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SCIENCE

CURRENT PROBLEMS IN RESEARCH

Magnetic Storms

From satellite data should come new understanding of magnetic storms, auroras, and the ionosphere.

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The next decade should see rapid progress in our understanding of the nature and cause of the transitory changes in the geomagnetic field known as magnetic storms. We also expect to improve our understanding of related phenomena such as the aurora, cosmic ray time changes, and ionospheric storms.

The reason for this present optimistic point of view is the arrival of the space age, through which an added dimension has become accessible. Rocket- and satellite-borne magnetometers and counters are already extending the measurement of geomagnetic changes and radiation to regions thousands of kilometers above the earth, thereby augmenting human knowledge by providing directly measured data on magnetic storms and auroras in their natural surroundings.

It may be of interest here to recall briefly the history of the study of magnetic storms. Hiorter in 1741 is usually credited with the discovery that the geomagnetic field undergoes occasional changes in intensity on nights of aurora. Even earlier the British astronomer Edmund Halley had ascribed auroras to "magnetic effluvia" constrained to move along the direction of the lines of force of the geomagnetic field within the atmosphere. In view of the very early date, this was a most remarkable exhibition of scientific insight. By about the middle of the 19th century the relationships between electricity and magnetism were better understood. Also, the technique of geomagnetic measurement had progressed so far that it was possible to discover that the amplitude of geomagnetic changes on days of magnetic storm was greater in some years than in others, and that it varies in correspondence with the average number of sunspots. As the magnets suspended by fine fibers moved in response to changes in the geomagnetic field, attached mirrors directed a beam of light onto photographic paper a meter or two away, where the changes in field as a function of time were recorded. These installations were called magnetic observatories. The program of magnetic observatories was begun with instruments devised by the great German mathematician C. F. Gauss (*1*), near the middle of the 19th century. And during the International Geophysical Year, 150 to 200 such observatories, fairly well distributed over the earth, provided especially full coverage, monitoring the magnetic field and its changes with time.

Measurements are made of changes in the magnetic field in the horizontal plane, the horizontal component H of the field intensity being measured along the direction of the compass, and also along the direction perpendicular to H (giving the component of declination D). Also measured is the vertical, downward component Z. The continuous photographic record obtained during a magnetic storm is shown in Fig. 1. The magnetogram for the day shows a sudden change in field value, called a "sudden commencement," which occurs practically simultaneously over the entire earth. The irregular changes in H, D, and Z represent magnetic disturbances or stormy conditions. On a few days each year these periods show especially large field changes with time. These disturbances are classed as magnetic storms.

It is found that departures of the magnetic field from normal depend to a considerable extent on the latitude of the observatory and on the position of the sun relative to the station at various times of day. In addition, a substantial variation with storm time (time measured from the commencement of the storm) is found. Figure 2 shows the storm-time variation averaged for various latitudes for a number of moderate magnetic storms. During the first hour or so the average geomagnetic north force is above normal, only to show a decrease of much greater magnitude some 15 hours or so later. There is then a slow recovery toward the normal, undisturbed value. Changes in east force are relatively smaller, and changes in vertical force also tend to be small and opposite in sign to those in H.

When the storm departures are averaged according to local time, and hence independently of the time of commencement, a diurnal variation is found. The changes near the auroral zones are particularly marked for this variation, which shows a sharp maximum at the auroral zone, and the vertical component shows a reversal of sign as the auroral zone is crossed in latitude.

