The Growth of the Storm-Time Radiation Belt and the Magnetospheric Substorm

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Summary

Important features of the radiation belt (or the so-called 'ring current') which grows in the magnetosphere during geomagnetic storms are summarized. The growth of the belt is studied in relation to a frequent occurrence of intense magnetospheric substorms (of which manifestations in the polar upper atmosphere are the auroral and polar magnetic substorms). It is concluded that during the magnetospheric substorm, the particles responsible for the storm-time belt are produced locally in the trapping region in the evening sector, but not in the midnight sector.

1. Introduction

In 1933, after completing their study of the impact of a fully ionized gas on a magnetic dipole, Chapman & Ferraro (1933) examined the formation of a 'ring current' around the Earth and its stability. Their study was intended to explain a large decrease of the horizontal component ($H$) of the Earth's field during the main phase of geomagnetic storms. The results appeared in the last paper of the series 'A new theory of magnetic storms' with the subtitle 'Part II—The Main Phase'. Their toroidal ring current consisted essentially of positive ions and electrons circulating around the Earth, in which their centripetal force due to the circular motion is balanced by the Lorentz force.

The stability of such a current system was, however, questioned by Alfvén (1955) and others. It appears now that their study was an unsuccessful one on this particular subject, but it marked an epoch in geomagnetism, since they correctly located the 'ring current' inside the cavity carved in the solar wind, which is now called the magnetosphere; for some earlier concepts of the 'ring currents' see Chapman (1952, p. 213).

In examining possibilities as to how the ring current is formed, Chapman & Ferraro (ibid., p. 80) thought that positive ions near the morning side of the magnetospheric boundary tend to leap across the cavity, but drift closer to the Earth. Further, they tend also to drag the electrons from the evening side of the magnetospheric boundary and may eventually form the ring current.

Although the formation of the 'ring current' does not seem to be as simple as they inferred in their paper, it has now become one of the most challenging problems in magnetospheric physics.

The purpose of this paper is first to review both morphological and theoretical studies of the formation of the 'ring current' and associated phenomena during the main phase of geomagnetic storms, particularly the auroral substorm (Sections 2 and 3). In the second part (Section 4), we try to find the clues for the process responsible for the onset of the growth of the 'ring current' and magnetospheric substorms.
2. Main phase of geomagnetic storms

We recognize Singer (1957) for the development of the present concept of the "ring current". He pointed out that charged particles trapped in the geomagnetic field will form a circulatory current around the Earth as a natural result of their adiabatic motions. The "ring current" results thus from a radiation belt that grows abnormally during geomagnetic storms. Later, the field of such a storm-time radiation belt was studied theoretically by Dessler & Parker (1959), Akasofu & Chapman (1961, 1967), Apel & Singer (1962) and Skopke (1966). Fig. 1 shows the distribution of the field of a model storm-time belt which Akasofu and Chapman (1961) called the 'V3 Belt'; the belt is located at a geocentric distance of 6a (a = Earth radius). A large decrease near the centre line of the belt is caused mainly by the diamagnetism. In Section 4, we shall discuss some of the satellite data by using Fig. 1.

![Fig. 1. The distribution of the magnetic field produced by a model storm-time belt, called the 'V3 Belt'.](image)

Magnetometers and particle detectors carried by satellites have confirmed the growth of the storm-time belt in the trapping region of the magnetosphere during geomagnetic storms. Cahill (1966, 1967) has shown that the magnetic field produced by the belt can be fairly well estimated by the method developed by Akasofu, Cain & Chapman (1961). During the geomagnetic storm of 1967 April 17-18, the centre-line of the belt was located at about 3-4a. Frank (1967) has shown that a great enhancement of low energy protons (the peak energy 10 keV) occurs inside the trapping boundary during geomagnetic storms.

Akasofu & Chapman (1963) found that the growth of the storm-time belt is associated with a frequent occurrence of intense auroral and polar magnetic substorms.

