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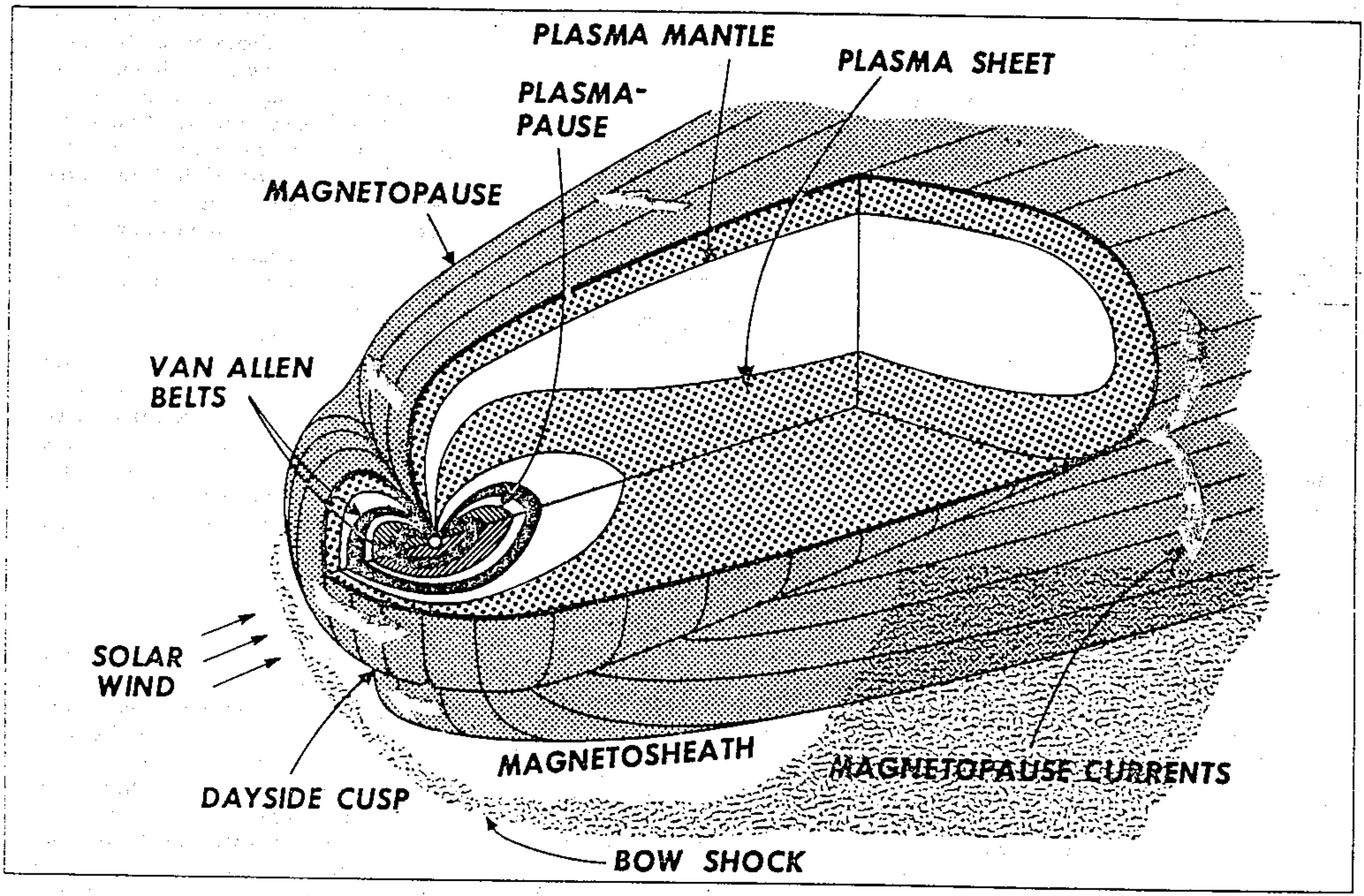
ISLAND EARTH IN A SOLAR SEA

Aeronomers, meteorologists and atmospheric physicists are seeking—and finding—intimate relationships where the solar wind embraces the magnetic earth.



The magnetosphere. The region of complex forces and currents, where the earth meets the solar atmosphere, has large effects on the terrestrial environment. How large is coming to be known.

L. J. Lanzerotti and C. G. Park

Like an island in the middle of the Pacific Ocean, the earth stands in the way of a fast-running cosmic current—the solar wind. That wind, a great stream of charged atomic particles, flows out from the sun, through the solar system and around the planets, just as an ocean current sweeps around and past the island members of an archipelago.

But, unlike all but one other planet in the solar system, Jupiter, the earth is known to have a strong magnetic field. (Mercury and the moon have weak fields; others, such as Saturn and Uranus might be expected to, but there is little evidence.) The earth's magnetic field surrounds the planet as coral reefs do certain islands. It protects the earth from the brunt of the solar wind, but also interacts with the stream of particles to produce such effects as auroral phenomena and geomagnetic storms. In addition to these well-established effects in the upper atmosphere, an increasing number of scientists have become concerned with a possible influence of these effects, in turn, on the pattern of weather on the surface of the earth—particularly what might prove (if the lines of linkage could be established) to be an intimate and intricate relationship to atmospheric electrical disturbances and thunderstorm formation.

The earth's magnetic field and the space it encloses are known as the magnetosphere. It is cometlike in shape, compressed to some 10 earth radii (about 64,000 kilometers) by the impact pressure on the sunlit side of the earth and extended to perhaps 1,000 earth radii (6.4 million kilometers) on the night side.

