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Azimuthal Drift and Precipitation of Electrons into the South Atlantic Geomagnetic Anomaly during an SC Magnetic Storm

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The south Atlantic geomagnetic anomaly provides a permanent sink for trapped particles in the inner radiation belt. Losses occur during the longitudinal drift of these particles, when their mirror altitudes dip lower down in the region of the anomaly, thus resulting in a loss of energy owing to interaction with atmospheric constituents. Day to night changes in the precipitation are believed to take place owing to the corresponding changes in the atmospheric density. More significant changes, however, occur owing to disturbances produced as a result of injection of charged particles into the radiation belt either by artificial means such as occur during high-altitude nuclear explosions (for example, the 'Starfish' explosion of 1962) or by geophysical disturbances produced by the sun. The latter phenomena in particular provide a natural means of studying the coupling or the interaction between the magnetosphere and the ionosphere over low latitudes. Very few such investigations, however, have been made so far. Recently some studies [for example, *Mendes et al.*, 1970] were made on the propagation of very low frequency (VLF) signals through the geomagnetic anomaly that showed that the phase and amplitude of VLF signals received at a station located within the anomaly underwent changes during certain polar cap absorption (PCA) events that could be interpreted as being due to particle precipitation into the anomaly. More recently, direct measurement by balloon-borne detectors of particle precipitation into the anomaly at the time of a sudden commencement magnetic storm has also been reported [*Martin et al.*, 1973]. In the present work we discuss an absorption event recorded by a 30-MHz riometer and also the VLF phase changes observed during a sudden commencement (sc) magnetic storm that occurred on August 4 to 5, 1972. The results provide evidence for the azimuthal drift and precipitation of electrons into the geomagnetic anomaly. Further evidence on the spatial nonuniformity in the particle precipitation is also presented.

The experimental arrangement consisted of a riometer working at 30 MHz and several VLF phase track receivers located at Itapetinga Radio Observatory, Atibaia, Sao Paulo (−23° 11′, 45°W). In the riometer installation, the input of the riometer was switched between two four-element Yagi antennas, one directed vertically upward and the other at an angle of 45° from the vertical, directed westward and away from the center of the anomaly. The switching rate was 4 min for each antenna. When absorption takes place owing to a uniform ionization, the oblique antenna is expected to detect nearly 1.4 times more absorption than the vertical antenna. The VLF receivers continuously monitor the phase and amplitude of VLF signals received from several long-distance transmitters. In the present study we have used phase measurements of the 17.8-kHz NAA Transmission from Cutler, Maine, USA. During the same period VLF tracking at several frequencies was also going on at Curitiba (−25° 53′, 49°16′W) in southern Brazil, which is believed to be located closer to the center of the anomaly than Sao Paulo. These measurements were being made as part of a research program

that Mackenzie University is sponsoring in collaboration with the Brazilian Air Force, called 'Project MOB-VLF' [*Ananthakrishnan*, 1973]. The phase recording of the 17.8-kHz NAA transmission received at this station is used for the present study.

Figure 1*a* shows the riometer record during the night of August 4–5, 1972. The broken smooth curve in the figure represents the variation of the unabsorbed cosmic noise intensity. In Figure 1*b* we have presented the corresponding magnetic records for Vassouras, Rio de Janeiro, which is located some 350 km northeast of Atibaia. A storm sudden commencement is seen at about 2100 UT for which no corresponding change is noticeable in the riometer record. A more intense sc occurred around 2240 UT. Associated with this, an absorption onset can be seen in the riometer record. (There appears to be indication of an earlier onset in the oblique antenna record, which cannot be confirmed, however, because of an interference in the record preceding the event). The absorption event lasted for about an hour and went through a maximum midway through its duration. Later, around 0030 UT, during the main phase of the storm, a second absorption event began. This event lasted longer and also appears