Both auroral and polar magnetic substorms are caused by an intense influx of energetic particles into an oval-shape band (the auroral oval) in the polar upper atmosphere. Each substorm has the lifetime of order 1-3 hr and occurs in an
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explosive manner (Akasofu 1964a). It is most likely that both auroral and polar magnetic substorms are a manifestation of an energetic process that takes place intermittently in the magnetosphere. Brice (1967) proposes to call this magnetospheric process a magnetospheric substorm.

Therefore, the main phase of geomagnetic storms is characterized by both phenomena.

Main phase =

Growth of the storm-time belt

+ Frequent occurrence of magnetospheric substorms

and:

\[
\text{Manifestations in the polar upper atmosphere}
\begin{align*}
\text{Auroral substorm (brightening and violent motions of visible auroras in the auroral oval)} \\
\text{Polar magnetic substorm (intense polar electrojet flowing along the oval)} \\
\text{Energetic electron precipitation (X-rays, riometer absorption)}
\end{align*}
\]

Before discussing relationships between the growth of the storm-time belt and the magnetospheric substorm, it is important to know the basic structure of the magnetosphere. Recent extensive studies of the magnetosphere by satellites and ground-based stations have revealed three circumpolar structures, the auroral oval, the proton aurora, and the mid-latitude trough, corresponding to structural features of the magnetosphere, namely the outer boundary of the trapping region, the storm-time belt, and the plasmapause, respectively; see a review paper by Akasofu (1967) and references cited there. Fig. 2 shows schematically the above relations in a rather simplified way.

The magnetospheric substorm occurs near the outer boundary of the trapping region (and other regions connected to the boundary region by the field lines), and the storm-time belt grows within the trapping region. It is suggested here that an

Fig. 2. The three circumpolar structures in the ionosphere and the corresponding structure in the ionosphere.
obvious source of the so-called ‘proton aurora’ (which is a diffuse band of luminosity containing the hydrogen emissions) is high energy tail protons leaking out from the ‘tip’ of the storm-time belt.

3. Important features of the storm-time belt

In this section, some of the important features of the storm-time radiation belt are discussed.

3.1 The kinetic energy flux of the solar wind is not directly related to the development of the main phase. In Chapman & Ferraro’s theory, the impact of the solar plasma is the necessary and sufficient condition for the formation of the storm-time belt. Their morphological knowledge was based on the concept of the average storm established by Chapman’s analysis (1919). By examining a large number of individual storms and noting the great variety of their development, Akasofu & Chapman (1963a, b) showed, however, that an enhanced plasma flow may be the necessary condition, but is not the sufficient condition. An intense plasma flow (manifested by a large storm sudden commencement and long initial phase) often fails to develop an appreciable main phase. Akasofu (1965) noted also that an intense storm-time belt can grow without a clear indication of an enhanced flow or even after a sudden decrease of the plasma flow, manifested by an intense negative sudden impulse (Akasofu 1964).

These studies indicate simply that there is no obvious direct relationship between the energy flux of the solar wind and the intensity of the storm-time belt. Though such a conclusion appeared to be unacceptable to some workers (cf. Cole 1966), it has increasingly become clear from the satellite studies that this is generally the case. Wilcox, Schatten & Ness (1966) have shown that both kinetic energy flux and momentum flux are not related to the $K_p$ index in any obvious way. Gosling et al. (1966) have shown that during the growth of the main phase of the geomagnetic storm of 1965 April 17–18, the solar wind parameters (such as temperature, number density, velocity) were normal and that no obvious changes were associated with the growth.

Dungey (cf. 1966) has proposed that a southward directed interplanetary magnetic field is essential for the development of the main phase. After an extensive study of Imp satellite data, Fairfield (1967) supports this view by noting that a quiet condition is more often associated with a northward directed field than a southward directed field and that a disturbed condition is more often associated with a southward directed field than a northward directed field. However, a southward field does not seem to be the single critical condition and is only a favourable condition.

