Central plane of the ring current responsible for geomagnetic disturbance in the South-American region

by

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1. Introduction

The most spectacular feature of geomagnetic disturbances is a large decrease of several hundred gamma in the component at low latitudes, occurring within a few hours and recovering in a few tens of hours. Schmidt (1967) was the first to ascribe it to an overhead eastward electric current, probably caused by coronal streams or clouds from the sun. Chapman and Bartels (1952) deduced mathematically the constancies of a model toroidal ring current, with protons and electrons circulating around the geomagnetic axis at slightly different speeds and in opposite directions, thus moving westward. However, Alfvén (1958) stated that such a current is not likely to be stable. Pfitzer (1957) proposed that the particles had actually two motions, circling in loops around the magnetic axis, oscillating rapidly to and fro between mirror points in high northern and southern latitudes and, ring around the earth, the protons westward and the electrons eastward and, the last (drift motion) corresponded to the "Ring Current". Dessler and Axford (1959) and Akasofu (1960) discussed further the ring current and its field. Akasofu and Chapman (1961) carried out calculations and inferred that during magnetic disturbances, protons of energy of a few hundred keV are intermittently captured between 5-8 Re (Earth-radii).

All these formulations are relative to a dipole field. Thus, it is implied that the ring current will have a central plane coincident with the geomagnetic equatorial plane. However, during different seasons, the equatorial plane of the earth (geographic as well as magnetic) makes different angles with the orbital plane of the earth round the sun. Figure 1 (from Ness, 1969) shows the orientation in J months (northern summer). If the ring current particles are entering through the geomagnetic tail, the entry will be below (south of) the geomagnetic equatorial plane in the J months and above (north of) this plane in D months (northern winter), while in E months (equinoxes), the entry will be in the plane. Does the mirroring from northern to southern hemisphere (and vice versa) obliterate the effect of the initial entry conditions or, does the ring current retain the memory of the entry point? If the ring current plane is making some angle with the geomagnetic equatorial plane, the storm effects, observed

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Fig. 1

Configuration of the geomagnetic tail and neutral sheet vis-a-vis the geomagnetic equatorial plane during J months i.e. northern summer (Ness, 1969).

on ground, will have maximum $H$ depressions not at the geomagnetic equator but at a different latitude. To study such a possible deviation, observations would be needed at a closely spaced network of equatorial and low latitude observatories, all in the same longitude. Whereas no such network exists in the permanent global network, a program of electrojet studies was carried out during IGY-IGC, under the joint auspices of the Instituto Geofisico de Huancayo, Peru and the Department of Terrestrial Magnetism, Carnegie Institution of Washington, USA, and the data are published by Forbush and Casaverde (1961). In this paper, we examine these data to study the possible location of the overhead ring current responsible for geomagnetic storms.

2. Data

The data were in the form of 24 hourly values of $H$, $D$, $Z$ for 20 selected quiet days, and 10 selected disturbed days in each of the three seasons (northern summer, winter, equinoxes) for five locations, Talara, Chilca, Chimbote, Huancayo and Yauca during 1958-60. We supplemented these data from five other regular observatories in this region. Table 1 gives details of all these locations.

Though Forbush and Casaverde (1961) have given hourly values for 10 selected disturbed days in each season, many of these are single days with only moderate disturbance activity. From their data, we could choose only one storm in J months, that of July 8-9, 1958 having a storm-time depression of about 400 gamma, two storms in $E$ months, those of Sep 35, 1959 (about 250 gamma) and Mar. 27-29, 1958 (about 350 gamma) and only one small storm in $D$ months, that of Jan. 9-10, 1960 (about 100 gamma). Data for La Quiaca were available only for the Jul 8-9, 1958 event and a part of the Sep 3-5, 1958 event. Data for Pilar were also available only for these two events. Since the local times of La Quiaca and Pilar are about one hour ahead and those of Tatuoca and Vassouras are

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<td>+16°.9</td>
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<td>81°.3W</td>
<td>+6°.6</td>
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<td>79°.8W</td>
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Plot of hourly values of $H$ for the Jul 8-9, 15, 1958.
two hours ahead of the other locations (Huancayo etc.), and since we have done correlation analysis with UT values, there is a slight mismatch when original values are used; but the discrepancy reduces considerably when UT-corrected values are used as explained further on. For the Sep. 3-5, 1958 event, the storm started at about 1700 UT on Sep. 3 and the Dst values (Sugiura and Poros, 1971) show that the maximum depression (about 300 gamma) occurred on Sep. 4 at about 22 UT. Unfortunately, Forbush and Casaverde (1961) have reported data only for Sep. 3 and Sep. 5 but not for Sep. 4. Thus, only a change of about 250 gamma in the recovery part is available for analysis. The storm of March 27-29, 1959 actually started on March 26 and had its maximum depression on March 27. Thus, here too, we had data only for the recovery phase.