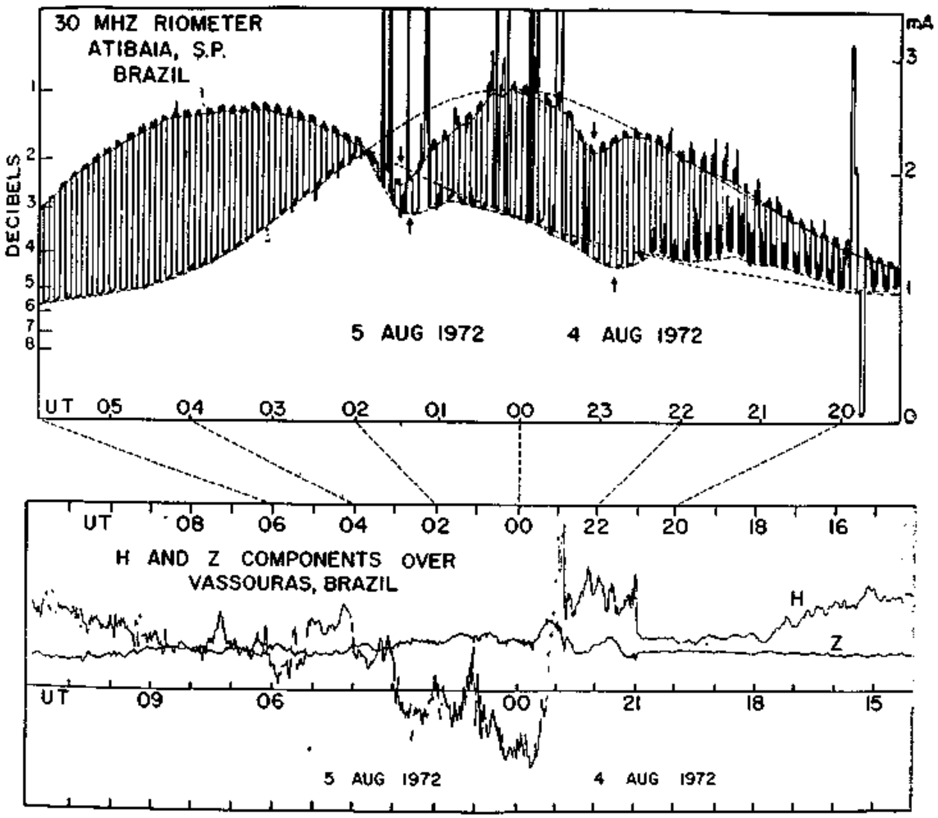

Fig. 1. (*a*) Thirty-MHz riometer record during the night of August 4–5, 1972. The galactic peak in the ratio noise that occurs around 0000 hours UT corresponds to the vertical antenna. The westward looking oblique antenna shows the peak after approximately 3 hours. The dashed lines represent the smooth variation of the undisturbed cosmic noise intensity on both the antennas. The times of peak absorption are indicated on both the curves. (*b*) The magnetograms on August 4-5 for Vassouras, Rio de Janeiro. Note that the time scale is different here from Fig. 1*a* (the times in the two records are joined by slant lines).

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to exhibit more features than the first event. The maximum in the absorption occurred approximately half an hour before the complete recovery, which took place at about 0200 UT.

The occurrence of cosmic noise absorption at about 2240 UT in Figure 1 provides evidence for particle precipitation into the anomaly at the time of an sc of a magnetic storm. It is interesting to note that the sc that occurred at about 2100 UT and that was less intense as compared with the second sc did not produce any absorption. This suggests that there might be some threshold level for the magnetic field changes for the resulting particle precipitation to be detectable by a riometer. The suggestion is further supported by the fact that during the second absorption event a rapid increase occurred soon after the large change in the magnetic field, which was around 0100 UT during the main phase of the storm.

The following additional aspects of the absorption are of particular significance.

(1) There is a clear time difference between the absorption maximums observed on the vertical and oblique antennas. The time difference is larger in the first absorption event, but it is smaller and less conspicuous in the second event. Such time differences would suggest that the absorption was a result of precipitation from a cloud of charged particles that was drifting longitudinally in the inner radiation belt. Further, during both events the oblique antenna that was looking westward recorded the maximum absorption earlier than the vertical antenna, thus suggesting an eastward drift for the charged particles. The precipitating particles therefore are electrons. The present observation thus provides the first evidence for the azimuthal drift and precipitation of electrons into the anomaly during a magnetic storm.