It once was thought that the magnetosphere simply carved a cavity in the solar wind, like a cocoon inside of which the earth resided, unaffected by the solar flux. Since the advent of the space age, however, scientists have come to know the magnetosphere as a complex, generator, the earth's atmosphere may also be regarded as a giant electric generator. Some of its currents flow all the way down to the ground and then, laterally, along the ground for great distances before turning upward into the ionosphere and magnetosphere to close the circuit. This circuit shares its path with other circuits, such as those of the thunderstorms, and may provide a means for one natural generator to interact with another.

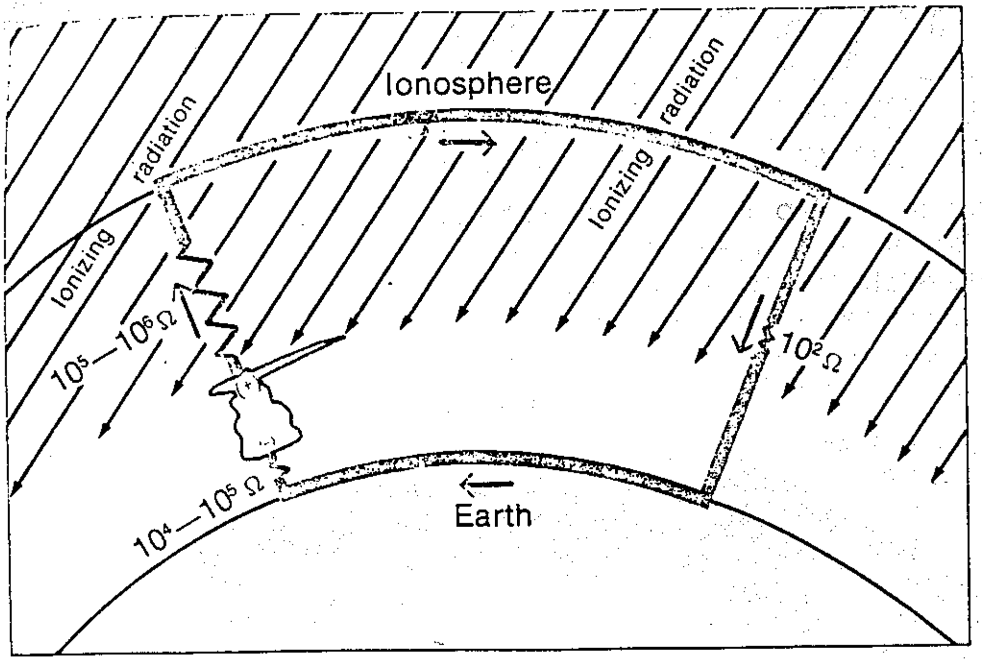
J. Doyne Sartor of the National Center for Atmospheric Research in Boulder, Colorado, for example, has found from computer modeling studies that if the strength of the electric field in the model's upper atmosphere is increased by about a third, then the electric field inside a lightly electrified cumulus cloud in the atmosphere below can jump from perhaps 1,000 volts per meter to 100,000 volts per meter. The result is a full-scale thunderstorm, modifying greatly the electric field around it, Sartor explains.

It's a great big feedback system, says Park. But according to him and many scientists, the physical processes involved are so complex that a great deal more work is needed before it can be understood how thunderstorms work and how their behavior is influenced by what goes on in the earth's upper atmosphere and the solar atmosphere beyond.

A partial view

From what is beginning to be suspected, the process would begin with a solar flare, one of those stupendous explosions within the sun's atmosphere. Expelled from the sun with great force, the solar wind becomes a transient solar hurricane. Its velocity jumps abruptly from a few hundred kilometers per second to roughly twice that. Slamming against the magnetosphere, the solar wind causes the malleable magnetosphere to deform.

But there the picture grows fuzzy. Beyond an increase in the generator's efficiency, it is not entirely clear what events follow in the regions above the earth when an exceedingly strong solar wind lashes the magnetosphere; that knowledge is one of the principal goals of the IMS. It appears, however, that the electric fields, magnetic fields, plasmas and waves throughout the magnetosphere all change rapidly and drastically. Protons that had energies of 1,000 electron-volts (1 keV) when they were part of the quiet solar wind are now accelerated to 20 keV. Electrons that normally would move in the solar wind with energies of 20 to 40 electron volts



Global circuit. A postulated global electrical circuit, with arrows indicating the flow of positive charge. The thunderstorm depicted represents the global electrical generator—the totality of all global thunderstorms.

Ralph Markson

Magnetospheric regimes

The better to understand sun-earth interactions, it might be helpful to have a clear picture of the structures of the magnetosphere, the regime in which the solar and terrestrial environments meet and mix. Beginning with the outermost feature and working in toward the earth, one finds the:

- **Bow shock.** This is a wave, similar to the one created by a boat moving through the water, that marks the movement of the earth and its magnetic field through the solar wind. Its existence has been known since 1963, when a satellite's sensors first discovered it, but there is a lot about this shock wave that is unknown. It appears to oscillate in and out at distances of 77,000 to 83,000 kilometers on the side facing the sun and at speeds between about 10 and 200 kilometers per second. The shock wave is thought to heat the charged particles in the solar wind.

