

Advancing Our Understanding of the Atmosphere and Ionosphere Using Remote Sensing Techniques

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Many human activities affect or are affected by physical and chemical processes occurring in the Earth's atmosphere, ionosphere, and near-Earth space environment. In this article, we review a wide range of remote sensing research activities being carried out within the APL Space Department that have provided a better understanding of these processes. The research, conducted from both the ground and satellites, includes techniques employing optical remote, radar remote, and particle remote sensing. We concentrate on the scientific accomplishments of these efforts with particular emphasis on contributions to atmospheric, ionospheric, and magnetospheric research. (Keywords: Atmosphere, Ionosphere, Magnetosphere, Remote sensing.)

INTRODUCTION

Merle Tuve, the first Director of APL, was noted for his contributions to the discovery of the ionosphere—the outermost region of the Earth's atmosphere where gases become increasingly ionized—as well as for his development of the pulsed-echo technique that eventually led to the development of radar.¹ His pioneering work in ionospheric research with remote sensing techniques is still being built upon within the Atmospheric and Ionospheric Remote Sensing Group of the APL Space Department. We would like to believe that Dr. Tuve would be interested in this ongoing work as well as associated work on the physics and chemistry of the upper atmosphere and near-Earth space. Much of the current ionospheric research uses radars and has evolved from Tuve's pioneering efforts.

In addition, the space age has enabled data to be obtained with optical instrumentation and energetic particle detectors carried on spacecraft. The research extends to all levels of the Earth's atmosphere (troposphere, stratosphere, mesosphere, thermosphere, and exosphere) and throughout the ionosphere. These atmospheric layers cover an altitude range extending from just above the Earth's surface to ≈ 1500 km.

Prior to the 1980s, space research at APL had largely been confined to *in situ* measurements of energetic particles and magnetic fields in the upper reaches of the Earth's ionosphere and in near-Earth space. Since then, it has broadened considerably. Laboratory scientists and engineers have developed instruments that have been flown on spacecraft to study the Earth's magnetosphere,

interplanetary space, and remote planetary bodies (see the article by Williams et al., this issue). They have also used optical and radar remote sensing techniques to study the Earth's ionosphere and atmosphere, both from space and from the ground.

Substantial research efforts directed toward the high-latitude ionosphere and atmosphere using remote sensing instrumentation began in the early 1980s with the development of ultraviolet (UV) and visible-light auroral imagers for the Defense Nuclear Agency's HILAT and Polar BEAR satellites (see the article by Paxton and Meng, this issue) and high-frequency (HF) radars operating in Alaska and Canada. Both of these activities have expanded over the years. Additional opportunities for optical remote sensing became available through the Strategic Defense and Ballistic Missile Defense Initiatives, where knowledge of natural emission levels in near-Earth space at UV, visible, and infrared wavelengths was required. Space Department radar research of the ionosphere has spawned an internationally funded network of radars, known as SuperDARN, that is finding increased application as a monitor of weather in our near-Earth space environment. The different optical instruments have been described in earlier issues of the *Digest*^{2,3} and are also summarized in this issue by Paxton and Meng. In what follows, we highlight some of the research activities that have resulted from the use of this instrumentation. We also describe several *in situ* research activities based upon energetic particle measurements from polar-orbiting satellites.

ATMOSPHERIC RESEARCH

The Troposphere/Stratosphere

One primary thrust area of atmospheric research within the Space Department has been the dual issues of tropospheric and stratospheric ozone (O_3). Human activity over the past two centuries has led to dramatic changes in our Earth's atmosphere.⁴ Two of the most important global-change issues are the production of photochemically active pollution in the troposphere (the lowest layer of the atmosphere extending from the ground up to about 10 to 16 km) and the catalytic destruction of ozone higher up in the stratosphere (the layer extending from 10 to 16 km up to about 50 to 60 km above the Earth's surface).

Ozone is a tropospheric pollutant that causes respiratory distress and eye irritation. The government has imposed severe restrictions on driving and other pollution-generating activities to attempt to minimize the photochemical production of ozone in major cities. Ozone in the stratosphere, however, provides a thin but crucial umbrella that protects human life on Earth from the Sun's harmful UV radiation. Without this shield,

life as we know it would be impossible. Human activity has disturbed the Earth's natural ozone balance in the worst possible manner. It has depleted ozone in that region of the atmosphere where it is most important, as can be seen in the annual declines of stratospheric ozone in the polar regions—notably the Antarctic “ozone hole”—and increased it in the troposphere where it is most harmful.

These two ozone issues result from two highly reactive chemicals: the hydroxyl radical, OH, and nitrogen dioxide, NO_2 . The former is primarily formed by the interaction of UV radiation with ozone, followed by a chemical reaction with water vapor. The troposphere is rather like a slowly burning flame, in which hydrocarbons (natural gas, propane, butane, gasoline, etc.) are oxidized by OH and O_3 to produce carbon dioxide and water vapor, much as they are in combustion, except slower. The reaction of sunlight with ozone to produce OH is the spark that starts the reaction, and OH is the key chemical species throughout the reaction sequence. During this slow combustion process, ozone begins to build up in the troposphere as the by-product of a complex chain reaction. Nitrogen dioxide hangs in a dull reddish-brown haze over many cities in the summertime, and its reaction with sunlight is key to the formation of urban ozone. In contrast, OH and NO_2 molecules in the stratosphere act as catalysts in the destruction of ozone. A catalytic process is one in which a small amount of catalyst facilitates a sequence of chemical reactions, with the catalyst being regenerated at the end of the cycle. Therefore, very small amounts of OH or NO_2 can lead to the loss of comparatively large amounts of ozone in the stratosphere.

The key to understanding the production and loss of O_3 , OH, and NO_2 in the troposphere and stratosphere is a quantitative evaluation of the rate at which UV sunlight reacts with various chemicals. Since most of the atmosphere is relatively inaccessible to experimenters (very few aircraft can fly the heavy equipment required to make the necessary observations), computer models have been developed to calculate the rates of interaction of UV and visible sunlight with ozone and other molecules throughout the atmosphere. The APL Radiative Transfer Model⁵ calculates photolysis rate coefficients called J values, which are then incorporated into larger photochemical models to determine the ultimate impact of human activity on the Earth's atmosphere.^{6,7}

NASA is one of the few organizations in the world that maintains aircraft capable of flying into the lower stratosphere. Their high-altitude ER-2 airplane is a modified U-2 spy plane, outfitted with dozens of experiments designed to make measurements directly within the Earth's “ozone layer.” One of these instruments, called a spectroradiometer, makes direct observations of the intensity of UV and visible sunlight at altitudes of

up to 21 km. Data from this instrument, flown by colleagues at Environment Canada, can be directly compared with the output of the APL Radiative Transfer Model. Figure 1 shows the generally excellent agreement among various ways of determining the rate coefficients for one particular photochemical reaction, $\text{NO}_2 \rightarrow \text{NO} + \text{O}$, where sunlight breaks apart the nitrogen dioxide molecule into a molecule of nitric oxide and an oxygen atom.

