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LONG-PERIOD GLOBAL OSCILLATIONS OF MAGNETOSPHERE AND THE RELEVANT EFFECTS IN RADIATION BELTS

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Abstract

Long-period (~1–3 hours) storm-time DP-1 and DP-2 geomagnetic variation effects in radiation belts are analyzed. We use the Molniya-1 satellite (~40,000-km apogee, 500-km perigee, ~63^o inclination) data to demonstrate the DP-2 variation effect on radiation belt particles. The non-stationary peaks in proton spectra on L~2.5 occur due to the giant quasi-periodic DP-2 variations, whose periods coincide with the proton drift periods on the respective L-shells. The giant DP-2 variation amplitude may reach ~1000 nT in a sunlit polar cap. We analyze the quasiperiodic geomagnetic disturbances for the 25 May 1967 storm (D_{st}~400 nT) to explain the resonant acceleration of >280 keV electrons measured on the 1963 58C satellite in the inner radiation belt. The quasi-periodic (a few hours) variations of the relativistic electron intensity in a geostationary orbit are studied basing on the GOES 8 and 10 measurements and on the ACE interplanetary data. The results obtained support the self-excited quasiperiodic substorm occurrence under persistent southward orientation of IMF observed 3 decades ago. The relevance of named variations for the geomagnetic storm development features is discussed.

[1] Invited review paper presented at ISEC 2003, September 2-5, 2003, Toulouse, France

1. Introduction

The global quasi-periodic geomagnetic field variations with periods from a few tens of minutes to a few hours are often observed during magnetic storms. The electric fields generated during such disturbances may significantly affect the intensity distribution of charged particles, whose magnetic drift periods are close to the characteristic times of quasi-periodic geomagnetic disturbances.

The resonant acceleration of radiation belt particles under impact of quasi-periodic geomagnetic variations was observed many years ago. The selective transient ~1 MeV electron peaks of the differential spectra of relativistic electrons were observed at the inner edge (L~1.15) of the inner radiation belt [*Imhof and Smith*, 1965]. The relevant calculations have shown that the peaks are due to particle acceleration by the electric fields induced by quasi-periodic equatorial electrojet variations with periods of a few tens of minutes [*Cladis*, 1966]. The author assumed that the given type of resonant acceleration was not uncommon because the equatorial electrojet fluctuations with periods of tens of minutes were frequent during magnetic storms [*Pai and Sarabhai*, 1964].

The resonant acceleration of protons with energies of a few hundreds of KeV was observed according to the Molniya-1 measurements [*Vernov et al.*, 1972a,b]. The peaks of proton spectra on L~2.5 are due to the giant global DP-2 quasiperiodical variations, whose periods coincide with the proton drift periods on the respective L-shells.

The DP-2 variations are known to correlate well with IMF B_z fluctuations [*Nishida,* 1968]. Even during relatively quiet periods, are the B_z fluctuations accompanied by correlated fluctuations of trapped 50-150 keV electron fluxes in geosynchronous orbit [*Parks and Pellat*, 1972].

The substorm-time charged particle injections in geosynchronous orbit are often of quasi-periodic character. The meaningful period is 2.5 hours [*Parks et al.*, 1972; *Borovsky et al.*, 1993; *Tverskaya,* 2001; *Tverskaya and Krasotkin*, 2002; *Reeves et al.*, 2002, *Huang et al.*, 2003].

The origin of quasi-periodic substorms has still to be found. In some cases, they correlate with the solar wind pressure oscillations [*Huang et al.*, 2003]. This result is quite expectable because the substorms have been known for three decade to occur during sudden commencements of magnetic storms [*Akasofu and Perreault*, 1969; *Schielde and Siscoe,* 1970; *Tverskaya and Khorosheva*, 1974]. In other cases, the quasi-periodic substorms are observed during persistent southward IMF orientation even under steady solar wind [*Ivanov and Mikerina*, 1973; *Tverskaya and Khorosheva,* 1975; *Tverskaya,* 2000, 2001; *Tverskaya and Krasotkin*, 2002; *Reeves et al*., 2002, *Huang et al*., 2003]. We suggested such substorm generation to be of inner-magnetospheric origin and called that process the self-excited regime in magnetospheric substorms [*Tverskaya and Khorosheva*, 1975].

The present report is a review of some works, which studied the influence of long-period geomagnetic variations on charged-particle distribution in the inner and outer radiation belts. We shall also discuss the interrelationship of the above variations with the geomagnetic storm structure.

2. Inner belt variations

This section examines the resonant acceleration of protons and electrons in the inner radiation belt during magnetic storms. We shall also discuss some cases of relativistic electron diffusion into the inner belt.

