Ann. Geophysicae 17, 650–658 (1999) © EGS – Springer-Verlag 1999

Annales Geophysicae

Characteristics of ≥ 290 keV magnetosheath ions

I. Karanikola, G. C. Anagnostopoulos, A. Rigas

Department of Electrical Engineering, Demokritos University of Thrace, Xanthi 67100, Greece
E-mail: anagnosto@xanthi.cc.duth.gr

Received: 25 June 1997 / Revised: 27 August 1998 / Accepted: 26 October 1998

Abstract. We performed a statistical analysis of 290–500 keV ion data obtained by IMP-8 during the years 1982–1988 within the earth's magnetosheath and analysed in detail some time periods withdistinct ion bursts. These studies reveal the following characteristics for magnetosheath 290–500 keV energetic ions: (a) the occurrence frequency and the flux of ions increase with increasing geomagnetic activity as indicated by the Kp index; the occurrence frequency was found to be as high as P ≥ 42% for Kp ≥ 2, (b) the occurrence frequency in the dusk magnetosheath was found to be slightly dependent on the local time and ranged between ~30% and ~46% for all Kp values; the highest occurrence frequency was detected near the dusk magnetopause (21 LT), (c) the high energy ion bursts display a dawn-dusk asymmetry in their maximum fluxes, with higher fluxes appearing in the dusk magnetosheath, and (d) the observations in the dusk magnetosheath suggest that there exist intensity gradients of energetic ions from the bow shock toward the magnetopause. The statistical results are consistent with the concept that leakage of magnetospheric ions from the dusk magnetopause is a semi-permanent physical process often providing the magnetosheath with high energy (290–500 keV) ions.

Key words. Magnetospheric physics (magnetosheath; planetary magnetospheres). Space plasma physics (shock waves).

Introduction

Observations of energetic ions and electrons in the magnetosheath can provide important information concerning processes occurring at the bow shock, the magnetopause, and the magnetosheath itself. In particular, the significance of various sources of low energy (~30–40 keV) ions within the magnetosheath still remains a matter of dispute (Scholer *et al*., 1989; Sarris *et al*., 1990; Kudela *et al*., 1992; Fuselier *et al*., 1993). Possible sources include Fermi and shock-drift acceleration at the bow shock, as well as leakage from the magnetosphere (Fuselier *et al*., 1993; Anagnostopoulos and Kaliabetsos, 1994; Paschalidis *et al*., 1994).

Fermi acceleration mechanism, which operates at the quasi-parallel bow shock, may effectively accelerate a seed population of incident solar wind ions up to energies as high as ~100–150 keV (Scholer *et al*., 1989, 1992; Ellison, *et al*., 1990), or even ≥~300 keV, if, in addition, an ambient energetic ion population of solar or interplanetary origin is present (Ellison, 1987; Anagnostopoulos *et al*., 1998). Because of the spiral interplanetary magnetic field (IMF), a quasi-parallel bow shock region is statistically more likely to appear upstream of the dawnside magnetosphere rather than upstream from the duskside magnetosphere. Hence, we expect the flux of Fermi accelerated ions to be higher in the vicinity of the dawn bow shock, and lower in the dusk magnetosheath. We also expect the ion intensities to fall with distance from the bow shock and, therefore the existence of intensity gradients from the magnetopause toward the bow shock (Scholer *et al*., 1989).

Shock-drift acceleration (SDA) at the bow shock is another possible source of energetic particles within the magnetosheath. This process is expected to accelerate both ions and electrons up to energies of some keV at the bow shock, although higher energies (≥1 MeV) may be attained in the presence of a pre-existing energetic ion population and special solar wind conditions (Anagnostopoulos and Kaliabetsos, 1994). SDA is particularly effective at the quasi-perpendicular bow shock, which, most often, lies on the duskside of the magnetosphere.

The magnetosphere is an enormous potential source of energetic ions and electrons. Magnetospheric energetic ions drift westward to the dusk magnetopause; electrons drift eastward to the dawn magnetopause

Correspondence to: G. C. Anagnostopoulos

(Takahashi and Iyemori, 1989; Paschalidis *et al.*, 1994). Observations of magnetopause shadowing confirm that magnetospheric particles, which reach the magnetopause, are lost from the outer magnetosphere and populate the magnetosheath (Sibeck *et al.*, 1988). With such a source of particles at the magnetopause we expect the fluxes to decrease with distance away from the magnetosphere, towards the bow shock. Indeed, recent studies have confirmed that energetic ions escaping from the magnetopause produce intensity gradients from the bow shock toward the magnetopause/magnetosphere (Paschalidis *et al.*,1991,1994; Kudela *et al.*, 1992). Furthermore, statistical studies of low energy (30–40 keV) ions in the magnetosheath have shown that their occurrence frequency ranges between 25%–56% (Fuselier *et al.*, 1993).

High energy (≥300 keV) ions within the magnetosheath and the region upstream from the bow shock are mostly of a magnetospheric origin (Sarris *et al.*, 1978; Krimigis *et al.*, 1978; Meng *et al.*, 1981; Pavlos *et al.*, 1985; Paschalidis *et al.*, 1994; Anagnostopoulos, 1995). Previous analysis of representative ion events has provided significant information on the behavior of the high energy (> 100–300 keV) ion population. It has been suggested that high energy ions continuously leak from the magnetopause in the magnetosheath (Sarris *et al.*, 1978; Paschalidis *et al.*, 1994) and show (1) energy dependent intensity gradients in the direction from the bow shock to the magnetopause at dusk, and from the magnetosheath to the magnetosphere (Pavlos *et al.*, 1985; Paschalidis *et al.*, 1994; Anagnostopoulos *et al.*, 1995), (2) high intensities at times of intense geomagnetic activity (Sarris *et al.*, 1978), and (3) harder spectra and higher intensities upstream from the dusk magnetopause/bow shock than upstream from the dawn magnetopause/bow shock (Sarris *et al.*, 1978, 1987; Pascalidis *et al.*, 1994).

