23 April 1965, Volume 148, Number 3669 SCIENCE

Auroral Phenomena

Associated with auroras in complex ways are an extraordinary number of other physical phenomena.

B. J. O'Brien

Few research areas in the physical sciences have the richness and variety found in auroral phenomena. When auroras occur, the radio stars may appear to twinkle or scintillate, and there may be low rumbling subsonic pressure waves and also audible hissing and crackling sounds, as well as a hiss of electromagnetic radiation in the audio-frequency range. Intense fluxes of electrons and protons bombard and heat the atmosphere causing a "blackout" of radio communications, and there may be violent oscillations of the geomagnetic field and a flow of large currents high in the atmosphere and deep in the earth below.

The relations and correlations between the various auroral phenomena may provide clues to their causal mechanisms. Because these auroral phenomena are uncontrollable, the scientist cannot vary given parameters and note the effects on other parameters. It must therefore be emphasized that a simple correlation between two auroral phenomena does not imply a causal relation between them.

However, several cause-and-effect relations are established, and these are depicted in Fig. 1. The local (or terrestrial) cause of auroral phenomena is shown as a question mark (center) to represent little-understood energization and acceleration processes that are the source of the particle accelerations and magnetic perturbations that in turn lead to the auroral phenomena shown in the lower part of Fig. 1. These unknown processes occur in the outer regions of the magnetosphere (Fig. 2), which is the cavity hollowed out in the solar wind by the geomagnetic field.

The author is professor of space science, Rice University, Houston, Texas.

The solar wind is a stream of plasma blown radially out from the hot solar corona. Near the earth the wind consists mostly of protons with energy of about 1000 electron volts (1 kev) and electrons with energy of about 10 ev in a density of approximately 10 particles per cubic centimeter (*1*). The solar wind is supersonic, so when it hits the geomagnetic field a shock front is created at a standoff distance of about 20,000 kilometers from the magnetopause, or boundary of the magnetosphere (Fig. 2).

The geomagnetic field is distorted, and field lines are blown back to form a long tail (*2, 3*) on the dark side of the earth (Fig. 2). The magnetosphere is the region around the earth at altitudes above about 500 km where the geomagnetic-field-energy density is greater than the kinetic-energy density of all charged particles, so that the motion of these particles is controlled by the field and some of them are trapped as Van Allen radiation (Fig. 2). By contrast, in interplanetary space the kinetic-energy density of the solar-wind particles is greater than the magnetic-energy density (*1*), and so the solar-wind particles control the direction of the magnetic field and distort it into the form of an Archimedes' spiral. In the magnetosheath is a confused realm between the above two extremes.

As discussed below, several auroral phenomena have the characteristics that (i) they are continuously occurring but with (ii) changing strength and characteristics. It it generally supposed that the continuous yet gusty solar wind is responsible for these features (that is, it can be validly included in Fig. 1). When the velocity of the wind increases, so does the level of geomagnetic activity (*1*). However, the actual coupling mechanism whereby energy and perhaps particles are extracted from the solar wind and utilized in auroral phenomena is not at all clear, as indicated by the query in Fig. 1. The amount of power dissipated in known auroral phenomena (*4*) over the world during large magnetic disturbances is approximately 10^{18} ergs per second. Two apparent sources of such power are the solar wind, which brings about 10^{20} erg/sec to the front of the magnetosphere, and simply the rotation of the earth, which has rotational kinetic energy of about 10^{37} ergs. So both sources are included in Fig. 1. Perturbations in the solar wind and plasma instabilities that naturally grow in the magnetosheath are both included in the figure, although their relative importance is unknown.

It is certain that the sun is important in these causal relations. The great auroras are invariably preceded, a day or so earlier, by unusually intense solar activity (*5*).

Because of this relation auroras are seen at low latitudes most often during the portion of the 11-year cycle when the sun is very active. Auroral activity, like geomagnetic activity, lags behind the sunspot activity by about a year, so the relation is not by any means a perfect one.

The time delay of 1 day between a great solar flare and the occurrence of a great geomagnetic storm and aurora implies that the perturbation (see Fig. 1) is carried by slowly moving corpuscular radiation rather than by electromagnetic radiation traveling at the speed of light. The fact that an aurora is continuously present (*4*) implies that the perturbation and the appropriate medium are always present, and, of course, a gusty solar wind fulfills these requirements. However, the actual particles (electrons and protons) of the solar wind have far too little energy (about 10 ev and 1 kev, respectively) to penetrate to auroral depths (around 100 km) in the atmosphere even if they had allowed trajectories, since the requisite penetration energies are about 10 kev and 150 kev, respectively. Therefore there must be a "local" (that is, magnetospheric) acceleration or energization process, although whether this acts on solar-wind particles, on thermal residents of the magnetosphere, or on low-energy trapped Van Allen particles is still unclear (*4*). This acceleration process must then be triggered or initiated by a perturbation in the solar wind.

This article deals in detail with the phenomena that follow the query of Fig. 1.

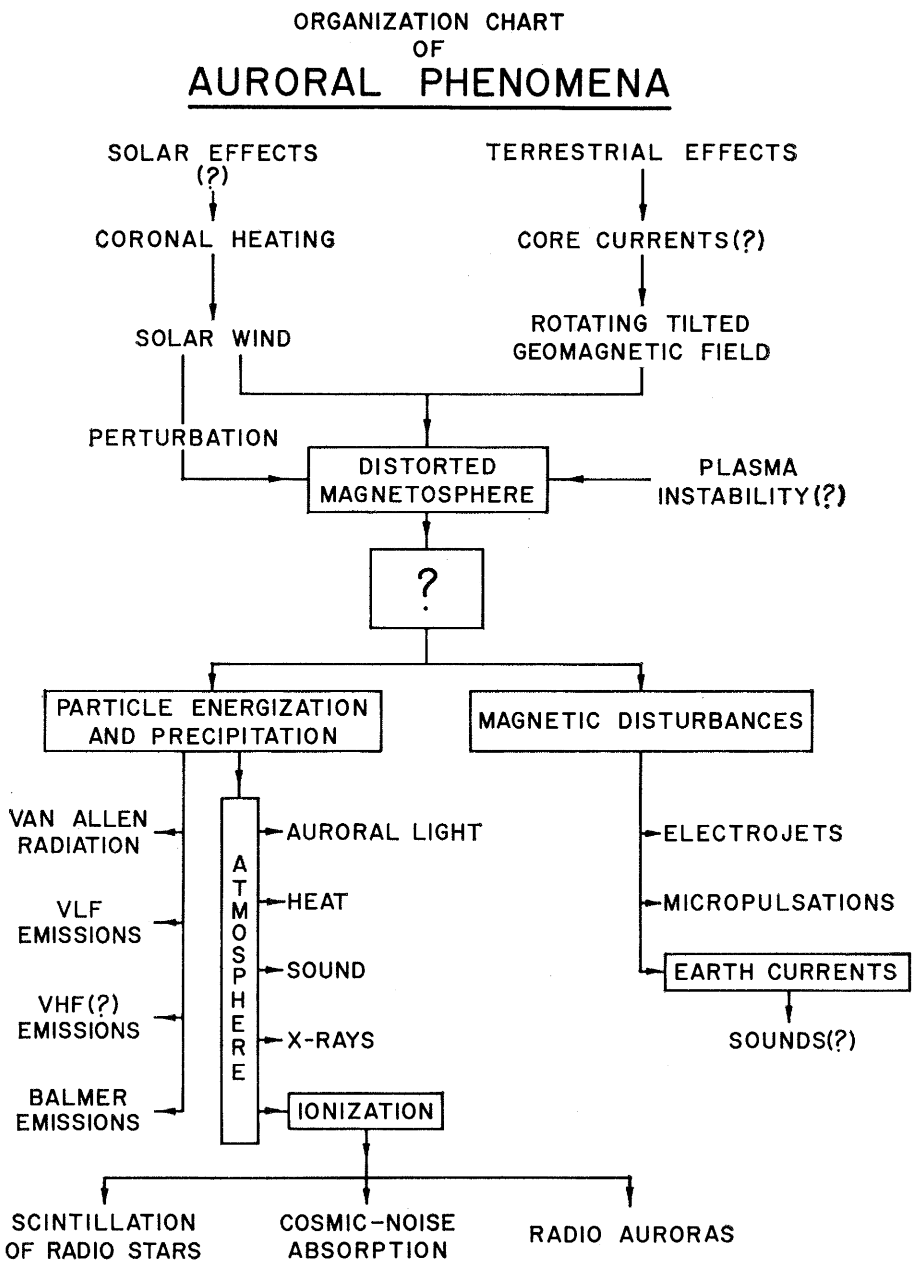

Fig. 1. Diagram of causal relations in auroral phenomena. The question marks after several items indicate that they are little understood or have not been extensively measured. The large central question mark is a temporary substitute for an adequate auroral theory.

Auroras and Their Light

Auroras occur most often near the polar regions in both hemispheres, but after a violent outburst or flare on the sun, great auroras may occur at far lower latitudes, sometimes even as close to the equator as Singapore. The region where auroras occur every night is called the auroral zone, which extends in two rings around the earth (*5*). The solar wind distorts the magnetosphere and compresses it more on the dayside than on the nightside (see Fig. 2). Consequently the auroral zone in each hemisphere is tilted and is between magnetic latitudes of about 73° to 78° on the dayside but 65° to 70° on the nightside (*4*). The very existence of such a zone is presently a puzzle.