A variety of ER-2 field campaigns have taken place over the past decade to investigate the chemical reactions and meteorological conditions which affect the Earth's ozone balance. The first of these, based in Punta Arenas, Chile, in 1987, allowed the ER-2 aircraft to fly directly into the Antarctic ozone layer. This campaign resulted in the first conclusive determination that chlorine released from chlorofluorocarbons was responsible for the dramatic seasonal loss of stratospheric ozone over the South Pole, a phenomenon known as the Antarctic ozone hole.⁸ These results established the causal link between industrial refrigerants and the ozone hole. On this and subsequent NASA field campaigns, APL scientists have provided J values for reactions of interest in the lower stratosphere and upper troposphere along the ER-2 flight track.⁹ Careful comparison between these calculated J values and those inferred from spectroradiometric observations and *in situ* chemical observations has increased confidence in our current understanding of the suite of photochemical reactions that affect the Earth's lower atmosphere.¹⁰

Observations of ozone and other minor constituents with high-altitude aircraft are but one means of understanding the ozone problem. These measurements are inherently short-term and local. Long-term, vertically resolved measurements of the global distribution of O_3 and H_2O in the lower atmosphere are also needed to

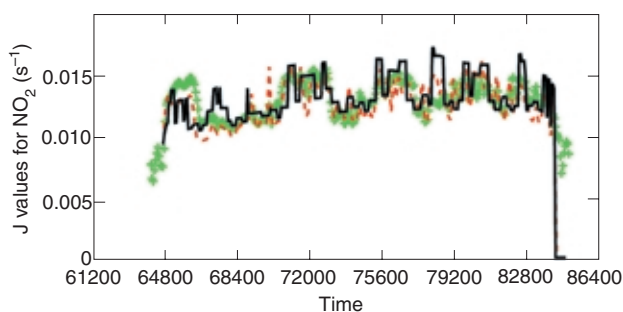


Figure 1. Photolysis rate coefficients (J values) for NO_2 along the ER-2 flight track as a function of solar zenith angle for the 15 September 1997 Polaris flight. Shown are J values from the APL Radiative Transfer Model using surface reflectivity observations from the Total Ozone Monitoring Satellite (black), from the same model using surface reflectivity observations from the onboard Canadian Composition and Photochemical Flux Measurements (CPFM) Experiment spectroradiometer (orange), and as calculated from *in situ* flux measurements made by the CPFM spectroradiometer (green). Time is in seconds of the UT day.

establish trends and to provide input to atmospheric and climatological models. The Earth Observing System, a network of large environmental satellites, is being developed by NASA to enhance our understanding of the lower atmosphere. However, such missions are cost-prohibitive from the standpoint of long-term monitoring. Consequently, NASA is also seeking to develop compact, low-cost instruments capable of making these measurements and flying on a variety of spacecraft platforms. This new approach is an integral element of NASA's research objectives for ozone and climate studies into the 21st Century.

Over the past 2 years, atmospheric scientists at APL have had exciting opportunities to develop new techniques that are likely to be used in NASA's future efforts in atmospheric ozone research. Stellar occultation data obtained with the Ultraviolet and Visible Imagers and Spectrographic Imagers (UVISI) aboard the Midcourse Space Experiment (MSX) have been used to develop advanced techniques for determining ozone profiles throughout the upper troposphere and stratosphere.³

Two types of occultation techniques have been used for decades to determine the composition and structure of the atmospheres of the Earth, other planets, and their satellites. Extinctive occultations occur when atmospheric constituents absorb or scatter incoming stellar radiation. Because extinction cross sections are generally wavelength dependent, spectral measurements obtained as a star sets deeper into the atmosphere are diagnostic of the atmospheric composition (Fig. 2), and constituent profiles may be determined from the relative transmission (i.e., the ratio of occulted to unocculted spectra). As a result, extinctive occultation measurements are self-calibrating and ideal for long-term monitoring of climatic trends. Refractive occultations occur when density gradients in the atmosphere refract the incoming radiation, causing it to follow curved

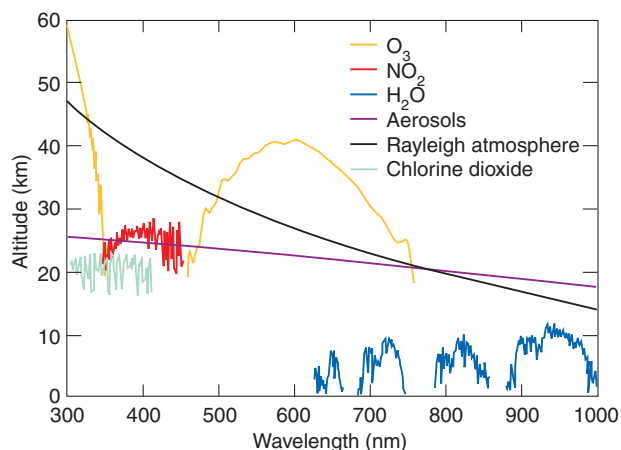


Figure 2. Altitude where the line-of-sight optical depth reaches 0.1 (0.01 for chlorine dioxide) for several atmospheric species.

paths through the atmosphere. Relative measurements of the degree to which the path of incoming radiation is refracted yield the bulk properties (density, pressure, and temperature) of the atmosphere.

These two methods of occultation have been used separately in the past; however, recent analyses of UVISI data have shown that they can be combined to retrieve atmospheric composition simultaneously with profiles of temperature and density. In Fig. 3 we show an example of a simultaneous retrieval of an ozone profile and an atmospheric temperature profile using data from the occultation of a star of visual magnitude 2.4. Also shown in the figure are ozone density and temperature profiles obtained from nearby observations with a ground-based lidar located at Haute Provence, France. The two sets of results are in good agreement and have raised sufficient interest at NASA to warrant funding for analysis of the entire MSX database of stellar-occultation experiments.

