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Evidence for energetic electron and ion dispersive microinjections in the Earth's magnetotail as far as 27 R_E

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Abstract. High energy and time resolution measurements of energetic electron and ion fluxes obtained by the DOK-2 experiment on board the Interball-tail satellite provide us the opportunity to study the short-lived (1–3 min), localized, and often periodic and dispersive flux increases within the plasma sheet. We have deliberately selected and studied two intervals corresponding to the dawn and dusk magnetotail flanks. Dispersive electron (ion) bursts in the dawn side (dusk side) are observed from L=7 to L=27. These bursts, having an individual entity, are termed microinjections and are observed in radial distances greater than those predicted by the "injection boundary model." In this paper we suggest that the dispersive fluxes at widely separated radial distances are produced by multiple pulsating isospectrum surfaces ordered in succession. At the inner edge of the plasma sheet, the isospectrum surface is considered by Sarafopoulos (2002) as a meandering injection boundary. Roughly, we estimate that the wavelength for an oscillating isospectrum surface is $\sim 7 R_E$. A newly-injected population can coexist with the population from another injection center. These electron-ion drifts probably lead to the formation of the profound dawn-dusk species dependent asymmetry of energetic particles within the plasma sheet.

Key words. Magnetospheric physics (plasma sheet; energetic particles, precipitating; MHD waves and instabilities)

1 Introduction

Quasi-periodic dispersive flux increases of energetic electrons with 4-min periods are identified in the morning sector of the inner plasma sheet by Sarafopoulos (2002), and are termed "microinjections" because they exhibit dispersive signatures like the classical substorm-associated injections. Sarafopoulos (2002) introduced the pulsating isospectrum surface as a meandering injection boundary near the Earth, and suggested that the dispersive fluxes are due to this surface. In this paper we observe the same mode of repetitive particle microinjections to extend radially from ~ 7 to $27 R_E$. These identified rhythmic particle drifts probably produce the energetic particle dawn-dusk asymmetry within the plasma sheet (Krimigis and Sarris, 1980; Sarafopoulos et al., 2001). Bursts with dispersive or dispersionless signatures seem to succeed one another and often in a periodic fashion. Each short-lived 1–3 min distinct burst seems to have its own individuality: Particles at once leave a space-limited region or a surface boundary and follow their own energy dependent trajectories. These "microinjections" may originate from widely separated "injection centers." At a given moment, distinct populations from different injection centers can coexist. We estimate in this case that a typical microinjection region has a size of less than $7 R_E$. We introduce the geometry of multiple pulsating isospectrum surfaces ordered in succession. This layered structure of plasma sheet may suffice to produce the repetitive dispersive fluxes observed at widely separated radial distances.

2 Observations

The Interball-tail probe was launched in a highly eccentric elliptical orbit with 62.8° inclination and $\sim 31 R_E$ apogee. The energetic particle measurements in this work were obtained from the DOK-2 instrument on board the Interball-tail spacecraft (Lutsenko et al., 1998) and specifically, from the detector pair that is constantly looking toward the antisolar direction. This fixed detector has full aperture angles 27° and 12.7° for electrons and ions, respectively, and can provide spectra composed of 56–57 energy channels. The accumulation time interval for each spectrum is variable from 1 to 1464 s, depending on the particles' intensity that is sufficient to provide a given statistical accuracy. The accumulation time can differ for the ion and electron detectors. The ion (electron) spectra range extends from ~ 27 to 821 keV (~ 27 to 426 keV). Therefore, we have a great opportunity to search for dispersive bursts that flow earthward in the plasma sheet.