The actual light seen as an aurora (Fig. 3) is emitted at altitudes between about 90 and 1000 km. Most of this light comes from atmospheric constituents between 100 and 120 km excited by bombardment by electrons of some 10 kev energy. The most abundant of these constituents are oxygen and nitrogen, and spectral analysis of auroral light shows that their emissions are the brightest (Fig. 4). In fact, analysis of auroral light from various altitudes can provide information on the relative composition of the atmosphere at these altitudes. As the relative brightness of the spectral lines (from atoms) and bands (from molecules) changes from aurora to aurora, so does the apparent color of the aurora.

The colors most often seen in auroras are a pale green from the atomic oxygen line (OI) at 5577 angstroms and a deep red from the atomic oxygen lines at 6300 to 6364 Å, with the latter most pronounced at high altitudes (*5*). Another very intense auroral emission is the band from ionized molecular nitrogen N_2^+, whose "head" is around 3914 Å (see Fig. 4). In most auroras, emissions at 5577 and 3914 Å are of comparable intensity, and these are the brightest emissions over the spectral range 3800 to around 7000 Å. The human eye has peak spectral sensitivity around 5550 Å, and its response to light at 3914 Å, in the deep purple regions, is less than 1 percent of its response to an equal flux of 5577-Å photons, so most auroras appear pale green or, if they are barely visible, white.

Besides the visible light emitted in

auroras, there are also infrared and ultraviolet emissions. To detect the ultraviolet one has to carry detectors to altitudes higher than 30 km above the absorbing atmospheric ozone.

The brightness of auroral light can vary from below visual thresholds to intensities 1000 times this threshold. The brightness is classified by an International Brightness Coefficient (IBC) ranging from IBC I to IBC IV in tenfold steps of brightness. Thus an IBC I aurora is just visible and is roughly as bright as the Milky Way, whereas an IBC IV aurora illuminates the ground as brightly as the full moon (*5*). A more objective measure is the intensity of OI (5577 Å), which in an IBC I is 10^9 photons cm^{-2} sec^{-1} or 1 kilorayleigh (*5*), while an IBC IV radiates 10^{12} photons cm^{-2} sec^{-1} of 5577 Å or 1000 kilorayleighs. The brighter an aurora is, the less frequently it occurs (*5*). There is always some auroral emission in the auroral zone, although often it may be too faint to be seen (*4*).

There are some rare types of aurora other than those found in the auroral zone. There is the "polar glow" of 3914 Å, caused when solar protons bombard the polar cap with sufficient energy (about 10 Mev) to penetrate deeply into the atmosphere. There they lose most of their energy at such low altitudes that there is essentially no atomic oxygen and most of the light is emitted by molecular nitrogen. There are also the high-altitude and the mid-latitude red arcs (*6*) and the occasional great red auroras, such as the one that was seen on 11 February 1958, whose light was almost entirely 6300 to 6364 Å emitted by atomic oxygen. The excitation mechanism in these phenomena must be some low-energy process that can provide 2 ev of energy to atomic oxygen to generate 6300 Å or 6364 Å but not 4 ev which would generate comparable brightness of the green 5577 Å (see Fig. 5).

Auroras vary in shape as well as in color. The shapes may be roughly classified as either horizontal or vertical. If horizontal, they are called arcs or bands; generally these lie at an altitude of about 100 to 130 km and may be a few kilometers in latitudinal extent and several thousand kilometers in longitudinal extent. If auroral structures are magnetically vertical, they are called rays (see Fig. 6) and when viewed from the side give an appearance like a searchlight beam about 1 km in diameter but extending in altitude from about 100 km to sometimes as high as 1000 km. As I discuss later, the arcs are certainly excited by bombardment of the atmosphere by electrons of around 10-kev energy. It is difficult to explain the rays as being produced by a simple particle bombardment; they may represent an effect of a space-charge instability that causes an aurora to wrap around itself and be pleated vertically like a curtain, so that when one sees the additional brightness of several thicknesses of the "curtain," one sees a ray.

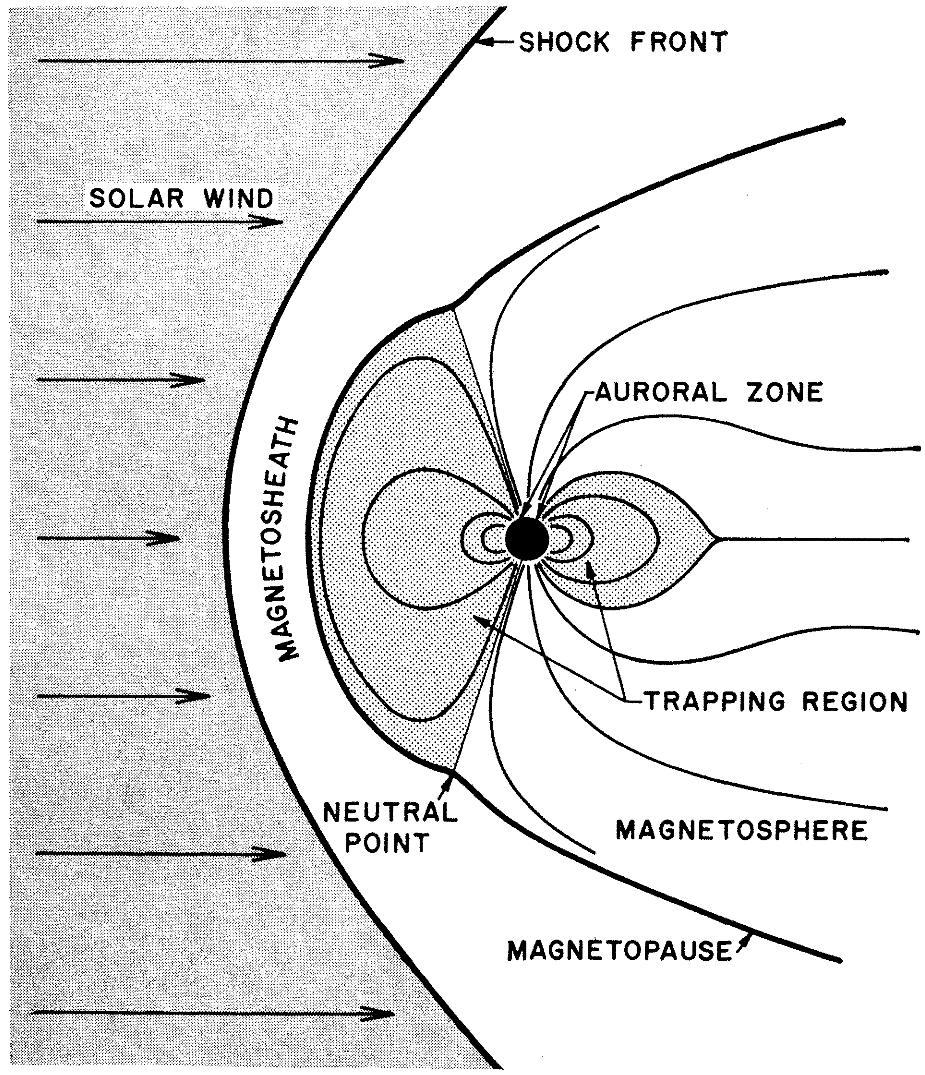

Fig. 2. Sketch of the earth's environment. The auroral zone is at the boundary of trapping of Van Allen radiation, at about 75° magnetic latitude on the midday side but about 69° on the midnight meridian. The sketch is an admixture of theoretical predictions and experimental facts. [After Dessler and O'Brien]

The motions of rays are often reminiscent of wavelike motions, and indeed Chamberlain (*5*) describes the effect as follows for a bright-rayed band: "A region a few degrees wide and including a number of rays may appear much brighter than the rest of the band and this bright patch will move rapidly in either direction, resembling a searchlight sweeping across a gigantic bamboo curtain" (see Fig. 6). He concludes that it is not the individual rays that are moving but rather the excitation pattern, although the cause of this motion is not understood. Recently a ground-based television system has measured (*7*) ray motions as fast as 100 km/sec horizontally (see Fig. 6).

There are also auroral-zone emissions without distinct structure, and these have been given the name of mantle auroras (*8*). It is the mantle aurora that makes the night sky always so bright in the auroral zone that the Milky Way can scarcely be distinguished by the human eye.

Bombardment of Auroral Atmosphere by Energetic Charged Particles

From laboratory studies of gas discharges, it was known several decades ago that if air was bombarded by energized electrons (cathode rays) it would glow and emit light. It was then commonly thought that a similar process might be the cause of auroral light. The magnetic control of auroral features such as the auroral zone and the alignment of rays along the magnetic field lent plausibility to the concept that the excitation was produced by charged particles whose motion would be controlled in such ways. The occurrence of great auroras a day or so after very large solar outbursts led to speculation that the bombarding particles might have been energized in and then come from the sun; although, as I pointed out earlier, the first part of this hypothesis is certainly not true, the second may be. It was reasonably assumed that, if charged particles did cause auroras, the most likely species would be the commonest, protons and electrons.

That protons with energies of tens to hundreds of thousands of electron volts sometimes bombard the auroral atmosphere was proved in 1950 by ground-based measurement of their characteristic spectral emissions of Balmer lines. As a proton spirals down around the magnetic field line into the denser atmosphere, it may capture an electron and become a hydrogen atom in an excited state. The electron then returns to the normal or ground state, and a photon of characteristic energy is radiated to take away the difference of the two energy states. Each proton with an initial energy of about 100 kev goes through this process hundreds of times as it plunges into the atmosphere and is absorbed. Most of its 100 kev will ionize the atmosphere, but it will emit many photons of the Balmer series (*5*), including about 60 photons of H_α, the red emission nominally at 6563 Å.