Since the information we have about the high energy (> 100–300 keV) ion population in the magnetosheath has been based on some case studies, an extensive statistical study was needed that could improve our understanding of this ion population and of various processes taking place in the magnetosheath and their boundaries, the magnetopause and the bow shock. In addition, an evaluation of the probability of observing the high energy ion population in the magnetosheath as a function of position and of geomagnetic activity would be a useful tool in order to estimate how dynamic processes within the magnetosphere influence the composition of the energetic ion population in the magnetosheath (West and Buck, 1976; Paschalidis *et al.*, 1994). Finally, it would be useful to study the possible relationship between the magnetospheric high energy ion population and the low energy ion population within the magnetosheath. If the occurrence frequencies of the low (30–40 keV) and the high (≥ 300 keV) energy ions were comparable, this would support the concept that magnetospheric ions escaping from the magnetopause provide the main contribution to the energetic ion population within the magnetosheath (Anagnostopoulos, 1994).

Here we present a six year (1982–1988) statistical survey of high energy (290–500 keV) ions within the magnetosheath, which will help to determine some important characteristics and the origin of this particle population (Sarris *et al.*, 1976, 1978; Pavlos *et al.*, 1985). A first result of our statistical study is that the high energy ion bursts display a dawn-dusk asymmetry in their fluxes, with higher fluxes appearing in the dusk magnetosheath. This finding confirms the results of Meng *et al.* (1981) in the region with X ≤ 0. The statistical analysis also shows that the 290–500 keV ions often populate the whole area of the far dawn and the dusk magnetosheath and that they show intensity gradients from the bow shock towards the magnetopause at dusk. Both the occurrence frequency and the counting rates of high energy ions were found to be positively correlated with the index Kp of geomagnetic activity. The occurrence frequency was found to be high in general; it was evaluated to range between 30%–46% and to be as high as ≥42% during time intervals with Kp ≥ 2. The data we analysed confirm that leakage of magnetospheric particles through the dusk magnetopause is a semi-permanent process, providing the magnetosheath with high energy (290–500 keV) ions.

Instrumentation

For our statistical analysis we used energetic ion data obtained from the channel P1 (290–500 keV) of the Charge Particle Measurement Experiment (CPME) and from the channel L1 (50–220 keV) of the Energetic Particles Experiment of National Oceanic and Atmospheric Administratation (EPE/NOAA). The CPME instrument consists of a number of detector assemblies with their field-of-view pointing perpendicularly to the spacecraft spin axis. Specifically, the proton – electron telescope system consists of three solid-state detectors, inside an anti-coincidence scintilator cup, with full opening angle of 45°. The geometric factor for the channel P1 of CPME is 1.51 cm^2.sr. The details of the CPME instrument can be found in Sarris *et al.*, (1976). The EPE detector system consists of a main magnetic deflection telescope assembly and two auxiliary detectors, all utilizing surface barrier solid-state detectors. The angular response of the main telescope is determined by a collimation cone with full opening angle of 15°, oriented perpendicularly to the spin axis of the spacecraft. The auxiliary detectors point at an angle of 45° to the spin axis of the spacecraft. The geometric factor for the channel L1 of EPE is 0.011 cm^2.sr. A detailed description of the NOAA/EPE instrument is given by Williams (1977). Nearly identical sets of EPE and CPME instruments were flown aboard the IMP-7 and IMP-8 spacecraft.

Energetic (E ≥ 290 keV) ion survey

The present study examines ion data within the magnetosheath during a period of almost six years, from day 182, 1982 to day 176, 1988. For most of the statistical studies, we accepted that the spacecraft was inside the magnetosheath when its real position was in the area defined by the average position of the bow shock and the magnetopause (Appendix I). Since our intention was to determine the features and check the origin of high energy (E ≥ 290 keV) ions in the Earth's magnetosheath, first an algorithm was produced, in order to determine the time periods when high energy ions were present. To do this, we used a variable selective criterion dependent on the intensity background of the solar ambient energetic ion population (Appendix II). However, in some cases of distinct ion bursts, magnetic field measurements were analysed in order to determine the actual region of burst observation.

Figure 1 shows the counting rate R of 290–500 keV ions detected by the spacecraft IMP-8 within the dawn (a) and the dusk (b) magnetosheath as a function of the geomagnetic index Kp; the inset in the upper panel shows the average positions of the bow shock and of the magnetopause along with the trajectory of IMP-8 on the ecliptic plane. We found that there is a strong positive correlation between the values of R and of Kp in both the dawn ($r = 0.6$) and the dusk ($r = 0.58$) magnetosheath. In order to examine whether this statistical result is affected by non magnetosheath observations during high Kp periods, we analysed magnetic field observations and we examined the actual position of the magnetopause relative to the position of spacecraft for the subset of bursts detected during times with Kp ≥ 4. We found that under those conditions a small percentage (<~10%) of the bursts considered in the statistics was observed at the boundary layers or within the magnetosphere, and that, therefore, a withdrawal of this small percentage of bursts do not seriously affect the statistical results of Fig. 1.

Figure 2 displays the occurrence frequency of ions as a function of the index Kp within the dawn (Fig. 2a) and the dusk (Fig. 2b) magnetosheath. The histograms of both panels show that the occurrence frequency of ions increases with increasing the index Kp and that there is a high probability P of observing high energy (290–500 keV) ions. For instance, the probability of detecting ions during times with 2 ≤ Kp ≤ 3 is $P \cong$ 42–44% in both areas, and the probability of detecting ions during times with 5 ≤Kp ≤ 6 was found to be as high as $P \cong 73\%$ at dusk and $P \cong 60\%$ at dawn. However, it should be noted that the evaluated probability for high Kp conditions may be a little overestimated due to the possible expansion of the magnetopause at those times and the consequent inclusion of magnetospheric observations in the statistic.

