

I-1-P1. Morphology of Magnetic Storms

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The geomagnetic field frequently has superposed upon it magnetic fluctuations which undergo world-wide changes in pattern and intensity with time. The morphology of storms is concerned with these transitions in form of the field with time. The geomagnetic-field patterns of disturbance, almost always present in some degree, have been measured until recently only at the earth's surface, but there now appear fleeting indications of the form of the disturbance field and its associated charged particles in nearby space from observations by various space probes and earth satellites. The present article is intended to provide a summary of the better known and well established features of the morphology of storms.

A magnetic storm often has a sudden beginning, known as a sudden commencement, which has a world-wide field pattern related to the position of the sun. The onset is sudden to about one minute or less the world over, and the field changes tend to involve an increase in the northward horizontal intensity H of some tens of gammas above normal. The onset is usually greatest in polar regions. There is often magnification of the initial increase by a factor two or so on the sunward side of the earth along the magnetic equator.

In low latitudes, the initial change in H , usually positive, may be maintained and even increased over an hour or so to form an initial phase of the storm. The value of H then decreases and reaches a minimum (below the normal value) 15 to 20 hours after the sudden commencement. The value of H then returns to normal over a period of some days.

The polar disturbance field during bays tends to rotate westward with time at a rate of order 5° - 10° of longitude per hour at, or just north of, the auroral zone. Outside the zones current-patterns appear to drift eastward. There is also evidence of a slow drift to the east of the eastward-directed electrojet at the auroral zone.

§ 1. Introduction

It will be the aim here to summarize briefly a number of the major descriptive features of magnetic (earth) storms. An attempt will also be made to integrate some recent rocket and satellite magnetometer measurements in a systematic way into the previous surveys of the morphology of disturbance (*Chapman and Bartels, 1940, Vestine, et al., 1947, Sugiura and Chapman, 1960, Akasofu and Chapman, 1961*). Finally, some electric current configurations and their driving forces are discussed.

Geomagnetic time fluctuations or disturbances, often, on a world-wide scale, frequently appear superposed upon the normal geomagnetic field present during magnetically quiet periods. The changes in the field

pattern with geographic position during the course of time constitute the morphology of disturbance. The more intense disturbances are known as storms.

Magnetic disturbance is most intense within two belts or zones encircling the earth near geomagnetic latitudes $\pm 67^{\circ}$, where aurora also appear with highest frequency and intensity. These so-called auroral zones are oval in form and in general a few degrees of latitude in width. In auroral regions, the field fluctuations are often oscillatory and irregular, and associated with irregularities in ion concentration in the ionosphere and with aurora. These irregular field changes with time decrease rapidly equatorwards, and less rapidly toward the center of the auroral zone. The aurora may simultaneous-

ly appear in several adjacent arcs near the average position of the auroral zone.

The disturbance field D includes parts which grow and then decay with one part (D_s) displaying patterns depending mainly upon latitude and solar position, as well as a major part (D_{st}) that varies mainly with geomagnetic latitude and time reckoned from the beginning of a storm. There is also an irregular part (D_i) that is mainly related to (D_s). In this notation D stands for disturbance field, S for solar, and st for storm-time (Sugiura and Chapman, 1960).

The intensity of disturbance varies with time. In auroral regions it is apparently always present in some degree, and when weak may be localized at ground level or significant within an area only some hundred kilometers in linear cross section. Very intense disturbances may appear locally, but

then are usually apparent in some measure on a world-wide scale. When such world-wide disturbances become specially intense, they are called magnetic storms. These usually begin suddenly (in less than a minute) over the entire earth. Storms may recur more than once in time sequence. In this case the onset or commencement is blurred, and may often be determined only to within an hour or so, the storms may recur at intervals of about a solar rotation of 27 days, in which case they are called recurrent storms. The latter are apt to be less intense than many of the sudden commencement storms (Chapman and Bartels, 1940).

