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A STATISTICAL STUDY OF THE DYNAMICS OF THE EQUATORWARD BOUNDARY OF THE DIFFUSE AURORA IN THE PRE-MIDNIGHT SECTOR

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Abstract. We present a statistical study of the dynamics of the equatorward boundary of the diffuse aurora. This Soft Electron Boundary appears to be best fitted by using the AE index values averaged over the 5 hours preceding the measurements. This inertia of the boundary is interpreted as indicative (1) of the action of a polarization electric field braking the inward motion of the corresponding equatorial plasma during increasing magnetic activity so that several successive perturbations are needed to obtain a consequent inward displacement and (2) of a weak wave-particle interaction during periods of decreasing magnetic activity.

Introduction

After the detection of the existence of a permanent, broad, and rather uniform diffuse auroral emission [Lui and Anger, 1973], simultaneous particle observations at geostationary orbit and near conjugate field lines have shown that the spectral shape and differential fluxes of precipitating electrons responsible for the diffuse aurora are very similar to those of the trapped plasma sheet electrons [Meng et al., 1979]. This result has led to the conclusion that the diffuse aurora is produced by a direct dumping of the plasma sheet electrons. It has been suggested that the electron cyclotron harmonic waves detected near the equatorial plane aboard OGO-5 and IMP-6 are at the origin of the strong pitch angle diffusion of ∿keV plasma sheet electrons into the atmospheric loss cone and of their subsequent precipitation into the auroral ionosphere [Lyons, 1974]. However, this generally accepted view has been challenged recently by measurements of electrostatic electron cyclotron waves performed aboard the GEOS satellites showing that more than 85 % of the time the minimum wave electric field amplitude for strong diffusion is not reached [Belmont et al., 1983]. Belmont et al. [1983] conclude from their analysis that these waves are not the only cause of diffuse electron precipitation or alternatively that the wave particle interaction is weak.

It must be stressed that the nature of the wave-particle interaction, together with the convection electric field, control the nature and dynamics of the earthward termination of the plasma sheet inner edge or equivalently of its ionospheric projection: the equatorward boundary of the diffuse auroral zone [see Southwood and Wolf, 1978]. Two extreme cases can easily be conceived : in the case of a particle lifetime much larger than the characteristic convection time the inner edge of the plasma sheet would correspond, for stationary conditions, to the boundary of the "forbidden" region for inward-moving plasma (Alfvén Layer) which is determined by the strength and pattern of the convection electric field. Such an assumption has implicitly been made in order to derive the equatorial electric field strength from particle measurements of the plasma sheet inner boundary [see e.g. Hultquist et al., 1982] or of the equatorward boundary of the diffuse auroral zone [Kamide and Winningham, 1977]. For non-stationary conditions, i.e. if the characteristic time for electric field variations is shorter than the particle lifetime, the instantaneous boundary position will depend on the past history of the geomagnetic activity (so that no information on the convection electric field can reasonably be deduced from the instantaneous boundary location). On the other hand, in the case where particle lifetime is shorter than the characteristic convection time, the boundary position, even for stationary conditions, is no longer fixed by the pattern of the convection electric field : the corresponding flux tube is empty of plasma sheet particles when it reaches the convection boundary of the forbidden region for inward-moving plasma. As the plasma is rapidly lost from the inward-moving flux tube we can expect a weak inertia of the boundary under non-stationary conditions.

This paper presents a statistical study of the dynamics of the equatorward boundary of the diffuse auroral zone in the 22 - 24 MLT sector as a function of the past history of the geomagnetic activity evaluated from the AE values averaged over different time periods preceding the boundary crossings. This Soft Electron Boundary (SEB), considered to be the ionospheric projection of the inner edge of the plasma clouds injected into dipolar flux tubes during substorms, appears to be best organized by using AE values averaged over the 5 hours preceding the measurements, indicative of a strong inertia under non-stationary conditions. This result implies that the convection characteristic time is short compared to the particle lifetime and shows that the inner magnetosphere dynamics cannot be studied without taking into account the past history of the geomagnetic activity, i.e. of the past solar wind - magnetosphere coupling. Tentative correlations between the SEB location and the intensity of the IMF Bz component, although carried out on fewer samples, indicate the same result.

