CONTROL OF PARTICLE PRECIPITATION BY ENERGY TRANSFER FROM SOLAR WIND

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***Abstract*:** The influence of the solar wind on the precipitation of high energetic particles into the middle atmosphere has been investigated by means of ionospheric absorption data measured during the participation of three GDR-groups in the 21st–23rd Soviet Antarctic Expeditions at the Soviet Antarctic Station Novolazarevskaya and by means of other ionospheric and geomagnetic data from high and middle latitudes. It could be shown that the energy transfer function ε as introduced by PERREAULT and AKASOFU (Geophys. J. R. Astron. Soc., **54**, 547, 1978) is a good quantity to describe the energy transfer from the solar wind into the magnetosphere and ionosphere as demonstrated by a comparison of the longterm variation of ε with the variation of the geomagnetic *Ap*-index and the excessive particle-induced absorption in mid-latitudes. A correlation analysis confirms also the significant connection between hourly values of different geomagnetic indices and of ionospheric absorption data from high latitudes with the energy transfer function ε and suggests a time delay of particle injection into the magnetospheric ring current and the precipitation into the ionosphere of about one hour in relation to ε. Investigations of individual geomagnetic storms in mid-latitudes demonstrate that the particle precipitation during the main phase of the storm is markedly controlled by the energy transfer function, whereas during the post-storm phase the internal magnetospheric processes play an important role, too.

The influence of the solar wind, including the polarity of the interplanetary magnetic field (IMF), on the precipitation of high energetic particles into the atmosphere has been investigated for many years mainly for high latitudes but also for middle latitudes (AKASOFU, 1977; LAUTER *et al.*, 1978; BREMER and LAUTER, 1984). These investigations demonstrate the important influence of negative B_z components of the IMF and also of the velocity of the solar wind (high speed solar plasma streams) on particle precipitation. PERREAULT and AKASOFU (1978) derived the following equation for the energy transfer function (ε) from the solar wind into the magnetosphere and the ionosphere:

$$\varepsilon[\mathrm{erg\ s^{-1}}]=vB^2\cdot l_0^{\,2}\cdot F(\theta)$$

with

$$F(\theta)=\sin^4\frac{\theta}{2}\,,$$

where v is the solar wind speed, B is the IMF magnitude, $l_0=7$ earth radii, and θ is the polar angle of the IMF-vector in the Y-Z plane of the solar-magnetospheric coordinate system. By using the $F(\theta)$-function the energy transfer is high during times of negative B_z values but low during periods of positive B_z data.

To investigate the long-term variation of particle precipitation and its relation to the solar wind speed (v) and the IMF-magnitude (B), yearly averaged values (CROOKER *et al.*, 1977; KING, 1981) are presented in Fig. 1. From these data we calculated mean ε values with $F(\theta)$ set equal to unity because mean θ values were not available. But this assumption should not be very critical because there is no reason for a long-term variation of θ. The absolute level of ε calculated in this way is overestimated, as $F(\theta)$ is normally less than unity. For the same period (1963 to 1979)

