near sunspot maximum, and specific events occur frequently throughout the solar cycle.

Protons make up the dominant fraction of solar cosmic rays; however, in many events a large flux of helium nuclei, up to approximately 25 percent of the proton flux, is observed. Still heavier nuclei, up to iron, have been detected. These different charges cannot be resolved by surface techniques. However, they were first identified with balloon-borne instruments; and indeed, even today, the principal information on the chemical composition of solar cosmic rays comes from balloon and rocket experiments.

Intense electromagnetic emissions are directly related to the acceleration of cosmic rays on the sun. These include radio, optical, ultraviolet (uv), x-ray, and gamma-ray emissions. Ground-based studies of the radio, optical, and uv emissions form an important part of the endeavor of other disciplines. Historically, energetic x- and gamma-ray emissions (>100 keV) were first identified through the use of balloons in 1958. Since they play an important role in determining the time and mechanism of acceleration of solar cosmic rays, it seems appropriate to refer to them here.

We shall now consider how the various ground-based measurements contribute toward achieving the basic objectives of solar cosmic-ray research.

Acceleration Features--Charge Composition, Energy or Rigidity Spectra, and Related Emissions

To understand the mechanisms whereby particles are accelerated to high energies, at least three features of the solar cosmic rays are of importance: their charge composition, energy or rigidity spectrum, and related emissions.

In general, the chemical composition of solar cosmic rays follows quite closely the elemental abundance in the solar atmosphere, suggesting that the acceleration process is independent of charge. However, very little is known concerning solar cosmic rays with charge greater than about 14, and their composition is crucial to the location of the accelerating region in the solar atmosphere.

Balloon-borne detectors, although they have the disadvantage of a relatively limited exposure time, have been valuable in the study of the composition of solar cosmic rays. This is due in part to the comparatively large area of the sensors in balloon systems--approximately 1000 times larger than typical detectors operating in space--an extremely important feature in view of the very low intensity of nuclei heavier than helium. Furthermore, balloon systems can be designed specifically to study the heavy nuclei, thus providing a wider dynamic range than satellite experiments which until now have been limited to $Z \leq 16$. Improvements in balloon instrumentation suggest that this technique will be competitive with satellite observations of heavy solar cosmic-ray nuclei in the foreseeable future.

The two types of energy or rigidity spectra considered for solar cosmic rays--exponential or power-law--imply quite different types of acceleration processes. Although some studies indicate exponential spectra, power-law spectra are still favored in some instances, and it may be that both types occur depending on the specific event. In order to differentiate between exponential and power-law spectra, it is necessary to make measurements over as wide an energy range as possible. Balloon and surface measurements provide an extension of the lower-energy satellite observations up into the GeV ranges.

Electron, neutron, x-ray, and gamma-ray emissions are strongly correlated with the acceleration of cosmic rays and are relevant for determining the precise time of acceleration and the location of the source on the sun. In addition, the intensity of x radiation, of possible gamma-ray nuclear line emission, and of solar neutrons (as yet undetected) provides important information on the acceleration process. The details of the energetic electron spectrum above approximately 10 MeV also require further investigation. Balloons, which can carry large cross-section, low-background, specialized detectors, are and will continue to be an economic method for studying these high-energy emissions associated with solar-particle acceleration.

Propagation Features--Intensity-Time Profile, Anisotropies, and Energy or Rigidity Spectra

To understand the propagation of solar cosmic rays in the interplanetary medium, three features of the typical solar cosmic-ray event are of importance: intensity-time profile, anisotropies, and energy or rigidity spectra of the radiation.

The intensity-time profile of solar cosmic rays is energy-dependent as a consequence of variations in the interplanetary medium of the propagation characteristics as a function of energy. A study of the characteristics at the onset of an event, for example, provides details of the magnetic-field configuration between the earth and the sun; similarly, the decay characteristics of an event provide information on the interplanetary magnetic field at distances greater than 1 AU. At energies less than a few hundred MeV, the intensity-time profiles can be studied on satellites. In the 5- to 50-MeV energy range, ground-based radio propagation techniques, specifically riometers and ionospheric forward-scatter circuits, provide a continuous measure of particle intensities and are a valuable supplement to the direct satellite observations. Because a number of ground-based systems are located at multiple points in the polar regions, they may be used to study the passage of these particles through the earth's field and their arrival at high latitudes. At energies above a few hundred MeV, ground-based neutron intensity detectors at many locations with different cutoff rigidities and directions of viewing provide continuous intensity-time profiles. These high-energy observations are an essential complement to those at lower energies, and together they yield a description of the interplanetary magnetic field over a large range of scale sizes.

The propagation of solar cosmic rays is, in general, highly anisotropic and results from the fact that cosmic rays move along magnetic field lines much more readily than they move across them. That this anisotropy persists throughout the onset phase of most solar cosmic-ray events is demonstrated by the fact that perhaps only one out of 20 ground-level events observed to date can be traced to a flare on the far side of the sun. The neutron detector provides a powerful tool for studying the directional properties of the solar cosmic rays at high energies. Each high-latitude station has a particular direction of viewing which resembles that of a coarse radio telescope (approximately 10° by 10°). As the earth rotates, a contour map of intensities is obtained both in and off the ecliptic plane. The details of this map and its development with time provide important information on the scattering of cosmic rays by magnetic-field irregularities. Instruments on satellites can study energies up to 100 MeV with somewhat coarser angular resolution, making possible correlation of observations at low and high energies to provide direct information on the scattering process over different scale sizes.

The energy or rigidity spectra of solar cosmic rays change continuously throughout an event since particles of various energies interact differently to the interplanetary propagation conditions. Study of their time variations provides another method for ascertaining the details of the propagation process.

GALACTIC COSMIC RAYS

At present, the galactic cosmic-ray research relating to solar-terrestrial physics focuses on observations of temporal variations in intensity. The basic data used are intensity versus time measurements, as a function of energy, for the various charged-particle components. The scale of observed time variations ranges from minutes to 20 years. Except for a minute (and highly controversial) sidereal effect, all known periodic, recurrent, and transient time variations or modulations of galactic cosmic-ray intensity represent spatial anisotropies arising from solar phenomena.

The sun exercises control over the electromagnetic conditions in space through the solar wind--the outwardly expanding coronal gas, with its frozen-in magnetic fields, which moves at hypersonic velocity. All the characteristics of the interplanetary magnetic regime--including the Archimedes spiral pattern of the magnetic field, the irregularities over a large range of scale sizes, the sector structure, the changes in plasma velocity and in the magnetic-field polarity, and hydrodynamic shock waves--in one way or another affect almost all the cosmic rays in the inner solar system. The gyroradius of a 10^{12}-V particle in the magnetic field of about 5 gamma is of the order of 5 AU; hence the interplanetary field dominates the motion of particles with energies below this limit. These particles constitute 99.9 percent of the cosmic radiation.

The effectiveness of each of the several processes that modulate cosmic rays is determined by the detailed structure of the interplanetary medium. Thus, for example, the distribution of the scale sizes of magnetic irregularities and their mean separation are significant factors. Clearly, the mode of scattering when a particle encounters a clump of twisted and tangled magnetic field lines depends on whether its gyroradius is small or large compared with the dimensions of the scattering center. Consequently, an important characteristic of any modulation process is its dependence on magnetic rigidity.

The electromagnetic conditions in the heliosphere respond to discrete outbursts on the sun and reflect the changes in the general level of solar activity. Hence, in addition to transient cosmic-ray intensity fluctuations associated with individual storms, there are long-term changes in the average characteristics during the solar activity cycle. All periodic and transient variations evidence these changes.

The 11-year solar-cycle modulation is the most important modulating process of cosmic rays, and its effects transcend those of all other temporal changes. The total reduction in cosmic-ray intensity from solar minimum to solar maximum is roughly 50 percent for primary protons with energies exceeding 1 GeV, 25 percent for the nucleonic component at sea level, and 6 percent for mesons. This phenomenon is a consequence of the convective removal of galactic cosmic rays by magnetic irregularities carried outward from the sun by the solar wind. The cosmic-ray density in the inner solar system represents a balance between outward convection and inward diffusion. Even at solar minimum a residual modulation remains, implying that the observed spectrum is not the same as it is beyond the boundary of the heliosphere, and that, furthermore, there is always a radial density gradient. Many questions remain concerning the rigidity and charge dependence of the modulation, especially at low energies. The size of the heliosphere, a parameter for which cosmic rays thus far provide the only data, remains to be determined. The three-dimensional characteristics of the cosmic-ray intensity modulation, and hence of the solar magnetic cavity, are not known. Other significant unsolved problems concerning the modulation mechanism include the role of acceleration and deceleration processes.

Diurnal variations in cosmic-ray intensity are evident at the earth's surface because of the earth's rotation in an anisotropic flux. The location of the apparent source of this solar diurnal anisotropy--90° east of the sun-earth line and in the solar equatorial plane--is predicted by a theoretical model which envisages corotation of the isotropic cosmic-ray gas with the spiral interplanetary magnetic field rigidly attached to the sun. However, although the maximum intensity occurs at 1800h local solar time (after correction for geomagnetic bending), corresponding to 90° east, the amplitude is not constant from year to year, and its magnitude in free space (~ 0.4 percent) is less than the theory predicts. Furthermore, there exist large day-to-day fluctuations in amplitude and phase which are not understood. Another puzzling facet of the solar diurnal variation is the recently discovered 20-year wave, which has its maximum amplitude in the asymptotic direction 128° east of the sun-earth line and which passed through zero in 1958 when the sun's poloidal field reversed.

Also there is an apparent semidiurnal variation, with amplitude somewhat smaller than that of the 24-h wave (~ 0.05 percent) and with the apparent direction of anisotropy along the spiral interplanetary field line. The verification or explanation of this variation is somewhat controversial. Such a 12-h variation might be expected to arise from a theoretically predicted intensity gradient perpendicular to the plane of the ecliptic. To confirm the existence of this effect experimentally is of great importance. Transient north-south asymmetries associated with specific cosmic-ray storms have been detected and have opened up a new field for investigation.

The still smaller (~ 0.01 percent) sidereal variation is not believed to be of solar origin. Yet its presence could affect observations of the solar diurnal variation with underground meson detectors because their energy response is near the limiting rigidity above which there is no bulk streaming of the cosmic-ray gas with the corotating interplanetary magnetic field.

In contrast with the diurnal variation, which is a local time effect due to the earth's rotation, the Forbush decrease is a universal time phenomenon in which the cosmic-ray intensity drops rapidly by as much as 10 or 15 percent, usually within a few hours, and recovers much more slowly. Several alternative theoretical models of the modulation mechanism involving blast waves or magnetic tongues or bottles have been proposed to account for the very complex features related to these so-called "cosmic-ray storms." Disturbances in cosmic-ray intensity tend to recur at intervals of 27 days just as do geomagnetic storms which exhibit similar recurrence tendencies for the same reason. This corresponds to the synodic rotation period of the sun. Another phenomenon, trains of enhanced diurnal variation, is also believed to be related to the sun's rotation.

On a much finer scale size, rapid fluctuations (minutes to hours) in cosmic-ray intensity are observed, but it is not yet possible to make any general statements concerning their significance.

It is interesting to note that many significant advances in ground-based cosmic-ray research, including the recently discovered 20-year anisotropy, have been achieved with a small network of classical detectors which, in some circles, were long ago regarded as obsolete. The meticulous supervision over the last three decades of the Carnegie Institution's ionization chambers at Huancayo, Cheltenham, Godhavn, and Christchurch, and the rigorous statistical procedures invoked for extracting the maximum amount of scientific information, serve as prototypes for this type of investigation.

The importance of maintaining long-term continuity cannot be overstressed. The normalization of new-generation detectors to the instruments which they replace should be carried out with great care over a long period of overlap in order to ensure the integrity of the data on phenomena characterized by a long time base.

PROPAGATION OF COSMIC RAYS THROUGH THE MAGNETOSPHERE

As noted earlier, particles with energies such that the geomagnetic field is the primary controlling factor in determining their arrival at specific locations on the earth are of major interest to solar-terrestrial physics. The classic work of Störmer mathematically described the motion of charged particles in a dipole field and introduced the concepts of allowed and forbidden regions of access and also of cutoff rigidities. The cutoff rigidity defines the lowest particle momentum (per unit charge) permitted for arrival at a specified location for all particles incident from a specific direction. Thus it turns out that the properties of the geomagnetic field are such that the cutoff rigidities are an approximate function of geomagnetic latitude; there is a maximum value near the geomagnetic equator, decreasing to zero at the magnetic poles.

In addition to the cutoff rigidity of a particular station, each observing site on the earth's surface is characterized by a unique set of directions that are accessible from space for a specified energy. These directions define an asymptotic cone of acceptance through which the extraterrestrial particles must pass in order to be detected. As the earth rotates, each station scans an identifiable portion of the celestial sphere, and the data from several stations or types of instrument are often combined to deduce properties of the cosmic radiation in space as well as those of the interplanetary medium through which the particles traveled before interacting with the magnetosphere.

Cosmic-ray particles arriving at the earth must traverse the magnetosphere, their motion within this region being controlled by the magnetic fields of both terrestrial and magnetospheric origin. For particle energies detectable by ground-based instrumentation, the geomagnetic field of internal origin is the controlling factor, and the intensity is modulated to a lesser extent by the external fields originating in the magnetopause and in the magnetospheric tail and those generated by ring currents. A numerical point-by-point integration of the equation of motion of a charged particle in a specified magnetic field is necessary to determine its trajectory, because the general equation for a particle traversing the geomagnetic field cannot be solved in closed form. Although early calculations were based on a dipole approximation of the earth's magnetic field, this was later found to be inadequate to explain many cosmic-ray observations, and various semiempirical methods were introduced. Now, with the availability of high-speed digital computers, it is possible to calculate the motion of charged particles within the magnetosphere to a degree of precision limited only by the accuracy of the mathematical description of the magnetic field. For particle energies above approximately 1 GeV, well-defined, quiescent, internal magnetic-field coefficients are available, which, together with their time derivatives, are sufficient to calculate the majority of cosmic-ray trajectories. Unfortunately, for energies below approximately 1 GeV, the internal field models alone are inadequate.

The identification of the earth's magnetic cavity, and a description of the external current sources necessary to maintain the magnetospheric configuration, have improved our knowledge of the magnetic fields that control charged-particle motion in the vicinity of the earth. This is true even though the available magnetospheric models are relatively crude. The unique configuration of the magnetosphere with its long tail has a significant influence on the cosmic-ray flux seen at the surface and at balloon altitudes. For example, the magnetospheric tail allows protons with energies above a few MeV to penetrate deeply into the magnetosphere; solar particles also have access to the polar regions via this route. Accurate measurements of these lower-energy particles, particularly with balloon-borne detectors, are necessary for a better understanding of both solar and galactic particle propagation through the magnetosphere. Recent theoretical results reveal that the asymptotic cones of viewing do not rigidly corotate with the stations as the earth rotates on its axis but often point down the tail during large portions of the day. In addition, significant daily variations in geomagnetic cutoff rigidities at high latitudes have now been observed experimentally and calculated theoretically.

Significant theoretical advances have been made in this field during the last five years, and an improved understanding of certain experimental observations has been achieved. Yet, recent experimental results clearly indicate that our present knowledge concerning many magnetospheric phenomena is still extremely limited. With respect to cosmic-ray physics, further theoretical and experimental research is necessary to elucidate the magnetospheric environment. Balloon measurements in the polar region are essential to permit derivation of theoretical models on the dynamics of particle transmission through the magnetosphere. Considerable research is also necessary to describe the quiescent state of the magnetosphere, including solstice conditions when the tilt of earth's axis with respect to the solar wind is maximum.

An adequate description of perturbed geomagnetic conditions is also needed. This is of considerable importance to solar-terrestrial research, not only with respect to the cosmic radiation but also from the viewpoint of the many interrelated geophysical effects including the acceleration and precipitation of particles in the magnetosphere. For example, cosmic-ray measurements on the surface and from balloons have shown that geomagnetic cutoffs decrease during disturbed geomagnetic conditions. In the future we would hope to develop our knowledge of magnetospheric physics to predict accurately the magnitude of this decrease. More research in this area is required.

Ground-based observations are essential for the measurement and identification of particle precipitation into the atmosphere. This phenomenon involves a variety of solar-terrestrial effects such as aurora, polar-cap absorption, relativistic electron precipitation, and other geomagnetic phenomena, as well as magnetospheric problems of particle entry, storage, local acceleration, and dumping out of the magnetic confining regions. All these processes are poorly understood. The technique of simultaneous balloon experiments at magnetically conjugate points, and across the polar cap, seems to offer particular promise for obtaining measurements that will improve our knowledge of particle motions within the magnetosphere.

INTERACTION WITH OTHER DISCIPLINES

Investigations of solar cosmic rays with ground-based instruments are important to many other areas of study. Some of the more important areas and the types of physical measurements that best exemplify this interaction are as follows:

Interplanetary Physics

Both galactic and solar cosmic rays are charged probes of the interplanetary electromagnetic environment. In contrast with the *in situ* measurements made by spacecraft, they provide information on the large-scale character and gross features of the interplanetary magnetic field. This embraces the average character of the field as well as the superimposed fluctuations. Since the magnetic field is frozen into the solar plasma, cosmic-ray probes give information on the gross character and the fluctuation in density of the plasma itself. Cosmic-ray observations are also closely correlated with the interplanetary-field sector structure. The magnitude of the average velocity of the solar wind is directly related to the convection of cosmic-ray particles out of the solar system. Finally, the gross extent and boundary of the region of solar influence is of direct interest in the cosmic-ray modulation problem. The cosmic-ray observations, therefore, relate closely to all the *in situ* measurements of these parameters in interplanetary space.

Solar Physics

Since the majority of solar cosmic rays are believed to be accelerated in solar flares, as discussed earlier, this facet of cosmic-ray research is closely related to other studies of flare-associated electromagnetic emissions using optical, radio, x-ray, and gamma-ray techniques. In addition, observations relating to the growth and decay of solar-active regions are of extreme interest to those working in cosmic-ray research. Since the effects on the ionosphere of solar uv and x radiation indicate the magnitude and time scale of these emissions, and since x rays are closely associated with the cosmic-ray acceleration process, such observations are relevant to cosmic-ray research. The fundamental question of the hydrodynamic outflow of the solar corona which results in the solar wind has bearing as well. Solar observations relating to the structure of the corona (e.g., as obtained during eclipses) are of direct interest to cosmic-ray research.

Magnetospheric Physics

This field has broad interaction with cosmic-ray studies. The geomagnetic field controls the access of cosmic-ray particles to the earth and determines the cutoff rigidities and asymptotic directions associated with each point on the globe. Geomagnetic information of all types is therefore relevant, including an accurate description of the quiet-time field, studies of field variations during magnetic storms, and delineation of effects due to the magnetospheric tail and to ring currents flowing in the magnetosphere. In the polar regions, cosmic rays are often detected by various ionospheric radio-probing techniques. Hence, cosmic-ray physics interacts directly with radio and aeronomic observations of the D and E regions of the ionosphere where cosmic rays dissipate much of their energy.

RATIONALE FOR GROUND-BASED COSMIC-RAY RESEARCH

Ground-based cosmic-ray research has provided crucial information on many solar-terrestrial phenomena. New and significant advances are still being made with data emanating from continuously recording networks, and ground-based programs can undoubtedly continue to make significant contributions to solving problems of fundamental importance. Many experiments ultimately intended to be performed in space are first tested and evaluated with balloon-borne equipment. Certain other types of data can be obtained only with surface or balloon techniques. The experimenter has the capability with these techniques of maintaining direct supervision and control over all phases of the experiment and analyzing the data to obtain a definitive result, within a comparatively short time interval.

As we suggested in the beginning of this chapter, the earth itself is an interplanetary monitoring platform. Since its magnetic field acts as a particle momentum analyzer, energy discrimination over a large range is possible. Data provided by stations viewing in various directions from many countries are analyzed to deduce the properties of the interplanetary medium through which the cosmic rays have probed. The data from certain cosmic-ray stations are now being utilized in real time for environmental monitoring in support of manned space exploration. Nevertheless, cosmic-ray measurements should be supported on the basis of the value of the specific research being conducted, and monitoring alone is not sufficient to justify the operation of any specific cosmic-ray station.

RECOMMENDATIONS*

1. The total support currently available for cosmic-ray research allows a minimal productive program, but it does not

---

**Note:* In reviewing this report, the Director of the National Center for Atmospheric Research (NCAR) submitted the following comments pertaining to balloon technology. Although some aspects may be more pertinent to atmospheric physics, the comments are of special interest to this discussion.

NCAR's ballooning experts foresee long-duration flights at 120,000 ft simultaneously at selected locations in the two polar caps. NCAR has had long-duration flights (well over one year) with very light loads and at considerably lower altitude. The same techniques can be used for higher and heavier systems, and NCAR now has under way a development program to explore these techniques. It is difficult to say what are the limits of the superpressure technique that has permit growth, and it is extremely difficult for competent young scientists to enter this field of research. Therefore, we *recommend* that the present downward trend in available funds be reviewed in favor of a modest upward one. We *further recommend* that agencies that utilize cosmic-ray data from ground-based stations contribute toward the programs that provide these data. The responsibility for disseminating environmental information has been vested in the Environmental Science Services Administration, and it is therefore appropriate that this agency should be encouraged to contribute toward the support of the cosmic-ray research that is immediately relevant to its mission.

2. The potential of balloon experiments in conjunction with surface cosmic-ray observations to provide new and significant advances in solar-terrestrial physics is extremely large. We *recommend* that the level of support for this type of research be increased.

3. We *recommend* that a mobile neutron detector unit be established to carry out a number of special experiments, including determinations of rapid time fluctuation, diurnal anisotropy on a day-to-day basis, the atmospheric limitation imposed on observational precision, and other studies of limited term. The unit would comprise a pair of independent neutron intensity detectors that are readily transportable and would be devoted to specific investigations rather than to use as a permanent station or for routine surveys. The mobile unit should be made available to research groups on

---

been employed, but as loads and altitudes get higher and balloons get larger, the materials requirement to handle the overpressure gets increasingly difficult.

An alternative approach, using ballasted systems, can be employed up to very large sizes. At the present time, for flights of duration of more than about a week, the technique is exceedingly expensive because of the amount of ballast needed for a given payload. There are various suggestions and concepts for much more efficient ballast systems, perhaps using liquid hydrogen as a ballast--liquid hydrogen not only would serve as a ballast but provide replacement gas for any losses that occur. These concepts should be explored now that the demand for long-duration flights with heavy loads has appeared along with the desire to recover the payloads.

In addition to better superpressure balloons and more efficient ballasting systems, development of tracking at long range and, in some cases, a mobile recovery system will also be required. Long-duration flights in the polar regions probably are not so difficult as in the lower latitudes, because a balloon flying constantly in the sun or in darkness has greater vertical stability. Some satellite navigation system may be a feasible means of tracking. Telemetry relayed by satellite may also be possible. Several simultaneous flight pairs per year, flown in both polar caps, might be possible where the two systems would be aloft simultaneously for a few hours. The operational coordination and logistic problems will try the patience of even the best trained crews, however. In addition, there are problems inherent to handling balloons in extremely cold environment which will escalate costs.

the recommendation of a users' committee and on the basis of individual research proposals. In general, the types of experiments envisioned would involve the combination of detectors, which would be transported to appropriate sites where they could be separated by an easily variable distance to meet the specific requirements of the given investigation.