It is quite easy to see now why it is difficult to find a simple relationship between the kinetic energy flux of the solar wind and the growth of the main phase. The lack of the relation means that the main phase does not result from a direct conversion of the solar wind energy. For example, if the main phase would result from the ‘fusion’ of the magnetic field lines in the tail region of the magnetosphere, as Dungey (cf. 1966), Axford, Petschek & Siscoe (1965), and Piddington (1967) have proposed, there are at least two basic processes which are crucial in the development of the main phase; the solar wind energy is first converted into the magnetic field energy that is stored in the magnetospheric tail; that is, the process of the tail formation. The onset of the main phase must, however, depend on at least another parameter that controls the rate of the conversion of the magnetic energy thus stored into the energy of the main phase; at least one of the above two processes is thus not directly related to the kinetic energy flux of the solar wind.

3.2 The intensity of the main phase depends critically on the location (solar disk) of responsible solar flares. It has long been known that solar flares which occur near the central region of the solar disk tend to produce greater geomagnetic storms.
Akasofu & Yoshida (1967) studied this tendency quantitatively by using the Dst index (see Section 3.3) which is proportional to the total kinetic energy of the storm-time belt. They showed that Dst is proportional to $\text{sech}^2(\Omega)$, where $\Omega$ denotes the angular distance between the centre of the solar disk and the location of the responsible solar flares. Many intense (3 +) limb flares are found to produce an appreciable storm sudden commencement (ssc) and initial phase, but not a significant main phase. On the other hand, the time lapse between the onset times of solar flares and resulting ssc's is of order 40 hr and is not a clear function of $\Omega$.

These findings suggest either that the energy for the main phase is sharply concentrated along the line connecting the solar centre and the location of a flare or that there exists favourable conditions for the development of the main phase along this line or both. If the Earth happens to be located along the line, the main phase tends to be intense. On the other hand, the constant time lapse for ssc's suggests a nearly hemispherical front of the storm-producing plasma. Akasofu & Yoshida (1967) suggest that these results can be reasonably combined to give a consistent picture by assuming the generation of an interplanetary shock wave by the jet of the solar plasma ejected by a solar flare. An intense main phase develops when the magnetosphere is engulfed by the jet.

The origin of the plasma jet, if it exists, is one of the most important problems in the field of solar-terrestrial physics. The fact that solar flares appear to be a chromospheric phenomenon has long suggested that the jet originates in the chromosphere.

3.3 The storm-time belt is greatly asymmetric during the growth of the storm-time belt. Chapman (1919) analysed the storm field $D$ into the longitudinally independent component (Dst) and the harmonic component (DS)

$$D = a_0 + \sum_n a_n \sin (n\lambda + \epsilon_n),$$

where $a_0 = \text{Dst}$,

$$\sum_n a_n \sin (n\lambda + \epsilon_n) = \text{DS}$$

where $\lambda$ denotes the longitude measured from the midnight meridian and thus $\lambda/15^\circ$ gives the local time.

It has long been thought tacitly that in low latitudes the longitudinally independent component (Dst) is produced by an axially symmetric 'ring current' and the DS component by an ionospheric current system generated in the polar region. Chapman (1952) extended his study to examine the storm-time variations of both Dst and DS and concluded that they may be independent; DS reaches a maximum stage and decays earlier than Dst.

Akasofu & Chapman (1964) found, however, that the storm-time belt by itself is axially asymmetric and the major part of the DS expresses the asymmetric part of the field of the storm-time belt. Near the maximum epoch of the storm, the field of the storm-time belt $D$ is approximately expressed by

$$D = a_0 + a_1 \sin \lambda.$$

Therefore, the $D$ field has a minimum at about 18 LT (local time) so that the main phase decrease is largest there. Akasofu & Chapman (1964) thought that the asymmetry could be due to the fact that the storm-time belt has a gap in that section and thus that the whole current system is completed by an induced (westward) ionospheric current in the gap sector. Cummings (1966) proposed that the asymmetry is caused by a greater concentration of the belt particles in the evening sector. The satellite observation conducted by Cahill (1966) supports the latter view. The expected ionospheric current induced by such an asymmetric system is, however, not well understood and should further be examined. For this particular point,
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Swift (1967) has made an interesting study to examine the coupling between an asymmetric belt and the ionosphere and showed that an intense ionospheric current is induced along the intersection line of the outer boundary of the belt and the ionosphere.

