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Earth Storms: Retrospect and Prospect

Sydney CHAPMAN

Geophysical Institute, University of Alaska; High Altitude Observatory, Boulder, Colorado; Institute of Science and Technology, University of Michigan; U.S.A.*

The Early Beginnings

We are met to review the present state of our understanding of earth storms. Our field is modern compared with such venerable science as mathematics and astronomy. Cosmic ray research is a branch of science whose very beginning is within the memory of some of us, and ionospheric science is but little older. Nonetheless, our origins are more remote than many might think. We may date them at around 1600 A.D., when Gilbert first announced that our globe is a magnet. A few years later Galileo's astonished eyes beheld the sunspots, and thereby learned that the sun rotates.

Long afterwards sunspots came to be regarded as visible tokens of storms on the sun. But the word *storm*, as applied to physical events, only gradually had its meaning extended beyond the domain of weather. The term magnetic storm seems to have been a 19th Century innovation. Later it was applied to solar events, and in the present century to ionospheric and cosmic ray disturbances.

The knowledge of magnetic disturbance goes rather far back. The *transient* changes of the earth's magnetic field were discovered by Graham, a famous London instrument maker, in 1722. This was 87 years after the recognition of the *secular* magnetic variation. With a microscope Graham watched the small changes of direction of a compass needle. He found a regular daily variation, greater in summer than in winter. But these systematic changes were at times interrupted by larger and irregular deflections. Later similar observations were undertaken at Uppsala in Sweden by Celsius — to whom we owe the Centigrade scale of temperature. In 1741, 220 years ago, correspondence between Celsius and Graham disclosed not only that both places were *simultaneously* affected by such irregular magnetic disturbance, but also that at Uppsala it was accompanied by auroras. Already de Mairan in Paris in 1731 had published his grand physical and historical treatise on the aurora. He recognized it as a planetary phenomenon, and linked it, though rather obscurely, with the sun.

The association between magnetic disturbance and aurora was an outstanding discovery in the field of time relationships in geophysics. In 1770 Wilcke, also of Sweden, added another first-rate discovery, this time a morphological connection between auroras and the earth's magnetism. He found that auroral rays lie along the magnetic lines of force.

The Nineteenth Century

The decades around 1800 were times of intense interest in the development of Newton's dynamical astronomy, especially by the great French mathematicians. But Gauss in 1803, and Hansteen in 1819, urged mathematicians to apply themselves also to geomagnetism. Gauss himself did this magnificently in his *Allgemeine Theorie des Erdmagnetismus*, published in 1838. He also put magnetic observation on a proper basis, showing how to measure and record all three components of the field, in absolute units. Gradually, under his influence and that of Humboldt and Sabine, magnetic observatories were set up in many parts of the world. It began to be possible to make global synoptic studies of the magnetic changes, regular and irregular.

Meanwhile the spots on the sun claimed the attention of a few devoted observers. Schwabe, an amateur, followed their appearances and disappearances from 1826 to 1850. In 1843, in the *Astronomische Nachrichten*, he indicated a "decennial" variation in his yearly numbers. This discovery of the sunspot cycle was surprisingly long deferred. Even so, it remained unnoticed until in 1851

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* There engaged on a program of research sponsored by the National Bureau of Standards and the Air Force Geophysics Research Directorate.

Humboldt publicized it in Volume 3 of his *Cosmos*. In 1851 and 1852 a similar periodicity in the magnetic variations was announced, indepently by Lamont and by Sabine. It was a landmark in natural science to find that intrinsic changes on the sun could thus affect the earth.

In the year 1859 a great solar flare was observed for the first time. It was seen, surprisingly and fortunately, by two men independently, Carrington and Hodgson, in London. A small magnetic disturbance occurred at the same time, and a very great one followed 18 hours later: but a proper caution restrained conclusions that these events were connected. The magnetic storm lasted for four days with varying strength, and was accompanied by widespread intense aurora. The storm and aurora constituted one of the outstanding geophysical events of the 19th Century. The American scientist Loomis collected and published all the information he could find about this auroral display. Kimball (1960) has recently made a valuable synoptic study of this collection of auroral data.

The next year, 1860, Loomis drew the first complete map of the auroral zone, based on arctic and other auroral data. This map embodied another major discovery about the aurora, partly morphological, partly time-related. In 1873 Fritz published a great auroral catalog, which enabled him to draw the first map of isochasms, or lines of equal frequency of visibility of auroras. This added much to the quantitative knowledge indicated on Loomis' map.

The simultaneous occurrence of auroras and magnetic storms, found by Graham and Celsius in 1741, made it likely, after the discoveries of Schwabe, Sabine and others concerning the association between sunspots and magnetic storms, that auroras also would manifest the 11-year cycle of frequency variation. This was indeed later established, but only after some decades of uncertainty. The delay was due to the unsystematic nature of the auroral records. They depend much on the work of the few devoted observers who watch regularly for the aurora over periods of years. John Dalton, the father of the atomic theory in chemistry, was one of these.

During the 19th Century the record of solar and magnetic and auroral data gradually grew in volume and scope, notably by the application of the spectroscope to the sun and to the aurora. Thus material became available for studies of many different types. This 19th Century material is still not fully exploited.

