Almost Monoenergetic Ions: New Support for Alfvén Ideas on the Role of Electric Currents in Space Plasmas?

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Abstract. A new kind of energetic particle spectra consisting of 1-3 narrow lines was discovered in the DOK-2 experiments on board of the Interball-1 and 2 spacecrafts during a period from August 1995 to August 1999 in the region upstream of the Earth's bow shock, in the magnetosheath, and near the border of the magnetotail plasma sheet. The relative width at half maximum of these lines was of 15–30%. Ion energy values varied for different events from 30 to 600 keV but were almost unchanged during each event. In two-peak spectra the energy values ratio was 1:2, and in three peak spectra the ratios were 1:2:(5–6). Such line spectra cannot be explained by current models of particle acceleration or escape from the magnetosphere. We propose a hypothesis explaining the origin and the main features of these ions by solar wind ions acceleration in a burst of strong electrostatic field (50–100 mV/m) in a small region (1000–5000 km). This burst can be a result of a disruption of a current filament of the magnetopause or the magnetotail current system. By such a disruption the whole potential difference over the magnetosphere due to convective electric field develops over a small region accelerating plasma ions to energies ~100 keV. If this mechanism is really working it may give a new support to Alfvén ideas on the dualism and the role of electric currents in space plasmas.

1 Introduction

It is generally accepted that particles with energies of tens to hundreds of keV, which are observed in the Earth's magnetosheath, magnetotail, and in the solar wind upstream of the bow shock, originate from several sources: leakage of energetic particles from the magnetosphere (Kudela at al., 1990), acceleration of solar wind ions by Fermi process upstream of the bow shock (Ipavich at al., 1982), by the shock-drift acceleration process at the bow shock itself (Decker, 1983), and by the betatron mechanism (Zelenyi et al., 1998) in the geotail plasma sheet. It is essentially that in all of these processes particles are accelerated by the inductive electric field. The energy of a particle escaping the source will depend on the magnitude and the time behavior of the electric field, and on the positions where the particle come into acceleration and come out of it. It is also true for the particle energization in the geotail current sheet by the cross-tail convective electric field (Speiser, 1965; Lyons at al., 1982). The resulting energy spectra of ions and electrons in all of these mechanisms should have continuous, smooth shapes with a negative slope at E>30 keV. Just such spectra were observed in numerous space experiments during last thirty years. To our knowledge the only case when ruther narrow peaks were observed in energetic particle spectra were observations of precipitating electron spectra during aurora (Evans, 1968; Arnoldy at al., 1974). Energy values were here of 1–10 keV, FWHM of 40–50% and the peaks supposed to be a result of electron acceleration by parallel electrostatic field of double layers.

In this connection the discovery of almost monoenergetic, of short duration (~1 min) but often very intensive beams of energetic ions in the magnetosheath and upstream regions (Lutsenko at al., 1999) was quite unexpected. We found later also several cases of such beams at the plasma sheet - lobe and auroral zone - polar cap borders. It was done in a course of the DOK-2 experiment on board Interball-1 spacecraft (Lutsenko at al., 1995, 1998). Ion energy values varied for different events from 30 to 600 keV, but were almost unchanged during each event. The relative width at half maximum of these lines varied from 15 to 30%, that is why we use the term "Almost Monoenergetic Ions" (AMI) for these events. The total number of the events exceeds now 250. The fact that AMI events were not observed in numerous previous experiments can be explained by

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insufficient energy resolution of spectrometers used before and by a short duration of the events. Our analysis showed that AMI spectra cannot be a result neither of some instrumental effects nor of some space or time dispersion effect.