Electric Current Systems

Data such as those of Fig. 2 have been used by Chapman (*1*) and others to derive averaged electric current systems flowing in electrically conducting regions of the ionosphere in the special case where the ionosphere is regarded as a nearly spherical electrically conducting sheet. Similar derivations have been made, also, for individual hours of particular storms—especially for those of the International Polar Year

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1932–33, because in that year, as in the International Geophysical Year, many additional stations were operating. Figure 3 shows an electric current system derived by Fukushima (2) for the Northern Hemisphere, for the main phase of a magnetic storm, for flow of current in the ionosphere causing the departures in magnetic field at ground level. The amount of current between successive current lines is 100,000 amperes. Strong electrojets or concentrations of current flow are shown at the auroral zone, which has expanded southward from its average position during this major part of the storm. During the same time interval other electrojets tend to appear in the southern auroral zones. It will be noted that the electric current rises to about 1 million amperes at the auroral zone. In very great storms current intensities perhaps 5 times as great are known to appear (2, 3).

A difficulty with these rather elegant descriptive summaries presented in terms of overhead electric currents is that the form and location of the currents cannot be inferred uniquely from the available data. Hence, a part of the current probably flows at higher levels above the earth, perhaps well beyond the atmosphere, at least in the case of some of these variations. For instance, Störmer (1), Chapman and Ferraro (1), Bennett (4), Singer (5), and others have inferred that a part of the current flows in the form of an equatorial current ring at a distance of a few earth radii. This ring current may be broadly distributed in latitude as well. There also appear to be electric currents flowing and decaying several earth radii above the earth. This is regarded by some workers as a logical suggestion because the storm-time variation is often accompanied by the Forbush decrease in cosmic rays. One possible explanation is that the magnetic fields in extensive weak electric currents in the solar corona nearby, in the neighborhood of the earth, slow up or modulate the flux of cosmic rays arriving at ground level during some magnetic storms. However this may be, there is no doubt, from potential theory, that the electrojets shown in Fig. 3 flow mainly within the lower ionosphere, and that the presence there of these highly concentrated electric currents requires explanation. Many of these currents appear almost daily in auroral regions, but their magnetic fields extend only weakly to lower latitudes.

In recent interesting discussions in the literature there have emerged objections to ring-current theories of magnetic storms, as well as uncertainties respecting quite fundamental applications of electromagnetic theory. Parker (6) has indicated that the ring-current theory is untenable, since the changing field that it proposes cannot penetrate the electrically conducting ionosphere to reach the ground. In some discussions of this type there has been a return to some early concepts, such as the first theory of Chapman (7), which proposed that during the initial phase of storms the earth's atmosphere is compressed and that the atmosphere becomes expanded during the main phase. Hines and Storey (8) claim that the ring-current concept remains tenable, since the changing ring-current field can penetrate the ionosphere as a hydromagnetic wave. In any event it has been noted that a substantial part of the sudden-commencement and initial phase has its immediate cause in the lower ionosphere, because the field pattern at ground level is too complicated to arise directly from ring-current sources. The contribution of atmospheric sources to the sudden-commencement and initial phase of storms has

