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Spatial distribution of upstream magnetospheric ≥50 keV ions

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Abstract. We present for the first time a statistical study of ≥50 keV ion events of a magnetospheric origin upstream from Earth's bow shock. The statistical analysis of the 50–220 keV ion events observed by the IMP-8 spacecraft shows: (1) a dawn–dusk asymmetry in ion distributions, with most events and lower intensities upstream from the quasi-parallel pre-dawn side (4 LT–6 LT) of the bow shock, (2) highest ion fluxes upstream from the nose/dusk side of the bow shock under an almost radial interplanetary magnetic field (IMF) configuration, and (3) a positive correlation of the ion intensities with the solar wind speed and the index of geomagnetic index *Kp*, with an average solar wind speed as high as 620 km s^{-1} and values of the index $Kp > 2$. The statistical results are consistent with (1) preferential leakage of ∼50 keV magnetospheric ions from the dusk magnetopause, (2) nearly scatter free motion of ∼50 keV ions within the magnetosheath, and (3) final escape of magnetospheric ions from the quasi-parallel dawn side of the bow shock. An additional statistical analysis of higher energy (290–500 keV) upstream ion events also shows a dawn–dusk asymmetry in the occurrence frequency of these events, with the occurrence frequency ranging between ∼16%–∼34% in the upstream region.

Key words. Interplanetary physics (energetic particles; planetary bow shocks).

Introduction

Energetic (E ≥ 30 keV) ions display a complicated picture upstream and downstream from Earth's bow shock, and a lot of work has been done to define their origin. Since the bow shock is the boundary between the interplanetary space and the geomagnetic complex, both bow shock accelerated ions and ions of a magnetospheric origin are expected to be present upstream from the bow shock under certain conditions. Indeed, both sources, leakage from the magnetosphere and bow shock acceleration, have been confirmed as providing the region upstream from the bow shock with energetic ions (Anagnostopoulos *et al.*, 1998, 1999a, and references therein).

The contribution of each of the two ion sources, i.e. bow shock acceleration versus leakage from the magnetosphere, has been a hotly debated topic in the scientific community for about two decades (Anagnostopoulos, 1994; Anagnostopoulos *et al.*, 1998, 1999a). Recently, we presented results from an exhaustive statistical analysis of energetic ion and electron observations obtained by the IMP-8 spacecraft upstream from the Earth's bow shock, during a 6-y period, that provides strong evidence that the magnetosphere is responsible for the generation of the vast majority (>80%) of the energetic (E ≥ 50 keV) ion events (Anagnostopoulos *et al.*, 1999a).

In this study we present the results of a statistical study of upstream ≥50 keV ion events, under special conditions suggesting a magnetospheric origin for these events, so that we can determine some important characteristics of the upstream magnetospheric ions. The implications of this study to the research of upstream energetic ions are: (1) it provides information about the spatial distribution of the magnetospheric component of the upstream ion population for the first time, (2) it allows us to draw important conclusions concerning the leakage process of magnetospheric ions, and (3) it provides a broader observational basis to the general research on the origin of the upstream ion events.

Statistical survey

We analyzed observations obtained by the IMP-8 spacecraft to examine the spatial distribution of

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≥50 keV ion events of magnetospheric origin upstream from the Earth's bow shock. The IMP-8 has a nearly circular orbit around the Earth, and, therefore, upstream ion events were included in our statistical analysis at all local times. We examined two different event samples.

Upstream magnetospheric ions in the energy range 50–220 keV

In Fig. 1 we show observations of upstream magnetospheric 50–220 keV ion events as detected by the L1 channel of the Energetic Particles Experiment (EPE) of National Oceanic and Atmospheric Administratation (NOAA) on board the IMP-8 spacecraft. More explicitly, Fig. 1 displays the positions in the XY_{SE} plane at which upstream magnetospheric 50–220 keV (L1) ion events were detected between May 1974–August 1976.

The statistical sample of upstream ion events of Fig. 1 is unique in the sense that we demanded that they should obey very strict criteria, which confirm a magnetospheric origin for the energetic ions. The restrictions we demanded for selecting the L1 ion event sample were the following: (1) presence of an ion population with energy spectrum extending to high energies (≥290 keV), and (2) simultaneous detection of intense (≥1e $cm^{-2}s^{-1}sr^{-1}$) relativistic (≥220 keV) electron bursts; the ≥220 keV electron and the ≥290 keV ion observations were obtained by the Charge Particle Measurement Experiment (CPME) of Johns Hopkins University (JHU) Applied Physics Laboratory (APL) on board IMP-8.