Already before 1900 it became clear that magnetic storms are worldwide, and that many begin nearly simultaneously all over the earth. Some of their main morphological features were recognized. They have a first phase, during which the horizontal force at the earth's surface is increased, for minutes or hours. This is followed by the second phase, during which in many storms, but not in all, the horizontal force shows a larger and more prolonged decrease. Recovery towards the normal value follows only over many hours or even days. Arctic expeditions revealed that magnetic disturbance is exceptionally intense near and within the auroral zone. The first International Polar Year, 1882/3, provided improved material for the study of disturbance in those regions. But such studies were still in a rather primitive state, until the second International Polar Year, 50 years later, in 1932/3, gave more reliable and extensive data. By that time the ionosphere and cosmic rays had begun to be actively observed, and ionospheric observations were included in the program for the second Polar Year.

Birkeland, Störmer and Lindemann

Shortly before and after 1900 two Norwegians, Birkeland and Störmer, began a series of momentous researches on auroras and magnetic storms. Birkeland, physics professor, at Oslo knew that the motion of electrons, then recently discovered, is affected by a magnetic field. He had the insight to see that the earth's field might enable electrons from the sun to enter the atmosphere in high latitudes and on the night side of the earth. He found support for these ideas in laboratory experiment, in which he directed an electron beam towards a magnetized sphere. Inspired by his hypothesis, Störmer, mathematics professor at Oslo, sought to develop it mathematically. Poincaré had already studied the motion of a single charged particle in the field of a magnetic pole. Störmer discussed the motion in the field of a dipole.

Both Birkeland and Störmer considered solar streams of particles of one sign only, and Störmer's calculations ignored the mutual interaction of the particles. Birkeland and others, including myself, tried to explain magnetic storms on the same basis. Schuster strongly criticized such one-sign theories of auroras and storms. In 1922 Lindemann similarly criticized my first storm theory. He added the important constructive suggestion that storms are caused by *neutral* ionized streams or clouds, containing equal numbers of electrons and positive charges.

Störmer's work on the motions of single charges in a dipole field later proved highly valuable for cosmic rays, unknown when he began. He had less success in explaining the aurora, his first and lifelong aim. Ferraro and I later showed how essential it is to take into account the interaction of the positive and negative charges. But Störmer won undying fame in auroral annals also by his observational studies. They established some main features of auroral geometry — the height, location in plan, and in latitude, and relative to the earth's shadow line — and something of the physics — the color and spectrum, to which his colleague Vegard made major contributions. Later Alfvén, by his brilliant conception of the guiding center, greatly improved our understanding of the orbits of charged particles moving in magnetic fields.

Birkeland, unlike Störmer, studied magnetic storms as well as auroras. He first collected and synoptically studied the facts then known about magnetic storms. He also extended the data, by setting up new, temporary arctic magnetic observatories. He was led to distinguish five types of magnetic storms. Two he called polar, and two equatorial; in each case he called one positive, the other negative. These signs referred to increase or decrease of horizontal magnetic force. He tried to explain how his five types could be produced by streams of electrons from the sun.

The fifth type differed from the others, particularly in that it affected only the sunlit hemisphere. His explanation based on solar particles was later superseded by a quite different explanation. This is based on solar X-rays, that are unaffected by the geomagnetic field. These rays, much increased during solar flares, fall on the hemisphere facing the sun, and enhance D layer ionization. This allows additional electric currents to flow there, under the impulse of dynamo forces like those that in the E layer produce the quiet day magnetic variation at the earth's surface. The extra D layer currents augment this daily variation, during and a little beyond the brief life of the flare. The D layer also at such times produces radio fadeouts, now taken as an indication of the occurrence of solar flares, even unseen. Our understanding of these events goes back to the 1930's, in radio by the work of Mögel and Dellinger, and in magnetism by that of Fleming and McNish.

Birkeland ascribed the storm changes of magnetic force to electric currents outside, that is, above, the earth. When the horizontal force is increased, the current must be eastward, and when decreased, westward.

Birkeland's ideas on magnetic storms were published in three important memoirs, of 1901, 1908 and 1913. A distinctive feature of his magnetic storm studies was that he discussed individual cases.

Magnetic Storm Average Morphology and Conventional Current Systems

The Indian scientist Moos, Director of the Magnetic and Meteorological Observatory at Bombay, published in 1910 a monumental discussion of the long series of Bombay magnetic data. His many-sided studies included the *average* features of the magnetic storm changes at Bombay. In 1917 I applied the same methods to study the average features of moderate storms at many stations, in different latitudes. The method geometrically separates the average storm field into a part *Dst* symmetrical about the earth's axis, and the remaining part *DS*. In this notation D denotes disturbance and *st* denotes storm time, reckoned from the onset of the storm; in *DS*, S denotes solar, because the *DS* part of the storm field depends not only on storm time and latitude, but also on local time, or position on the earth as viewed from the *sun*. They depend also on the storm intensity. Whereas *Dst* decreases with increasing latitude, *DS* increases greatly towards the auroral zones; it is also intense, though less so, within the polar caps enclosed by the zones.