Data Selection

The equatorial SEB was determined using in situ measurements of auroral electrons in the energy range 0.2 - 16 keV made aboard the non stabilized AUREOL-1 and AUREOL-2 polar satellites. On each spacecraft three identical spectrometers were used:

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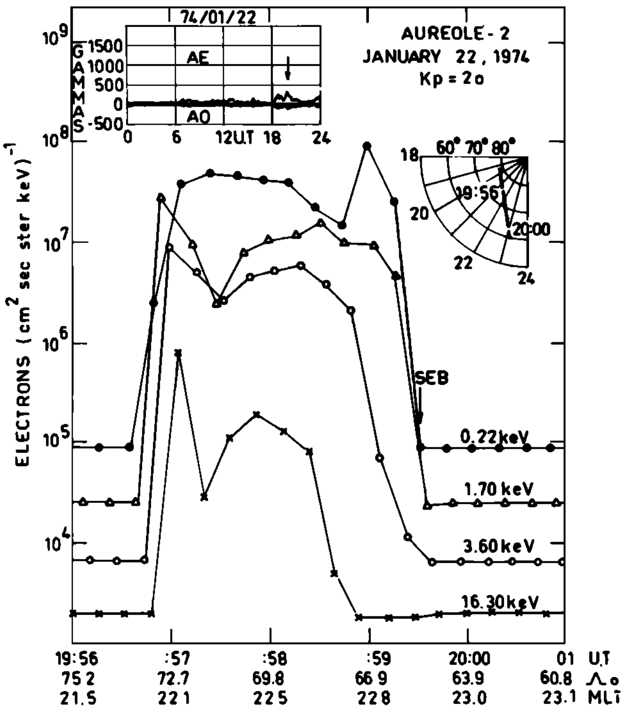

Fig. 1. Differential electron flux for selected energies along a satellite pass from the poleward boundary of the discrete auroral oval to the equatorward boundary of the diffuse auroral zone.

two viewing opposite directions, the third viewing at a 90° angle to them. For this study we have taken into account the SEB crossing in the 22 - 24 MLT sector and in the altitude range 400 - 1 000 km for pitch angles inside or close to the loss cone. The SEB position is defined by a threefold increase of the 1 - 2 keV electron flux which, except during substorms, is usually displaced by 1° - 2° poleward of the softest (0.2 keV) electron precipitation.

Figure 1 illustrates some differential electron flux variations along a typical AUREOL-2 crossing of the auroral zone from North to South in the 22 MLT sector. These measurements refer to the end of the expansion phase of a substorm with an amplitude of about 300γ, around 20:00 UT on January 22, 1974. The northern boundary of the auroral electron precipitation is well defined and probably corresponds to discrete auroral forms which are known to reach their highest latitudes at this epoch of a substorm [Starkov and Feldstein, 1971]. The equatorward boundary of the soft electron precipitation exhibits an energy-dependent structure with the lowest energy electrons precipitating at the lowest latitudes; however, the 0.22 keV and 1.70keV electrons show the same latitudinal profiles at the SEB. The SEB location is indicated by an arrow at $\Lambda_0 = 65.3°$ and MLT = 22.9 H. The SEB location may obviously depend on the detector sensitivity and on the criteria selected for its determination. In order to test the validity of our SEB determination we have compared the location of this boundary independently using the AUREOL-2 and DMSP/F2 data sets.

From the DMSP/F2 satellite the fit to the SEB as a function of Kp in the 22 - 23 MLT sector gives [Gussenhoven et al., 1981] :

$$\Lambda_{oSEB} = 68.3 - 1.79\ Kp \qquad (1)$$

From the AUREOL-1 and 2 satellites the analytical model of the SEB invariant latitude as a function of the magnetic local time and the Kp index is given as follows [Galperin et al., 1977] :

$$\Lambda_{oSEB} = 71.47 - 1.25\ Kp - 0.018\ Kp^2 - (2.84 + 1.24\ Kp - 0.076\ Kp^2)\left(\frac{MLT}{6} - 3\right) \qquad (2)$$

Figure 2 illustrates a comparison of these two models. The agreement is exceptionally good, with a latitudinal difference between 0.1 and 0.7° for a Kp index higher than 1. It must be stressed that comparison between the location of the equatorward boundary of the 6300 Å diffuse aurora, determined from ground based photometer data, and the SEB location also shows an extremely good agreement [Slater et al., 1980]. From these correlations we conclude that the SEB measured onboard the AUREOL satellites represents the equatorward boundary of the diffuse auroral zone with a high degree of confidence.

Dynamics of the Boundary

The fact that the equatorial boundary of the diffuse auroral zone can be organized by the 3 hour Kp index is already a strong indication that this boundary is stable over periods of several hours. However, this magnetic index, computed for fixed UT intervals, does not allow a detailed study of the boundary dynamics. The 2.5-minute AE index appears adequate to perform this kind of study as it can be averaged over any chosen time period and furnishes a measure of the ongoing substorm activity which is known to control the plasma sheet dynamics [Arnoldy and Chan, 1969]. In this study the AE index has been averaged over the 1/3, 2, 3, 5, 10 and 20 hour periods preceding the exact time of the SEB crossing in the 22 - 24 MLT sector. Figure 3 presents the invariant latitude of the SEB as a function of the various averaged values of the AE