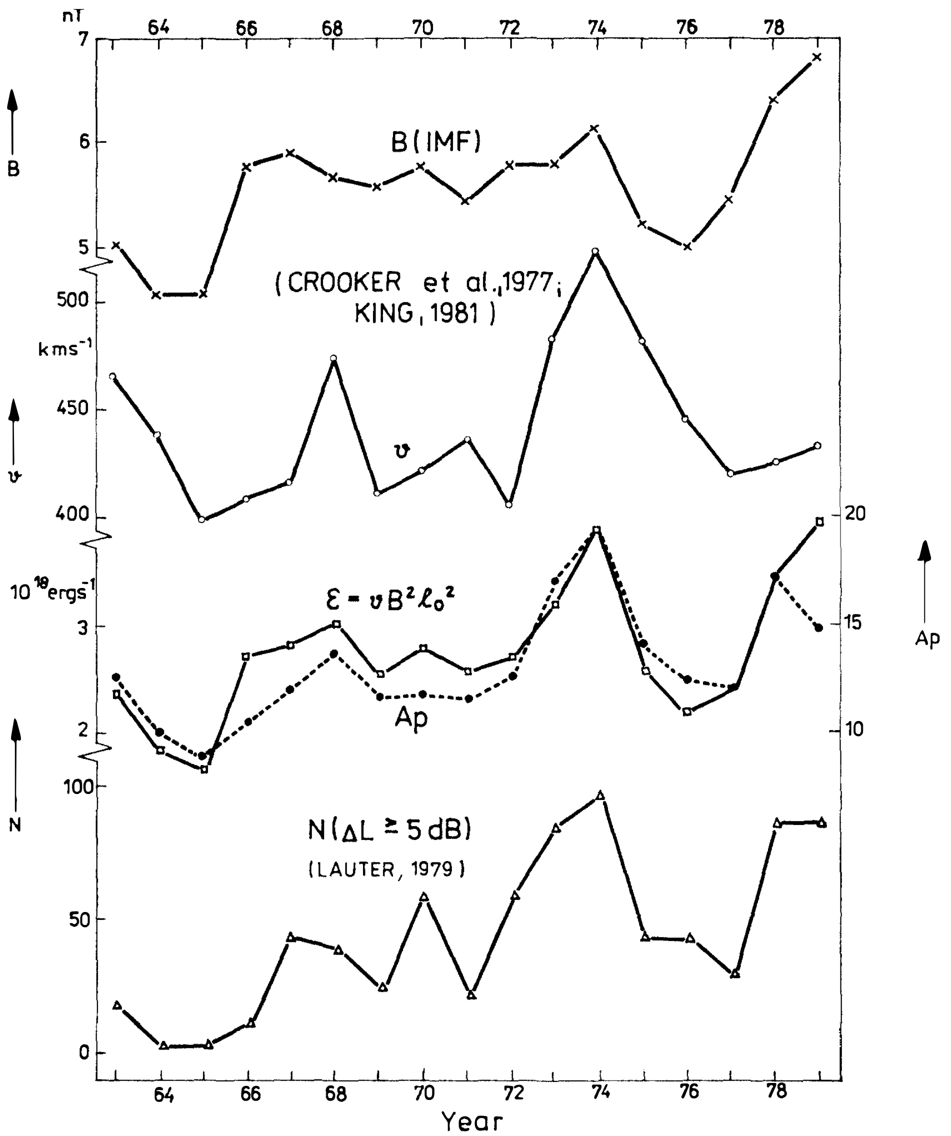

Fig. 1. Comparison of long-time trends of particle-induced ionization in mid-latitudes (number of days with excessive LF-absorption ≥5 dB) and of the Ap index with the IMF magnitude B, the speed of the solar wind v and the term $vB^2l_0^2$ ($l_0=7$ Earth radii).

the geomagnetic *Ap* indices are shown together with the number of days (*N*) with excessive absorption ($\Delta L \geq 5$ dB) in the LF-range (120–250 kHz) during twilight and nighttime conditions in the mid-latitudes (Central Europe) which is caused by precipitating high energetic particles (LAUTER, 1979). The correlation between *Ap* and ε as well as $N(\Delta L \geq 5$ dB) and ε is highly significant ($R=0.82$ and $R=0.87$, respectively), whereas the relation between *Ap* or *N* with *B* or *v* is not so close. Therefore, the energy transfer function (ε) seems to be a good quantity to describe the long-time control of the particle precipitation by interplanetary parameters.