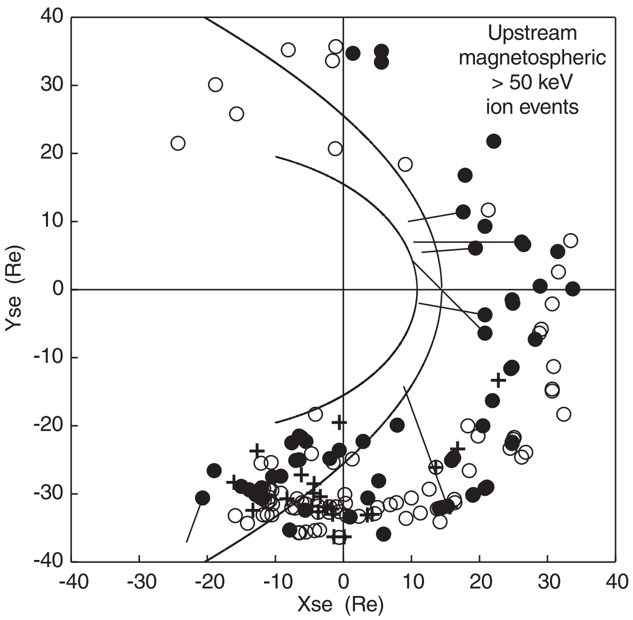

Fig. 1. Scatter plots of locations of upstream magnetospheric ion bursts. Bursts of low (*crosses*), moderate (*open circles*), and high (*solid circles*) intensities are indicated. The *straight lines* indicate the direction of the IMF and the connection point with the bow shock in the case of bursts with the highest intensities. The statistical results suggest that the magnetospheric ~50 keV ions escape preferentially from the dawn bow shock

Since the generation of relativistic electron bursts in the region upstream from the bow shock cannot be explained by shock acceleration (Scholer *et al.*, 1981), whereas relativistic (≥220 keV) electrons and high energy (≥290 keV) ions are often accelerated within the magnetosphere and propagate up to interplanetary space (Sarris *et al.*, 1978; Anagnostopoulos *et al.*, 1986, 1998, 1999a), our event selective criteria (1st: presence of intense relativistic electron bursts, 2nd: presence of ions with energy spectrum extending to ≥290 keV) strongly suggest that leakage of magnetospheric energetic charged particles upstream from the bow shock was in process at the times examined. By applying the two criteria referred to, we selected 166 events over a period of 27 months, that is a small percentage (Anagnostopoulos *et al.*, 1999a) of upstream magnetospheric ion events during the whole time interval considered. Thus, we infer that our analysis concerns a special kind of magnetospheric upstream ion events.

Figure 1 displays the positions of ion bursts with maximum differential intensities in the following ranges: $j \leq 25$ p $cm^{-2}s^{-1}sr^{-1}keV^{-1}$ (crosses), $25 \leq j \leq 125$ p cm^{-2} s^{-1} sr^{-1} keV^{-1} (open circles), and $j \geq 125$ p cm^{-2} s^{-1} sr^{-1} keV^{-1} (solid circles). Also in Fig. 1 straight lines indicate the direction of the IMF at the times of observation of the most intense bursts together with the connection points of these bursts with the bow shock. From Fig. 1 we see that: (a) the large majority of ion bursts were detected upstream from the dawn (quasi-parallel) side of the bow shock, (b) the highest ion fluxes were detected during times of an almost radial IMF, upstream from the nose and the dusk side of the bow shock, and (c) when ion events of higher intensities are considered, the distribution of ion bursts extends toward dusk (open and solid circles).

The histogram of Fig. 2a displays the number of the L1 ion bursts of Fig. 1 as a function of local time. From Fig. 2a we see that most bursts were observed at predawn local times, in the range between 4 LT–6 LT.

Figure 3 displays a scatter plot of the intensities J of the upstream magnetospheric 50–220 keV ion events as a function of the hourly averaged solar wind speed V, and the distribution of events as a function of the same parameter V (inset in the figure). From Fig. 3 we see that there is a positive correlation between the ion intensities J and the solar wind speed V ($r = 0.46$) at the times of the upstream magnetospheric 50–220 keV ion events. Furthermore, we see that the upstream magnetospheric ion events were observed during times of high-speed solar wind streams; the average solar wind speed was evaluated to be as high as $\langle V \rangle \cong 620$ km s^{-1} in the time intervals considered.