Figure 2 shows the storm of July 8-9, 1958, in the middle portion, H component at the top, D in the middle and Z at the bottom. To the left and the right are plotted values for two quiet days (July 5 and July 15), chosen nearest to the storm period from a set of 20 quiet days, given by Forbush and Casaverde (1961). Vertical lines separate day-time and night-time values. During day-time, there are large fluctuations, due to ionospheric $S_q$ and equatorial electrojet effects, which are largest at Huancayo nearest to the equator. For our analysis, night-time values (shown by thicker lines) are of more interest as these are of purely magnetospheric origin and hence related to the ring current fluctuations.

Figures 3, 4, 5 refer to the other three storms. The following may be noted:

a) The quiet day patterns for the two days, one prior to and the other after the storm, are not always alike. Not only the daily range of $H$ may vary by almost a factor of 2 (e.g. Jan 8 and Jan 16, 1960 in Fig. 5), but there might occur even qualitative changes in $D$ patterns. Price and Stone (1964) have indicated that the $D$ variation has a morning maximum and a dusk minimum in the northern hemisphere and a reverse pattern in the southern hemisphere. At equator, $D$ pattern should reveal whether the region is under the influence of the northern $S_q$ current system or southern, or both. Hutton (1967 a, b) showed, from the IGY data, that in the vicinity of Huancayo, the region was generally under the influence of the southern $S_q$ current system. Our plots confirm this. The seasonal and day-to-day changes are very large. This was also pointed out by Hutton. The $Z$ variations indicate a pattern reversal at Huancayo, from a day-time minimum in the north to a day-time maximum in the south, indicating that the electrojet centre is very near Huancayo. However, the $Z$ variation at Huancayo is of the northern type on some days and almost zero on some other days, even though the electrojet strength (as indicated by the $H$ range) is quite large. Thus, even though the dip angle of Huancayo is $2^\circ$N on the average, the electrojet centre is not always to its south but may shift northwards to come occasionally right above Huancayo. For the electrojet centre, this is a very large latitudinal excursion indeed.

b) The night-time levels of $H$, $D$, $Z$ on quiet days are almost constant, indicating absence of electrojet or $S_q$ effects. However, on some of these days (e.g. Sep. 12, 1958 in Fig. 3), the night levels show fluctuations, indicating that not all the quiet days, reported by Forbush and Casaverde (1961), are completely quiet. On disturbed days, both $H$ and $D$ show large changes, even during night. Thus, storm-time effects are not confined to the $H$ component only. In their detailed analysis of the morphology of geomagnetic storms, Sugiura and Chapman (1960) and Akasofu and Chapman (1961) have reported very small magnitudes for the $D$ variation. In the storm of July 8-9, 1958 shown in Figure 2, fluctuations in $D$ as large as 50 gamma are noticed even during night. This means that the overhead ring current is not always flowing east-west and may have occasionally a substantial north-south component. In the vicinity of Huancayo, the geomagnetic equator is parallel to the geographic equator, though shifted by about $12^\circ$. But a few degrees to the west, the geomagnetic equator curls northward (see Fig. 9, shown later). However, the changes in $D$ are too large to be accounted for by this feature.
The plots in Figs. 3 and 4 show the hourly values of $H$, $D$, and $Z$ during the geomagnetic storms of Sep. 3, 5, 1958, and Aug. 21 and Sep. 12, 1958, respectively. These storms were marked by significant changes in the magnetic field components, which are likely due to the passage of interplanetary phenomena.

The plots in Figs. 5 and 6 illustrate the hourly values of $H$, $D$, and $Z$ during the geomagnetic storm of Jan 10-11, 1960, and Jan. 16, 1960. These storms also showed notable variations in the magnetic field, indicating the presence of solar wind disturbances.