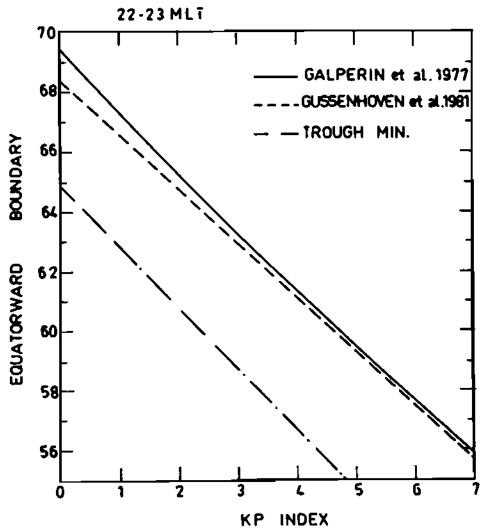

Fig. 2. Latitude of the equatorward boundary of the diffuse electron precipitation as a function of the Kp index. Comparison between the AUREOL-1/2 results and the DMSP/F2 results. Statistical location of main ionospheric trough determined by Kohnlein and Raitt [1977] is indicated by a dot-dashed line.

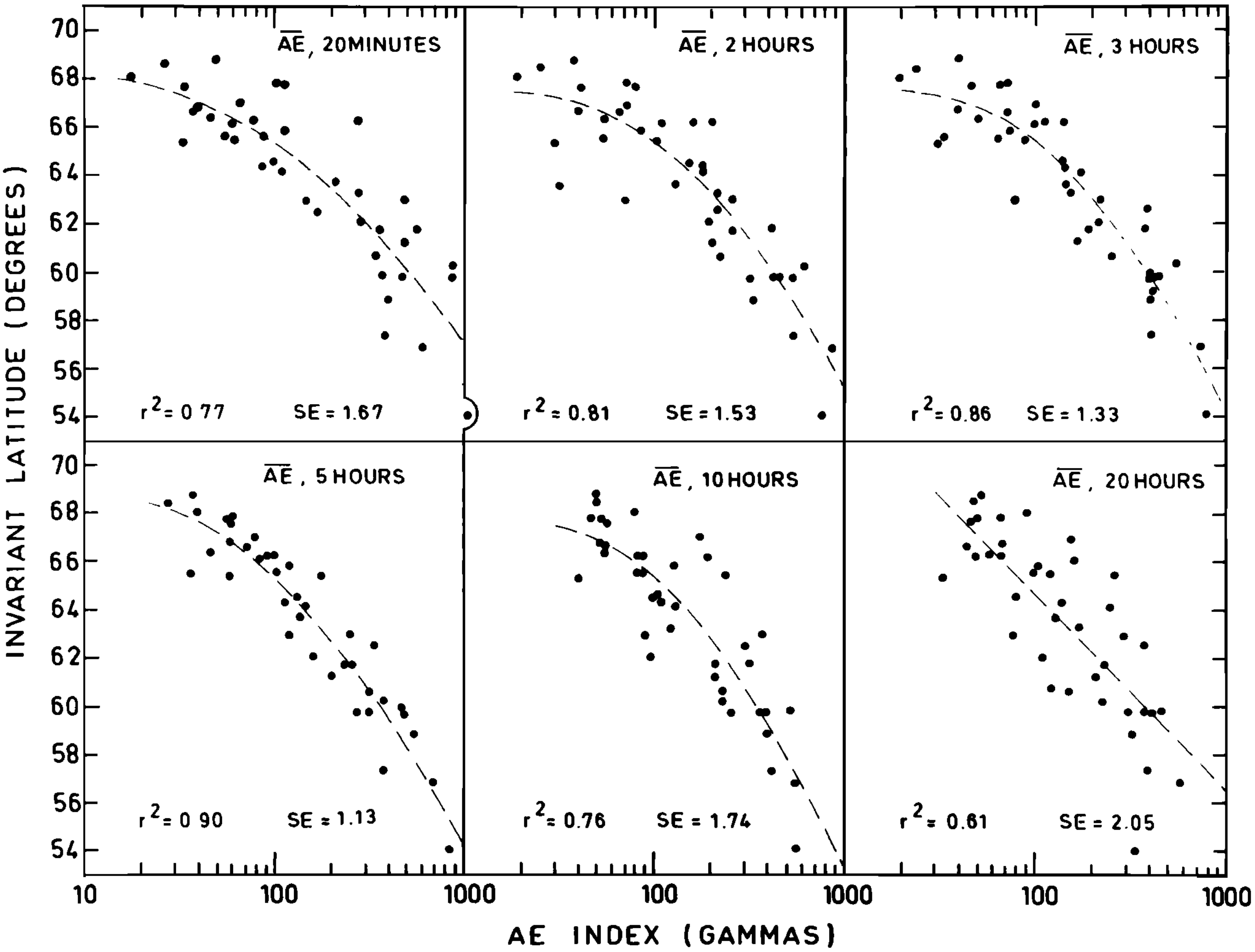

Fig. 3. Dependence of the SEB on the AE index averaged over 20 minutes, 2, 3, 5, 10 and 20 hours before each crossing. Dashed line indicates a quadratic fit determined by the standard least squares method.