4. We *recommend* the development of new instruments for balloon use to study specific cosmic-ray problems. A particular need exists for large-area, high-counting-rate detectors, low-background x- and gamma-ray detectors, and high-charge-resolution cosmic-ray telescopes.

5. We *recommend* that a capability of flying very large balloons within the polar cap be established. Simultaneous flights in both hemispheres, correlated with satellite measurements, are essential for studying anisotropies and conjugate-point phenomena. With regard to southern polar regions, there is the possibility of flights of several days' to one week's duration without encountering difficulties resulting from overflight of national boundaries.

6. We *recommend* development of an instrument for fundamental studies of the various modulations and anisotropies of cosmic radiation at high energies. The ideal instrument would include the following characteristics: high counting rate (10^6 counts per hour); negligible correction for meteorological effects; and energy discrimination, especially in the range 50 to 500 GeV. No presently available instrument approaches these capabilities. Standard techniques using neutron multiplicity detectors or meson telescope arrays would entail inordinately large expenditures. A new technique should be developed, possibly utilizing the atmosphere as a calorimeter and extending recent developments in air-shower technology to energies below the conventional range ($>10^{12}$ eV).

7. We wish to bring attention to the need for long-term monitoring of cosmic radiation using neutron monitors at the following locations: at the geomagnetic equator, one location near the knee of the latitude effect, and one in the polar regions. We *recommend* that, although the data from certain cosmic-ray stations have been accepted as an environmental monitor, the measurements should be supported on the basis of the specific research being conducted. Neutron intensity detectors fulfilling these criteria should be continued.

8. We *recommend* continued support of long-term solar modulation studies designed to measure accurately the energy spectra of protons, helium nuclei, and electrons with balloon-borne instruments through at least the next solar minimum.

These studies should be carefully correlated with the 1965 sunspot minimum period during which only limited satellite observations were available.

9. We *recommend* a continued effort in the development of very-large-volume balloons and techniques for long-duration (many weeks) balloon flights. Also, thin-film and other microcircuit technology offers new prospects for lightweight balloons. At altitudes as low as 120,000 ft, balloons may be considered essentially at the top of the atmosphere for the purpose of many cosmic-ray studies. The costs of even very elaborate balloon experiments can be less than a thousandth that of earth satellites.

10. We *recommend* continued efforts to derive ionization rates as a function of altitude on a continuous basis using ground-based riometers and ionospheric forward-scatter circuits. Since the ionosphere below approximately 100 km is analogous to a large ionization chamber, the calibration of this ionization chamber provides a direct measure of the intensity and energy spectrum of the incident particles.

11. We *recommend* that improved mathematical descriptions of the magnetic fields (with emphasis on the external fields) be developed for both geomagnetically quiet and disturbed conditions as a step toward better understanding of charged-particle motion, particularily below 1 GeV. The ability to compute the effect of the terrestrial magnetic fields on charged particles is limited by the accuracy of the magnetic field models available.

12. We *recommend* that a classification scheme be developed for solar-active regions that will reflect their particle-acceleration potentiality. We *recommend* that general magnetospheric indices be further investigated, including parameters to represent quiet- and storm-time equatorial ring currents. Also we encourage the development of indices that will represent solar and galactic cosmic-ray activity.

13. We *recommend* international interchange of personnel among research institutions and encourage other nations to support cosmic-radiation research programs; at the same time, we question the advisability of the United States funding existing or new cosmic-radiation stations in countries that already support cosmic-ray research.

4 Geomagnetic Observations

Geomagnetic science has played a pioneering role in exploring the electromagnetic environment of the earth and solar-terrestrial relations, in general. Ground-based observation of the geomagnetic field and its variations has a long history of international coordination and achievements. The description of the main magnetic field, originating deep in the earth's core, and morphological studies of geomagnetic variations have steadily advanced as techniques and global coverage improved. With the advent of rockets and satellites, a new phase has opened to geomagnetic research. A new dimension, not directly accessible from the ground, has now been added, giving us a far more complete picture of the true physical state of the earth's field environment. Satellite magnetometers provide the necessary *in situ* information. However, these data are field values at a given position for a given time, and spatial and temporal effects are often difficult to separate. Particularly for long-term effects, ground geomagnetic stations provide a continuous two-dimensional view of the field configuration complementary to space observations. Permanent and standardized geomagnetic observations at fixed locations on the earth's surface are an essential ingredient to understanding the configuration of the magnetosphere, the physical processes occurring in it, and the interaction of the magnetosphere with the solar wind.

During quiet and disturbed periods, electric currents flowing in the ionosphere and the magnetosphere affect the surface magnetic field. Geomagnetic observations give indirect information on these currents and, in turn, on the driving electric fields or distributions of drifting charged particles, depending on the nature of the source mechanism in question. The surface magnetic field, with the aid of physical models based on space measurements, can be used to monitor a number of physical processes occurring in space during quiet and disturbed times.

A wide range of magnetospheric wave phenomena propagate through the ionosphere and produce signals that are recorded routinely at ground stations. These micropulsation signals are potential diagnostic probes for remote sensing of magnetospheric parameters because they have characteristic frequency bands, dispersion properties, and amplitude variations which are related to physical processes in the magnetosphere.

Systematic magnetic-field observations have been carried out for more than a hundred years. Early observatory measurements had insufficient frequency response and sensitivity to have much relevance to modern micropulsation work, but they are adequate to show the development of large-scale disturbances such as magnetic storms and substorms. Our present understanding of the essential physics of most of the processes involved now enables us to go back to old records, reinterpret them in the light of new ideas, and obtain basic information on some of the important solar-terrestrial features during the past eight or ten 11-year solar cycles.

SCIENTIFIC QUESTIONS

All solar-terrestrial processes that can be explored with ground-based geomagnetic observations are related to ionospheric and magnetospheric dynamics. Thus, most major scientific questions to be answered in this field are intimately related to, or identical with, many of the problems discussed in the Space Science Board's 1968 report, *Physics of the Earth in Space--A Program of Research, 1968-1975,* Chapter 6, "The Magnetosphere."

THE EARTH'S MAIN MAGNETIC FIELD

The earth's main magnetic field originates in the fluid core and, as observed on the surface, is modified by magnetized materials in the earth's crust. The regional crustal features, described as "local anomalies," can be eliminated in a description of the main field. The only crustal effects relevant to solar-terrestrial phenomena are those arising from anomalously large conductivity regions which can affect interpretation of ground-based observations of time variations in the magnetic field.

The main-field component in the magnetosphere must be described as accurately as possible, especially for the study of near-earth phenomena, because at low altitudes it appreciably deviates from that of a dipole field. This main field can be expressed as a spherical harmonic series; the International Geomagnetic Reference Field (IGRF) recommended by the International Association of Geomagnetism and Aeronomy (IAGA) includes terms up to order and degree 8 for both the main field and its secular variation. Although the coefficients expressing the secular variation are admittedly uncertain, especially those of higher order and degree, IGRF is recognized as the best main-field description available at present. The World Magnetic Survey, under the auspices of which many of the data for the IGRF were assembled, will terminate in December 1969, and IAGA's Working Group on The Analysis of Geomagnetic Fields will continue international coordination on this topic. Activities of this working group should be supported to ensure continued improvement of the description of the earth's main field and its secular variation.

THE QUIET-DAY MAGNETIC FIELD

The geomagnetic cavity is the region of space surrounding the earth and threaded by magnetic field lines linked to the earth. It may be pictured as a huge, deformable container of charged particles, of either solar or terrestrial origin and with a wide range of energies. The cavity is limited in extent by the action of static and dynamic pressures of the solar wind on the earth's magnetic field. The boundary between the geomagnetic cavity and the solar wind is called the magnetopause. The streaming of the solar wind along the magnetopause produces tangential stresses which stretch the cavity to great distances in the antisolar direction to form the region known as the geomagnetic tail. Energy from the sun reaches the cavity via electromagnetic radiation and fluxes of solar particles.

Changes in the properties of the magnetized solar-wind plasma as it interacts with the geomagnetic cavity are the ultimate cause of most of the dynamical processes in the magnetosphere. These changes may trigger instabilities, excite oscillations, and produce other transient effects that manifest themselves by variations in the surface magnetic field.

The study of the undisturbed magnetosphere is essential to understanding the physics of the system and to establishing the proper base line against which to compare the effects of disturbances. We would like to understand the steady-state regime of the magnetosphere. By this we mean the behavior of the cavity during intervals in which the properties of the solar wind and the interplanetary magnetic field remain practically constant. A steady-state solar wind may not produce a steady-state cavity at all. In fact, the question of whether the cavity ever exists in a steady state under quiet solar-wind conditions is of major importance in solar-terrestrial physics. In the study of the surface field, magnetically quiet days are assumed to be those in which the solar wind approaches a steady state; there is some evidence that a relatively low solar-wind velocity is another necessary condition. For empirical studies of the magnetic field at the surface on quiet days a primary task is to identify components of the daily variation and, where possible, any constant components other than those of the earth's main field. Combined surface, rocket, and satellite measurements are being used to develop physical models of the principal current systems in the geomagnetic cavity. Based on these models, it should be possible to monitor continuously from the ground a number of parameters that would tell us the state of the magnetosphere. The ability to rely on such base lines would greatly accelerate our progress toward understanding the physics of the solar wind-geomagnetic field interaction.

Solar and Lunar Daily Variations

The heating of the atmosphere by the sun is nonuniform and is greatest at the subsolar point. This nonuniform heating produces convective flow in the atmosphere and excites atmospheric oscillations. The uppermost layer of the atmosphere is partially ionized by the ultraviolet and x radiation from the sun and therefore acts as an electrical conductor. The winds in the ionosphere then constitute a flow of conducting matter across the geomagnetic field lines producing electric fields in the medium. Since the medium is conducting, the electric fields produce electric currents. This is called a dynamo process, and the current system produced by this particular dynamo process is called the Sq (solar quiet) system.

The existence of ionospheric currents of sufficient magnitude to account for the Sq system has been established by rocket measurements of the altitude profile of the magnetic field in the ionosphere. Sq-field enhancements associated with solar flares and Sq-field decreases during solar eclipses demonstrate that this current system is mainly controlled by electromagnetic radiation from the sun.

Considerable progress has been made in describing the Sq system using measurements of the daily variation of the surface magnetic field taken during magnetically quiet times. In most models the current is assumed closed in a thin ionospheric layer so that it is essentially two dimensional. Nevertheless, several questions remain to be answered. One concerns the equatorial electrojet, an especially intense part of the Sq system that flows eastward, roughly along the geomagnetic dip equator, in the sunlit hemisphere. There is a day-to-day variation in this electrojet field which appears to be due to variations in the local current density that leave the net total Sq current unaffected. This day-to-day variation is not related in any obvious way to geomagnetic activity, as measured by the indices Kp and Dst, nor to the intensity of solar x rays or the electron density in the *E* region. Thus, it cannot be explained in terms of a variation in the ionospheric conductivity.

Another question arises because of obvious asymmetries in the Sq system, most significant during solstices. In turn, asymmetries in the wind systems, in the distribution of electrical conductivity, and in the dynamo-generated currents are implied. Since the northern and the southern hemispheres of the ionosphere are connected by highly conductive field lines, any electric polarization field asymmetry may produce appreciable currents along the field lines between the two hemispheres. Values of these field-aligned currents at the solstices have been estimated from theoretical models, and the predicted contribution to the surface field at the equator is small--~1 gamma. Also, these models indicate that the Sq current system may in reality be three dimensional.

Another ionospheric current system, denoted by L (lunar), is associated with the dynamo action of atmospheric tides generated by the moon. The existence of an L current system has been satisfactorily demonstrated, but its properties are not yet well established. This problem is one of importance in solar-terrestrial work because the effect of the L system must be separable from those of the other current systems in the geomagnetic cavity.

The essential observational tasks related to the study of Sq and L current systems are: (1) to make *in situ* measurements of the ionospheric currents directly or by three-dimensional mapping of the magnetic field vector, (2) to measure the conductivity profile, (3) to measure the wind velocity in the ionosphere, and (4) to measure the electric field intensity by barium cloud experiments. These tasks can be accomplished by coordinated simultaneous measurements with rocket-borne and ground-based instruments. Once the current system is known, measurements of the surface field can be used to monitor a component of the ionospheric convection system.

Conventional techniques cannot yield precise information on field gradients or on the daytime wind velocity in the ionosphere. New techniques are necessary. Rockets equipped with multiple payloads, multiply ejected, could be used to map the ionospheric parameters, particularly the components of the magnetic field gradient. Electromagnetic (e.g., laser, radar) excitation of an atmospheric volume element in the region of interest, and subsequent tracking of the excited volume element as the plasma decays to the unexcited state, may be a promising technique for neutral wind-velocity measurements. Further studies of eclipse and flare effects are needed to provide quantitative data on the relationship of solar electromagnetic fluxes to the magnitude of the Sq current. Particularly valuable information can be extracted from the changes, during a solar flare, in the x-ray spectrum that cause the ionization altitude profile to change. Ionospheric soundings are also needed in conjunction with such a study.

For studies of the equatorial electrojet, comparative field measurements are essential in South America and India, where the magnetic equator is different from the geographic equator, and in Africa, where both equators are close to each other. U.S. stations at Koror and Jarvis would be important sites in this work.

The Chapman-Ferraro Current

The most distant current system in the geomagnetic cavity is generated directly by the interaction between the solar wind and the geomagnetic field. This current flows in a thin layer along the magnetopause. Satellite measurements indicate that the classical Chapman-Ferraro model for this boundary is a good first-order representation over a considerable area of the magnetopause centered at the subsolar point. The current in the Chapman-Ferraro model provides the magnetic force needed to balance the pressure of the solar wind and thus to maintain the magnetopause in dynamic equilibrium.

In steady state, the cavity boundary is symmetrical about the sun-earth line (neglecting the effects of the earth's orbital motion and of the spiraled interplanetary magnetic field).

Its closest approach to the earth is at the stagnation or subsolar point, located at 10 earth radii on the average. The magnetopause currents produce a daily variation of the surface field on the rotating earth and, since the position of the magnetopause and the magnitude of the Chapman-Ferraro current in the region of the stagnation point are directly related to the dynamic pressure of the solar wind, surface field measurements could in principle provide a continuous measure of the quiet-day solar-wind pressure. Since Sq variations mask the Chapman-Ferraro contribution, the contributions of this current system to the magnetic field at the earth are rather small (a few tens of gammas)--much less than the Sq variations. These must be filtered out in order to use ground observations as a solar-wind pressure monitor.

Further work, both theoretical and empirical, is required to establish adequately the properties of the magnetospause current field before such monitoring will be possible. The empirical studies will require coordinated, simultaneous measurements by satellites and ground-based instruments. Simultaneous magnetic field measurements in synchronous orbit and on the surface near the "feet" of the synchronous satellite's field lines and near the geomagnetic equator are particularly valuable. Theoretical studies on magnetospheric models should be encouraged.

The Tail Current

The topology of the geomagnetic tail has been determined from satellite and space-probe data. As viewed in cross section from the earth, the tail current system has the form of the Greek letter θ, with currents flowing counterclockwise in the upper half and clockwise in the lower half and both branches closing across the central region called the neutral sheet. The near edge of the neutral sheet is at $\sim$ 10 earth radii on the average. The length of the geomagnetic tail is unknown but probably quite variable; the current system, as just described, extends to at least 80 earth radii.

Recent comparisons of satellite magnetometer data and surface magnetograms reveal that tail-current effects are observable at ground stations. Theoretical computations predict that the diurnal variation of midlatitude and high-latitude magnetic conjugency should also be considerably influenced by the tail current. Theoretical studies have shown that the magnitude of the tail current and the location of the inner edge of the neutral sheet depend on the tangential drag exerted by the solar wind on the geomagnetic cavity. Thus, surface field measurements could be used to diagnose the state of the tail current, which in turn is a measure of the tangential drag and the rate of energy transfer from the solar wind.

The Ring Current

The existence of a quiet-day ring current in the geomagnetic cavity was predicted for some time to explain the main phase of the magnetic storms and has recently been confirmed from satellite measurements. This current in its most symmetrical form is produced mainly by the azimuthal drift of trapped protons. The properties of the ring current are determined by their spatial and energy distribution. The processes by which these particles are injected, accelerated, transported, and lost are still largely unknown, and the behavior of these particles is a subject of great interest. The continuous monitoring of the state of the ring-current field component could therefore be an important aspect of surface-field measurements. However, the quiet-time contribution of the ring current is small and masked by other effects. This again points to the need for a comprehensive physical model for *all* steady-state currents in the magnetosphere and ionosphere.

Daily Variation in the Polar Regions

The existence of an independent quiet-time current system over polar regions has been established from measurements of the surface field at high latitudes. The field from this system is superimposed on that from the Sq system. There has been some progress in developing models of this polar system under the assumption that the current is confined to a thin ionospheric layer, i.e., that it is essentially two dimensional.

This polar system may be generated directly or indirectly by the flow of plasma in the distant magnetosphere. Electric fields associated with this flow are "mapped" into the polar ionosphere along the nearly equipotential field lines and drive the current system. One of the working models of the steady-state convection in the cavity was deduced in part from the features of the early models of this polar current system. Surface-field measurements in the polar cap will therefore permit monitoring of the convection of plasma in the outer magnetosphere. Since this convective flow is sustained by energy and momentum transferred from the solar wind to the magnetosphere, continuous information on the flow from these measurements would permit more rapid progress toward an understanding of the transfer processes.

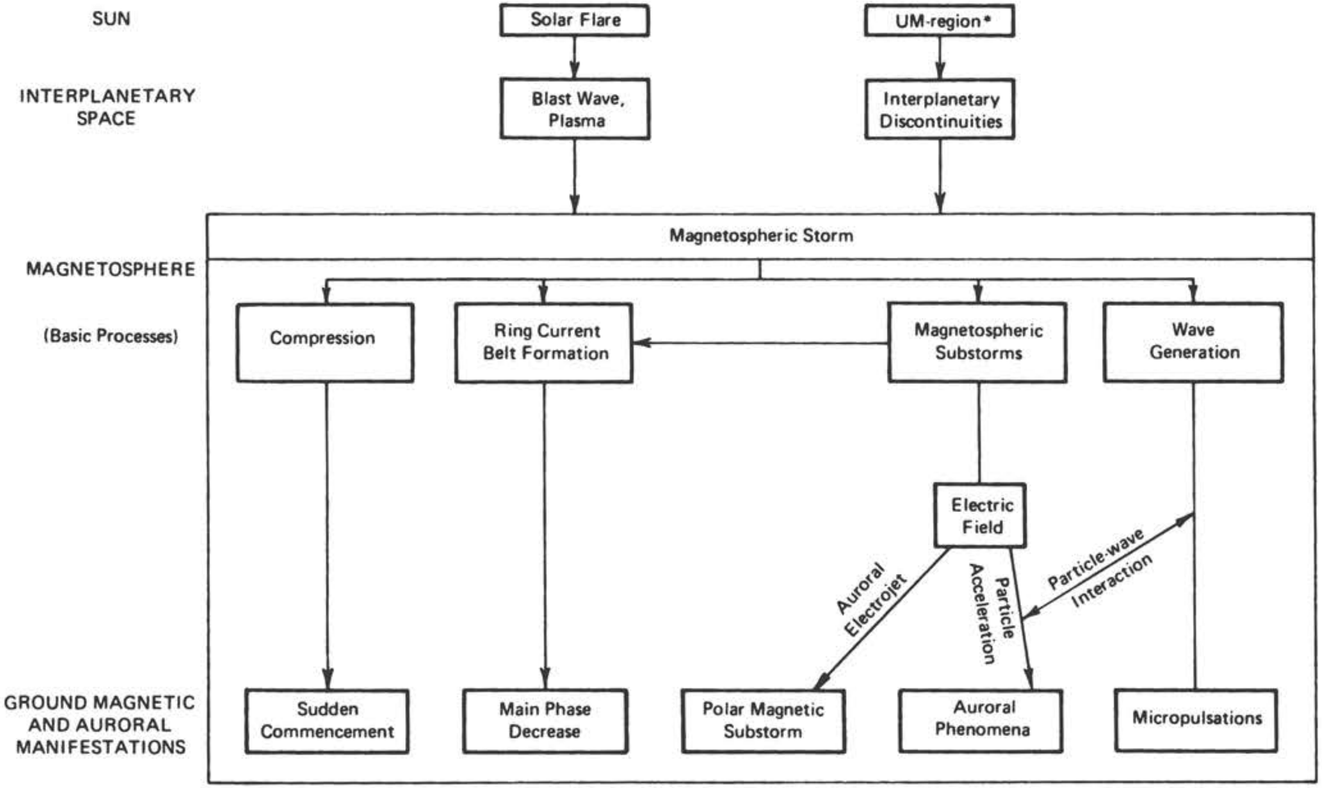
To provide the necessary empirical information for the establishment of a better physical model, further coordinated satellite, rocket, and ground-based measurements are required. In particular, systematic barium releases are important for the determination of electric fields. Experiments are also needed to determine whether there is a field-aligned component of this current system which connects the ionosphere to the distant magnetosphere and to the solar-wind plasma.

GEOMAGNETIC DISTURBANCES

The magnetosphere is disturbed with varying frequency and intensity by perturbations in the solar wind. Changes in the solar-wind dynamic pressure, whether sudden (as in discontinuities) or more gradual, result in a compression or expansion of the magnetosphere. The effects are transmitted inward as hydromagnetic waves and are manifested on the ground as an increase (for compression) or decrease (for expansion) in the magnetic field, representing a magnetospheric response of the simplest kind.

Magnetospheric Substorms

Although the exact nature of the interaction between the solar wind and the magnetosphere at its boundary is not yet clear, there is increasing evidence that particles and other forms of energy are injected into the magnetosphere continuously or in bulk. It appears that when energy accumulated in the magnetosphere reaches a certain level, it is released rather abruptly in what is termed a magnetospheric substorm. The substorm involves a large-scale reorganization of the high-energy particle population, of the thermal plasma, and of the magnetic and electric fields in the magnetosphere; it also produces a severe magnetic disturbance on the surface of the earth at high latitudes, which is called a polar stat or magnetic substorm--a complex phenomenon accompanied by other manifestations such as particle precipitation, auroral activity, infrasonic wave development, and generation of electromagnetic



*UM-region, unipolar *M* region.

FIGURE 2 Schematic of major processes and their effects during a magnetic storm.