Figure 4 displays a scatter plot of the upstream L1 ion intensities J and of the distribution of the L1 ion events (inset in the figure) as a function of the index of geomagnetic activity Kp. We see that there is a small ($r = 0.29$) trend for the detection of increasing upstream L1 ion intensities J as the index of geomagnetic

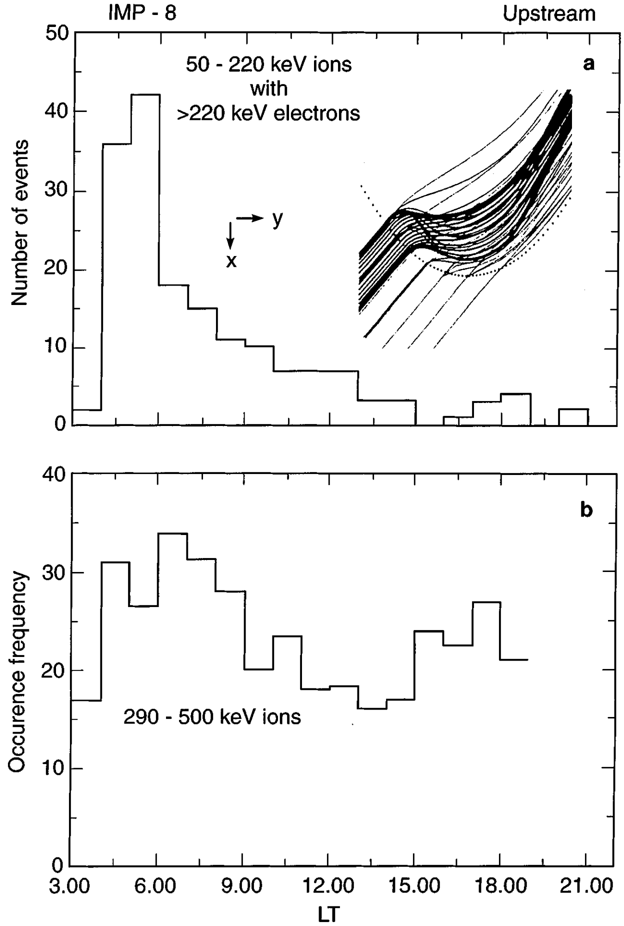

Fig. 2a, b. Spatial distribution of magnetospheric upstream ion events. The statistic **a** is consistent with nearly scatter free motion of ~50 keV ions within the magnetosheath and final leakage preferentially at early local times (the *inset* was adapted from Fig. 1c of Luhmann *et al.*, 1984). High-energy ions probably escape from a broader region of the bow shock

activity *Kp* increases, and that the values of the index *Kp* are generally high, with most of the events observed during times with $Kp \geq 2$.

High energy (290–500 keV) ions

In Fig. 2b we present results of a statistical analysis of high-energy ion measurements obtained by the IMP-8 spacecraft upstream from the Earth's bow shock. In particular, Fig. 2b shows the occurrence frequency of 290–500 keV ion events observed by the P1 channel of the CPME/APL experiment between 1982–1988, as a function of the local time.

In our statistical analysis we worked as follows. We defined as a P1 ion «event» each P1 ion flux increase, for which the ratio $n = R/R_b$ of the 5.5 min averaged counting rate R over the lowest value R_b of the counting rate within a 6-h interval (R_b was considered to be the solar background level) exceeded a value varying with the solar background counting rate level (Karanikola *et al.*, 1999). Furthermore, we defined as «occurrence frequency» of the upstream P1 ions, the ratio $f = N_e/N$ of the number N_e of P1 ion events observed by IMP-8 in some space over the whole number N of 5.5 min intervals spent by the spacecraft in the same space (Karanikola *et al.*, 1999). Due to the large number of events examined ($\sim 7000 < N_{LT} < \sim 10\,000$ only in the