Because the hydrogen atoms are moving with respect to the observer when they emit this light, their wavelength λ is Doppler-shifted by a fractional amount $\Delta\lambda$, where

$$\frac{\Delta\lambda}{\lambda} = \frac{v}{c} \quad (1)$$

where v is the velocity of the atom relative to the observer and c is the speed of light. Wavelength shifts of several angstroms are observed, as shown in Fig. 7.

The profiles shown in Fig. 7 are explained (*5*) by the assumption that the light comes from atoms that on the average spiral around and down the magnetic field lines **B**. The individual neutral hydrogen atoms are not guided by the geomagnetic field, of course, but when each loses its electron (as it does repeatedly in atomic collisions in the atmosphere) it becomes a proton and is then guided by the Lorentz force that acts on any charged particle that moves in a magnetic field. When one views the magnetic horizon one looks edge-on at the spiraling particles, so that equal numbers are moving away from and toward the observer, and the Doppler profile is simply broadened. When one looks toward the magnetic zenith most of the particles are moving toward the observer, and the Doppler profile is shifted toward shorter wavelengths.

Such observations of Doppler-shifted Balmer emissions were the first conclusive evidence of particle bombardment in auroras. However, ground-based photometric analyses of auroral light later showed that most localized auroral emissions are not sustained by proton bombardment (*5*). The technique used by Omholt and others (*5*) is the comparison of the relative brightness of a molecular nitrogen emission (such as 3914 Å) and a Balmer emission of hydrogen (such as that around 4861 Å). The brightness of 3914 Å is proportional to the total energy dissipated (1 erg cm^{-2} sec^{-1} of charged particles will produce 200 rayleighs of 3914 Å at 100 km), while the brightness of 4861 Å is roughly proportional to the flux of incident protons, with 150 rayleighs of 4861 Å from a proton energy flux of about 1 erg cm^{-2} sec^{-1}. So if protons sustained the auroral light, one would expect to measure 3914 Å and 4861 Å with comparable brightness, whereas in fact the first is usually ten or more times brighter than the second.

Auroral electrons emit electromagnetic radiation in the audio- and radio-frequency range, as I discuss below. But unlike protons they do not have such characteristic optical emissions that can be observed on the ground and they were detected directly only when appropriate instruments such as Geiger tubes and scintillation detectors were flown on rockets into the actual particle fluxes at altitudes of above 100 km.

The first measurement was made in

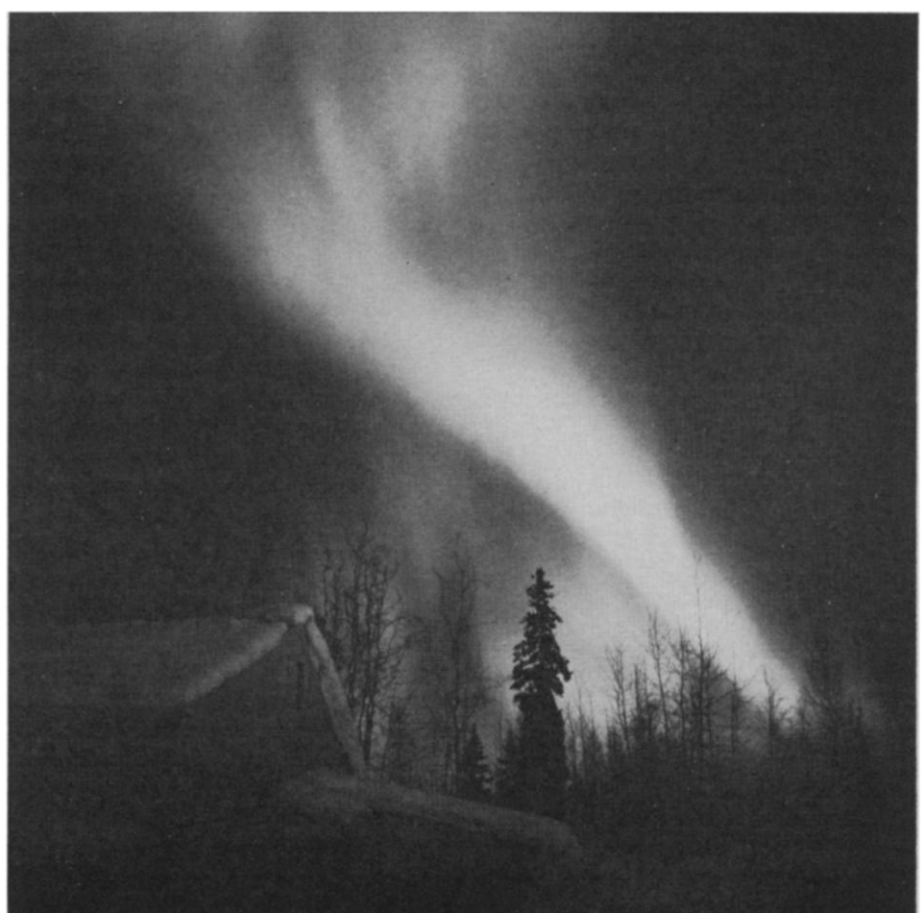

Fig. 3. An auroral band. [Courtesy V. Hessler]

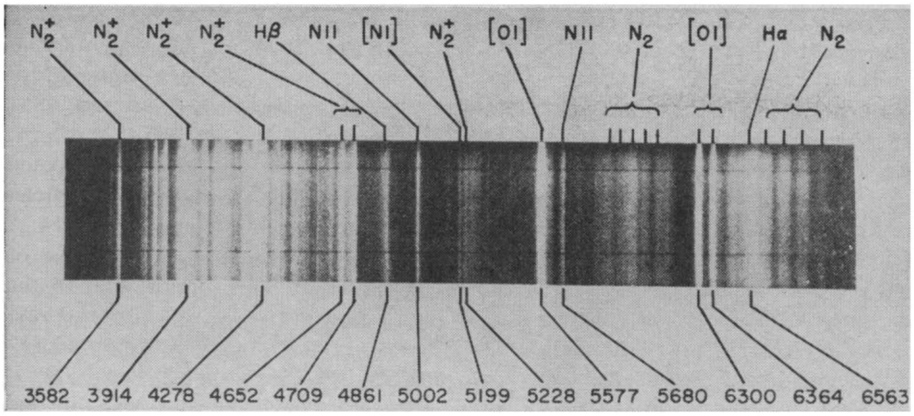

Fig. 4. Spectrum of the bright aurora of 2 March 1957 obtained with a 27-minute exposure of a patrol spectrograph which viewed a meridian section of the sky from Yerkes Observatory, with north at the top and south at the bottom, and horizontal dark lines at zenith angles of 45°. The lower numbers are wavelengths in angstroms. [Courtesy J. Chamberlain]

the northern auroral zone around 1953 by a group headed by J. A. Van Allen from the State University of Iowa. The group sent up Geiger tubes by rockoons (rockets launched from balloons) in a latitude survey of cosmic radiation, and an "anomalous" excess of particle flux was detected in the auroral zone (*9*). All the rockoon flights took place during the day, and the flux was not directly associated with an aurora, but only in a general way with the auroral zone.

In February 1958, during the International Geophysical Year, two groups fired rocket-borne instruments directly into visible auroras and observed simultaneously both cause and effect—that is, both particle fluxes and auroral light (*10*). They proved that on several occasions electrons with energies about 10 kev bombarded the atmosphere in sufficient numbers to sustain the visible auroras. Furthermore, the electron fluxes appeared most intense where the light was most intense, and they varied greatly in time and space as do auroras. The particular horizontal shape of the aurora (for example, see Figs. 3 and 6) is then a consequence of the shape or morphology of the beam of electrons, but what determines this shape is not known. The proton fluxes, by contrast, were relatively constant in time and space and carried too little energy to sustain the bright auroral forms. The energy spectra of the protons and electrons were measured, and those of the electrons were found to be much more variable from flight to flight than those of the protons. Later simultaneous satellite-based measurements of auroral light and the particles that excited it showed (*4*) that these electrons are precipitated into the atmosphere from altitudes above 1000 km. Thus their source must be in the magnetosphere (see Fig. 2) although its altitude has not yet been determined.

When auroral electrons are slowed down in the atmosphere they, like any declerated electrons, emit x-rays or bremsstrahlung, which are much more penetrating than the electrons themselves. So, although the auroral electrons themselves do not penetrate below altitudes of about 90 km, the x-rays they produce may go down to about 30 km. Most of the energy loss of the low-energy auroral electrons is caused by many small collisions with atmospheric constitutents, which then emit the auroral light, and only about 0.1 percent of the particle energy is dissipated in bremsstrahlung. Nevertheless, several groups have used balloon-borne detectors such as scintillation counters as very powerful tools in studies of the precipitation of electrons. In such studies (*11*), the conversion ratio, 10^5 electrons cm^{-2} sec^{-1} give 1 photon cm^{-2} sec^{-1}, is generally valid to a factor of about 3. Anderson (*11*) has found repetitive pulses of x-rays that occur with about 0.2-second duration and about once per second. This effect must be caused by temporal changes in the primary electrons, and it indicates a systematic dynamic acceleration process in the magnetosphere which is not understood at present.

Data from balloon-borne detectors flown from Alaska and from Macquarie Island at the same time have shown that similar electron precipitation occurs at the same time in both hemispheres in regions called conjugate areas, which are at opposite ends of magnetic field lines (*11*). Such studies and others of auroral phenomena imply that there must sometimes be a form of "communication" such as closed magnetic field lines between the two hemispheres. However, it is not certain that visual auroras themselves are identical at conjugate areas. This matter is discussed below since it is vital to resolution of the problem of whether the source of auroral electrons occurs on "open" field lines or on "closed" lines (see Fig. 2).