- **Magnetosheath.** Immediately behind the shock wave, it is a zone of considerable turbulence, much as would be found in the wake of a supersonic jet aircraft or a bullet. Protons and electrons are found circulating here with energies 10 to 4,000 times those of particles on the other side of the shock front, in the free-flowing solar wind.

- **Magnetopause.** This is the outer boundary of the magnetosphere. That portion of the magnetic field facing the sun is compressed by the solar wind to something less than 10 earth radii, while the downstream sector is extended by the wind out to perhaps 1,000 earth radii. Separating these two sectors are the polar "cusps"—long, irregularly shaped funnels formed by the field lines as they dive almost straight down onto the geomagnetic north and south polar regions.

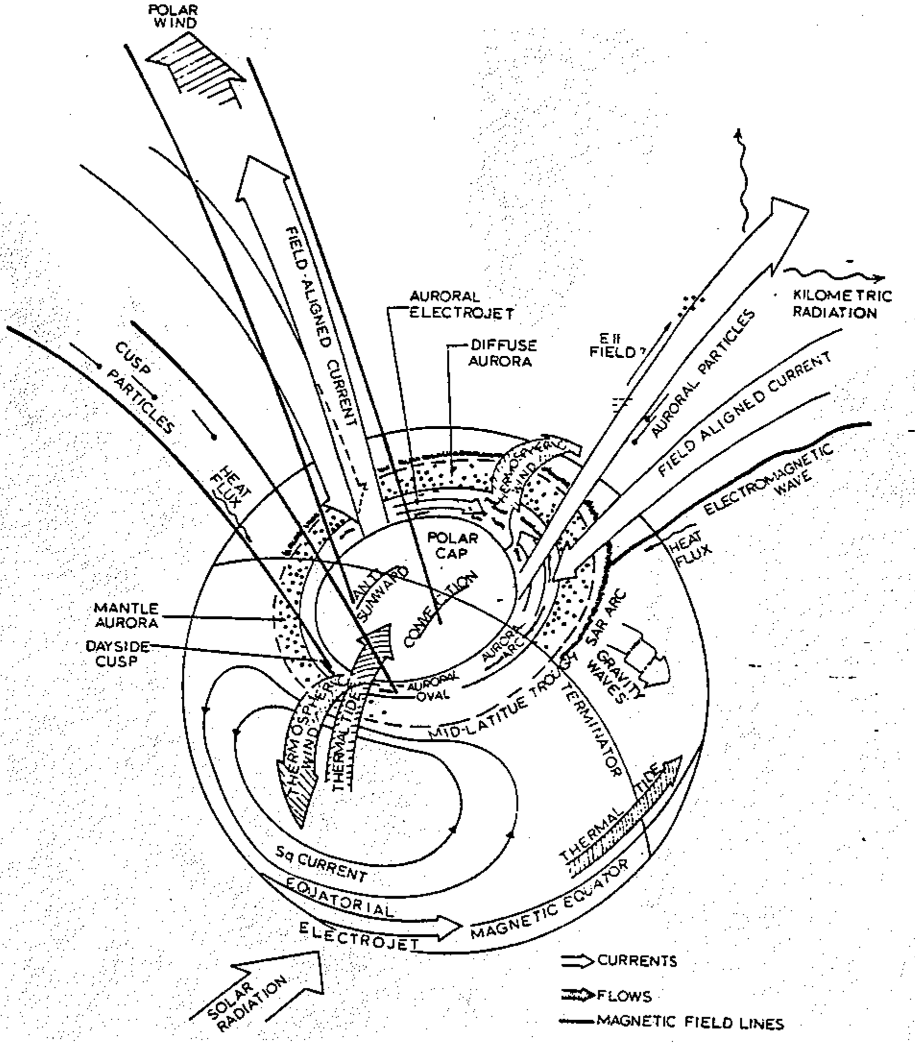
- **Plasma sheet.** Like a gaseous Gulf Stream, this flow of ionized particles begins somewhere behind the cusps and runs down through the central part of the magnetospheric tail. Long thought to be populated by protons and electrons from the solar wind, the ionized gas is now known to contain heavy ions, like those of oxygen, which probably have come from the earth's atmosphere. The plasma sheet is also thought to be a capacitor of sorts, storing energy and periodically discharging it into the magnetospheric system.

- **Plasmasphere and Van Allen Radiation Belts.** The plasmasphere is a doughnut-shaped region encircling the earth and populated by low-energy protons and electrons; radiation belts are zones of electrically charged particles, but with considerably more energy. ●

multifaceted environment. "It is a very large volume of space with many pockets of diversity," says Chung G. Park, a senior research associate at Stanford University's Radioscience Laboratory, "some dominated by chemistry, some by electrical forces and some by magnetism." It has, as well, many effects on the earth; the magnetosphere is no cocoon.

A principal problem facing upper-atmospheric scientists at the moment, says Park, is to understand how these different forces fit together and how they form a link between solar causes and terrestrial effects. Toward that end, a consortium of more than 20 nations is presently engaged in the International Magnetospheric Study (IMS). The primary objective of this four-year (1976-1979) effort, according to Juan G. Roederer, director of the Geophysical Institute of the University of Alaska and IMS steering committee chairman, is to see the magnetosphere "whole, as a single system of interacting plasmas, fields, waves and energetic particles."

Indeed, the very complexity of the magnetosphere's structure and the dynamic interplay between it and the solar wind cannot be examined without this sort of multifaceted approach. For, like a coral reef, the magnetosphere protects, but does not isolate, the island-earth from the impact of the solar wind. Charged particles from the sun "leak" into the inner regions of the magnetosphere and interact with the magnetic fields and gases there.