2 Examples of AMI events observed in different regions

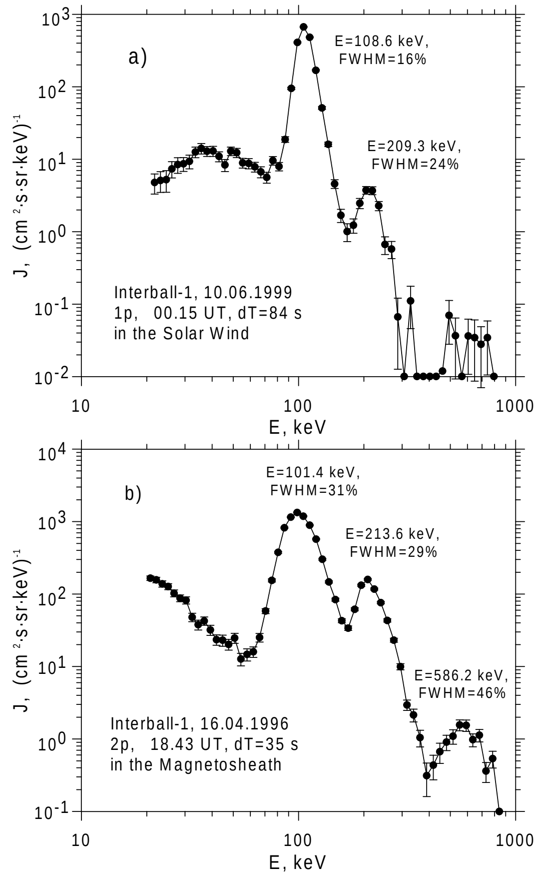

Fig. 1. Examples of AMI spectra measured (a) in the solar wind upstream of the bow shock on June 10, 1999 at 00:15 UT and (b) in the magnetosheath on April 16, 1996 at 18:43 UT. GSM coordinates were [23.27, -2.87, -13.89] R_E for (a) and [11.07, -3.89, 10.32] R_E for (b).

Figure 1 shows two examples of ion spectra measured upstream of the bow shock (a) and in the magnetosheath close to the model bow shock (b). In most cases ion spectra consist of two components - a "normal" continuous spectrum with a negative slope and a line spectrum with 1, 2 or 3 peaks. An analysis of Lutsenko at al. (1999) showed that energies of the 1-st, 2-nd and 3-rd peaks have specific ratios 1:2:(5–6) and the average value of the first peak energy is about 80 keV. We did not observed any peaks in electron spectra in these regions. Our measurements of angular distributions for different parts of the spectrum presented in Fig.1 (b) showed that ions in "normal" and line components were both nongyrotropic and had sharp intensity maxima at pitch angles of 110^o and 65^o. It means that they moved in opposite direction along the magnetic field line and hence they had different sources. High intensity of continuous spectra makes line spectra observation more difficult. While the great majority of our AMI observations are related to the magnetosheath and upstream region, where intensity of the continuous background spectrum is often very low, we found also AMI events in some other regions.

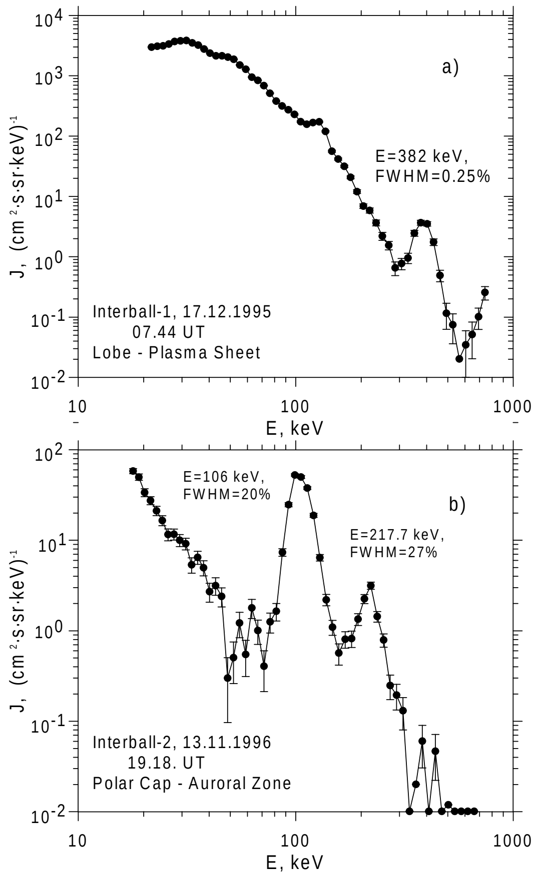

Fig. 2. Examples of AMI spectra measured near the plasma sheet - lobe interface: (a) on December 17, 1995 at 07:44 UT in the magnetotail (Tail Probe, GSM coordinates [-15.07, 4.07, -3.07] R_E) and (b) on November 13, 1996 at 19:18 UT close to the Earth (Auroral Probe, GSM coordinates [-2.48, -0.12, 2.23] R_E).