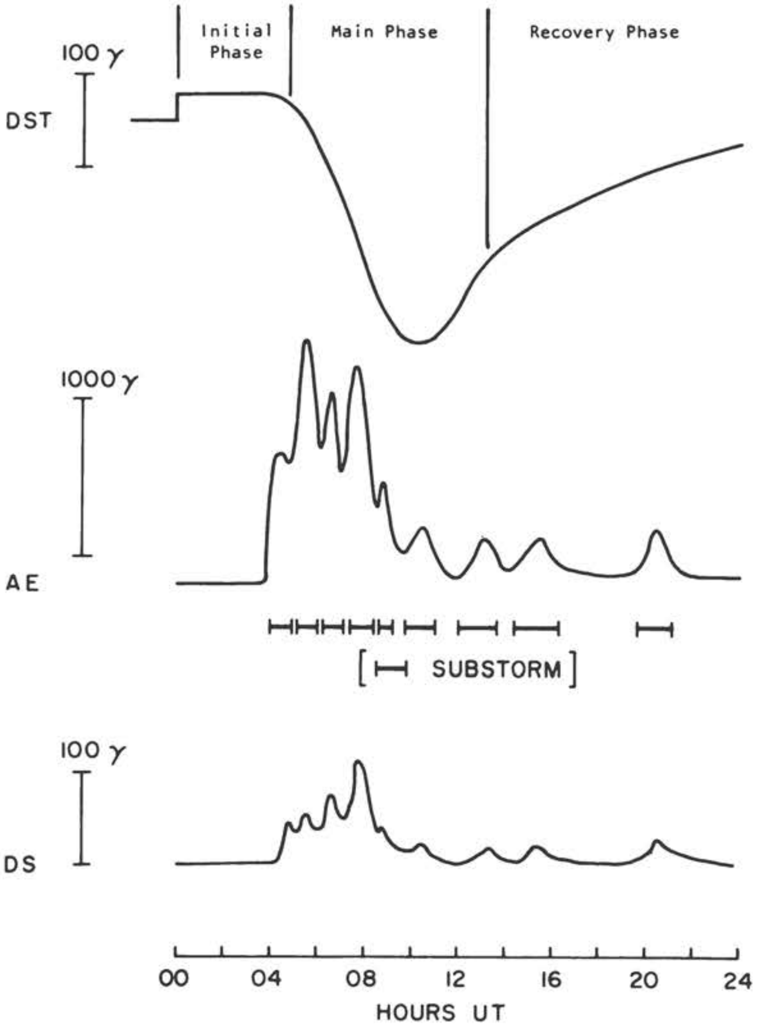


FIGURE 3 An example of a typical geomagnetic storm showing the three characteristic phases and the relationship between the Dst, AE, and DS indices. The Dst index is a measure of the magnetic field intensity of the ring current and also of the total kinetic energy of the ring current belt. The AE index is a measure of the intensity of magnetospheric substorms. The DS index is a measure of the magnitude of the asymmetry of the ring current field.

signals. Magnetospheric substorms often recur at intervals of 3 or 4 h, suggesting that this duration is the time constant for the buildup and release of energy in the magnetosphere.

As just mentioned, a magnetospheric substorm has a variety of manifestations over the entire earth, each of which may provide an important clue to the basic processes involved. Recent studies indicate that the magnetospheric substorm is associated with a sudden growth of electric fields. These electric fields generate the auroral electrojet in the polar ionosphere and accelerate auroral particles, which, in turn, can produce visible auroras and x-ray bursts when they interact with the atmosphere.

The study of polar magnetic substorms alone is not sufficient to understand the whole phenomenon of magnetospheric substorms. Intensive interdisciplinary studies of polar upper-atmospheric disturbance phenomena are also needed. Compact, transportable, geophysical observatories equipped with identical standard instruments are suggested for such studies. A major effort in the analysis of polar upper-atmospheric disturbance phenomena should be directed toward the establishment of a model for the distribution of electric fields consistent with various manifestations of the magnetospheric substorm. The next step is to infer how these electric fields are produced as a consequence of the interactions between the "disturbed" solar wind and the magnetosphere. Such studies may provide clues to important problems, including: How can solar-wind energy enter the magnetosphere? How is this energy stored and finally converted into the energy for a magnetospheric substorm?

Geomagnetic Storms

The magnetosphere is severely disturbed during magnetic storms, which often occur about two days after an intense solar flare, or sometimes following the passage of a boundary in the interplanetary plasma sector structure. Several hours after the onset of a magnetic storm, a rapid succession of severe magnetospheric substorms occurs and the geomagnetic field is globally depressed owing to a formation of a ring current in the magnetosphere. Physical processes that take place during a magnetic storm are extremely complex and many are not well understood. The major processes involved and their effects as observed in the magnetic field at the ground are shown schematically in Figure 2.

A typical geomagnetic storm has three phases: initial, main, and recovery (see Figure 3). A compression of the magnetosphere, manifested by a sudden commencement, is the major feature of the initial phase. The main phase is characterized by the growth of an intense ring-current belt and frequently by severe magnetospheric substorms. During the development of the main phase, as many as ten magnetospheric substorms may occur in close succession, as illustrated in Figure 3. These substorms are observed from the ground as a repetition of rapid growth followed by decay of the polar magnetic substorms. The "AE" index has been derived to express the activity of these polar magnetic substorms and thus of magnetospheric substorms.

The ring-current belt which develops during the main phase is predominantly composed of 5- to 50-keV protons. On the ground, the net effect of the ring-current system is a reduction of the horizontal component of the magnetic field in midlatitude and low latitude. An important aspect of the ring-current belt is a large axial asymmetry during buildup. The "Dst" component represents the average intensity of the ring-current field on the earth's surface, and "DS" gives the amplitude of the asymmetric component. There is some indication that the time variation of DS is similar to that of the AE index, suggesting that the asymmetric component of the ring current is closely associated with magnetospheric substorms. An east-west chain of geomagnetic stations is vital for examining the instantaneous distribution of the asymmetric part of the ring current.

Typically, about 6 h after the onset of the main phase, the polar magnetic substorm activity begins to decay, while the main phase develops for an additional few hours. After the height of the main phase, the field begins to recover, sharply for a few hours and then more gradually with time. This can take several days or even longer.

SHORT-PERIOD VARIATIONS

The geomagnetic field displays considerable variability over a broad temporal spectrum between 10 min and 0.2 sec. Some variations have quasi-sinusoidal features, whereas others appear to be totally aperiodic. Concurrent events measured at numerous separated stations on the ground demonstrate that short-term field changes originate above the earth's surface; high-latitude and magnetically conjugate observations show that many pulsations are of magnetospheric origin. In recent years, satellites have begun to observe these field changes in space. Such observations have often been of limited value for studies of the short-period changes because of low sensitivity and slow data-transmission rates. There is a great need for further coordinated measurements of these magnetic-field phenomena made simultaneously at the earth's surface and within the magnetosphere.

Of those micropulsations that show quasi-sinusoidal features, the hydromagnetic wave energy propagates both in so-called Alfvén and fast modes at frequencies above ~ 0.1 Hz. The Alfvén mode is restricted to frequencies below the proton cyclotron frequency, and its group velocity is closely guided by the geomagnetic field. The fast mode propagates at all frequencies below the electron cyclotron frequency, and its group velocity is essentially isotropic. Below 0.1 Hz, this propagation is characterized by magnetospheric cavity resonances along tubes of force because of the longer wavelengths. Both poloidal and toroidal oscillations, and combinations thereof, are found at the eigenfrequencies of the bounded system.

Quasi-Sinusoidal Events

MICROPULSATIONS OF 0.2- to 10-SECOND PERIODS

There is a class of structured micropulsation events in the 0.2- to 10-sec period band consisting of a series of rising tones that repeat at regular intervals. The characteristic frequency-time dispersion of the repetitive elements led to their interpretation as Alfvén-mode wave packets which propagate back and forth along field-line paths. At the foot of the magnetospheric path, the energy from each successive echo scatters into a thick ionospheric waveguide in the *E* and *F* layers and subsequently leaks to ground stations over a broad area.

The morphology of these events is now well established. They are observed at all except equatorial latitudes, principally during the calm following a geomagnetic storm. They do not appear to be correlated with any ionospheric effects or particle precipitation. Although their propagation properties are understood, the source of the excitation is not. Dispersion analysis has determined that their propagation paths lie beyond the plasmapause with an invariant latitude distribution similar to the auroral oval. In addition, the dispersion is a measure of the plasma density along the path, and thus the signals are useful probes of the dynamic process following storms. Interpretation of polarization measurements is obscured by the ionospheric waveguide where coupling occurs between the Alfvén and fast modes, but our understanding of ionospheric transmission, reflection, and absorption has progressed through theoretical studies. The energy necessary to sustain events which contain many elements requires an active amplification mechanism because only a small fraction of the signal can be reflected by the ionosphere. Cyclotron resonance interaction between the waves and charged particles has been proposed as the energy source, although simultaneous particle and field measurements are needed to test the theory.

Other types of micropulsation signals also occur in this band, but their morphology has not yet been scrutinized and no physical explanations have been developed.

MICROPULSATIONS OF 10- to 50-SECOND PERIODS

These rather smoothly varying pulsations are observed at nearly all world locations, for a large part of the daytime, on most days of the year. Amplitudes and periods change with solar-terrestrial disturbance levels; a high correlation between these micropulsation-activity levels and solar-wind velocity has been reported. Physical models currently favor occurrence of a natural resonance whose eigenfrequencies and amplitudes are sensitive to the geometry of the magnetospheric boundary and the energy delivered from the solar-terrestrial disturbance excitation source. Simultaneous satellite and surface observations should verify the appropriate model; then this phenomenon could possibly lead to day-to-day monitoring of magnetospheric parameters with just a few selected ground-based observatories.

In addition to cooperative ground-satellite determinations, further study of the interrelations of these field changes with ionospheric electron density and aurora is required. More detailed arrival-time and polarization-sense determinations are needed on the earth's surface. A study of the dependence of this phenomenon on the major magnetic disturbances could give further information on the excitation process.

MICROPULSATIONS OF 50- to 500-SECOND PERIODS

These phenomena have larger amplitude but are neither as frequent nor as long-lasting as the shorter-period, quasi-sinusoidal pulsations. They seem to be more localized near auroral latitudes, although at times the events are traceable to the equatorial regions. The characteristic periods, field-vector polarization senses, and occurrence locations have been explained as a geometric-type resonance, but differing from the previous case in that tubes of high-latitude field lines constitute the bounding region. Although the physical structure is clearly different, there are problems similar to those mentioned for the 10- to 50-sec period pulsations that require further study.

Aperiodic Events

IRREGULAR MICROPULSATIONS

These phenomena are irregular changes in field amplitude with periods over a rather broad range, from 0.2 sec up to those of the magnetic substorm, and amplitudes that increase with increasing period. The spectral display of a typical event seems to be composed of many discrete frequencies, often showing a disappearance of signal at particular frequency bands, and at times masking concurrent quasi-sinusoidal pulsations of the types described above. The signals are worldwide, frequently with a gradual change in overall composition and amplitude as a function of distance from the region of maximum activity under active aurora. These pulsations are clearly associated with auroral electron precipitation and ionization enhancement at high latitudes. Some discrete parts of the signal may be explicable in terms of hydromagnetic wave propagation. Auroral electrojet modulation by enhanced ionospheric conductivity in regions of auroral electron bombardment has been proposed as the source mechanism.

SUDDEN IMPULSES

It is thought that discontinuities in the momentum flux of the solar wind cause sudden compressions or expansions of the magnetospheric cavity, giving rise to the sudden impulses (SI). These events are isolated, large-amplitude changes in the magnetic field and of short duration; they are observed simultaneously at many stations. These events may represent one of the simplest forms of response to transient changes in the solar wind. Propagation of the perturbation seems to be in the fast mode to low latitudes and in the Alfvén mode to auroral latitudes. A study of the SI during very quiet days is an important tool for analyzing the propagation process between the magnetospheric boundary and the earth's surface. To do so requires concurrent satellite and surface observations.

RECOMMENDATIONS

1. A better understanding of many magnetospheric phenomena requires experiments using a temporary array of stations equipped with standardized instruments distributed in a carefully selected pattern, a pattern which, in general, does not coincide with the location of existing permanent observatories. Therefore, we *recommend* that a group of approximately ten transportable, compact, low-cost geomagnetic observatories, equipped with identical instrumentation, be built and placed under a special users committee which will identify the problems and assign priorities. The selection of the geographical distribution of the stations will depend on the problem under study. Several specific, temporary setups (each of several months' duration) in accessible regions are recommended:

a. A close north-south chain to achieve better understanding of polar geophysical phenomena

b. A close east-west chain to study the propagation and longitudinal distribution of disturbance fields

c. A chain along the geomagnetic dip equator to study the equatorial electrojet

d. A network clustered around one of the points at which the magnetic field line through a geostationary satellite intersects the earth

e. A network clustered at the conjugate point of a geophysical observatory

f. A distribution at key points for selected experiments in conjunction with satellites and rockets to study magnetic storms, substorms, and micropulsations

Standard equipment for each transportable observatory should be a dc magnetometer with digitized output in standardized format and an induction magnetometer. In certain instances, these detectors should be complemented with other instrumentation (for example, a polar network would need riometers, all-sky cameras, and, from time to time, coordinated balloon flights monitoring auroral electron bremsstrahlung x rays.

Data acquisition via satellite would be the most practical method of data retrieval.

2. The acquisition of data from geophysical observatories via satellite links is now practical. The technique has obvious advantages for automatic, unmanned observatories and for stations of difficult access. The cost of this form of data acquisition appears to be competitive with conventional pro-

cedures, even in the case of accessible observatories. Accordingly, we *recommend* that necessary facilities be made available to the scientific community to accomplish this purpose. Transponders can be placed on specially designed satellites or as an additional package on a mission. We *further recommend* that the possibility be explored of establishing a channel on a COMSAT satellite for this purpose. A standard TV channel has bandwidth to acquire data simultaneously from more than 100 stations.

3. In view of the usefulness of digital geomagnetic data to compute indices and to perform other analyses, we *recommend* that a study be made of the feasibility of replacing the conventional variometers by standardized magnetometers with an automatic recording system, at high-latitude observatories and at key low-latitude stations. For such a study a careful coordination with foreign countries is required, and an imaginative approach to international cooperation is urged.

In particular, we urge that the United States make every appropriate effort, either directly or through support of pertinent international organizations, to ensure that, where feasible, stations of the following chains are modernized with standardized instruments:

a. For AE index: College, Alaska; Tungsten (or Meanook), Canada; Fort Churchill, Canada; Great Whale River (or Fort Chimo), Canada; Julianehaab, Greenland; Leirvogur, Iceland; Tromso, Norway; and Dixon Island, Tixie Bay, and Cape Wellen, USSR.

b. For Dst index: Honolulu, Hawaii; San Juan, Puerto Rico; M'Bour, Senegal; Tashkent, USSR; and Kakioka, Japan.

In establishing new permanent magnetic observatories in the United States, we *recommend* that the responsible agencies continue their policy of taking into consideration the special requirements of solar-terrestrial research programs.

4. Since the effects of many magnetospheric processes propagate along field lines, the need to correlate ground and satellite observations is well recognized. To implement systematic, simultaneous observations, it is important to publish data regularly on the times of satellite passages near field lines rooted at ground observatories. We *recommend* that a prediction service be developed for orbit-field-line intercepts for designated satellites and ground stations. The predictions should be distributed to interested experimenters so that increased data acquisition and special experiments can be arranged during the intervals of interest.

5. The World Data Center A, established by the Special Committee for the International Geophysical Year and continued in the post-IGY period, has played an important role in the exchange of ground-based geomagnetic data with foreign observatories and in making the collected data available to scientists who require them. Since efficient international data exchange is essential to future progress in geomagnetic research, we *recommend* that World Data Center A be continued and strengthened. Improvements should be made in: (a) the quality of data stored and (b) more rapid collection of data. Although portions of these problems fall within the responsibility of international organizations (International Association of Geomagnetism and Aeronomy, Inter-Union Commission of Solar-Terrestrial Physics), a leading role can be played by the United States with respect to point (b).

The desirability for WDC-A to produce, store, and distribute "digested" material in such form as indices and space parameters is well recognized. However, it is realized that, in general, neither the Data Center nor the institutions furnishing the key data have enough scientific personnel or funds to carry out the task. On the other hand, the analytical work required for this purpose may sometimes not be appropriate for graduate-student research, and the lack of these published indices may cause delays in publication of results. The implementation of appropriate indices may have a far-reaching impact on future geophysical studies.

Therefore, we *recommend* that mechanisms be established through which, on a proposal basis, a scientist can work at the WDC-A, or at the institution providing the relevant data, for an extended period of time with the specific objective being to extract analytical information from long-term raw data and to study its conversion into an index or a time-dependent parameter. If considered appropriate, this information could then be published regularly as an additional service of WDC-A to the scientific community. Participation and support of foreign scientists in such a program, under supervision or sponsorship of a national group, should be particularly encouraged.

The need for more rapid data collection applies particularly to data from satellite observations. We realize that pioneering experiments should not be hampered by forcing immediate release of data before experimenters have had an opportunity to analyze them; however, satellite data of a routine monitoring nature should be submitted regularly to the Data Center with the shortest delay possible. Such data include solar-wind parameters, boundary crossings, local-time variations of the magnetic field at the synchronous orbit, magnetic fields and plasma in the geomagnetic tail, and general behavior of ring-current particles.

"Digested" material should be collected and disseminated for more effective evaluations of new theoretical and experimental research. An essential prerequisite for the successful accomplishment of this point is to continue and to expand the present progress for data digitization at the Center. Relevant physical parameters and indices would be listed hourly when available and presented in a standard, annotated format for, for example, the sun, solar wind, magnetosphere boundary, geomagnetic field, trapped and precipitated fluxes, auroras and airglow, very-low-frequency and ultra-low-frequency signals, and ionospheric density and current flow at selected latitudes. Such a program will require scientific guidance and routine input from experimenters, and it must be sufficiently flexible to allow updating as new data are received and format changes as new physics develops. To implement this recommendation, we urge that provisions be established for scientists to work at the WDC-A or at the institutions providing relevant data, with the specific objective of developing new physical parameters and indices. Participation and support of foreign scientists should be actively encouraged.

6. We *recommend* that investigators of magnetospheric and ionospheric problems use the International Geomagnetic Reference Field as the main-field description so that related studies can be more accurately compared.

7. We *recommend* that ground observatories and ground surveys necessary to update the International Geomagnetic Reference Field at regular intervals be continued. Special attention should be given to the determination of more accurate coefficients of secular change. Magnetic surveys by low-altitude satellites should be repeated periodically.

8. We *recommend* that coordinated experiments involving surface, rocket, and satellite measurements be conducted for the following purposes:

a. To establish the vertical distribution of ionospheric current systems associated with the quiet-day variation of the geomagnetic field

b. To find the relationships between these currents and the variables in the ionospheric dynamo process, such as neutral-wind profile, electric fields, and conductivity distribution

c. To determine the causes of day-to-day changes in amplitude and pattern of solar quiet, particularly in the equatorial electrojet region

9. Surface magnetic records are useful for observing ionospheric and magnetospheric current systems if the lunar tidal effects are known with sufficient accuracy. We *recommend* further rocket experimental research and numerical analyses of ground data to elucidate this problem.

10. Theoretical estimates show that the quiet-time ring current and the currents in the magnetospheric boundary and neutral sheet should give a measurable contribution to the quiet-day variation of the surface field. We *recommend* that a system be developed by which the nonionospheric component of the surface-field daily variation is extracted, using this information to monitor parameters of the magnetosphere. To implement this task, a careful study is necessary to explore correlations between ground observations and satellite measurements of magnetopause position, tail-field intensity, neutral sheet portion, ring current, and magnetic field, for example. In addition, further theoretical work will be necessary to construct a magnetospheric model.

11. A good synoptic description of the quiet-time polar-cap current system is not yet available. We *recommend* that more surface measurements be carried out, preferably with a north-south chain of transportable stations. In addition, barium-cloud experiments are recommended to determine the electric-field behavior above the stations.

12. The complexity of the magnetospheric substorm requires intensive interdisciplinary study. We *recommend* that investigators who are concerned with polar upper-atmospheric phenomena, with the plasma sheet in the geomagnetic tail, and with the trapped particle population should be encouraged to cooperate in studying the magnetospheric substorm in the broadest interdisciplinary sense.

13. In addition to studies of basic physical phenomena associated with substorms, we *recommend* that synoptic studies of individual polar upper-atmospheric disturbance processes be made. These synoptic studies would provide a "projection" onto the earth's surface of the processes that take place in the outer magnetosphere, including the tail region.

14. There is a relationship between the Dst, AE, and DS indices. The Dst index is a measure of the magnetic field intensity of the ring current and also a measure of the total kinetic energy of the ring current belt. The AE index is a measure of the intensity of magnetospheric substorms. The

DS is a measure of the magnitude of the asymmetry of the ring current field. The United States has taken the initiative to provide the AE and Dst indices. We *recommend* that this project be continued.

15. A class of micropulsations near 1 Hz is now sufficiently understood to permit its use as a magnetospheric probe of the distribution of thermal plasma beyond the plasmapause. We encourage future application of this technique to the study of dynamical processes. Although the physics of micropulsations at lower frequencies is not so well developed, the potential use of these signals as remote sensors of magnetospheric parameters warrants continued exploration.

16. Wave-particle interactions evidently play a significant role as an energy source for repetitive signals and as a source of emissions. We *recommend* that continued theoretical investigations be encouraged, and that vigorous cooperation between ground and spacecraft observation be pursued to unravel the complex physics.

17. Propagation of micropulsations in and through the ionosphere is complicated by mode coupling, absorption, and reflections. We *recommend* that more detailed theoretical studies be undertaken to filter out these effects, making possible direct ground observations and magnetospheric propagation. To support the theoretical efforts, observers should make more accurate determinations of such properties as group velocity, wave polarization sense, and ionospheric transmission of the hydromagnetic signal.

18. We *recommend* further measurements of the surface distribution of short-period field changes, especially at polar latitudes, concurrent with appropriately located satellite observations of magnetic and electric fields and other dependent parameters, so that the excitation or propagation characteristics of the signals through the magnetosphere may be investigated.

19. We *recommend* that sponsoring organizations encourage detailed studies of carefully selected cases of magnetic-field fluctuations and their relationship to such phenomena as particle composition and energy, magnetospheric boundary and tail changes, and auroral luminosity.

5 Whistlers and Other Wave Phenomena

Because of the strong dependence of whistler-mode waves on the thermal and energetic components of the magnetospheric plasma and the static magnetic field, whistlers and associated very-low-frequency (vlf) wave phenomena are powerful tools for the study of the magnetosphere. Very-low-frequency energy from a lightning stroke (i.e., a whistler) or a transmitter tends to be guided along field-aligned paths extending great distances above the surface of the earth. These waves carry with them an imprint of the medium through which they have traveled.

Measurements of whistlers and related phenomena are made on the ground and by rockets and satellites. The ground measurements give unique data on ducted whistlers, from which electron density in the magnetosphere is deduced. Ducted whistlers cannot be observed by satellites in sufficient quantity to be useful for this purpose. On the other hand, satellites and rockets provide unique data on nonducted phenomena that are not observable from the ground. From this type of measurement has come new information on ion and electron concentrations, particle temperatures, wave absorption, and sources of discrete emissions. Some experiments require coordinated ground-based and space-probe measurements. For example, the sources of whistlers observed in satellites are found from simultaneous ground recordings, and the absorption of hiss in the auroral zone is measured by comparing simultaneous ground and satellite data.

At the present time, broadband whistlers are being used to study the thermal plasma of the magnetosphere, including identification of convection patterns and tracing of the temporal and spatial history of the plasmasphere and electron density during magnetic storms. Correlation of data from various disciplines is increasing rapidly, and new technological developments, involving unmanned observatories and controlled experiments with vlf transmitters, are receiving increasing attention.

Very-low-frequency emissions related to such phenomena as auroras, particle fluxes, *D*-region absorption, x-ray microbursts, geomagnetic micropulsations, and the general level of magnetic activity are not so well understood as whistlers but show much promise as diagnostic tools for studying both energetic and thermal particles in the magnetosphere. By artificially stimulating these emissions, wave-particle interaction processes can be studied quantitatively.