Figure 3 shows the occurrence frequency of 290–500 keV/n ions as a function of local time. Dawn is on the left hand side and dusk is on the right hand side. Written on each part of the histogram is the number of bursts found in each interval. From this figure it is obvious that: (a) the high energy ion bursts are observed

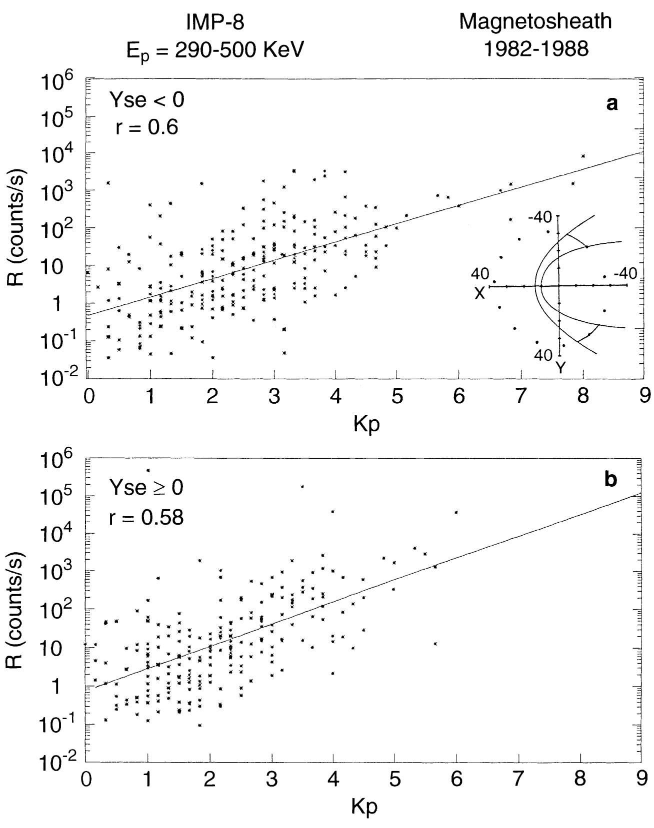

Fig. 1a,b. Maximum counting rate of the 290–500 keV ions as a function of the index Kp for the **a** dawn and **b** dusk magnetosheath. A strong correlation is evident between the counting rate of the high energy ions and the level of the geomagnetic activity

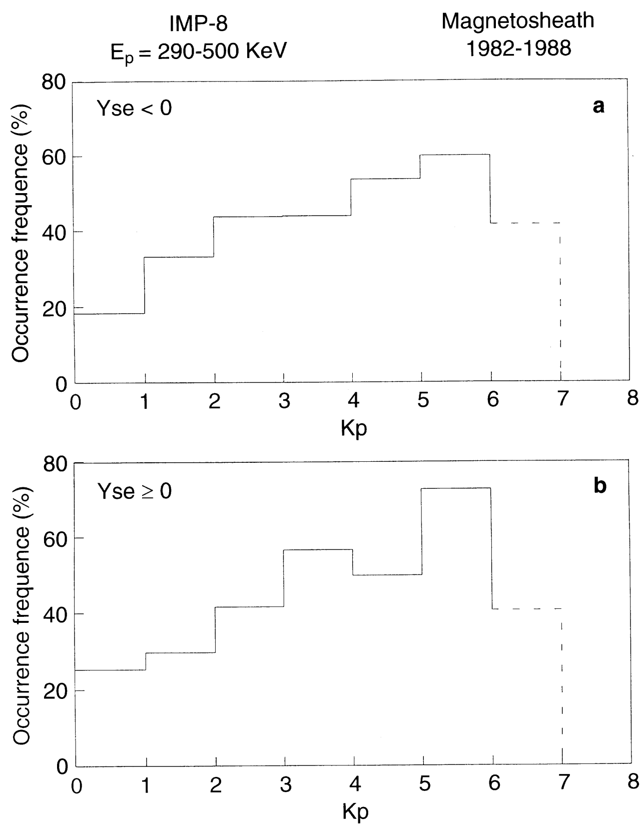

Fig. 2a,b. Occurrence frequency of the 290–500 keV ions as a function of the index Kp in the **a** dawn and **b** dusk magnetosheath. The occurrence frequency increases when the index Kp increases

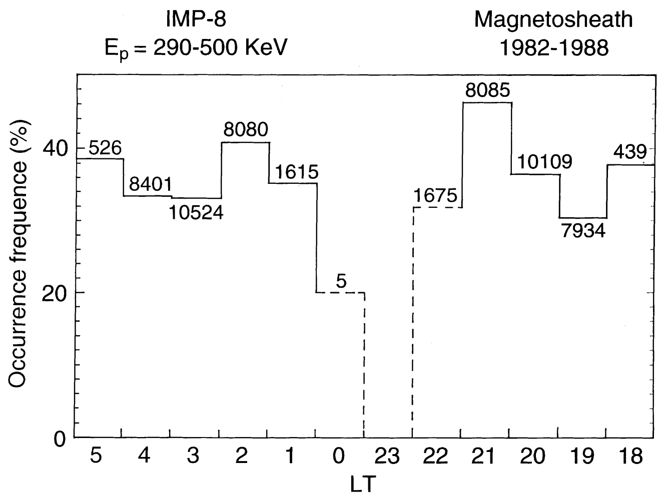

Fig. 3. Occurrence frequency of 290–500 keV/n ions in the magnetosheath as a function of local time. The highest occurrence frequency was detected near the dusk magnetopause, between 21 LT and 22 LT

in the distant magnetosheath at all local times, (b) the occurrence frequency ranges between ~30% and ~46%, and (c) the highest occurrence frequency (46%) was detected near the dusk magnetopause, between 21 LT and 22 LT. The average occurrence frequency was computed to be ~37% in the dusk magnetosheath and ~35 at dawn, which suggests an almost similar probability of observing high energy ion bursts in the dawn and the dusk magnetosheath.