From the time difference between the absorption maximums observed on the two antennas, it should be possible to estimate the energies for the precipitating electrons, which at the same time should be consistent with the expected absorption heights. In addition to the drift motion due to the magnetic field gradient, however, a charged particle is also subjected to an $\mathbf{E} \times \mathbf{B}$ drift, and thus a knowledge of the possible magnetospheric electric fields is necessary to estimate the electron energy. This estimation was made follows.

If d is the ionospheric separation of the axes of the two antenna beams corresponding to an absorption height h, L is the corresponding magnetic shell parameter, and Δt is the time difference between the maximums, the observed drift rate of the particle (in degrees per second that the guiding center of the particle makes at the center of the earth) is given by,

$$\frac{58\,d}{R_0 L\,\Delta t} = \frac{6}{44} L\epsilon - \frac{58\mathbf{E}}{\mathbf{B}_{eq} R_0} L^2$$

The right hand side of the equation is the net longitudinal drift expected as a result of the magnetic field gradient and $\mathbf{E} \times \mathbf{B}$ force. The first term is obtained from the expression for the azimuthal drift period for the electrons taken from *Hess* [1968]. $\mathbf{B}_{eq}$ is the surface magnetic field intensity at the equator, R_0 is the radius of the earth, ϵ is the electron energy, and $\mathbf{E}$ is the electric field, which here is considered positive if directed upward in the equatorial plane and negative if downward. (The upward direction corresponds to a westward drift and the downward direction corresponds to an eastward drift.) The above equation was used to calculate values for the electron energies that would satisfy the observed Δt values for a wide range of electric fields and for a given absorption height. The results of calculations corresponding to Δt = 16 min in the first absorption event are presented for 80, 100, and 300 km in Figure 2. Because of the almost complete lack of information on magnetospheric electric fields applicable to low latitudes, there is some difficulty in using Figure 2 for obtaining energy ranges of the precipitating electrons. However, some reasonable values may be assumed, based on the results of electric field measurements made at auroral latitudes that have shown large increases during disturbed periods. For example, *Mozer and Serlin* [1969], *Wescott et al.* [1969], and *Potter* [1970] have measured values up to 60 or 70 mv/m near bay-producing current systems. The corresponding field mapped on to the equatorial plane in the magnetosphere (assuming perfectly conducting magnetic field lines) could be some 20 times smaller. Values for the low-latitude ionospheric electric fields may not be as high as in the auroral zone even under severely disturbed conditions. But the field value mapped on to the equatorial plane is reduced only by a small factor. For example, if we compute according to *Mozer* [1970], the field in the equatorial plane corresponding to $L = 1.2$ could be nearly 0.6 times less than the ionospheric values as compared with a factor of 20 for the auroral zone. Therefore, from the above discussion, it appears that an assumption of around 10 mv/m for the magnetospheric electric fields in the present case may not be unreasonable. From this electric field, if an absorption height between 80 and 100 km is assumed, it is seen from Figure 2 that the observed time difference (namely Δt) can be explained by electron energies near 30 kev. From Table 1, which shows the heights of maximum ionization for electrons of different energies precipitating into the atmosphere (as calculated according to *Rees* [1963]), it can be seen that the corresponding height is near 95 km. (By checking the consistency of the results between Figure 2 and Table 1 in this way, we can arrive at a reasonably good estimate of the average energy for the electrons.) If absorption took place at still lower levels, then, to explain the observation, we will have to postulate larger magnetospheric electric fields. Thus absorption heights below 85 km for which the electric field should be greater than 20 mv/m appear unlikely.