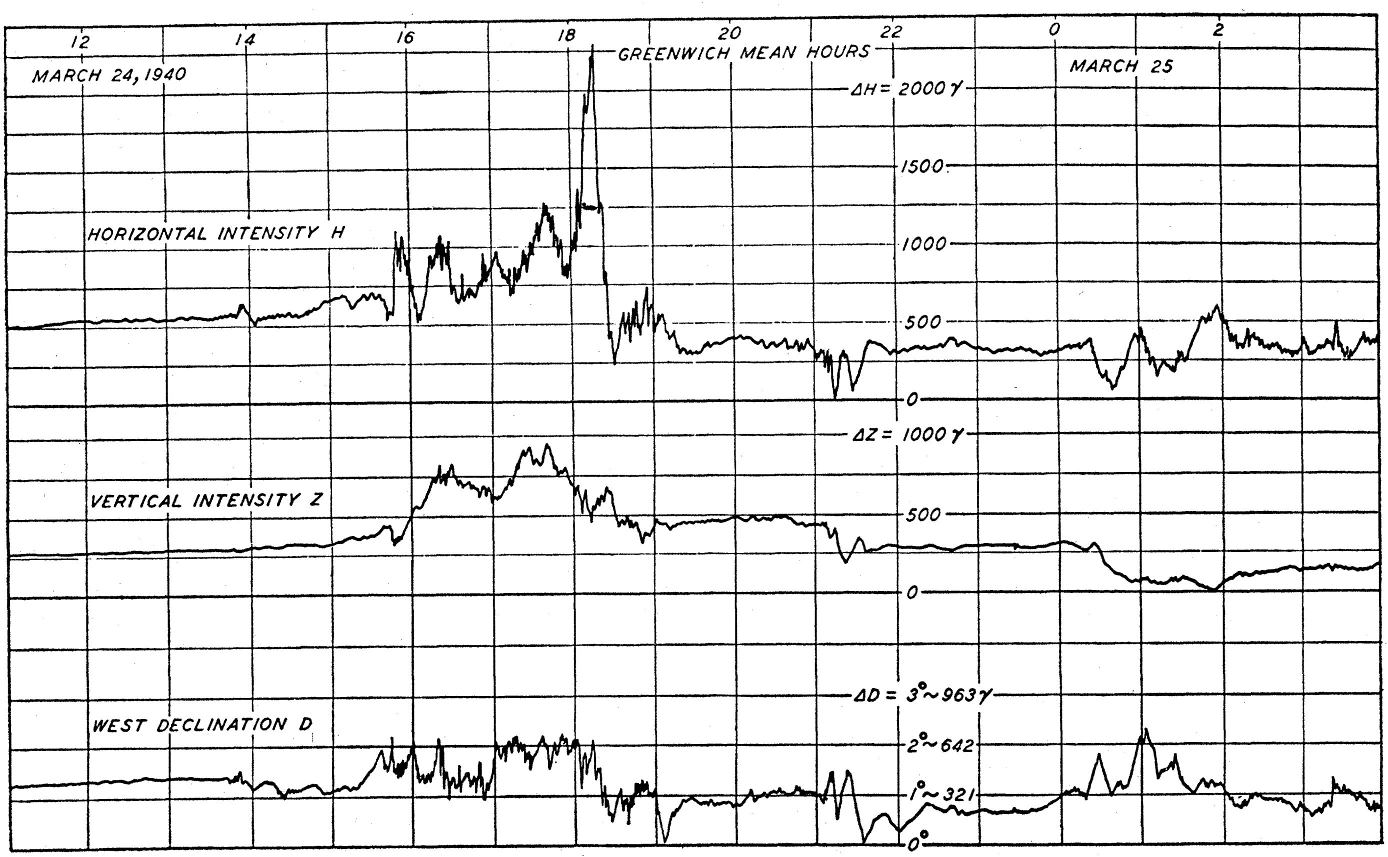

Fig. 1. Wide-range magnetogram, Potsdam-Niemegk, 11 hours Greenwich Mean Time (GMT), 24 March, to 4 hr GMT, 25 March, 1940. [After G. Fanselau]