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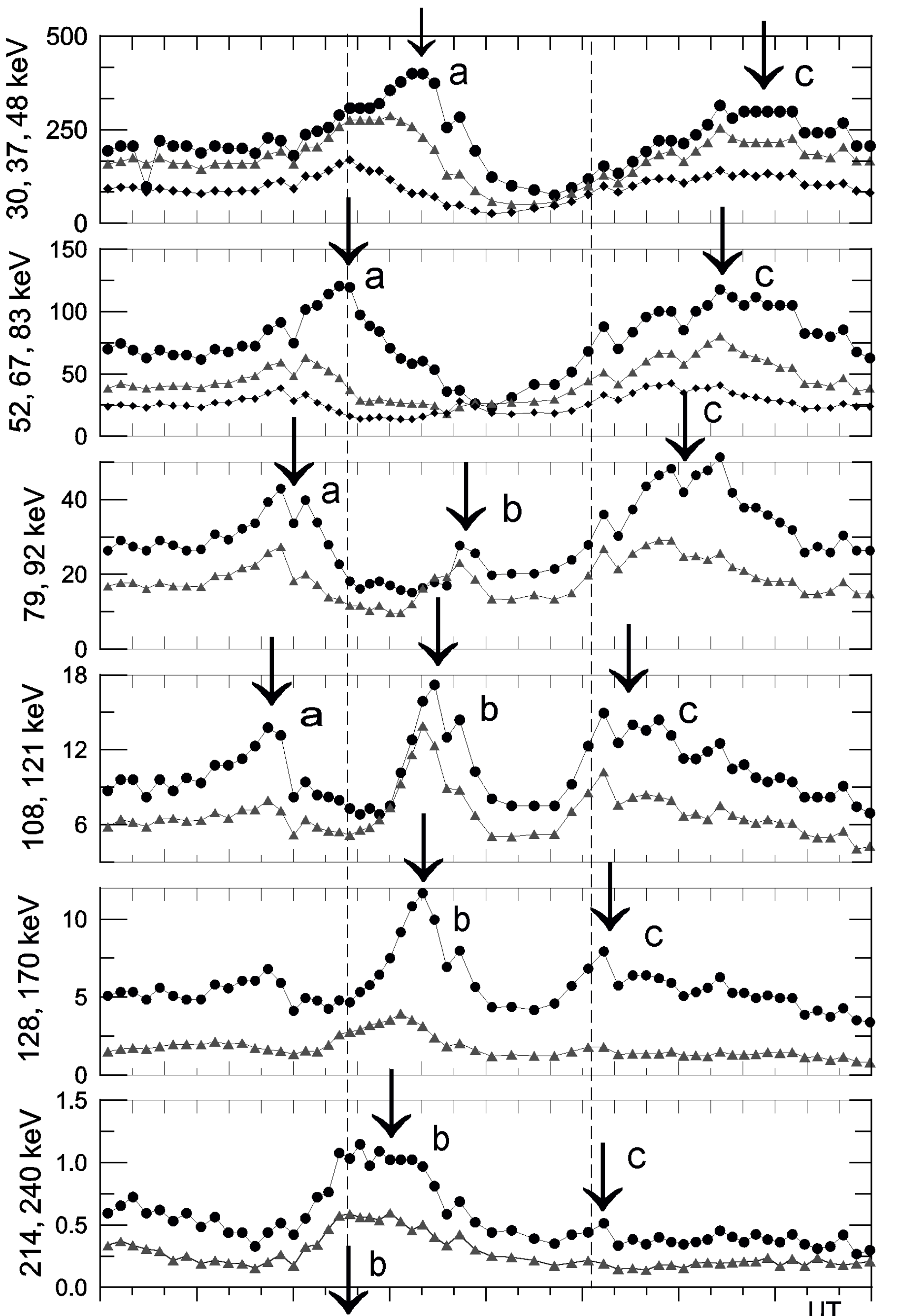

Fig. 1. From top panel downward differential electron fluxes for progressively higher energy channels are shown. The injected electrons in each of the three flux increases are seen first at higher energies.

2.1 Dawn side electron dispersive microinjections

We display, from top to bottom in Fig. 1, electron differential fluxes at progressively higher energy channels. Three distinct, successive, short-lived and dispersive electron flux increases seem to originate from different "microinjection centers" and drift dawnward. At 08:46 UT populations from the flux increase marked as "a" and "b" and coexist. The lifetime for each structure may be longer than the individual burst duration. The initial activations and subsequent microinjections take place westward of the spacecraft. Each burst does not cover the same energy range, although it is observed at the same site $(X, Y, Z)_{\mathrm{GSM}} = (-5.7, -9.7, -2)R_E$, at L=11.4. The satellite position is shown in Fig. 2, which shows the projected Interball trajectory over the XY_{GSM} plane from 21:00 UT of Day 285 to 13:00 UT of Day 286, 1996. During this period, Interball moved from $(X, Y, Z)_{\mathrm{GSM}} = (-14.6, -15.7, -0.3)$ to $(-0.38, -5.5, -4.2)R_E$ within the