The AMI spectrum shown in Fig. 2(a) was measured by the DOK-2 instrument on Interball-1 spacecraft at 07:44 UT December 17, 1995 in the geotail on the plasma sheet - south lobe interface. Some signs of peak presence in ion spectra here were found earlier in experiments on ISEE-1 (Williams, 1981). The GSM coordinates in our case were $X = -15.07, Y = 4.07, Z = -3.07$ R_E. The energy of the first peak was of E=382.5 keV and the relative FWHM of 25%. The second peak with about double energy which is on the end of the instrument range is only partly seen. The spectrum accumulation time was of 87 s. According to magnetic field model

(Tsyganenko, 1987) the foot of the magnetic field line at the moment of measurements had the magnetic latitude $MLAT = -66.13^o$ and the magnetic local time MLT of 21.47 h. We should expect that while propagating along this line AMI can be detected closer to the Earth on the border between the auroral zone and the polar cap. Indeed our observation with the second DOK-2 instrument onboard of the Auroral Probe (Interball-2) confirm this assumption. Fig. 2 (b) shows the AMI spectrum measured at 19:18 UT November 13, 1996 on the inner edge of the auroral oval in the point with $R = 3.29$ R_E, $MLAT = 76.5^o$, MLT=1.28 h. Here we have two peaks with the energies of 106.0 and 217.7 keV. The AMI event duration was of 22 s.

The magnetotail plasma sheet is always filled by high energetic particle fluxes with "normal" spectra (Taktakishvili et al., 1998). Nevertheless the high energy and time resolutions of the DOK-2 allowed to find several cases of a very active processes in the central plasma sheet where the ion spectra had many narrow peaks arising and disappearing in seconds on the continuous background. We call this events the "plasma boiling". Here we observed short time (5–10 s) but great changes in limited energy intervals while other parts of a spectrum remained almost unchanged. These periods are characterized by high level of magnetic field fluctuations.

Fig. 3 shows the example of measurements in the plasma sheet on January 22, 1996 at 13:20-14:20 UT. The GSM coordinates of the observation point at 14:00 UT were [-23.17, 12.10, -2.36] R_E. Four upper panels show the time variation of the magnetic field GSM components, the lower one – the ion intensity variation for 3 energy intervals: 22–29, 47–61 and 102–133 keV for the 1p-telescope of DOK-2 measuring ions moving earthward. After 13.56 UT, when the spacecraft entered the neutral sheet, the magnetic field and ion intensity fluctuations increased greatly. The fluctuating distance between lines corresponding to different energy intervals shows on fast spectrum shape variations. Three sharp positive spikes in B_z marked by numbers may correspond to reconnection events close to the observation point – the process leading to the particles acceleration by the inductive electric field (Zelenyi et al., 1998).

Figures 4 (a–f) show changes in successive spectra (the later spectra are drawn by thicker lines). Fig. 4 f) shows a part of the panel e) in linear scales. The accumulation time for successive spectra was of 2–5 s. The presence of narrow peaks in different parts of ion spectra may be an indication on spikes of the electrostatic field in multiple acceleration events. As for AMI events in the solar wind and in the magnetosheath we did not observe any peaks in electron spectra here

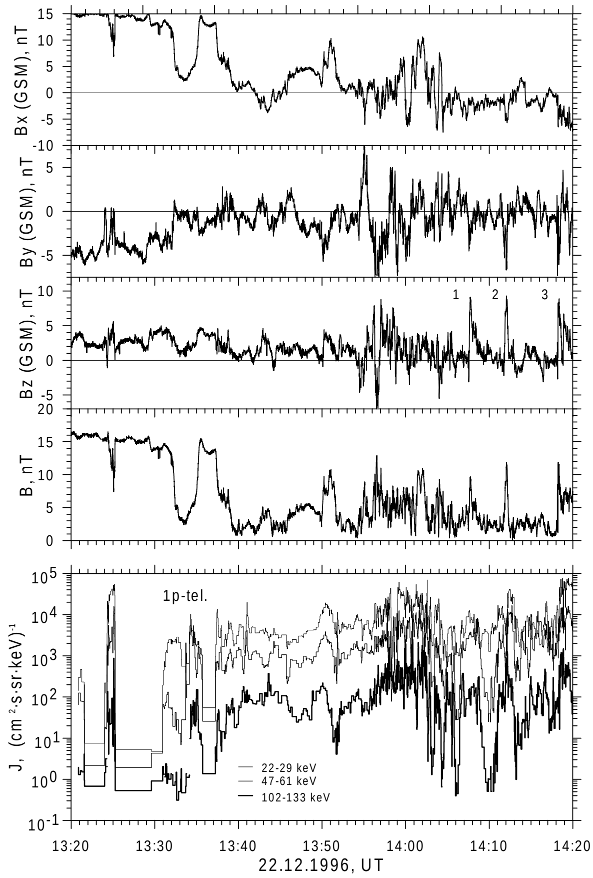

Fig. 3. Time profiles of the magnetic field components (GSM) and earthward ion fluxes in the plasma sheet on December 22, 1996 during relatively quiet (13:32–13:56 UT) and very active (13:56–14:20 UT) periods. The second period was in the neutral sheet. Three short (~20 s) reconnection events occured close to the spacecraft position are marked by numbers in the B_z -panel.