§ 2. Sudden Commencements

Fig. 1. shows a fairly typical example of a sudden commencement storms observed at Kakioka, Japan, on April 18, 1951 (Kamiyama,

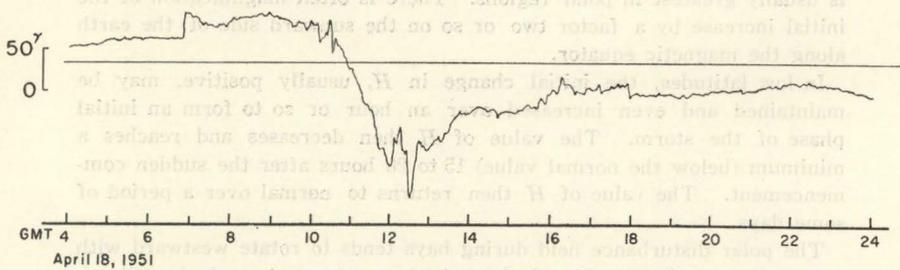


Fig. 1. Copy of the magnetogram recorded at the Kakioka magnetic observatory.

1952). The sudden commencement of about 40 gammas (one gamma= 10^{-5} cgs-unit) is clearly apparent as a rise in horizontal intensity (tangential and nearly northward). It will be seen that the field remains above the pre-storm value for some hours. During the first hour or so the increase can be ascribed to a shell of current in the ionosphere (or described in terms of an associated field distortion). This current flows from west to east and is concentric about the geomagnetic or dipole axis of the earth. The sudden commencement, in fact, usually ushers in an initial or positive phase of the storm.

The amplitude of sudden commencements varies both with latitude and time of day. According to Oguti, the morphology of a sudden commencement can be represented in terms of the signals from overhead current patterns of the type shown in Fig. 2, as

viewed from directly above the north geomagnetic pole in northwestern Greenland (Oguti, 1956). In the initial impulse, above the pole the current flows always from the sun so that the magnetic field will be directed roughly toward the dawn, or 6:00 a.m. meridian. This feature may give a preliminary reverse impulse in the forenoon. In adjacent areas the field may be opposite in sense. Within a minute the patterns shown in Fig. 2(b) and (c) may have appeared in sequence, growth from 2(a) being mainly due to the addition and superposition of an eastward flowing overhead current over the entire earth increasing in intensity with time. The general features, at least in part, agree with other derivations of SC currents (Nagata and Abe, 1955; Jacobs and Obayashi, 1956). The results also seem compatible with other estimates of time variations of

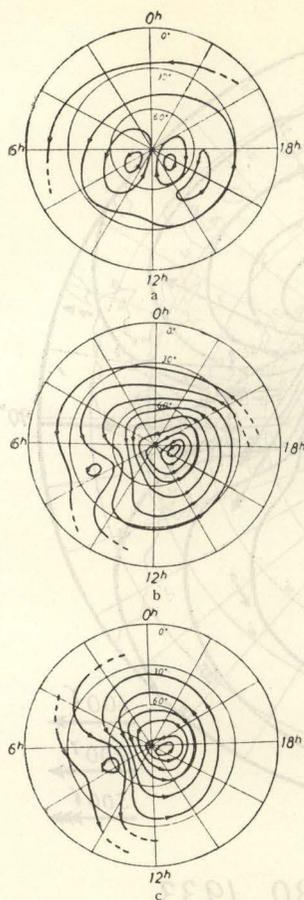


Fig. 2. The equivalent overhead electric current-system of SC. a, b and c represent respectively the first, the main and the last stages of SC. Electric currents of about 2.4×10^4 amp. flow between successive stream lines in the direction indicated by arrows. (after Oguti)

the field (Newton, 1948; Kato, 1952).

A feature not indicated is the augmentation of the SC field, by a factor about two, at the magnetic equator (Sugiura, 1953; Forbush and Vestine, 1955). This is explained in terms of more intense equatorial currents flowing in the low ionosphere along the magnetic equator (Jacobs and Obayashi, 1956). Highly localized intense features may accompany a sudden commencement or sudden impulse in the polar regions.

It will be clear that a part may be interpreted in terms of localized currents or atmospheric sources both in polar regions, and also near the magnetic equator, and a part to sources at higher levels, if desired.