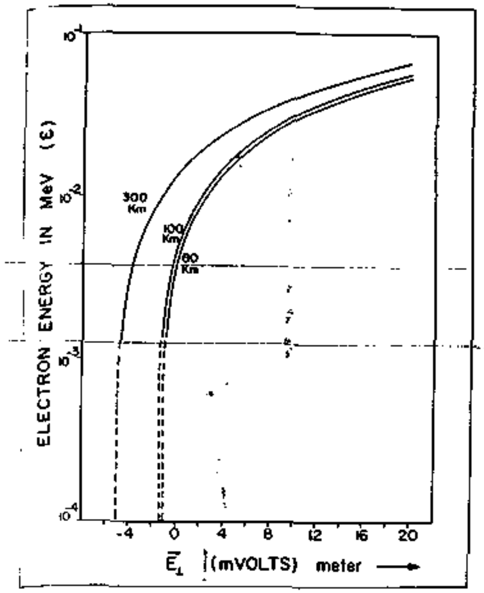

Fig. 2. Electron energies required to explain the time difference observed between the maximums on the two antennas plotted as a function of the magnetospheric electric fields, corresponding to three assumed absorption heights, namely, 80, 100, and 300 km (for explanation, see text).

Alternatively, from Figure 2 it would appear that the observation can also be explained in terms of an electric field directed downward in the equatorial plane and absorption taking place near 300 km in the F region. But this seems unlikely for the following reasons. (*a*) The electric field required to produce the observed Δt corresponding to the energies that ionize at F region heights (<1 kev) cannot exceed 5 mv/m. During a severe disturbance such as the present one, the electric fields could be higher. (*b*) Probably more decisive than the above is the fact that the recovery of the absorption took less than half an hour, a faster rate than is consistent with the relaxation time of the F_2 layer, which is around 45 min [*Appleton*, 1953].

Further, since the VLF results to be described below also showed phase advances during some part of this absorption event, we may conclude that the lower altitude ranges and upward-directed electric fields were operative in these absorption results.

For the second absorption event, the time difference between the maximums is not very clear but is certainly less than in the first case and may be taken to be near 7 min. Here we can show that if we assume the same electric fields as before, the absorption would be occurring at a height lower by some 5 km.

2. The absorption values observed on the two antennas tabulated in Table 2 show that they are nearly the same in both the cases, whereas, if the absorption is due to a uniform and horizontally stratified ionization, we should expect a difference between them. The fourth column in the table gives the equivalent vertical absorption calculated from the observed oblique absorption and is clearly less than the observed vertical absorption. The difference is significantly more than the accuracy limit of the measurements, which is ±0.05 db, and suggests that there was a gradient in the ionization, namely, that the ionization decreased westward, indicating thereby that the electron precipitation increased toward the center of the anom-

aly. The center of the anomaly is known to be located on a longitude east of Sao Paulo.

Figure 3 shows the phase records for the 17.8-kHz NAA transmission received at Curitiba (curves *a*) and Atibaia (curves *b*) during the night of August 4–5. The magnetic record for the same period is also presented in this figure. No noticeable change at the time of the sc was present in the VLF phase, which at this time was changing rapidly as a result of sunset along the propagation path. Later, at about 2340 UT, 1 hour after the sc and during the main phase of the storm, a clear phase advance could be observed at both the receiving sites. An interpretation for the absence of any observable phase change at the time of the first absorption event could be that the precipitation did not penetrate to the VLF reflection height at this time but that later, when the height increased (owing to the sunset) or the precipitation reached lower levels owing to a change in the particle energy, the effect became observable. (A different interpretation that might appear more consistent is mentioned later.) The disturbance on the phase continued for the rest of the night, but instead of a phase advance as seen in the beginning of the event, a retardation in phase prevailed after midnight. The post-midnight variation could be produced by a Forbush decrease in the cosmic rays, which reportedly started near midnight (Solar Geophysical Data, 1972). Similar phase variations during Forbush decrease events have been observed in a previous study [*Ananthakrishnan and Hackradt*, 1972].