WHISTLERS

Whistlers ceased to be a mere scientific curiosity and became the object of serious study in 1953 when they were identified as dispersed impulses of atmospheric electrical discharges in which the amount of dispersion is dependent on the electron density at distances from the earth of several earth radii. With the discovery of "nose" whistlers, it was shown that the frequency of minimum propagation delay, or nose frequency, provides information on the location of the propagation path in the outer atmosphere, while the propagation delay provides information about electron density along this path. The frequent experimental observation of several discrete and persistent propagation paths led to the suggestion that whistlers are trapped in "ducts" in the outer ionosphere. By 1960 it was shown that these waves could indeed be trapped in field-aligned ducts with enhancements of ionization as small as a few percent, and that the frequency-time dispersion of these ducted whistlers is the same as that of a wave propagating purely longitudinally along the center of the duct. Thus it became possible to use multicomponent nose whistlers to measure equatorial electron density as a function of distance, often over a range of several earth radii.

In 1963, the discovery of the "knee" whistler showed that equatorial electron density, in addition to a general, gradual decrease with radial distance, often shows a very sharp decrease of roughly an order of magnitude at ~ 4 earth radii. This boundary, or "plasmapause," between regions of high- and low-density plasma was totally unexpected. While the distance to the plasmapause is a function of time and magnetic activity, the density decrease is an essentially permanent feature of the magnetosphere, separating the outer, low-density region, where the dynamics of the plasma are controlled largely by

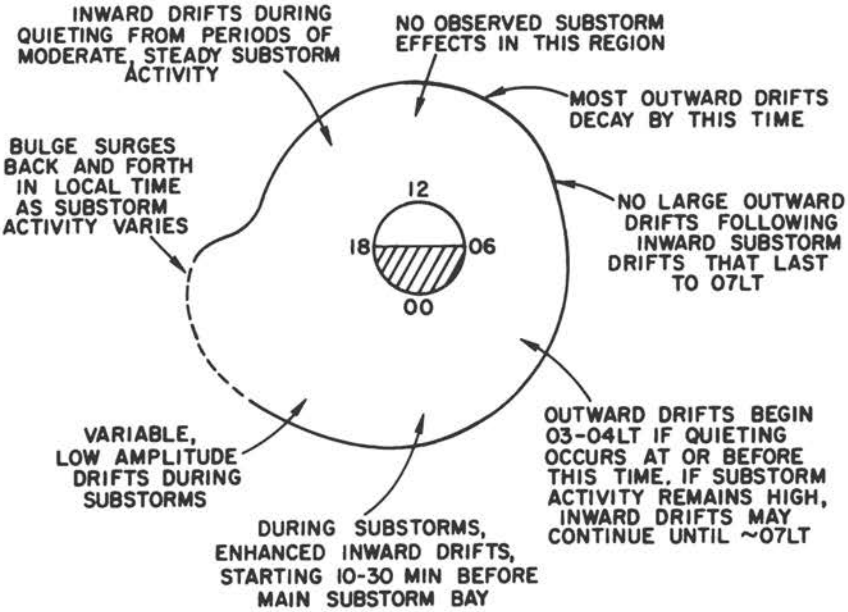


FIGURE 4 Major patterns of convection identified in the plasmasphere.

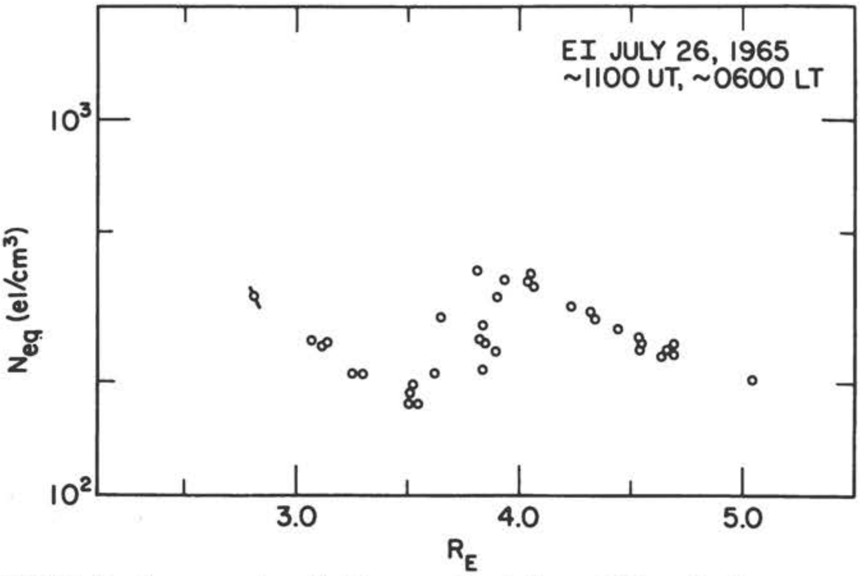


FIGURE 5 An example of the equatorial profile of electron density in the plasmasphere.

the solar wind, from the inner, high-density region, where the dynamics and densities are dominated by the terrestrial ionosphere. Together with positions of other transition regions, such as the bow shock and the magnetopause, the location of the plasmapause is now recognized as a fundamental parameter of magnetospheric physics. In 1966, cross-*L* movements of whistler ducts were used to identify certain features of magnetosphere convection. Large surging increases in this cross-*L* convection activity were discovered and related to magnetospheric substorms a year later. Figure 4 indicates several of the major patterns of convection that have been identified.

Some details of recent studies of irregular structure in the plasmasphere are presented in Figure 5, which shows an equatorial profile of electron density with a "hump" near *L* = 4. Profiles of this kind are believed attributable to a combination of the mixing effect of perturbing magnetospheric convection processes and effects of the coupling between the *F* region and the protonosphere. The coupling between the ionosphere and the overlying region is important in establishing

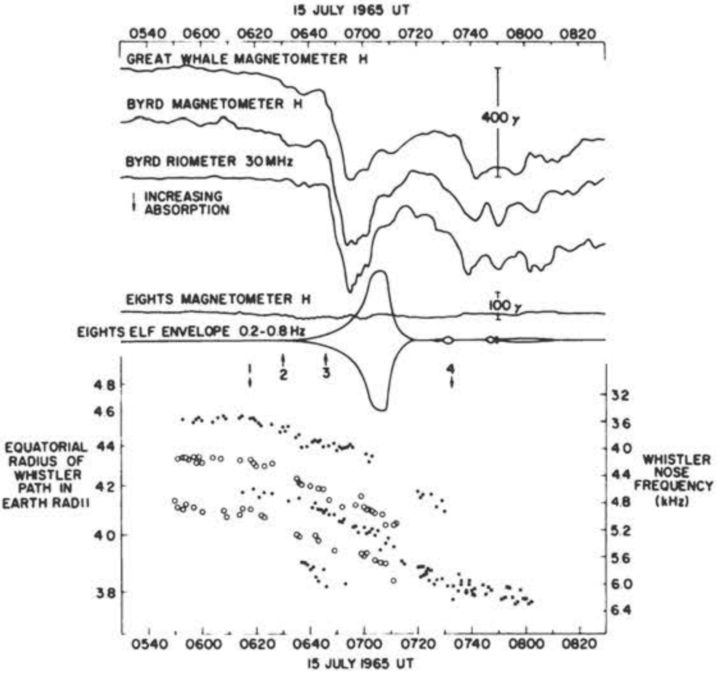


FIGURE 6 An example of cross-*L* drifts of whistler paths during a relatively isolated substorm.

a certain tendency toward irregularity in the profile, a tendency that is then "amplified" by the convection process.

An example of the use of the whistler method to detect substorm convection phenomena is illustrated in Figure 6, which shows cross-*L* drifts of whistler paths during a relatively isolated substorm. Some indices of substorm activity at the conjugate stations Byrd and Great Whale ($L \sim 7$) are shown in the upper part of the figure, and below are shown the equatorial radii of a number of whistler paths. Successive positions of the different paths are indicated by different symbols. A significant feature of the event is the tendency for well-defined drifts to be established near $L = 4$ some 30 min before the development of the substorm bay near the meridian of observations.

Broadband Whistler Diagnostics

Whistlers provide a unique means of studying the dynamics of the plasmapause and the relation of motions within the plasmasphere to other magnetospheric disturbance phenomena. The whistler technique, moreover, is the only one currently available for mapping large-scale convection patterns at distances of several earth radii in the magnetosphere. The technique is currently being applied to the identification of quiet-day and substorm patterns of magnetospheric convection and to the study of dynamic variations in plasmasphere electron density and plasmapause shape during magnetic storms.

The whistler method provides a relatively accurate (roughly ±20 percent within the plasmasphere) measurement of the electron content in tubes of ionization above heights of 1000 km in the ionosphere and extending to the equatorial plane. The method also provides a relatively accurate (roughly ±30 percent within the plasmasphere) measurement of equatorial electron density. Although this is an integral measurement, the integral is weighted to be sensitive to density at great heights along the path.

Certain ground stations such as Eights, Antarctica, have viewing ranges extending from $2.5 < L < 6$ and over $\pm 15^\circ$ of longitude. Prevailing multipath whistler activity frequently covers a significant fraction of this sector, affording the possibility of continuously monitoring large segments of the equatorial profile. Path equatorial radius is measured relatively accurately, and while longitude is not measured directly, it may on some occasions be identified through spaced station comparisons and through temporal development of certain types of irregular behavior.

A single electron-density measurement based on a single whistler component represents a kind of average over a magnetospheric duct whose diameter may be several hundred kilometers at the equator (the east-west dimension may exceed the radial dimension by as much as a factor of 5). Because the ducts themselves appear to represent relatively small (~ 5 to 10 percent) enhancements over the background densities, the density measurements from many ducts distributed over the viewing area of a station provide spatial resolution in the radial profile of ~ 500 km. The broad radial coverage of the measurements from a single location provides a means of identifying the position of the plasmapause from a relatively small number of suitably placed stations.

The whistler nose frequency provides a measurement of the equatorial magnetic field strength on the associated whistler duct. As this value of field strength changes during the radial drift of a duct or tube of ionization, the successive radii of equatorial crossings of the tube may be measured from a succession of whistlers propagating in the duct. From the rate of change of this position, the radial drift velocity and hence the east-west component of magnetospheric electric field may be inferred.

VERY-LOW-FREQUENCY EMISSIONS

Soon after the discovery of the radiation belts, it was recognized that energetic particles are probably the energy source of the audiofrequency radio waves called vlf emissions that are frequently found in whistler recordings. Two basic types of emission processes were hypothesized, associated with, respectively, the longitudinal or Cerenkov resonance and the transverse or cyclotron resonance. In the early 1960's it was observed that the emission of these waves could be triggered by other waves, either man-made or of natural origin, with the latter sometimes causing periodic emissions. By 1963 the importance for triggered emission of trapping of energetic particles in potential wells of the wave was recognized, and it was shown that in the case of cyclotron resonance wave emission can cause and is associated with precipitation of energetic electrons. Quantitative studies in 1966 showed that as a result of the emission process, there is effectively an upper limit on the flux of energetic electrons that can be stably trapped in the outer magnetosphere. Further observations have demonstrated that when the occurrence of diffuse or broadband emissions is greatest, other phenomena associated with electron precipitation into the atmosphere are also at a maximum.

Four basic classes of vlf emissions are recognized from ground-based measurements. These are the auroral hiss, polar chorus, midlatitude discrete emissions and associated hiss, and artificially stimulated emissions.

Auroral hiss is found at frequencies above 4 kHz and extends on occasion up to several hundred kHz. It is generally believed to originate in the ionosphere, although no widely accepted theory of generation yet exists. Auroral hiss occurs primarily in the hours just before midnight and is usually associated with substorm activity. It is frequently observed shortly before the onset of overhead auroral activity, often with a short intense burst of hiss at the onset. The disappearance of the hiss after the onset of the aurora may be due to increased absorption in the lower ionosphere. It has been suggested that the occurrence of auroral hiss indicates the existence of a pre-expansion phase of the polar substorm. Additional evidence for such a phase is found in whistler measurements of convection activity preceding substorm bays and in "precursor" magnetic activity.

Polar chorus is also an auroral-zone phenomenon. It consists of an intense, continuous band of noise at frequencies in the range from a few hundred hertz to 2 kHz. It is observed in the midmorning to late morning hours and is correlated (statistically) with radio aurora, cosmic-noise absorption, diffuse aurora, and precipitation of energetic electrons. Polar chorus is probably generated in the equatorial plane at distances of several earth radii through a plasma instability that also causes some precipitation of energetic electrons. It has been suggested that this process is the primary mechanism for precipitation in the morning hours of outer-radiation-belt electrons of energies from a few tens to a few hundreds of keV. This suggestion requires further study and development.

While midlatitude discrete emissions and associated hiss have spectral characteristics that differ from polar chorus, satellite data suggest that they are closely related and probably have the same basic generation mechanism. The generation of discrete emissions may be stimulated or triggered by other waves--either whistlers or previously produced emissions. (In the latter case, periodic emissions occur.) Observations of whistler-triggered emissions show a strong preference for triggering at a frequency equal to half the electron gyrofrequency in the equatorial plane.

Closely related to the discrete triggered emissions are the artificially stimulated emissions. These events, triggered by man-made signals, have provided important information about the emission process. In addition to the obvious amplitude threshold for the triggering signal, there is frequently a duration threshold; pulses 50 msec long may not trigger, whereas pulses 150 msec long will. The onset of the stimulated emission is typically delayed with respect to the onset of the triggering pulse by ~ 100 msec, and the emission appears to begin at a frequency slightly above that of the triggering pulse (by up to 300 Hz). As with whistler-triggered emissions, there is a strong preference for triggering at a frequency equal to half the electron gyrofrequency in the equatorial plane. During generally favorable conditions, every transmitted pulse will trigger an emission provided that the pulse exceeds some minimum amplitude and duration. A substantial need remains for more quantitative information on the emission process.

The theory required to explain the various vlf emissions is much more complex than that of whistlers, since the energy of the emissions is derived from the nonthermal component of the magnetospheric plasma, while propagation is controlled by the thermal component. Emission occurrence appears to be tied to fluxes of energetic electrons in the 1- to 50-keV range. While auroral hiss is believed to originate at lower altitudes by a different process, all other classes of emissions are thought to be generated by the same basic process in or near the equatorial plane.

Exchange of energy occurs through the cyclotron resonance, with an increase of wave energy being tied to a decrease in particle pitch angle. Mutual interaction between the waves and particles is required, and, for the discrete emissions, trapping of electrons in potential wells of the wave plays an important role. Applying these principles, it is now possible to understand a number of puzzling features of emissions in terms of the local gradients of electron plasma and gyrofrequency near the equator. Fundamental to this interpretation is the trapping period of electrons in the magnetic potenial well of the wave. Phase bunching of resonant electrons in one-quarter of this period leads to large temporary increases in the flow of energy to and from the wave. This process may account, at least in part, for the self-excited, variable-frequency, narrow-band emissions that originate near the equatorial plane. It may also play a role in the growth and decay of waves passing through the region.

FUTURE LINES OF DEVELOPMENT

Broadband Whistler Diagnostics

Further activity in studies of thermal plasma dynamics of the magnetosphere should develop within the context of interdisciplinary studies, multistation studies, controlled experiments, and worldwide plasmapause monitoring, which may include use of unmanned observatories.

Interdisciplinary studies should involve virtually all forms of quasistatic electric-field measurements, observations of the properties of the subauroral ionosphere near the plasmapause, the injection and cross-*L* diffusion of energetic particles in the magnetosphere, airglow phenomena at midlatitudes, and various features of protonosphere-ionosphere coupling.

The whistler method of deducing magnetospheric electric fields should be applied in conjunction with balloon techniques which observe the electric field as it appears below the ionosphere, and with the barium-cloud technique as it appears in and above the ionosphere. As presently interpreted, the balloon method is sensitive to horizontal fields of scale ~ 400 km or greater. These fields are believed to fringe down with relatively little attenuation from the overlying ionosphere to balloon altitudes. The balloon technique is applicable at many locations and on some occasions provides information for as long as 24 h at a time. Barium clouds provide a local measurement of electric field through information on the $E \times B$ drift of the cloud. This technique is elegant but somewhat difficult to apply because of twilight constraints, the difficulty of tracking the cloud optically, and a number of other problems. The whistler method provides more or less continuous information over a relatively wide sector in *L*-space and from 10° to 30° in longitude. The most detailed information can represent the plasmasphere from say $L \sim 3$ to $L \sim 5$. The whistler method provides more or less continuous information on cross-*L* drifts and hence on the east-west component of the magnetospheric electric field. The information most readily available is a spatial average of this field over an equatorial interval of roughly 1 to 2 earth radii in radius centered at $L \sim 4$. Time resolution is of the order of minutes. With increased effort, estimates can be made of variations with *L* in the east-west electric field.

For the study of subauroral ionospheric phenomena near the plasmapause it is important that ground observations of whistlers be regularly conducted in regions of suitable whistler activity. These should be coordinated on occasion with rocket firings, barium-cloud releases, and eclipse observations. The picture obtained from ground-based whistler observations may be strengthened and extended by vlf and plasma-probe measurements on satellites in polar orbits separated in longitude from that of the ground whistler receiver. Several phenomena, including ionospheric density troughs, midlatitude peaks in electron temperature, and rapid latitudinal variations in ion composition and in absorption of upgoing vlf waves, appear to exhibit a direct spatial connection to the plasmapause and are thus well suited to correlative studies involving whistlers.

Whistler information on the details of magnetospheric electric fields is most plentiful in and near the portion of *L*-space where injection and cross-*L* diffusion of energetic particles is reported. Theoretical work has shown that pronounced diffusion effects should be associated with the kinds of substorm-associated electric fields already reported from whistler data. In future experiments it would be desirable to coordinate energetic particle observations in the middle magnetosphere with detailed ground observations of electric fields using whistlers.

Most studies of the nighttime *F*-region ionosphere have been conducted in the absence of detailed knowledge about the overlying protonosphere. Whistler observations indicate that electric fields in the magnetosphere provide a strong pumping action on the nightside, involving both lowering of the ionospheric layers and downward diffusion from the protonosphere. The incoherent scatter technique of detecting plasma-drift motions at ionospheric heights should be compared with simultaneous whistler measurements of cross-*L* drifts of whistler ducts. Airglow and whistler measurements should be compared, because there is a real possibility that sudden nightside lowering of the ionosphere and associated enhanced airglow may be related to cross-*L* drifts of magnetospheric plasma observed by the whistler technique.

Recent preliminary studies indicate that a number of ground-based geomagnetic and radio observations are closely related to substorm plasma drifts observed by whistlers. These include the IPDP phenomenon (irregular pulsation of diminishing period) at ~ 1 Hz and diffuse radar echoes. In the latter case, echoes are observed primarily from subauroral regions in the dusk sector of the earth.

A most desirable platform for correlations with ground-based whistler stations would be an equatorial satellite at

3 to 6 earth radii monitoring at grazing incidence to the fine structure of the plasmapause both in terms of wave and particle phenomena. Also, data from ground stations and from a synchronous or nearly synchronous sounder in the outer magnetosphere should be correlated to sound the "walls" of the plasma trough effectively and thus identify localized drift patterns.

Multistation Recordings

Over a range of latitudes and longitudes a network of stations is needed to determine the fine structure of convection patterns, to study the development of east-west irregularities of magnetospheric electron density, and to detect the east-west component of magnetospheric convection. For example, recordings at $L \sim 4$ with a longitude separation of 30° to 60° can help to identify the development of east-west gradients in magnetospheric plasma during E-field events and to identify the extent of localization within the magnetosphere of substorm plasma-drift events. Recordings at $L \sim 4$ and $L \sim 2$ can aid in determining the extent of penetration of perturbing E-fields to the inner plasmasphere. Recordings at $L \sim 4$ and $L \sim 7$ will help to determine if the mechanism of establishing an abrupt plasmapause geometry is operative at quiet times and to identify the plasma diffusion processes responsible for the increased size of the plasmasphere in quiet period.

Initial emphasis should be placed on recording near the 0° geomagnetic meridian in the Antarctic because of the known high rates of whistler activity of suitable quality in that region. There must be a general emphasis on flexibility of recording schedules and on capability of recording up to 24 h a day for periods of days or weeks.

The recent plan to place a vlf transmitter at $L \sim 4$ in the Antarctic is strongly encouraged. Through phase-path measurements, such a facility could permit an order-of-magnitude improvement in sensitivity and time resolution in studies of motions of magnetospheric tubes of ionization. Utilizing a variable-frequency transmitter in this facility, phase and ground-path measurements can significantly extend our understanding of propagation losses over magnetospheric paths. This transmitter, with receivers at $L \sim 4$ and $L \sim 7$ in the conjugate region, would provide the basis for plasmapause monitoring during periods of low whistler activity and would also provide an excellent source of signals for a program of direction finding on path exit points.

Furthermore, establishment of a worldwide plasmapause monitoring network should be studied. These feasibility studies should review data already recorded and should explore the possibility of regular detection of the plasmapause at various locations such as Halley Bay, Antarctica, and the Kerguelen, Indian Ocean-Sogra, USSR conjugate network. A plasmapause monitoring program might provide not only summaries of plasmapause behavior but also forecasts for use in barium-cloud experiments and balloon and rocket launches. Requirements may include automated techniques for data reduction and interpretive material to accompany any published indices of plasmapause behavior.

Unmanned observatories may be necessary for plasmapause monitoring in some locations, and further development of the unmanned geophysical observatory concept should be of priority importance.

Many promising areas of whistler studies have been opened but not yet explored. For example, subprotonospheric (SP) whistlers have been observed for a number of years at ground stations. These low-dispersion whistlers, frequently observed in satellites, are apparently reflected back to earth from points between 1000 and 3000 km in the ionosphere. Because of this localized path, dispersion measurements can provide information on total electron content up to the height of reflection. Other features of the whistler may provide information on the plasma near the reflection height. The SP phenomenon is an attractive possibility for study by a controlled transmitter experiment.

Very-Low-Frequency Emission Diagnostics

The principal areas of development in the study of vlf emissions are expected to be in correlations of emissions with other disturbance phenomena, in the introduction of active experiments to investigate wave-particle interactions, and in the theory of generation of the emissions.

From analysis of auroral-zone observations it is clear that auroral hiss provides an important, if not yet understood, clue to the physics of substorms. Polar-chorus emission may be fundamental to the process of precipitation of trapped electrons in the outer radiation belt. Future studies of auroral hiss and polar chorus must be coordinated with observations of other phenomena related to energetic particle precipitation, including auroral (optical aeronomy), cosmic-noise absorption (radio probing), and changes in the geomagnetic field (geomagnetism). A program of this complexity will require use of a calibrated, standardized measurement instrument with computer-compatible output.

The further development of a vlf transmitter facility mentioned above and of the unmanned geophysical observatory concept falls within the framework of present planning for research in the Antarctic. Recommended future activities in the northern hemisphere will require modest increases over present funding levels to cover the costs of a three-station network instrumented for reception of signals from the Antarctic transmitter and for vlf radiometric studies with computer-compatible output. The stations would then have a useful lifetime of about 10 years.

Recent theoretical developments suggest that spatial inhomogeneties may play a decisive role in the generation of discrete emissions, thereby opening up exciting new diagnostic possibilities. Emission properties as measured on the ground might be useful in measuring the local parameters of the generation region near the equator. Such data, including magnitude of spatial gradients, would be complementary to the whistler method, which is integral in character. Before such possibilities can be realized, much more experimental work is needed both on the ground and in space. The Antarctic transmitter facility discussed above would be especially useful as a controlled source (transmitter) for stimulating emissions. Potential applications of such a transmitter in the area of wave-particle interactions include exploration of (1) linear and nonlinear gain and loss processes in the magnetosphere associated with particle resonances, using variable transmitted power, frequency, and duty cycle; (2) generation of emissions using controlled wave amplitude, frequency, rate of change of frequency, pulse duration, and duty cycle; and (3) production of particle acceleration and deceleration or precipitation, with a view to changing the fluxes of energetic electrons in the radiation belts.