Upper polar atmosphere. The poles are where the mix of fields, forces and currents that mark solar-terrestrial relationships are most accessible. The earth's magnetic field lines funnel solar particles in to cusps at the geomagnetic poles. One consequence is the aurora (right).

C. G. Park

The coupling

Beneath all of this, and somehow related to it, is the earth and its atmosphere. Although scientists recognize that the ionosphere, high in the atmosphere, is tightly coupled to the overlying magnetosphere, it is a recognition that has come only in recent years. "It used to be," says Park, "that ionospheric and magnetospheric scientists seldom talked to each other. But now, in the past ten years or so, the realization has dawned that you can't explore what's happening in the ionosphere without knowing what's going on at the same time in the magnetosphere."

For example: If, as science has long believed, the ionosphere is created by the ionizing effects of solar ultraviolet and X-radiation penetrating the magnetosphere, then there should be no ionosphere on the darkened side of the earth, shielded as it is by the earth's bulk from the solar stream. And yet there is a night-side ionosphere, somewhat different from the sunlit ionosphere, to be sure, but present on the shadowed half of the earth nevertheless.

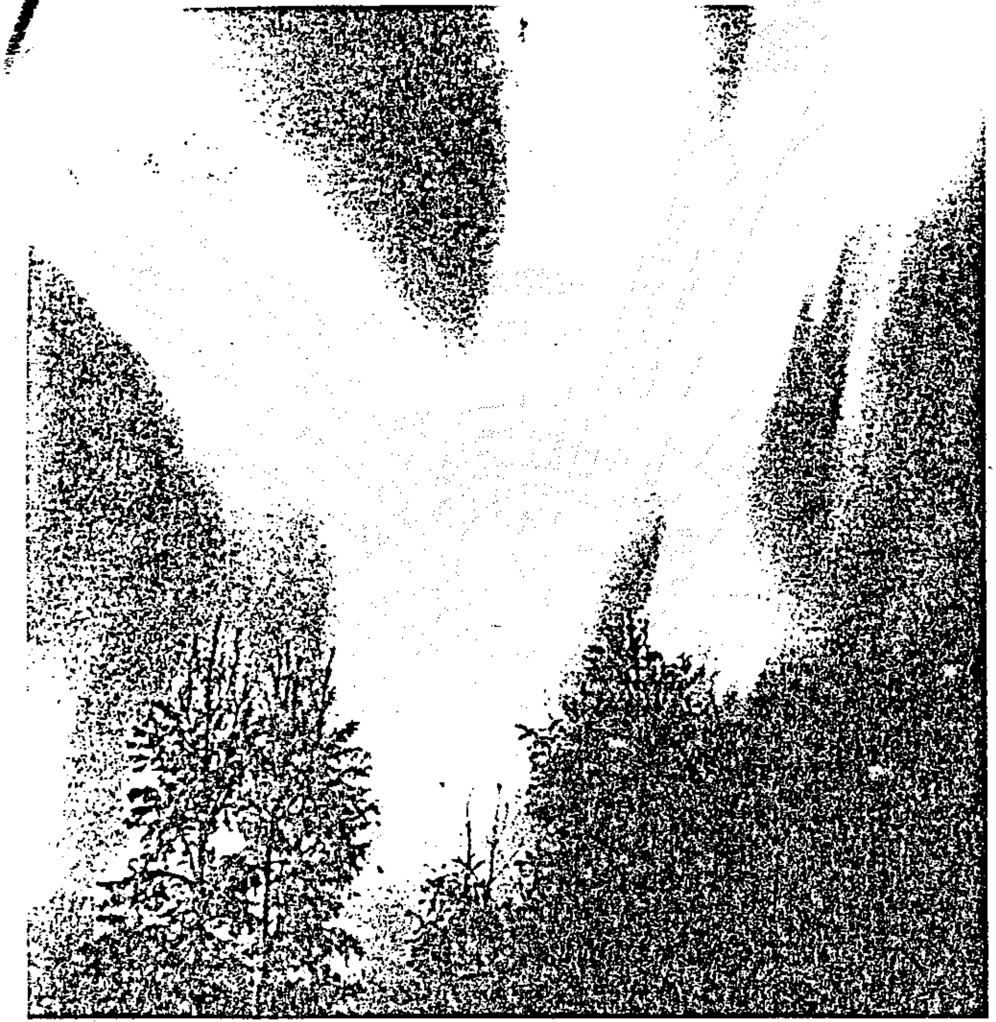
The explanation of this dark-side ionosphere is to be found, Park believes, in the interplay of several factors between the ionosphere and the overlying magnetosphere: The plasma falls out of the magnetosphere and down into the ionosphere at night (or on the night side), and that flow is reversed during the day.

"When the ionosphere is sunlit," says Park, "it produces so much ionization that some charged particles move up along the earth's magnetic field lines into the higher regions of the ionosphere. Then, as the earth turns and this region passes into darkness, the process is reversed. The ions cool and recombine, the pressure balance changes and the particles fall back down along the same field lines, back into the ionosphere. They sort of slosh back and forth."

Plasmas and magnetic fields have a restrictive influence on each other. A magnetic field tends to act as a barrier to the flow of the ionized particles that constitute a plasma, splitting it and producing a cavity within the flow; the plasma, in turn, tends to confine the field and force it to occupy a smaller volume than it would in the absence of the impinging stream. Together, plasmas and magnetic fields generate electric fields, and it is in these fields, some atmospheric physicists are increasingly persuaded, that the link between the solar dog and meteorological tail will ultimately be found.