Therefore, Chapman's finding, that DS develops and decays earlier than Dst, can now be interpreted that the asymmetry is most conspicuous during the growing phase of the storm-time belt. It tends to disappear rather quickly after the maximum epoch of the main phase, and thus a fairly uniform belt is established during the recovery phase (Cahill 1966; Meng & Akasofu 1967).

Chapman (1952) found also the phase angle $\phi$, increases systematically from $-75^\circ$ in an early phase of the storm to about $+30^\circ$ in a later phase. This indicates that the local time of the largest main phase decrease changes from about 23 LT to 16 LT; in a frame of reference fixed with respect to the Sun–Earth line, this change is seen as the westward shift of the region of the maximum main phase decrease from the late evening sector to the afternoon sector. This was confirmed later by Sugiura & Chapman (1961) by their extensive study.

This change of the phase angle of DS as a function of storm-time gives an important clue in understanding the formation of the storm-time belt. Akasofu & Chapman (1967) suggest that the westward shift is caused by the westward drift motion of particles which have the major responsibility for the storm-time belt; the direction of the shift suggests that positively charged particles are responsible for the belt, and the rate of the shift suggests that the energy of the particles is of order 10 keV for protons.

4. The relationships between the storm-time belt and the magnetospheric substorms

We have now seen that during the growing phase of the storm-time belt,

1. the storm-time belt is asymmetric and intense in the evening sector,
2. the proton aurora is produced by the leakage of high energy tail protons from the storm-time belt, and
3. intense magnetospheric substorms occur frequently.

In this section, we examine relationships between the storm-time belt and the magnetospheric substorm by observing simultaneously the auroral substorm and the proton aurora. For the study of the latter, we are indebted to Belon, Romick & Swift (1967) for their new photometric instrument and analysis.

4.1 The midnight sector. The first sign of a typical auroral substorm is an increase of the brightness of the southernmost arc (in the northern hemisphere), that is, the equatorward ‘edge’ of the auroral oval (Akasofu 1964) or the formation of a new arc near the equatorward edge of the oval (Swift 1967). During this early phase of the substorm, the proton aurora remains relatively quiet without changing the brightness significantly (compared with electron auroras in the oval), or shifts equatorward in the midnight sector.

Figs 3(a–c) show a few examples of the explosive phase of the substorm. The example shown as Fig. 3(a) was studied in detail by Swift (1967). An arc-like luminosity seen in the southern sky of College at 0005 LT contained significant hydrogen emissions and is identified as the proton aurora. At 0008 LT, a new arc was formed just to the poleward side of the proton aurora and moved rapidly poleward. However, the proton aurora did not seem to show any significant change, compared with the newly-formed arc which showed a typical feature of the substorm. In Fig. 3(b), a weak proton aurora is seen in the southern sky of Farewell, Alaska. At 2335 LT, a new arc was suddenly formed little south of the zenith there and advanced rapidly poleward. Again, there was no definite sign that the proton aurora was enhanced.
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significantly; at 2339 LT, it seemed to fade away (or perhaps shift greatly equatorward). Fig. 3(c) shows the onset of an intense substorm observed in the southern sky of Farewell. There is no particular indication that a proton aurora was formed to the south of the activated arc. Fig. 4 shows in negative the onset of a substorm observed at Saskatoon. A new arc was seen to form at 0010 LT, and moved rapidly poleward (see the photographs between 0010 and 0020 LT). The proton aurora seemed to show a little increase in brightness and an appreciable equatorward motion.

4.2 The evening sector. In the evening sector, however, the behaviour of the proton aurora is quite different from that in the midnight sector. The most typical auroral activity in the evening sector of the oval is the westward travelling surge which is generated by the violent poleward motion of the auroras in the midnight sector (Akasofu 1964a).