Equally important in the emission program is a vigorous continuation of efforts to resolve the difficult theoretical problems behind emission generation. Work in this area is expected to lean heavily on the contributions of plasma physics and on techniques of computer simulation.

RECOMMENDATIONS

1. We *recommend* a program of controlled sounding of the magnetosphere based on a vlf transmitter facility at $L \sim 4$ in the Antarctic. The program would be directed toward diagnostics of both the thermal and energetic components of the magnetospheric plasma. A site near the 0° geomagnetic meridian is recommended. Receiving stations in the conjugate hemisphere should be located at $L \sim 4$ and $L \sim 7$ near the 0° meridian and at $L \sim 4$ but displaced by ~ 30° in longitude.

2. We *recommend* the planning of interdisciplinary, mission-oriented programs involving natural or man-made whistler signals. Emphasis should be on: (a) studies of magnetospheric convection and associated E-fields; (b) identification and description of the plasmapause by both space and ground techniques; (c) studies of the physics of the ionosphere near the plasmapause; and (d) studies of protonosphere-ionosphere coupling. We urge that studies correlated with space and ground measurements of various substorm phenomena be conducted, such as *in situ* measurements of energetic particles diffusing under the influence of E-fields correlated with synoptic whistler measurements of E-fields, and measurements of irregular pulsation of diminishing period and Pc 1 micropulsation events whose generation may be related to details of plasma drifts in the magnetosphere.

3. We *recommend* establishment of multistation recording of broadband whistlers to expand studies of plasmasphere dynamics and, in particular, to obtain information on (a) the fine structure of convection events, (b) the azimuthal component of convection, and (c) details of processes such as the development of spatial irregularities and the growth of the plasmasphere during quieting. Recommended locations are at $L \sim 2.5$, $L \sim 4$, and $L \sim 7$ in the Antarctic near the 0° geomagnetic meridian and at $L \sim 4$ but removed by 30° to 60° from the 0° meridian in longitude. Stations at $L \sim 4$ and $L \sim 7$ near the 0° meridian are recommended for the conjugate region. The emphasis should be on flexibility and on intensive recording for periods varying from days to weeks. (Note: The operation of networks in other longitude sectors is encouraged, but details should depend on the distribution of whistler activity.)

4. We *recommend* study of the feasibility of a program of worldwide plasmapause monitoring using whistlers, including development of standardized recording and analysis techniques and of appropriate indices of activity.

5. We *recommend*, as part of a plasmapause monitoring program, further development of the unmanned geophysical obser-

vatory concept for use at remote sites in correlation studies involving vlf emmisions.

6. We *recommend* development of a vlf radiometer program involving correlation of vlf emissions with other phenomena related to energetic particle precipitation. For the vlf recordings, a calibrated, standardized instrument with computer-compatible output is recommended.

7. We *recommend* increased support for development and fabrication of systems for direction finding, for monitoring the phase path of an experimental, vlf transmitter, and for other field activities requiring either a new or a more sophisticated approach.

8. We *recommend* increased support for data analysis and continuing support for theoretical studies of wave-particle energy exchange.

6 Radio Probing of the Upper Ionosphere

Until about 10 years ago, the history of solar-terrestrial research was necessarily inseparable from the development of ground-based measurement methods. During this period before the blossoming of the space age, radio methods identified most of the structural features of the earth's ionosphere, its many scales and types of time variation, the principal regular and irregular solar variations to which the atmosphere responds, evidence of atmospheric movement, and morphological aspects of the ionosphere and high atmosphere. This exploratory period revealed many questions that radio techniques could not answer unaided and that now fall in such diverse fields as aeronomy, solar physics, meteorology, electromagnetic theory, and plasma physics.

Radio probing was introduced in 1925-1926 through pioneering experiments that verified the existence of the ionosphere. The forerunner of the present ionosonde appeared in 1932. This radar-type instrument probed essentially simultaneously at many closely spaced frequencies in the high-frequency range to obtain the height of total reflections at vertical incidence. It opened up the possibility of measuring the structure of the ionosphere and, especially, of delineating the peak electron densities of the ionospheric layers as a function of time and, when used in a network, as a function of the geographical location. Approximately a dozen ionosondes were in systematic operation in 1940, and the number grew to approximately 150 worldwide for the International Geophysical Year, 1957-1958. This observational effort produced a huge amount of new information and identified many phenomena that needed to be explained. The gross features of the ionospheric structure and variations were found to follow Chapman's basic theory, but there were almost as many anomalies as regularities. During the past decade a great deal of work has been done in determining detailed and more accurate profiles of electron density and in enhancing the utility of the ionosonde for more meaningful physical measurements, solar-terrestrial phenomenology, and radio-propagation research and practical applications.

In addition to vertical probing by ionosondes, probing at oblique incidence and in the ground-backscatter mode has been used quite extensively since the 1950's and has provided many data relevant mainly to radio propagation but also to ionospheric physics and solar-terrestrial research.

The advent of rocket and satellite techniques permitted several new extensions to ground-based radio probing. Observations began of total electron content by ground-based measurement of Faraday rotation and Doppler shifts of transmissions of radio beacons carried in satellites. More important, the ionosonde technique, both multifrequency and sweep frequency, was introduced into satellites, and the topside of the ionosphere was probed as a complement to the bottomside measurements with ground-based ionosondes.

The practicality of using incoherent (sometimes called Thomson) scattering of radio waves by electron-density inhomogeneities in the upper atmosphere was predicted and verified in 1958. The first major facilities were established beginning in 1963, and six are now in operation. Initially used to measure electron density throughout the *F* region, the technique has been extended through rapid development of theory and experimental expertise to provide quantitative measurements of the principal physically significant parameters of the ionosphere, including electron and ion temperatures, ion composition, collision frequencies, magnetic-field strength, and plasma velocities.

Both the more conventional radio probing and incoherent scatter have been used to explain ionospheric dynamics as well as structure and, particularly since the IGY, have provided much data on scales of motion from turbulence to traveling ionospheric disturbances of continental dimensions. A prominent feature of radio probing has been its use in interdisciplinary studies, such as the association of ionospheric disturbances with geomagnetic storms in the Second Polar Year, 1932-1933; the discovery of the Mogel-Dellinger radio fadeout in time-association with solar flares in 1936; the major interdisciplinary studies stimulated by the IGY; and the large number of modern investigations combining space and ground-based techniques.

SCIENTIFIC QUESTIONS

The scientific areas that are assisted in important ways by ground-based radio probing of the atmosphere above 100 km include essentially all aspects of the physics and chemistry of the ionospheric *E* and *F* regions and certain problems of the magnetosphere and the neutral atmosphere. The contribution of ground-based science is greatest when the variation of parameters with time and height are important, and some problems can be attacked only or best by ground-based radio-probing techniques. Radio probing depends on the interaction of electromagnetic waves with free electrons mainly, and weakly with ions; thus the measurements refer directly to these components and only inferentially, such as when the components can be treated as tracers, to the neutral atmosphere. But because ionozation by photons or energetic particles is a major manifestation of solar-induced effects on the earth's atmosphere, radio-probing techniques play a major role in solar-terrestrial science.

The results of radio probing have been of interest primarily to three groups--those concerned with understanding the physical and chemical processes of the high atmosphere, those trying to describe and understand the behavior of the ionosphere on a regional or global scale under various solar-terrestrial conditions, and those concerned with telecommunications. The first require the most accurate and pertinent measurements and are often obliged to forego comprehensive and widespread monitoring. The second group, many of whom originally worked in the field of radio propagation, have contributed much to identifying the problems needing detailed attention and to the interdisciplinary study of solar-terrestrial physics. The greatest progress has been made in describing ionospheric behavior, but considerable progress has also been made in explaining this behavior. The traditional applications of ionospheric studies to high-frequency radio telecommunications still loom large, and the beginnings of high-atmosphere meteorology are largely based on radio probing and the knowledge gained on the ionosphere.

The outstanding scientific questions 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 mild 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, neutral chemistry, and dynamics as a function of height, geography, and time?

AERONOMIC SYSTEMS REQUIREMENTS

In developing designs for new aeronomic facilities such as incoherent-scatter sounders, it is necessary to consider the constraints placed on their performance by the aeronomic problems to be solved. We do not discuss here in detail each specific problem and its associated requirements; however, Table 2 presents, in summary form, the spatial resolution required for measurements of electron density, electron and ion temperature, and plasma drift. Requirements for the accuracy with

TABLE 2 Resolutions Desired from Future Aeronomic Observations

Height (km)	Spatial Resolution for Electron Density and Plasma Drift (km)		Height Resolution for Electron and Ion Temperature (km)
	Vertical	Horizontal	
Below 130	1	10	5
130-160	2	15	5
160-200	3	20	10
200-250	5	25	25
250-300	10	50	25
350-500	20	50	50
Above 500	50	50	100

which these must be determined have been omitted, because the attainable accuracy and time resolution with any given system are usually linked in a reciprocal manner. Spatial constraints on the temperature measurements in the horizontal direction have also been omitted, because these are less stringent than for the electron density and plasma drift.

GROUND-BASED IONOSONDES

The ionosonde has long been the standard means for recording the height and time structure of the ionosphere. A simple relationship exists between the radio frequency of measurement (f) and the electron density (N) for total reflection at vertical incidence ($N \propto f^2$). Through use of a wide range of observing frequencies (typically 0.25 to 30 MHz), the ionosonde is a direct probe of the entire range of E- and F-region electron densities. Pulsed signals give apparent heights of reflection, but because of the strongly dispersive nature of the reflection process, the apparent or "virtual" height (h') always exceeds the true height, often by a large amount. In fact, for this unavoidable sacrifice of directness a great advantage is gained because the virtual height is roughly proportional to the reciprocal electron-density height gradient at the reflection level; observed $h'(f)$ curves thus indicate very sensitively details of the vertical structure of the ionosphere. Furthermore, the real height, and hence the $N(h)$ profile, can be recovered by well-developed calculation methods which preserve continuity of the vertical gradient. Height differences within the profile are usually accurate to 0.1 km, and no significant errors in frequency (electron density) need arise. The most severe limitations of the technique are its inability to observe with equal directness the structure at the low densities of the D region (below ~ 90 km) and in "valley" and topside regions where reflections at the appropriate frequencies are shielded by underlying ionization. These limitations also lead to variable height and gradient errors in the lower E and lower F regions which diminish slowly with increasing height. However, these errors may be reduced by using additional information such as the amplitude, phase, and group path of both magnetoionic modes. Loss of direct information in the E-region valley (120 to 140 km) must be considered serious for future applications, in view of the importance and complexity of thermal, chemical, hydrodynamic, and electrodynamic processes in this region.

The resolution of total reflection sounding in time and space is typically limited by the reflection process itself: The time-of-flight of the probing pulses is a few milliseconds, and the region responsible for reflection from a reasonably smooth ionosphere is a few kilometers (one Fresnel zone) in diameter. Although most ionosondes employ, in effect, 1000 to 2000 discrete frequencies to produce the familiar ionogram, thus permitting a minimum few seconds' time resolution, much of this information is redundant; virtual height data at 10 to 50 frequencies is sufficient to define the electron-density profile, and the time resolution might therefore be improved accordingly.

The familiar ionogram serves as an approximation to a photograph of the instantaneous ionization profile of the upper atmosphere. This is an irreplaceable virtue for exploratory studies and event identification, but it does not conveniently serve the growing needs for quantitative parameter measurement because of the tedious manual data reduction required. There is great promise in the development of digitally controlled ionosondes, capable of automatic, real-time data reduction.

Ionosondes comprise the largest number and the most widely distributed of instruments capable of measuring *E*- and *F*-region electron densities. Some 200 ionosondes are in operation worldwide, about half of them active in systematic observatory programs. Through a measure of international coordination by the International Union of Radio Science (URSI) on such matters as schedules of operation, standards of data quality, and data reduction and interchange, these stations form a network which is used for monitoring, for morphology studies, and for providing data in support of various other experiments. United States participation includes some eight stations in the United States, two in Antarctica, one abroad operated by U.S. personnel, and approximately ten U.S.-owned ionosondes on loan to overseas institutions. In addition, the United States provides supplies to about ten other stations in return for data. The other half of the world's ionosondes are used for special programs and do not systematically exchange data; about 20 U.S. ionosondes fall in this category.

Most of the U.S. ionosondes date from the IGY or earlier; only one type of network ionosonde is relatively modern. As a consequence, the present network is not so effective as it might be and has not yet received the advantages of recent developments in techniques. The equipment should be modernized, supplied with digital data processing, and optimized to the current monitoring objectives.

COHERENT-SCATTER TECHNIQUES

High-frequency (hf) and very-high-frequency (vhf) radars of moderate power can observe signals coherently backscattered from meteor trails, and from the *D*, *E*, and *F* regions, with or without an intermediate ground reflection. The technique has permitted mapping of *F*-region maximum electron densities over a wide area from a single location, identification of the two-stream instability process in equatorial sporadic-*E* measurements of the solar-quiet field in the nighttime equatorial electrojet, and forms the basis of a number of radar-meteor methods of measuring winds and electron densities in the 80- to 110-km region. The radar-meteor methods afford wind-velocity accuracies of the order of 10 percent, height accuracies of 1 km, and time resolution ranging from 30 to 50 measurements per hour, depending on the meteor flux. They constitute the best ground-based determination of winds in this height range; the principal drawback is the paucity of meteors.

A high-power hf radar facility is scheduled for completion this year in Colorado. The facility, which will be accessible to visiting scientists, will be used for a number of studies of the ionosphere above 100 km: traveling ionospheric disturbances (TID's), sporadic *E*, the effect of heating of the *F* region, and ducting in the magnetosphere.

High-power radar facilities for measuring backscatter from the ground, reflected by the *F* region, are of interest for radio communications but are generally not pertinent to aeronomy.

CONTINUOUS-WAVE MONITORING OF RADIO PHASE

For detection of certain events such as ionospheric responses to solar flares and acoustic gravity-wave effects, continuous monitoring of variations in the ionospheric electron-density profile is quite informative. Phase measurements are preferable for monitoring slowly varying phenomena (e.g., gradual fadeouts), whereas Doppler frequency measurements give the best response to fast events (e.g., sudden frequency deviations). Frequency measurements are also useful for detecting atmospheric waves resulting from solar-particle precipitation in the auroral zones and reveal rapid ionospheric changes during geomagnetic sudden commencements and ionospheric storms. There is no significant limit on the time resolution achievable, and Doppler shifts of less than 0.1 Hz are easily displayed.

MEASUREMENT OF MOTIONS AND MICROSTRUCTURE

Other information on ionospheric structure and motion is brought to the ground by radio echoes. The amplitude and radio-frequency phase of an echo vary more or less randomly with periods of the order of 1 sec. With spaced antennas, this fading pattern may be observed to move across the ground, implying motions near the radio reflection level. In a similar way, comparisons of fading at closely spaced frequencies (hence heights of reflection) provide information on vertical motions. A statistically rigorous method of analysis is available which reduces these observations to a description of the total mean and random motions, scale size, lifetime, and anisotropy of the random irregularities in the echo pattern. The central problem is to identify these results with their specific counterparts in the atmosphere. The nature and behavior of the corresponding ionospheric irregularities are largely unknown; they may move with the ionization itself or differently with the neutral air or propagate through one or the other medium as waves; and these possibilities may vary with altitude and with the circumstances of the experiment. The radio-scattering and wave-diffraction processes which generate the echo patterns at the ground are imperfectly modeled, and the scaling laws which connect the measured irregularities with the fine structure in the atmosphere are still uncertain. These interesting problems are receiving active investigation, and the promise of depending on spaced antenna measurements for considerable increases in our knowledge of motions and microstructures is very high.

GROUND-BASED OBSERVATIONS OF SATELLITE RADIO TRANSMISSIONS

Reception of satellite radio beacon transmissions at a ground station provides a means of determining the integrated electron content along the propagation path and gives information on its spatial distribution and temporal variations. The two primary techniques are Faraday rotation of the plane of polarization and measurement of phase-path effects, such as by dispersive Doppler. The Faraday effect is a measure of the dispersion between two magnetoionic modes and as such is weighted by the magnetic field strength as well as by geometric factors. Phase-path effects are frequency-dependent but independent of magnetic-field strength. Accordingly, the two techniques used together can be made to distinguish between electron content in the ionosphere and that farther out in the magnetosphere.

Synchronous satellites offer, in addition, the capability for purely time-dependent (e.g., sunrise) studies and measurements of ionospheric movements. Total variations in electron content during magnetic storms and solar flares are particularly informative. The occurrence and height of thin-layer irregularities in the *F* region can be established by scintillation observations.

Two types of satellite beacon studies are currently in use for studying total electron content with the Faraday method. The first, a low altitude (1000-km) satellite, Explorer 27, is utilized for synoptic studies of total electron content as a function of time of day, season, and magnetic condition. Polar latitudes can be studied with this satellite. Observations of 137-MHz telemetering beacons on board synchronous satellites are available at middle latitudes for the longitudes 30° E, through the Atlantic region, to approximately 220° W. Areas in the longitudes of India and the Middle East do not have these synchronous satellite signals available.

INCOHERENT SCATTER

Measured Parameters

Of all the radio-probing techniques, the incoherent-scatter radar method is able to measure by far the largest number of parameters of the upper atmosphere: electron density, electron temperature, ion temperature, ion composition, mean plasma drift velocity, ion-neutral collision frequency, and the direction of the earth's magnetic field. Electron density influences the scattered signals at all altitudes and can be determined in a number of separate ways. The other parameters manifest themselves by altering the shape of the power spectrum (or the autocorrelation function) of the scattered signal. In any given altitude range only a few of the parameters produce a significant effect; consequently, they can usually be interpreted without ambiguity in that range, but, as indicated in Table 3, the ranges of altitude over which each may be studied are also limited. In Table 3 those quantities that may be measured directly are listed separately from a second set which may be *derived* utilizing two or more of the measured parameters or by employing theoretical relations. These derived parameters are discussed in the next section.

TABLE 3 Ionospheric Parameters Obtained from Incoherent-Scatter Radar Measurements[a]

Height (km)	Measured Parameters	Derived Parameters
> 600	N_e T_e T_i V_d	E_{ph} vertical fluxes
	$O^+ \rightarrow H^+$ transition	(heat/particle)
600-200	N_e T_e T_i V_d	E_{ph} T_∞ $V_\perp$ (E fields)
220-120	N_e T_e T_i V_d	$V_{\|\|}$ (neutral winds)
	$XO^+ \rightarrow O^+$ transition	
< 120	N_e T_i V_d ν_{in}	$N[XY]$

[a] Where: N_e is electron density, T_e is electron temperature, T_i is ion temperature, V_d is drift velocity with respect to the radar, E_{ph} is photoelectron energy, $V_{||}$ is drift velocity parallel to the magnetic field, $V_\perp$ is drift velocity perpendicular to the magnetic field, and ν_{in} is ion-neutral collision frequency.

The accuracy of the incoherent-scatter measurements of various parameters has been evaluated by comparison with other (primarily rocket and satellite) techniques. Very few meaningful, i.e., truly coincident in time and space, comparisons have been made to date. Comparisons of electron-density profiles obtained by incoherent-scatter measurements and topside sounder observations have shown good agreement at high altitudes and in the value of the electron density at the layer peak. However, at intermediate altitudes the topside sounder profiles are systematically depressed in height compared with incoherent-scatter profiles. This discrepancy does not seem to reflect a time disagreement but rather an inherent problem in some aspects of topside ionogram analysis. Good agreement between bottomside ionosonde data and incoherent-scatter profiles has been found at several observatories.

Incoherent-scatter measurements in the *E* region indicate that $T_e/T_i = 1$, in contrast with some satellite and rocket experiments which have yielded substantially higher values. Recently satellite measurements of T_e in the *F* region have been found to be about 50 to 70 percent higher than those obtained from simultaneous incoherent-scatter observations, while in some instances rocket and incoherent-scatter measurements of *F*-region temperatures appeared to be in reasonable agreement.

There is every indication that the incoherent-scatter $N(h)$ profiles are correct, and hence the discrepancies in the temperature measurements are somewhat disturbing. Examples of the evidence in support of the scatter results include the agreement of the shape of spectral curves with the relevant plasma theory, the agreement with theoretical expectations of measured T_e, T_i, and deduced values of the neutral temperature T_n, and the agreement between incoherent-scatter temperature data with those from airglow measurements. It thus appears that the incoherent-scatter technique provides reliable and accurate measurements of aeronomic parameters.

Since the electron density N_e, as well as T_e, T_i, and the ion composition can be measured throughout the ionosphere at frequent intervals from the ground by incoherent-scatter radars, this technique becomes an almost ideal probe for the upper atmosphere. In addition to the above parameters, drift-velocity measurements provide important inputs to the continuity equation governing the ionosphere.

Rocket, satellite, and incoherent-scatter measurements nicely complement each other. Incoherent-scatter measurements provide comprehensive data with good altitude coverage, good time coverage, and good resolution at a particular location. Satellites can provide global coverage of a restricted range of altitudes and can measure most of the important aeronomic parameters but provide only "snapshots" at a particular location. Quantities not measurable by the incoherent-scatter technique can be obtained by means of rocket experiments which can also give extremely fine altitude resolution.

Derived Parameters

ELECTRIC FIELDS

Above an altitude of ~ 250 km, the conductivity of the ionospheric plasma is sufficiently great that the magnetohydromagnetic approximation applies; namely, the magnetic field may be regarded as "frozen" in the plasma. The electric field *E* carried along the lines of the earth's magnetic field into the ionosphere either from the *E* region or down from the magnetosphere can be measured as a plasma convection velocity normal to the magnetic field, and of magnitude $V_\perp = -E \times B/B^2$. A westward electric field gives an inward drift of the ionospheric ionization.

NEUTRAL TEMPERATURE AND DENSITY

Three distinct relationships between the properties of the ionized plasma and the neutral atmosphere enable incoherent-scatter measurements to provide detailed information about the structure of the neutral atmosphere above approximately 100-km altitude.

1. Since ion and neutral temperatures are substantially equal at altitudes near 250 km, the exosphere neutral temperature T_∞ may be determined more or less directly.
2. The transition of the ion temperature from equality with the neutral temperature at ~ 300 km to equality with the electron temperature at ~ 600-km altitude is determined by the ratio of the electron concentration to the neutral-gas density. Neutral densities in the altitude range 400 to 600 km can thus be determined from the electron and ion temperatures compared with neutral temperatures extrapolated upward from 250 to 300 km.
3. The power spectrum of the incoherent-scatter signal at altitudes from ~ 90 to 110 km is substantially affected by the ion-neutral collision frequency ν_{in}, which in turn is proportional to the neutral density $N[XY]$ (see Table 3). Accordingly, careful measurements of the incoherent-scatter spectrum in this altitude region will give neutral atmosphere densities. While measurements are not yet being made for the purpose, the technique in all likelihood has the capability of determining the speed and direction of neutral winds at altitudes < 160 km, where the winds are able to blow the ionization across the field lines.

PLASMA FLOW ALONG MAGNETIC FIELD LINES ($V_{||}$)

In addition to its ability to measure plasma velocities normal to the magnetic field, a suitably aligned incoherent-scatter radar can measure the velocity $V_{||}$ of the plasma in a direction parallel to the magnetic field. The distribution of ionization along a field tube is determined by photochemical effects below ~ 250 km, while above that altitude (in the topside *F*2 layer) diffusion predominates, and the plasma is essentially in hydrostatic equilibrium.