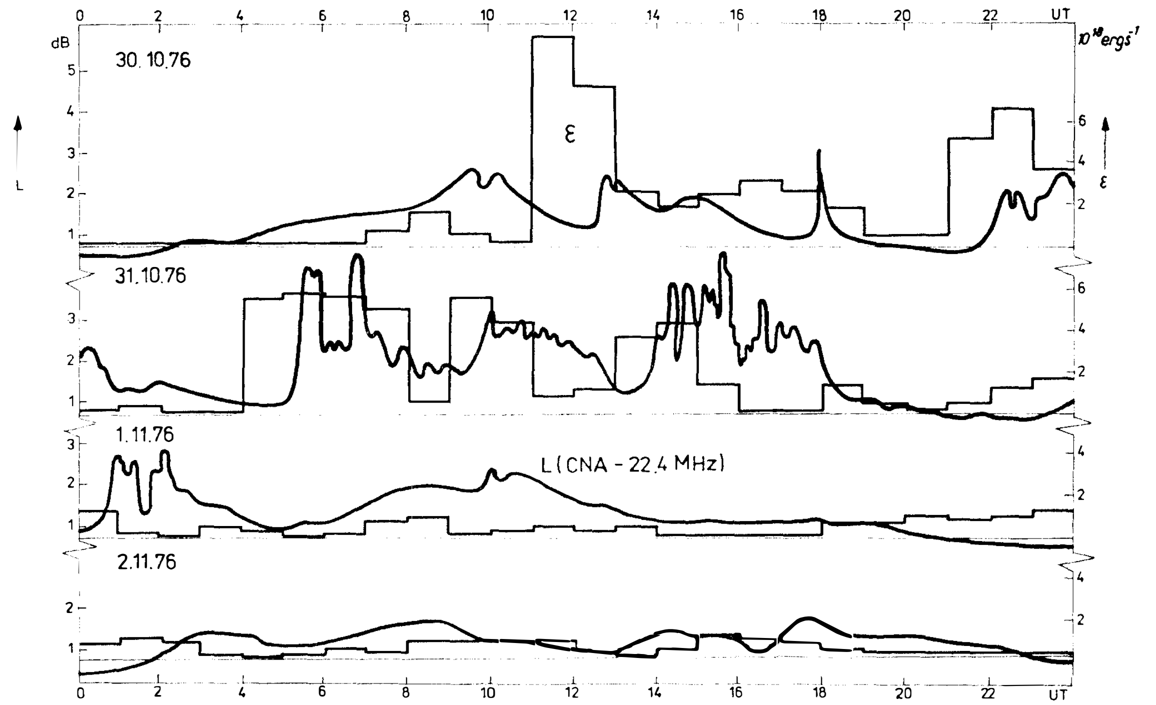

Fig. 2. Temporal variation of the energy transfer ε and of the cosmic noise absorption (CNA at 22.4 MHz) at Novolazarevskaya for the period 30.10 to 2.11 in 1976.

To test this control in more detail we calculated hourly ε values from satellite-measured solar wind and IMF-data (KING, 1977, 1979) and compared these data with corresponding geomagnetic (*AE* and D_{st} indices) and ionospheric data (*CNA*-measurements at the Soviet Antarctic Station Novolazarevskaya carried out by three GDR-teams during the 21st, 22nd and 23rd Soviet Antarctic Expeditions from 1976 until 1979). In Fig. 2 the calculated hourly ε data are shown for the geomagnetic disturbances on October 30 and 31 and the two following days and *CNA* observations at 22.4 MHz. It can be seen that the *CNA* values are increased about 1 to 2 hours after the maximum energy transfer function (ε) is reached, but the variations of CNA do not depend only on the level of the ε values. On days after the main disturbances (November 1 and 2) the energy transfer is markedly reduced (often below 10^{18} erg s^{-1}) but the *CNA* level is enhanced nevertheless. In contrast to the strong fluctuating character of the *CNA* disturbances during the primary phase of the disturbances on October 30 and 31 (which is typical of directly precipitating particles), smooth *CNA* variations can be observed during the aftereffect on November 1 and 2 (which should be caused by precipitation of temporarily trapped particles). This kind of precipitation, which can be detected also in mid-latitudes after geomagnetic storms, will be described below. In high subauroral latitudes the steady aftereffect variation is often modulated by directly invading particles. The ring current not shown in Fig. 2 increases with the main energy transfer on October 30 and reaches its highest values during the disturbances on October 31, whereas it decreases thereafter and reaches its normal undisturbed level on November 5.