While it was fortunate that the pointing stability of the MSX spacecraft and the quality of the UVISI imagers and spectrophotometers were adequate to identify a new approach to height-resolved ozone profile analysis, NASA will require compact low-cost instruments for ozone monitoring into the 21st Century. Toward that end, the Space Department has recently been awarded a grant under the NASA Earth Sciences Enterprise Instrument Incubator Program to develop an optimized prototype of a next-generation occultation instrument. The new instrument will be self-calibrating and accurate for long-term measurements of ozone and water vapor from space. It will also be capable of flying on a variety of platforms of opportunity. If successful,

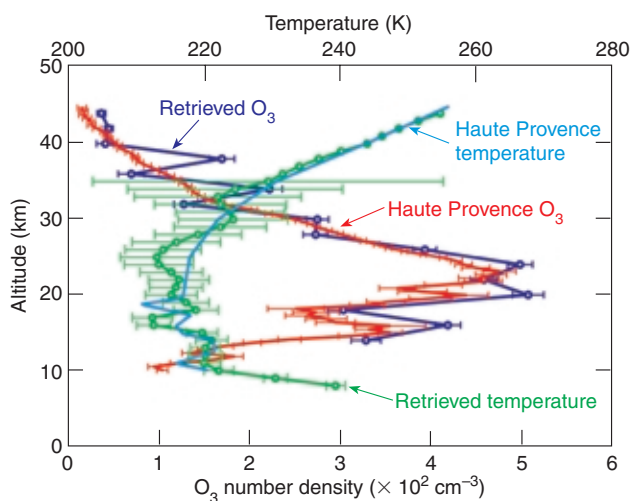


Figure 3. Ozone density and temperature profiles as a function of altitude as retrieved from MSX/UVISI stellar-occultation measurements and compared with nearly co-located measurements obtained with a ground-based lidar located at Haute Provence, France. The two sets of observations were separated by 7 km in latitude, 90 km in longitude, and 2.6 h in time. Bars show range of potential error in determination.

this instrument could provide substantial research opportunities for atmospheric scientists at APL well into the next century.

The Mesosphere

Moving upward in the atmosphere, we come to the mesosphere. In this region, which extends from 35 to 90 km above the Earth's surface, temperatures decline with altitude until, at its upper limit, we reach the coldest point in the Earth's atmosphere. Here, polar mesospheric clouds (PMCs) composed of water ice are found. The water, however, does not come from the lower atmosphere; that water is frozen or precipitated long before it can reach mesospheric altitudes. The water in PMCs is formed by the chemical breakdown of methane, which is produced at the surface and diffuses upward through the atmosphere. Methane is partially produced by modern farming practices. Interestingly, PMCs had not been reported until about 1892. Now they are seen every year and in ever-greater amounts, and are considered a visible signature of the effect of anthropogenically induced changes on the biosphere. MSX UVISI data have been used to map the location of these clouds and their extent (Fig. 4). These observations are adding to our knowledge of PMC composition and structure. Recently, Space Department scientists have received a NASA research grant for continued study of PMCs with the MSX data set.

Finally, there are natural as well as man-made sources of chemically active gases in various regions of the atmosphere. Among the most destructive and visible of these are volcanoes. Volcanoes represent a significant threat to human lives. They alter the land and change the chemistry of the atmosphere. The ash clouds in volcanic plumes have also been the direct cause of engine failures in aircraft. Consequently, they are monitored by the Federal Aviation Administration and are a concern to both civil and military aviation. An example of a volcanic plume observed with UVISI is shown in Fig. 5.

IONOSPHERIC RESEARCH

Above an altitude of 90 km, the Earth's atmosphere becomes increasingly ionized through processes such as photoionization by solar extreme UV radiation and direct energetic electron and ion impact. This ionized region is often referred to as the ionosphere. At its lowest levels (the D and E regions extending from 90 to 150 km), the ionized gases are strongly coupled to the neutral atmosphere via collisions. Collisions retard the movement of ions, while electrons drift under the influence of ionospheric electric and magnetic fields, causing electrical currents to flow. Moreover, significant energy and momentum are exchanged

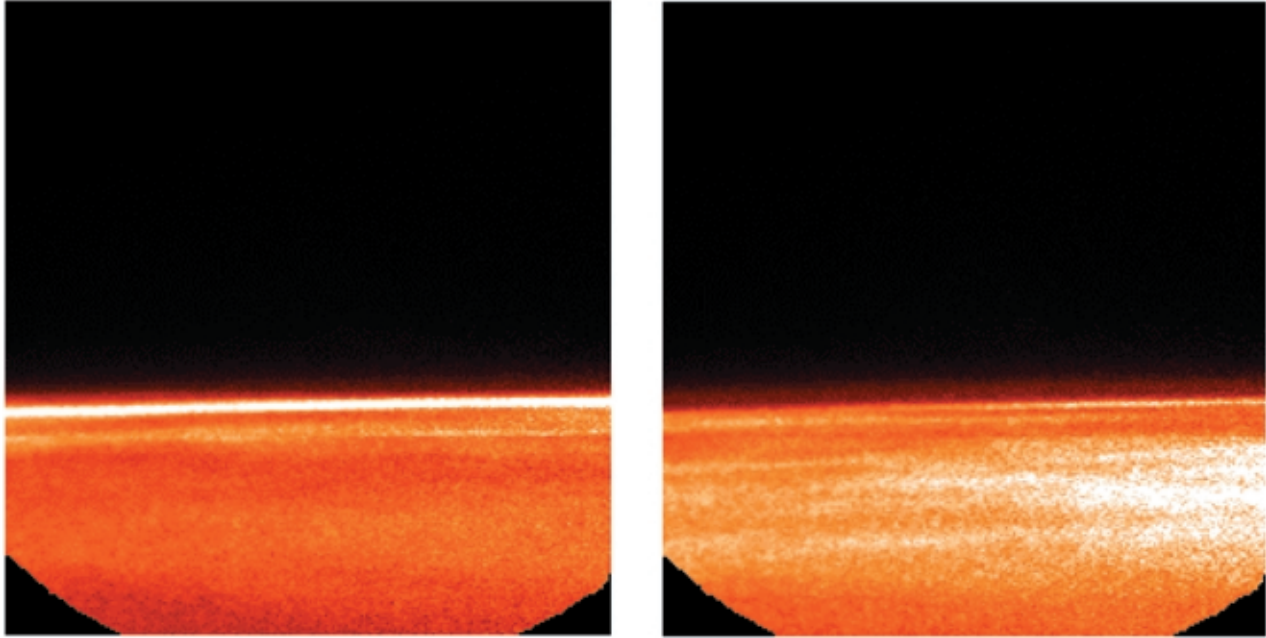


Figure 4. Polar mesospheric clouds as observed with the MSX UVISI at high northern latitudes in June 1997 (left) from a distance showing the thin vertical extent and (right) from a higher viewing angle that reveals the horizontal structure.

between the ionized and neutral components of the atmosphere. Above 150 km, collisions become relatively unimportant and ionized gases behave largely as a collisionless plasma. This portion of the ionosphere is commonly referred to as the F region, the area in which Merle Tuve performed much of his pioneering work and

Space Department radio scientists have conducted high-latitude ionospheric research for nearly 20 years.

The ionosphere is important for over-the-horizon communications at HF frequencies (3 to 30 MHz), for radar surveillance at HF and higher frequencies, and for satellite-to-ground communications at any frequency.