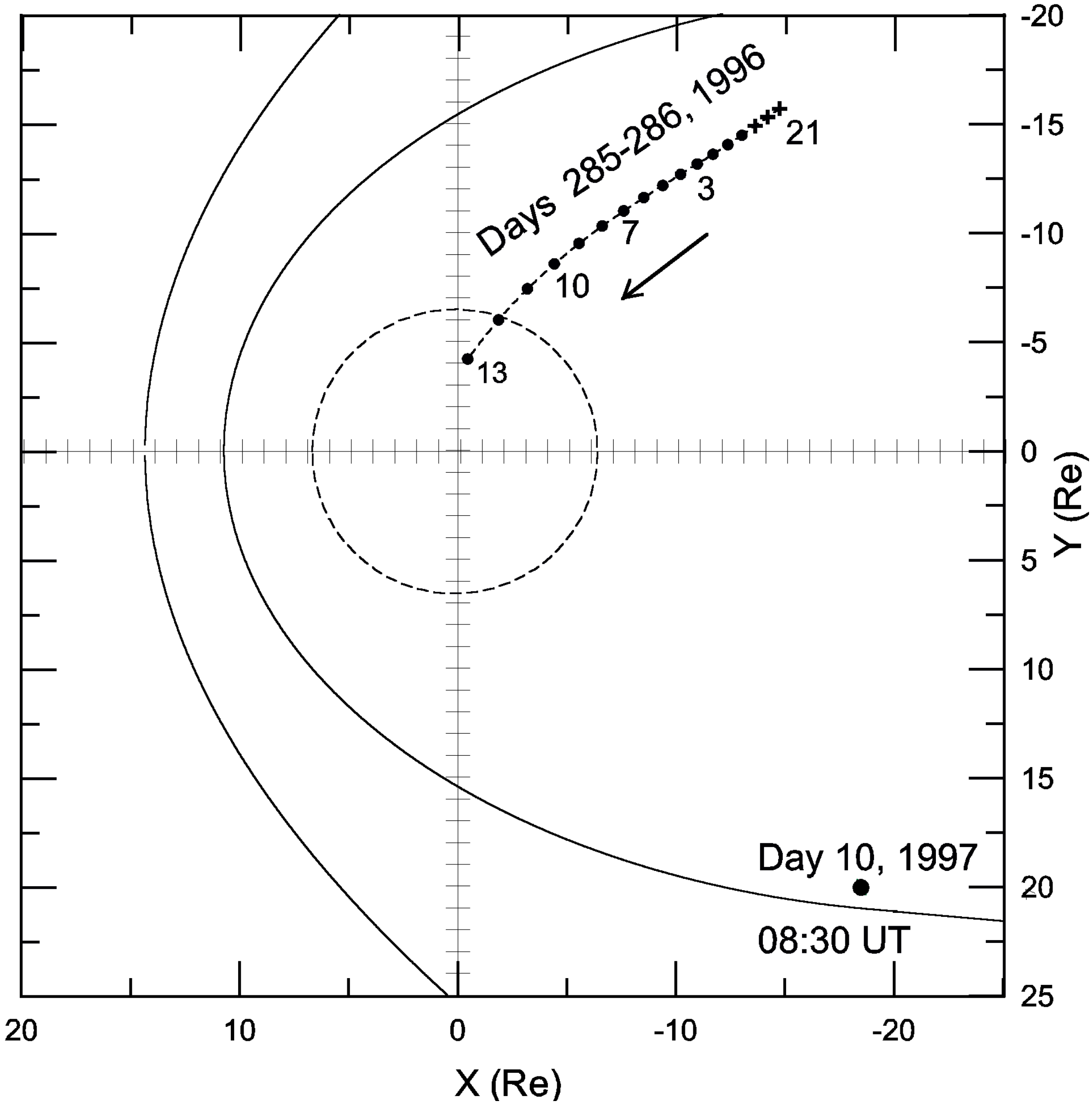

Fig. 2. Interball trajectory projected on the XY_{GSM} plane and corresponding to the interval from 21:00 UT of Day 285 to 13:00 UT of Day 286, 1996, and Interball position at 08:30 UT of Day 10, 1997. Trajectory is divided by one symbol per hour. Average bow shock and magnetopause positions, as well as the GEO orbit (dashed line), are shown.

dusk side plasma sheet, and one symbol per hour is used along the trajectory.

Another event closer to the Earth, at L=7.5, is shown in Fig. 3 that provides strong evidence that an old population can co-exist with a newly-injected one. The first injected population at 11:07 UT (burst "a" along the 202 keV electron flux trace, bottom panel), drifts dawnward and mixes with that from another microinjection activated after ∼10 min. The latter flux increase "c" is locally energized at 11:17 UT and displays dispersionless character. Thus, it seems that two distinct and successive injection centers a few R_E apart are probed. A minor flux increase between the "a" and "c" fluxes is also observed. Therefore, in this event, as well as in that of Fig. 1, a repetition cycle of 5 min is apparent. Moreover, between these two events, two additional periodic events are shown in the past by Sarafopoulos (2002), which display in all 13 dispersive flux increases a ∼4 min periodicity. During the same day, closer than L=7.5 periodic (although dispersionless) flux increases are also detected (not shown here). Importantly, we detect dispersive bursts even earlier during this day. Figure 4 shows a dispersive electron flux corresponding to L=18. The major peak flux is first seen at the bottom panel for the highest energy electron channel and progressively, it is shifted to gradually lower energies (upward panels). This dawnward drift may accumulate negative energetic population to the dawn side plasma sheet. Moreover, the major peak flux of ∼250 keV (bottom panel) occurs with a weak flux increase of ∼30 keV (top panel). In parallel with the dispersive feature, a dispersionless population is also present and is probably due to the source extent along the Y-axis. A similar episode to that of Fig. 4 was observed at ∼21:40 UT of Day 285 and L=21 (not shown here).