To establish the relationship and possible time delays between the investigated data, including data of the auroral electrojet activity (*AE* index), correlation coefficients have been calculated on the basis of the data shown in Fig. 2 and other days with moderate geomagnetic activity. To diminish the influence of extreme values in these investigations we calculated tetrachoric correlation coefficients as described by TAUBENHEIM (1969). We used hourly mean values of the whole day (0–24 UT) and calculated the correlation coefficients for time lags $\Delta t=0, 1, 2, 3, 4$ hours between the *CNA*, *AE* and D_{st} data with respect to the ε values. In Fig. 3 the results are represented together with the error probability level of 0.1%. The maximum correlation between *AE* and ε (Fig. 3a) was obtained for a time lag of about $\Delta t \leq 1$ h, whereas the D_{st} index has its maximum at about 1.5 h (Fig. 3b) and the *CNA* events at about 2 h delay with respect to ε (Fig. 3c). As demonstrated from extensive investigations by BERKEY *et al.* (1974) the main injection of energetic particles into the magnetosphere should be at about local geomagnetic midnight. While some of these particles precipitate directly, others drift around the earth (electrons which are mainly responsible for *CNA* drift eastwards) and cause *CNA* events during the daytime. For an elimination of the time delay due to this drift motion we also calculated the correlation between *CNA* and ε separately for forenoon (0–12 UT) (Fig. 3d) and afternoon hours (13–24 UT) (Fig. 3e). While the forenoon *CNA* values have a time delay of about 1.5 h, the afternoon data are 2.5 h delayed with respect to ε. This difference of 1 h between the forenoon and the afternoon data corresponds to a drift velocity of 70–80 keV electrons. The maximum correlation during forenoon ($R=0.53$) is markedly higher than during afternoon ($R=0.37$). This effect can be understood because the occurrence probability of *CNA* events has a maximum in the forenoon but a minimum in the afternoon. Therefore, many of the particle injection processes cannot be detected in *CNA* measurements in the afternoon period. Considering the drift velocities of electrons derived above, the time delay between *CNA* events near local midnight with respect to ε is only about 1 h. It is thus comparable with the time lags derived from *AE* and D_{st} data. Therefore, the mean time lag between particle precipitation into the atmosphere relative to the particle injection from the solar wind should be about 1 h in accordance with other authors (*e.g.* NISHIDA, 1983). The significant correlation of particle precipitation with the solar energy injection (ε) suggests that substorm processes are directly driven by the solar wind (driven process as described by AKASOFU, 1979) but the time difference of about 1 h points to a temporary storage of substorm energy in the magnetotail (unloading process). The large differences between ε and *CNA* activity as shown in Fig. 2 (October 30 and 31, 1976) support this conclusion (also given by NISHIDA, 1983) that ionospheric substorm processes in high latitudes are in part directly driven by the solar wind including IMF