§ 3. Initial Phase of Storms

There is considerable variability from storm to storm in the character and intensity of the earliest changes or initial phase of a storm. In general, a representation in terms of a current pattern such as Fig. 2(c) as drawn for sudden commencements, is often appropriate to the initial phase. The general pattern may persist for some minutes to several hours.

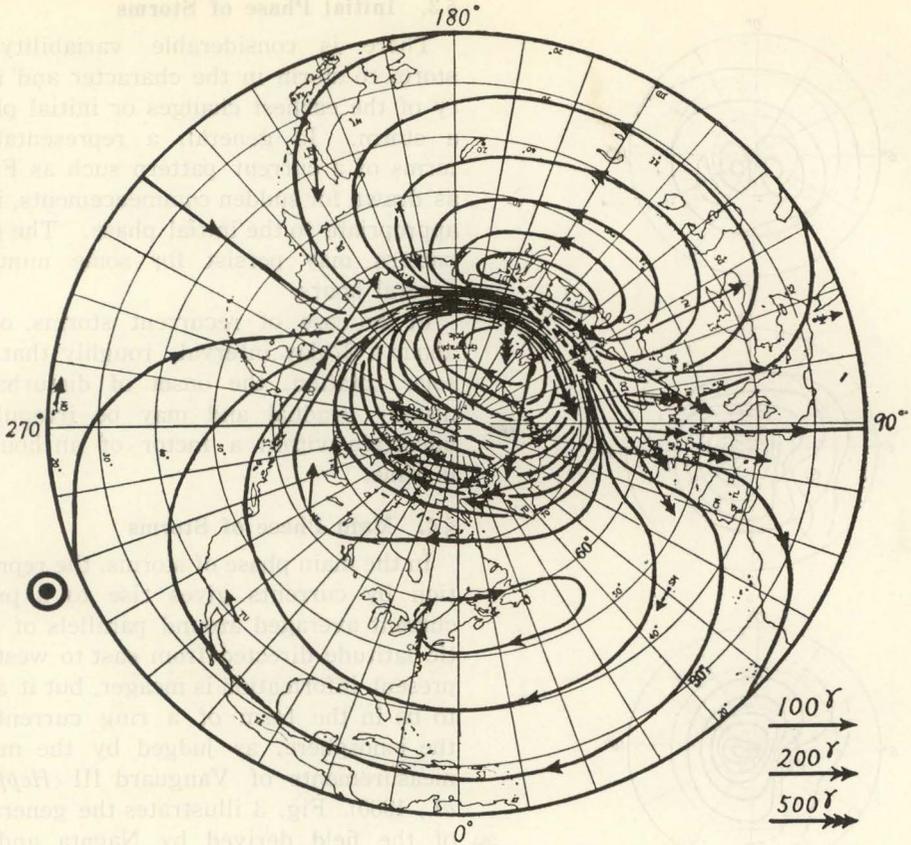
In the case of recurrent storms, often at about a 27-day interval, roughly that of the solar rotation, the onset of disturbance is usually gradual and may be irregular and uncertain within a factor of an hour or so in time.

§ 4. Main Phase of Storms

In the main phase of storms, the representation by currents gives rise to a principal current averaged around parallels of magnetic latitude directed from east to west. The present information is meager, but it appears to be in the form of a ring current above the ionosphere, as judged by the magnetic measurements of Vanguard III (Heppner *et al.*, 1960). Fig. 3 illustrates the general form of the field derived by Nagata and Fukushima for a particular instant of the main phase of the storm of May 1, 1933 (Nagata and Fukushima, 1952; Fukushima, 1953). The polar intensifications at the auroral zone may last for one to three hours, repetitive at the same locality on several successive nights during the main and recovery phases (Chapman and Bartels, 1940). Pulsations in field, both regular and irregular, of period a few tenths of a second to several minutes, usually appear during a storm noted at a high latitude station (Kato and Watanabe, 1957; Kato, 1959). Occasionally these are accompanied by auroral pulsations in illumination (Campbell, 1960; Vestine, 1943).