Generators in the sky

"The magnetosphere is a kind of generator," says Syun-Ichi Akasofu, professor of geophysics at the University of Alaska, "generating 10^{11} to 10^{12} [several hundreds of billions to a trillion] watts. That's one hundred times more than the total U.S. power output," Akasofu notes. But "to understand what



is happening, you have to start at the sun [see "Magnetospheric regimes," accompanying this article] and come all the way down to the upper atmosphere."

The solar wind, the Alaska scientist explains, breaks over the bow shock wave, and the ions flow around the magnetosphere. Some of these apparently punch through the magnetopause and enter the magnetosphere. Some of the captured particles are guided along the force lines that emanate from the cusp formed around that day-side polar region.

The ions flowing around the magnetopause are slightly deflected according to their electrical charge, the Alaska scientist says. This effect sends the electrons to the dawn side of the magnetosphere and the protons to the dusk side. The effect might be imagined to be like that between the terminals of a battery having a 50-kilovolt potential and a current flow of some million amperes. Much of the current [illegible]s across the midplane of the magnetosphere, from negative to positive—electron-rich dawn side to proton-rich dusk side. But, Akasofu estimates, perhaps a few million amperes or so flow down the magnetic field lines, coming to "ground" at the auroral oval around a geomagnetic pole. "People used to think that the aurora was simply the result of charged particles impinging on the polar atmosphere," says Akasofu. "But now we know that a powerful electromotive force must first be created before the aurora can occur. It is this electrical process that really matters."

As the current-carrying electrons spiral down the magnetic field lines, they collide with atoms and molecules (such as oxygen and nitrogen) in the upper atmosphere, at altitudes ranging from a few hundred to perhaps 1,000 kilometers above the surface of the polar regions.

"This is an enormous discharge," says Akasofu of the collisions between the current-carrying electrons and the rarified gas particles in the upper polar atmosphere. "The oxygen and nitrogen, both atomic and molecular, are excited by the process and emit photons."

The energetic ions, being confined to the magnetic field lines around the pole, strike gas particles only in a narrow belt ringing the poles, the auroral ovals. Having excited the upper atmospheric gases to produce the ethereal greenish-white shimmer of the aurora, the current then travels around to the evening side of the oval and leaves the polar area as it came in: on magnetic field lines. The circuit is closed when this current reaches the dusk side of the magnetosphere.

It isn't the beauty of the aurora alone, of course, that draws scientists like Akasofu, Park and the others to the polar and other stations from which sun-earth relationships can be studied. It is more significantly the processes that create the lights and that also have profound effects on the earth's upper atmosphere that they seek. These processes may also have important effects on the weather at the surface of the earth and help channel in the solar disturbances that otherwise plague human activities on and near the surface.

A feedback loop

In fact, it is such electric fields—which have similarities to magnetic fields, but are based on electric charges and the attractive or repulsive character of those charges—that are more and more being seen as the links connecting the diverse parts of the magnetosphere and atmosphere.

"There are several sources of electric fields," says Stanford's Park, "but they are all interrelated; they share the same circuit paths. Within the atmosphere, the strongest electric fields are vertical to the earth's surface and strongest nearest the ground. These fields," says Park, "are generated by electric currents in thunderstorms; they diminish with altitude and spread horizontally as they get higher and higher.

"Electric currents flow upward from thunderstorms and fan out, just as electric fields do. Far away from the storms, the currents eventually flow back down to earth in fair-weather regions. The circuit is closed when the currents flow through the ground back to the original point. It's very much like a recirculating water fountain."

In a fair-weather electric field, the strength of the field is typically a hundred to several hundred volts per meter near the ground. In a foul-weather field, under a thunderstorm, the field strength can be 1,000 times as strong or more. At any given time, there may be several thousand active thunderstorms around the world, each acting like the nozzle of a water fountain, funneling electricity back toward the upper ionosphere where the sun and earth environments meet.

In addition to the magnetospheric

would be whipped in the flare-lashed magnetosphere to energies of 5 keV or more.

The result is that a magnetospheric electrical or magnetic (and auroral) substorm blows up and plasma flows earthward from the tail region of the cometlike magnetosphere, influenced by and influencing electric fields at high altitudes along the way.

The geomagnetic poles, where the magnetic field lines are oriented vertically relative to the surface of the earth, are situated some 11 to 12 degrees of latitude and several hundred miles away from the geographic poles. In the Northern Hemisphere, the geomagnetic polar region is a broad circle overlying many of the islands just north of Canada's Hudson Bay.

It is thousands of kilometers from the tropical and near tropical belts where the majority of the earth's thunderstorms take place. Nevertheless, it is the place in the Northern Hemisphere where magnetospheric electricity has access to the atmosphere and could be responsible for those storms recorded in the higher latitudes. Scientists seeking what seem to them to be logical interconnections between the two generators are drawn inevitably to those poles.

Sartor, for instance, finds it more than coincidental that the north geomagnetic pole lies along the parallel of longitude that passes near the major region of thunderstorm activity in the Southern Hemisphere.

Aware of the absence of any apparent *local* connection between magnetospheric and lower atmospheric electrical activity near the pole, he believes that he has found a link nevertheless in a new model of global atmospheric electricity developed by P. B. Hays of the University of Michigan's Space Physics Laboratory and R. G. Roble of NCAR. "You don't need thunderstorm activity in the high latitudes to show the connection," Sartor reports. "The model shows that the response is global."