Figure 4 shows the projection on the *Y-Z* plane of the positions at which the maximum counting rate was detected through a time period needed for the spacecraft to move 30° in the plane *X-Y*. The ion bursts were separated into three groups, with low (0.01 c/s ≤ R ≤ 1 c/s), medium (1 c/s < R ≤100 c/s) and high (R > 100 c/s) counting rates and they have been displayed separately in Fig. 4 a, b and c, respectively. From Fig. 4 it is implied that a larger number of intense (Fig. 4c) ion bursts was detected in the dusk magnetosheath (115) than in the dawn (69) magnetosheath, and a larger number of less intense (Fig. 4a) bursts was detected in the dawn (113) magnetosheath compared with the dusk side (86); the number of ion bursts in the intermediate counting rate range (Fig. 4b) is distributed almost equally at dawn (285) and dusk (290). Other information, implied from Fig. 4, is that there are more ion bursts at high latitudes (i.e Z ≥ 10 Re) than at low latitudes. Later in this study we examine this finding in more detail.

Figure 5 exhibits the local time distributions of intense (R ≥ 100 c/s; Fig. 5a) and of small (0.01 ≤ R ≤ 1 c/s; Fig. 5b) bursts in the dusk magnetosheath for values of the geomagnetic index Kp ≥ 4 and Kp < 4 between days 182, 1982 – 365, 1987. In this statistical sample only bursts actually observed within the magnetosheath were included (checked by magnetic field measurements) from the sample of events of Fig. 4. We see that, during times of low geomagnetic activity (Kp < 4) the number of low counting rate events dramatically decrease (Fig. 5b) and the number of high

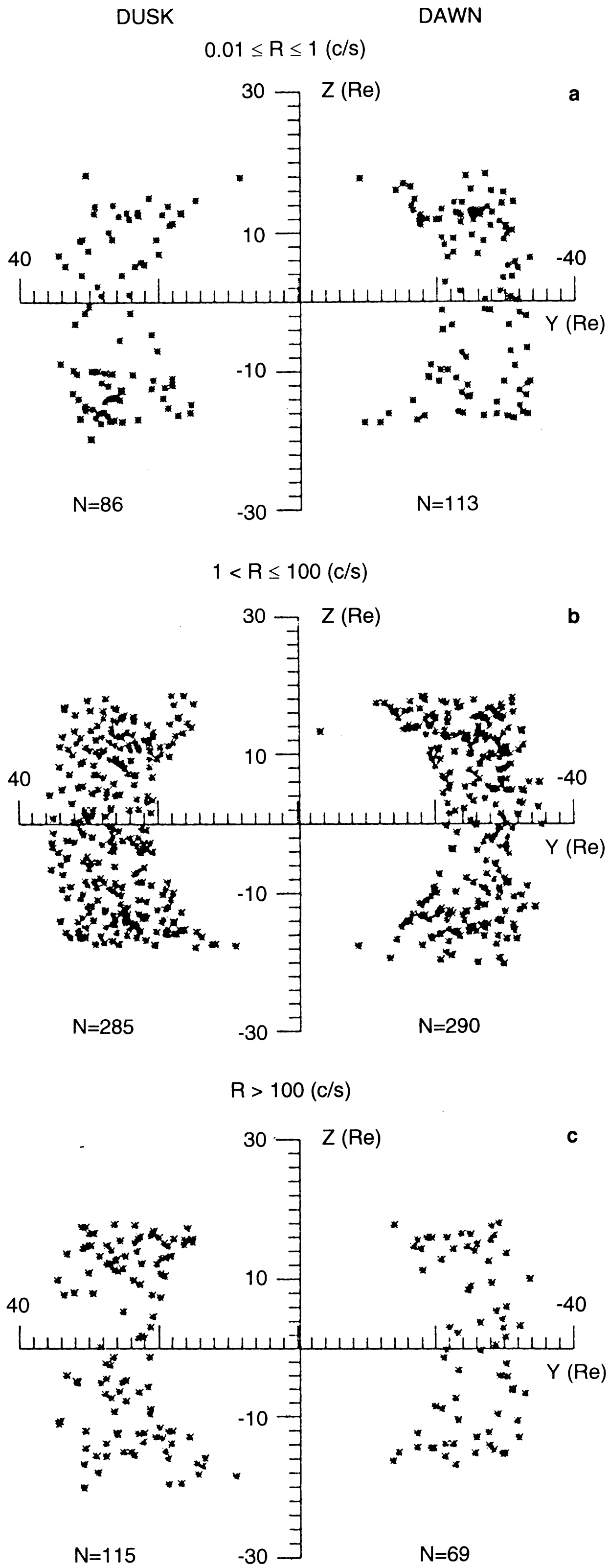

Fig. 4a–c. Projection on the *Y-Z* plan of the positions at which ion bursts were detected for three different ranges of the counting rates. More intense bursts were detected in the dusk magnetosheath

counting rate events slightly increase (Fig. 5b) as we move from the bow shock (afternoon local times) towards the magnetopause (local pre-midnight times).

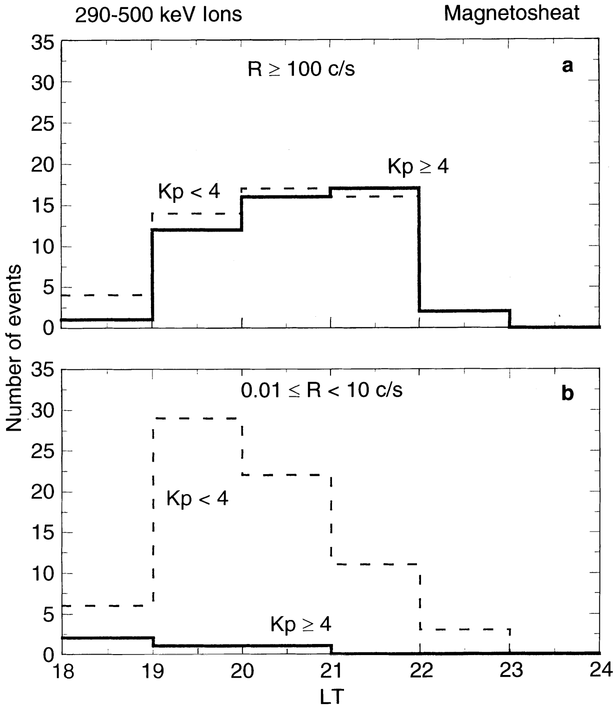

Fig. 5a,b. The number of ion bursts as a function of local time in the dusk magnetosheath, for **a** intense and **b** low particle activity (distributions have been evaluated for two ranges of the index Kp of geomagnetic activity). The observations are consistent with existence of intensity gradients in the direction from the bow shock (evening local times) toward the magnetopause (pre-midnight local times), in particular during times of low particle activity

During times of intense geomagnetic activity (Kp ≥ 4) almost only bursts of high intensities were observed, which also show a trend for event numbers increasing toward higher local times. These observations suggest the existence of intensity gradients from the bow shock toward the dusk magnetopause, which is more evident at times of low particle activity. From a further examination of data we found that: (a) there is no correlation of event number with local time in the dawn magnetosheath, (b) ion bursts are detected under a variety of magnetic field directions, from parallel to perpendicular to the magnetopause/bow shock, and (c) ion bursts are observed in the whole area of the distant magnetosheath from the magnetopause up to the bow shock front.