§ 5. Simultaneity of North and South Polar Disturbances

Nagata and his students have recently studied the simultaneity in polar electrojet effects at Baker Lake, Canada, geographic position ($64^\circ 18' N, 96^\circ 05' W$) and Little America ($78^\circ 18' S, 162^\circ 10' W$) (Nagata and Kokubun, 1960). Machine calculations give for a Baker Lake mirror point at height



21h15m GMT on Apr. 30, 1933

Fig. 3. Dipole-type polar magnetic storm. (after Fukushima)

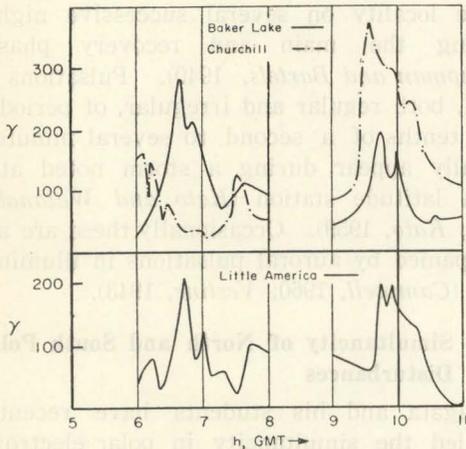


Fig. 4. Horizontal disturbance force at different stations (Bay-type variation. Local night time). (after Nagata and Kokubun)

100 km the conjugate (75° 36' S, 172° 40' W) with mirror point height 266 km. At night,

good correspondence is often found between the time changes at the two stations, as shown in Fig. 4. The correlation found was good on magnetically quiet days but poor on stormy days; the outer geomagnetic field may be more distorted and irregularly organized in the case of the latter.

§6. Morphology of Storm Field at Points Distant From the Earth

An irregularity in the geomagnetic field of about 400 gammas was noted by space probe at a height of about 22,000 km (Dolginov and Pushkov, 1959; Antsilevish and Shevnin, 1960). This measurement by rocket was made about 6 hours after the sudden beginning of a small storm-type disturbance.

Fig. 5. shows an interesting result found by Sonett and his colleagues in the flight of the space probe Pioneer V (Coleman, Sonett,

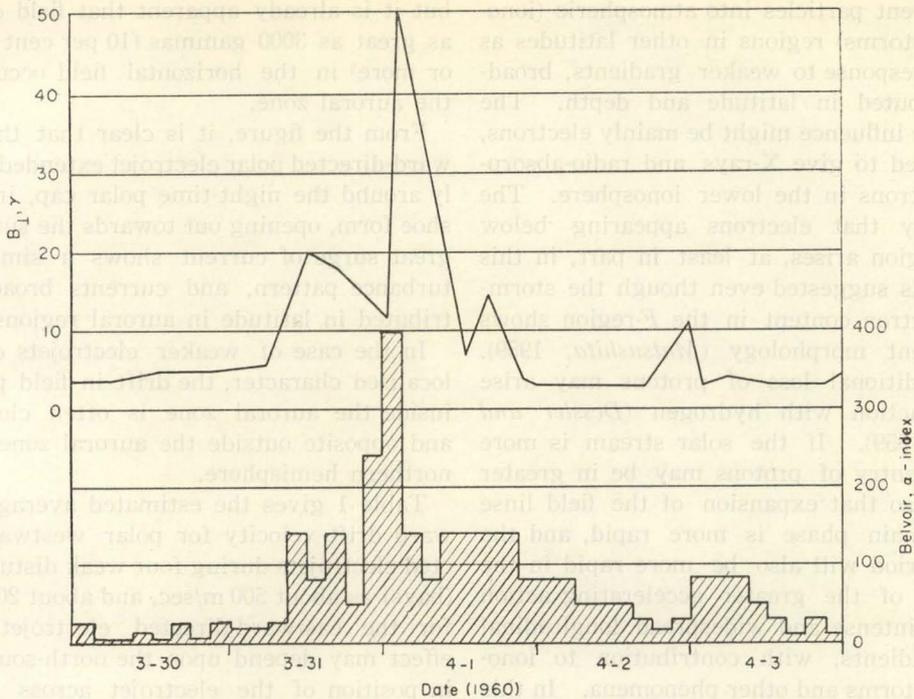


Fig. 5. Comparison of observations of interplanetary magnetic field and the magnetic a -index (Fort Belvoir) versus time. (after Sonett)

Judge, and Smith, 1960). The magnetic field time changes of some gammas detected appear to show correspondence with those recorded at ground level at Ft. Belvoir, Virginia.