The nature of the storm field is conveniently indicated by diagrams of current systems flowing at a constant height above the earth, that *could* produce the *Dst* and *DS* variations. In 1935 I drew idealized current diagrams corresponding to the *Dst* and *DS* parts of the storm field, and to the total storm field (Fig. 1). Later Vestine drew such current systems for several individual storms, using data from the second Polar Year, 1932/3. More recently such current diagrams have been drawn and discussed by Fukushima, Jacobs and Obayashi, and others. Their current diagrams somewhat resemble my idealized pattern, but the polar part is rather differently oriented relative to local time, and in some storms the orientation changes irregularly. All these diagrams show strong laterally limited currents, or electrojets, flowing along the auroral zones. These are mainly westward, but eastward electrojets also occur. The electrojets complete their circuits mainly over the polar caps, but also partly over the great middle belt of the earth, between the two auroral zones.

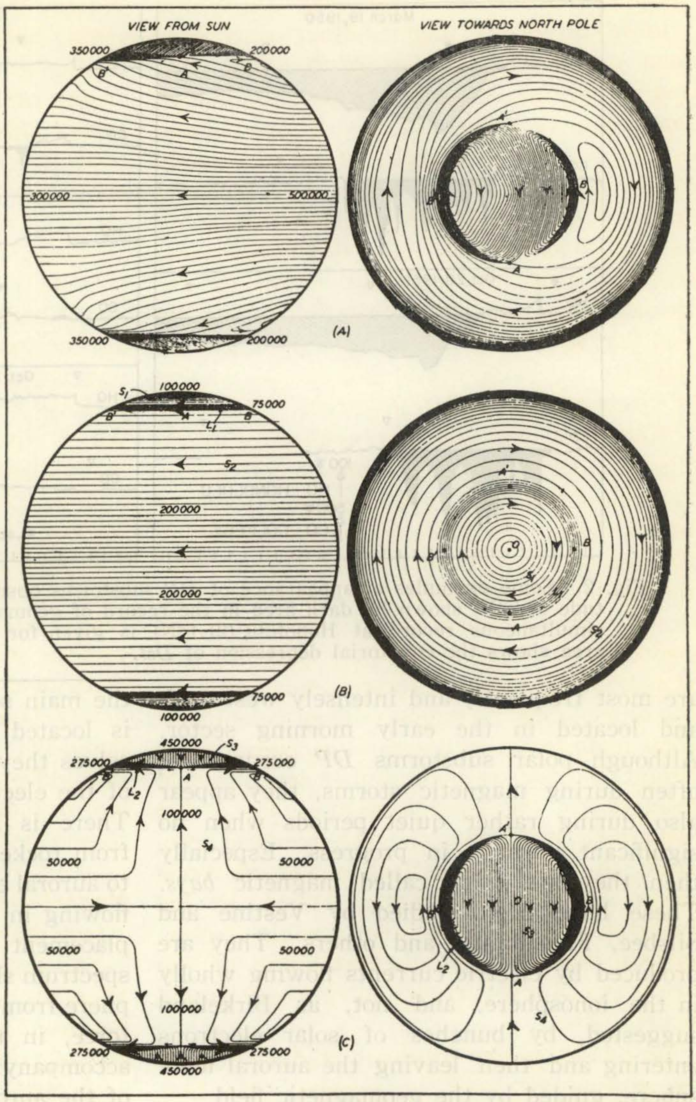

Fig. 1. **Idealized overhead electric current-system that could produce (A) total field, (B) *Dst* part, and (C) *DS* part of the average disturbance field during the main phase of magnetic storms of moderate intensity.**

Magnetic Storms and Polar Substorms

The characteristic average course of a storm led me to regard a magnetic storm as a unity, with a beginning, middle and end. I suggested that Birkeland's four types of storm, equatorial and polar, positive and negative, are but parts of a fairly standard whole. I identified his equatorial positive and negative storms with the first and second storm phases as manifested in low latitudes, and his polar positive and negative storms with the occurrence of eastward and westward auroral electrojets and their return currents. Birkeland himself recognized a certain "genetic connection" between his four types of storm. Thus his polar storms I call *polar substorms*, and denote them and their currents by *DP*.

After establishing the *average* morphology of magnetic storms, it is natural to look into the features of individual storms. Each storm develops and progresses differently. The polar substorms are rather sporadic and intermittent. Their life is usually short, one or two hours, and they occur in rather random fashion, though the auroral electrojets

