explanation of the spiral or curved patterns found for blackout and sporadic E ionization, and for the predominant occurrence of one phenomenon on the light side of the pole and for the predominance of the other on the dark side. The relative role of positive and negative particles in these two phenomena is still an open question.

The principal cause of the PCA clearly seems to be solar proton emission, but many detailed features of the phenomenon need further elucidation. Sometimes PCAs are accompanied by magnetic storms and sometimes not. The incidence of PCA is not simultaneous at the north and south polar caps, and there is also evidence for delays in latitude and longitude. Why does the sudden commencement of a magnetic storm during a PCA cause a reduction in ionospheric absorption? Why does the spatial distribution of PCA show a marked bias toward the light side of the polar cap? Further study is necessary of the development of PCAs and their relation to the auroral zone absorption. Are the long period D-region phenomena, those with an after-effect of many days, observed in medium latitudes related to the PCA phenomenon?

For the $F2$-region we need a completely satisfactory explanation for the formation of this region. In such a theory we need to decide the part, if any, which is played by drift from one hemisphere to the other, as has been suggested between magnetically conjugate points. We need to explain the existence of an $F2$ region with a substantial electron content during the long polar winter night, and to explain the regular movements and variations observed at such times. It is necessary to explain why, at temperate latitudes, during a storm the *total* content of the layer is diminished, and why at equatorial latitudes it appears to be increased. In polar latitudes we need to understand the relative influence of particles and electric currents, and to decide what are primary and what are secondary effects. Storm phenomena involving very large increases in the peak electron density of $F2$ need further study.

These are but some of the problems to be solved before we can say that we understand well the storm behaviour in the ionosphere.

JOURNAL OF THE PHYSICAL SOCIETY OF JAPAN Vol. 17, SUPPLEMENT A-I, 1962
INTERNATIONAL CONFERENCE ON COSMIC RAYS AND THE EARTH STORM Part I

I-6-P3. Electric Current in the Ionosphere and the Aurora

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The occurrence of magnetic disturbance indicates the addition of a disturbing field (D) to those normally present, namely to the main field M and the fields Sq and L of the solar and lunar daily magnetic variations. By spherical harmonic analysis or otherwise the D field can be divided into a primary part D_e, of external origin, and the remaining part, $D-D_e$, that is due to currents induced within the earth by the changing field D_e. It is also possible to derive a "conventional" electric current system flowing in a thin concentric spherical surface at some chosen height above the earth, that could produce D_e. The currents that actually cause D_e are not of this kind: they do not flow at any one height above the earth. In the middle belt of the earth the Dst part of D_e is due mainly to two systems of electric current that flow at a few earth radii above the earth's surface. One of these systems (DCF) flows in the surface of the hollow carved by the geomagnetic field in the solar stream; in and near the equatorial plane the flow is eastward; this current system produces the increase of H, the horizontal magnetic force, observed in the main belt of the earth during the initial phase of a storm. The other system (DR) is a ring current associated with the belt or belts of energetic particles that spiral and drift in the geomagnetic field; this flows partly eastward, but mainly westward; it produces the decrease of H observed during the main phase in the middle belt.

The remainder of the D_e field is produced by electric currents flowing in the ionosphere. Suppose the above-mentioned conventional current system is derived for a height of 100 or 125 km above the earth. By estimating in some way the part of this system that corresponds to the DCF and DR currents, and subtracting it from the conventional system, it is possible to derive an approximation to the ionospheric current system. This has not yet been done, but I hope to do it at an early date, for some selected magnetic storms. This current system may be denoted by DP, because it is strongest in the polar regions, where it supplies almost all the D_e field. It consists of a westward electrojet (a concentrated approximately "linear" current) flowing westward along a considerable part of the auroral zone, and often also includes a weaker eastward electrojet along the remainder of the zone; these electrojet currents complete their circuit in the ionosphere mainly over the polar cap, but also spread over the main belt of the earth between the auroral zones. At least sometimes (as observed at Huancayo, during sudden commencements) this last part of the DP current system is enhanced at stations that lie under the Sq and L *equatorial* electrojets (Sugiura 1953, Forbush and Vestine 1955).

The Sq and L current systems are generated by the dynamo action of ionospheric airflow in the presence of the geomagnetic field. These systems extend over the whole earth, including the polar caps; but there, except at extremely quiet times, they are insignificant compared with the DP currents. These grow and decay intermittently, with peak intensity that varies over a wide range, whenever there is magnetic activity; only during magnetic storms are they accompanied by DCF and DR currents with appreciable fields at the earth's surface.