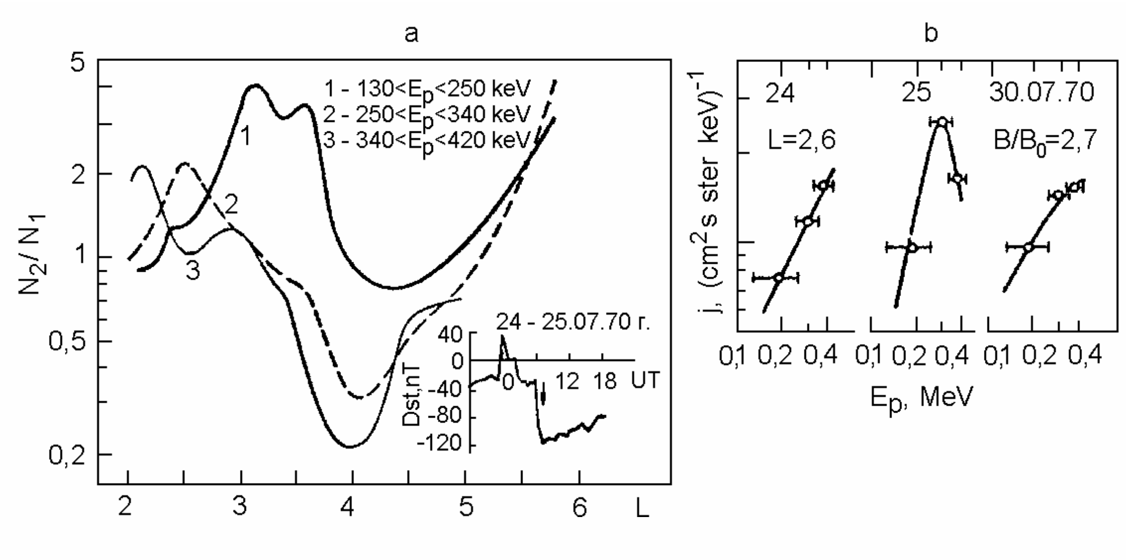

Fig. 1. Variations of radiation belt protons in July 25, 1970 storm: a) relation of storm-time (N2) and quiet (N1) count rates in 3 spectrometer channels; b) proton spectra at L=2,6 [Vernov et al., 1972a].

Fig. 1 shows the variations of the radiation belt proton intensity and spectrum during the 25 July 1970 storm [*Vernov et al.*, 1972a,b]. The data are from the differential proton spectrometer flown on Molniya-1 (~40,000-km apogee, ~500-km perigee, ~12-hour orbiting period, ~65^o orbit inclination). The storm was rather strong, the D_{st}-variation amplitude peaked at 120 nT. The arrow indicates the Molniya-1 pass through radiation belt on 25 July 1970. Fig. 1a shows the ratio of the count rates measured in three spectrometric channels (130-250, 250-340, and 340-420 keV) during the pass to the count rates measured during quiet time. The most significant increase (by factor 4) with a peak on L~3,2 was observed in the 130-250 keV channel and was due to a strong ring current injection. The high-energy proton intensity decreased within the L = 3.5-4.5 interval. The major contribution to the >250 keV proton intensity decrease was from the adiabatic variations due to storm ring current.

An interesting feature is the relative intensity increase in the 250-340 keV and 340-420 keV ranges on L =2.6 and 2.2, respectively. The "selective" transient maxima were observed in the proton spectra. Fig. 1b shows the proton spectra on L = 2.6 during quiet-time, during the storm main phase, and in five days after the storm. On 30 July, the spectrum was close to quiet.

The above-mentioned proton spectrum variations are most probably due to the quasi-periodic trains of magnetic (and, hence, electric) field disturbances [*Cladis*, 1966]. The period of magnetic drift was estimated to be 53 min on L = 2.2 at mean energy 340-420 keV and 57 min on L = 2.6 at mean energy 250-340 keV.

Analyzing the geomagnetic field variations has shown that the giant global DP-2 type quasi-periodic variations began a few hours before the occurrence of the selective proton intensity maxima. Fig. 2a shows the geomagnetic field X-component at the Resolute Bay polar cap station, the H-component at Vladivostok low-latitude station, and the AL, D_{st}, and K_p indices [*Tverskaya and Khorosheva*, 1974]. The shaded area represents the synchronous X- and H-component variations observed