"In essence," Sartor declares, "this model provides a missing quantitative link between the ionospheric-magnetospheric models and those of the weather-producing lower atmosphere, and should be a great boon to the physical understanding of the effect on the atmosphere of the solar particulate emissions and the resulting earth's sensible weather changes."

Evidence from Antarctica that atmospheric electricity is directly influenced by

Windows at the poles

The Arctic and Antarctic regions provide excellent vantage points from which scientists can observe the dynamic activities in the upper atmosphere. For it is there that the earth's magnetic field lines flare like trumpet horns down into the regions around the geomagnetic poles.

Indeed, there are several dozen stations at the north and south geomagnetic polar regions—some dating back to the International Geophysical Year (1957-1958), some still being added—where several hundred scientists from nearly a score of nations carry out a broad spectrum of experiments.

Using cameras, magnetometers, photometers, cosmic ray detectors, radio receivers and radars, some footed firmly to the ground and some flown aboard balloons or sounding rockets, these scientists are trying to map the boundaries between the magnetosphere (see main story), the ionosphere and the ground, along magnetic field lines. These boundaries change both with time and place as the solar plasma interacts with the magnetosphere.

By taking simultaneous measurements of the magnetic, electric and particle changes occurring at opposite ends (called "conjugate points") of a geomagnetic field line, scientists are able to follow the motions of the inner parts of the magnetosphere. (One such pair of points lies between Antarctica's Siple Station and Roberval, on Lake St. Jean, Quebec.)

More than that, scientists can also induce changes in the upper atmosphere by pumping very low-frequency waves into the magnetosphere. At Siple Station, for example, Stanford University scientists this year are installing a powerful new transmitter to operate with a 21-kilometer-long dipole antenna.

It is virtually the only place on the surface of the earth, according to Stanford's Robert Helliwell, where experiments can be carried out on the interactions between very low-frequency waves and energetic particles in the magnetosphere. The thick ice sheet, above which the antenna wire is strung on aluminum posts spaced every 190 feet, minimizes electric losses from antenna to ground and thus improves the antenna's radiating efficiency.

In addition, the plasmapause—the outer boundary of the plasmasphere—is also the inner boundary of a large reservoir of charged particles encircling the earth. It dips fairly close to the surface of the globe above Antarctica, bringing it within range of the transmitter. There is an accessible conjugate point at the opposite end of the field line at Roberval, which can receive the signals from Siple for later analysis.

Paradoxically, the Antarctic Continent is also considered by scientists to be an advantageous site for research because of things it *lacks:* national boundaries and air traffic. Because of this, balloons of more than 30,000 cubic meters and sounding rockets can be sent aloft, carrying instruments to altitudes of 40 to 160 kilometers without fear of violating some other nation's air space or of posing a threat to commercial jet liners.

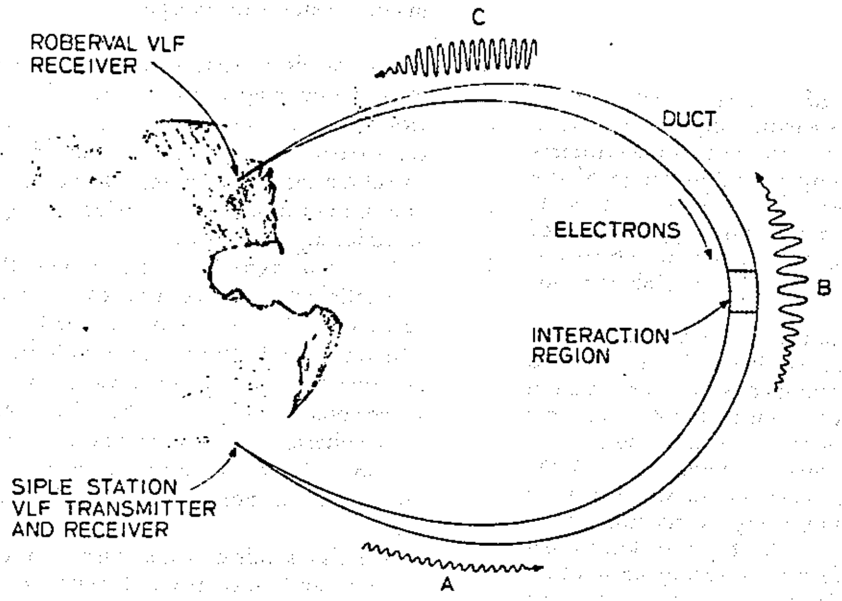
In the Northern Hemisphere, the North American Continent, the Scandinavian Peninsula and the Soviet Union are all areas within or near the Arctic Circle (roughly 67 degrees north latitude) where important magnetospheric investigations are being carried out as part of the International Magnetospheric Study (IMS).

Because magnetic variations in the upper atmosphere are at present one of the most reliable means of monitoring continuously from the ground what's happening in the magnetosphere above, the IMS has called for the establishment of a series of magnetometer networks along geomagnetic meridians.

The networks, consisting of anywhere from 5 to 13 stations on a particular meridian, use such instruments as all-sky (wide angle) cameras, magnetometers, riometers (relative ionospheric opacity meter, basically a narrowly tuned, single-frequency radio receiver), photometers and ionospheric sounders to record the development and decay of magnetospheric storms.