It has been suggested by many writers (Rikitake 1948, Fukushima 1953, Nagata and Fukushima 1952, Obayashi and Jacobs 1957, including myself in 1926) that the DP currents may be due to dynamo action, mainly operative in the polar regions. The airflow involved, according to this view, may be that normally present in these regions: or it may be this together with additional flow set up by the entry of the electrons into the atmosphere, that cause the aurora. This entry must certainly heat the ionosphere to some extent, perhaps as proposed by Cole (1961), and this will generate air motion. The currents arising from such dynamo action must certainly be powerfully influenced, in morphology and intensity, by the additional ionization created by the primary auroral particles.

Such dynamo action seems likely to play some part in generating the DP current system. But it seems likely also that at least at times a part of the electromotive forces (emf) that drive the DP currents is of electrostatic origin. This could arise if the mean latitude of entry of the primary auroral particles is different for protons and electrons. Akasofu (1960) has suggested that the westward auroral electrojet is caused by the latitude of entry for protons being higher than that for electrons, creating a southward emf; on account of the anisotropic electrical conductivity of the ionosphere (caused by the geomagnetic field) the resulting currents would flow westward. The eastward electrojet would on this view be caused by a converse difference between the latitudes of entry. The cause of the proposed latitude differences is not yet clearly explained. But only some such cause seems adequate to explain the reversal of the DP currents disclosed by Oguti (1956) in his studies of the polar currents in the earliest stages of certain magnetic storms; at such times the DP currents may not show the auroral electrojets.

Other explanations of the DP currents have been proposed. Birkeland thought that the electrojet current entered the atmosphere from outside, by inflow of charged particles of one sign, and then left by the outflow of such particles. But Vestine (1938) and later

Kirkpatrik (1952) showed that the polar magnetic data are less well fitted by such currents than by the completely ionospheric *DP* system; and Birkeland's ideas on this point seem untenable also on other grounds. Martyn (1951) ascribed an important rôle in the production of the *DP* currents to a north-south emf in auroral latitudes, which he supposed transmitted along lines of geomagnetic force from a ring current of a now discarded toroidal form considered earlier by Chapman and Ferraro (1932). Though his theory would no longer be upheld, his discussion introduced important new ideas in the discussion of magnetic storms. Dungey and others have proposed origins for the *DP* emfs that use some of Martyn's ideas. Dungey (1961) stresses the possible importance of neutral points caused by the combination of the geomagnetic field with a supposed southward magnetic field transmitted from the sun by a solar stream or cloud; his ideas are still in an early stage of development, and it is not yet clear whether they can account for the observed form and location of the auroral zones. Axford and Hines (1961) are developing a different set of ideas that may explain these properties of the aurora and also the generation of the *DP* emfs.

A striking feature of the *DP* current system is its irregularity and intermittence. Many magnetic storms include several periods during which the *DP* currents grow and decay (causing Birkeland's elementary polar storm, positive and negative, which may also be called *DP* substorms, often combining simultaneously both of Birkeland's types). Quieter periods with little or no *DP* current intervene. Some magnetic storms have few or no *DP* substorms. There seems to be a striking association between the occurrence of *DP* substorms and the development of the main phase of a magnetic storm (see Fig. 2, p. 10). Akasofu and I (1961) have suggested that the *DP* substorms may be associated with the capture of volumes of solar gas, and their spread round the earth, during the onflow of solar streams or clouds in which energetic particles are carried along with the stream by transported solar magnetic fields. Such capture, and the associated growth of the ring current, could be linked with the development of the second, active stage of auroral displays, which is well correlated with the onset of *DP* substorms. We have not yet offered any explanation of the mode of the proposed capture, and in this and other ways our suggestions are tentative and subject to modification. Dessler and Parker (1959) and others have concluded that the solar particles are not captured, but energize background charged particles in the region of the radiation belts, by electromagnetic or shock wave acceleration.

The magnetic changes at the earth's surface during storms and at other times also manifest pulsations of many kinds, studied especially by Kalashnikov, Troitskaya and their colleagues in the USSR, by Kato and his colleagues in Japan, by Wright, Campbell and others in Canada and the U. S. A., by Bouska in Czechoslovakia, and others. (Refer to the papers presented at the session II-1B. Geomagnetic Rapid Variation.) Such pulsations offer many interesting problems as to their origin and transmission to the earth, but I regret I am at present not competent to discuss them.

The aurora is of the most striking and interesting features of disturbance in the ionosphere, and one that offers many problems still unsolved. For a brief account of present ideas in this field I refer to my statement in the plenary session II-6. Synthetic Theory of the Earth Storms.

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