The following additional aspects in the features of VLF and magnetic variations are particularly significant. (1) There is a striking similarity between some of the short-duration changes observed on the VLF phase and those present in the *H* component of the magnetic field. These are indicated by the vertical lines in Figure 3. This might suggest that at times the magnetic changes are associated with corresponding changes in the precipitating particle flux. A similar relationship was also present during the initial phase of an sc storm in the balloon results of *Martin et al.* [1973]. (2) A comparison between the VLF records at Curitiba and Atibaia shows that the initial phase advance was visibly more pronounced in the former than in the latter. (The phase values normalized to the length of the trajectory also showed an appreciable difference). This might be due to the fact that the center of the anomaly is situated at a latitude that is closer to Curitiba than to Atibaia.

TABLE 1. Heights of Maximum Ionization for Electrons of Various Energies that Precipitate into the Atmosphere

Electron Energy, kev	1	5.6	10	20	40	100
Height of Maximum Ionization, km	~180	115	108	100	92	84

It may be noted from Figures 1 and 3 that there is no correlation between the VLF and absorption changes. Postulation of a small difference in the height regions sensitive to the two techniques might not completely explain this result. A more significant contribution could arise from the fact that the VLF effect is the result of that seen along the entire trajectory lying within the anomaly. If one considers [see *Mendes et al.*, 1970] that the affected portion of the trajectory is that lying within the 0.26-gauss contour, the length of trajectory affected for NAA becomes 1800 km. The riometer antenna beam, on the other hand, would see an approximately circular region of radius 75 km above the receiving station.

TABLE 2. Some Features of the 30-MHz Absorption Events Observed on the Vertical and Oblique Antennas

Absorption Event Onset Time, UT	Values of Maximum Absorption, db			Time Difference between Maximums, min
	Observed		Equivalent Vertical	
	Vertical	Oblique		
~2240	0.55	0.5	0.35	16
~0020	0.85	0.85	0.61	~7

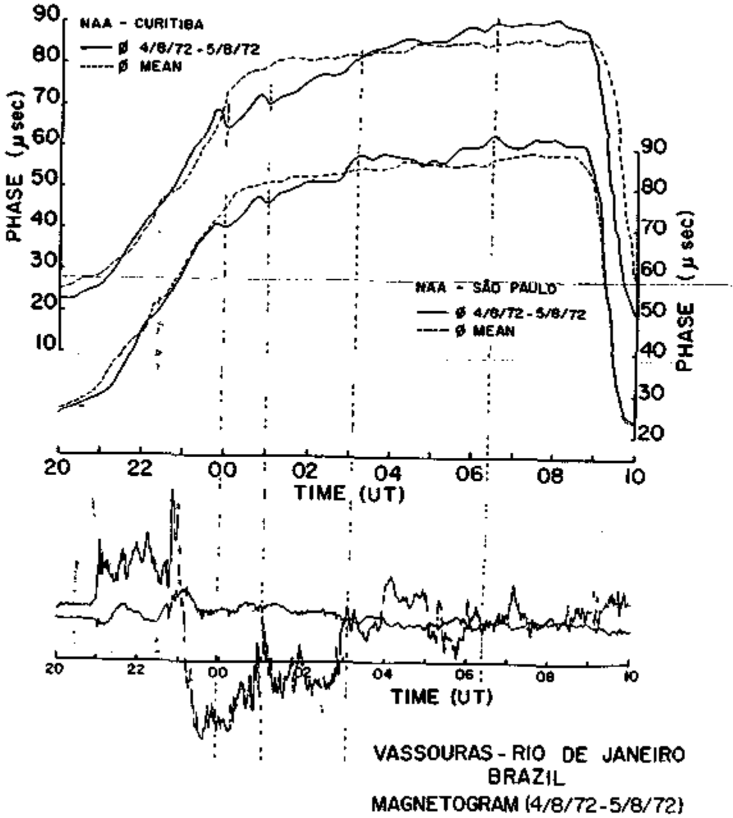

Fig. 3. The variation in the phase of the signal from the 17.8-kHz NAA transmitter, received at (*a*) Curitiba, Paranã, and (*b*) Atibaia, São Paulo (solid curve), on the night of August 4–5, 1972. (The broken curve represents an average of 7 nights before the event.) The corresponding magnetic record for Vassouras, Rio de Janeiro, is shown in the lower half of the figure.