The statistical analysis of Fig. 6 examines the distribution of ion fluxes as a funtion of the distance *Zse* from the ecliptic plane. In the case of the dusk magnetosheath (Fig. 6a) we see that the (maximum) counting ion rates increase as we move to greater values of *Zse*, whereas in the case of the dawn magnetosheath (Fig. 6b) we see that the counting rates *R* reduce when increasing the distance *Zse*. However, for both statistics we found a very low correlation between *R* and *Zse*: $r = 0.051$ at dusk and $r = 0.160$ at dawn.

The last statistical analysis of Fig. 7 was performed in order to further elaborate the increase in the number of ion bursts toward higher latitudes, which we saw in Fig. 2. In order to check whether this finding should be attributed to a physical phenomenon or is an artificial result, we have compared in Fig. 7 the percentage of energetic ion events detected by IMP-8 (solid line) and the relative time spent by the spacecraft (dashed line) within 5 *Re* segments in the region $-25 \leq Zse \leq 25$ Re. The results shown in Fig. 7a and b correspond to the dawn magnetosheath,and the dusk magnetosheath, respectively. We see that the two curves are similar. At this point it was decided to examine whether the two curves were identical or not, so we determined the value of X^2 distribution with 9 degrees of freedom at a 5%

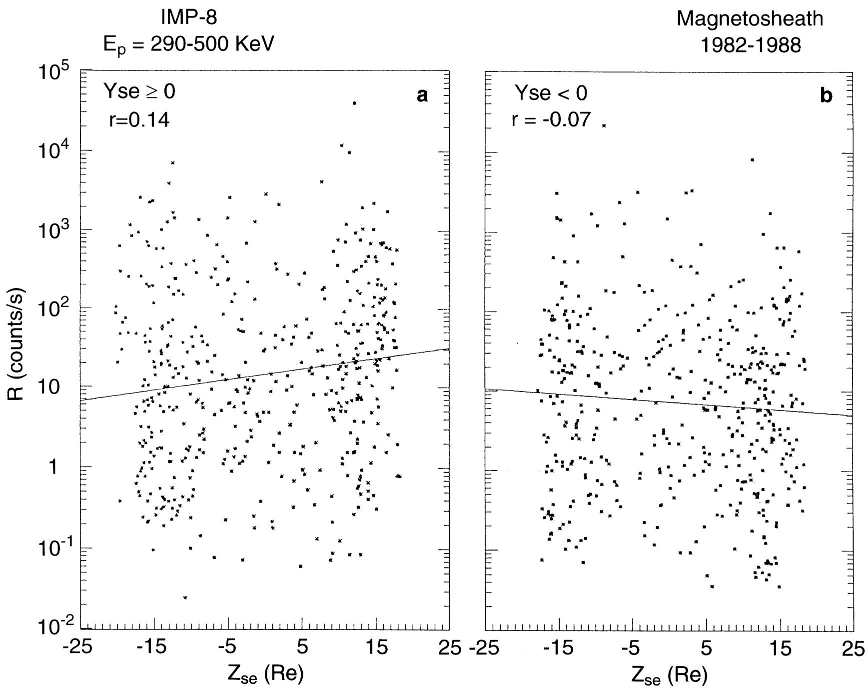

Fig. 6a,b. The distribution of the counting rate of 290–500 keV as a function of the latitudes in the **a** dusk and **b** dawn magnetosheath

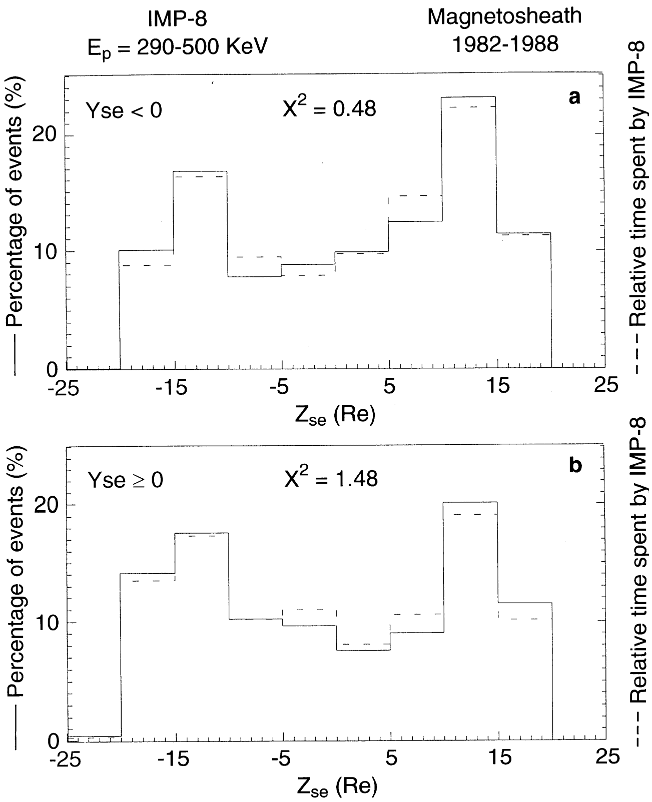

Fig. 7a,b. The percentage of energetic ion events (*solid line*) and of the relative time spent by the spacecraft (*dashed line*) as a function of the Z_{sc}coordinate for the **a** dawn and **b** dusk magnetosheath

significant level from suitable tables . This value was found to be 16.9 and compared with the value X^2 = 0.48 calculated from our analysis indicates that the two curves are identical; similar results were obtained for the observations in the dusk magnetosheath (Fig. 6b). Therefore, we conclude that the greater number of energetic ion bursts observed by IMP-8 at higher latitudes was due to the spacecraft's orbit, which spent longer times at those positions.