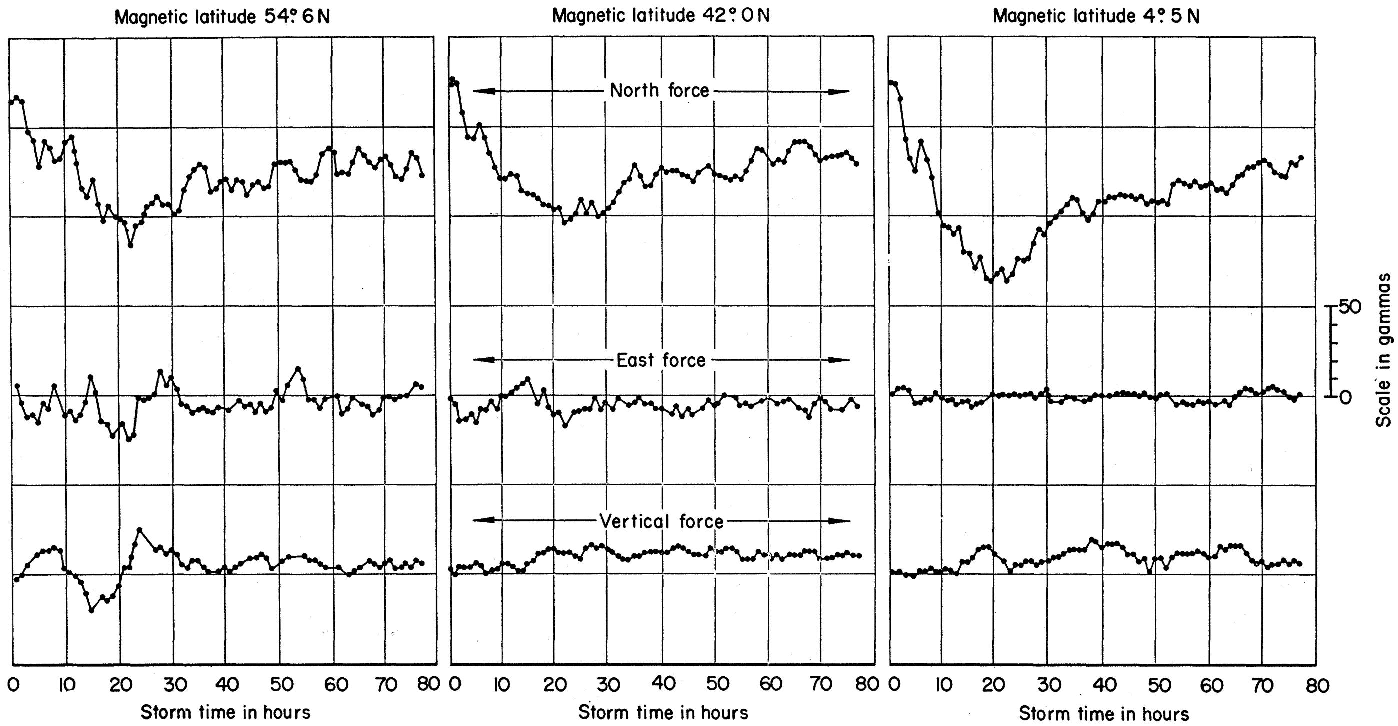

Fig. 2. Magnetic field changes for 11 storms, 1932 to 1933, averaged according to time measured from commencement of the storm.

been emphasized by Sugiura (*9*), Forbush and Vestine (*10*), Jacobs and Obayashi (*11*), Knapp (*12*), and Nagata (*13*). These studies strongly suggest that electric driving forces in auroral regions create electric current systems in the base of the ionosphere, and this conclusion may be checked by noting that the electric fields above these currents in turn lift (or lower) F-region ionization to a measurable degree. In fact, the measured changes in F-region ionization seem in good accord with expectations based on suggestions of Martyn (*14*) made some years ago in a discussion on the action of auroral electric polarization on the world-wide patterns of F-region ionization. It is therefore reasonably clear that the major part of the sudden-commencement and initial phase of storms is strongly contributed to by electric currents near or identified with the highly conducting E-region of the atmosphere.

It has also become clear that the major part of storms in higher latitudes is the S_D part, usually depending mainly on solar position and shown long ago by Birkeland to depend strongly upon electric current in the auroral zone. Hence, though the remaining part—the ring-current part—may arise from hydromagnetic or other action from outside, it seems inappropriate to identify it so all-exclusively as the field of magnetic storms. It is realistic to conclude that the polar disturbance field has atmospheric sources as its immediate and important cause. Martyn (*15*) has suggested, as an extension of the Chapman-Ferraro theory, that charges drain from a ring current into the auroral zones. Ionized solar streams also are supposed to drift past the earth, with a carving out of the Chapman-Ferraro hollow in the solar stream by action of the geomagnetic field to form a current ring. The average auroral zones are regarded as zones to which charges from the ring current drift along the lines of force of the geomagnetic field in producing aurora.