In the region above 160 km and below the *F*-region peak, a neutral wind will set up an ion drift along the field lines so that the meridional velocity component of such winds can be determined from observations of $V_{||}$ combined with appropriate theory.

The large reservoir of ionization in the plasmasphere is supported by electrostatic forces on the ionospheric ionization below 1000 km. Changes in the ionization density of the *F*2 layer, for example, its decrease during the night hours, lead to a downward diffusion of ionization from the plasmasphere into the ionosphere. This plasma motion has recently been directly observed by means of incoherent scatter. The downward motion is best measured at an altitude $\geq$ 600 km, where the velocity of the ionization is greater than at the *F*2 maximum, because the upward or downward ionization flux is approximately conserved with altitude.

Measurements along the magnetic field of density, temperature, and velocities at high altitudes provide estimates of particle and heat fluxes into and out of the protonosphere and are necessary to establish appropriate boundary conditions in attempts to study the continuity of the *F*-region ionization.

PHOTOELECTRON ENERGY DISTRIBUTION

At frequencies displaced from the radar frequency by an amount equal to $\pm f_n$, where f_n is the plasma frequency at any altitude, an echo component has been found whose intensity (in the daytime) depends on the number density of photoelectrons having a component of velocity in the direction of the radar matched to the phase velocity of the plasma wave ($f_n\lambda/2$) that gives rise to the echo. Thus by studying the intensity of these echoes it is possible to derive information concerning the steady-state photoelectron energy distribution. Unfortunately, a complete energy spectrum cannot be derived without assumptions concerning the altitude distribution of the photoelectrons and their pitch angles.

Present Facilities

Table 4 lists the locations of the existing incoherent-scatter facilities. All are located in regions where the ionosphere is under strong solar control and where the field lines are permanently closed. Magnetic field tubes from the magnetosphere to these stations are therefore believed to contain

TABLE 4 Location of Existing Incoherent-Scatter Facilities

Facility	Affiliation	Geographic		Geomagnetic Latitude	L(200 km)
		Latitude	Longitude		
Jicamarca Radio Observatory	Geophysical Institute of Peru	11.9°S	76.0°W	1°S	1.1
Arecibo Ionospheric Observatory	Cornell University	18.3°N	66.75°W	30°N	1.4
Stanford	Stanford Research Institute	37.4°N	122.17°W	43°N	2.2
Millstone Hill Ionospheric Radar	Lincoln Laboratory MIT	42.6°N	71.5°W	53°N	3.2
St. Santin	Centre National d'Etudes des Telecommunication				
	Transmitter:	44.65°N	2.19°W	47°N	1.9
	Receiver	47.37°N	2.10°E		
RRE Ionospheric Radar	Royal Radar Establishment	52.09°N	2.14°W	56°N	2.5

ionization produced by solar ultraviolet light. In the magnetosphere at approximately $L = 4$, there is an abrupt transition to lower ionization densities. The cause of the transition is not certain, but evidence suggests that the source of the ionization changes here from solar radiation to the solar wind that has penetrated the earth's magnetic field. The position of the transition is believed to be related to a trough of low ionization density appearing in the *F* region at night. None of the existing stations is located close to this trough, and in the section that follows, we propose the construction of a new incoherent-scatter radar to fill this gap.

No facility presently exists in the auroral zone. However, the Stanford Research Institute incoherent-scatter radar, located near Palo Alto, California, may be moved to a scientific rocket-launching site near College, Alaska. This would place a system at $L = 5.8$, close to the auroral-zone maximum. There is considerable need for a facility in such a location because the behavior of the auroral-zone ionosphere during magnetic disturbances is poorly known. Unfortunately, because of its limited sensitivity, the Stanford radar will be restricted chiefly to making *F*-region measurements. Nevertheless, this radar will provide data on whether very high (3500 K) ion temperatures exist in the auroral *F* layer, and it will give electron temperature and density profiles in the *F* region during auroras, a feat no other technique has accomplished. Used in conjunction with the rocket-probe capability and extensive ground-based optical observing equipment at the Alaska site, the radar should lead to improved knowledge of chemical and physical processes in the auroral *F* layer. Additional data on the auroral-zone ionosphere will be obtained if it becomes possible to detect the enhanced plasma line during auroral disturbances.

Although there is a clear scientific need for a major incoherent-scatter radar located in the auroral zone, experience at Millstone, Massachusetts, has indicated that auroral clutter can cause severe interference to a sensitive incoherent-scatter radar. Accordingly, it seems prudent to assess the gravity of this problem in the auroral zone before embarking on the construction of a large facility. The experience gained with the relatively small Stanford radar should be valuable for the design of an improved facility at a later time.

TABLE 5 Altitude Coverage (km) of Power Spectrum, and Velocity Measurements

Facility	Power	Spectrum (or Correlation Function)	Velocity Vector	
Jicamarca	200-3000 (150)-(8000)	200-1200	200-600	($V_\perp$)
Arecibo	90-2000	90-1400	100-1000	(V_z)[a]
Stanford	200-600	200-600		
Millstone	100-1000	200-900	450-900	(V_z)[b]
St. Santin	95-500	95-500	120-400	($V_{\|\|}$)[b]
Malvern	90-1000	200-750		

[a] Expected range--measurements not yet being made.
[b] Current range--may be extended to other altitudes.

CAPABILITIES OF EXISTING FACILITIES

In Table 5 are listed the altitude ranges in which power and spectrum (or correlation function) measurements are typically performed at the various observatories. The numbers in parentheses for Jicamarca are altitudes reached only occasionally. The spectrum category encompasses a wide variety of measurements (temperature, composition, plasma line, and collision frequency, for example), but no attempt is made here to give a more detailed summary, because the observations actually performed vary so widely with observatory, altitude, and time of day.

Typical values of time resolution, altitude resolution, and experimental errors also vary widely. In the *F* region, where the signal-to-noise ratio is greatest, measurements accurate to 5 or 10 percent are made with a time resolution of at least 5 to 10 min at all observatories. An altitude resolution of at least 10 to 20 km is common in measurements of electron density; however, the resolution is typically poorer when measuring other parameters such as temperature. The use of multiple-pulse correlation function measurements, on the other hand, yields altitude resolution with accuracy comparable with that obtained in measurements of electron density.

Table 5 also lists the height range over which useful drift-velocity measurements might be made, together with the component ($V_{||}$ or $V_{\perp}$) that can best be measured. In the case of Arecibo and Millstone, measurements are made in the vertical (z) direction with the result that it is not possible to separate the observed drifts into $V_{||}$ or $V_{\perp}$ components with complete certainty.

It will be noted that the perpendicular velocity component $V_{\perp}$ can be measured only at Jicamarca, so that ionospheric electric fields presently can be studied using this technique only near the equator. At none of the stations is it currently possible to measure more than a single component of the velocity vector; thus determination of neutral-wind speed and direction from observations of drifts at low altitudes ($\geq$ 160 km) remains to be realized. Finally, ionization exchange between the ionosphere and the magnetosphere can now be studied only at Millstone where measurements of $V_z (\simeq V_{||})$ at high altitudes ($\geq$ 600 km) are being made. These restrictions in studying the drifts of the ambient plasma arise because of severe limitations on the directions that may be viewed with the existing antenna systems (the exception being Stanford radar for which sensitivity limitations are the restricting factor).

SUPPORT

Despite the success of the incoherent-scatter technique all the U.S. supported stations suffer to some extent from shortage of funds or of scientific personnel. The funding situation is acute at Jicamarca and may become so at Millstone. Difficulties in recruiting scientists have also been experienced at Arecibo and Jicamarca, possibly because of their remote location.

Limitations in data-processing capabilities characterize all the facilities. As a result, only a small fraction of the data are returned to the antenna from each transmitted pulse, and observing periods each concentrate on one aspect alone of the measurements. If all the available information for each transmitted pulse could be received and processed, the data would become far more meaningful. There are various means toward this end, the most efficient being to add hardware in front of the computers.

JICAMARCA The Jicamarca Radio Observatory was turned over to the Peruvian Government by the United States on July 17, 1969. Interim funding has been provided by the Environmental Science Services Administration to allow the Geophysical Institute of Peru time to develop support.

The Jicamarca Radio Observatory has the following unique capabilities:

1. Measurements of ionospheric behavior peculiar to equatorial regions.
2. Measurement of electron densities and temperatures to considerably higher altitudes than at any other station because of the long wavelength employed.
3. Measurements of ionization drift perpendicular to the earth's magnetic field to provide a direct measure of electric fields. Jicamarca is in a unique position to measure, and even monitor, *F*-region electric fields by this technique. These data combined with those obtained from electrojet observations may assist in determining, for example, the horizontal north-south extent of the *E*-region electric fields seen at the equator.
4. Study of equatorial spread *F*, or field-aligned irregularities in the equatorial *F* region. Although this phenomenon has been observed for over 30 years, as yet no theory for its formation exists. It seems likely that vhf radar studies, such as have recently been made at Jicamarca, will lead to an explanation as in the case of electrojet phenomena.

5. Measurements on the frequency and polarization dependence of irregularities produced by plasma instabilities in the equatorial electrojet leading to a better understanding of this and related phenomena such as natural and artificial auroras.

ARECIBO In the transfer of the support of Arecibo from the Advanced Research Projects Agency to the National Science Foundation attention should be directed to preserving and strengthening the role of aeronomic studies at the observatory. Increased demands on the instrument for radio astronomy can be anticipated, especially when the surface is replaced by one capable of operating down to a 10-cm wavelength. Simultaneous ionospheric and radio-astronomy investigations are possible, in most instances, by taking steps to protect the radio-astronomy receivers from radar interference. Work now in progress to this end should be supported, as should acquisition of better data-handling equipment that will lower the time required for ionospheric investigations.

MILLSTONE HILL Because new and improved data-processing techniques have been developed (yielding, for example, information on drifts in the ionosphere) that have not been exploited to any great extent so far, the scientific usefulness of the Millstone Hill facilities at the MIT Lincoln Laboratory is far from having been exhaused. Means must be found to support the operation of these facilities for some time to come and to broaden their availability to other users.

Proposed New Facility

In this section we propose the construction of a major new incoherent-scatter radar system in the northern United States. This facility, by reason of its location (near $L = 4$) and by virtue of its design will be able to examine a number of scientific questions that cannot be tackled with existing instruments.

The major U.S.-supported incoherent-scatter facilities (Table 4) were designed at a time when there was considerable interest in the topside of the *F* layer, a region inaccessible to ground-based ionosondes. To this end the facilities were constructed with vertically, or near-vertically, directed antennas and were designed to determine the electron-density profile above the *F*-layer peak. The additional capabilities of measuring the electron and ion temperatures and other parameters listed in Table 3 were not wholly foreseen. Depite this, by making considerable improvements in the manner in which the radars are operated, it has been possible to extend their scientific usefulness radically. Limitations remain, however, regarding the geographic regions they examine, their ability to exploit fully the inherent capability of the technique for measuring plasma drifts, and, with the exception of Arecibo, their ability to examine regions below 150 km with adequate resolution and sensitivity.

SCIENTIFIC QUESTIONS TO BE STUDIED

ELECTRIC FIELDS The capability of the incoherent-scatter radar to measure electric fields by observing the drift velocity of the ionization across the magnetic field compares favorably with the other available techniques, such as ionized barium clouds from rockets (available only at twilight) and electric-field sensors on rockets, satellites, or balloons. A suitably designed incoherent-scatter radar located at high temperate latitudes would have the ability to monitor continuously the magnetospheric electric field and could thus make significant contributions to the resolution of physical problems having ramifications extending far beyond ionospheric processes. Examples are:

1. Physics of magnetospheric plasma convection, and the radial drift of whistler ducts
2. Motion of the plasmapause, both diurnally and in magnetic storms and substorms
3. Dynamo-region effects, diagnosed from the relation between electric-field variations in the magnetosphere, and magnetic-field variations produced by the dynamo current resulting from the electric field
4. Electrodynamically produced variations in the shape of the *F* layer (diurnal, day-to-day, and storm effects)

During severe magnetic disturbances the plasmapause is found to move inward from approximately $L = 5$ to $L = 3$. For greatest contribution to the study of electric fields in the ionosphere and the magnetosphere, the new facility should be located so that the plasmapause is situated sometimes above it, sometimes beyond. Hence an intermediate location near, say, $L = 4$ would seem best.

STRUCTURE OF THE NEUTRAL ATMOSPHERE Using the hydrostatic equation, a local atmospheric model can be constructed completely from incoherent-scatter determinations of the exospheric neutral temperature, T_∞, and measurements of density and temperature at altitudes = 120 km, where collisions are important. Compared with other techniques, such as satellite drag, ambient ionization gauges, and various rocket methods, all of which depend on deducing atmospheric structure by indirect means, the incoherent-scatter technique offers the opportunity for examining atmospheric structure in much greater detail. Problems that can be studied by this means include:

1. Physics of atmospheric models generally
2. Sources and characteristics of heat inputs into the neutral atmosphere
3. Origin of relatively rapid changes in neutral temperature in the atmosphere

Measurements of this type can be made at Arecibo, and there is a need to extend them to other latitudes in order to obtain a global picture of the behavior of the neutral atmosphere.

NEUTRAL WINDS By observing at $\leq$ 160 km the plasma drift set up by atmospheric winds, the velocity field of the atmosphere can be studied. This measurement is not currently possible at Arecibo because of the direction of the field of view. Also, it does not seem possible to modify the Arecibo radar system to make such measurements because of the lack of land at suitable distances from the radar on which additional receiving antennas could be located. A facility is required that can yield an altitude resolution of ~ 1 km and a horizontal resolution of ~ 5 km and determine the drift velocity with an accuracy of roughly 5 to 10 m per sec. The ability to probe the velocity field at will in this altitude region (compared with other techniques such as the tracking of chemical releases from rockets) gives the opportunity for studying the following physical problems in detail:

1. General circulation of the atmosphere in the region 100 to 160 km
2. Lunar and solar tides in the neutral atmosphere
3. Changes in upper atmosphere circulation associated with sudden changes in stratospheric structure

4. Direction and velocity of propagation of internal atmospheric gravity waves of medium scale (responsible for the wavelike structure observed in chemical releases from rockets)

F-REGION DYNAMICS Motion of the ionization in the *F* region is caused by a number of separate forces, *viz.*, gravity-induced ambipolar diffusion along the lines of the earth's magnetic field, opposed by collisions with the neutral gas; electric-field effects such as those described above under Electric Fields; and the drag on the ionization produced by movements of the neutral atmosphere in the horizontal direction. Above the peak of the *F* layer, gravity-induced ambipolar diffusion is the principal force governing the distribution of the ionization along the field lines and may be studied by measuring the drift component $V_{||}$.

Typical problems which are amenable to study by this type of measurement using incoherent scatter include:

1. Maintenance of the night *F*2 layer
2. Transport of ionization between the plasmasphere and the ionosphere and maintenance of the plasmasphere ionization
3. Thermal expansion and contraction of the *F*-layer ionization produced by changes in the thermal structure of the ionosphere
4. Transport of ionization between the northern and southern hemispheres and its possible contribution to seasonal variations of *F*2 layer
5. Explanation of the day-to-day changes in *F*2 layer shape and density

ELECTRON ENERGY DISTRIBUTION, INCLUDING THERMAL ECONOMY The capabilities of the proposed facility for studies of electron and ion temperatures, and for studies of the plasma line of the incoherent-scatter spectrum (produced by ionospheric photoelectrons) will be superior to those of any existing facility. However, since studies of both these classes of phenomena are being actively pursued with present facilities, it is difficult to project the nature of the outstanding problems at the time when the proposed facility will be completed. On the other hand, the excellent height resolution and high sensitivity of the proposed facility will permit the following studies, difficult with present facilities:

1. Comparison of ion and electron temperatures in the *E* region, 100 to 160 km, to determine whether thermal equilibrium exists to the extent predicted theoretically
2. Detailed studies of photoelectron energy and pitch-angle distributions through the *F* layer, using radio-wave propagation vectors directed at various angles to the magnetic field, to elucidate the pattern of photoelectron production and energy deposition throughout the *F* layer
3. Studies of ionospheric currents, from the asymmetry of the ion component of the incoherent-scatter spectrum, possibly permitting the detection of dynamo-induced currents along the magnetic field lines

ION CHEMISTRY The transition at high altitudes from O^+ to H^+ as the dominant ion species can be examined at Jicamarca and Arecibo but lies above the altitudes accessible to other existing radar systems (Table 5). There are therefore no high-latitude measurements of the diurnal variation of the altitude of this transition. Existing theories suggest large day-to-night changes in this altitude, which, together with charge transfer in the transition region, play a role in the maintenance of the nighttime *F* layer. The problems that may be studied by high-latitude composition measurements are principally the same as those listed above under *F*-Region Dynamics but in addition include:

1. Likelihood of obtaining the charge exchange rate between O^+ and H^+, and derivation of the abundance of neutral hydrogen, by combining observations of the transition altitude with vertical fluxes through 1000 km
2. Detection of He^+ ions, yielding information on the abundance of neutral helium

DESIGN, COST, AND LOCATION OF THE NEW FACILITY

The design of the facility should be guided by the need to meet the following specifications:

1. The facility should be capable of examining density and temperature, with adequate height resolution, in the entire region between 200 and 100 km and to as low altitudes as possible.
2. The facility should be able to explore density and temperature in the regions above 200 km up to ~ 2000 km, i.e., the altitude at which the ionospheric plasma has become entirely protons and electrons and the temperature largely isothermal.

3. Since the motion of the neutral atmosphere at *E*- and *F*-region heights very likely plays an important role in many aeronomic processes, the facility should be designed to obtain maximum information on this motion by means of drift measurements using the movement of ambient ions as indicators of the motion.

4. Since the magnitude of the impressed electric fields in the ionosphere can be determined by the drifts of ionization they produce in the *F* region normal to the magnetic field, the facility should be designed to determine this component of the drift also. This measurement is required both in the normal midlatitude ionosphere and in the region beyond the plasmapause ($L = 4$).

There is little doubt that a radar system can be designed to meet the objectives described above. It would probably consist of one large radar station and several (perhaps three) displaced receiving stations. With the possible exception of Arecibo, such a system would cost considerably more than any of the existing stations. This promptly raises the question of whether such an instrument should be a national facility available to a wide number of users. We suggest that, indeed, this would be most desirable, and that a national center for aeronomy might be created around the proposed new radar.

The design and cost of the new instrument cannot be considered separately, and, to complicate matters further, the design may to some extent depend on the choice of location. It is outside the scope of this report to propose an initial design, as this will require considerable study and prior agreement on all the scientific requirements to be met. The construction of a facility that would meet the specifications listed above and that, in addition, could examine the behavior of the ionosphere over a radius of ~ 500 km was proposed in 1967 by a group in the Midwest (Committee on Institutional Cooperation, Subcommittee on Aeronomy, *Program Study for a Thomson Scatter Radar*, Dept. of Electrical Engineering, University of Illinois, Urbana, Ill., May 1967). This group estimated the cost at approximately $25 million. We believe that the specifications listed here could be met by a less ambitious design costing perhaps half of this amount.

The highly desirable location at $L = 4$ would place the facility at a high temperate latitude close to the U.S.-Canadian border. Stations could be located on both sides of the border. If this seems desirable, and if appropriate arrangements can be made, the center would then be international rather than national.

The most desirable location scientifically may be removed from population centers. In this event, experience indicates that it would be preferable to operate the facility as a field station rather than to situate the entire institute at a place that is not conducive to family living. Personnel would be based in the nearest community that can optimize its success and growth potential, and appropriate transportation and schedules of visits would be developed.

The value of the facility would be enormously enhanced by ancillary instrumentation to carry out complementary and related observations. The types of equipment should be thought out carefully in advance and incorporated in the initial design. Additional instruments ideally should include an ionosonde of modern design, a meteor-winds radar system, photometers for airglow studies, and perhaps instrumentation (e.g., a partial reflection sounder) required for studies of the region below 100 km (see Chapter 7). It would also be desirable if the center were close to a rocket range capable of launching rockets to, say, 1000-km altitude. Unfortunately, this last condition would place severe restrictions on the choice of location, leading possibly to the difficulty now faced at Arecibo that suitable remote receiving sites cannot be found. However, proximity to a rocket launch range capable of handling rockets that can reach 120 km need not pose such a problem and might be considered in selecting a suitable site. As in the case of the design of the instrument, it is evident that the choice of location requires study and prior agreement on the criteria to be met.

In sum, the design and location of the new facility are matters for which agreed sets of criteria must be established and on which additional study outside the scope of the deliberations presented here is required. It would seem that the cost will be sufficiently high that the facility might profitably be established for national or even international use and, as such, might form the principal instrument at a center for aeronomic and/or ionospheric studies.

OPERATION AND MANAGEMENT OF THE NEW FACILITY

The proposed new facility should provide opportunities (as does the National Radio Astronomy Observatory) for both resident and visiting scientists, including graduate students, to undertake research projects on some agreed division of available operating time.

We envisage that the center would be administered by a director under policy guidance of an advisory committee or board representing the operating agency (perhaps a university consortium). The director may elect to establish a committee representing the principal scientific users to provide guidance concerning scheduling time and experiments.

The center should serve to foster the growth of aeronomy, of ionospheric physics, and of solar-terrestrial physics throughout the United States and Canada and should promote international cooperation in these fields of research.

SHAPE OF FUTURE PROGRAM IN THE UPPER IONOSPHERE

While the ability of the incoherent-scatter technique to measure a large number of vital aeronomic parameters above 100 km has been proven, no one existing facility is in fact capable of measuring all the available parameters. The biggest single requirement, therefore, is for a new second-generation incoherent-scatter facility capable of fully exploiting all available features of the technique.

While the need for a new facility is the biggest single requirement, there are many respects in which further development is required at existing incoherent-scatter facilities, especially in the area of data processing. In particular, because the pressure from radio astronomers to use the Arecibo Ionospheric Observatory is heavy and is likely to increase, action is required to speed up the data processing there and to introduce electronic arrangements to permit simultaneous use of the facility, when possible, for both aeronomy and radio astronomy.

Special action is urgently required in connection with the Jicamarca incoherent-scatter facility located on the geomagnetic equator in Peru. The Environmental Science Services Administration is moving to withdraw support from the observatory which, in consequence, is threatened with collapse. This would be a substantial loss to aeronomy and a setback to international scientific cooperation with Latin America.

There is a great need for an incoherent-scatter facility in the auroral zone. The opportunity may occur in the near future to move the facility now at Palo Alto, California, to College, Alaska. While this facility is only of moderate power, there are many excellent observations that it could make in the auroral zone. Moreover, it could explore what technical problems may arise from auroral clutter. The move from Palo Alto to College is therefore strongly to be encouraged.

Besides developing application of the incoherent-scatter technique to the aeronomic problems of the upper ionosphere, many other radio techniques should continue to be employed. In particular, multifrequency reflection sounding by ground-based ionosondes should continue to be made. The equipment in use largely is of obsolete design and more could be accomplished by this technique with the addition of new modern equipment and data-analysis methods.