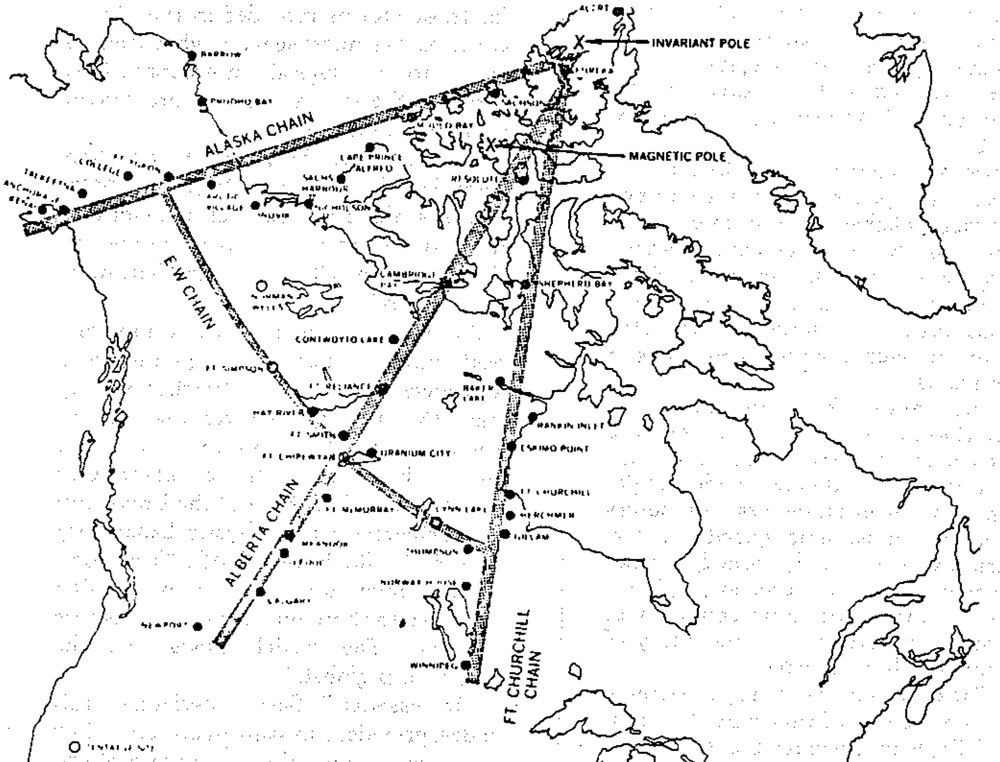
The polar regions are also the sites of stations like McMurdo in the Antarctic and Thule in Greenland, in the Arctic, where, because the earth's magnetic field influences the penetrability of very energetic particles, studies of cosmic ray penetrations are done.

By determining the asymmetry of the received cosmic rays at the polar regions, where they are almost perpendicular to the plane of the ecliptic, scientists can deduce something about interplanetary conditions outside the plane.●



Whistlers. Wave-particle interactions, called whistlers, are studied from conjugate points at which a geomagnetic field line touches down.

C. G. Park



IMS net. The North American high-latitude magnetometer network, planned as part of the International Magnetospheric Study.

solar activity was recently reported by lliam E. Cobb of the National Oceanic ...d Atmospheric Administration. Data gathered by electrosonde launches from Amundsen-Scott Station in late 1977, Cobb reports, revealed large electrical currents over the South Pole during a solar flare.

Cobb's first balloon was released, fortuitously, just before the flare's onset and showed "normal," weak levels of atmospheric electricity; subsequent launches revealed strong increases in air-to-earth current over the next two days. From the stratosphere to the ground, Cobb reports, the measured electrical current exceeded pre-flare values by more than 70 percent. Global circuit theories, Cobb declares, will have to be revised to accommodate solar as well as thunderstorm effects.

Cobb's findings do not extend, of course, to solar influences on thunderstorm activity, though partisans of that controversial connection will be able to draw the link, by inference.

Not only are the links between magnetospheric electricity and thunderstorms highly controversial, but the whole subject of interaction between magnetospheric and atmospheric electricity is fraught with pitfalls as well. As Park puts it, "Although evidence for the existence of sun-weather connections has been increasing in recent years, there still remain many well-respected skeptics."

Part way in

Ralph Markson of the Massachusetts Institute of Technology, for instance, is willing to go into the subject, but only so far: He limits his suggestion to the possibility that "the earth's electric field would be modulated by solar activity; whether this would affect thunderstorm development is highly speculative and depends on the thunderstorm-charging mechanism—something we do not know."

Markson suggests that the most intense ionizing radiation may penetrate to within 15 to 20 kilometers of the earth's surface at high latitudes; such altitudes are close to those at which the tops of thunderstorms form.

According to a classical "global circuit" model that postulates a giant "capacitor," Markson notes, the huge voltage drop between the lower ionosphere and the surface of the earth—and the current in the global circuit—derives from positively charged atmospheric ions flowing down toward the earth and negatively charged ions drifting upward toward the ionosphere.

Markson's hypotheses are interesting for several reasons:

- They would identify a possible mechanism for the solar control of atmospheric electrification and possible meteorological consequences.
- They postulate a link whose time characteristics seem to match the time span between observed solar activity and subsequent changes in certain aspects of the earth's weather—usually a day or so after a solar event such as a solar flare.

- Further, they provide—in the form of electric fields—a sequence of linked ents by which variable solar activity can ease energy already stored in the atmosphere as latent heat in water.