3 Possible AMI nature

The fact of existence and main properties of AMI which have been summarized by Lutsenko at al. (1999) cannot be explained in framework of currently accepted models of particle acceleration and propagation in the magnetosphere. The observed multiline structure and the time behaviour of AMI spectra cannot be produced by some natural filter from "normal", continuous spectrum, they should be created in an active process of ion acceleration.

As was shown by Lutsenko at al. (1999) the line energy ratios in 2- and 3- peak spectra allow to suppose AMI as H^+, He^{+2} and $(C,N,O)^{+(5-6)}$ solar wind ions accelerated in a burst of an electrostatic field to energies proportional to their charges q. The intensity ratios show an enrichment of accelerated ions by heavy components in comparison with the solar wind composition. This fact and absence of energetic electrons can be explained if we suppose that the acceleration takes place in a region which scale d is of order of ions gyroradius. In such a region electrons are totally magnetized and will

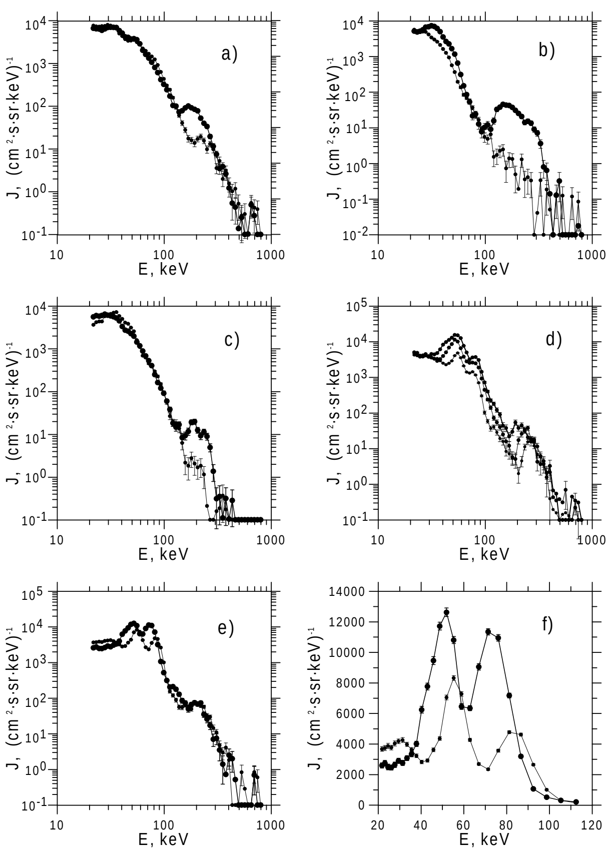

Fig. 4. Examples of successive ion spectra during the active period on December 22, 1996 13:56–14:20 UT. The accumulation time varied from 2 to 5 s. The later spectra are drawn by thicker lines. The panel f) shows a part of the panel e) in linear scales.

be swept by $E \times B$ drift without acceleration. Ions are not magnetized because of greater gyroradii and can be accelerated up to energies $q \cdot E \cdot d$. By the same reason the relative number of He^{+2} and $(C, N, O)^{+(5-6)}$ ions involved in the acceleration will be greater then for H^{+} which explains the observed enrichment.

The electrostatic field burst which is necessary for the AMI acceleration can be a result of a disruption of some current filament in the current sheet system forming the outer magnetosphere shape and its boundaries. The current filament disruption leads to the reconnection of magnetic field lines from two regions separated by the current sheet. After the disruption the current circuit could be rearranged so that it becomes closed through parallel currents and a high resistance ionospheric segment, but this rearrangement is not obligatory. In any case the total voltage drop on the magnetosphere due to convective solar wind electric field which is ∼100 keV develops over the small disruption region. The current here is a means of concentration in a small region of the potential difference and the energy distributed previously in a much greater volume.

The current sheet forming the magnetopause can be one possible place for the acceleration region giving AMI fluxes observed in the magnetosheath and upstream of the bow shock. Practically in all cases of AMI observation here the IMF B_z (GSM) was negative which is the neccessary condition for reconnection events. The cause of disruption here can be e.g. a solar wind plasma blob penetration (Lemaire at al., 1991) or some plasma instability.