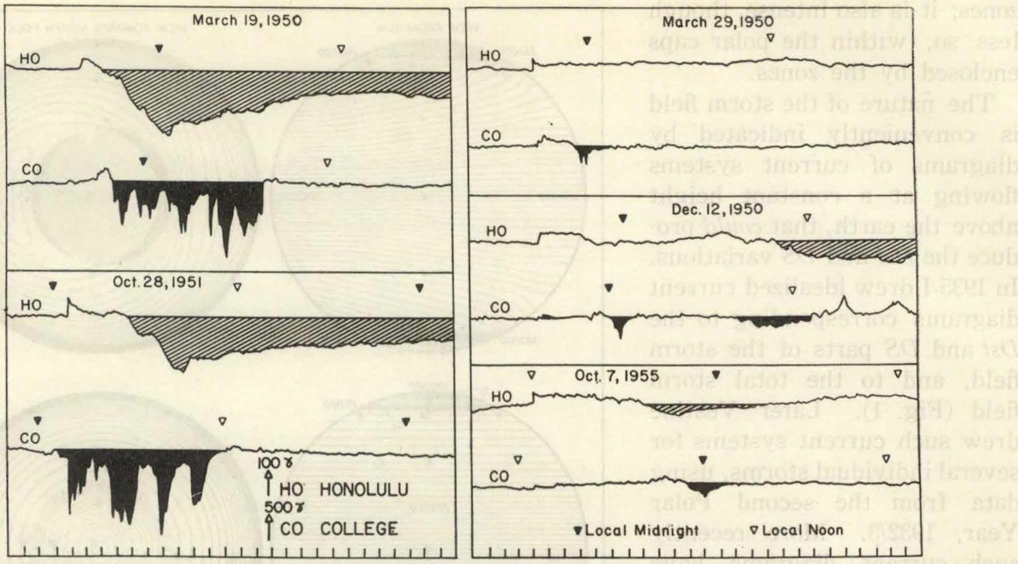

Fig. 2. Some examples of appearance of *DP* substorms observed at College (geomagnetic latitude 64.7°N) shown by dark area in the record of geomagnetic horizontal intensity. The simultaneous record at Honolulu (21.1°N) is given for comparison, in which the hatched area shows the equatorial depression of *Dst*.

are most frequently and intensely westward, and located in the early morning sector. Although polar substorms *DP* occur most often during magnetic storms, they appear also during rather quiet periods when no significant storm is in progress. Especially then they are often called magnetic *bays*. These have been studied by Vestine and Silsbee, Fukushima, and others. They are produced by electric currents flowing wholly in the ionosphere, and not, as Birkeland suggested, by bunches of solar electrons entering and then leaving the auroral ionosphere, guided by the geomagnetic field.

The individuality of magnetic storms is shown in Fig. 2. Each storm develops differently, both in low latitudes and in the auroral zones. It seems that storms with few or weak *DP*'s have only a small main phase, whereas those with many and intense *DP*'s have a strong main phase. Such a difference seems to have no definite relation with the range of the storm sudden commencement (ssc), which is a measure of the energy flux of solar streams. Such an individuality suggests irregularities in the solar streams, at least along the sun-earth line.

The Three Systems of Magnetic Storm Currents, *DCF*, *DR*, and *DP*.

The surface magnetic data indicate that the main source of the magnetic storm field is located above the earth. But in themselves they cannot tell us the precise location of the electric currents that produce the field. There is ample evidence, ionospheric and from rockets, that the *DP* substorms are due to auroral electrojets and their return circuits, flowing in the ionosphere. The Doppler displacement of the *Hα* lines in the auroral spectrum shows that protons enter the atmosphere from outside, along the lines of magnetic force, in the auroral zone. They and the accompanying electrons, which excite much of the auroral luminescence, strongly ionize the air along the auroral zone. The electromotive forces that drive the auroral electrojets and the whole *DP* current system have been ascribed to dynamo action. To me, however, Akasofu's theory seems more probable, namely, that the electromotive forces, which must be directed nearly along the meridian, result from a slight difference between the mean latitudes of entry of the primary protons and electrons. Electric forces along the meridian produce eastward or westward currents along the auroral zone. This is partly because of the strong anisotropy of the electric conductivity in the ionosphere — due to the geomagnetic field, as elucidated by Cowling, Schlüter, Martyn and Hirono — and partly because the zone is so highly ionized. The auroral electrojets can change very rapidly in intensity and even in sign, as shown especially by Oguti. This seems incompatible with dynamo-induced electromotive forces, but quite compatible with the small inertia of beams of electrons entering from outside.

Until recently there was no such clear evidence as to the locations of the currents that produce the *Dst* part of the field in the main belt of the earth. Thirty years ago Ferraro and I gave reasons for believing that the first phase of a storm, during which the horizontal surface field is increased, is due to electric currents flowing mainly eastward, on the sunward side of the earth. We tried to infer what would happen when a neutral ionized stream of gas ejected from the sun— as suggested by Lindemann in 1922 — impinged on the earth's magnetic field. We concluded that the field must carve a hollow in the stream. The protons and electrons approaching most directly must be turned back almost in their tracks, those to one or the other side are deflected sideways. There is a slight difference between the deflections of the protons and electrons, corresponding near the equatorial plane to an eastward current. This increases the magnetic field within the hollow, more on the sunward than on the night side. The currents shield the near body of the stream from the earth's field. These currents and their field may be denoted by *DCF*, the *CF* denoting corpuscular flux. The *DCF* field must persist as long as the stream continues to flow towards the earth.