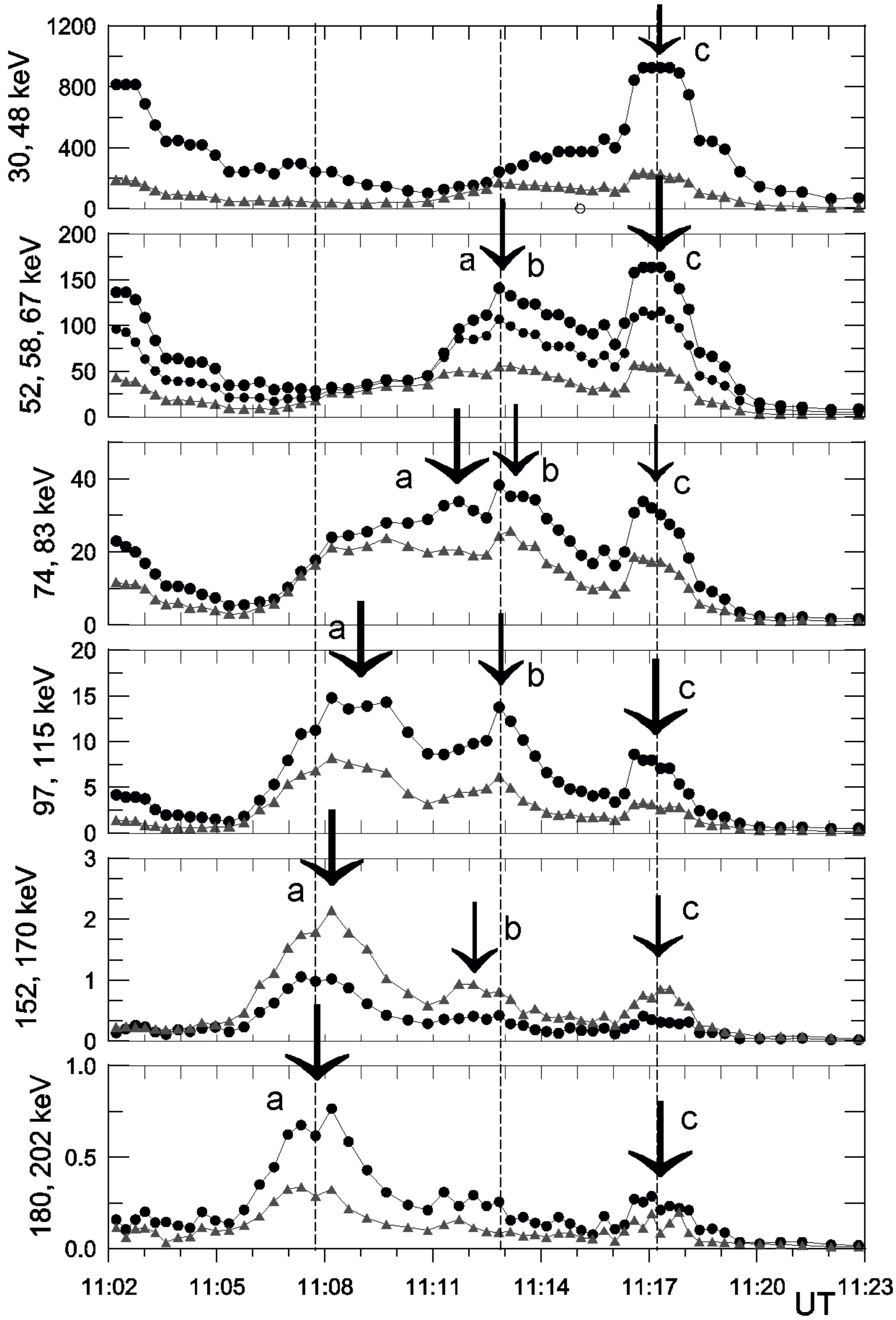

Fig. 3. Similar format as in Fig. 1. The flux c shows a dispersionless character.