RECOMMENDATIONS

1. Noting the major past accomplishments and the impressive future capabilities of the incoherent-scatter technique, we *recommend*, as highest priority, that a new facility be constructed capable of fully exploiting the incoherent-scatter technique, particularly with respect to the measurement of plasma motions both along and across the earth's magnetic field and the derivation therefrom of winds and electric fields, leading to a wide range of information about the dynamics of the ionosphere and magnetosphere. The precise site should be a matter of study and should depend on what action may be taken by other countries and on whether auroral interference at high latitudes proves to be a serious hindrance to the technique. Present thinking is that the new facility should be in the neighborhood of the magnetic shell $L = 4$, which would place it in the northern part of the continental United States. The cost of a new facility would probably be comparable with that of the Arecibo facility. The new observatory should be dedicated to aeronomy and should be operated as a national facility organized to ensure frequent and close participation by university faculty members and students in aeronomy, following the procedure successfully developed at the National Radio Astronomy Observatory. The possibility should be explored that the new facility be an international one involving Canadian participation. We *recommend* that the National Academy of Sciences appoint a panel charged with confirming the scientific need, developing criteria for the observatory, and supervising the design study. The first two items of the charge should be completed in one year or less. The design study should follow promptly. We *further recommend* that the Academy seek the support of the National Science Foundation for these studies.

2. We *recommend* that support for existing facilities be continued, specifically:

a. The Jicamarca Radio Observatory in Peru is uniquely located for aeronomic research. It has produced important results. There are significant scientific problems to be attacked by continued measurements with the present facility. Recognizing the severe logistical and political problems connected with the conduct of such scientific work at a remote location, we nevertheless consider that substantial efforts should be made by the United States to share in the benefits from continued experimentation. This Study Group believes that there is a good chance that adequate long-term arrangements for United States-Peruvian cooperation can be developed in a reasonable time, and *recommends* that the National Academy of Sciences appoint an *ad hoc* panel to explore this. However, to provide any possibility of success for these efforts it is crucial to provide financial support for a minimum holding operation for the Peruvian scientific and engineering staff. This Study Group urges in the strongest possible terms that the Environmental Science Services Administration arrange for such minimum support for the remainder of the present fiscal year even though the scientific output may be reduced.

b. Adequate funds should be provided to maintain the aeronomy work at Arecibo and Millstone Hill, at least at their current levels. This is especially important in the case of Arecibo during the transfer of funding of the facility from the Advanced Projects Research Agency to the National Science Foundation. Arrangements should be made to ensure the continued operation of the Millstone Hill radar at least until a new facility comes into use.

c. Improved electronics should be provided at the existing incoherent-scatter observatories to permit more effective use of the observing time and, in the case of Arecibo, to permit simultaneous use of the facility for aeronomy and radio astronomy in a wide range of circumstances.

3. We *recommend* that an incoherent-scatter facility be established in the auroral zone having moderate power capable of measuring electron density, electron temperature, and ion temperature in the *F* region (a) to attack the recognized aeronomical problems in the auroral zone and (b) to explore the operational problems (mainly clutter interference) that may be peculiar to the incoherent-scatter technique in the auroral zone. This could be achieved by moving to College, Alaska, the incoherent-scatter facility at present located at Palo Alto, California.

4. We *recommend* that the feasibility be explored of a floating incoherent-scatter facility that could be moved to

scientifically interesting locations such as the South Atlantic anomaly, the Arctic, and the Antarctic and could be used in various cooperative experiments with land stations, for example, at their magnetically conjugate points or as remote receiving stations. This suggestion might be explored in cooperation with the French workers who are responsible for it.

5. Recognizing that essentially all the ground-based reflection-type ionosondes operated in the United States are in need of replacement and that new developments in this technique are under way, we *recommend strongly* that new ionosondes incorporating modern data-recording and processing features adaptable for studying the dynamics of the ionosphere be developed and that their locations include aeronomical research centers such as incoherent-scatter and rocket-launch sites in the United States.

We *further recommend* that the United States continue to do its share in maintaining an ionosonde network for monitoring the solar-terrestrial environment, including stations primarily established for aeronomic and telecommunication purposes and that, to a greater extent than heretofore, the operators of special-purpose ionosondes cooperate with the World Data Centers as part of the cooperation in the international monitoring effort coordinated by the International Union of Radio Science and the Inter-Union Commission on Solar-Terrestrial Physics.

6. Recognizing the incomparable ability of the topside ionospheric reflection-type sounders to reveal the global picture of the topside of the ionosphere, we *recommend strongly* that this program be continued and that adequate funds be made available for data reduction.

7. Recognizing that the presence in the auroral zone of the radio aurora is a manifestation of the existence of electric fields and of the precipitation of ionization, and that the physics of the reflection and strongly scattering phenomena remains poorly understood, we *recommend* that radar studies be made which permit measurement of the properties of the medium with good resolution in space and in radial velocity.

8. We *recommend* that the study of radio-star scintillations for investigation of the solar wind be continued at the present level.

9. We *recommend* that study of the integrated electron density in the ionosphere be continued at the present funding level and that emphasis be placed on studies using transmissions from geostationary satellites.

7 Radio Probing of the Lower Ionosphere

The study of the *D* region, more than any other region of the ionosphere, is hampered by deficiencies in observational information. Conventional ground-based sounding and propagation techniques for obtaining electron-concentration profiles are handicapped by high collision frequencies and low electron densities. In contrast with the higher regions, where electron density can be determined easily by measuring plasma frequency, direct sensors are not available for any of the properties of the *D* region. The 50- to 100-km height range lies below the practical perigee of satellites, but rockets provide data that add significantly to the ground-based observations. *In situ* measurements, however, are of necessity only "snapshots," and the information required to understand the long-term mechanisms that govern the behavior of the 50- to 100-km range, and the potentially important coupling between this region and the weather systems of the lower atmosphere, are likely to come only from ground-based observations.

What radio-probing methods fail to provide in direct parametric measurement is partially compensated for by their ability to reveal important variations of the region. A number of techniques, sensitive mainly to the increased absorption of radio waves traversing the region, serve as convenient indicators of its response to solar activity, particularly to solar flares and particle influx. Furthermore, several indirect methods can infer electron-density profiles and their variations from absorption measurements. The cross-modulation, partial-reflection, and multifrequency riometer techniques are, basically, all measurements of absorption.

SCIENTIFIC QUESTIONS

Ground-based radio techniques can make contributions to the resolution of a number of major problems relating to the ionosphere below 100 km.

1. What are the important photochemical processes that determine the normal electron- and ion-density distributions in the ionosphere? Electron- and ion-density profiles, and information on their temporal and geographic variability, are required for resolution of this question.
2. What changes in the neutral atmosphere structure and composition account for the winter variability of electron density in the quiet *D* region (winter anomalous days)? Here, data on temporal and geographic variation of electron-density distribution in the *D* region on magnetically quiet days are needed for comparison with suitable parameters of the neutral atmosphere.
3. What is the relative importance of photochemistry and dynamics in explaining the anomalies and irregularities of the ionosphere? How are *D*-region irregularities formed? Information necessary to progress on these questions includes structure of the anomalies and irregularities that exist in the lower ionosphere and the wind field in this region.
4. What is the explanation of the changes that take place in the ionosphere during a solar flare? Rapid temporal changes in the electron-density profile during flares must be determined to permit detailed correlations with the x-ray flux and spectrum.
5. What are the important sources of electron heating in the ionosphere? Knowledge of the detailed electron distribution is needed to test for consistency with required heat production. So also are both the time taken by hot electrons to return to the temperature of the ambient medium and the processes involved.
6. In the polar ionosphere, how is the energy flux of precipitating energetic particles distributed? How much goes into, for example, luminosity or production of ionization or heat? The polar ionosphere clearly has unique problems. Simultaneous measurements of electron density, auroral luminosity, and energy flux of particles are required.

To these six questions may be added others concerned with the collisional frequencies of electrons and ions and with the electrical conductivity of the atmosphere.

The Required Measurements

It can be seen from questions 1, 2, 4, and 6 above that there is a need to determine the electron-density profile and to map its changes with time. An accuracy of 10 percent for each location is a minimum requirement for most of the studies. The needed height resolution varies from one study to another. For question 3, a resolution down to centimeters could be useful; while for question 2 a resolution of 1 km is quite adequate. One-second time resolution is needed in 4, whereas 15 min can be tolerated in 2.

The ion-density profile is needed to the same accuracy (10 percent) as that for electrons, but, for most purposes, a height resolution of 0.5 km will suffice. The positive ion and negative ion profiles are required separately.

Irregularities in electron density in the region below 100 km have many sources, for example, turbulence, meteor trail ionization, gravity waves, particle precipitation (at high latitudes), and wind shear. Determining their spatial and temporal variations is clearly one of the most challenging problems of radio probing. While the 10 percent criterion would be desirable, a factor of 2 in some of the scale parameters would be very helpful.

The wind structure in the lower ionosphere falls into two regimes. Below an altitude of ~70 km the collisional frequencies of both ions and electrons are greater than their angular gyrofrequencies, and the plasma behaves as part of the neutral gas. Above ~70 km the electron angular gyrofrequency exceeds the electron-neutral collision frequency and electrons exhibit a degree of magnetic control, a situation ions do not encounter until above ~ 140 km. We are more interested in the neutral wind than the electron drift velocity, but the former becomes progressively more difficult to obtain at higher altitudes. The parameter of interest is the three-dimensional wind vector. However, a two-dimensional vector in the horizontal plane will normally suffice. Knowledge of any two orthogonal components to 10 percent or 1 m sec^{-1} will normally be adequate.

The rate at which an electron loses energy below 100 km is a function of the electron-neutral collision frequency, the energy differential between the electron and the neutral particles, and a factor that expresses the fractional loss in excess energy in each collision. These three parameters must be determined to make progress toward resolving the problem of electron heating.

GROUND-BASED TECHNIQUES

The first realization of the existence of the lower ionosphere came about through observations of the propagation of low-frequency radio waves and of the absorption of medium-frequency and high-frequency radio waves. These techniques are still in use and continue to yield information on the gross variations of the lower ionosphere as a whole and to serve as indicators of the existence of abnormal conditions. Absorption measurements by the pulse-reflection or ionosonde (A1) method are carried out routinely at a few stations, mainly in Europe, but obtaining and reducing the data is a time-consuming operation and yields at best a height-integrated "bulk" description of the state of the lower ionosphere. An approximation to A1 is a ready by-product of normal ionograms and, while crude, has served a useful purpose in global studies. A few routine measurements of oblique-incidence, continuous-wave absorption (A3) have also been carried out but, again, without yielding many satisfactory physical results.

By far the most widely used of the absorption techniques is the riometer (A2), which is at its best in conditions of heavy absorption and can be used to give information about the spectrum of the ionizing radiation. The riometer technique for monitoring absorption of cosmic noise was developed in the 1950's primarily as a detector of high-latitude particle-precipitation events. Since then, major networks of high-latitude riometers have been operated for this purpose; again, they yield information on the total absorption of the lower ionosphere, with no altitude discrimination except during twilight periods when some such information can be obtained from the time variation of the shadow height.

The altitude distribution of the ionization in the lower ionosphere can in principle be studied through the use of multifrequency riometers, because the altitude sensitivity of the absorption is a function of frequency. This technique has been used to study polar-cap absorption (PCA) and auroral absorption events in Alaska but can only give information at heights below ~ 80 km. The A2 technique has also been used extensively to study the quiet lower ionosphere, especially in India. The magnitude of the absorption is small, however, and careful operation of the equipment and reduction of the data are essential. The measured absorption also contains a component originating in the upper ionosphere, and separation of the lower-ionosphere contribution is not always easy to carry out. At all latitudes, the A2 technique is a valuable detector of solar-flare effects, i.e., sudden cosmic-noise absorptions (SCNA's), but comparatively little quantitative work has been carried out using these observations.

The partial-reflection technique, using weakly scattered signals from electron-density irregularities in the *D* region, was introduced in Australia in 1953 and has been developed during the late 1950's and 1960's chiefly by groups in Canada, New Zealand, Norway, and the United States. The technique involves estimation of the differential absorption of the extraordinary and ordinary magnetoionic components of the partially reflected echoes from the *D* region, normally in the frequency range 2 to 6 MHz. The results depend on electron density and collision frequency in such a way that if one is known the other may be deduced. The partial-reflection technique appears to yield electron-density information with adequate height resolution between roughly 60 and 90 km, and although data reduction is not an entirely simple matter, it is capable of operation in a routine, systematic fashion. It is also, in principle, capable of yielding information on the nature of the irregularities responsible for the scattering of radio waves and, hence, on the dynamics of the lower ionosphere. Installations are relatively expensive and sophisticated.

Wave interaction (cross-modulation, or the Luxemburg effect) is the competing technique to partial reflections in the derivation of electron-density profiles in the *D* region. While the effect was first noted over 35 years ago, the method was refined to the point of obtaining useful quantitative data only in the mid-1950's. Since then, it has been used by several groups, notably in Norway, Greece, and Australia, though not on a systematic, long-term basis. It has recently been developed in a more sophisticated style than before by a group at The Pennsylvania State University, and observations are currently being carried out there. The technique is based on a train of "wanted" pulses reflected from the *E* or *F* region; as the pulses pass through the *D* region, alternate pulses are intercepted by "disturbing" pulses, thus imposing a cross-modulation on the wanted pulse train. To obtain the electron density it is necessary to know not only the electron-collision frequency but also the rate at which the heated electrons lose their excess energy through collisions. High-power installations are generally required.

Electron-density irregularities in the *D* region are probably responsible for the scattering of radio waves in the high-frequency (hf) and very-high-frequency (vhf) bands at oblique incidence as well, and this forward-scatter technique has been employed in the United States and Canada, chiefly for the study of particle-precipitation effects. It has been used successfully to arrive at the energy spectra of precipitating protons and electrons and, in polar regions, forms a complementary system to riometers. This technique originated as a by-product of the development of vhf ionospheric communications but is now operated as an ionospheric research tool in its own right.

As mentioned earlier, the lower ionosphere is primarily responsible for the propagation of low-frequency (lf) and very-low-frequency (vlf) radio waves, and a great deal of useful information ought to be obtainable through studies of these phenomena. Much of the data that have been obtained have come from long-distance propagation paths where the propagation takes place in the earth-ionosphere waveguide, and, as a consequence, little has been produced in the way of physically useful information. A large quantity of data on short-path propagation characteristics was obtained in England from the late 1940's to the early 1960's. When full-wave treatments of the propagation problem became available, this information was used to produce "average" profiles of electron density for different conditions. The use of pulsed lf signals from radio-navigational transmitters has also been employed in the United States in recent years to obtain information on variations in the lower ionosphere.

Motions of ionospheric irregularities and atmospheric winds below 100 km are observed using several ground-based radio-probing techniques. The two most important are the radio-meteor technique in the region 75 to 105 km and the spaced-antenna or multiple-receiver technique for the 80- to 120-km altitude range. The former method may be assumed to measure the motion of the neutral atmosphere, whereas the second method measures the drift of ionospheric irregularities by monitoring the ionospherically reflected diffraction pattern at a series of stations on the ground.

Incoherent scatter, a very powerful technique above an altitude of 100 km, yields useful information with only moderate time-altitude resolution at heights below 100 km. At present the method does not work at all at heights below 85 km.

Of the various ground-based techniques for probing the lower ionosphere, only two have proved capable of yielding information on the electron-density profile on a systematic basis. These are the partial-reflection technique and the cross-modulation technique. The problem of data handling in the case of the former is sufficiently tractable that its use as a synoptic tool for the long-term study of the lower ionosphere is quite feasible. For detection of abnormal events, the riometer technique in particular has proved to be a simple and relatively inexpensive monitor of solar-flare effects and particle-precipitation phenomena.

It is difficult to specify the accuracy of radio measurements of electron density below 100 km at a given point at a given time. Few simultaneous comparisons of techniques are available, and the ones that do exist do not lead to confidence: factor-of-two discrepancies are normal for heights below 90 km. On the other hand, long-wave [extremely low-frequency (elf), vlf, lf] are economical, particularly sensitive to changes in electron-density distribution, and widely used for monitoring purposes in connection with *D*-region disturbances. There is no adequate way, as yet, of obtaining sufficiently reliable electron-density profiles from ground-based observational data.

SHAPE OF FUTURE PROGRAM

Electron-Density Profiles

The radio rocket method for measuring profiles of electron density appears to be quite successful down to ~ 70 km. It is claimed to have the highest accuracy and the greatest height resolution of all available methods. In addition, rockets can measure other aeronomically vital parameters, such as ion density, below 100 km. Rockets have the disadvantage, however, that acquisition of every new profile uses up another rocket. It is therefore important to make ground-based techniques produce believable profiles of electron density, so that the variation in solar control of ionization below 100 km may be studied continuously. Perfection of the ground-based methods is important, even if their ultimate accuracy and height resolution are inferior to those of rockets. There is a need, therefore, to carry out ground-based partial reflection and cross-modulation measurements at a site where radio-rocket soundings can be made simultaneously. The three techniques should be studied and developed until they can routinely reproduce the same profiles at the same time, although not necessarily with the same accuracy and resolution. In all probability, the ground-based methods will require greatest improvement.

In selecting a site where the partial-reflection, cross-modulation, and rocket techniques may be used simultaneously, there is much to be said for using a site where lower-atmosphere studies are already in progress or where investigations of the ionosphere above 100 km are being developed in a major way. A possible location would be the observatory dedicated to incoherent-scatter studies proposed in Chapter 6. However, this facility does not necessarily require rocket-launching capability. If an auroral-zone rocket range were chosen to develop the partial-reflection and cross-modulation techniques, a third ground-based technique, the multifrequency riometer, could be used at the same time.

Air Motions

The above statements on electron-density profiles can largely be extended to the study of air motions. Below 100 km, there are two ground-based radio methods for studying air motions--the multiple receiver and the radar meteor--and four rocket or gun-probe methods--chemical release, radar chaff, inflatable falling sphere, and grenade. It is important to establish unequivocally whether one or both of the ground-based methods can reliably measure air motions at elevations approaching 100 km. Both the radio methods and all the rocket and gun methods should therefore be installed and developed together.

There are good reasons why the site chosen should be the same as that used for improving techniques of observing electron-density profiles. However, for air motions, an auroral-zone site would have no striking advantage, and a rocket range used for lower-atmosphere study might well be a more appropriate location.

Monitoring Techniques

There are other ground-based radio techniques which, although scarcely capable of providing detailed profiles, nevertheless contribute in a major way to detecting and monitoring solar-terrestrial phenomena involving the ionosphere below 100 km. These methods (elf, vlf, lf, and hf reflection, ionosonde absorption, hf phase-path measurements, single-frequency riometers, and vhf forward scatter) should continue to be exploited.

RECOMMENDATIONS

1. Noting the need to find a ground-based system sufficiently reliable for continuous probing of the lower ionosphere, and noting the apparent lack of agreement concerning electron-density profiles derived by the partial-reflection sounding method, the cross-modulation method, and the radio rocket method, we *recommend* that all three techniques be operated simultaneously at the same site for the purpose of reaching a condition in which the electron-density profiles obtained by all methods are in substantial agreement.

2. Noting the importance of understanding the dynamics of the atmosphere, and recognizing the need to select the best techniques for continuous probing of the wind field in the lower ionosphere, we *recommend* that both the radio-drift method and the radar-meteor method be compared at the same location with rocket or gun methods, such as those involving chemical releases, radar chaff, inflatable falling sphere, and grenades.

3. We *recommend* that the current program for monitoring and detecting solar-terrestrial events be continued at roughly present levels of support, and that each of the following techniques should have a place in the program: steep and oblique incidence at extremely low frequency, very low frequency, low frequency, and middle frequency; ionosonde absorption; phase path at high frequency; riometers; and very-high-frequency forward scatter.

8 Optical Aeronomy

The past decade has witnessed major advances in our knowledge of the airglow and the aurora and in our techniques for studying them. Prior to 1960, airglow observations had been carried out only during the night and twilight. Since the reactions responsible for exciting nightglow emissions are complex and are still poorly understood, study of nightglow beyond a certain point had yielded meager significant information. The development of techniques for observing the day airglow (dayglow), on the other hand, opened new vistas to the atmospheric sciences. A host of optical emission features have by now been studied in the daytime upper atmosphere by sophisticated ground-based sensors and by detectors carried on sounding rockets and satellites above the scattering and absorbing atmosphere. Excitation of spectral features of the dayglow in almost all cases is a result of a fairly direct coupling between solar radiation and the atmosphere. Hence analysis of the dayglow by straightforward methods has been fruitful and has told us much about the distribution of major and minor atmospheric species as well as about the conditions created in the atmosphere as a result of the absorption of solar energy. The distributions of such atmospheric constituents as Na, NO, H, O, N_2^+, O^+, and He^+ have been determined by observations of resonantly scattered sunlight. Infrared radiation from O_2 excited to the $^1\Delta$ state in the photolysis of O_3 has yielded information on the abundance of ozone and on the potentially important minor atmospheric species O_2 ($^1\Delta$). Other airglow features, such as the various forbidden and allowed lines of atomic oxygen, have been interpreted in terms of secondary processes involved in the absorption of solar energy. Among these processes are the scattering of fast photoelectrons by atoms and the recombination of electrons and molecular ions.

Dayglow studies such as these have produced major advances in our understanding of the photochemistry of the neutral and ionized atmosphere, the processes involved in converting solar energy to heat, the escape of gases from the atmosphere, and evolution of the atmosphere.

Most investigations of the aurora prior to the International Geophysical Year (IGY) and the International Years of the Quiet Sun (IQSY) were descriptive and of a statistical nature. This early work established the height ranges, statistical distribution, and many spectral characteristics of the aurora. Although the association of auroras with magnetic storms was recognized long ago, the detailed connection between auroras and storm magnetic variations was not fully realized until just before the IGY. A major success of the IGY and IQSY optical and magnetic observing programs was the identification of the interrelated auroral and magnetic substorms, a development having considerable impact on our concept of magnetosphere dynamics. The advent of rockets and satellites and the advance in ground-based spectroscopic and photometric observations have made it possible to obtain detailed information about the characteristics of auroral primary particles. Such measurements have shown important differences between proton and electron bombardment. The new capability to examine the spatial structure of emissions within auroral forms now gives greater hope of learning about the effects of secondary excitation and energy deposition in the upper atmosphere. Our recently acquired ability to produce artificial auroras with controlled particle beams promises further knowledge of the processes involved in the production of auroras. The new observational data, combined with other studies of the magnetosphere and the instability theory in plasma physics, allow theoretical work on the auroral phenomenon that is much less speculative and far more deductive than at any time in the past.

AVAILABLE TECHNIQUES

Techniques available for ground-based observations of auroras and airglow are summarized in this section, with emphasis on their particular capabilities and limitations. A characteristic common to all these methods is that they must take full advantage of optimized techniques in order to overcome the limitations imposed by the need to see through the earth's murky lower atmosphere.

Airglow Spectrophotometry

When optimizing spectrometric measurements, the need for high spectral resolution must be balanced against the need for high light-gathering power (LGP); the optimal choice will depend on the brightness of the emission, the sensitivity of detection apparatus, and the strength of the unwanted background spectrum which must be rejected by one means or another. Ground-based dayglow studies must always sacrifice LGP in favor of high resolution, and full advantage must be taken of polarization, i.e., of any naturally occurring difference between the wanted and unwanted components of the sky spectrum. At twilight the need to discriminate against the background is not so important. In daytime, over a wavelength interval comparable to the line width, the background is several orders of magnitude stronger than a typical emission line. Much interesting physics is associated with the first half hour after sunset (i.e., the 6300-A emission from O_2 photodissociation), and every effort should be made to push the observations as close to sunset as possible. Interferometric measurement at 0.1-A resolution or better is a necessary requirement. The requirements for nightglow investigation are primarily high resolution and high LGP; fast time resolution is usually not necessary.