It has also been suggested that electromotive forces originating in the auroral zone drive the so-called diurnally varying part of magnetic storms (*16*). The manner in which the polar electric fields arise to drive the electric currents of the auroral zone is not known.

One suggestion is that upper-air winds may play a part in accord with the Stewart dynamo theory (*17, 18*). According to this theory, the electric field E arises at least in part from a contribution $\mathbf{v} \times \mathbf{H}$, where $\mathbf{v}$ is the wind velocity and $\mathbf{H}$ is the geomagnetic field. Incoming clouds of ionization entering along lines of force of the geomagnetic field into auroral regions must also add considerably to the electric conductivity there. Hence, unless one proposes the absurd possibility that no E-region winds appear over the polar cap, a part of polar disturbance must be wind-produced during magnetic disturbance, though it need be only a minor part. Another part must arise as a result of differential penetration of charges along the geomagnetic field lines, as suggested by a number of workers (*10, 12, 19*). Martyn (*15*) estimated that the ring current should be at a distance of about five earth radii in order to provide drainage of charge into the auroral zone, but he did not succeed in tracing the consequences in the development of the auroral electrojets. The emphasis of Martyn and Alfvén upon drainage of charge into the auroral zones from a ring current is probably a major contribution to the clarification of the cause of magnetic storms and aurora. In support of this view it may be mentioned that my own calculations of geomagnetic field lines in space indicate that in fact the average northern and southern auroral zones appear to be linked by geomagnetic field lines. Also, the intersection of these field lines with the equatorial plane is an oval varying in radius from 5.6 to 5.8 earth radii.

Sudden Commencements

Associated with the larger-disturbance field changes discussed above are associated changes and pulsations of various kinds, including the sudden commencements of storms. In the case of sudden commencements a mechanism based upon the propagation of shock waves has been suggested by Gold (*20*) and discussed by Singer (*5*). In the case of sudden commencements of storms there is evidence of the existence of intense and strongly localized fields at the auroral zone; this finding tends to encourage the view that differential penetration of charge near the E-region and below provides the surge in electric current required. The oscillatory character of the pulse shows a capacity for reversal in field. In other cases the sudden commencement field is not so highly localized and could be associated with electric currents near the E-region or at much higher levels. It is not yet possible to determine the height of principal current flow.

It has also been suggested (*21, 22*) that propagation of hydromagnetic waves into the ionosphere is important as a cause of various regular pulsations. Van Allen (*23*) and others have suggested that the Van Allen radiation belt may be the source of auroral, magnetic, and ionospheric disturbances. They have stressed the similarity in effects in high latitudes, measured in rocket-borne counters, and in the Van Allen radiation belt discovered with earth satellites. Ionospheric effects of energetic radiation have been noted (*24*). Discharge of plasmas from the radiation belt reservoir must occur if additions from sources, solar and terrestrial, are irregular in time or in substantial amount. Geomagnetic field gradients will affect plasma motion (*25*).