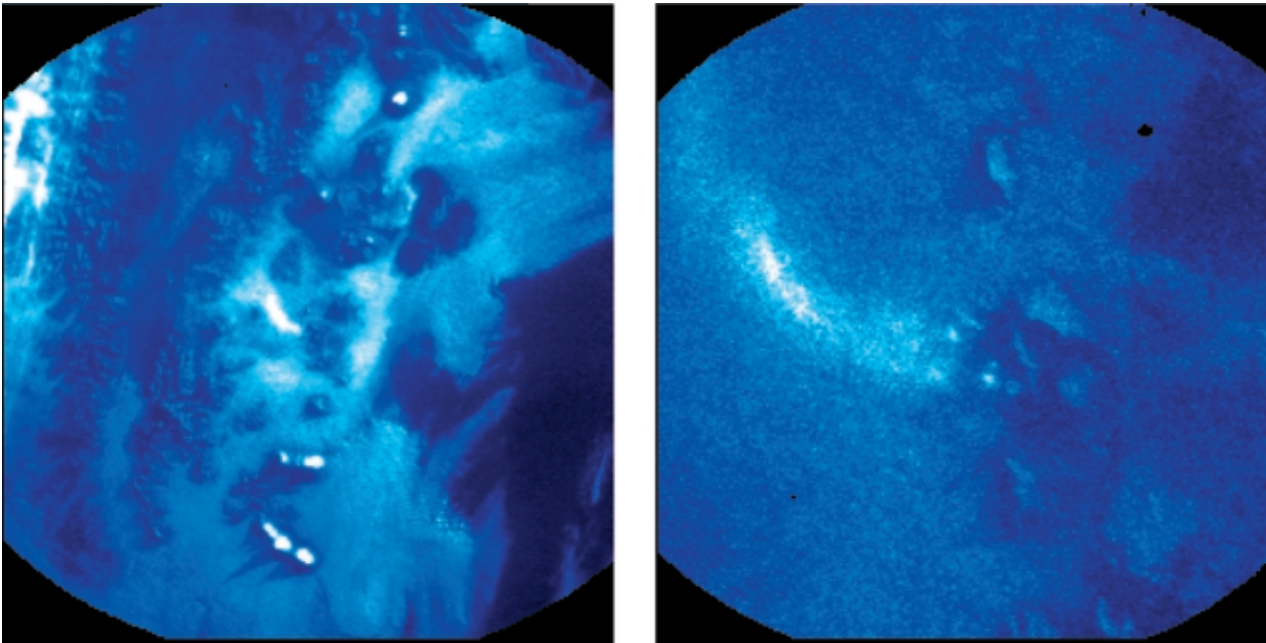


Figure 5. The Karymsky Volcano on the Kamchatka Peninsula of Russia (longitude, 159°E; latitude, 53.9°N) observed on 22 August 1997 with the UVISI narrow field-of-view ($1.6^\circ \times 1.3^\circ$) visible imager. The volcano crater is slightly right of center. Images show the plume, at an 800- and 80-m spatial resolution (left and right frame, respectively), streaming from the crater to the left.

Being an ionized medium, it is subject to electromagnetic storms just as the lower atmosphere is subject to conventional storms. The effects of these storms are particularly profound at high latitudes. Electromagnetic storms are associated with intervals of large ionospheric current flow, large electric fields, and brilliant auroras. Interesting analogies may be drawn between the two types of storms. The high- and low-pressure regions that drive winds in association with conventional weather systems are replaced by regions of high and low electrical potential that drive plasma winds and ionospheric current systems. Precipitation of moisture in the form of rain or snow is replaced by precipitation of energetic electrons and ions within the aurora. Just as clouds become highly structured and turbulent under stormy conditions, the ionosphere becomes highly structured and turbulent during even minor electromagnetic disturbances. Together, these electromagnetic storm elements modify the high-latitude ionosphere and disturb most forms of electromagnetic communication passing through it.

The term “space weather” has been coined to describe the disturbed electromagnetic and energetic particle environments that can permeate interplanetary space as well as the Earth’s magnetosphere, ionosphere, and upper atmosphere. Space weather disturbances strongly impact the technical systems of modern society, including communications, Earth remote sensing, electrical power distribution, and even man in space. Today, a significant goal of both civilian and DoD agencies charged with understanding and utilizing the space environment is to monitor and predict the current and future state of space weather. This is an area in which the ionospheric and magnetospheric research carried out within the Space Department can make significant contributions in the national interest.

Much of the ionospheric research we have conducted has been performed with radars operating in the HF band between 8 and 20 MHz. These radars detect the small-scale (8- to 18-m-wavelength) electron density irregularities that are produced in the E and F regions of the ionosphere as a consequence of plasma instability processes associated with electromagnetic storms and lesser disturbances. The irregularities are abundant at polar latitudes and are excellent scatterers of radiowave signals. Although a nuisance to surveillance radars, these irregularities are an excellent tool for studying the properties of the high-latitude ionosphere.

Space Department scientists and engineers established the first APL HF ionospheric radar at Goose Bay, Labrador, in 1983.¹¹ It was developed through support from the National Science Foundation, the Air Force Office of Scientific Research, and the current Air Force Research Laboratory. This radar has operated continuously since 1983 while being slowly upgraded to its present configuration. Analyses of data from the Goose

Bay radar demonstrated the broad utility of HF radar measurements to scientific studies of the high-latitude ionosphere.

In 1987, Space Department scientists showed that the drift velocity of F-region irregularities equaled the drift velocity of the ionospheric plasma.¹² This finding allowed HF radars to be used to investigate plasma circulation and electrical potential patterns in the upper atmosphere. The latter are determined through the relationship $\mathbf{E} = -\mathbf{V} \times \mathbf{B}$, where \mathbf{V} is the plasma drift velocity, \mathbf{B} is the ambient magnetic field, and $\mathbf{V} \times \mathbf{B}$ is the vector cross-product. Since an HF radar has a large field of view, it can measure ionospheric plasma motion and electric fields over a very large spatial area with reasonably high temporal resolution. Indeed, many advances in our understanding of the dynamics of ionospheric electric fields at high latitudes have resulted from HF radar research.

We now review the evolution of the original Goose Bay radar into the global network of radars known as SuperDARN and discuss the use of SuperDARN data today to monitor the impact of space weather on the high-latitude ionosphere.

Statistical Patterns of the High-Latitude Electrical Potential

The plasma in the high-latitude ionosphere circulates as a consequence of a dynamo interaction between the solar wind emanating from the Sun and a magnetic obstacle comprising the Earth and its magnetic field environment. The interaction creates a significant electrical potential drop across the Earth’s magnetosphere and a complicated pattern of magnetospheric plasma circulation. This electrical potential pattern maps along geomagnetic field lines into the high-latitude ionosphere, producing two or more large-scale cellular circulation patterns covering both of the Earth’s polar regions. The ionospheric plasma convects along the closed electrical potential contours that map into the ionosphere.