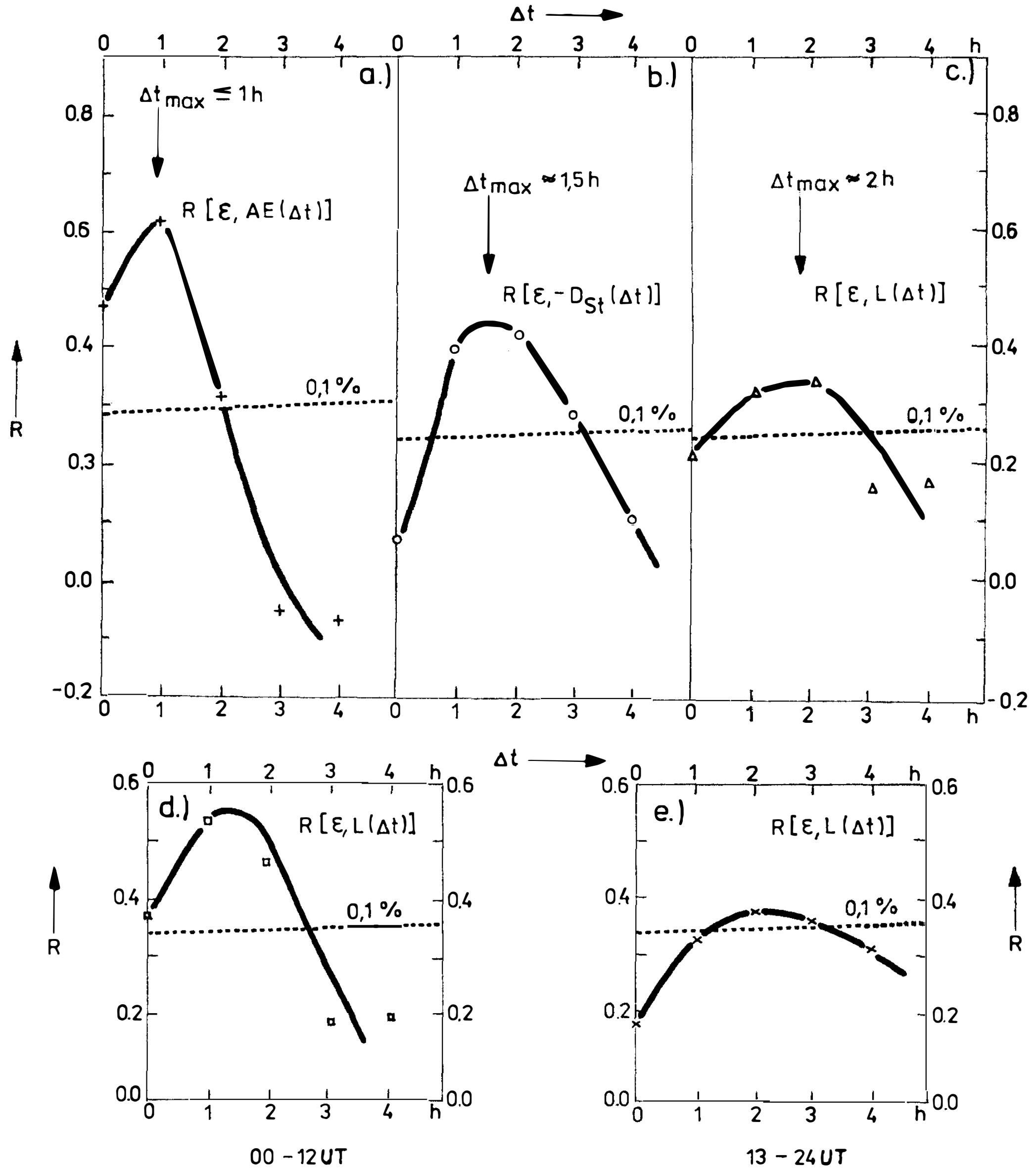

Fig. 3. Correlation coefficients of the energy transfer function ε (a) with the AE index, (b) with the D_{st} index and (c) with the absorption values (CNA at 22. 4 MHz) of the station Novolazarevskaya for time delays $\Delta t = 0 \sim 4$ hours with respect to ε. The correlation coefficients between ε and CNA are also separately shown (d) for the forenoon and (e) the afternoon values.

properties but also influenced by energy storage processes.

Particle precipitation in high latitudes is characterized mainly by substorm processes with time scales of about 30 min to some hours. By contrast, in the subauroral zone and the mid-latitudes the so-called after- or post-storm events (PSE) with durations up to 20 days can be observed during and especially after geomagnetic storms (LAUTER *et al.*, 1977). As shown by LAUTER *et al.* (1978) the particle precipitation during these PSE is partly controlled by IMF-sector structure. While the primary part of PSE during geomagnetic disturbances is caused by directly precipitating high energetic electrons, the precipitation after the disturbance is mainly due to pitch angle diffusion processes of trapped high energetic electrons with magnetospheric ELF and VLF hiss (WAGNER *et al.*, 1983). In Fig. 4 the PSE of March 1970 is represented by ionospheric absorption measurements in different latitudes (f_{min} measurements around noon from the ionosonde stations Kiruna, Halley Bay and Uppsala; LF-absorption measurements during twilight and nighttime conditions at Kühlungsborn)