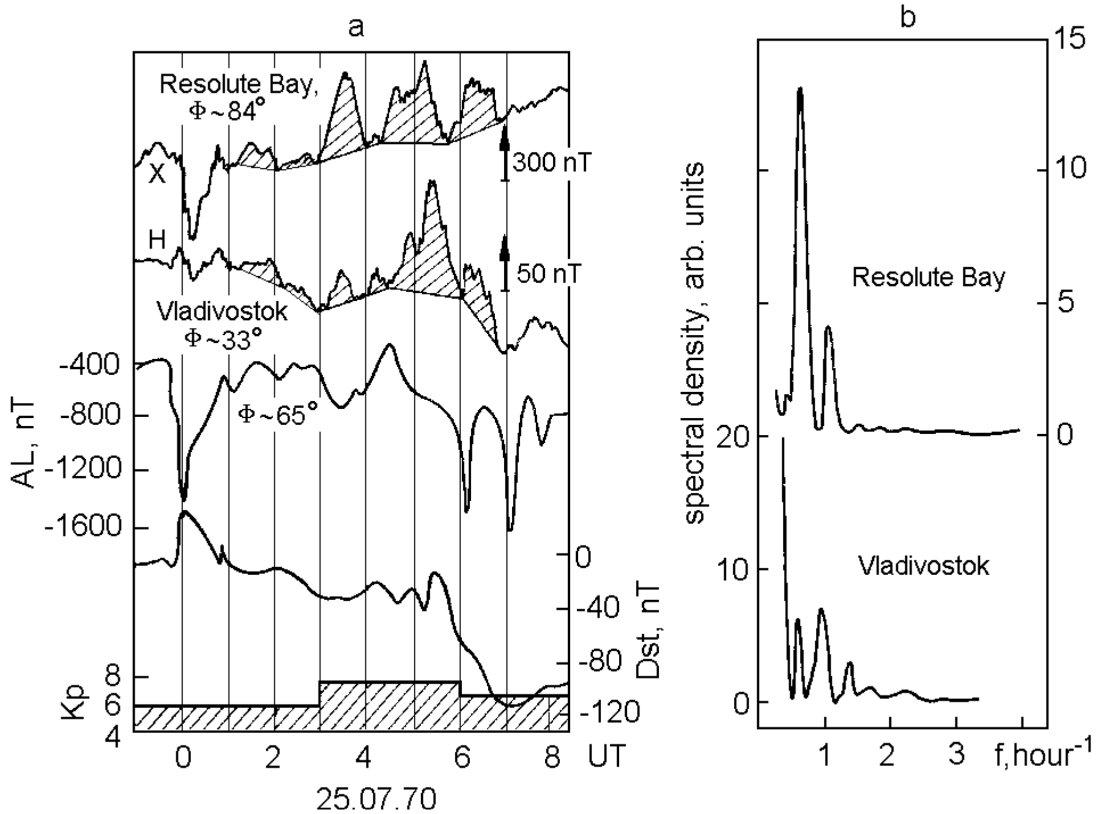

Fig. 2. Giant DP-2 variations in magnetic storm July 25, 1970; a) Kp, Dst, AL-indexes, X and H magnetic field components of stations Resolute Bay and Vladivostok; b) Fourier spectra of X and H magnetic field components of stations Resolute Bay and Vladivostok [Tverskaya and Khorosheva, 1974].

on 25 July in polar cap and in low latitudes. The Fourier spectra of the variations exhibit two maxima for periods of 94 and 55 min. (Fig. 2b). The 55-min period coincides with the drift periods of the resonant-accelerates protons on L = 2.2 and 2.6. In the case of the 94-min period the effect was observed on L<2. In that region, however, the background of the high-energy (>150 MeV) inner belt protons was only measured.

On Figure 3 variations of intensity of electrons of Ee > 280 keV in the inner radiation belt during strong magnetic storm on 25 May 1967 ($|D_{st}|_{max}$ ~ 400 nt) [*Bostrom et al*, 1970]. It is seen that electron intensity increase is most pronounced and shows the highest intensity within a narrow L-shell range (L = 1.3–1.4). Measurements were of integral character, so the drift period of measured electrons can not be established accurately in any way. A rough estimate gives ~ 2.5 hours for the threshold energy.

Geomagnetic data and results of the geomagnetic variation Fourier-analysis for this storm are shown on Figure 4 [*Tverskaya and Khorosheva*, 1974, 1975]. Figure 4a characterizes the peculiarities of DP-2 variation development (before the beginning of sharp D_{st}-variation decrease). After the second sudden commencement of very high amplitude (SSC, 12.35 UT) in auroral region strong electrojet currents have developed (H ~ 1700 nT). Later on starting from 15^h UT auroral disturbances has become weaker so much (H falls from ~ 1700 to 200–400 nT) that polar variation amplitude has exceeded auroral bay amplitude by several times. At that time during Dst-variations "step" has formed (see also Figure 2a for 25 June 1970) ~ 5 hours long. In Figure 4b results of Fourier-analysis for these variations are presented according to magnetogram data from stations Thule (polar cap), Witteven (middle latitudes) and Huancayo (equator). Disturbance spectrum in polar cap has spectral lines which could be clearly seen in middle-latitude and equatorial disturbance spectra. The main periods are 125 and 83 minutes.