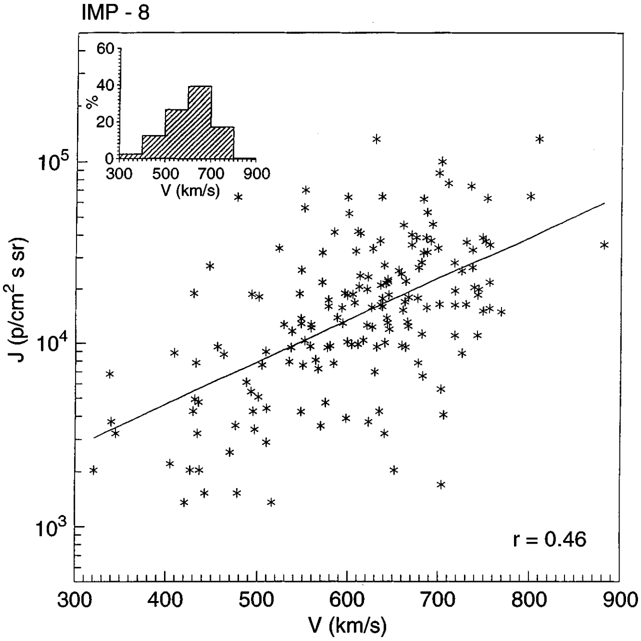

Fig. 3. Peak intensities of upstream 50–220 keV ion bursts with signature of magnetospheric origin (see text) versus solar wind speed. The ion observations were detected by the EPE/NOAA experiment on IMP-8 during a period of about two years (5/1974–8/1976). It is evident that more intense leakage of magnetospheric ions is observed when streams of high-speed solar wind reach the magnetosphere

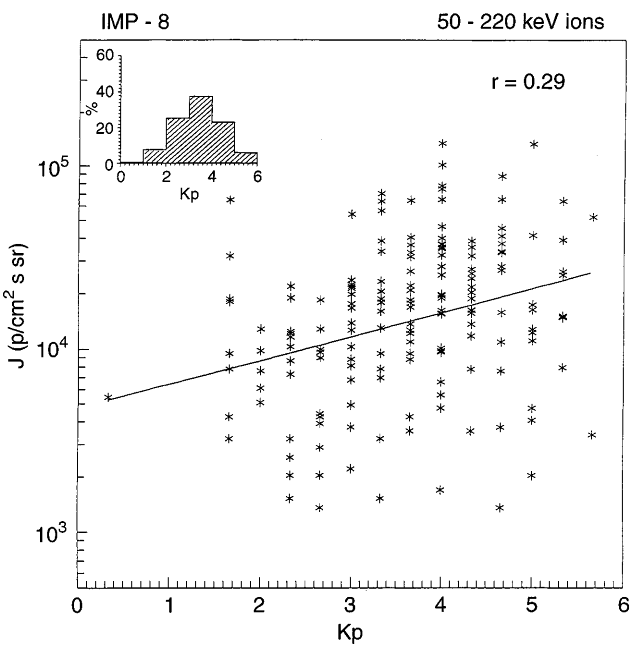

Fig. 4. The intensity of 50–220 keV ion events of magnetospheric origin as a function of the index of geomagnetic activity K_p. The high values of K_p found during the upstream events are consistent with the initial assumption of their magnetospheric origin

range of one hour), the upstream events were selected on the basis of the spacecraft position relative to a model bow shock.

From Fig. 2b we see that the values of the occurrence frequency of the 290–500 keV ions range from ~16% to ~34% in the upstream region, and that higher occurrence frequencies were detected at dawn, in the range between 4 LT and 9 LT, while a local maximum is also evident between 15 LT and 18 LT.

Summary and discussion

Although several models have been proposed in order to explain the ion observations upstream from the Earth's bow shock, we do not yet have a general consensus on the contribution of various physical processes, in particular bow shock acceleration versus leakage from the magnetosphere, in producing the upstream ≥30–50 keV ion population. For this reason, in this study we attempted to determine some important characteristics of the upstream magnetospheric ion population, under certain conditions which are generally accepted as confirming its (magnetospheric) origin. We performed two different statistical studies for the upstream magnetospheric ion population: one for ions in the intermediate energy range, between 50–220 keV, and a second one for ions of high (290–500 keV) energies.

Since the >300 keV upstream ion observations are in general consistent with a magnetospheric origin, and they are not consistent with bow shock acceleration (Sarris *et al.*, 1978; Scholer *et al.*, 1981; Anagnostopoulos, 1994; Anagnostopoulos *et al.*, 1986, 1998, 1999a), we can accept that the results of the statistical analysis of a very large sample of upstream 290–500 keV ion events, mostly concern magnetospheric 290–500 keV ions. In contrast since not only the magnetosphere, but also other sources (i.e. bow shock acceleration) contribute to the upstream ion population in the energy range 50–220 keV (Anagnostopoulos *et al.*, 1998), we selected a specific kind of upstream 50–220 keV ion events, which were observed under conditions strongly suggesting leakage of energetic particles from the magnetosphere. The statistical analysis of the selected events suggests that most of them were observed at times of high-speed solar streams ($\langle V\rangle \cong 620$ km s^{-1}) and intense geomagnetic activity, as indicated by the values of the index *Kp*, that is under conditions confirming the existence of a highly disturbed magnetosphere at those times (Garrett *et al.*, 1974; Kivelson and Russell, 1995).