Summary of observations

The statistical analysis we performed for high energy (290–500 keV) ions detected by the IMP-8 spacecraft over a time period of ~6 y (1982–1988) in the dawn and the dusk magnetosheath reveals the following characteristics:

1. The high energy (290–500 keV) ions often populate the whole space of the dawn and the dusk magnetosheath.
2. Ion bursts were detected under a variety of magnetic field directions, from parallel to perpendicular to the magnetopause/bow shock surface.
3. The ion counting rate R and the index Kp of geomagnetic activity are strongly positively correlated in both the dusk and the dawn magnetosheath.
4. The probability of observing high energy ions events increases when the index Kp of geomagnetic activity increases.
5. The occurrence frequency is in general high; it ranges between 30%–46% and it is $P \geq 42\%$ during times with Kp ≥ 2.
6. There is an evident dawn-dusk asymmetry in the ion counting rates, with higher values of energetic ions in the dusk than in the dawn magnetosheath.
7. The occurrence frequency of energetic ions is almost the same in the dusk (37.2%) as in the dawn (35.5%) magnetosheath; the highest occurrence frequency (46.2%) was evaluated near the dusk magnetopause between 21 LT and 22 LT.
8. More bursts of low intensities and fewer bursts of high intensities were observed towards the bow shock in the dusk magnetosheath; no clear evidence of a similar distribution was found in the dawn magnetosheath.
9. There appears to be a slight increase (r =0.160) toward the north magnetosheath at dusk, and a slight reduction (r = −0.051) of energetic ion flux toward the north magnetosheath at dawn.

Discussion and conclusions

As mentioned before, there are three different mechanisms suggested to explain the presence of energetic ions in the Earth's magnetosheath: (a) Fermi acceleration, (b) shock drift accelaration, and (c) leakage of magnetospheric ions across the magnetopause (Fuselier *et al.*, 1993; Kudela *et al.*, 1992; Paschalidis *et al.*, 1994). The presence of ion events with energy spectra extending above ~100–300 keV has been, in general, attributed to leakage of magnetospheric ions (Sarris *et al.*, 1976, 1978; Paschalidis *et al.*, 1994). The present study reveals some interesting characteristics of the high energy (≥ 290 keV) magnetosheath ion population, which confirm the magnetospheric origin of this population, and provide an observational basis for further conclusions concerning the origin of magnetosheath ion events in general.

Fermi acceleration mechanism is more effective in the vicinity of the quasi-parallel dawn bow shock. Under normal conditions, Fermi acceleration models as applied in the case of Earth's bow shock, predict acceleration of ions up to energies of ~100–150 keV (Ellison *et al.*, 1990; Scholer *et al.*, 1992) and the existence of intensity gradients in the direction from dusk to dawn (Ipavich *et al.*, 1981). Therefore, the presence of high energy (> 290 keV) ions in the magnetosheath can not be in general attributed to Fermi acceleration. Furthermore, the following results are not consistent with the predictions of Fermi acceleration models: (a) the existence of intensity gradients from dawn to dusk, (b) the existence of intensity gradients from the bow shock toward the magnetopause (in the dusk magnetosheath), and (c) the absence of any indication for existence of intensity gradients towards the bow shock in the dawn magnetosheath.

The shock drift acceleration, the other candidate acceleration process at the bow shock, is more effective at the dusk (quasi-perpendicular) bow shock, and gives rise to intensity gradients toward the bow shock (Anagnostopoulos and Kaliabetsos, 1994); this prediction is also in contrast to the finding of gradients of energetic ion intensity in the direction from the bow shock towards the magnetopause in the dusk magnetosheath.

The results of our statistical analysis are in agreement with the predictions of the leakage model for magnetospheric ions.

Firstly, the strong dependence of counting rates and of the occurrence frequency of ions on geomagnetic activity is consistent with a magnetospheric origin of the ion events.

Secondly, the existence of a dawn-dusk asymmetry, with higher fluxes of energetic (≥290 keV) ions within the dusk magnetosheath, and the existence of intensity gradients from the bow shock towards the magnetopause are consistent with a magnetospheric source. We know that ions of higher energies escape from the magnetopause at evening local time (Takahashi and Iyemori, 1989; Paschalidis *et al.*, 1994), cross the magnetopause, and then propagate within the magnetosheath. Such a propagation process can justify the existence of dawn-dusk asymmetry in ion fluxes and the reason for which the maximum occurrence frequency of 290–500 keV ions were detected near the dusk magnetosheath.

The concept that the 290–500 keV ion population is comprised of magnetospheric ions, leaking from the magnetopause, can also explain the detection of a greater (smaller) number of intense (low) bursts as the spacecraft moves from evening local times toward premidnight times. Indeed, the leakage model predicts that high energy ions, after they cross the dusk magnetopause, propagate within the magnetosheath, where they produce intensity gradients from the bow shock towards the magnetopause. Such intensity gradients will be observed as gradients of an opposite direction in the number of more intense and small bursts, respectively. However, since the high energy ions reach at dawn after a voyage in the dusk and the local noon magnetosheath, after significant scattering at magnetosheath magnetic field fluctuations, no gradients are expected in the dawn magnetosheath in the direction from the magnetopause toward the bow shock, in agreement with the observations.