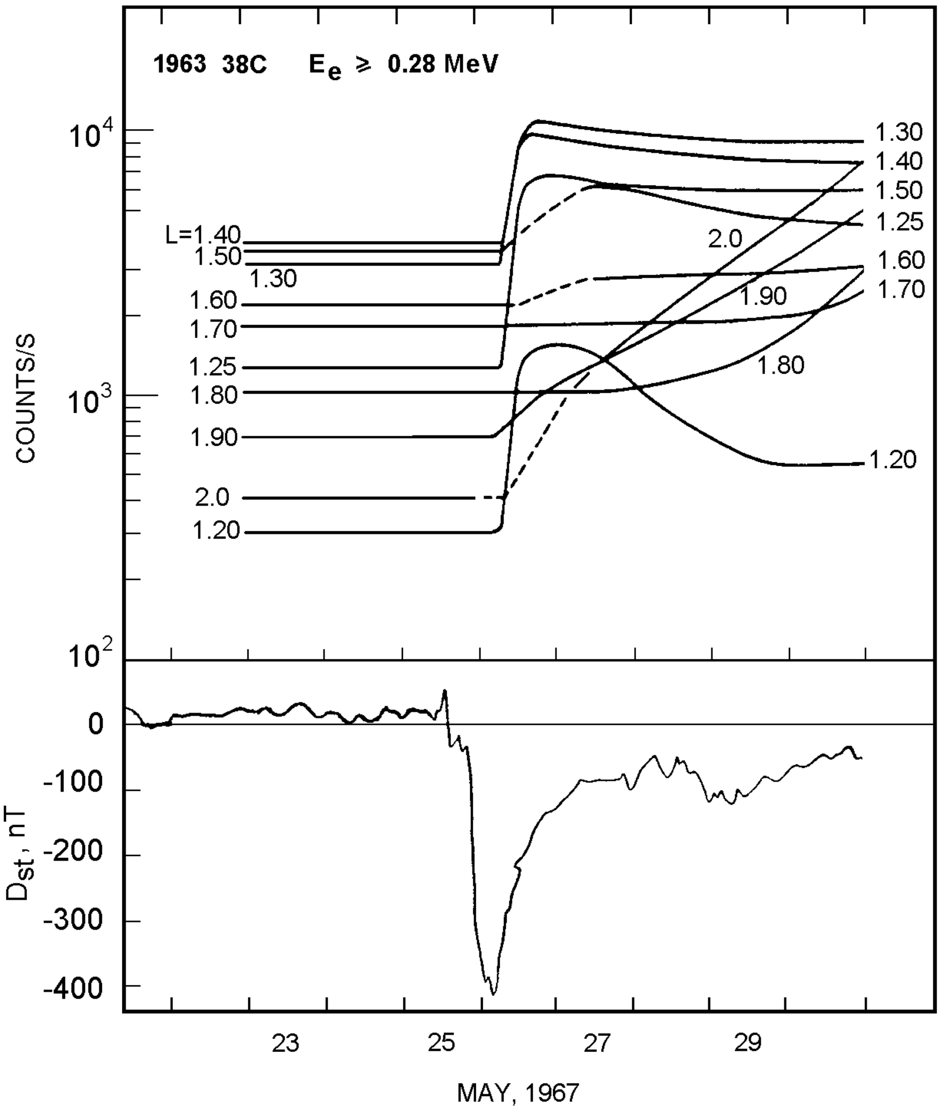

Fig. 3. The >0.28 MeV inner belt electron increase during the 25 May 1967 storm observed on the 1963 38C satellite [Bostrom et al., 1970].