In the following analysis, we intend to combine the data from these storms to examine the variation patterns of the two quiet days (one before and one after the storm), and their subsequent impact on the geomagnetic field. The analysis involves calculating the average of $S_q$ for each location and subtracting this value to obtain the storm-time values. We then analyze the results to determine the extent to which the quiet days were affected by the storm.

The corrected hourly values of $H$, $D$, and $Z$ at each location are used to investigate whether the storm magnitudes have a latitude dependence. This can be done by obtaining the range ($H_{\text{max}}$ minus $H_{\text{min}}$) at each location and plotting versus latitude. However, we recognize that this analysis involves estimating possible errors coming into the picture. A straightforward procedure would be to conduct a correlation analysis between the series of 48 consecutive values for each storm. If pairs of stations are used, 10 stations would involve 45 pairs, too many for obtaining an overall result. A more elegant procedure would be to evaluate the average of all locations for each UT and then obtain $\gamma_{\text{xy}}$ for $x$, $y$, and $z$ series, where the highly positive values are used for further analysis. These values are obtained and are given for the $H$ and $Z$ series. The errors of $\gamma_{\text{xy}}$ may be evaluated, and the $x$ series' response is observed.

Before proceeding, we must consider whether the deviations are statistically significant. If they are, we can say that the geomagnetic activity is correlated to the solar wind disturbances. The correlation coefficient $\gamma_{\text{xy}}$ would be indicative of a positive or negative relationship between the two variables. In this case, if the $\cos \theta$ dependence is strong and the $x$ series' response is observed, the correlation coefficient $\gamma_{\text{xy}}$ would be highly positive and can be used for further analysis. These values are obtained and are given for the $H$ and $Z$ series, where the errors of $\gamma_{\text{xy}}$ may be evaluated. The $x$ series' response is observed, and the $y$ series' response is evaluated. If the $x$ series' response is observed, we can conclude that the geomagnetic activity is correlated to solar wind disturbances. This analysis can be repeated for other storms and reveals similar trends.
correlate this with the values at each location. Thus, a linear regression of the type:

\[ y_j = (M_j \pm \Delta M_j) x + (N_j \pm \Delta N_j) \]  

would be attempted where \( y_j \) = the series of \( S_q \)-corrected values for the various locations, \( i = 1, \ldots, 10 \) stations and \( x \) = the Master Mean (MM) series. A correlation analysis would give the slope \( M_j \) with its standard error \( \Delta M_j \) as also the constant \( N_j \) with its standard error \( \Delta N_j \). However, this constant \( N_j \) only refers to the base line and hence is of no physical significance and would be ignored. If all locations had the same magnitude of the storm effect, \( M_j \) would be unity for all locations (all \( j \)). If the storm effect had a latitude dependence (e.g. a sine \( \theta \) dependence), \( M_j \) would show a maximum for some \( j \) and it would be of interest to see whether this \( \theta \) corresponds to the geomagnetic equator.

Before \( M_j \) is evaluated, it is necessary to check whether there are any errors in the \( S_q \)-corrected hourly values. Statistically, \( M_j \) is obtained as:

\[ M_j = \frac{\gamma_{xy}}{\sigma_x} \]  

where \( \gamma_{xy} \) = correlation coefficient between \( y_j \) and \( x \), and \( \sigma_x \) and \( \sigma_y \) are the standard deviations of the \( y_j \) and \( x \) series. If all values were correct, \( \gamma_{xy} \) would be highly positive (almost unity) and the various \( \sigma_y \) could be used for studying the latitude dependence. When hourly values are reported by various observatories, these are obtained by reading from actual magnetograms that are given as rounded numbers in gamma, at least for the \( H \) and \( Z \) components. Thus, an accuracy of about 1 gamma is implied. However, we have reason to believe (Kane, 1978) that especially during disturbed periods, several of these reported hourly values have errors of 5, 10, 50 or 100 gamma (sometimes other multiples of 5 or 10) probably due to wrong reading of the magnetograms. These can be detected if simultaneous data from nearby locations are available. A plot of the hourly values at one location versus hourly values at the other generally shows that most of the values lie on a straight line (not necessarily of slope unity but a straight line nevertheless) except for a few points which deviate considerably from the straight line. These can be checked either by comparing with a third nearby observatory or by examining original magnetograms. Our experience so far shows that such a detection is possible and reveals often errors of 5 or 10 gamma or their multiples. In the present case, this method should work admirably; because at least 5 of the 10 locations are fairly near to each other and none of these should show a erratic deviation of even 10 gamma without having any effect at the nearby locations, except during daytime when the equatorial electrojet is known to show less storm-time changes. During night-time, when changes can be only magnetospheric, it is unimaginable that any one of these locations can depict any change exclusively.