The other even more instable current sheet is one separating magnetotail lobes with opposite magnetic field directions. It can be expected that current filament disruptions followed by magnetic field reconnections are more common features here and can proceed simultaneously in many points at the same time. Taktakishvili et al. (1998) showed than space averaged spectra of ions and electrons accelerated in such a process by the inductive electric field resulting from explosive increase of B_z component should have smooth power low (for ions) and exponential (for electrons) shapes. DOK-2 measurements showed that time averaged spectra in the plasma sheet have in most cases just such shapes. However the inductive electric field cannot produce monoenergetic lines. It can be done by the burst of the electrostatic field which must accompany the current filament disruption. Because the process is going simultaneously in many points with different values of the energy gain we can observe line structures in different parts of the spectrum measured inside of this active "boiling plasma" region. One example of such an observation was given in Figs. 3, 4. Outside of this region the spectra from many individual acceleration events will be mixed, giving in result a smooth shape. If some of the acceleration regions arise close to the plasma sheet-lobe interface the AMI from this individual event can propagate without mixing along the border field lines to the auroral zone and can be observed closer to the Earth as was for the cases shown in Fig. 2.

We see here as two different approaches: local particle – fields and global current system studies complement each other. The first one explains continuous spectra while the second one – the line spectra. This complementarity idea, which is common in elementary particle physics, was stated first for space plasmas by Alfvén (1977).

The sketch in Fig. 5 (a) illustrates our idea of AMI acceleration region formation by a current filament disruption on the magnetopause and in the plasma sheet. Fig. 5 (b) shows in details the acceleration regions (AR) in the plasma sheet and on the magnetopause with perpendicular electrostatic and magnetic fields and trajectories of ions and electrons. In the plasma sheet case the inductive electric field around AR also presents. The condition necessary for the ion acceleration without acceleration of electrons: the AR dimension along the electric field d should be less then the ion cycloid trajectory width and much greater then that for electrons. Our estimation for the magnetopause with B=20 nT, E=100

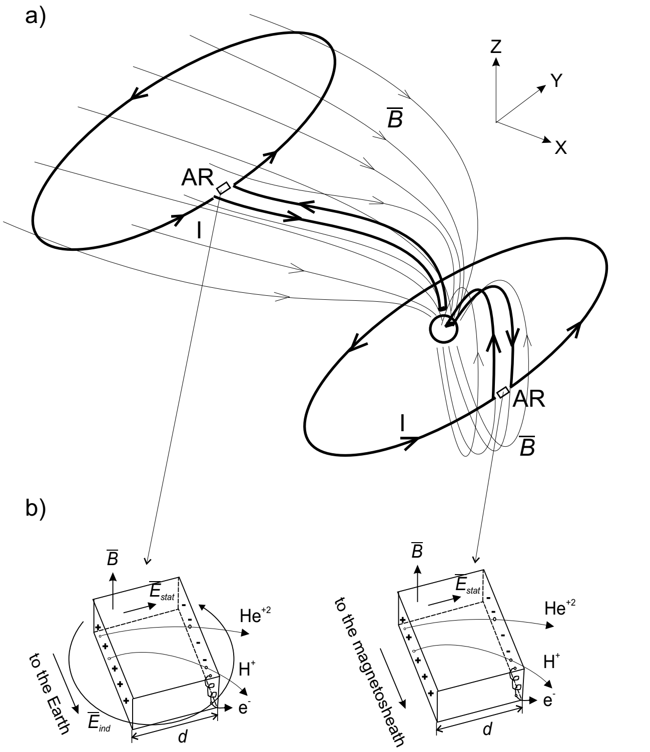

Fig. 5. (a) The sketch illustrating the idea of the AMI acceleration regions (AR) creation by a current filament disruption and a current circuit rearrangement on the magnetopause and in the tail plasma sheet. (b) The structure of the acceleration region AR with the perpendicular electrostatic E_{stat} and magnetic B fields and particles trajectories for the plasma sheet and the magnetopause. In the plasma sheet case the inductive electric field E_{ind} around the AR is also shown.

keV give d=1000–10000 km and the electrostatic field magnitude of 50–100 mV/m. The burst (∼1 min) of such a strong electrostatic field on the magnetopause was observed once by POLAR on May 4, 1998 (Wygant at al., 1998). This model seems to explain all main properties of AMI mentioned by Lutsenko at al. (1999).

4 Conclusions

In the great majority of all previously known mechanisms particles are accelerated essentially by the inductive electric field and this always results in smooth continuous spectra. Our observations of AMI give the evidence of great scale ion acceleration by the electrostatic fields and give a new support to the H. Alfvén concept on the great role of currents in cosmic plasmas (Alfvén, 1977). They show that some phenomena in near Earth's plasma cannot be understood studying only local plasma and fields properties without considering the dynamics of such global structures as current sheets.

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