Finally, besides the fact that the present statistical study confirms the magnetospheric origin of the high energy ions within the magnetosheath, it also allows some conclusions to be drawn on the origin of energetic ions near the bow shock in general. The present study shows that there is a high probability of observing ions of magnetospheric origin in the magnetosheath, i.e. a probability $P \geq 42\%$ during times with $\mathrm{Kp} \geq 2$. This high probability of magnetospheric ions suggests that the magnetosphere is a semi-permanent source of such kind of ions in the magnetosheath. Moreover, if we take into account that the probability evaluated includes the times with no magnetic connection with the magnetopause, we may assume that the probability of observing high energy ions under conditions of magnetic connections should be much higher than those evaluated in the present study. This fact allows us to suggest that leakage of high energy ions from the magnetopause is a semi-permanent process providing the magnetosheath with magnetospheric particles (Sarris *et al.*, 1978; Paschalidis *et al.*, 1994; Anagnostopoulos, 1994).

The correlation of the low energy (~30 keV) ion population with the high energy (~300 keV) ion population in the magnetosheath can be estimated by comparing their occurrence frequencies. The occurrence frequency of 290–500 keV ions was found by this study to range between ~30% −46% for local times between 1 LT–6 LT and 18 LT–23 LT. The occurrence frequency of 30–40 keV ions was earlier evaluated to range between 25%–56% for all local times (Fuselier *et al.*, 1993). However, although there is an almost common minimum probability (25–30%) of observing the two populations between 1 LT–6 LT and 18 LT–23 LT, the maximum in occurrence frequency for the low energy ion population was detected in the dawn magnetosheath (Fuselier *et al.*, 1993; their Fig. 2) instead of the dusk magnetosheath for the high energy ions (Fig. 3 of the present study). We have already discussed that a local maximum in high energy ion occurrence frequency near the dusk magnetopause is consistent with a leakage model of magnetospheric ions. The excess in occurrence frequency of the low energy ions in the dawn magnetosheath (5 LT-8 LT) is also consistent with the leakage model, since low energy ions escaping from the magnetopause move almost scatter free within the magnetosheath, under the usual Parker spiral IMF, and reach the dawn magnetosheath (Luhmann *et al.*, 1984; Anagnostopoulos *et al.*, unpublished manuscript); however the low energy ion observations are also consistent with Fermi acceleration of solar wind ions at the bow shock (Fuselier *et al.*, 1993).

In order to confirm the association of the two populations it should be examined whether the two populations are observed at the same time. In order to check this possibility, we examined 50–220 keV ion data from the EPE/NOAA experiment on board the spacecraft IMP-8, during times of detection of 290–500 keV ion bursts, and we found that bursts of high energy ions are in general associated with bursts of low energy ions.

However, the question still remains whether the magnetosheath low energy (< 100–300 keV) ion population, besides the magnetospheric component, has a significant second one, and to what extent. Since the energy spectra within the magnetosheath do not in general support the assumption in favour of two simultaneous sources of energetic ion events during times of a disturbed magnetosphere (Sibeck *et al.*, 1988; Paschalidis *et al.*, 1994), we believe that the low energy (30–300 keV) ion population has in most cases a unique source: the Earth's magnetosphere. Further studies on the composition and the energy spectra of magnetosheath ion population are needed in order to check the validity of this conclusion.

Appendix I

In order to decide about the times when IMP-8 visited the magnetosheath during the time interval considered in the statistic (182/1982–176/1988), we compared the real position of the spacecraft with the fitting equation

$$y^2 + z^2 + Bx^2 + E = 0$$

for the bow shock ($B = -0.0381$ and $E = -652.1\ R_E^2$) and the magnetopause ($B = 0.3818$ and $E = -240.12\ R_E^2$). This simple equation was derived by Mitchell and Roelof (1983) from the equation

$$y^2 + Axy + Bx^2 + Cy + Dx + E = 0 \quad \text{(Fairfield, 1971).}$$

Appendix II

In order to evaluate the occurrence frequency of 290–500 keV ions we derived an algorithm, which could compare the counting rate of ions R with the background rate R_b due to solar/ interplanetary ion activity. As background rate R_b was taken the lowest rate in each 6-h interval of 5.5 min averaged data. The result of the comparison between R and R_b was considered as positive (existence of ions) if the ratio R/R_b was above a certain value. Since the magnetospheric bursts of 290–500 keV ions detected by CPME are less distinguishable when the solar background counting rate is low, we demanded a reference ratio R/R_b increasing with the background rate R_b decreasing, as follows: $R/R_b = 2$, 3,4 and 5 for values of the background rate $R_b < 0.05$ c/s, $0.05 \leq R_b < 0.1$ c/s, $0.1 \leq R_b < 1$, $1 \leq R_b$, respectively. For the needs of our computations, we used 6-h averaged values of the index Kp.

Acknowledgements. We are grateful for the use of the IMP-8 CPME particle data provided by S. M. Krimigis, and the GSFC IMP-8 magnetometer data provided by N. F. Ness and R. P. Lepping. We also thank G. Kaliabetsos for his help in data processing. This work has been partially supported by the Secretariat for Science and Technology of the Greek Ministry for Development through the contract PENED 95/1783.

Topical Editor K.-H. Glassmeier thanks a referee for his help in evaluating this paper.

References

Anagnostopoulos, G. C., Dominant acceleration processes of energetic protons at the Earth's bow shock, *Phys. Scripta*, **T52,** 142–151, 1994.

Anagnostopoulos, G. C., On the role of the solar flare generated ions in producing the energetic (E ≥ 300 keV) ions events observed upstream from the Earth's bow shock, *Adv. Space. Res.*, **15, (8/9)**, 63–66, 1995.

Anagnostopoulos, G. C., and G. D. Kaliabetsos, Shock drift acceleration of energetic (E ≥ 50 keV) protons and (≥ 37 keV) alpha particles at the Earth' s bow shock as a source of the magnetosheath energetic proton events, *J. Geophys. Res.*, **99,** 2335–2349, 1994.

Anagnostopoulos, G. C., E. T., Sarris and S. M., Krimigis, On the origin of the forward velocity dispersion of ion events observed near the Earth's and Jupiter's bow shock, *Adv. Space Res.* **16, (4)**, pp. (4)49–(4)152, 1995.