Figure 6 shows a plot of hourly values of \( H \) at each location (as ordinate) versus the hourly values of the Master Mean MM (as abscissa) for the event of July 8-9, 1958. The left half shows day-time values only (6 AM to 6 PM, 75° WMT) and the right half shows night-time values only. All values are \( S_q \)-corrected by using the average of the two quiet days: July 5 and July 15, 1958 as average \( S_q \). Since at night the \( S_q \) values are almost zero, the night-time values are almost the same as the original values, except for La Quiaca and Pilar which are 1 hr ahead and Tatuca and Vassouras which are 2 hr ahead of the 75° WMT.

Two aspects are clear from Figure 6. Firstly, the day-time values show a larger scatter. Though inaccuracies in some hourly values are not ruled out, the deviations from the straight line could also be due to genuine storm-time fluctuations of a residual electrojet. Hence, even though we have manipulated some of these values to fall on the straight line, we will consider the results obtained from their analysis as less reliable. Secondly, a majority of the night-time values falls very nearly on a straight line. This gives us confidence that the method is sound. Also, the few values which are deviating from the straight line should be erroneous for some reason. Since some deviations are much larger than some others, and

![Fig. 6](image-url)

\( S_q \)-corrected hourly values of \( H \) at various locations (ordinate) versus Master Mean (abscissa) for day-time (left half) and night-time (right half) for the storm of Jul. 8-9, 1958.
since the Master Mean involves these erroneous values, it would be proper to eliminate these errors sequentially, larger ones first, and reevaluate the Master Mean every- time. This was done by eliminating first all errors exceeding 30 gamma, then 20 gamma and so on. A computer program was used in which a regression equation is fitted and the expected and observed values of \( y_j \) are compared and deviations exceeding limits mentioned above adjusted by adding or subtracting adequate multiples of 5 to \( y_j \), until, finally, the expected values differed from the observed values by less than 20 gamma for day-time values and less than 10 gamma for the night-time values. For the weaker storms of Mar. 27-29, 1959 and Jan. 10-11, 1960, these limits were reduced further to 15 gamma for day-time values and 8 gamma for night-time values. However, in each case, correlation analysis was also conducted without making any such adjustment of \( y_j \) values.

An odd feature in Figure 6 is in Chiclayo where night-time values seem to fall not on one regression line but two. This was suspected from a preliminary diagram in which the Master Mean was calculated from all the ten stations. In Figure 6, the Master Mean used is from nine stations only with Chiclayo excluded. It is obvious that a large base-level change is involved in Chiclayo values. A plot of Master Mean versus Chiclayo values for day and night together showed that from 1100 LT on July 8 to 0700 LT on July 9, Chiclayo values were too high by about 50 gamma (see Fig. 2). Hence, all these values were reduced by 50 gamma and the data were then used for further analysis of 10 stations.

Figure 7 shows plots of \( S_q \)-corrected hourly values of \( H \) for night-time only for various stations (ordinate) versus Master Mean (abscissa) for the other three storms. The plot in Figure 7, for the storm of Jan. 10-11, 1960 shows some large errors in the values of Huancayo, sometimes exceeding 20 gamma, which had to be adjusted. Surprisingly, these were in the early part of Jan. 10, when the storm had not even started. The reported values can be erroneous even in comparatively quiet periods.