The earth's atmosphere below auroras must be a significant source of x-rays that radiate into space.

Ionization

Bombardment of atmospheric constituents by energetic charged particles and by bremsstrahlung is a major source of high-latitude ionization. The usual sources of ionization that create the ionosphere at lower latitudes during the day (that is, sunlight, solar ultraviolet, and x-rays) also maintain an ionosphere in the auroral and polar regions. But particle bombardment can sometimes

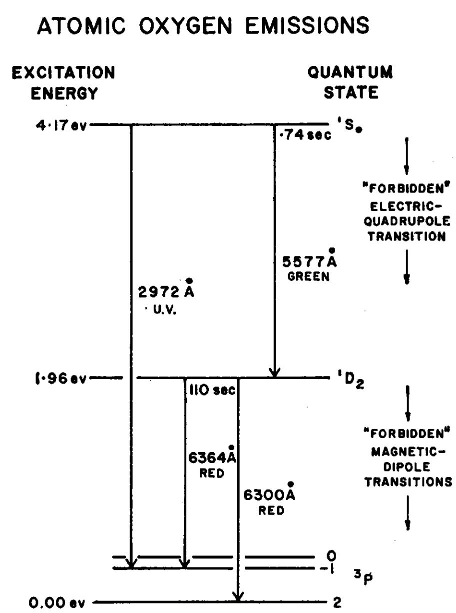

Fig. 5. Energy level diagram of the two excited states of atomic oxygen from which an electron returns and liberates a photon of the auroral lines at 5577 or 6300 Å (see also Fig. 4). These transitions or de-excitations are partially "forbidden" by certain quantum selection rules (*5*), so that the excited oxygen atom may wait for 0.74 second or 110 seconds in either state before the electron jumps down and a photon is released. If another atmospheric constituent collides with the excited oxygen atom in this time, the excess energy may be lost without liberation of a photon. So these emissions, particularly the red, come only from the high rare atmosphere.

create so much additional ionization that terrestrial radio waves become strongly absorbed, and a "blackout" may occur. Furthermore, the signal from cosmic radio sources may fade rapidly and repeatedly or scintillate in a manner analogous to the twinkling of a visible star. (The refractive index is changed over small areas, in the first case by anomalous electron density and, in the second case, by anomalous atmospheric density. This changed refractive index causes the region to act like a lens which deflects the wave.) The cosmic radio noise may then be absorbed, and the actual absorption in decibels as measured by a riometer (relative ionospheric opacity meter) then can provide an estimate of the ionization produced. The altitude at which the enhanced ionization occurs is a dominant parameter for the usual studies of frequencies around 30 Mcy/sec, and the more energetic electrons (say with energy $E_e \geq 40$ kev) that can penetrate to lower altitudes are relatively very effective. There is accordingly a reasonably close relation between, say, x-ray fluxes and riometer absorption levels. There is also evidence that pulsating and flaming auroras are more closely associated with strong and changeable absorption than are other auroral forms (*5*), but available rocket-based measurements are insufficient to determine whether such variable auroras have harder or more energetic electron spectra.

A more sensitive measure of higher-altitude ionization is obtained with an ionosonde than with a riometer. An ionosonde transmits pulses vertically with frequencies swept between 1 and 20 Mcy/sec which are reflected from regions where the electron density is sufficiently large that the plasma frequency f_p is the wave frequency f (in cycles per second). Since

$$N_e = 1.24 \times 10^{-8} f_p^2 = 1.24 \times 10^{-8} f^2 \quad (2)$$

one can estimate the electron density N_e (in electrons per cubic centimeter) from the frequency at which the wave is reflected. Such ionosonde studies have shown that often during aurora there is a blanketing layer of additional ionization called sporadic E or E_s at altitudes of about 100 km, but the relation with actual visible aurora is unclear.

Ionosondes have also been used to show that at auroral latitudes the upper regions of the ionosphere—the F regions at altitudes of around 200 km and above—rise during magnetic activity and auroral activity. This is presumably caused by a heating of the atmosphere which has now been observed with other techniques.

As mentioned above, radio stars appear to scintillate because of ionization irregularities in the upper atmosphere. Similar effects occur with radio signals from satellites. The scintillation has two measurable parameters, rate and magnitude. The rate is presumably a measure of the number of patches of excess ionization and their motions, whereas the amplitude is a measure of the anomalous density in each patch. There is apparently an increase in the rate with worldwide magnetic activity. The rate and the amplitude both increase with localized auroral activity. Heights of the irregularities of ionization that cause the diffraction of the radio waves are estimated (*12*) to be in the ionosphere in the F region and above, that is, at altitudes of about 150 to 1000 km, although they are relatively scarce above 600 km.

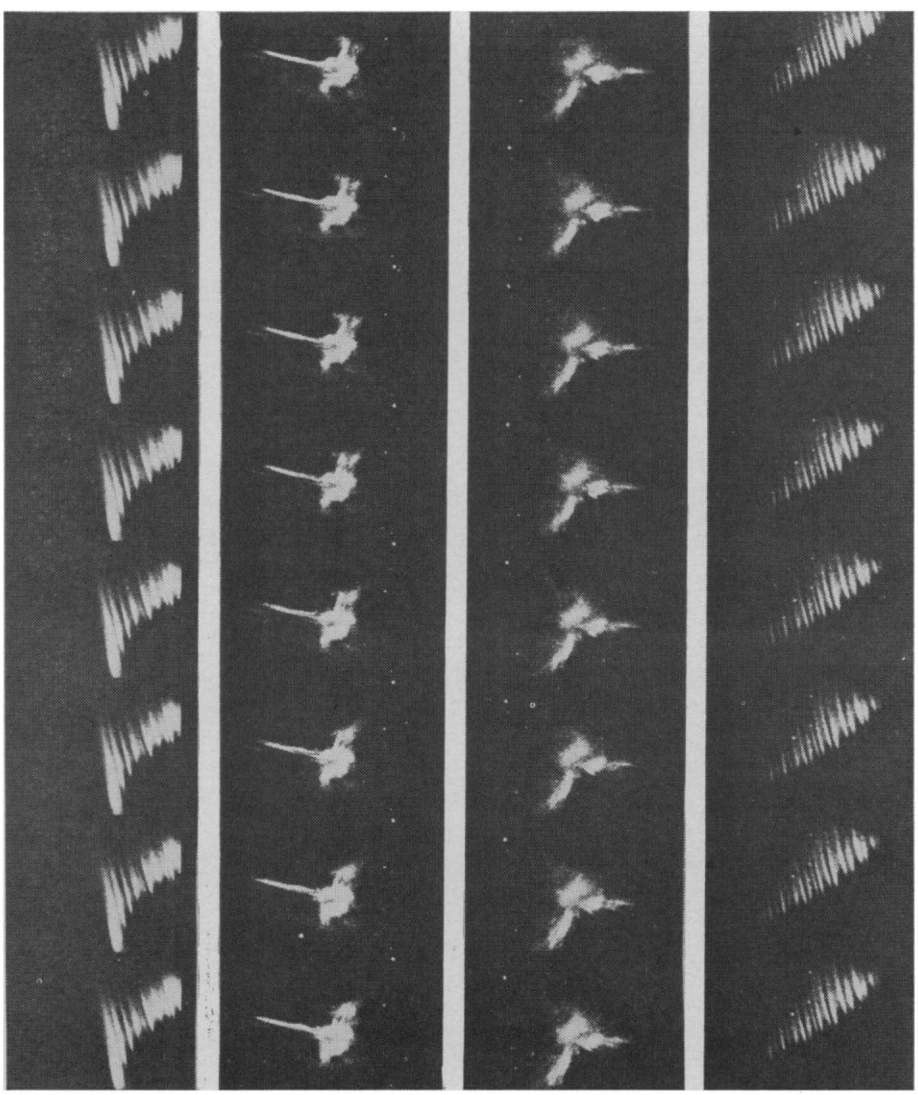

Fig. 6. In each of the four vertical sections are shown successive 1/60-second exposure photographs taken 1/24 second apart with an image-orthicon television system (*7*). The center photographs view upwards at the auroral zenith and so see the structures end-on. The two outside views show auroral rays about 2 km apart. Compare successive photographs to study temporal changes in the auroras. [Courtesy T. N. Davis]

Radio and Radar Auroras

Radio waves with frequencies of tens to thousands of megcycles per second are reflected at altitudes of around 100 km from regions that may be crudely associated with visible auroras. The detailed association with visible auroras is still controversial. But it is agreed (*5*) that "aurora is basically emitted radiation; radio aurora is basically ionization that reflects radiation. Emission of radiation requires active atomic processes, one of the most important of which is ionization. Freed electrons, when they give rise to the characteristic radio reflections, form the radio aurora."

The actual reflection mechanism that operates is not a matter of common agreement, since the two alternatives (*5, 13*) are a scattering by irregularities smaller than the radio wavelength λ and a reflection by a surface larger than λ. The second mechanism is that familiarly associated with radar studies. Generally λ is of the order of meters corresponding to frequencies of about 100 Mcy/sec. In any case, it is agreed that the reflection requires "anomalous" ionization, and it is agreed that reflection is best at near-perpendicular incidence to **B**. As a consequence, in the northern hemisphere there is a preferential reflection from the north, even if (as Dyce showed) one is inside the polar cap so that most auroras are to the south (*13*). (This directional preference is one of the reasons why it is difficult to relate radio auroras to visible auroras.) The actual reflection coefficient is quite small: for example, at 100 Mcy/sec, it is only 1 part in 10,000 of what it would be for a perfect reflector with the same dimensions as the visible structure (*5*).