In our theory we made no attempt to explain how the sun projects such streams and clouds. We felt forced to idealize the problem, in particular as regards the random speeds. We did not conceive the possibility that the earth's atmosphere extends outwards into the space, within a few earth radii, where we inferred that the important interactions between the stream and the field would occur. This conception only dawned 20 years later, through Storey's theory of whistlers. Nor did we consider any solar magnetic field in the gas — this was another conception of later date, due to Alfvén, Morrison, Gold, and others. Our lack of reference to these features of the actual problem did not imply any judgement as to their unimportance; we simply did not think of them at that time. Once recognized, they must be taken into account. Alfvén's hydromagnetic waves must play a part in transmitting to the earth's surface the field changes that Ferraro and I inferred. Though we succeeded in explaining the first phase of a storm, we were unable to account for the main phase. Our work, however, indicated the probable linear scale of the westward ring current that produces the large decrease of the earth's field during this phase. Different views have been held as to the location of this ring current. Some have concluded that the *Dst* field is largely produced in the ionosphere, within a few hundred kilometers of the earth's surface. Others, such as Adolf Schmidt, the Director of the Potsdam Observatory for many years, ascribed the *Dst* field to a westward ring current outside the atmosphere, but did not suggest any precise location for it. The arguments pro and con need not be given here. The situation has changed greatly as a consequence of the discovery and exploration of the radiation belts by Van Allen and Vernov and their colleagues, by instruments carried on satellites and cosmic rockets. Their nature and general location were recognized theoretically by Singer a year before their discovery.

Magnetic measurements by instruments similarly borne have shown changes of the field, at distances of several earth radii from the earth's center, which give clear proof of the presence of westward electric currents in the region of the belts. The magnitude of these changes can reasonably be linked with the changes of the field at the earth's surface. Hence the main *Dst* field may be attributed to such ring currents in the radiation belts. These currents may be denoted by *DR* (*R* for ring current).

In 1950 Alfvén published a work of great originality, *Cosmical Electrodynamics*, which bears closely on the phenomena of the radiation belts. The particles spiral round the lines of force, and oscillate to and fro along them between north and south latitudes. Also they drift round the earth, the electrons eastward, the protons westward. This was later confirmed by the remarkable Argus experiment, suggested by Christofilos. High energy electrons produced by nuclear explosions in the ionosphere spread round the earth in accordance with theory.

The drift motions constitute a westward current, but the main current is due to the diamagnetism of the gas, resulting from the spiral motions round the lines of force. Each particle is a small magnetic dipole directed opposite to the field. Thus a distribution of magnetization is associated with the gas. Its field is equivalent to that of a certain current distribution. If the belt is steady and symmetrical about the earth's axis, the ring current symmetrically encircles the earth. The major term in the expression for this current involves the pressure gradient in the belt, perpendicular to the field. The pressure gradient has opposite signs on the inner and outer sides of a belt, and the current flowing there has opposite directions. On the inner side it is eastward, on the outer side it is westward (Fig. 3). The westward part is the stronger, so the net current is westward, corresponding to the main phase of a storm. But the reversal of currrent direction within the belt produces a sharp dip in the field, to a minimum near the centerline of the belt (Fig. 4). Such a dip was observed by the satellites or rockets Mechta and Explorer VI and others. In the latter case (see Fig. 5) the minimum was at about 6*a*, where *a* denotes the earth's radius. The line of force of the dipole field that crosses the equatorial plane at that distance meets the earth's surface at latitude 66°, about the latitude of the auroral zone.

Akasofu and I have calculated the field of a model radiation belt with a center line of radius 6*a*, with a Gaussian radial distribution of density, and of breadth about two earth radii. We assumed a particular distribution of the angles — called pitch angles — between the particle velocities and the magnetic force, in the equatorial plane. We found that an energy density n_0E of protons, at the center line, equal to 150 kev/cm³, could reasonably account for the Explorer VI magnetic observations (See Fig. 5). This energy density might be provided, for example, by 1 proton /cm³ of 150 kev energy, or 2/cm³ of 75 kev electrons. Denoting the inner and outer Van Allen belts by *V1* and *V2*, we call the third belt, indicated by Explorer VI, belt *V3*.

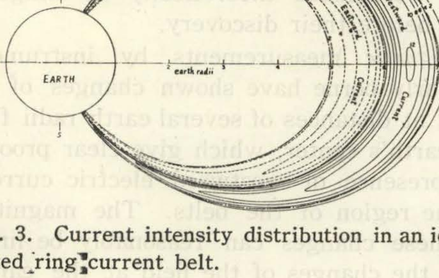

Fig. 3. Current intensity distribution in an idealized ring current belt.

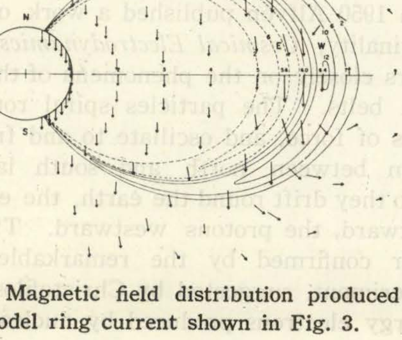

Fig. 4. Magnetic field distribution produced by the model ring current shown in Fig. 3.