In conclusion, the present study shows the following. (1) Evidence for particle precipitation into the south Atlantic geomagnetic anomaly during an sc magnetic storm is given. (2) For the first time we have observed azimuthal drift and precipitation of electrons into the anomaly. There is some difficulty in determining the average energies of the precipitating particles from the observed drift rate because of our lack of knowledge on the magnetospheric electric fields applicable to lower latitudes. In this context it is useful to point out that if simultaneous determination of the ionization enhancement is done by other techniques, a multiple antenna riometer system with sufficiently narrow antenna beams can be used to measure magnetospheric electric fields during disturbed times. (3) A reasonably good correspondence between VLF phase fluctuations and the horizontal field component variations is observed during the main phase of the storm. However, little similarity is observed in the features of absorption and VLF phase variations.

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Ionospheric Slab Thickness: Its Relation to Temperature and Dynamics

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Summary. The relationship between the ionospheric slab thickness and the temperature and dynamic processes in the ionosphere has been examined. It has been found that the slab thickness is a poor indicator of the temperature or of T_e/T_i. Nevertheless, some new expressions relating τ to H_p, H_n, and T_e/T_i are presented. Evidence is presented to show that the departures of τ from the values dictated by $\tau = 4.13H_p$ are strongly correlated with the departure from diffusive equilibrium as measured by the index $(D/H_n^2 - \beta)$.

The ionospheric equivalent slab thickness τ is defined as the ratio between the total electron content n_t and the maximum electron density in the ionosphere N_{max}. The physical meaning of this parameter is not very evident. It is, however, quite clear that the slab thickness should be related to the shape of the electron density profile: the smaller τ is, the sharper the profile is. In addition to this obvious significance, the slab thickness has often been thought to be proportional to the scale height of the ionizable constituent [*Wright,* 1960]. Another conjecture is that the slab thickness varies as the plasma scale height at the peak. *Mahajan et al.* [1968] have presented some indirect evidence suggesting a linear variation of nighttime τ with the neutral scale height at the peak.

It may be emphasized that the above-mentioned relationships are the descendants of the pre-Thompson scatter era of ionospheric physics, when neither the neutral temperature nor the plasma temperature around the F_2 peak could be measured. Naturally, the validity of the above-mentioned conjectures could not be subjected to direct verification. Such should not be the case anymore. Simultaneous measurements of the complete electron density profile and the relevant temperatures are now abundantly available from Thompson scatter facilities. In view of this situation we considered it worthwhile to make a direct analysis of the various current ideas about the relation of τ to temperature or scale height.

There has also been another consideration behind this work. *Mahajan et al.* [1968] drew attention to the greater scatter in the τ-H plot and emphasized the role of the highly variable extent of the thermal nonequilibrium. Recently, *Amayenc et al.* [1971] have examined the relationship between daytime τ and the mean gradient of the electron temperature in the F region. They used limited data from 1967 observations at the Saint-Santin-Nancay incoherent scatter facility in France. It has been emphasized by the authors that their equations relating τ to $\langle \partial T_e/\partial h \rangle$, the average gradient of the electron temperature in the F region, are highly restrictive and do not have general validity. Thus their relationship could not be extrapolated either to the nighttime condition or to any other situation than that characterized by certain conditions listed by *Amayenc et al.* [1971]. It would certainly be nicer to have empirical relations of somewhat wider applicability. The quest of such a relationship has been the additional motivation behind the study.

IONOSPHERIC SLAB THICKNESS VERSUS SCALE HEIGHT AND T_e/T_i

The data used in this work were gathered at the National Astronomy and Ionospheric Center at Arecibo, Puerto Rico, in the course of two series of experiments named N-11L and N-12 during the period 1966–1968. In the context of the electron content studies the N-11L series of experiments has been briefly described by *Mahajan et al.* [1968]. A description of the N-12 series of experiments can also be found in several