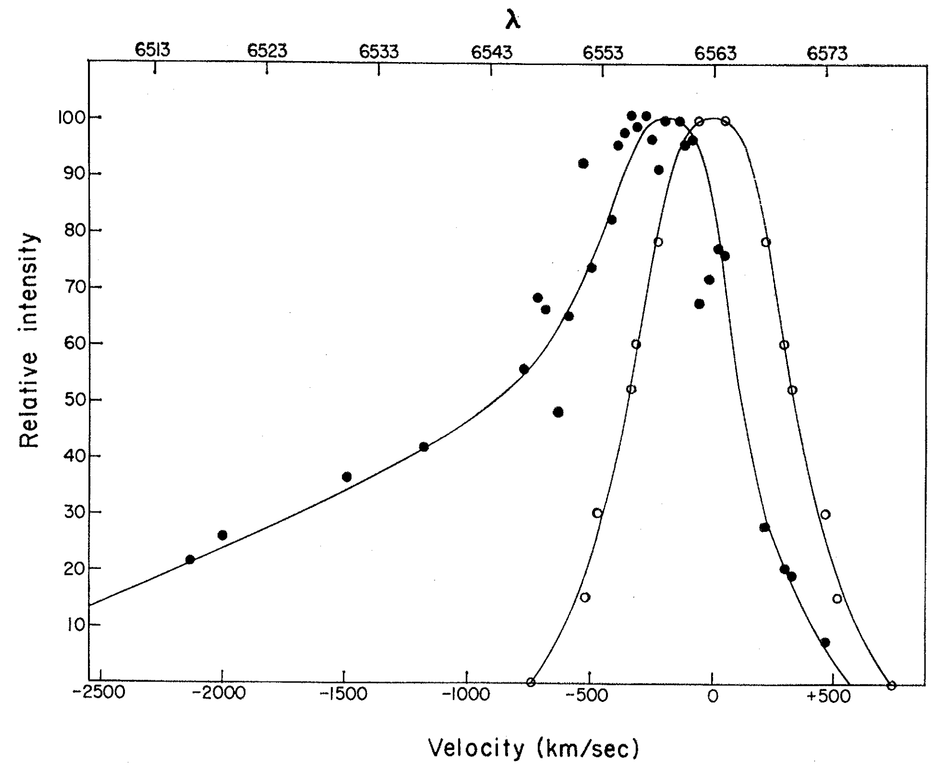

Fig. 7. Doppler-shifted Balmer emissions of hydrogen observed in auroras. The symmetric curve is from a view toward the magnetic horizon, while the skew curve is from the magnetic zenith (*5*). [Courtesy J. Chamberlain]

The fact that radio auroras were observed during the daytime provided the first proof that auroral-like phenomena do not occur only at night. Satellite- and balloon-borne detectors of energetic particles also demonstrate that the requisite conditions for excitation of auroras are present during the day (*4, 11*), and so any postulated source mechanism must produce particles during both day and night. Visual observations during the long nights of the polar winter also verify that auroras can occur over the 24-hour period.

Radio auroras conveniently provide a measure of motions of auroral ionization, since the frequency of the radar echoes is shifted or broadened as a result of the Doppler effect when the reflecting surface moves relative to the observer. The deduced motions are sometimes as fast as 1 km/sec, some 20 times faster than motions of the trails of ionization left by meteors at lower latitudes. It would appear that the radio-aurora motions are not due to local high-altitude winds (as are the meteor-trail motions) but rather to a motion of the ionizing agent (*5*) and thus of a region of ionization driven in an unexplained way. Even more rapid lateral motions are found in visual auroras, with speeds of over 100 km/sec (*7*).

The radio auroras and their effectiveness in reflection of radio waves in the range of 20 to 144 Mcy/sec have been known to amateur radio operators for many years. Transmission and reception on the "walkie-talkie" frequency of 144 Mcy/sec are generally restricted to line of sight, but when there are auroras there may be sufficient reflection to achieve long-range reception. [When auroras are not present, the electron density in the ionosphere is so low that frequencies as high as 144 Mcy/sec simply pass through it and are not reflected downward to the receiver as are lower-frequency ("short-wave") radio waves (see Eq. 2 above).] In the northern hemisphere, as noted above, the aspect sensitivity of the reflection implies that the "hams" should then point their antennas to the north rather than toward one another. The received signal fades repeatedly as the auroral ionization changes, but even so reception may be possible over an unusually long range.

Magnetic Phenomena

It has been known for more than two centuries that there is an association between auroras and magnetic activity (*5, 14*). This association is found on both a worldwide and a local scale.

During great magnetic storms, which disturb the entire geomagnetic field with changes at ground level of the order of 1 percent and which are associated with very extensive particle acceleration, "great auroras" are seen even at low latitudes (*14*). The geomagnetic disturbances can be detected on the ground even at the equator (although they are weaker there), but the accelerated electrons are constrained by the Lorentz force to spiral around the magnetic field lines and hence they cause auroras only at the base of the field lines threading through the active disturbance regions themselves.

Many localized studies of the association between auroras and magnetic activity have been made. The localized quasi-d-c magnetic changes which take minutes to occur and are of roughly reproducible patterns probably are produced in part by currents flowing in the ionosphere at altitudes of about 100 km, and in part by currents induced in the earth locally. For example, Heppner (*15*) found that when an auroral arc slowly moved over his magnetic observatory the local magnetic field changed in such a way as to be consistent with a current flowing along the arc. Various models for this current have been treated (*5, 14*). Any large currents are probably localized in the auroral arc because there the ionization and hence the conductivity have been increased greatly by the bombarding particles such as energetic electrons. But what drives the currents is not known with certainty. Also, such a current must complete the electrical circuit somewhere, but whether this is also in the ionosphere or high in the magnetosphere (*16*) is uncertain. Typical magnitudes of the currents are 10^5 amperes, generally estimated for an arc to be concentrated in a horizontal "tube" about 10 km in diameter. These horizontal currents are thought to reach peak values of about 1 to 0.1 microamperes per square centimeter. By contrast, even if one ignores neutralizing fluxes of protons, the vertical currents of bombarding electrons are thought to be less than 10^{11} electrons cm^{-2} sec^{-1} and hence less than 0.01 microamperes per square centimeter.

In addition to these slow and localized changes in the geomagnetic field near auroras, there are also rapid and worldwide oscillations with periodicities of seconds or fractions of seconds (*17*). These oscillations propagate over great distances and are detected all over the world, even at low magnetic latitudes. Since they are generally of small amplitude (less than 0.1 gamma or 10^{-6} gauss), whereas the earth's field near the ground is approximately 0.3 to 0.6 gauss, they are called micropulsations. In the auroral zones when auroras occur, these oscillations sometimes have amplitudes of tens of gammas. Some of these micropulsations are thought to be manifestations of hydromagnetic waves, oscillations of the geomagnetic field created by interactions between solar-wind irregularities and the outer regions of the geomagnetic field. There are storms of micropulsations which apparently are associated with localized fluctuations in the intensity of auroral light, with ionospheric absorption, and with other effects of particle bombardment, and it has been suggested (*17*) that these storms are caused by varying localized ionospheric currents rather than by hydromagnetic waves. There is a great need for satellite-based studies of these magnetic fluctuations at altitudes above the ionosphere which attenuates and modifies the fluctuations.

Earth currents are included among the magnetic perturbations shown in Fig. 1. When there is a large magnetic disturbance and a great flow of current in the auroral ionosphere, current is induced in the earth and in localized conductors below. The earth "currents" are usually measured as a potential or voltage developed between two points several kilometers apart, and these potentials may reach fractions of a volt per kilometer. Since these can be developed over telegraph cables some 100 km long, there are numerous examples of causal relations between the appearance of a large aurora and the blowing of a fuse in the telegraph line.

Heating of the Atmosphere

Bombardment of the atmosphere by energetic charged particles not only excites the constituents to emit light or become ionized, but also gives them some additional kinetic energy and so heats them. Chamberlain estimates (*5*) that in a bright aurora IBC III some 60 erg cm^{-2} sec^{-1} are probably dissipated as heat. There are about 2×10^{18} atoms and molecules per square-centimeter column above an altitude of 110 km, and if we assume each is given an equal share of the heat then their average rate of gain of thermal energy in such a bright aurora is approximately 2×10^{-5} ev/sec.

Now their normal temperature (T) is about 300°K or 27°C, which corresponds to a thermal kinetic energy (kT) of about 3×10^{-2} ev (k is Boltzmann's constant). Hence in about 10^3 seconds they would be heated to twice their original temperature if no appreciable cooling occurred. The estimated time scale for cooling (which takes place by radiation and downward conduction and gravity waves) is thought to be several hours, or many times the heating scale. So it seems plausible (*5*) that particle bombardment in a bright aurora might produce appreciable temporary localized heating.

Recently there have been two experimental verifications of "anomalous" heating in the auroral zone. Blamont and Lory (*18*) released sodium clouds from Nike-Apache rockets and deduced the high-altitude temperature from the measured width of the resonance line excited by sunlight. (When the temperature is increased, the atoms move faster, causing a Doppler broadening of this resonance line.) In control experiments the temperature was approximately 340°K at 125 km altitude. However, on one occasion, the temperature rose in 25 minutes from 380° ± 10°K to 950° ± 150°K. At the same time there was no strong visible auroral emission and no magnetic events, so the cause of the heating is puzzling.