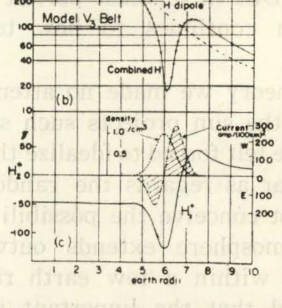

Fig. 5. (a) The magnetic field measurement H_n made by the magnetometer carried on the Explorer VI. (Smith *et al.*, J. Geophys. Res., **65**, 1856-1857, 1960).

(b) The field distortion produced in the equatorial plane by the model *V*3 belt indicated in (c), taking n_0E to be 150 (for example, $n_0 = 1/\text{cm}^3$ and $E = 150$ kev.)

(c) The number density distribution $n_0(r_e)$ for the model belt *V*3 and the corresponding distribution of current intensity $I(r_e)$ and magnetic field intensity H_z^* — all for the equatorial plane.

The counters that until recently have measured the radiation intensity could not detect protons of the suggested relatively low energy.

The Radiation Belts and the Aurora

The theory of the motions of the trapped particles in the radiation belts has a close bearing on the aurora. There are several invariants of the particle motions. One of them, given by Rosenbluth, enabled Vestine and Sibley to determine the two auroal zones theoretically, in good agreement with the zones found, with still imperfect accuracy, from observation. In the absence of electric fields the enegy and the dipole moment are constant for each particle. As a particle descends from its apogee in the equatorial plane, along a line of force, into a stronger field, its pitch angle steadily increases, until it becomes 90°; then it has lost all its forward motion, and it turns again to ascend along the line of force to the equatorial plane and beyond. The mirror point at which it turns back is determined, for a given line of force, by the pitch angle at the equator. For the lines of force that reach the auroral zones, only particles with pitch angles less than 4° can descend to auroral levels in the ionosphere. Particles with such pitch angles are caught in the atmosphere and lost to the belts. They are a small minority; most of the particles oscillate to and fro between northern and southern latitudes, at high levels in the atmosphere.

Akasofu and I have proposed an explanation of the ribbon-like form of auroral luminescence, on the basis of the particle motions and the morphology of the magnetic storm field. The auroral arcs in their quiet diffuse phase are only about 3 km thick, though sometimes hundreds of km in extent along the lines of force, and thousands of km long horizontally. The limiting lines of force are less than 40 km apart at their widest separation, where they cross the equatorial plane. As the belts are tens of thousands of km in radial extent, what causes the flow of particles to auroral levels to be confined within such narrow strips of the equatorial plane? Our answer is that particles can continue to flow to auroral levels, starting with very small pitch angles, only from the vicinity of a neutral line in the magnetic field. We believe that the ring current in the *V3* belt becomes strong enough, during magnetic storms, to reverse the field near the center line of the belt. This happens mainly on the dark side of earth. The field of the *DCF*

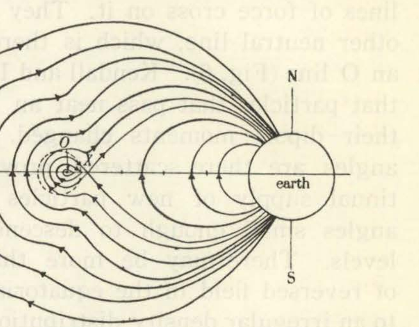

Fig. 6. Schematic diagram of the magnetic field configuration when a toroidal ring current (the cross-section boundary of which is indicated by the broken line) flowing round the earth. The X- and O-type neutral lines are also shown.

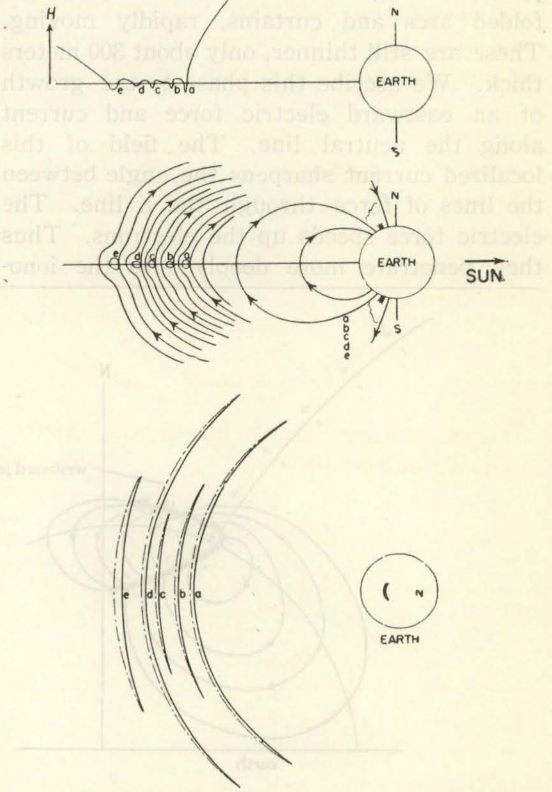

Fig. 7. Magnetic field intensity distribution with distance far outside the earth (upper figure), lines of magnetic force (middle), and the distribution of neutral lines in the equatorial plane (bottom figure). X- and O-type neutral lines are drawn respectively by full and chain lines.

currents checks the reduction of the field by the *DR* currents, on the sunward side of the earth. Thus the field reversal occurs mainly on the night side of the earth, in a narrow strip bordered by neutral lines where $H=0$. One of these is called an X line, because the lines of force cross on it. They encircle the other neutral line, which is therefore called an O line (Fig. 6). Kendall and I have shown that particles that pass near an X line have their dipole moments changed. The pitch angles are there scattered, providing a continual supply of new particles with pitch angles small enough to descend to auroral levels. There may be more than one strip of reversed field in the equatorial plane, due to an irregular density distribution in the *V3* belt. Each X line is associated with an auroral arc — thus explaining the multiple auroral arcs so often seen (Fig. 7).