When the surge travels along the oval, the proton aurora (which is located a little equatorward side of the oval; Fig. 2) becomes bright from its eastern part and shifts often equatorward; the increase of the brightness occurs often a little before the surge becomes visible near the eastern horizon. Fig. 5 shows an example of this phenomena. The simultaneous all-sky camera records taken at Bar I (dp lat 70° N) and College had a combined field of view extending from about dp lat 60° N to about 75° N; the same arc is seen at 0800 UT (= 2200 LT), to the south of Bar I and north of College.
Fig. 4. The all-sky camera photographs (in negative) of an early phase of the auroral substorm in the midnight sector; Saskatoon, 0004-0022. 105° WMT, 1958 February 21,
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Fig. 5. The all-sky camera photographs of an early phase of the auroral substorm in the evening sector (from College and Bar I; see the text) and the College magnetogram ($H$).
The surge appeared near the eastern horizon and rapidly moved westward, covering a large portion of sky at Bar I. A faint extensive luminosity appeared in the southern sky of College at about 0185 UT and became most intense at about 0845 UT. The spectroscopic data indicated that it contained intense hydrogen emissions. Fig. 6 shows in negative an example which shows the brightening and equatorward shift of the proton aurora; the photograph was taken from Saskatoon.

4.3 The interpretation of the ATS-B satellite data. We can infer then that in the midnight sector there is no clear sign that the proton aurora and thus also perhaps the storm-time belt are greatly enhanced. On the other hand, in the evening sector, it is quite common to observe a significant enhancement of the proton aurora and thus perhaps of the storm-time belt.

The above conclusions are consistent with results obtained by the synchronous satellite which has been placed at about the geocentric distance of 6\(\alpha\) and in the same longitude sector of College and Honolulu.

Cummings & Coleman (1967) showed that a weak positive bay in evening hours at College is associated with a significant decrease of the horizontal component at
the location of the satellite (Fig. 7); a similar decrease of the horizontal component is also observed at Honolulu. However, a negative bay in midnight hours at College is accompanied by a sudden recovery from the depressed level (associated with the positive bay) at both the satellite and Honolulu.

Before discussing the above relationships between positive, negative bays at College and the corresponding changes observed by the satellite and at Honolulu we must know the basic processes which cause the bays. Akasofu, Chapman & Meng (1965) showed that an intense polar electrojet flows westward along the auroral oval during the auroral substorm. Therefore, an intense negative bay is observed under activated auroras along the oval. In the dark sector, however, a positive bay is observed in both poleward and equatorward sides of the oval at about the same time; Akasofu, Chapman & Meng (1965) suggested that the positive bays are caused by an eastward return current from the polar jet; see also Meng & Akasofu (1967).

Since the auroral oval is eccentric with respect to the dipole pole, a typical auroral zone, like College, is located outside the oval in the evening sector and comes under the oval in the midnight sector as the Earth rotates; note that the auroral zone is the locus of the midnight sector of the oval. Therefore, positive bays are observed in the

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**Fig. 7.** ATS-B magnetometer and 50–150 keV electron records, College and Honolulu magnetic records and College riometer record on 1966 December 25. (After Cummings & Coleman (1967) and Lezniak et al. (1967).)
evening sector when College is located outside the oval and thus in the region of the return current, and negative bays along which the polar jet flows in the midnight sector under the oval.

In the evening sector, the centre line of the oval is located at about dp lat 70° or even at higher latitudes, at least a few hundred kilometres poleward side of the auroral zone. Therefore, westward travelling surges are not clearly seen from a typical auroral zone station, like College (see Fig. 5). The polar jet extends toward the evening sector from the midnight sector along the oval, and the surge is, in fact, the leading edge of the jet. Unfortunately, this extension of the polar jet in the evening sector had not been revealed in the past; therefore the eastward current causing positive bays in the evening sector of the auroral zone had been considered to be an eastward jet, rather than the return current. Recalling that the proton aura is enhanced to the equatorward side of the westward travelling surge, we can understand why a close relationship between the proton aurora and positive bay has been noted by many workers (although the importance of the surge had not been recognized).

In evening hours, there appear also magnetic disturbances which are neither a simple positive bay nor a negative bay; in general, a sharp negative 'bite' or 'indentation' is superposed on a rather gradual positive change; such a type is called the transition type bay (Rostoker 1966). This is an indication that the polar electrojet changes greatly its pattern during its life-time. Most of the transition type in the evening sector can be explained by supposing that the polar jet increases its width and covers the area which was initially the region of the return current.