Another relevant study (*19*) was that of the change in the atmospheric drag on the satellite Injun 3 while its perigee was at a high latitude and a magnetic storm occurred. Jacchia and Slowey found in previous studies how much the atmosphere was heated at lower latitudes during given magnetic disturbances, and from Injun 3 drag data they found that the heating was relatively stronger by a factor of four to five in the auroral zone. They derived (*19*) a quantitative empirical relation between the change in atmospheric temperature (ΔT deduced from the changed drag) and the change in magnetic perturbation measured by the usual index Δa_p with

$$\Delta T \ {}^\circ\mathrm{K} = c \ \Delta a_p \qquad (3)$$

where c is about 1.1 to 1.2 at low latitudes and about 5 in the auroral zone.

There are a number of mechanisms which could cause atmospheric heating during magnetic and auroral disturbances. One such mechanism is simply particle bombardment as discussed above, and shown as a cause in Fig. 1; another is hydromagnetic wave absorption in the ionosphere; and another is Joule heating through flow of ionospheric currents. Experimental information on the magnitude of the last two effects is lacking, but measurements of the particle fluxes indicate that the first effect can be important, particularly in the auroral zone.

Such latitude-dependent heating creates a problem of heat transport around the world since the quiet-time temperatures are essentially the same at different latitudes (*18, 19*). Hines suggested that gravity waves (*20*)—oscillations of the earth's atmosphere which are propagated with the speed of sound—may provide a suitable heat-transport mechanism to produce latitude equilibrium a few hours after heating has stopped. Heating in the auroral zones must therefore be included in a study of the heat balance of the earth. As is well known, direct heating by the sun is greatest at low latitudes, since there the earth offers a proportionately greater cross section to the sunlight. Auroral heating is greatest at high latitudes, but even there it is much smaller than the direct heating by sunlight during the day.

Sometimes observers of auroras report having heard a rustling or crackling sound whose loudness seemed to change as the auroral brightness changed. Bright auroras occur at such high altitudes (about 100 km) where the atmospheric density is so small (about 10^{-6} atmosphere at normal temperature and pressure) that an audible high-frequency sound cannot be generated and propagated from there. Chamberlain (*5*) stated that if the effect is real (which he doubted) it must be caused by some unknown phenomenon near the ground that is related to the aurora. It is sometimes suggested that during great auroral displays the very large changes in the geomagnetic field may induce such large electromotive forces in wires or conductors near the ground that corona and electrical discharges may occur, with the resultant emission of audible sound waves.

There certainly are auroral subsonic or infrasonic emissions (*21*) with periods of 10 to 100 seconds (the longest-period sound heard by the normal ear has a period of about 0.1 second). Provided incoherent noise from local winds is low, whenever there is a bright visible aurora or ionospheric evidence of aurora there are infrasonic waves or pressure oscillations with amplitudes of 1 to 10 dyne/cm². Conversely, on nights when there are no auroras there are generally no such "sounds" (*21*). A suggested cause, though admittedly a very indirect one, of such waves is the periodic heating of the atmosphere by particle fluxes of around 100 erg cm^{-2} sec^{-1}, such as are found in reasonably bright auroras. The particle bombardment periodically increases the ionization and hence the electrical conductivity so that (it is suggested) larger electric currents can flow at lower levels in the atmosphere, with consequent periodic heating and generation of pressure waves. Because these infrasonic waves have such long wavelengths, the ratio of wavelength to collision mean free path is large even at high altitudes, and the infrasonic waves, by contrast with the audible sounds, can be generated and propagated from the region of such heating.

Table 1. Approximate quantitative estimates of phenomena of Fig. 1 for a bright aurora of IBC III.

Phenomenon	Estimate
Solar wind (*1*)	700 km/sec and 10 particles/cm³
Distorted magnetosphere (*2, 3*)	Sunward radial distance to magnetopause 8 to 10 R_e [50,000 to 65,000 km]
Particle precipitation (*4, 10*)	400 erg cm^{-2} sec^{-1} localized and 10^{18} erg/sec worldwide
Van Allen radiation (*4*)	General increase in low-energy electrons and protons at $R \gtrsim 5\ R_e$
VLF emissions (*4, 24*)	10^{-6} erg cm^{-2} sec^{-1} over 1 to 10 kcy/sec
Balmer emissions (*5*)	10^{10} photons cm^{-2} sec^{-1} 6563 Å, 3×10^{9} of 4861 Å, etc.
Auroral light (*5*)	20 erg cm^{-2} sec^{-1}, including 10^{11} photons cm^{-2} sec^{-1} of 5577 Å
Heat (*18, 19*)	0.2 °C/sec and 60 erg cm^{-2} sec^{-1}
Sound (*21*)	1 to 10 dyne/cm² at periods 10 to 100 sec
X-rays at balloon altitudes (*11*)	Tens of photons cm^{-2} sec^{-1} with energy tens of kev (very dependent on electron energy spectrum)
Ionization (*5*)	7×10^{12} ion pairs cm^{-2} sec^{-1} giving maximum electron densities about $5 \times 10^{6}/cm^{3}$
Cosmic-noise absorption (*27*)	Several db (very dependent on radio frequency and electron energy spectrum)
Magnetic disturbance (*14, 15*)	10^{-2} gauss or about 1 percent change in the surface field below the aurora
Micropulsations (*17*)	10^{-5} gauss with periods of order seconds
Electrojets (*16*)	10^{5} amp in localized patterns with postulated 10-km cross-section at altitudes of about 100 km
Earth currents (*5*)	Potential of about 1 volt/km

Plasma Phenomena

A plasma is a gaseous collection of charged particles which is neutral overall, but fully ionized, and in which the charged particles are not bound rigidly but are free to "quiver" if perturbed. The solar wind is an example of a very hot, low-density streaming plasma. The region from the outer area of the magnetosphere through the auroral regions may be regarded as a plasma, as may the highly ionized upper regions of the atmosphere. In such plasmas, there are particular and peculiar interrelations between the charged particles and electric and magnetic fields. There may be collective motions and oscillations of the charged particles and therefore they cannot be understood from a single-particle model or a single-particle trajectory.

Chamberlain (*22*) has suggested that a plasma instability in the outer magnetosphere may cause particle acceleration and precipitation which in turn may cause auroras. The suggested mechanism involves low-frequency waves traveling through a nonuniform plasma; the instability was demonstrated theoretically by plasma physicists studying laboratory plasma.

Nishida (*23*) suggested that the "micropulsation storm" might be due to a plasma instability. This "storm" is a burst of irregular pulsations in the geomagnetic field and is commonly observed in the auroral zone at the onset of a sharp negative bay (a decrease in the horizontal component of the magnetic field) around local midnight. There is evidence from auroral light and ionospheric measurements that at the same time the atmosphere is bombarded by an intense beam of electrons. Nishida considered that this beam, when passing through the "magnetospheric plasma," might transfer some kinetic energy to hydromagnetic waves, leading to instability and the micropulsation storm. He commented that the situation is analogous to "runaway electrons" observed in plasma studies in the laboratory in Project Matterhorn.

Herein, of course, lies part of the fascination of auroral studies. It is possible that careful, lengthy theoretical consideration of all the magnetospheric conditions will lead directly to an explanation of acceleration and precipitation of auroral particles. But it is also possible that some completely new mechanism may be recognized in these phenomena, which occur on a scale impossible to simulate in the laboratory.

Electromagnetic Radiation

In addition to the emissions of "light" with frequencies of about 10^{15} cycles per second, there are other electromagnetic auroral emissions of much longer wavelength and lower frequencies that are radio waves. The emission most often associated with auroras is called auroral hiss. It occurs over a relatively broad range of frequencies of hundreds of cycles per second to about 10 kcy/sec. Another very-low-frequency (VLF) emission is given the name of "chorus." Initially, it was called "dawn chorus," as it was detected in the early morning and was likened to the sound of warbling birds. In chorus the emissions are discrete and yet closely spaced and often overlapping. It is, indeed, convenient to divide the VLF emissions into the two categories of hiss and discrete emissions (*24*).

Very-low-frequency emissions, like "whistlers" from lightning strokes, can be detected by coupling a magnetic or electric antenna to an audio amplifier. They are attenuated greatly, though by variable amounts, in the ionosphere, and so satellite measurements have some advantages over ground-based studies. Like whistlers, also, these emissions may exhibit dispersive characteristics. Thus the different frequencies emitted from a lightning stroke "sound" like a "crack" or like the static on a radio if one is near the source. But when the electromagnetic waves travel through the ionosphere and magnetosphere, guided along the magnetic field lines, the different frequencies travel at different velocities and so arrive at the observer at different times, with a dispersive spread over a second or so. The initially distinct "crack" then sounds like a long whistle with a slowly changing tone or frequency.

Unlike those of whistlers, however, the causes of VLF emissions cannot be isolated simply. Although lightning can provide sufficient energy to account for the observations, there is no adequate explanation of how it can produce anything but a whistler. An alternative source of energy is that in auroral particle fluxes, which may be many millions of times larger than the local VLF energy fluxes 10^{-22} to 10^{-17} watt per square centimeter per cycle per second, or 10^{-18} to 10^{-13} watt/cm^2 for a typical emission with a bandwidth of about 10 kcy/sec (*4*).