3. Results

Figure 8 shows the final results where the regression coefficient \( M_j \) for \( H \) is plotted versus geomagnetic latitude for the storms of (a) Jul 8-9, 1958; (b) Sep 3-5, 1958; (c) Mar 27-29, 1959; and (d) Jan 10-11, 1960. In each case, the top curve marked OR refers to analysis of original values. As already mentioned, \( M_j \) for each location \( j \), is obtained by a correlation analysis. The correlation coefficients were reasonably high (exceed +0.80) for every location. However, the plots OR are not useful for the study we have in mind, because the day-time electrojet effects are still present as can be seen by the peak near Huancayo. The next set of curves marked \( S_q \) is obtained by using the \( S_q \)-corrected values. Here too, some electrojet effect seems to be still lurking specially in the storm of Jan. 10-11, 1960 (Fig. 8d). The correlation coefficients were quite high (exceed +0.90). The next set of curves marked \( N \) is free

![Diagram](image)

**Fig. 7**

\( S_q \)-corrected hourly values of \( H \) at various locations (ordinate) versus Master Mean (abscissa) for night-time for the storms of Sept. 3 and 5, 1958 (left), Mar. 27-29, 1959 (middle) and Jan. 10-11, 1960 (right). Arrows indicate highly erratic values.
here the regression versus geomagnetic 1958; (b) Sep 3-5, Jan 10-11, 1960. In refers to analysis of respective, \( M_f \) for each loco-analysis. The correlation high (exceeding 0.9), the plots OR are in mind, because the present as can be seen next set of curves \( S_q \)-corrected values. The correlation coefficients exceeded + 0.98. In both \( M_f \) and \( N \) even erratic values were included. If these are adjusted, the correlations improve still further (exceed + 0.99) and the plots \( S_q' \) and \( N' \) represent analysis of such adjusted values. The statistical standard errors are very small, as indicated.

The question is, do the latitude dependences, depicted by \( S_q \) and \( N \) or \( S_q' \) and \( N' \) in Figure 8, represent effects due to an overhead ring current? The reason for such doubt is the presence of some odd features in Figure 8. For example, \( M \) values for Chimbote (and to a lesser extent, Huancayo) seem to be consistently smaller than the \( M \) values for Yauca on one side and Chiclayo on the other. No ring current system far away above the equator could possibly account for such an oddity. Since there is no local anomaly involved. Forbush and Casaverde (61) have reported, from a study of 4 night-time \( SSC \) events, that the average magnitudes of \( H \) variations at Trujillo, Chiclayo, Chimbote, Huancayo and Yauca were 30, 34, 40 and 39 gamma respectively. Thus, they obtained an anomalously low value for Chimbote. They hinted that this might be due to a possible local inhomogeneity in crustal conductivity. Recently, Uda and Maeda (78) reexamined the same data and reported similar results. Earlier, Rastogi et al. (66) examined the night-time fluctuations during two storms and even though they reported that "the amplitude decreases steadily from Huancayo to Talara" and attributed this to a possible existence of a remnant equatorial electrojet current during night-time, their plot of amplitude versus magnetic dip clearly showed an anomalously low value for Chimbote. Schmucker et al. (67) studied the magnitudes of \( H \) variations during magnetic bays at night, in the same region, and found a similar discrepancy and attributed it to an anomalous internal (induced) current flowing under the Andes in a north-west direction. Soon after, Casaverde et al. (68) extended this study by operating additional instruments in Peru and Bolivia. In Figure 9, we show on a map, the locations of the 10 stations for which data were used in the present analysis (big dots) and the other locations used by Casaverde et al. (68) for the study of the Andes Anomaly. The position of the conductivity anomaly observed by them, is also shown as a thick line. Obviously, several of the locations used in our analysis must have been affected by this anomaly. However, the latitudinal profiles shown for \( S_q' \) and \( N' \) in Figure 8, cannot be attributed completely to this anomaly; because the patterns differ considerably from storm to storm. If the \( S_q' \) and \( N' \) plots for the four storms are averaged, the averages \( S_q' \) and \( N' \) would represent the anomaly effect plus any genuine latitude dependence common to all storms. In turn, if these averages are subtracted from the original values, the deviations \( \Delta S_q' \) and \( \Delta N' \) would give the latitudinal profiles characteristic of each storm.