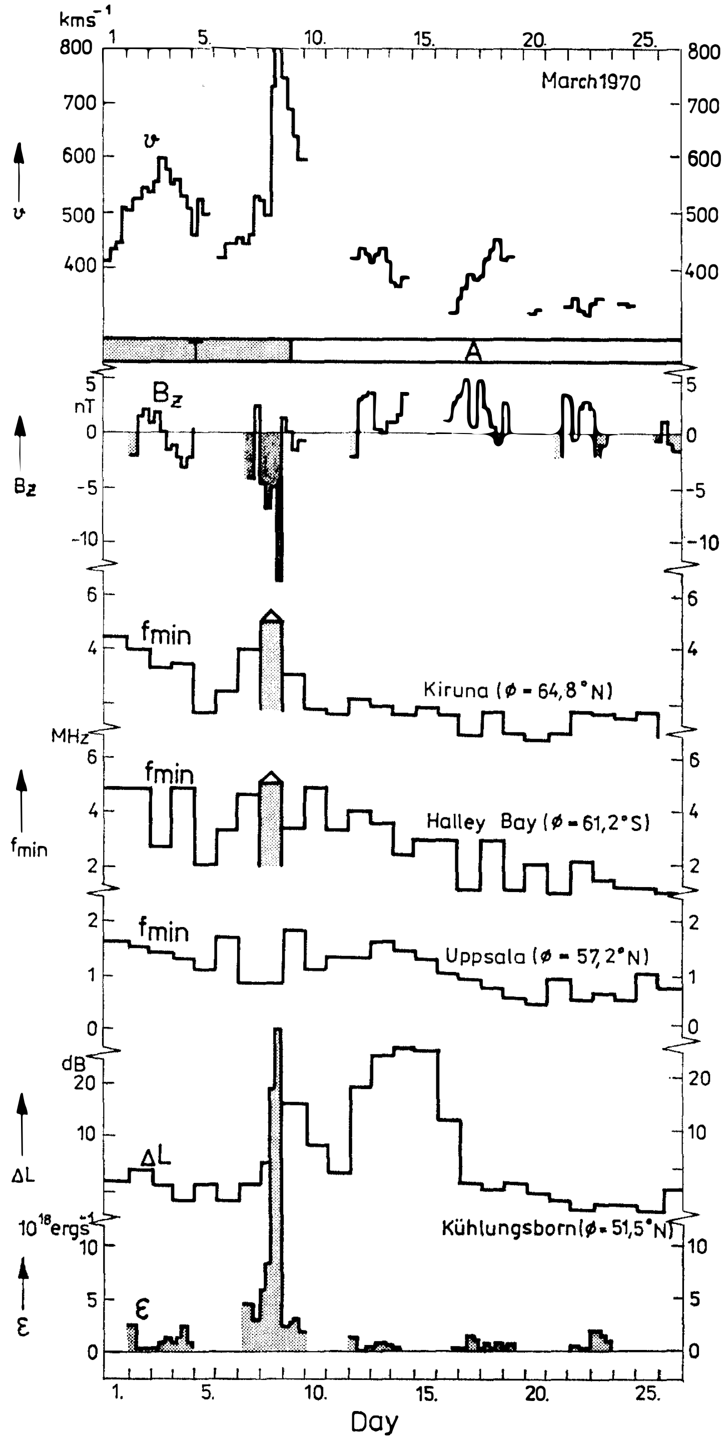

Fig. 4. The post-storm event of March 1970 detected by ground-based ionospheric absorption measurements in different latitudes and compared with solar wind parameters: velocity v, IMF direction, B_z component of the IMF in the solar-magnetospheric coordinate system and the energy transfer function ε.

in comparison with solar wind data after KING (1977): solar wind speed (v), B_z component of the IMF in the solar-magnetospheric coordinate system and the energy transfer function (ε). The PSE is caused by a large increase of the solar wind speed and large negative B_z values on March 8, 1970 which produce a very large solar energy input ε (6 h-average: $\varepsilon=6.5\times10^{19}$ ergs^{-1}; maximum hourly value even 1.45×10^{20} ergs^{-1}). Together with the change of IMF sector polarity from T to A polarity the B_z values are positive afterwards and the energy transfer nearly vanishes. Therefore, in high latitudes no excessive ionization is observed after the primary energy input. In contrast to this behaviour, in the mid-latitudes a well pronounced PSE can be seen especially at Kühlungsborn (excessive LF-absorption up to 26 dB) and a smaller one at Uppsala during the time of the strongly reduced solar energy transfer. This after-effect is caused by precipitation due to the internal magnetospheric loss processes, as mentioned above, of high energetic electrons which were trapped by the Earth's magnetic field lines in the magnetospheric slot region ($L=2\sim6$) during the main injection on March 8. Small disturbances in solar wind and IMF data (negative B_z-values) before the main disturbance on March 8 cause enhanced particle precipitation only in high latitude location as far south to Uppsala.

There are of course other examples of PSE not shown here where the solar energy transfer is enhanced also during the second phase of the PSE. These additional injections often prolong the duration of PSE.

In summary we can state that in high latitudes the precipitation of energetic particles into the atmosphere is markedly controlled by the properties of the solar wind including a time delay of about one hour caused by magnetospheric storage processes. In the mid-latitudes only injection processes in the primary phase of PSE are controlled by external solar-induced processes, whereas during the real after-effect period mainly internal magnetospheric processes play the dominant role.

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