index. The general trend is a boundary motion toward a lower latitude when the magnetic activity is prolonged and gradually increases. In each case the dependence is nonlinear and can be approximated as :

$$\text{Inv.lat.(deg)} = A + B \ln(\overline{AE}) + C[\ln(\overline{AE})]^2 \qquad (3)$$

This fit was determined by the least squares method and is shown by a dashed line. Table 1 summarizes the values of the three parameters (A, B, C) of Eq. 3, the square of the correlation coefficient (r^2) and the standard error (SE).

The first conclusion which can be derived from these numbers is that the boundary position is best organized by taking the AE index averaged over the 5 hours preceding the boundary crossing. The corresponding correlation coefficient is furthermore higher than in the cases of fits using the Kp index [Galperin et al., 1977; Gussenhoven et al., 1981] or the hourly value of the Bz component of the interplanetary magnetic field [Kamide and Winningham, 1977]. This result indicates that the boundary location depends mainly on the past magnetic activity and apparently presents a strong inertia which can schematically be described as the consequence of two effects : a strong magnetic activity sustained over several hours is necessary to consequently displace the earthward termination of the plasma sheet inner edge closer to the Earth relative to its quiet time position and, on the other hand the precipitation boundary, though less intense, can still be observed for several hours near the lowest position reached even when the magnetic activity is decreasing. In several cases this weak and remanent precipitation which still produces an observable enhancement of the F-layer ionization can be simultaneously observed with a new and more intense precipitation, due to more recent injections, located at higher latitudes

TABLE 1. Result of the fitting procedure for various average AE values.

Averaging period	A	B	C	r^2	SE
20 minutes	64.81	2.61	-0.54	0.77	1.67
2 hours	60.69	4.61	-0.78	0.81	1.53
3 hours	59.29	5.40	-0.88	0.86	1.33
5 hours	64.11	3.71	-0.75	0.90	1.13
10 hours	57.53	6.41	-1.02	0.75	1.74
20 hours	81.11	-3.54	0	0.61	2.09

[Khalipov et al., 1977; Valchuk et al., 1979]. During disturbed periods the five hour period includes several substorm-associated plasma injections toward the inner magnetosphere. Note that this statistical study does not take into account probable radial motions of the boundary in the course of individual magnetospheric perturbations.

Discussion and Conclusion

During weak magnetic activity periods, corresponding to near stationary conditions, the 5-hour memory of the equatorward boundary of the diffuse aurora implies a weak pitch angle diffusion of the low energy electrons forming the boundary : at $L = 6$ ($\Lambda_0 = 66°$) a strong pitch angle diffusion would lead to a precipitation time scale of $\sim$20 minutes for 1 keV electrons [Kennel, 1969]. Under such conditions, the SEB can be likened to a convection boundary continuously fed by plasma sheet particles; in fact, the convection flow characteristic time scale can be estimated to be about 2.5 hours at $L = 6$ for a total potential drop across the magnetosphere of 30 kV. The corresponding precipitation is weak, with a nearly empty loss-cone so that at the SEB the measured electron integral energy flux can be as low as 3×10^{-3} erg (cm^2.sec.ster)$^{-1}$. As shown by Vondrak and Rich [1982] in such quiet time periods an abrupt termination of the electric field and field aligned currents is observed at the equatorward boundary of the diffuse aurora; this is probably due to the development of an Alfvén layer that significantly shields a further penetration of the convection electric field earthward from the SEB [Southwood and Wolf, 1978].

For periods of increasing magnetic activity, the inertia of the boundary can be accounted for by the fact that the polarization electric field breaks the equatorward displacement of SEB so that this motion can only be achieved by several sequential steps (each for a new substorm) followed by particle drift, precipitation, ionospheric conductivity enhancement and finally discharge of the polarization charges. Once injected toward the Earth, as relative plasma clouds into dipolar field lines, a weak precipitation enables the particles to drift for hours near the equatorial plane, as evidenced by the SEB memory during decreasing magnetic activity periods. This is in full agreement with the results deduced from low energy particle measurements at geostationary orbit [De Forest and McIlwain, 1971]. It must finally be stressed that these results imply that the source of the diffuse aurora during disturbed periods constitutes a variable low energy part of the outer radiation belt located between the plasmapause [Jorjio et al., 1978; Horwitz et al., 1982] and the inner boundary of the region continuously fed by plasma of solar wind origin, i.e. the plasma sheet inner boundary.

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