Figure 10 shows the results. The top plots \( A_1 \) and \( A_2 \)
Fig. 9

Map shows the geographical locations of the various observatories, for which data are used in the present analysis (big dots) and by Casaverde et al. (1968) for anomaly studies (smaller dots) as also the position of the conductivity anomaly under the Andes as determined by them.

refer to the results of Forbush and Casaverde (1961) and Takeda and Maeda (1978) respectively, for nighttime SSC magnitudes normalised to Huancayo as 100%. The plot $A_3$ refers to Rastogi et al. (1966) for night-time fluctuations, while $A_4$ refers to the results of Schmucker et al. (1967) (reproduced from Takeda and Maeda, 1978) for night-time magnetic bays. All these show considerable quantitative differences. For example, Talara is only 63% of Huancayo in one case but 88% in another. If the maximum at Huancayo even at night is interpreted as the effect of a remnant night-time equatorial electrojet as Forbush and Casaverde (1961) and Rastogi et al. (1966) have done, this variability could be attributed to variations in the electrojet strength from event to event. To us, such large electrojet effects at night seem incredible and somewhat improbable. But the low values at Chimbote are an unmistakable induction anomaly feature. Plots $S_O^Q$ and $N^Q$ are our averages of $S_O^Q$ and $N^Q$ for the four storms (Fig. 8). In general, these are comparable to the other curves above; but our values at Yauca are considerably higher than those at Huancayo. This also could be an induction anomaly but it could also possibly indicate that the overhead current system is always shifted considerably to the south of Huancayo, probably above Yauca. The lower half of Figure 10 shows the deviations $\Delta S_O^Q$ and $\Delta N^Q$ for the four storms. Considerable differences are observed from storm to storm. Thus, whereas the profile for (a) the storm of July 8-9, 1958 is almost flat, that for (b) Sep 3-5, 1958 shows a monotonous rise of about 10% from the south to the northern hemisphere. Also, even though (b) and (c) both refer equinoxes, their profiles are not exactly alike. The profile (d) for Jan. 10-11, 1960 is reverse to that of (b). Thus, whereas there is no clear-cut seasonal effect, there are clear changes in latitudinal pattern from storm to storm far in excess of a simple cos $\theta$ dependence, which should have been at the most $\pm 6\%$ for a latitude range of $\pm 20^\circ$. It may be noted that most of the cos $\theta$ dependence should be present in the average curves $N^Q$ and $N^N$ while $\Delta S_O^Q$ and $\Delta N^N$ would depict deviations from the same.

Similar analysis was carried out by using $S_O$ and $N^Q$ instead of $S_O^Q$ and $N^N$. Results were almost similar with slightly larger statistical errors.

Since the patterns change so much from storm to storm, it may be relevant to check whether the remain the same, during the course of the main storm. In Figure 11, we show the Master Means (MM) as well as the deviations from the MM, for each location for the two large storms of July 8-9, 1958 and Sep.
protons and noticed significant asymmetries in the ring current development, as also a decrease in the radius of the ring current with enhanced activity. Our results indicate the additional possibility that the central plane of the ring current is subject to latitudinal excursions from storm to storm and even during the course of the same storm.

4. Summary and conclusions

This study of the latitude dependence of geomagnetic storm effects shows that whereas there is a considerable induction effect anomaly under the Andes, there are also considerable external effects which change not only from storm to storm but also during the course of the same storm, and indicate large latitudinal excursions of the overhead ring current system.

These changes have serious implications for studies of conductivity anomalies. In induction studies, the usual assumption is that the external field is uniform over wide areas and hence, if variations at adjacent stations are found to be consistently different, these could be attributed to the effect of inhomogeneities of the electrical conductivity distribution within the earth. In mid-latitude, this assumption is valid, but for the equatorial electrojet region, it may not be valid, even during night because of the possibility of violent latitudinal and altitudinal excursions of the overhead ring current system. Thus, quantitative estimates of the anomalies in electrical conductivity, based on the assumption of a uniform external field, could be erroneous. An elaborate way of studying this problem would be to obtain data from two networks of observatories simultaneously, one situated in the anomaly region and another nearby, but outside.

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Schmucker U., S.E. Forbush, O. Hartmann, A.A. Giesecke


The solar wind cause the emission of electrons and protons seen by spacecraft (Heikkila et al., 1972; Frank, 1971; Frank, 1973; Winnick and Domingo, 1979). The solar wind is a supersonic flow of charged particles that is generated by the Sun's magnetic field. These particles, known as solar wind protons and electrons, are believed to be responsible for many of the phenomena observed in the Earth's magnetosphere. The solar wind can also interact with the Earth's magnetic field, creating auroras and affecting the Earth's upper atmosphere. The interaction between the solar wind and the Earth's magnetic field is a complex process that is not fully understood.