An extension of our theory offers a speculative explanation of the second auroral phase, during which one sees rayed, and folded arcs and curtains, rapidly moving. These are still thinner, only about 300 meters thick. We ascribe this phase to the growth of an eastward electric force and current along the neutral line. The field of this localized current sharpens the angle between the lines of force through the X line. The electric force speeds up the electrons. Thus they penetrate more deeply into the ionosphere, often causing the lower border of the rayed curtain to be tinged with the red light of nitrogen bands. The current flowing along the X line is unstable, and becomes wavy and changing. This form and motion is transmitted along the lines of force to the auroral zone. The sheet of electrons moving from the X line towards the atmosphere along the lines of force has another, finer, instability, to which we ascribe the pleating of the auroral curtains.

The rise of the eastward electric field along the X line we associate with the spread of newly captured solar gas, on the sunward side of the earth, around the globe. The neutral lines form an unimpeded channel for electric current flow along the equatorial plane, whereas elsewhere such flow, transverse to the magnetic field, is hardly possible.

It is during this second auroral phase, which is closely associated with *DP* substorms, that the electron beam (according to Akasofu) is displaced, usually southward, relative to the proton beam. This provides the electric field necessary to set up the auroral electrojets and their extensions over the whole earth (Fig. 8).

During a magnetic storm with many *DP* substorms and associated auroral displays, we believe that there are many accessions of solar gas to the belt. These enhance the ring current, when the gas has spead around

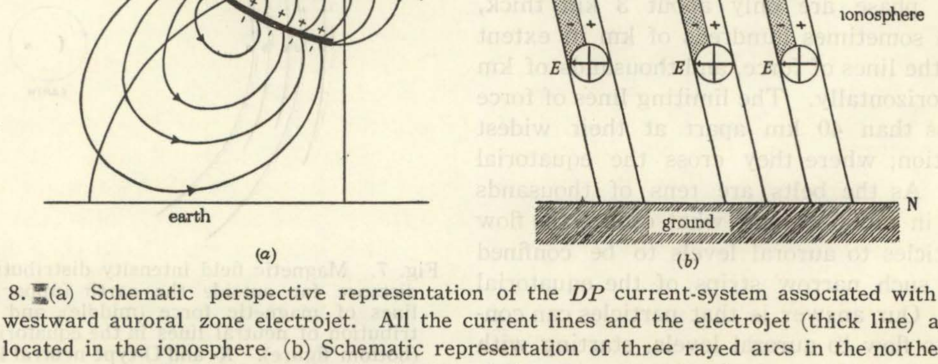

Fig. 8. (a) Schematic perspective representation of the *DP* current-system associated with a westward auroral zone electrojet. All the current lines and the electrojet (thick line) are located in the ionosphere. (b) Schematic representation of three rayed arcs in the northern auroral zone with the supposed distribution of electron and proton fluxes.

the earth. Hence the main storm phase is well developed. If there are few or no accessions of solar gas, the storm consists of a long continued first phase, with only slight development of the main phase.

Objections have been raised against our proposed reversal of the earth's field in the body of the *V3* radiation belt. But such reversals have been observed in the thermonuclear reaction vessels in which a very hot plasma is confined by a strong magnetic field.

Changes in the Radiation Belts and Cosmic Rays

The protons in the inner Van Allen belt, which we name *V1*, are ascribed to the decay of neutrons that ascend from the atmosphere below, where they are generated by impact of cosmic rays on atomic nuclei of the air. The origin of the electrons in the *V1* belt is still uncertain.

The particles in the main radiation belt, *V2*, are generally believed to come from the sun, though some dissent from this view. This belt changes rapidly, especially, at times, during magnetic storms. The detailed processes of capture of the solar gas are still imperfectly understood. Akasofu and I regard the irregular occurrences of *DP* substorms during magnetic storms as indicating irregularities along the solar streams, perhaps associated with regions in which more than usually energetic particles are carried along in tangled magnetic fields.

Cosmic ray studies will help to resolve these questions. During the two phases of cosmic ray recording, first of mesons, later of neutrons, they have revealed most interesting solar and geophysical relationships.

Steinmauer in 1933 and later Duperier and Forbush first observed decreases of cosmic ray intensity during magnetic storms. One suggested explanation of this was the increase in the dipole moment of the geomagnetic field by the enhanced ring current during a magnetic storm. But the cosmic rocket Pioneer V indicated that the Forbush decrease is not geocentric but heliocentric, because a decrease of as much as 28% was observed five million km away from the earth. Alfvén was the first to envisage magnetic fields carried from the sun by streams as the cause of the Forbush decrease.