In the latter half of the 1980s and early 1990s, it became increasingly apparent on the basis of satellite data sets that electric fields and plasma convection in the high-latitude ionosphere were strongly dependent on the orientation of the interplanetary magnetic field (IMF).¹³ Spacecraft data sets were then beginning to provide statistical models of high-latitude plasma convection, but patterns derived from ground-based radar observations had not yet reached a similar level of sophistication. Finally, in 1996, Space Department scientists used data from the Goose Bay radar to develop the first radar-derived statistical patterns of IMF-dependent high-latitude convection. An example is shown in Fig. 6. These patterns are similar to the convection patterns derived from satellite observations.¹⁴

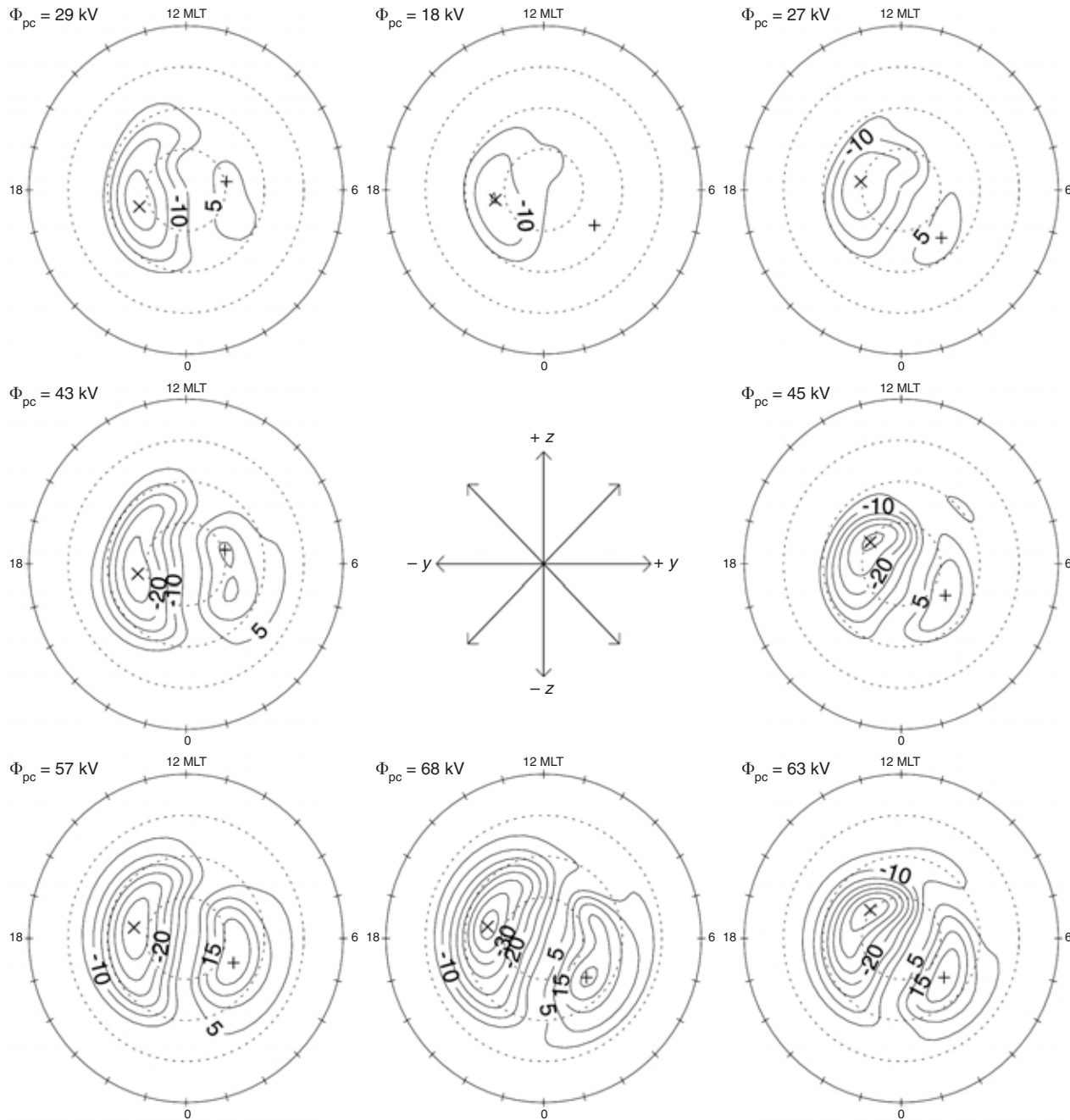


Figure 6. Statistical models of the high-latitude electrical potential pattern for various orientations of the interplanetary magnetic field as determined by the APL HF radar at Goose Bay, Labrador. The equipotential contours are in kilovolts and represent the convection paths followed by the ionospheric plasma. Higher flow velocities occur where the contours are close together. The outer circles are at 50° magnetic latitude. Φ_{pc} = electrical potential drop across the polar cap.

Other Studies

Statistical studies of convection with the Goose Bay radar served primarily to confirm results that had been obtained earlier with other techniques. However, ground-based radars have unique advantages, including the ability to make observations over extended areas for extended periods of time. The evolution of these patterns reveals the dynamical response of ionospheric

convection to changes in the magnetosphere and the solar wind. An early example of this capability was demonstrated when scientists from APL and the British Antarctic Survey made the first conjugate (opposite ends of a geomagnetic field line) observations of convection in the dayside high-latitude ionosphere.¹⁵ This study showed the ability of radars to track the evolution of the high-latitude convection pattern as the IMF changes orientation.

This research has also covered a broad range of other processes relevant to the high-latitude ionosphere. For example, the mechanisms leading to the formation of ionospheric irregularities have been investigated with the Goose Bay radar and another HF radar in Schefferville, Quebec, that was operated by French scientists. These studies have demonstrated the importance of the ion acoustic and electrostatic ion cyclotron plasma instabilities in producing high-latitude irregularities.^{16,17} These instabilities are only operative in regions where significant currents flow along magnetic field lines between the magnetosphere and ionosphere.

Data from the Goose Bay radar have also been used to identify a distinct signature of internal atmospheric waves with dimensions of hundreds of kilometers (atmospheric gravity waves) that produce a long-period (30- to 40-min) modulation in the intensity of radar returns. These waves are caused by the energy and momentum coupling that exists between the high-latitude ionosphere and upper atmosphere that we have noted previously.^{18,19}

In addition, Space Department scientists and their colleagues in Canada and South Africa have used data from the Goose Bay radar to study large-scale hydromagnetic waves resonating in the magnetosphere-ionosphere cavity.^{20,21} These waves also produce unique 5- to 10-min signatures in the radar returns and are another important mechanism for energy transport between the magnetosphere and the high-latitude ionosphere and atmosphere.