Auroral Spectrophotometry

Unlike the airglow which is the result of widespread, slowly changing conditions in the upper atmosphere and magnetosphere, the aurora is a phenomenon that changes rapidly, both spatially and temporally. Moreover, the emissions from various atmospheric species of aurora cover a very large range of intensities. Auroral spectrophotometric investigations are in three classes: spectroscopic morphology, low-resolution spectrophotometry, and high-resolution spectrophotometry.

In spectroscopic morphology, the primary requirement is high spatial and temporal resolution. The narrow-band, sky-scanning filter photometer is the primary instrument used in such investigations and is most useful when triangulation measurements are made at two or more stations located on the same geomagnetic meridian.

In low-resolution spectrophotometry, a satisfactory compromise is achieved between spectral resolution, spectral range, and temporal resolution. Light-gathering power and spatial resolution are secondary in importance although still important. The choice of instruments is primarily controlled by the compromise between the spectral range and LGP that the investigated phenomenon requires. Among the topics that can be investigated by this technique are vibrational and rotational temperature of molecular emissions and the Doppler profile of auroral hydrogen emission.

The only adequate instrument for high-resolution spectrophotometry is the Fabry-Perot interferometer, which has a spectral resolution of approximately 0.01 A. The Doppler profiles of the 6300-A and 5577-A lines of atomic oxygen obtained by this technique give neutral temperatures over the height range 100 to 400 km and may provide information on neutral winds over this range of altitude.

Imaging Techniques

Before the IGY, visual observations and normal-field photography were the main sources of data on the structural morphology of aurora. Since the IGY, the all-sky camera has been a mainstay for synoptic work and for specialized studies requiring information on gross structural morphology. Recently, the availability of fast black-and-white and color films has increased the usefulness of direct photography, but the method still suffers from a lack in temporal resolution. Within the past few years, image orthicon television and image intensifiers have become particularly useful because of their high sensitivity and imaging capability. It is possible now to record the complex, detailed structure and motion in auroras and to obtain high time-resolution spectra of auroras and nightglow. The ability to convert an optical image into an electrical signal makes television instrumentation potentially useful on spacecraft vehicles as well.

Advantages and Limitations of Ground-Based Optical Observations

The earth's surface is a large, stable base for aeronomical observations. The size and power consumption of the instrumentation employed are not inherent constraints as they are on moving platforms. Compared with observations made from moving platforms (aircraft, balloons, rockets, and satellites), ground-based observations have several obvious advantages: economy, continuity of observations, potential for short elapsed time between initial concept and final research result, and freedom from the complexity due to integrating experiments into research vehicles. For these reasons, ground-based observations are attractive to the individual scientist or small university research group and are ideal for the training of graduate students.

The major limitation to ground-based optical observations is the fact that each observation gives the total emission and absorption integrated from the observing instrument along the line of sight to infinity. Absorption in the atmosphere limits observations to wavelengths greater than 3000 A, and thermal emission from the lower atmosphere prevents useful measurements at wavelengths longer than 2.5 µm. Scattering in the lower atmosphere is a serious problem to ground-based dayglow observations; both absorption and scattering affect twilight and night airglow observation but are a lesser problem to ground-based auroral observations. A more serious hindrance to auroral studies, especially to synoptic observations, is cloud cover.

Aircraft and Balloons

These auxiliary platforms have specific features which complement measurements made at ground level. Jet aircraft permit observations above much of the obscuring lower atmosphere and allow great mobility. In recent years, aircraft have been used successfully for optical studies of eclipses, latitude dependence of airglow, conjugate aurora, polar-cap emissions, and constant-local-time flights in the auroral zone. The important features are the great mobility of aircraft combined with the significantly reduced absorption at altitude, particularly in the infrared. Balloons, through their ability to perform measurements to 40 km and above, permit observations in the infrared and detection of high-energy-particle fluxes through x-ray measurements.

RELATION OF TECHNIQUES TO PHYSICAL PHENOMENA

The physics of the principal emissions, current knowledge about their excitation processes, and the ways in which optical techniques have been used to study them, are summarized in this section.

Luminescent mechanisms are the various paths by which solar energy is deposited in the earth's atmosphere. For example, auroral emissions can be thought of as the deposition of energy by high-energy particles in which collisional excitation dominates. Any deposition, whether by particles or by light, can produce unstable species which may themselves react and produce additional luminescence. These chemiluminescent reactions are predominant in the airglow; they may, in certain cases, prove to be significant in the aurora. A less direct manifestation of energy deposition involves emission via resonance fluorescence; here, the optical emission is used as a probe to measure directly the concentration of minor species such as Na or N_2^+, or sometimes even major species as in the case of the atmospheric O_2 bands in the dayglow.

Low-energy impact excitation, particularly by electrons, is important in the dayglow where the photoelectron energy spectrum extends up to ~ 100 eV. There are also interesting effects, particularly in production of the 6300-A oxygen line, due to even lower-energy quasi-thermal or "hot" electrons; in the ionosphere, the electron "temperature" often exceeds the neutral temperature by a factor of 2 or more.

The physics behind some of the prominent emissions is reviewed below, organized into several height ranges which are, in certain ways, physically distinct.

20 to 70 Kilometers

The direct effect of particle precipitation is almost always negligible up to ~ 70 km in comparison with the effects of solar photons and dynamical transport. The outstanding emission feature is the infrared system of O_2 (1.27 and 1.50 µm--the 0.0 and 0.1 bands) in the dayglow and early twilight. Despite certain contradictory laboratory evidence it is difficult to find any other source for O_2 $(^1\Delta)$ than the uv photolysis of ozone. The laboratory quenching rates are such that they require essentially unit quantum efficiency for the production of O_2 $(^1\Delta)$ if the observed intensity is to be explained. Because of quenching, the large integrated emission intensity in the dayglow reflects the ozone density from ~ 40 km upward; only at twilight does the bulk of the emission come from above 70 km.

70 to 100 Kilometers

The major emissions that can be seen from the ground in this height range are OH, $O_2(^1\Delta)$ in the twilight and presumably in the nightglow, nightglow OI 5577 A, and the alkali metal in the dayglow, twilight, and nightglow. It is here also that noctilucent clouds and meteor trails are visible. At present, the quality of observations in most cases exceeds the quality of interpretation. Although good intensity measurements and, where appropriate, measurements of the rotational temperature can be made, the proper physical interpretation of the measurements is difficult. The production of OH is so bound up with the water-vapor chemistry that use of OH emission as a tool requires a much better understanding of the chemical and transport processes affecting the water vapor. O_2 ($^1\Delta$) at twilight is mainly an afterglow from the daytime and, as such, reflects the ozone concentration near 70 km just before sunset. The 1.27-μm band has been detected in the aurora very recently, and the intensity of the band has raised what may turn out to be considerable problems: in at least some cases it cannot be explained, in terms of energy accounted for, by electron precipitation as determined from the intensity of the N_2^+ bands. In some auroras all the airglow emissions mentioned, as well as other impact-excited radiations such as the N_2^+ first negative and the N_2 first positive bands, can be excited. During polar-cap absorption (PCA) events some radiation is produced throughout this height range.

Nightglow 5577 A is another case in which data far exceed understanding. Once again the theoretical interpretation (including dynamical effects) is deficient. Remarkable fluctuations in the Doppler temperature of 5577 A are known to exist along with intensity variations of the nightglow; the problem is how best to use such observations to elucidate the physics of the 90- to 100-km region at night.

The alkali metal emissions have been studied exhaustively at twilight and at a few locations in the dayglow. We know that at twilight the intensity of the emission gives a direct indication of abundance of the metal and some information on its distribution with height; the abundances that have been measured to date are not understood. Large diurnal and seasonal variations introduce additional complexities. At nighttime the situation is even more difficult; while the excitation is presumably chemiluminescent in origin, we know next to nothing about the relationship of nightglow intensity and its fluctuations to the *D* lines.

The nightglow continuum originates at ~ 90 km; we know it is there from both rocket and ground-based observations, but it is another feature, of strong total intensity, about which we can say little at present.

100 to 150 Kilometers

Few airglow features observable from the ground are excited in this range. Rocket studies reveal many dayglow features produced in the 100- to 150-km range by solar radiation, photoelectron excitation, and ionic reactions, but they are not yet accessible to the ground-based observer. On the other hand, almost all auroral excitation normally occurs at these altitudes: the OI 5577 A, 7774 A, and 8446 A lines; band systems of N_2, O_2, N_2^+, and O_2^+; O II and N II lines; and the Balmer lines of hydrogen are excited by primary and secondary auroral elections and by precipitating protons. The N_2^+ emission rate provides a convenient remote measurement of primary particle energy flux. Analysis of the other emission features is now providing valuable information on physical conditions in the region of the auroral energy sink where the electrojet current flows.

150 to 600 Kilometers

Many emissions produced in the 150- to 600-km range are closely coupled to ionospheric processes. In the nightglow, the 6300-A oxygen doublet and a minor portion of the 5577-A line originate in this region apparently as a result of ion recombinations. So also does the emission from $N(^2D)$ at 5200 A. In auroras and midlatitude red arcs these same emission features can be observed emanating from this region, although in those cases the predominant excitation processes probably involve scattering of hot electrons.

In early twilight, the 6300-A doublet, and possibly the 5577-A line as well, is greatly enhanced as a result of O_2 photolysis in the 150- to 250-km range. Resonant scattering of the (0,0) first negative band of N_2^+ during twilight, allows us to measure the concentration of this minor ion in the 50- to 600-km region and above.

Above 600 Kilometers

Fluorescent scattering from helium and hydrogen producing the He I 1.05-μm line and HI Balmer α allows ground-based monitoring of exospheric densities in this region. Studies of these emissions show great promise of elucidating the processes by which gases escape from the atmosphere.

RELATION OF GROUND-BASED OPTICAL STUDIES TO SPACE RESEARCH

The aim of solar-terrestrial physics is to understand the origin and transport of energy from the sun and its final disposition in the earth's atmosphere. Space vehicles study the problem through the magnetosphere to the thermosphere. The ground-based optical program has the special and complementary task of illuminating the complex paths through which solar energy is degraded into atmospheric kinetic energy. Its goal is to attain that degree of precision and sophistication which allows us to follow upper-atmosphere and magnetospheric processes in detail and continuously in time. Examples of this complementary role are: the optical auroral substorm, as a manifestation of magnetospheric ordering, and the airglow red arc, which gives direct evidence of plasma heating in the magnetosphere.

Ground-based optical studies of auroral morphology led in large part to the concepts of magnetospheric convection and the magnetospheric substorm. These concepts, one theoretical and the other empirical, are influencing the interpretation of satellite data and the design of satellite and probe experiments. A direct result is the great current interest in *E*-probe and barium-probe vapor-release techniques. At the same time the importance of understanding the plasma dynamics of the magnetosphere is stimulating further theoretical and laboratory investigation.

The dramatic enhancement of the OI 6300-A line (the red arc) on an apparently global scale, first detected in ground-based programs, is almost certainly the result of heating of ambient *F*-region electrons by conduction downward from the magnetosphere along magnetic shells. In contrast with "normal" areas at high latitude there is here a coupling of airglow emission to the magnetosphere by way of plasma heat conduction alone.

DIRECTIONS OF RESEARCH

Approach to the Observational Problem

Firm knowledge of the physics and chemistry of the upper atmosphere is emerging from ground-based, space, and theoretical research. We are on the threshold of understanding, in terms of elementary physical principles, the remarkable phenomena exhibited in this region of the atmosphere. Ground-based optical techniques can now be used to study fairly fundamental questions in aeronomical physics. But, to do so, we require increased sophistication in the design of instrumentation and a closer alliance with laboratory and theoretical studies, with space experiments, and with other ground-based techniques. The days of random amassing of observational data are now, to a large degree, past. While routine observations still have their place, such effort may be completely wasted if no clear rationale is followed. They require, moreover, careful optimization of spectral resolution, precision of measurement, and the ability to resolve in time.

The general justification for continued and expanding support of optical aeronomy is its development into an exact science. Projects directed toward specific scientific questions are increasingly important, however, and warrant major support. Some of the most promising areas in which work might be concentrated are the following.

AURORA

The central problem in auroral physics is what sorts (species and energy spectrum) of particles precipitate and why they precipitate when and where they do. Optical measurements tell us when and where, and, with proper interpretation, these measurements can tell us a great deal about the types of particles and their energy spectrum. The great advantage of ground-based measurements is the ability to study in detail the variation in time of a number of interrelated emission features. The absolute and relative intensities, the Doppler width of lines, the rotational temperature of bands--these features all give important clues to the physical processes taking place. With a net of several stations, including pairs at opposite ends of a field line, we can examine the precipitation pattern in space and time. Satellites can give some sort of global picture, and rockets provide accurate height profiles and measurements of other quantities of interest, such as energetic particle spectra and ion densities. But they cannot follow the rapid magnetospheric instabilities in the way that ground-based measurements, at their best, can do.

AIRGLOW

The purpose of studying airglow is to understand the effects of solar electromagnetic radiation on the upper atmosphere, including large-scale dynamical movements in which tracer species, like the alkali metals or atomic oxygen, reflect the transport. In the past, considerable effort has gone into monitoring a few airglow emission features using broadband filters, and the data accumulated are large enough that there seems no pressing need merely to obtain more. Most important now is to understand thoroughly the physical processes giving rise to the airglow, and particularly nightglow, features. This is most likely to be accomplished by emphasizing laboratory studies in chemiluminescent reactions and the nascent interest in the interaction of dynamics and chemistry in the upper atmosphere.

Some nightglow emission features can now be quantitatively interpreted [e.g., OI (6300 A) from ionic recombination in the *F* region], but others [e.g., OI (5577 A)] remain quantitatively uncertain. The dayglow spectrum is only in small part the result of chemical reactions; it is primarily produced by resonant scattering of sunlight and excitation by photoelectrons. Thus, in the future, nightglow studies (quiet condition) should be directed toward understanding dynamical motions through their effects on chemistry. Dayglow, on the other hand, will be useful either for measuring minor species through resonant scattering or in following the path by which solar energy is degraded into the kinetic energy that ultimately drives the motions. A mixture naturally occurs at twilight. For example, the 6300-A oxygen line may be used to (a) deduce the O_2/N_2 ratio up to ~ 250 km; (b) measure, or set a limit on, conjugate photoelectrons; (c) follow the decay and movements of *F*-region ionization; and (d) detect magnetospheric and subsequent *F*-region plasma heating in the red arc.

REQUIRED PROGRAMS

Laboratory Programs

The recent surge in laboratory studies of ion-molecule reactions suggests that the importance of aeronomically related laboratory work is finally being widely recognized. There are other areas of laboratory measurements that require comparable expansion. Cross-section study of metastable production of electron impacts is one such area; quenching of excited states, again metastables in particular, is another. The reactions that produce most of the nightglow emissions are still far from adequately identified, for example, the specific reaction rates for the processes that yield excited states in atomic and molecular oxygen, OH, sodium, and to a lesser extent N_2 and the continuum sources that might contribute to the nightglow. The dependence of the rate constants on temperature and the states of the reactants may be large and significant. For the auroral radiations, knowledge is needed of excitation cross sections for electron impact, particularly near threshold, for dissociative processes, and for excitation from metastable states, as well as cross sections for proton and hydrogen-atom collisions, both charge-exchange and direct. Theoretical and experimental investigation of dynamical processes should be pursued in complement with this work.

Reaction rates of metastables are beginning to become available, but knowledge of the products of the reactions is still limited and badly needed. Whether the result of the collision is deactivation or reaction and what are the final states of the products must be determined. For example, we can ask whether the collision of $N(^2D)$ with O_2 produces NO or merely ground-state N, or whether the quenching of $O(^1D)$ by N_2 results in vibrational excitation of nitrogen.

For ionic recombination processes we need to know the branching ratios of O_2^+ and NO^+ recombination into $O(^1D)$, $O(^1S)$, and $N(^2D)$ terms and the dependence of these rates on electron and ion temperature as well as ionic excitation.

Many of the techniques for laboratory work in aeronomy now exist, including methods for detecting very weak optical emissions and intermediate active species, such as atomic oxygen. High-intensity ultraviolet light sources--possibly synchrotron radiation--will be required, however, if we are to simulate conditions in the upper atmosphere.

Single-Station Observations

Although high-latitude auroral programs often require a network of stations (e.g., for height triangulation and study of morphology), the need for single stations will remain, particularly for midlatitude and low-latitude studies of airglow. In such cases, a few well-equipped and well-manned stations, with the capability of making special investigations, are far more likely to produce useful physics than a large number of field sites performing routine monitoring. Most important advances will be made only with equipment optimized to study the particular problems in question, working at full efficiency, and operated by specialists able to respond to what emerges by virtue of their understanding of the physical processes involved. Each program must be directed toward a certain physical problem that is best attacked by a certain instrument used in a certain way at a certain time--with a full awareness of the limitations of ground-level measurements and the need, if any, for augmentation by other types of observation. A search for periodic fluctuation in airglow emission at the few percent level is an appropriate example of single-station work that has not received adequate attention.

Multiple-Station Observations

In contrast with the IGY and IQSY during which there was emphasis on large station networks for synoptic studies, the current trend is toward the application of smaller networks or closely spaced station groups to specialized problems. The need for multiple stations may be more acute in optical aeronomy than in related areas, because optical observations typically are highly directional in space. An example is the productive technique using station pairs equipped with narrow-field scanning photometers to determine height-luminosity profiles in auroras. A latitudinal array of all-sky cameras and magnetometers is now being established in western Canada to study latitudinal variations in auroras and related phenomena. A crossed latitudinal and meridional array exists in Alaska for the same purpose and for use in learning more about the local-time effects and dynamical characteristics of auroral substorms. Temporary or permanent groupings of three or four optical stations on baselines of the order of 100 km are frequently used as the prime data source for those studies of atmospheric, ionospheric, and magnetospheric dynamics that utilize rocket-borne injections of sodium vapor, trimethyl aluminum, barium, or energetic electrons and ions.

Conjugate Studies

Pairs of stations and of aircraft equipped with optical instrumentation appear to be the most promising methods with which to study auroral conjugacy. Imaging instruments with a time resolution of 0.02 sec are now available to contribute to the important question of the locations and nature of the mechanisms by which auroral primary radiation is accelerated in the magnetosphere. Current and future studies are expected to delineate the distortion in the outer magnetosphere caused by magnetospheric boundary currents, body currents, and tail currents.

Aircraft and Balloons

We anticipate that jet aircraft will be of growing value through their ability to make measurements at remote and inaccessible areas where important geophysical activity takes place. The future value of balloons for optical work will doubtless lie in extending our knowledge of the airglow and auroral spectrum much further into the infrared; our present knowledge is almost nonexistent beyond a few microns.

Induced Phenomena

The development of sophisticated ground-based optical instrumentation and the proven ability to generate known energetic-particle beams with rocket-borne accelerators now makes it possible to use the upper atmosphere as a controlled laboratory. Future studies should contribute to our understanding of magnetic-field configurations, plasma physics, and interactions of particles with atmospheric gases. There is also the potential for modification of ionosphere-magnetosphere coupling through injection of large quantities of particles or chemicals as another method for studying these and other ongoing processes.

Artificial airglow caused by the man-made release of a wide variety of chemical species in the upper atmosphere is now a well-established technique in aeronomy. The barium experiments are particularly exciting because they provide a new means for studying photochemical reactions in the upper atmosphere and are a tool to explore high altitude neutral-wind motions and the electric field in the ionosphere and magnetosphere. This method, which relies heavily on ground-based optical observations, is expected to contribute much to our understanding of dynamical convection in the magnetosphere. An important need in this area, particularly for wind measurements, is to extend observations into the daytime. Observations on meteor trains may appropriately be mentioned here. The occasional long-enduring train is still one of the best means to measure mesospheric winds.

Integrated Studies

Coordinated studies are a most fruitful area since, in the long run, ground-based optical studies must stand in a complementary relation with such areas as ionospheric and optical solar measurements and rockets and satellite programs. Simultaneous use of optical spectrophotometry and incoherent scatter in and out of auroras should be particularly rewarding. The incoherent-scatter technique provides electron and ion temperatures which may be elevated by conductive heat flow from above, particle fluxes, and electric fields; often it can measure a low-energy electron flux. But knowledge of the temperature may not be sufficient to determine the energy source, and here spectrophotometry can be of great benefit.

It is essential to carry out carefully designed *in situ* measurements with fully instrumented rockets--e.g., those that measure optical emission, charged and neutral composition, electric fields and particle fluxes--fully coordinated with ground observations. The resulting illumination of the physical processes may then permit optimal planning of extended optical studies from the ground. In turn, optical studies will improve as a tool for studying the development of the physical processes in the upper atmosphere. Unfortunately, the value of integrated ground-based and rocket experiments has often been decreased by the difficulties created from the involvement of several agencies, each responsible for different aspects of the experiment. Increased scientific effectiveness could thus be gained by better cooperation among agencies.

COSTS AND MANPOWER

Since World War II there has been a healthy interest in optical aeronomy among physicists and astronomers in many countries. Provided that financial support and facilities are adequate, no shortage in quantity or quality of research expertise is anticipated.

In the past, optical aeronomy has received support from a number of agencies; but the most important continuing source of support has been the National Science Foundation. Decreased funding in this area could easily have the effect of stopping completely, and perhaps irreversibly, an important and stimulating area of geophysical research. Generally speaking, budgets in this area are modest. In fact, this area of research is an example of high scientific output for relatively small expenditure.

The atmosphere as a physical-chemical laboratory is a concept that has great appeal. The special techniques required are those of the physical chemist; and although in general we should not expect more than a temporary interest from people with the necessary skills, opportunities for this type of research should be made better known to chemists. It is also important that sources funding geophysical research provide additional support for laboratory experiments in this area.

In the realm of large facilities, the integration of optical aeronomy with incoherent scatter provides outstanding opportunities. It is of great importance that the major existing facilities (Arecibo, Jicamarca, and Millstone Hill) be available for aeronomic work. It is also highly desirable to have an incoherent-scatter facility in the auroral zone.

The construction of high-energy x-ray sources such as synchrotrons would not be justifiable for optical aeronomy alone, but it is important that access to existing facilities be provided to scientists working in aeronomy.

RECOMMENDATIONS

1. There is an urgent requirement for additional studies of certain reaction rates associated with the emission of optical radiation from the upper atmosphere. We *recommend* a substantial increase in funding for laboratory aeronomic work, accompanied by an effort to bring the relevant problems to the attention of research workers not at present involved.

2. There is insufficient effort to integrate ground-based and rocket research in optical aeronomy. This is possibly due to the fact that the principal responsibility for the two areas has been undertaken by different agencies. We *recommend* that federal agencies seek means to support integrated research programs through a single source of funding.

3. Important advances can be anticipated from optical observations performed in combination with incoherent-scatter measurements. The uncertain funding situations at Jicamarca, Peru, and Millstone Hill, Massachusetts, are therefore a matter of serious concern. We are, however, encouraged by the exciting possibilities opened up by the proposal to relocate the Stanford Research Institute facility at Palo Alto to the auroral zone, at College, Alaska. We *recommend* that this relocation be adequately supported by the appropriate agencies, and that the installation be improved as funding permits, and in the direction indicated by exploratory investigations.

We *further recommend* that, at a later date, the construction of a second auroral facility be considered at a higher geomagnetic latitude for operation in conjunction with optical observations.

4. Optical aeronomy is a good example of a subject with high scientific output at relatively low cost which is particularly suited to graduate school programs. The present period is one of increasing sophistication in experimental methods and the development of new ideas about the physics of the upper atmosphere. We therefore anticipate an upswing of activity in aeronomy in general and optical observations in particular. We *recommend* that the relevant federal agencies reflect this growth potential in their support of aeronomic research.