The role of Van Allen's belts

Indeed, the electric field fluctuations hold considerably more weight in some scientists' opinions than solar radiative heating of the atmosphere as an explanation for thunderstorm response to solar change—especially in light of the presence of a reservoir of charged particles with which the fluctuations can interact; the Van Allen radiation belts are such a reservoir.

Individual particles in the Van Allen belts may have a range of energies from a few electron-volts to several million electron-volts, according to Robert Helliwell, professor of electrical engineering at Stanford. "Consider a particle with an energy of 35 keV," Helliwell says, "just sitting there in the belts. But if it's perturbed and knocked out of the belts, it can ionize upwards of 1,000 particles—giving up 35 electron-volts in each collision—before it becomes a low-energy particle."

Like water droplets on a tree shaken by the wind, these high-energy particles can be precipitated out of the Van Allen belts by several forces: the low-frequency electromagnetic waves created by lightning flashes and known as "whistlers," the waves (also low-frequency) of navigational or communications transmitters and even the radiation from utilities' high-voltage power lines, a very low-frequency discharge discovered to have this effect by Helliwell and his colleagues from Stanford only a few years ago.

What happens in such wave-particle interactions, Helliwell explains, is that the very low-frequency signal given off by a lightning stroke sometimes enters a magnetic field line. It is caught there, like a marble in a drainpipe, oscillating back and forth along the ductlike field line from one geomagnetic pole, up through the Van Allen belts and down to a point at the opposite geomagnetic pole. It does this, at speeds approaching that of light, for perhaps as long as five seconds. And every time it passes high above the equatorial zone, where the density of charged particles in the belts is the greatest, it interacts with some of the belts' particles. These particles amplify the wave, generate new frequencies within it and send them spiraling down the field line into the polar atmosphere, where they are heard as rising or falling "whistler" tones on radio receivers.

Sweeping the belts

By precipitating energetic electrons from the Van Allen belts, these different electromagnetic waves alter the conductivity of the transitional layer between the earth's upper stratosphere and lower ionosphere. Whether this affects the electric fields in *this* layer enough to influence the growth and development of storms below, Helliwell says, is not presently known. But the finding—if the interactions are powerful enough—does suggest a way of temporarily "sweeping clean" the belts.

This might be considered a desirable or even necessary ability for some contemplated space projects, especially those carrying equipment susceptible to damage from energetic particles as space tugs maneuvered them from near-earth orbit, where the structures would be assembled, up through the Van Allen belts to a high, stationary orbit.

Before the maneuver would be carried out, Helliwell speculates, it might be possible for earth-based transmitters to beam low-frequency waves into the magnetic field lines and thus depopulate the belts of their charged particles. "After astronauts had got the satellite to where it was supposed to be," Helliwell adds, "you'd stop sweeping the belts out and allow them to recharge themselves."

Alfvén's wave

Wave-particle interactions are also of interest to Louis J. Lanzerotti, an atmospheric physicist and member of the technical staff at the Bell Laboratories in Murray Hill, New Jersey. Ever since the eighteen-sixties, Lanzerotti notes, it has been known that the earth's magnetic field undergoes rapid, unexplained, transitory changes in both intensity and direction—changes that scientists like Lanzerotti call "geomagnetic pulsations."

Just as the flow of wind over a lake or body of water can induce the formation of ripples in the water, Lanzerotti says, so too can the flow of the solar wind over the magnetosphere give rise to a wave-form called a hydromagnetic wave, or Alfvén wave (after Hannes Alfvén, the physicist who predicted back in 1940 that waves could exist in an ionized, magnetic medium).

From the distribution of the geomagnetic pulsations recorded during the International Geophysical Year of 1957-1958, scientists concluded that these quick fluctuations in the magnetic field, each lasting only a few minutes or less, were indeed attributable to hydromagnetic waves.

There is much that is still unknown about these ultralow-frequency and very long-wavelength ripples, says Lanzerotti, but it does appear that they, too, can depopulate the magnetosphere's reservoirs of charged particles, particularly protons.

"Additionally, there are indications that hydromagnetic waves can heat the solar corona and interstellar dust clouds," Lanzerotti notes, "and a recent Japanese experiment suggests that Alfvén waves can contribute some amount of heating of the plasma in a Tokamak [experimental thermonuclear fusion] machine."

Some of the best places from which to do research on the magnetosphere, Lanzerotti notes, are the geomagnetic polar regions (see "Windows at the poles," accompanying this article). "These sites are unique in relation to certain parts of the magnetosphere," says the Bell physicist, "like the cusps."

The Arctic and Antarctic sites provide researchers with conjugate points—places located at opposite ends of the same magnetic field line like Siple on the Antarctic Continent and Roberval in Canada—from which to measure the motions within the magnetosphere. The sites also provide a good vantage point from which instruments can record the interactions among plasmas, waves, magnetic fields and electric fields.

As part of the International Magnetospheric Study effort, new facilities have either been or soon will be emplaced in the Arctic and Antarctic. A network of magnetometer stations has been set up along three meridians in Alaska and Canada where, with all-sky cameras, magnetometers and riometers (a radio receiver tuned to a particular narrow frequency), the growth and decay of magnetic storms in the auroral oval overhead will be monitored.

When all of these data, including that obtained by satellites dedicated to IMS research, by superballoons launched from the icy surface of Antarctica, by aircraft and other means, are finally collected, scientists will then have at least the raw material needed to forge the synthesis that scientists say must be forged if the relationships between the earth and the sun are ever to be understood—both in their broad scope and their fine, important detail.•

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