One intriguing possibility is that solar streams impinging on the highest reaches of the terrestrial atmosphere may substantially affect the geomagnetic field lines in a manner depending upon the density and velocity of the stream. The geomagnetic field lines on the dark side of the earth may be bent during the night in the direction away from the sun, thus reducing the intensity of the magnetic field in the upper atmosphere. In this way the particles in the radiation belt may be able to penetrate to lower levels of the atmosphere while reaching their mirror points before spiraling upward along the lines of the geomagnetic field. A concept of this kind may, for instance, be useful in explaining the maximum that occurs in auroral displays near midnight. Unstable drainage of the radiation reservoir may occur even as the reservoir is being replenished, in the event that the solar streams distort and weaken the geomagnetic field locally by their tendency to drag the field lines into regions of lesser field intensity. As the stream intensity increases, more widespread drainage should occur. In fact, as the strong westward-directed electric currents flow along the auroral zone, the geomagnetic total intensity just to the south will be further reduced, and this will lower the Störmer mirror points for particles. North of the electric current the mirror point will be higher, and this might make auroral rays possible. This may in turn result in an expansion southward of the aurora, the electric current, and the associated radio blackout area. An interesting possibility, therefore, is that the atmospheric component of magnetic disturbance may be linked to plasma oscillations within the radiation belt, which are perhaps related to pulsations in field sometimes actually noted during disturbances. According to this view, magnetic bays may develop from drainage of the radiation belt deep into auroral regions, with expansion of blackout regions southward after lowering of the mirror points for reflection of electrons and protons due to weakening of the field of the electric currents. Then, after maximum expansion of the auroral zone currents southward has been reached, discharge from the radiation reservoir may stop, to start again the following evening when the geomagnetic field is again suitably oriented relative to the solar stream. Actually, of course, storage and drift motions of auroral particles within the outer Van Allen region may be only temporary, extending over periods of minutes to hours, say, the main supply reservoir being the nonuniform solar stream itself. The latter may endure for several days during each solar rotation, and there may be more than one such stream.

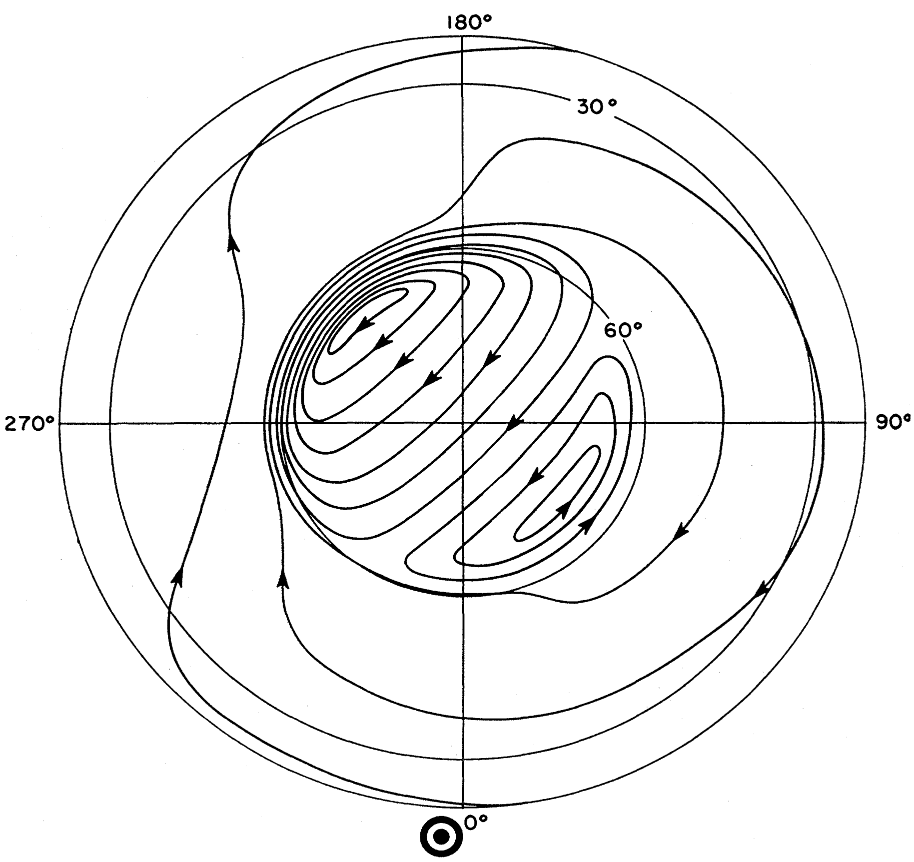

Fig. 3. Instantaneous electric current pattern of storm, at 16 hr 50 min GMT, 1 May 1933; 100,000 amperes flow between successive current lines. (View from above North Pole.) [After Fukushima]