§7. Associated Conjectural Morphological Events

According to the Chapman-Ferraro theory of storms and its modern extensions, a solar stream (or Parker's wind) interacts with the outer geomagnetic field which becomes compressed and distorted.

According to information supplied by Heppner and his co-workers, the results of Explorer X suggest that blobs of gas may proceed from the sun with a velocity of about 10^8 cm/sec (see *COSPAR Bulletin* No. 5, pp. 17-25). Such blobs would cause transient distortions of the outer geomagnetic field and, in fact, have been suggested previously on the basis of surface data, for instance (Vestine *et al.*, 1947, p. 362). They may involve frequent irregularities in weak solar stream, giving impulses such as those reported by Nishida and Jacobs (I-1-6).

The effect of the distortion can be such as to produce a longitudinal magnetic field

gradient, hydromagnetically communicated, and directed nearly sunward at dawn and evening polewards from the equatorial plane. Such gradient can give rise to separation of temporarily trapped protons and electrons in a radial direction, transient acceleration of such particles along field lines to produce atmospheric currents, and an acceleration mechanism (Kern, 1961). Acceleration may also occur as auroral flutes develop due to instabilities. In the same way, during initial contact with the solar stream, these gradients cause particles to be driven into the polar caps to give the localized features of the sudden commencement field shown in Fig. 1. The eastward-flowing component of the averaged system would correspond to the compression of field. On entry of solar-stream constituents, as many have shown, the centrifugal force of protons should expand the field to give the equivalent of an equatorial ring current (Dessler and Parker, 1959). In the presence of longitudinal gradients, at first intense but shallow in depth, acceleration of trapped radiation will ensue, to provide the polar electrojets. There may also arise drainage and dissipation of the

ring-current particles into atmospheric (ionospheric storms) regions in other latitudes as well, in response to weaker gradients, broadly distributed in latitude and depth. The causative influence might be mainly electrons, accelerated to give X-rays and radio-absorptive electrons in the lower ionosphere. The possibility that electrons appearing below the *E*-region arises, at least in part, in this manner is suggested even though the storm-time electron content in the *F*-region shows a different morphology (*Matsushita*, 1959). Some additional loss of protons may arise from reaction with hydrogen (*Dessler and Parker*, 1959). If the solar stream is more intense, entry of protons may be in greater amount, so that expansion of the field line in the main phase is more rapid, and the decay period will also be more rapid in the presence of the greater accelerating action of more intense and widespread longitudinal field gradients, with contribution to ionospheric storms and other phenomena. In this way, the more rapid development in time of the various storms phases with increasing intensity of storm may be described. Thus the sunward directed magnetic field gradients near dawn and evening meridians in the equatorial plane at many earth radii within a developing Chapman-Ferraro hollow of decreasing size is envisaged; these gradients may provide the charge separation leading to injection of particles in the polar caps. The Hall currents driven by these charge distributions will give the reverse impulse of *SC*, followed some seconds later by the hydromagnetically communicated *SC* increase in *H*. If it is supposed that these longitudinal field gradients may reverse and oscillate in direction, in response to fluctuations in energy density in the solar stream in contact with the magnetosphere the oscillating field patterns in polar magnetograms might be explained due to the ensuring acceleration and dumping of charged particles into the polar cap.

§ 8. Current System During Intense Storm

Fig. 6. shows the approximate field vectors for the instant 7 GMT, November 13, of the great magnetic storm of November 12-20, 1960. Field changes are gradually being derived as more data reach the Data Centers,

but it is already apparent that field changes as great as 3000 gammas (10 per cent change or more) in the horizontal field occurred at the auroral zone.