The SuperDARN Radar Network

In the early 1990s, growing international interest led to extensive expansion of the then-existing network of high-latitude HF radars. Today, 10 nations (Australia, Canada, Finland, France, Italy, Japan, South Africa, Sweden, the United Kingdom, and the United States) are collaborating in the development and operation of a near-global network of radars that continuously monitor the electrodynamic state of the high-latitude ionosphere over the polar regions of the Northern and Southern hemispheres.²² Ten radars are in operation, and additional radars are under construction in Alaska, western Canada, Tasmania, and Kerguelan Island in the southern Indian Ocean. Figure 7 shows the fields of view of the existing and planned radars.

Although the SuperDARN network is used primarily for scientific research, it can also monitor the state of the high-latitude ionosphere. In fact, some real-time data from SuperDARN are made available to the general public. To demonstrate the rapidity with which changes in the high-latitude ionosphere can occur, we present in Fig. 8 four images of the polar cap convection pattern during a 14-min interval in which there was enhanced coupling between the magnetic field of the

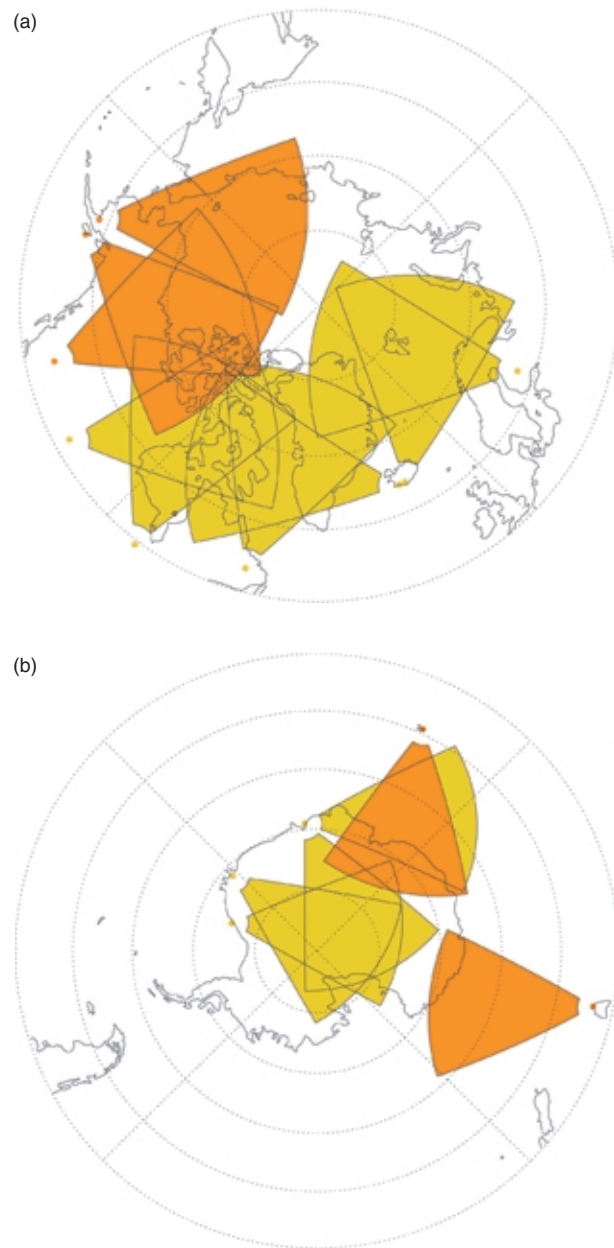


Figure 7. Fields of view of SuperDARN radars in the Northern (a) and Southern (b) hemispheres. Operational radars are represented in gold; those under construction are shown in orange.

solar wind and that of the Earth's magnetosphere. Enhanced coupling leads to enhancements in the high-latitude potential patterns and increased plasma convection. Each of these images was acquired over a 2-min radar scan, and every second scan is shown. It can be seen that the plasma convection velocity in the ionosphere increased substantially over very large spatial areas on time scales of minutes, *much* faster than the evolution of normal weather systems in the lower atmosphere. If we are to protect high-technology systems