New Opportunities at Hand

Rockets and satellites will soon provide means of locating the various electric current systems in the atmosphere and in adjacent space through direct measurements. These measurements will also provide a means of estimating the current densities and the complexities of the electric currents that cause magnetic disturbance. In particular, the position and strength of ring currents, if any exist, will probably soon be determined. Since the strength of upper-air winds in the ionosphere will also be estimated, the part played by magnetic disturbance resulting from the dynamo action of winds driving ionized air across the lines of force of the geomagnetic field can be determined. The various rather vague theories about magnetic storms now currently studied can then be revised or replaced with others, in order to explain the results of observation. Observations of effects due to meteors, cosmic dust and gases, x-rays and radio waves, and the polar aurora are being ascertained. Hence, new and rapid progress seems inevitable (*25a*).

Current Theories Awaiting Test

It is clear that a number of hypotheses respecting the cause of geomagnetic disturbance require further study (*26*). The Birkeland-Störmer ideas about electric current flowing vertically along the lines of magnetic force of the earth's magnetic field can be tested by rockets or satellites. These measurements may also serve to check some similar hypotheses in the modern version of this theory, as revised and extended by Hulburt and Bennett. The Chapman-Ferraro theory postulated motion of solar streams in the earth's vicinity giving rise to electric currents gathered in the face of the advancing solar stream. These currents were supposed to be caused by interaction with the geomagnetic field. It is clear that this prediction will also be susceptible to early check with magnetometers aboard satellites or rockets (*27*). As the earth rotates through solar gases in its yearly motion around the sun, various electric phenomena will inform the scientist about seasonal changes in the interaction of the geomagnetic field with solar streams. There will also be opportunity to check electrical effects and possible toroidal fields (*18*) because of slippage of the earth's atmosphere and of its magnetic field within the solar corona. In the same way it may be possible to infer whether or not the electric fields within the solar corona suggested by Alfven will yield auroras and polar and other magnetic disturbances, as well as certain cosmic-ray changes with time; some workers suggest that these electric fields are very small, even negligible. Finally, as knowledge of the upper-air winds is extended, the actual atmospheric component of geomagnetic disturbance will be estimated and related to the various solar processes and flares which are now little understood but which undoubtedly provide some of the radiation responsible for magnetic storms and related phenomena. There are also available extensive new data for relating solar events on a statistical basis to the ground noise level of the geomagnetic field.

The swift advance in technology, scientific knowledge, and understanding that has characterized the present era will be shared in many areas, and, happily, there seems good reason to hope also for the speedy solution of several very puzzling problems of long standing in connection with geomagnetic time changes.

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25a. *Note added in proof.* Since I wrote this account, the article "The universe discloses its mysteries" (*Pravda*, 15 July 1959) has reported that on 2 January 1959 the Soviet moon rocket Mechta detected an electric current layer 20,000 to 21,000 km above the earth's surface, which is of high interest in relation to the ring-current hypothesis for the cause of magnetic storms. Even though a storm was not in progress, the observation is of interest, because it may represent a decaying effect of an earlier storm. Observations of the Van Allen radiation belt were also obtained [see S. N. Vernov, P. V. Vakulov, A. Y. Chudakov, Y. I. Logachev, *Doklady Akad. Nauk S.S.S.R.* **125**, 304 (1959)]. A survey magnetometer carried aboard the Pioneer I space probe on 11 October 1958 apparently did not encounter a distortion of the geomagnetic field near 20,000 km above the earth, as did the rocket Mechta. (See C. P. Sonnett, D. L. Judge, A. R. Sims, and J. M. Kelso, "A radial rocket survey of the distant geomagnetic field," *J. Geophys. Research*, in press.)

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