2.2 Dusk side ion dispersion signatures

We observe dispersive ion flux increases (instead of electron) in the dusk sector plasma sheet. Two ion dispersive flux increases observed on 10 January 1997, are shown in Fig. 5. They occurred when Interball was located at $(X, Y, Z)_{\mathrm{GSM}} \cong (-18.5, 20.3, 1) R_E$, at L=27.4. Nevertheless, in contrast to the large radial distance, the drift mechanism seems to work, accumulating energetic ions to the dusk side plasma sheet. The more energetic ions drift faster and are seen prior than the lower energy particles. In Fig. 5 the dispersive structures are marked with arrows and their duration is ~1 min. The ion fluxes occur at the central plasma sheet, when the local magnetic field B_x is less than 5 nT (not shown here), and the local lobe magnetic field level is ~30 nT. No abrupt B_x transition accompanies the fluxes. Therefore, we believe that these dispersive signatures are probably due to westward ion drifts (and not due to a velocity selection effect at the plasma sheet boundary layer).

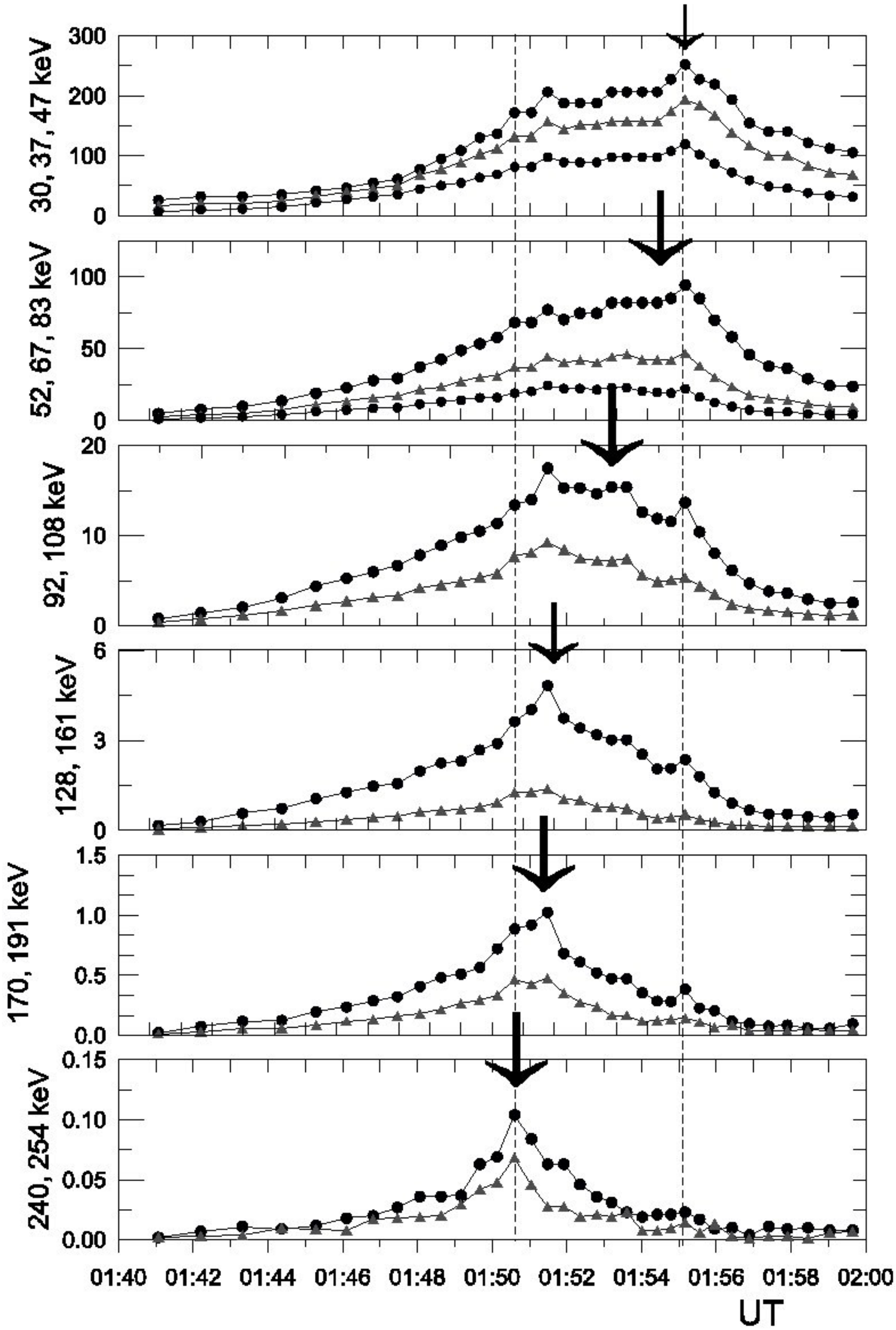

Fig. 4. Similar format as in Fig. 1. Dispersive electron flux increase observed at L=21.