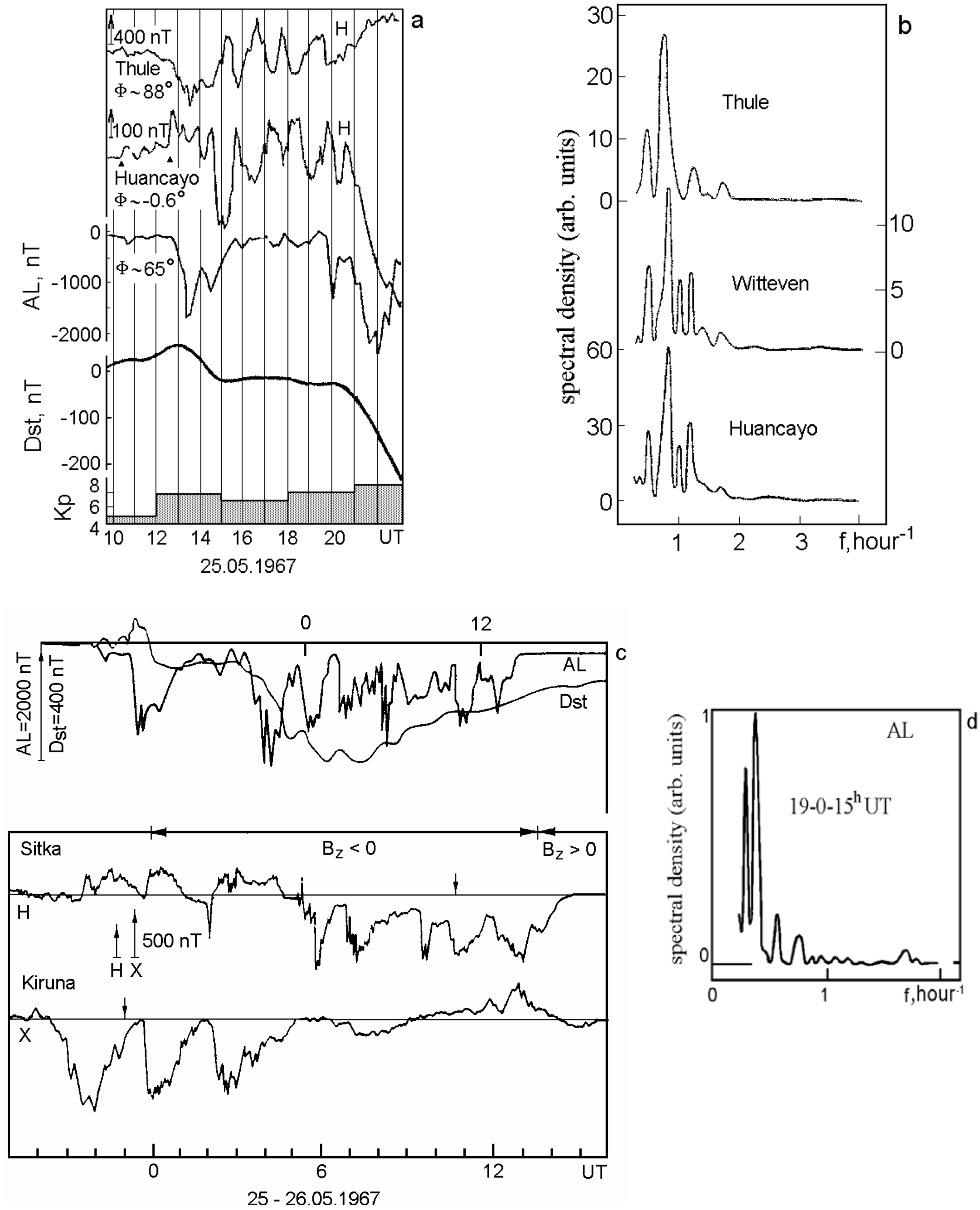

Fig. 4. The 25 May 1967 storm geomagnetic variations: a) Kp, Dst, AL, H-component of Huancayo and Thule stations; b) Fourier spectra of Thule, Witteven and Huancayo H-component; c) Dst, AL, H- and X-components of Sitka and Kiruna stations; d) Fourier spectrum of AL-index index during the interval from 19:00 UT on 25 May to 15:00 UT on 26 May [Tverskaya and Khorosheva, 1974,1975].

Disturbances in auroral regions in this storm also had quasiperiodical nature. These peculiarities are illustrated by Figure 4c [*Tverskaya and Khorosheva* ,1975]. In the upper part of the figure Dst-variation and AL-index are shown, in the lower part magnetograms from Sitka (H-component) and Kiruna (X-component) stations for which the local time differs by ~ 12 hours are given. There is no complete interplanetary medium data on this storm. However it is known that at least from 00:00 to 13:30 UT 26 May IMF B_z was < 0 [*Williams and Bostrom,* 1976]. AL-index Fourier-analysis has shown the presence of two spectral lines at periods ~ 2.5 and 3.2 hours. It is most probable that resonance increase of electrons of E>280 keV observed within the storm on 25 May 1967 follows from the described quasiperiodical geomagnetic field variations [*Tverskaya,* 2001].

In [Huston and Pfitzer, 1998] cases of sharp enhancement in >80 MeV proton fluxes at low L-shells (1.14 and 1.4) have been described. Parts of them have been registered during the strong SEP events. Apparently all of them took place during strong magnetic storms. The origin of these enhancements is not clear. If one would suppose that these transient peaks have been caused by electron contamination (bremsstrahlung of some hundred keV electrons) they also may be explained by global quasiperiodical disturbances influence like on 25 May 1967.

Global quasiperiodical geomagnetic field disturbances developed during magnetic storms may lead to fast diffusion of radiation belt particles having appropriate magnetic drift periods.

Fast diffusion of electrons of energies >0.9 MeV in the inner belt has been discovered according to data from Molniya-1 satellite: for 2 weeks maximum of intensity of electrons injected during magnetic storm has moved from L ~ 2.2 to L ~ 1.8 [*Tverskaya,* 1996 and ref therein]. During these 2 weeks geomagnetic field was strongly disturbed and at high-latitude parts of Molniya-1 satellite trajectory variations of intensity of electrons and protons of energies of tens keV were registered simultaneously with ground variations DP-2 type. [Kovrygina et al., 1976].

During the most powerful storm for the whole space era on 13 March 1989 according to data from Meteor satellite fast diffusion in the inner radiation belt of electrons of Ee ~ 2 MeV has been observed. Maximum of their intensity has moved from L ~ 2.5 to L ~ 2.2 in two days. For the same time intensity maximum of >8 MeV electrons remained at L ~ 2.5 [*Tverskaya et al,* 2003]. During this storm intensive geomagnetic field pulsations were registered with a period of 20 minutes [Zaitsev, private communications, 2000] that may cause fast diffusion of electrons of energies ~ 2 MeV.