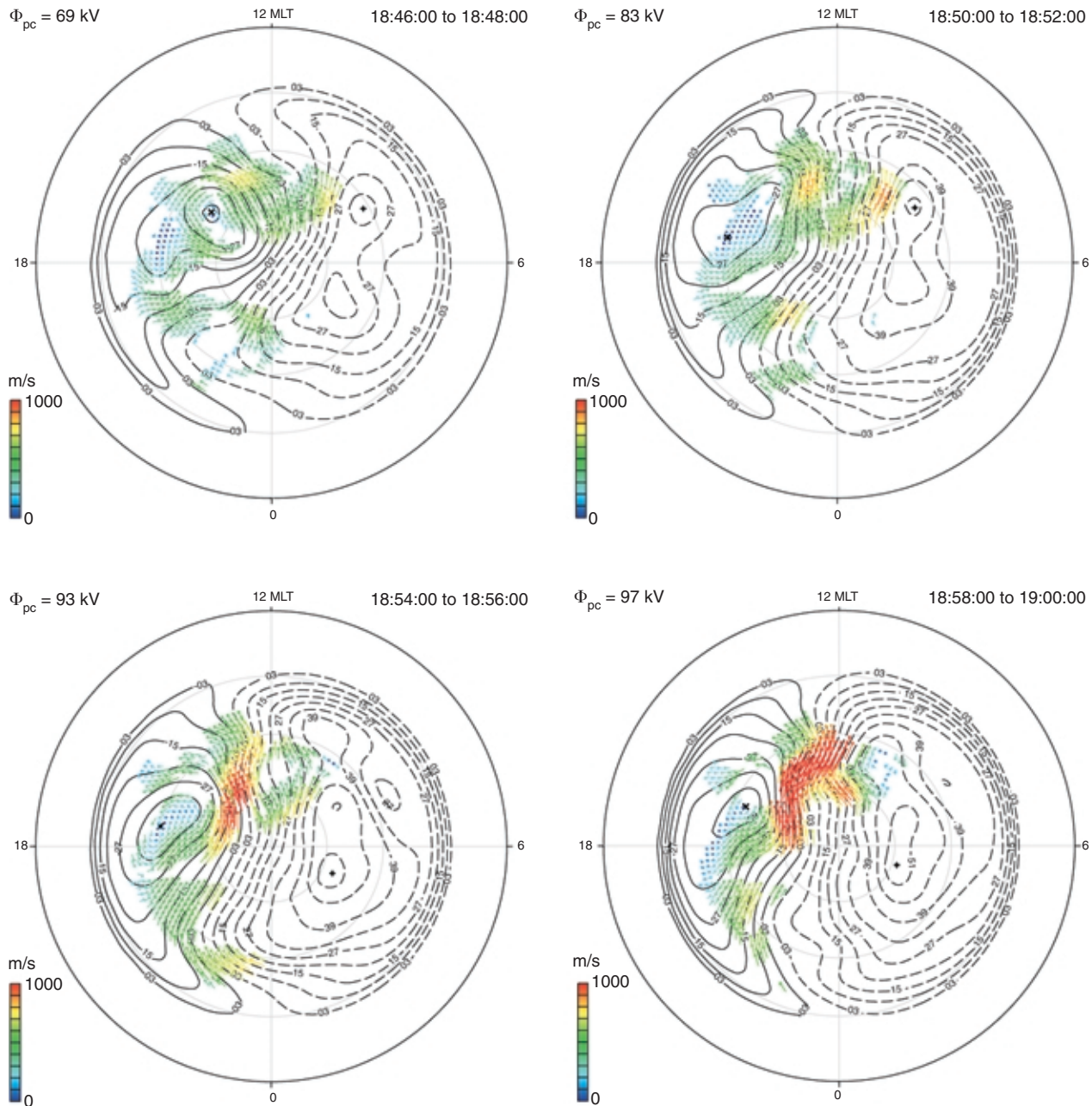


Figure 8. Four images of the high-latitude electrical potential pattern showing the global response to a significant increase in dayside reconnection in the time interval 18:46–19:00 UT on 13 November 1996. Each image is a 2-min scan average separated by 4 min. Notice the rapid onset of high-velocity convection in the high-latitude postnoon ionosphere. Color bars show speed of plasma controlled by the electrical potential pattern.

from electromagnetic storms, then we need adequate warning of their onset.

A Web site has been established at <http://superdarn.jhuapl.edu> where it is possible to observe near-real-time global maps of plasma circulation and the distribution of electrical potential. In the future, this site will also contain other information on the state of radiowave propagation throughout the high-latitude ionosphere.

AURORAL PARTICLES AND IMAGING

Since the late 1970s, the Space Department research staff has been studying magnetospheric processes through (1) *in situ* detection of auroral particles on polar-orbiting spacecraft and (2) optical remote sensing of their impact on the high-latitude ionosphere. Much of this research has emphasized statistical studies obtained from large satellite data sets, particularly those

of the Defense Meteorological Satellite Program (DMSP). To maximize the geophysical information extracted from these data sets, various pattern recognition techniques have been used. In 1988, Space Department scientists developed the first quantitative algorithm for identifying various regions of the Earth's magnetosphere that contribute to energetic electron and ion precipitation into the high-latitude ionosphere.²³ The identified procedures are still widely used by space scientists throughout the world.

Follow-up work at APL identified other magnetospheric domains contributing to charged particle precipitation into the dayside ionosphere. A neural network-based identification system was developed that led to the first map relating magnetospheric plasma sources with particle precipitation zones in the dayside high-latitude ionosphere.²⁴ Figure 9 shows this map, which appeared on the cover of *Geophysical Research Letters* in 1992.

The aurora borealis or "northern lights" is a natural phenomenon that has attracted public attention, particularly in the northeastern and north-central United States, where it is observed under disturbed geomagnetic conditions. Auroras are produced by accelerated magnetospheric electrons and ions precipitating into the upper atmosphere, where they excite and ionize the ambient gases. These gaseous emissions are typically observed only at night when sky conditions are sufficiently dark for this relatively faint phenomenon to be observed. Although auroras are only seen at night, auroral researchers commonly believed that the processes leading to auroral precipitation also occurred

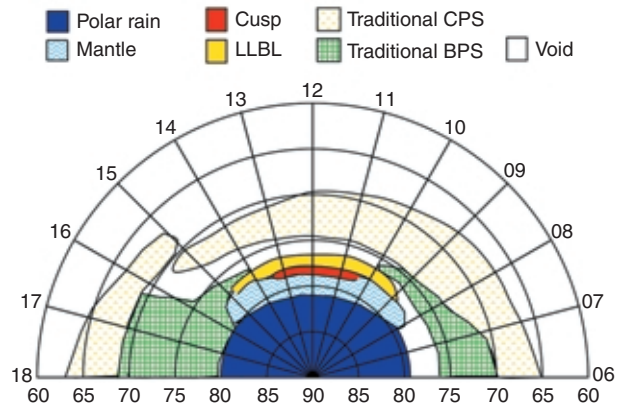


Figure 9. Map of magnetospheric source regions contributing to particle precipitation into the high-latitude ionosphere. The different regions are identified by the characteristic energies and fluxes of the *in situ* plasma. (LLBL = low-latitude boundary layer, CPS = central plasma sheet, and BPS = boundary plasma sheet. Regions without any substantial precipitation are identified as void.)

during daylight hours. Surprisingly, recent work by Space Department scientists has shown that this conjecture is incorrect.

Auroras are actually suppressed in sunlight.²⁵ Figure 10 presents a statistical study of auroral precipitation as observed with the DMSP satellite during winter and summer seasons in the Northern Hemisphere. It is apparent, particularly in the evening hours, that auroras are much more common in winter, since they occur, in part, as a consequence of the large-scale currents flowing between the magnetosphere and ionosphere. If the