3 Discussion

3.1 Isospectrum surfaces ordered in succession

In the original formulated models of classical injections, McIlwain (1974) postulated the existence of a sharp boundary located near the geosynchronous orbit (GEO), behind which an energization mechanism causes the rapid accumulation of hot plasma. At the injection time, particles of all energies leave the regions at and behind the boundary, and follow drift orbits. Sarafopoulos (2002) considered that "the injection boundary," at times, forms meanderings. Behind this wavy surface, the region is assumed to be replete with higher fluxes of energetic particles (shaded region in his Fig. 4). This surface was termed an isospectrum surface and, like the injection boundary (see Mauk and Meng, 1983), was assumed that (a) it is the same for particles of all energies, and that (b) it spirals outward across contours of constant

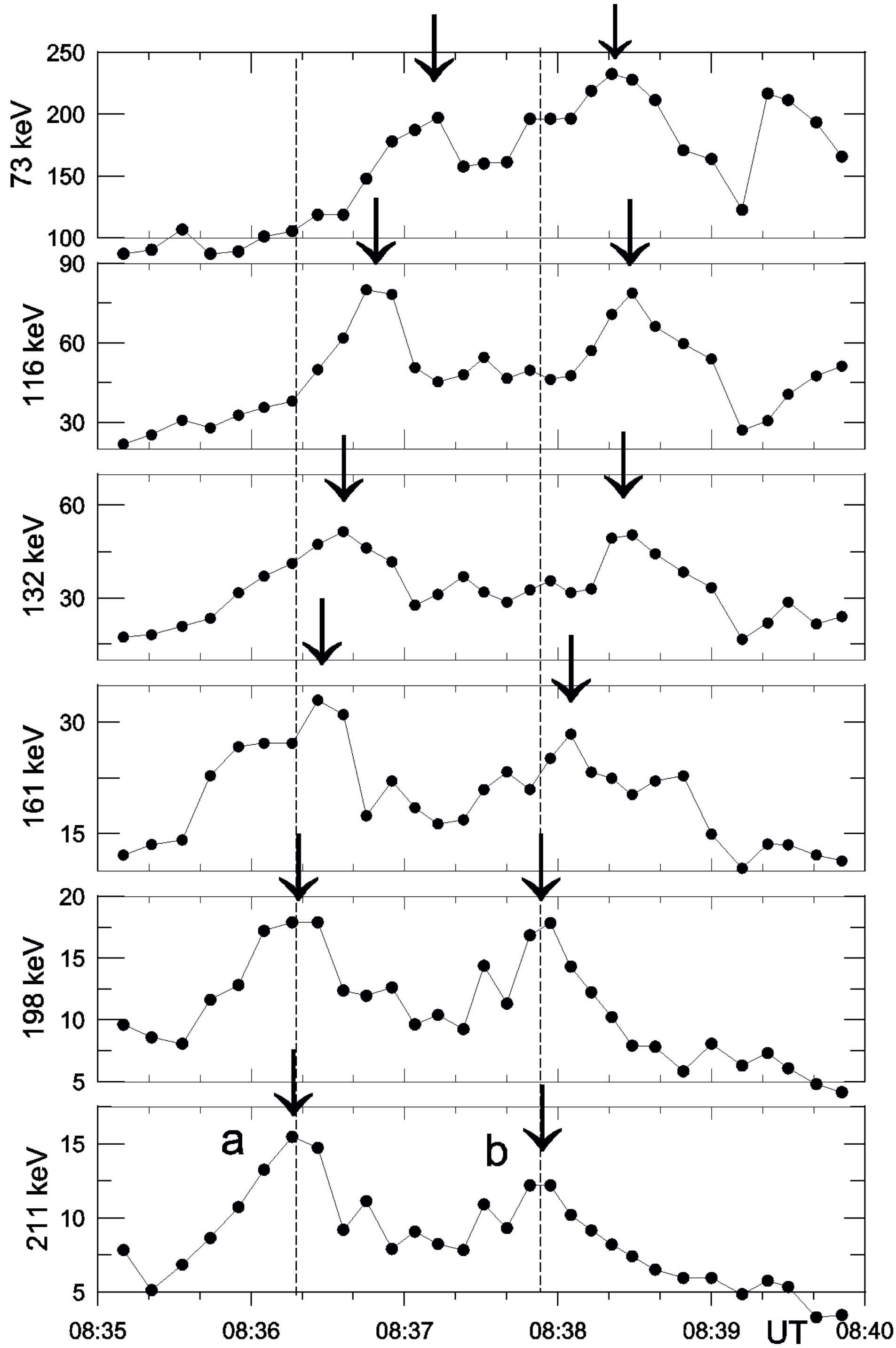

Fig. 5. Similar format as in Fig. 1, but for two ion dispersive flux increases.