The fact that in many magnetic storms a Forbush decrease is not observed led Morrison to suggest that solar streams are of two types, magnetic and non-magnetic. Magnetic solar streams prevent or reduce the penetration or diffusion of galactic cosmic rays into their volume, and this is observed on earth when our planet is immersed in such streams.

Gold presented the conception of streams constituting "magnetic bottles", stretching out the tubes of magnetic force nearly radially, from active regions of the sun. The irregular occurrence of low energy cosmic ray bursts, observed by Ney at Minneapolis during magnetic storms, may be due to spasmodic emission into such a magnetic bottle.

It seems now clear that solar activity modulates the incidence of galactic cosmic rays in interplanetary space including the region surrounding the earth. The 11-year cycle in cosmic ray intensity has been interpreted as indicating gross changes in the electromagnetic conditions in the interplanetary space.

In 1942 it was noticed by Berry and Hess and by Lange and Forbush that the sun produces relativistic particles, the solar cosmic rays, during large solar flares. Such high energy particles arrive at the earth in about half an hour after a flare. They produce a sudden increase of the counting rate, sometimes by as much as a few hundred percent of the normal rate. At least ten such increases have been observed to date. Neutron monitors detect them more easily and more often than meson counters. During the spectacular increase observed on Feb. 23, 1956, following the outbreak of a large solar flare on the western limb of the sun, the sun produced particles with energy as high as 15 Bev.

The propagation of such cosmic ray particles through interplanetary space has proved to be a powerful tool for the exploration of electromagnetic conditions there. It was inferred that during the 1956 February event, high energy particles quickly filled the whole inner interplanetary space, and then diffused away gradually. It has recently been shown that the particles do not come exactly from the direction of the sun, suggesting somewhat complicated paths of such particles between the sun and the earth.

In 1959 it was found that the sun also produces so-called low energy solar cosmic rays. The particles are not energetic enough to penetrate to middle latitudes, but can impinge on the polar regions, where they produce the polar cap absorption (Leinbach and Reid 1959). Such particles have recently been extensively studied, using balloons and satellites, by Simpson, Winckler, Van Allen, and Lin and their colleagues. Such methods have also given most interesting records of the entry of high energy electrons and also of γ-rays associated with flares and magnetic storms. At this conference we shall learn much about these events from some of the main experts in this field.

Ionospheric Storms

Ionospheric storms associated with geomagnetic storms offer many complicated problems, and are likely to prove extremely important for the better understanding of geomagnetic storms and auroral phenomena.

The intense and sporadic ionization in the *E* region of the auroral ionosphere was first studied by Appleton and Naismith in 1933, during the Second International Polar Year. In 1936 Harang found that such intense ionization coincides with intense auroral displays and large local magnetic changes or *DP* substorms. More recently extensive studies of auroral ionization by radar techniques have revealed the occasional presence of auroral curtains on the sunlit as well as on the night hemisphere. Kaiser and his colleagues and Nichols have studied the electron drift of sporadic ionization during polar magnetic storms, and connected it with the auroral electrojets. They found that the eastward and westward motions of the (secondary) electrons in the auroral zone coincide with negative and positive polar magnetic storms, respectively.

One most remarkable feature of ionospheric storms is the decrease of the critical frequency, *foF2*, and the increase of the virtual height of the *F2* layer. Early examples of them are found in a series of papers by Berkner and Seaton (1939–1940). The increase of virtual height is now interpreted as due mainly to retardation of the sounding radio waves, rather than to upward motion of the *F2* layer as a whole. This has been clearly demonstrated by Thomas (1959).

Further, extensive analyses of ionospheric data from all over the world reveal that the change of *foF2* is complicated and may be either negative or positive, depending on the local time, the location and season (Obayashi).

A present view is that a large distortion of the *F2* layer during magnetic storms is primarily due to drift motions of the ionization there (Martyn, Sato and Maeda). During magnetic storms, intense currents, auroral electrojets, flow along the auroral zone. Such currents set up an electric polarization field all over the ionosphere, in order to complete the current circuit. The electric field thus generated produces the drift motions of ionization perpendicular to both the electric field and the magnetic field. The drift motion can be either upwards or downwards, depending on the direction of the electric and magnetic fields.

A great complication arises because of the long life of the ionization at high levels, and a large change of the recombination coefficients with height in the *F2* region. Therefore it is difficult to calculate how the *F2* layer behaves even if the drift motion were known.

Another important question regarding ionospheric and magnetic storms and auroral displays relates to the spiral geographical distribution inferred by Nikolsky, Piggott and others. Further evidence and clarification of this question is evidently desirable. As regards the spirality of auroral forms, the best evidence might be provided by satellite photography of the whole arctic region in the northern winter months. This might be able to show us the complete simultaneous auroral distribution over the polar cap. Meanwhile we must await the piecing together of all-sky camera films from many stations in the hope that they will throw light on this question.

Thus I end this survey of earth storms, conscious of the inequality of my treatment of its many phases. Now that so many able minds and such ample financial resources are being devoted to this subject, we may look for future progress to outdo in rapidity and scope even the remarkable advances of the last three years.