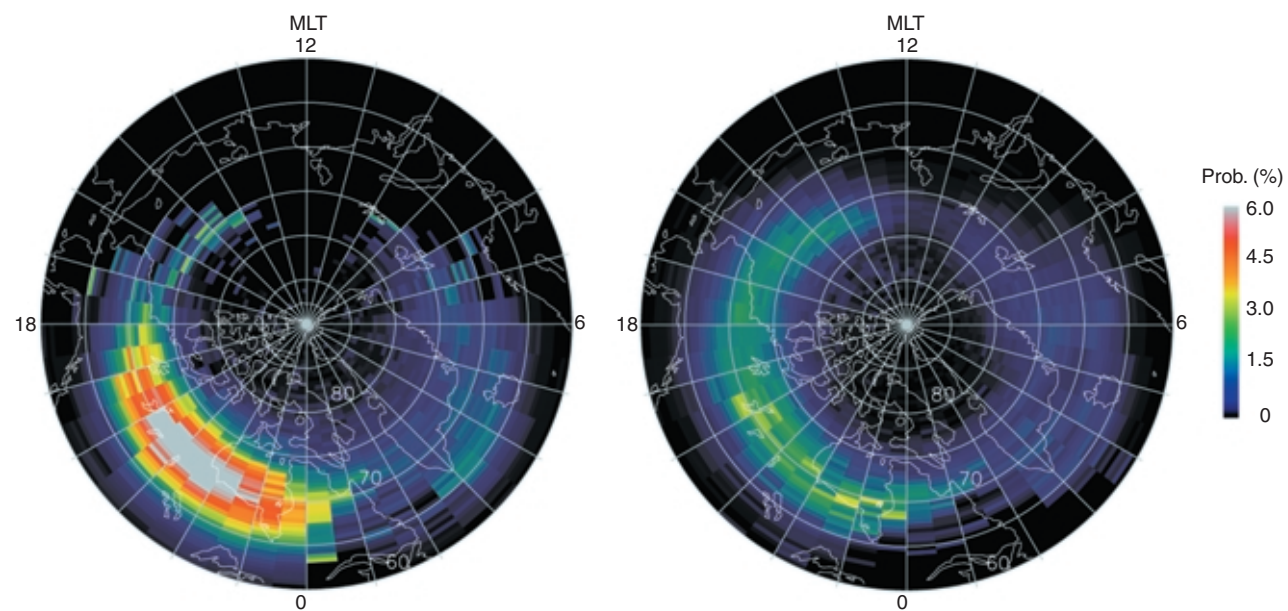


Figure 10. Intense, discrete auroras occur much more frequently in darkness (left) than in sunlight (right). This effect is attributed to the increase in ionospheric conductivity caused by sunlight. These plots show the probability of observing intense discrete auroras (>5 ergs/cm²s) in corrected geomagnetic coordinates, with the continental outlines shown at 06:00 UT.

ionosphere has insufficient conductance to carry these currents, then an additional process, i.e., auroral acceleration, must occur to enhance the conductance and allow the currents to flow. The accelerated electrons and ions bombard the upper atmosphere, thus producing auroral emissions, ionizing the ambient gases, and significantly increasing the conductance. Where solar UV radiation ionizes the gases of the upper atmosphere, there is a higher level of conductance and a lesser need for auroral acceleration processes to occur.

Space Department scientists have also shown that the global frequency of auroras is higher under sunlit conditions at the minimum of the 11-year solar cycle than at the maximum. The same arguments again apply. Under solar maximum conditions, higher levels of ionizing radiation are emitted by the Sun and, consequently, there is a reduced need for particle acceleration processes to enhance ionospheric conductance.

When enhanced energy and momentum coupling from the solar wind to the Earth's magnetosphere occur, the magnetosphere is stressed into a disturbed state that ultimately discharges in the form of a magnetospheric substorm. A crude analogy might be that of a thunderstorm in which electrostatic charges build up in the atmosphere until they are released in the form of a lightning stroke carrying a large current to the ground. In the case of a magnetospheric substorm, the Earth's magnetosphere is distorted until, for some as yet unknown reason, there is a large current surge from the magnetosphere to the nightside ionosphere, producing an auroral substorm.

Recently, APL researchers have had the opportunity to analyze images from the Ultraviolet Imager (UVI) experiment on the NASA Polar spacecraft and have obtained a number of new results on auroral substorms^{26,27} and substorm timing.²⁸ One of the more interesting of these results relates to the timing of the onset of an auroral substorm. Figure 11 shows a sequence of UVI auroral images. The auroral substorm is associated with the brightening and expansion of the red region in the lower right-hand corner of each image. Most likely, the onset time of this substorm is

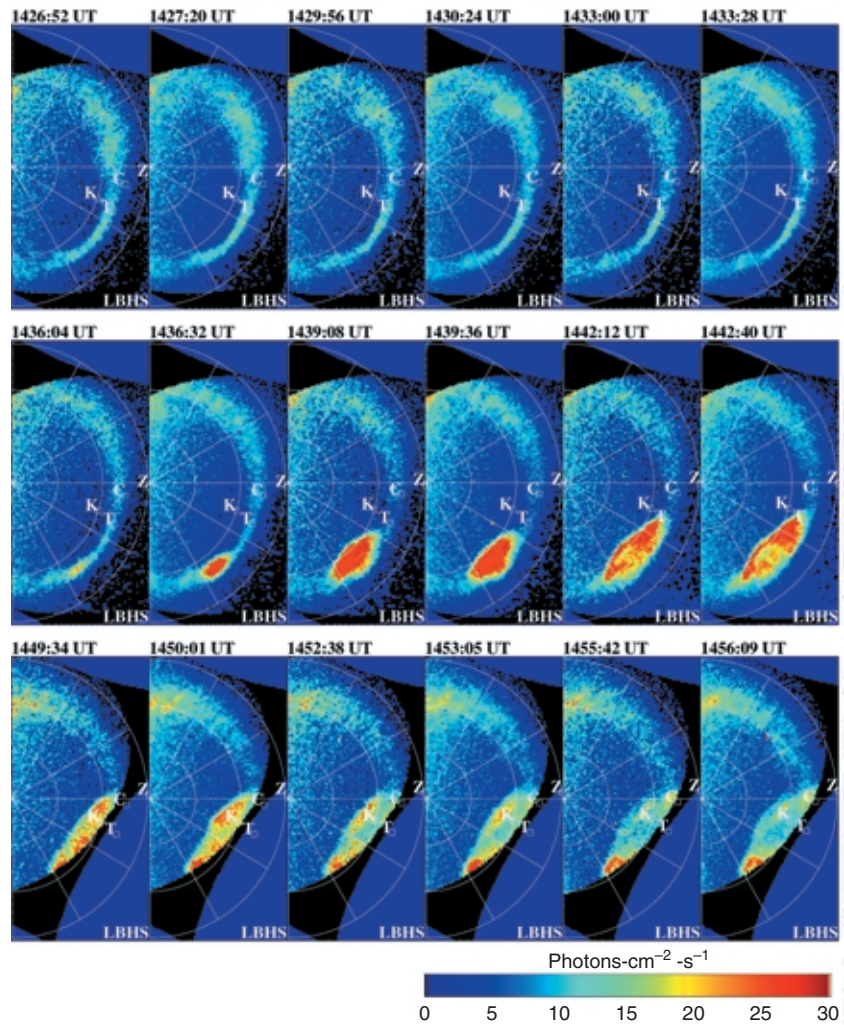


Figure 11. A sequence of UVI auroral images showing the onset of a substorm. These images were obtained in the short-wavelength portion (S) of the Lyman-Birge-Hopfield (LBH) band system at 140–160 nm. The letters K, T, C, and Z indicate the sites of ground-based magnetometers used in this study.

identified with the left-hand image in the middle row. If one were on the ground under this region, one would observe a blazing display of bright and rapidly moving auroras filling the entire sky. Images such as these are providing a better understanding of how the signatures of substorms that have been identified with ground and *in situ* satellite measurement techniques relate to the global-scale evolution of substorm phenomena.

SUMMARY

Merle Tuve used radio techniques to be among the first to venture into near-Earth space. The APL Space Department continued this heritage with rockets and satellites and has compiled a distinguished record in both the technical and scientific aspects of putting instruments into space and using the data to advance our scientific knowledge of the Earth's atmosphere and immediate plasma environment. The remote sensing

activities currently being pursued by scientists and engineers within the Space Department as they are applied to important issues relating to the Earth's environment will continue to be of importance well into the next century. We hope that Tuve would find the results of this challenging research effort interesting and of scientific value.

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