One mechanism of energy conversion is the Čerenkov effect wherein, if a charged particle moves through a medium at a speed greater than the local phase velocity of an electromagnetic wave of a given frequency, it will radiate a wave of that frequency. Another mechanism is the emission of cyclotron radiation produced as an electron is constrained to spiral around a geomagnetic field line. The electron is therefore being continually subjected to an acceleration (in direction) so that it radiates bremsstrahlung. To an observer who looks edge-on at the spiral, it is as if two oppositely directed electric dipoles are radiating at the cyclotron or rotational frequency. Since the electrons also have a component of motion along the magnetic field and relative to the observer, the emission will be Doppler-shifted. The fundamental cyclotron frequency is proportional to the local magnetic field strength, and so the wave radiated by an electron has a frequency of kilocycles per second in the equatorial plane and of megacycles per second in the ionosphere. The group from the University of Alaska at College has recently reported emissions in megacycles per second during auroras. Both these mechanisms involve each auroral particle radiating as a separate entity, and in such cases it can be shown that at most about 10^{-20} watt/cm^2 can be converted to very low frequency emissions (*24*), so that these single-particle mechanisms are too inefficient to explain the observed phenomena.

A potentially more promising explanation is based on the fact that the auroral electrons may act as a group or coherently. For example, an electromagnetic wave which has a component of its electric field parallel to **B** will tend to accelerate electrons alternately in opposite directions and to "bunch" them. The electrons may already be traveling parallel to **B**, and so these bunches and the wave may move together and exchange energy, resulting in both periodic VLF emissions and periodic x-ray bursts (*24*).

At present I think it is likely that particle energization and precipitation are the causes of VLF emissions, as shown in Fig. 1. There are theorists who believe that the causal relation is just the opposite, that is, that VLF causes particle acceleration and precipitation; however, the coordinated satellite-based experiment (*4*) discussed above, in which the amount of energy in each form was measured, indicates this is unlikely.

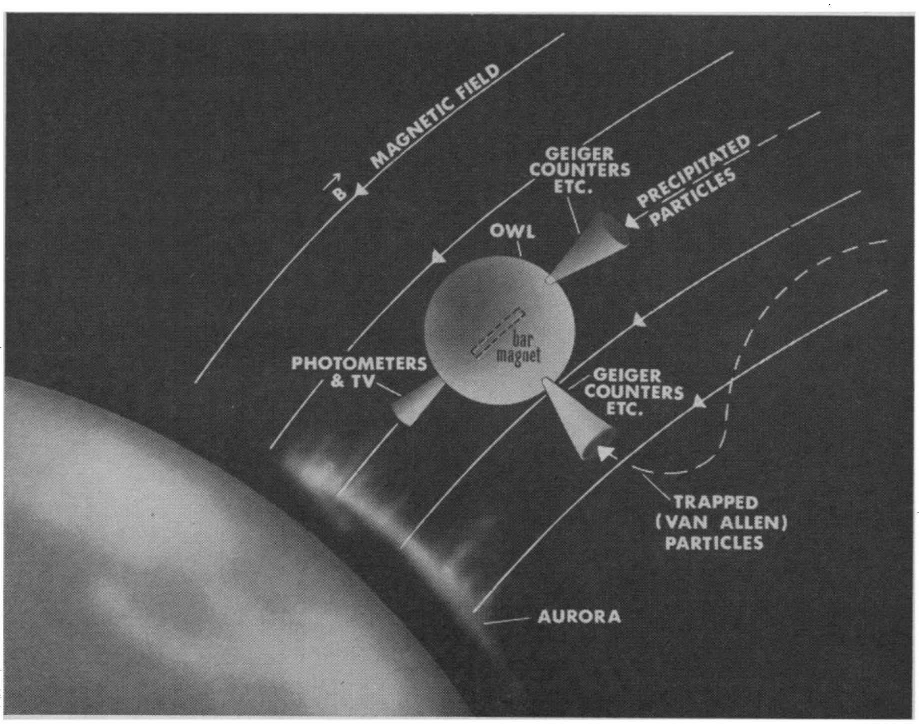

Fig. 8. Illustration of the use of a magnetically-oriented satellite to view auroras, the precipitated particles that cause them, and the associated Van Allen radiation. This technique was successfully applied with the Injun 3 satellite, and it will also be used as shown with the Rice University Owl satellites, recently approved by the National Aeronautics and Space Administration as the first in the University Explorer Satellites program.

Miscellaneous Phenomena and Correlations

Because there are so many auroral phenomena, it is advisable to examine to what extent cross-correlation of these phenomena can be useful and to what extent it can be misleading if causal relations are rashly deduced from the simple occurrence of two phenomena at the same time and place. There are numerous examples in geophysics of theories of cause-and-effect relations developed from an *ad hoc* selection of arguments about such a coincidence. An excellent criticism of such procedures has been given by Kinsman (*25*).

In his analysis, Kinsman treated a paper entitled "The role of the Gulf Stream in the prediction of iceberg distribution in the North Atlantic." The iceberg paper demonstrated a correlation coefficient of 0.65 between the mean monthly temperature anomalies at Key West, Florida, and the monthly counts of icebergs sighted in the Atlantic south of 48°N. This correlation was used to support the contention that the fluctuation in the Gulf Stream System is the single cause of the iceberg distribution, whereas the "commonly held opinion (was) that the causes are many and related in a complex fashion." Kinsman sought a higher correlation coefficient between the icebergs and some other parameter that definitely had no causal association with icebergs. He simply used the number of typeset commas per printed page of the original paper, and by pairing pages 111 to 102 with the iceberg counts of the years 1942 to 1951 he obtained a correlation of −0.81. He concludes "This is considerably better than 0.65 but no one would argue that commas cause icebergs."

"Iceberg statistics" must therefore be treated with very great care in searches of auroral phenomena for causal relations. The problem of the statistical significance of a given finding is extremely difficult to assess in auroral studies, because there is no control or ability to reproduce the phenomena and repeat the experiment, and such repetition lies at the base of the usual statistical tests of significance. So the auroral physicist is in a curious halfworld where perhaps a scientist may not roam because, following Aristotle, the subject matter of science is that which happens always or for the most part, whereas the unique event is a subject for history (*25*).

There are some correlations that are useful even if imperfectly understood. One, for example, is the correlation between numbers of sunspots and auroral phenomena, which is useful in planning and preparing for an International Geophysical Year (IGY) or International Years of the Quiet Sun (IQSY) (see *26*, fig. 5).

One example of an empirical relation between two phenomena far removed from a causal relationship is that between the absorption (A) of cosmic radio waves and the local change (ΔH) in the horizontal component of the geomagnetic field. A least-squares analysis of some data (*27*) found

$$A = 6.8 \times 10^{-4} (\Delta H)^{1.35 \pm 0.2} \quad (4)$$

where A is expressed in decibels and ΔH in gammas.

Now the numerical value of A is a function of the anomalous ionization distribution with altitude, which in turn is a function of the intensity and energy spectrum of the bombarding electrons as well as the radio wave frequency, atmospheric properties, and other variables. The value of ΔH is assumed to be dependent on the strength, relative locations, and dimensions of the hypothetical ionospheric current systems, which in turn are dependent on the amount of local ionization and also on the (unknown) driving mechanisms which may, in turn, be partly responsible for the characteristics of the precipitated flux. (The above speculations were rightly avoided by Brown and Barcus, *27*.)

On the other hand, under certain conditions there is an explicit theoretical relation (*5*) between the absorption (A in decibels) of a radio wave of frequency (f in megacycles per second) traversing the ionosphere vertically and the number density (N_e) of electrons which have a collision frequency (ν) over an altitude range (dh). The relation is

$$A = \frac{1.17 \times 10^{-14}}{f^2} \int N_e \, \nu \, dh \quad (5)$$

where the integration is over the entire ionosphere.

Typical magnitudes of various auroral phenomena that might accompany an IBC III aurora are listed in Table 1. It is interesting to note that only about 20 percent of the particle input energy of about 400 erg cm^{-2} sec^{-1} is manifested in known processes such as heat and the emission of light. There is a need for an adequate treatment of the energy balance which includes all the other items listed in Table 1 and Fig. 1.