3. Outer belt variations

Figure 5 shows the results of Molniya-1 dayside measurements of > 40 keV electrons and > 65 keV protons [*Kovrygina et al,* 1976]. Particle distribution in this local time is minimally affected by substorms. The synchronous ~ 1-hour electron and proton variations are quite evident. The ground-based observations shows the DP2 type global variations (see Thule polar cap data and the Huancayo equatorial data), which redistribute the trapped particle intensity in the distant magnetosphere. The variation behaviours synchronism in the ground-based and satellite data indicate that the disturbances are global and temporal rather then spatial. A similar effect for 50–150 keV electrons was also observed in the geosynchronous orbit [*Parks and Pellat,* 1972].

In greatest detail quasiperiodical charged particle enhancement variations connected with magnetic substorms development were studied according to

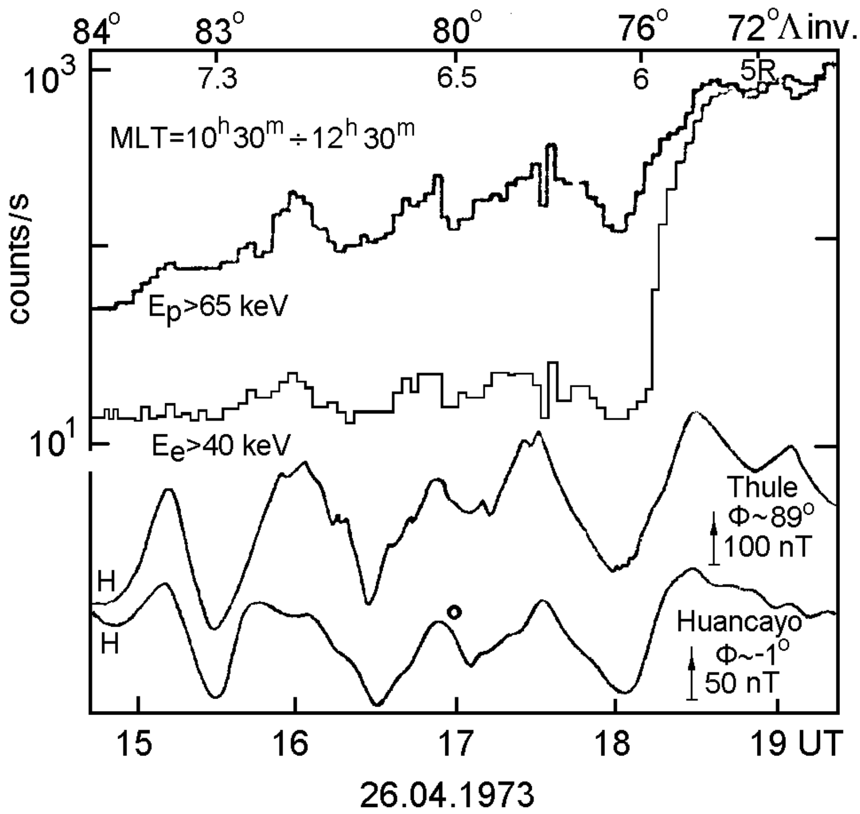

Fig. 5. The >40 keV electron and >65 keV proton flux variations inferred from the Molniya-1 measurement data. The upper scale shows the invariant latitude and the geocentric distance. Two lower curves are the H-components of the Thule and Huancayo magnetic observatories. The slite circle denotes local noon [Kovrygina et al.,1976].

geosynchronous satellite data. Even the very first study of tens-hundreds keV electron intensity variations have shown that there exists considerable power contribution in the frequency interval around 0.4 c/hour, corresponding to a 2.5 hour period [*Parks et al,* 1972]. Authors have come to a conclusion that magnetospheric substorms recure periodically every 2–3 hour during active geomagnetic times. Further investigations have shown that quasiperiodical series of substorms could develop under prolonged south orientation of interplanetary magnetic field even during relatively stable parameters of the solar wind [*Ivanov and Mikerina, 1973; Tverskaya and Khorosheva, 1975*].

Because of the existence of almost persistent set of data on interplanetary environment (ACE, WIND) and charged particle substorm injections on geostationary orbits (GOES, LANL) the above processes can be nowadays studied in more better detail.

In Figure 6 [*Tverskaya,* 2001] variations of intensity of electrons of Ee > 0.6 and 2 MeV according to GOES-8 and GOES-10 satellites data during the storm on 10–11 August 2000 are shown. In the upper part of the figure ACE interplanetary data (IMF B_z, solar wind velocity and density, AL-index, Dst-variation) are given.