1. The results obtained by the statistical analysis enable us to make conclusions for the paths of the magnetospheric ions leaking from the magnetopause and propagating within the magnetosheath. In particular, the appearance of a shifting in the occurrence frequency of the 50–220 keV ion events of higher intensities towards dusk, in combination with the appearance of the ion events of highest ion intensities upstream from the nose/dusk side of the bow shock at times of an almost radial IMF (Fig. 1), are consistent with preferential leakage of the magnetospheric 50–220 keV ions from the dusk magnetopause; preferential leakage of high-energy (≥50 keV) ions from the dusk magnetopause is a prediction of the leakage model of Takahashi and Iyemori (1989) and Paschalidis *et al.* (1994) and with the results of other observational studies (Sarris *et al.*, 1987; Paschalidis *et al.*, 1994; Karanikola *et al.*, 1999).

2. The detection of a strong dawn-dusk asymmetry in the occurrence frequency of ~50 keV upstream magnetospheric ions, with highest occurrence frequency during morning times, mostly between 4 LT and 6 LT (Fig. 2a), in combination with the previous conclusion (1), suggests that the magnetospheric ~50 keV ions, after their leakage from the magnetopause, are not usually strongly scattered by magnetosheath magnetic fluctuations, and that they eventually escape from the dawn side of the Earth's quasi-parallel bow shock.

According to the predictions of Luhmann *et al.* (1984) and the inset of Fig. 2a (adapted from Fig. 1c of Luhmann *et al.*, 1984), during a Parker spiral IMF configuration ($\varphi \cong 45°/135°$), energetic ions which leak from the dusk magnetopause and follow the sheath lines will escape from the dawn bow shock at local times ≅/ > 6 LT, i.e. a peak in the distribution of ion events it is expected a little later than 6 LT. This prediction is not consistent with the observational results of Fig. 2a. We believe that the shift in the distribution of 50–220 keV ion events of Fig. 2a towards earlier times (4–6 LT) is due to one of the selective criteria that we applied. Since, we demanded the existence of a high-intensity ($R_e \geq 1$ e cm^{-2} s^{-1} sr^{-1}) relativistic electron burst in order to select an upstream magnetospheric ion event, and the relativistic electrons show strong intensity gradients from the bow shock/upstream region toward the magnetopause, it is expected that, at dawn, more particle events will fulfill the selective criterion towards earlier local times, as is the case.

3. The high-energy (290–500 keV) ions show a broader distribution, i.e. a peak between 4 LT–9 LT (Fig. 2b), compared to the lower (50–220 keV) energy ions, which show a peak between 4 LT–6 LT (Fig. 2a). This difference in the spatial distribution of ions of various energies should be further checked in future studies, since the two distributions compared here were produced by applying different selection criteria. However, we note that the broader distribution of higher energy ions resulting from the comparison of Fig. 2a,b is consistent with an energy dependent propagation of magnetospheric ions in the magnetosheath inferred from other independent investigations (Anagnostopoulos and Chroni, 1992; Anagnostopoulos *et al.*, 1999b).

4. The appearance of a local maximum in the distribution of the 290–500 keV ions, between 15 and 19 LT (Fig. 2b), can be attributed: (a) to leakage of magnetospheric ions during times of unusual IMF directions (b) to strong scattering and propagation of these ions perpendicular to the magnetosheath field lines during a Parker spiral IMF configuration and (c) to shock drift acceleration at the dusk quasi-perpendicular side of the bow shock.

5. The detection of magnetospheric high energy (290–500 keV) ions upstream from the whole front of the bow shock, from ~4 LT up to ~20 LT (Fig. 2b), with an occurrence frequency as high as ~34% between 6–7 LT, suggests that leakage of magnetospheric ions is a semi-permanent process in the region upstream from the bow shock, and in particular upstream from the dawn side of the bow shock (Anagnostopoulos *et al.*, 1999a). Furthermore, we note that the occurrence frequency of magnetospheric high-energy ions in the upstream region found here is consistent with the detection of a higher occurrence frequency (~46%–~30%) of magnetospheric 290–500 keV ions within the magnetosheath (Karanikola *et al.* 1999), and, therefore, further confirms our initial assumption that the 290–500 keV upstream ions are generally of a magnetospheric origin.

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