Now, returning to the satellite data, we can see that when the satellite, College, and Honolulu were in the evening sector, the rapid decrease of the horizontal component at the location of the satellite was associated with positive bays at College. Several weak surges were seen to the north of College between 0650 and 0900 UT, although unfortunately the moonlight was too bright to see the proton aurora which was expected to appear in the field of view of College at that period. During this period, a medium negative bay was observed in the midnight sector of the oval (Great Whale River, Canada).

The decrease of the horizontal component at the location of the satellite was also associated with a similar change at Honolulu. Akasofu & Meng (1967) have recently shown that the so-called 'negative bay' which is observed in the evening sector in low latitudes, is caused by the asymmetric ring current; in the past, it had been thought to be an indication of the return current from an eastward 'jet' which causes positive bays in the auroral zone. The satellite data seem to confirm our view. In particular, it can be easily noted that the magnitude of the negative bay at Honolulu is too large to be caused by a weak eastward current over College.

The satellite and Honolulu records are thus consistent with our inference that the storm-time belt grows in the evening sector and that the activation of the proton aurora is an indication of it.

In the midnight sector, however, the onset of the substorm is associated with a rapid recovery of the horizontal component from the depression which occurred at the time of the positive bays in the evening sector. There are at least a few possible explanations for this particular phenomenon: (1) the decrease of the intensity of the storm-time belt, (2) an inward movement of the belt without or with an increase of the intensity (in this case, the relative location of the satellite with respect to the belt moves outward (see Fig. 1)), or (3) both. In any case, the particles constituting the storm-time belt disappeared rapidly from the location of the satellite.

The corresponding positive change at Honolulu can be interpreted in two ways. Firstly, it was commonly believed that the positive change in low latitudes at the time of the substorm is caused by the eastward return current from the polar electrojet (cf. Silsbee & Vestine 1942). Secondly at least a part of the positive change is caused by the decrease of the storm-time belt in the midnight sector. In any case, it is clear
that the storm-time belt is not significantly enhanced in the midnight sector, although it could move inward.

A motion of the magnetospheric plasma across geomagnetic field lines could be detected by observing geomagnetic disturbance fields associated with it. This is because the motion (of velocity $v$) should result from an electric field $E$, namely $v = E \times B / B^2$. Any inward motion of the plasma should be associated with a westward electric field which generates a poleward electric current in the ionosphere and thus a westward disturbance field, provided that the Hall conductivity is significantly greater than the Pedersen conductivity. Our analysis of polar magnetic disturbances does not reveal such a motion; in fact, the plasma seems to move outward over the entire evening sector; details of the results will be published elsewhere. Therefore, the protons should be generated locally at a geocentric distance of about 3a-4a (well inside the trapping region) in the evening sector, rather than brought from outside the trapping boundary.

Cummings & Coleman (1967) showed also that a sudden recovery can occur even in the evening sector after the initial decrease. This advance of the time for the recovery toward early evening hours during a stormy period, can be expected from the fact that the time of the first appearance of the negative bay advances in a similar way. During a period, the auroral oval shifts equatorward, so that even an auroral zone station can come under it in evening hours. Therefore, the size of the trapping region and the storm-time belt must have considerably shrunk when the recovery is observed in early evening hours.

Lezniak et al. (1967) showed a decrease of 50–150 keV electrons at about the time of the positive bays at College; this could partly be due to the betatron effect associated with the diamagnetism of the storm-time belt (Fig. 1). However, the onset of the negative bay was associated with a large increase of the electrons; further the riometer record at College showed the entry of such electrons. These phenomena suggest that the storm-time belt particles were replaced by auroral particles at the satellite location at the time of the substorm and that both College and the satellite were approximately on the same field line.

5. Conclusion

From the above studies, it may be concluded that during the magnetospheric substorm, the particles (protons) responsible for the storm-time belt are produced locally in the trapping region in the evening sector, but not in the midnight sector. In the midnight sector, there may even be a depletion of the belt. Such a non-uniform (in longitude) behaviour of the belt makes it difficult to infer basic processes involved in the growth of the belt in terms of $Dst$. There is also an indication that the radial distribution of the belt particles may change considerably during a single substorm.

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