From the figure, it is clear that the westward-directed polar electrojet extended strongly around the night-time polar cap, in horseshoe form, opening out towards the sun. This great surge of current shows a simple disturbance pattern, and currents broadly distributed in latitude in auroral regions.

In the case of weaker electrojets of more localized character, the drift in field patterns inside the auroral zone is often clockwise, and opposite outside the auroral zone, in the northern hemisphere.

Table 1 gives the estimated average westward drift velocity for polar westward-directed electrojets during four weak disturbances (bays) as about 500 m/sec, and about 200 m/sec for the eastward-directed electrojet. The effect may depend upon the north-south drift in position of the electrojet across lines of equal integral invariant when there is dependence upon time measured at the polar center of the lines of equal integral invariant, as well as rotation of the earth about the geographical axis.

§ 9. Summary

The morphology of magnetic storms can be simply represented in terms of ionospheric current systems changing in form and intensity with time. Using such models, the sudden commencement or initial phase of storms at ground level will be due to a world-wide west-east circulation of current, plus two opposed atmospheric polar current circulations flowing away from the sun near each geomagnetic pole. After some minutes to an hour or more, the current systems reverse in sign and the two opposed polar circulations extend equatorwards and develop electrojets at the auroral zone. The latter tends to attain a maximum level in intensity prior to that of the main east-west current flow on an average about 15 hours after the sudden commencement. In weaker storms the electrojets, enduring strongly for a few hours, may tend to be repetitive near the same hour on several successive nights. Their advent may be preceded by pulsations in field of some seconds to several minutes

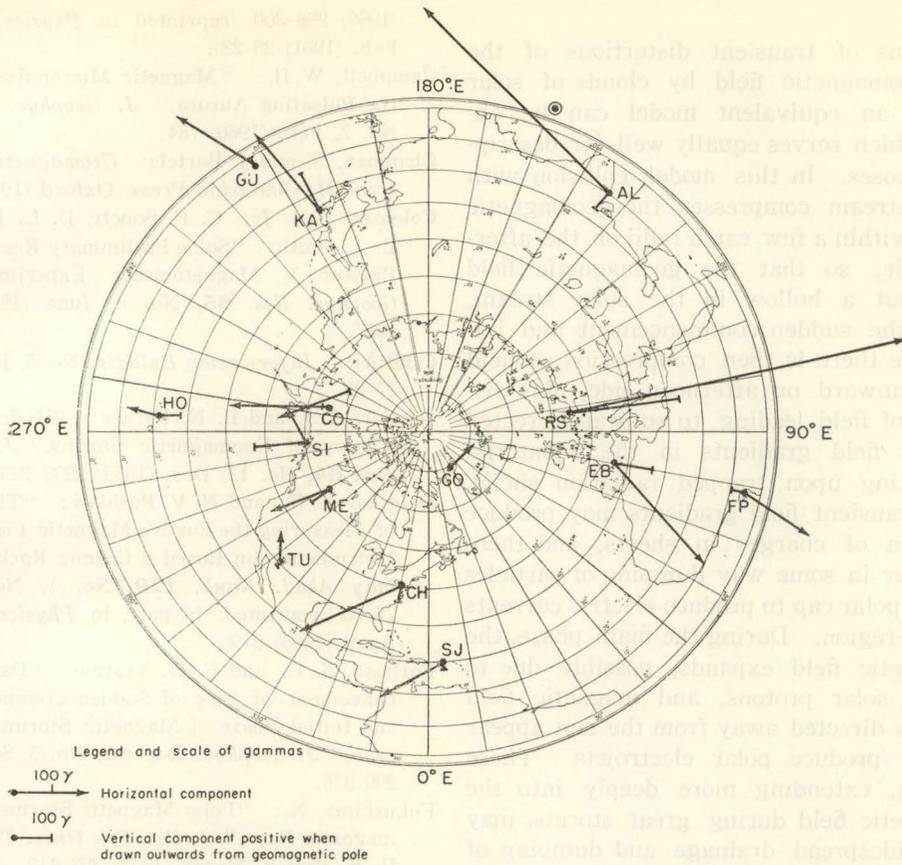


Fig. 6. Field vectors, late main phase of geomagnetic storm, 7 GMT, November 13, 1960. Geomagnetic coordinates (Values at latitudes $>60^\circ\text{N}$, at one-tenth scale).