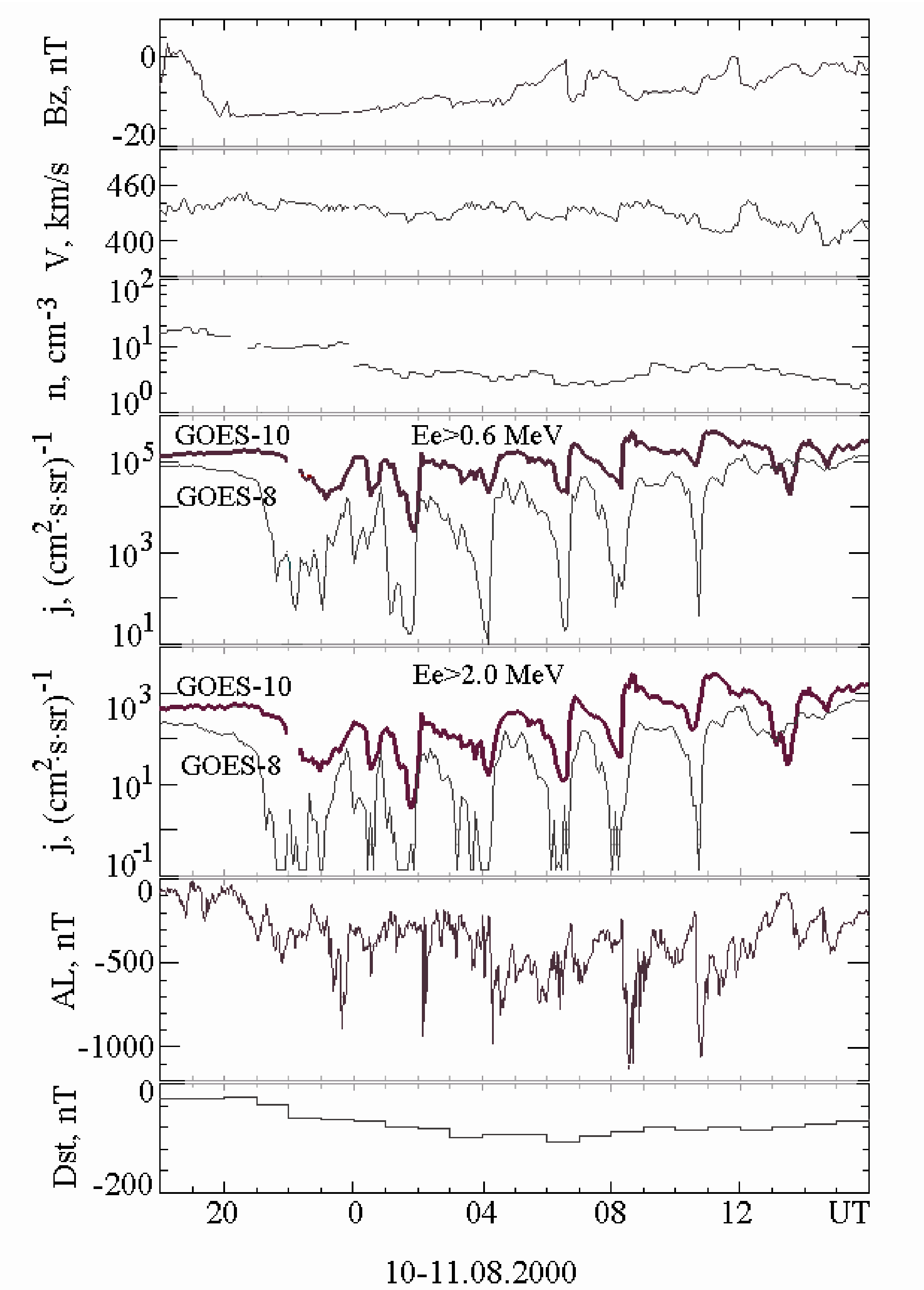

Fig. 6. The >0.6 MeV and 2.0 MeV electron intensity variation recorded on the GOES-8 and 10 geosynchronous satellites. Also shown the ACE interplanetary data (IMF Bz, solar wind velocity and density), AL-index, and Dst [Tverskaya, 2001].

Quasiperiodical electron intensity variations could be clearly seen for both satellites. Period is ~ 2.5 hours. B_z component of interplanetary magnetic field was negative for ~ 24 hours. The solar wind velocity varied a little around 450 km/s. The solar wind density (and also fluxes of interplanetary electrons and protons, not shown) slightly changed, but without the periodicity like relativistic electron fluxes have. The provisional AL-index data show good one-to-one correspondence. As it follows from the figure quasiperiodical electron intensity variations occur continuously at the storm main and recovery phase. We have chosen the storm with moderate amplitude ($|D_{st}|_{max}$ ~ 100 nT) to illustrate the qusiperiodical injections. During the storms with $|D_{st}|_{max}$ < 100 nT AL-index still realistically reflects the substorm disturbance dynamics, because westward electrojet does not shift during that storms to the latitudes lower than ground-based station latitudes, according to which data AL-index is measured [*Tverskaya and Khorosheva*, 1983; *Khorosheva,* 1986].