magnetic field magnitude, as well as across contours of constant radial distances. In this work we have presented dispersive electron fluxes from L=7 to 21 in the dawn side, and dispersive ion fluxes at L=27 in dusk side. It seems that successive isospectrum surfaces are formed in the whole near-Earth plasma sheet. In Fig. 6, we indicatively show three successive isospectrum surfaces with an outward gradient of energetic particles. Energetic electrons that leave regions A, B, and C of the innermost surface and follow the three drift trajectories shown with thick-dashed and circular lines, create dispersive fluxes at different radial distances. Importantly, energetic electrons leaving the protrusions B or B′ that correspond to different isospectrum surfaces will create dispersive fluxes at different spacecraft (S/C) positions marked

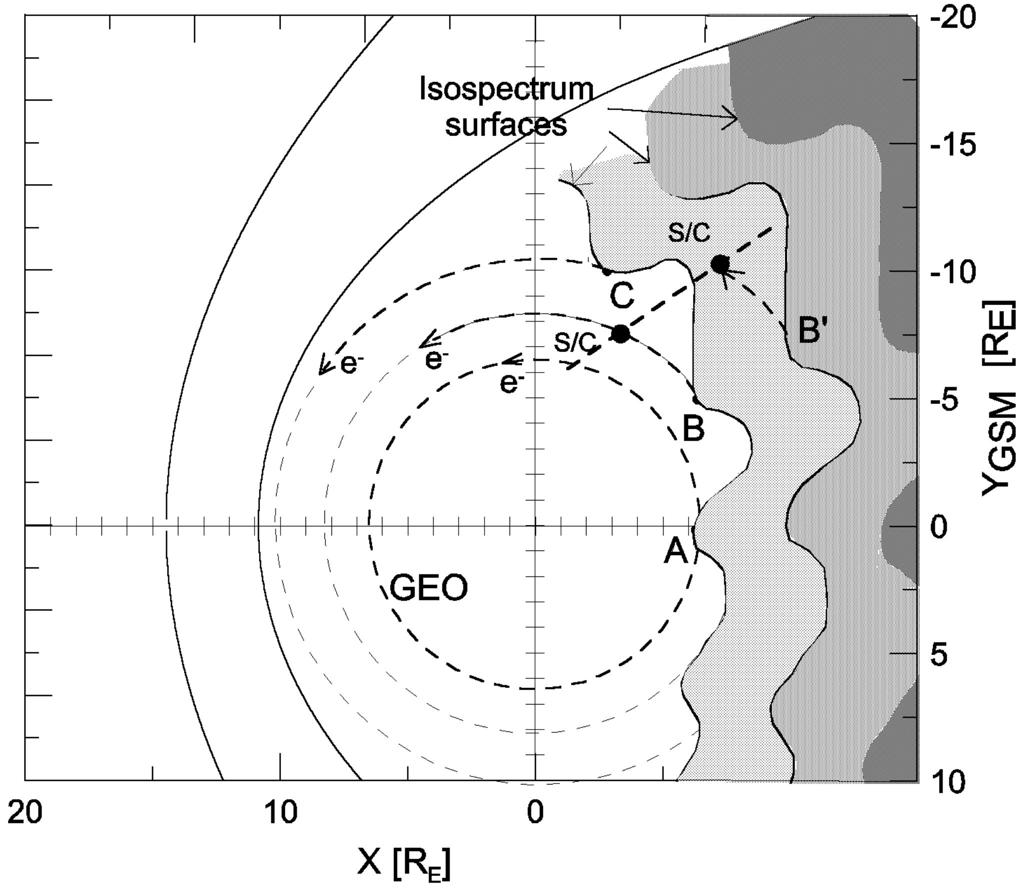

Fig. 6. Schematic showing three successive and meandering isospectrum surfaces. The darkest area corresponds to the densest populated region. The injected electrons from the earthward protrusions A, B, C and B′ produce dispersive fluxes at increasing radial distances. The bow shock and magnetopause surfaces (solid lines), the GEO (thick- dashed line) orbit and the satellite (S/C) trajectory are shown.

with solid dots. The energy dependent eastward drift produces the recurrent dispersive electron bursts at Interball. If the satellite were positioned at B, then dispersionless pulsations would be anticipated, like the burst "c" in Fig. 3. Therefore, pulsating isospectrum surfaces ordered in succession may suffice to produce the rhythmic character of detected dispersive fluxes at widely separated radial distances.

3.2 Wavelength for a pulsating isospectrum surface

At ~11:08 UT of Day 286, 1996, the burst "a" along the 202 keV electron flux trace (Fig. 3, bottom panel) is observed ~5 min earlier than the 52 keV electron flux increase (Fig. 3, second panel). If we take into account the spacecraft radial distance L=7.7, the magnetopause standoff distance to be $10R_E$, and the drift periods for the two above mentioned energy channels, then a rough estimate concerning the injection site, for the burst "a," will locate it $\sim 3.5R_E$ westward of the spacecraft. Additionally, if the spacecraft is assumed equally distanced from the two successive plasma sheet earthward protrusions (Regions B and C in Fig. 6), then the oscillating isospectrum surface will have a $\sim 7R_E$ wavelength.