Table I. Estimated angles (A) at geomagnetic north pole between most intense point of electrojets, westward-directed (w) and eastward-directed (e); also westward and eastward velocities V_w and V_e of these points, respectively, (data of Fukushima used).

Date of Magnetic Bay	Time GMT	A_w	A_e	V_w	V_e
April 3, 1933	h m	140°	15°	°/minute	°/minute
	11 06	172	25	0.70	0.22
	12 05	178	30	0.45	0.39
April 9, 1933	9 40	182	10		
	10 00	218	-20	1.80	-1.5
	11 00	180	60	-0.63	1.3
April 10, 1933	15 00	190	-10		
	15 10	205	—	1.50	—
	15 30	250	—	2.20	—
April 23, 1933	5 48	214	-20		
	6 20	223	-10	0.28	0.31
	7 20	170	50	-0.88	1.00

period.

In terms of transient distortions of the outer geomagnetic field by clouds of solar particles an equivalent model can be obtained which serves equally well for descriptive purposes. In this model, collision with a solar stream compresses the geomagnetic field to within a few earth radii on the afternoon side, so that the geomagnetic field carves out a hollow in the solar stream. During the sudden commencement and initial phase there is then compression of field on the sunward or afternoon side, plus distortions of field leading to sunward-directed magnetic field gradients in the equatorial plane acting upon trapped radiation shells. These transient field gradients may produce separation of charges in sheets, and there may occur in some way dumping of particles into the polar cap to produce electric currents in the *E*-region. During the main phase, the geomagnetic field expands, possibly due to entry of solar protons, and magnetic field gradients directed away from the sun appear and may produce polar electrojets. These gradients, extending more deeply into the geomagnetic field during great storms, may cause widespread drainage and dumping of particles into the low ionosphere causing radio wave absorption. These stream-produced field gradients may continue, less localized in pattern during the recovery phase of the storm over a period of days, supplementing the loss of protons due to interaction with exospheric hydrogen. In this model short-period oscillations of the geomagnetic field lines may locally assist the dumping of groups of particles separated by field gradients.

This publication continues a study of charged particles and field in space undertaken under contract No. NAS5-276 for the U.S. National Aeronautics and Space Administration.

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Discussion

Discussion for Papers I-1-P1 and I-1-P2 is combined and given after the Paper I-1-P2.

In this paper some important features are pointed out for the geomagnetic disturbance, which is considered to be originated mainly in the electric current flowing in the ionospheric region. Therefore, some of irregular variations including geomagnetic pulsations are not dealt with here, although they are also very important to understand the morphology of magnetic storms. The problems discussed in this paper should be carefully examined when theories of magnetic storms are studied.

Revised Morphology of the Average Magnetic Storm in Middle and Low Latitudes.

M. Sugiura and S. Chapman have recently published the results of very comprehensive

geomagnetic variations observed on the earth's surface will conventionally be divided into two kinds, extraterrestrial and terrestrial parts, according to whether the location of the origin of the disturbance is far outside or very near the earth's surface. Here this classification is applied only for the magnetic field variation with its origin in the external space of the earth, and the electric current induced in the earth's interior by the very-external magnetic field is not dealt with. The disturbances originated far outside the earth's surface are such as those caused by the interaction of the solar corpuscular stream with the earth's permanent magnetic field in the magnetosphere, and the equatorial ring current. They are mainly responsible for the world-wide geomagnetic change called the W_s -field. On the other hand, the longitudinal inequality component called W_s -field (or W_s') field for the average storm) of the disturbance should have its origin in the immediate vicinity of the earth, say in the ionospheric region.

Most of the magnetic variations recorded on ordinary magnetograms with paper speed of 15 or 30 mm/hr are now studied conventionally by means of the equivalent overhead electric currents in the ionosphere. This method is especially useful for the W_s -field, in which the intense electric current along