It's also important that in this storm the main phase developed slowly (~ 10 hours), and during that time a few substorm particle intensity increases have occured with a period ~ 2 hours. In [*Huang et al,* 2003] authors have studied quasiperiodical tens-hundreds keV proton and electron intensity increases on geosynchronous orbit (so-called "sawtooth injections") during three strong magnetic storms ($|Dst|_{max}$ = 358, 207 and 192 nT). During the storm on 25 September 1998 ($|Dst|_{max}$ = 207 nT) IMF B_z was negative between 01:03 and 15:14 UT. Authors identified the start of sawtooth injection at 06:28 UT when AL-peak coincides with the beginning of particle intensity increase on LANL satellite. Apparently from LANL data sawtooth injections started at least at ~ 04:30 UT. At that time westward electrojet center has moved probably to the middle latitudes (according to the formula defining the dependency of its location from Dst-variation amplitude [*Tverskaya*, 1986; *Feldshtei*n, 1993], in that case it reached ~ 57° of invariant latitude), that's why AL-index does not have a peak corresponding to this injection. Thus within this storm sawtooth injection occurred during the whole time when B_z had been negative, including the main phase of the storm. Peculiarities of sawtooth injection during the storm on 4–5 October 2000 we will discuss in the next section.

4. Long-period geomagnetic variations and geomagnetic storm structure

As it was shown in [Tverskaya and Khorosheva, 1974] during some strong magnetic storms global quasiperiodical disturbances of very high amplitude develop. Disturbances occur on all latitudes from the pole to the equator. Amplitude is maximal in polar caps and on sunlight cap may exceed 1000 nT. Main oscillation periods – 1–2 hours. Apparently these disturbances could be related to DP2 variations. Auroral region at that time behaves relatively quiet: AL-index decreases from ~ 1500 nT (substorm developing with SSC) to 200–700 nT. Amplitude of disturbances in polar cap becomes comparable (Figure 2a) or even of several times higher amplitude in auroral region (Figure 4a). Described above quasiperiodical variations are most evident on the certain stage of the storm: between its initial and main phases. On the graph Dst-variation forms the "steps" (Figures 2a and 4a). At the same time K_p-index increases or at least remains at the same basic level, that it reaches during the substorm, developing with SSC. This proves the dominating contribution of DP2-variations into mid-latitude disturbances of that phase of the storm. Let us note that DP2-variations do well correlate with B_z component of IMF variations [*Nishida*, 1968].

So called "sawtooth" particle injections on geostationary orbit [*Tverskaya, 2001; Tverskaya and Krasotkin, 2002; Reeves et al, 2002; Huang et al, 2003*] are substorm injections. That was obviously demonstrated in [*Reeves et al, 2002*] on the basis of multipoint spacecraft and ground-based observations. It occurs that sawtooth energetic electron and proton flux increasing is accompanied with plasma particle injections, magnetic field dipolarization and auroral substorm signature.

Quasiperiodical substorm injections also occurred in deeper magnetospheric regions. According to data of simultaneous measurements on 3 GPS-satellites 3 consecutive (with the interval of 2–3 hours) hundreds keV electron injections at L = 4.2–4.5 have been registered [*Li et al, 1999*] as the result of quasiperiodical substorms developed with prolonged negative B_z IMF component [Tverskaya, 2000].

In [*Huang et al, 2003*] sawtooth injections during October 4–5, 2000 storm were analyzed. The data are given until 24:00 UT October 4. However B_z was still negative on October 5 and reached –30 nT to 07:00 UT. Later on fast reorientation of B_z to the North has happened. In [*Reeves et al, 2002*] the data on geostationary observations of protons of energies 75–400 keV for the whole storm are given. It is clearly seen that on October 5 sawtooth injections also took place, but their period changed essentially from ~ 2 hours at the time of 02–04 UT to ~1 hour at 04–07 UT. That confirms earlier obtained results [*Ivanov and Mikerina, 1973; Tverskaya and Khorosheva, 1975*] about period changing in substorm consistencies with B_z amplitude variation under prolonged southward IMF orientation.

We see that quasiperiodical substorms occurs at any stage of magnetic storm when B_z is being negative for long enough time.

5. Conclusions

During some strong magnetic storms giant global quasiperiodical disturbances of DP2-type develop. Amplitude of these DP2 is maximal in polar cap and in sunlight cap may reach 1000 nT.

Giant DP2 variations are evident on the certain stage of magnetic storm, that on Dst graph appears as the “step” between the initial and main storm phases.

Under persistent southward IMF orientation quasiperiodical substorm consequence develops. Most often periods of 2–3 hours occur. However the period may decrease when the amplitude of negative B_z increases. The origin of these substorms is unknown. We call them “self-excited” substorms emphasizing by that their inner-magnetospheric origin.

Global quasiperiodic magnetic field variations have sufficient influence on redistribution of inner and outer radiation belt particles. At geosynchronous altitudes quasiperiodical DP2 variations and substorms occur simultaneousely with energetic charged particle flux increase We have demonstrated the cases resonance acceleration of particles having the same magnetic drift period with magnetic variations. Fast inner radiation belt high-relativistic electron diffusion observed by Molniya-1 and Meteor satellites occurs also due to global quasiperiodical geomagnetic field variations.

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