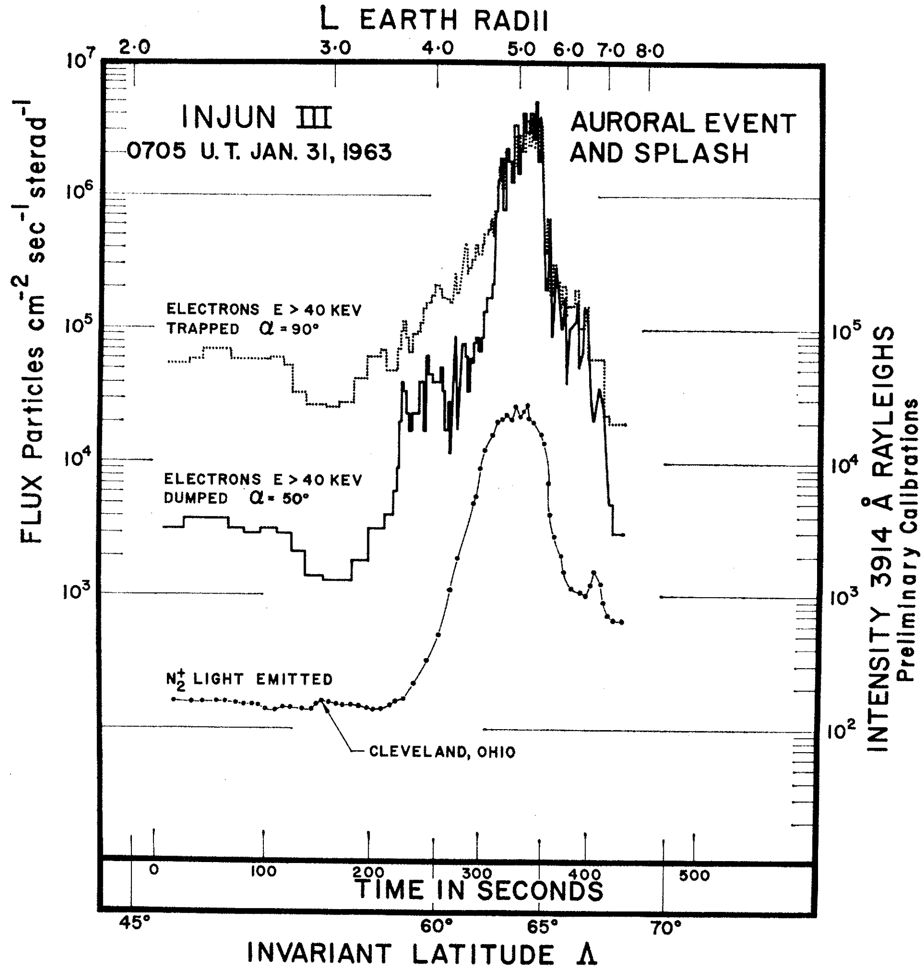

Fig. 9. Data from three of the 23 detectors of auroral phenomena (*4*) on the satellite Injun 3, which was magnetically oriented. An auroral photometer then viewed the ground in a northbound pass over North America, detecting first the city lights of Cleveland and then a bright aurora. The flux of trapped Van Allen electrons was much larger than that of precipitated electrons at low latitudes, but over the aurora they both increased greatly and approached equality. Beyond the aurora (that is, beyond the "boundary of trapping") they both decreased greatly.

Satellite-Based Studies

To avoid the danger of statistical correlations which do not represent causal relations, a coordinated study should be made at one time on a given auroral "event." Recognition of this principle has led to the creation of multi-faceted geophysical observatories near the auroral zone, such as the Geophysical Institute of the University of Alaska and the Antarctic research bases. Here I comment only on satellite-based observations made with a similar philosophy, with the Injun series of satellites, particularly Injun 3 (*4*), and with several polar-orbiting satellites (*28*).

Injun 3 was magnetically oriented. Auroral photometers then were pointed down the magnetic field vector **B** to measure the intensity of auroral light at 3914 and 5577 Å. Particle detectors with various characteristics were pointed back up **B** to measure the flux and energies of the electrons that were being precipitated to cause the aurora. Other particle detectors were oriented perpendicular to **B** to observe particles that mirrored at the satellite altitude, that is, Van Allen particles (Fig. 8). A loop antenna was coupled to an audio amplifier that then permitted measurement of the power and frequency spectrum of very-low-frequency electromagnetic radiation over the frequency range from about 700 cy/sec to 10 kcy/sec.

Typical observations are shown in Fig. 9. From these and other measurements, it has been concluded (*4*) that auroras occur at the high-latitude boundary of trapping and they probably delineate this boundary (Fig. 9). However, it is uncertain whether the auroras are just inside the boundary or just outside it or whether they simply straddle it. In other words, it is uncertain whether the auroral acceleration mechanism occurs on the last closed magnetic field lines, or the first open ones or straddling them (see Fig. 2). This is an extremely difficult question to resolve but an extremely important one.

These Injun 3 studies also showed that the angular distribution of energetic ($E \geq 40$ kev) electrons above auroras approaches isotropy over the upper hemisphere at altitudes of around 1000 km. Thus the flux of quasi-trapped electrons (that is, those with local pitch angles of about 90° that must mirror near the satellite altitude) increases as the flux of precipitated electrons increases. From this and other higher-altitude studies it has been concluded (*4*) that the unknown acceleration mechanism that energizes auroral electrons probably energizes Van Allen electrons as well (see Fig. 1).

By contrast, when the Van Allen radiation was discovered, it was often suggested that it was the immediate source (or "cause") of auroral particles. The Injun 3 studies also provided proof that above auroras the amount of energy manifested as VLF was only a millionth or less of the energy in the electron beams. So if there is a causal relation at all between these two phenomena, it must be that the particles radiate very low frequencies rather than that the very low frequencies accelerate the particles, as is sometimes suggested.

Another important result from Injun 3 was the demonstration that there is always not only an aurora but also precipitation of electrons within the magnetosphere. The auroras may often be below the threshold of visibility—that is, less than 1 kilorayleigh—but they are always present. This implies that the particle energization and precipitation mechanism is always present and not merely a "big bang" phenomenon. Such precipitated electrons were those found in the rockoon studies mentioned above.

The Lockheed studies (*28*) combined satellite-based measurements of particle fluxes above auroras with ground-based and airborne measurements of auroral light and of radio propagation. The telemetry from the satellite at several frequencies was received in the plane which flew underneath but parallel to the satellite path. The radio propagation was thereby affected by the ionization between the satellite and the plane, which ionization was created by particle bombardment and partly manifested as auroral light. The satellite-borne particle detectors were capable of measuring electrons with energies as low as 80 ev, and it was found that the unknown auroral acceleration mechanism imparts at least 1 kev to any participating electrons, or else that most of the electrons resident in the source region always have energies of order 1 kev; that is, the region is extremely "hot."

Such coordinated satellite-based experiments are necessary to pursue certain auroral and magnetospheric phenomena further. They must be associated, of course, with extensive ground-based and rocket-based experiments which also have unique advantages of their own.

Summary

The array of auroral phenomena involves all the basic types of physical phenomena: heat, light, sound, electricity and magnetism, atomic physics, and plasma physics. The uncontrollability, the unreproducibility, and the sheer enormity of the phenomena will keep experimentalists and theorists busy but unsatisfied for many years to come. The greatest challenge in this field of research is an adequate experimentally verifiable theory of the local energization of auroral particle fluxes. Once that is achieved, there is every likelihood that the multitude of correlations between auroral phenomena can be understood and appreciated. Until that time, however, such correlations are to be regarded like icebergs—the parts that can be seen are only a small fraction of the whole phenomenon, and it is the large unseen parts that can be dangerous to theorists and experimentalists alike.

References and Notes

1. C. W. Snyder, M. Neugebauer, U. R. Rao, *J. Geophys. Res.* **68**, 6361 (1963).
2. A. J. Dessler, *ibid.* **69**, 3913 (1964).
3. N. F. Ness, C. S. Scearce, J. B. Seek, *ibid*, p. 3531.
4. High-latitude geophysical studies with the satellite Injun 3 are discussed in a series of papers by O'Brien and others in *J. Geophys. Res.* **69**, 1–90 (1964). These describe the satellite, studies of precipitated electrons and the auroras they cause and the associated VLF emissions.
5. An excellent comprehensive review of auroral phenomena is given by J. Chamberlain in *Physics of the Aurora and Airglow* (Academic Press, New York, 1961), with an extensive bibliography of relevant work reported prior to January 1960.
6. F. E. Roach and J. R. Roach, *Planetary Space Sci.* **11**, 523 (1963).
7. T. N. Davis and G. T. Hicks, *J. Geophys. Res.* **69**, 1931 (1964).
8. B. P. Sandford, *J. Atmospheric Terr. Phys.* **26**, 749 (1964).
9. J. A. Van Allen, *Proc. Natl. Acad. Sci. U.S.* **43**, 57 (1957).
10. C. E. McIlwain, L. R. Davis, O. E. Berg, L. H. Meredith provide reports on auroral particle fluxes in *Space Research, Proceedings, International Space Science Symposium*, (North-Holland, Amsterdam, 1960), pp. 715–720, 721–735.
11. K. A. Anderson, *Univ. Calif. Publ. UCB 64/4* (1964).
12. R. P. Basler and R. N. de Witt, *J. Geophys. Res.* **67**, 587 (1962).
13. H. G. Booker, in *Physics of the Upper Atmosphere*, J. A. Ratcliffe, Ed. (Academic Press, New York, 1960), pp. 355–377.
14. S. Chapman, in *Space Physics*, D. Le Galley and A. Rosen, Eds. (Wiley, New York, 1964) pp. 226–269.
15. J. P. Heppner, *Can. Defence Res. Board Rep. DR 135* (1954).
16. J. A. Fejer, *J. Geophys. Res.* **69**, 123 (1964).
17. W. H. Campbell and S. Matsushita, *ibid.* **67**, 555 (1962).
18. J. E. Blamont and M. L. Lory, *Nature* **201**, 593 (1964).
19. L. G. Jacchia and Jack Slowey, *J. Geophys. Res.* **69**, 905 (1964).
20. C. O. Hines, *Can. J. Phys.* **38**, 1441 (1960).
21. W. H. Campbell and J. M. Young, *J. Geophys. Res.* **68**, 5909 (1963).
22. J. W. Chamberlain, *ibid.* p. 5667.
23. A. Nishida, *ibid*, **69**, 947 (1964).
24. R. A. Helliwell presents a critical review of observed VLF phenomena and their possible causes in *Space Research, Proceedings, 5th International Space Science Symposium* (North-Holland, Amsterdam, in press).
25. Blair Kinsman, *Tellus* **9**, 408 (1957).
26. M. Pomerantz, *Science* **142**, 3596 (1963).
27. R. R. Brown and J. R. Barcus, *J. Geophys. Res.* **68**, 4175 (1963).
28. R. C. Sharp, J. E. Evans, W. L. Imhof, R. G. Johnson, J. B. Reagan, R. V. Smith, *ibid*, **69**, 2721 (1964).