3.3 Dawn-dusk asymmetry of energetic particles

The mechanism producing the dawn-dusk asymmetry of energetic particles, which was recently studied by Sarafopoulos et al. (2001) and earlier by Krimigis and Sarris (1980), is directly observable in this work through distinct examples demonstrating electron dawnward and ion duskward drifts at large radial distances in the nightside magnetosphere. The repetitive and dispersive (or dispersionless) flux increases in this work, as well as the periodic events presented by Sarafopoulos (2002), are probably associated with Pc5 standing waves commonly observed over the plasma sheet boundary layer (Sarafopoulos and Sarris, 1991), or the wavy modulated lobe magnetic field structure (Sarafopoulos, 1995), or the low-latitude boundary layer waves (Sarafopoulos, 1993). We speculate that the whole near-Earth magnetosphere often vibrates in the Pc5 mode, and consequently, successive isospectrum surfaces are developed, which on the earthward edge of the plasma sheet forms a pulsating injection boundary. The latter may be a fundamental element in a process leading to the growth of an instability that eventually triggers a substorm. A pulsating injection boundary probably produces the nine-peaked proton fluxes accompanying a substorm-associated injection in the case studied by Belian et al. (1984).

3.4 Dispersive fluxes and the "Injection boundary model"

From 21:00 UT of Day 285 to 12:00 UT of Day 286, 1996, the K_p index successively takes the values 2-, 2, 3+, 2+, and 3. Mauk and McIlwain (1974) have formulated the injection boundary as a function of K_p. They obtained the result $R_b = (122 - 10\ K_p)$/(LT–7.3), where R_b is the injection boundary radius in R_E at a given local time (LT) for a given K_p. This equation traces a spiral and is only valid for the premidnight region to ∼01:00 LT (which should be expressed as 25 LT in the above equation). This surface was assumed as a stationary boundary, tailward of which all electrons and protons are energized together at the same time (Mauk and Meng, 1983; Lopez et al., 1990), producing dispersionless signatures. Certainly, in this work we do not present substorm associated injections; instead we show short-lived dispersive flux increases that they occur, at times, at radial distances larger than those that the above model predicts. In any case, dispersive fluxes behind the injection boundary remain unexplained by this stationary model. Dispersionless substorm onsets frequently occur around midnight at local times (see the statistics performed by Friedel et al., 1996), which seems to indicate that the satellite must be very near or within the acceleration source region, in order to see different energy particles before they drift apart.

3.5 Dispersive fluxes and BBFs.

Throughout the interval 09:55–11:25 UT of Day 286, 1996, quasi-periodic and dispersive energetic electron flux increases are shown in Figs. 1 and 3, and in the past by Sarafopoulos (2002). This interval is discussed below in the context of Bursty Bulk Flow events (BBFs). We use the CORAL plasma experiment with 2-min resolution of plasma moments due to a 2-min spin of Interball. The conclusion is that our dispersive fluxes are not associated with BBFs. BBFs are fast flow plasma samples concentrated in 10-min timescale intervals of plasma sheet flow enhancements (Angelopoulos et al., 1994 and references therein). Angelopoulos et al. (1994) are defined BBFs as continuous ion flow events with magnitude above 100 km/s, while during the BBF event low flow (Vi< 100 km/s) samples do not intervene. In contrast, our dispersive flux increases occur with plasma velocity almost continuously lower than the level of 100 km/s, or the velocity slightly exceeds this level for one or two samples. Additionally, they observed that earthward BBFs are more frequently close to midnight and away from Earth, up to a distance of $\sim 19 R_E$, whereas our observations occur at $Y_{\rm GSM} > -5\, R_E$ and near the Earth. Another significant element is that the studied dispersive fluxes occur with very low geomagnetic activity (see Fig. 5 in paper by Sarafopoulos, 2002), whereas the BBFs are positively correlated with the AE index.

4 Conclusions

Duskward (dawnward) ion (electron) drifts were detected as far as $\sim 27 R_E (21 R_E)$ from the Earth. Therefore, the propagation paths of energetic particles, which probably produce the energetic particle dawn-dusk asymmetry (see Sarafopoulos et al., 2001), are better understood. Although injections are commonly observed at $6.6 R_E$, the exhibited "microinjections," in other words, the short-lived and dispersive flux increases, are seen up to L=27. We introduce the geometry of successive and pulsating isospectrum surfaces in the near-Earth plasma sheet, which probably produce the detected dispersive fluxes. We estimate that the oscillating isospectrum surface roughly has a wavelength of $\sim 7 R_E$.

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