Anagnostopoulos G. C., E. T. Sarris, A. G. Rigas, and S. M. Krimigis, Characteristics of upstream energetic (E ≥ 50 keV) ion events during intense geomagnetic activity, *J. Geophys. Res*, **99,** 2335–2349, 1998.

Ellison, D. C., Comment on Magnetospheric origin of energetic (E ≥ 50 keV) ions upstream of the bow shock: the October 31, 1977, event by G.C.Anagnostopoulos, E.T.Sarris, and S.M.Krimigis, *J. Geophys. Res.*, **92,** 12 458–12 460, 1987.

Ellison, D. C., E. Mobius, and G. Paschmann, Particle injection and acceleration at earth's bow shock: comparison of upstream and downstream events, *Astrophys. J.*, **352,** 374–394, 1990.

Fairfield, F. D., Average and unusual locations of the Earth's magnetopause and bow shock, *J. Geophys. Res.*, **76,** 6700–6716, 1971.

Fuselier, S. A., P.Hill, W. Baumjohann, and J. T.Gosling, Local occurrence frequency of energetic ions in the Earth's bow shock, *Geophys. Res. Lett.*, **20,** 551–554, 1993.

Ipavich, F. M., M. Scholer, and G. Gloeckler, Temporal development of composition, spectra, and anisotropies during upstream particle events, *J. Geophys. Res.*, **86,** 11 153–11 169, 1981.

Krimigis, S. M., D. Venkatesan, J. C. Barichello, and E. T. Sarris, Simultaneous measurements of energetic protons and electrons in the distant magnetosheath, magnetotail and upstream in the solar wind, *Geophys. Res. Lett.*, **5,** 961–964, 1978.

Kudela, K., D. G. Sibeck, M. Slivka, S. Fischer, V. Lutsenko, and D. Venkatesan, Energetic electrons and ions in the magnetosheath at low and medium latitudes: Prognoz 10 Data, *J. Geophys. Res.*, **97,** 14 849–14 857, 1992.

Luhmann, J. G., R. J. Walker, C. T. Russell, J. Spreiter, S. S. Stahara, and D. J Williams, Mapping the magnetosheath field between the magnetopause and the bow Shock: Implications for magnetospheric particle leakage, *J. Geophys. Res.*, **89,** 6829–6834, 1984.

Meng, C. -I., A. T. Y. Lui, S. M. Krimigis, S. Ismail, and D. J. Williams, Spatial distribution of energetic particles in the distant magnetotail, *J. Geophys. Res.*, **86,** 5682–5700, 1981.

Mitchell, D. G., and E. C.Roelof, Dependence of 50-keV upstream ion events at IMP-7 and 8 upon magnetic field bow shock geometry, *J. Geophys. Res.*, **88,** 5623–5634, 1983.

Pavlos, G. P., E. T. Sarris, and G. Kaliabetsos, Monitoring of energy spectra of particle bursts in the plasma sheet and magnetosheath, *Planet. Space Sci.*, **33,** 1109–1118, 1985.

Paschalidis, N. P., S. M. Krimigis, E. T. Sarris, D. G.Sibeck, R. W. McEntire, S. P. Christon, L. J.Zanetti, Ion burst events in the Earth's dayside magnetosheath, *Geophys. Res. Lett.*, **18,** 377–380, 1991.

Paschalidis, N. P., E. T. Sarris, S. M. Krimigis, R. W. McEntire, M. D. Levine, I. A. Daglis, and G. C. Anagnostopoulos, The magnetosphere as a continuous and dynamic source of magnetosheath energetic ions, *J. Geophys. Res.*, **99,** 8687–8703, 1994.

Sarris, E. T., S. M. Krimigis, and T. P. Armstrong, Observations of magneto-spheric bursts of high-energy protons and electrons at ~35 R_E with IMP-7, *J. Geophys. Res.*, **81,** 2341–2355, 1976.

Sarris, E. T., S. M. Krimigis, C. O. Bostrom, and T. P. Armstrong, Simultaneous multispacecraft observations of energetic proton and electron bursts inside and outside the magnetosphere, *J. Geophys. Res.*, **83,** 4289–4305, 1978.

Sarris, E. T., G. C. Anagnostopoulos, and S. M. Krimigis, Simultaneous measurements of energetic ion (≥50 keV) and electron (≥220 keV) activity upstream of Earth's bow shock and inside the plasma sheet Magnetospheric source for the November 3 and December 3, 1977 upstream events, *J. Geophys. Res.*, **92,** 12 083–12 096, 1987.

Sarris, E. T., S. M.Krimigis, and N. P. Paschalidis, Comment on «Multispaceraft observations of energetic ions upstream and downstream of the bow shock» by Scholer *et al.*, *Geophys. Res. Lett.*, **17,** 1165–1168, 1990.

Sibeck, D. G., R. W. McEntire, S. M. Krimigis, and D. N. Baker, The magnetosphere as a sufficient source for upstream ions on November 1, 1984, *J. Geophys. Res.*, **99,** 14 328–14 342, 1988.

Scholer, M., E. Mobius, L. M. Kistler, and F. M. Ipavich, Multispacecraft observations of energetic ions upstream and downstream of the bow shock, *Geophys. Res. Lett*., **16,** 571–574, 1989.

Scholer, M., K. J. Trattner, and H. Kucharek, Ion injection and Fermi acceleration at Earth's bow shock: the 1984 September 12 event revisited, *Astrophys. J*., **395,** 675–681, 1992.

Takahashi, S., and T. Iyemori, Three-dimensional tracing of charged particle trajectories in a relativistic magnetospheric model, *J.Geophys. Res*., **94,** 5505–5509, 1989.

West, H. Jr., and R. M. Buck, Observations of > 100-keV protons in the Earth's magnetosheath, *J. Geophys. Res*., **81,** 569–584, 1976.

Williams, D. J., The ion-electron magnetic separation and solid state detector detection system flown on IMP-7 and 8: E ≥ 50 keV, E ≥ 30 keV, *Tech. Rep. ERL 393-SEL 40*, Natl. Oceanic and Atmos. Admin., Boulder, Colo., 1977.