GEOPHYSICAL RESEARCH LETTERS, VOL. 26, NO. 3, PAGES 413-416, FEBRUARY 1, 1999

Almost monoenergetic ions near the Earth's magnetosphere boundaries

Volt N. Lutsenko

Space Research Institute, Russian Academy of Sciences, Moscow, Russia

Karel Kudela

Institute of Experimental Physics, Slovak Academy of Sciences, Košice, Slovakia

Abstract. More than 200 cases of energetic ion beams with an energy spectrum consisting of 1–3 narrow lines were observed during a period from August 1995 to August 1998 in the Earth's magnetosheath and in the region upstream of the Earth's bow shock. The observations are from the DOK-2 experiment on board of the Interball-1 spacecraft. Because the relative width at half maximum of these lines is of only 15–30%, we use the term "Almost Monoenergetic Ions" (AMI) for these events. 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 main features of AMI as solar wind ions acceleration in a strong electrostatic field burst in a small region, possibly on the magnetopause or on the bow shock.

Introduction

It is generally accepted that particles with energies of tens to hundreds of keV which are observed in the Earth's magnetosheath 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 the Fermi process upstream of the bow shock [*Lee*, 1979] and by the shock-drift acceleration process at the bow shock itself [*Decker*, 1988]. Sometimes energetic particles of solar and interplanetary origin are also observed in these regions. All these sources give continuous, smooth ion energy spectra with a negative slope at E>50 keV. Such spectra were observed in numerous space experiments during last thirty years. In this connection the discovery of almost monoenergetic, of a short duration (~1 min), but often very intensive beams of energetic ions in the above mentioned regions was quite unexpected. The measurements were made with the DOK-2 instrument on board of the Interball-1 spacecraft (see [*Lutsenko at al.*, 1995, 1998] for details). Ion energy values varied for different events from 30 to 600 keV but they were almost unchanged during each event. The relative width at half maximum of these lines varied from 15 to 30%, therefore we use the term "Almost Monoenergetic Ions" (AMI) for these events. The fact that AMI events were not observed in numerous previous experiments can be explained by 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 of either some instrumental effects or some space or time dispersion effect. We deal here possibly with some new process in near Earth's plasma or some unexpected manifestation of previously known processes.

Paper number 1999GL900002.
0094-8276/99/1999GL900002$05.00

Experiment DOK-2 and Examples of AMI Spectra

The DOK-2 spectrometer measured energy spectra of electrons and of ions using four telescopes with solid state silicon detectors. The energy ranges and resolutions were: 20–850 keV and 7–9 keV for ions, 25–400 keV and 5–6 keV for electrons. The spectra were measured in these ranges by amplitude analyzers with 56 logarithmically spaced channels. The high energy resolution is what has made the AMI discovery possible. Full description of the instrument was published elsewhere [*Lutsenko at al.*, 1995, 1998].

The upper panel of Figure 1 shows an example of "normal" ion spectra measured by DOK-2 in the solar wind on April 14, 1996. The great majority of spectra measured in the solar wind and in the magnetosheath were of such a type. The lower panel of Figure 1 shows examples of AMI spectra with one, two and three narrow lines measured upstream of the bow shock. For the spectrum a) the accumulation time interval depending on the particle intensity was of only 6 s and the spectrum consists practically of the single line. Four successive spectra like this one were measured during 27 s. The least square fitting of the peak with a Gaussian gives a maximum energy of 90.9 keV and a full width at half maximum (FWHM) of 18.3 keV. Taking into account the detector resolution (7 keV) the intrinsic ion line FWHM was of 16.9 keV. For spectra b) and c) the measurment time interval was much greater (658 s and 347 s). This is why these spectra consist of two components: a "normal" continuous spectrum of power low type and an AMI spectrum with 2 or 3 lines. All these types of spectra were also observed in the magnetosheath. More than 200 AMI events were found in these regions from August 1995 to August 1998.

Because such line spectra have never been observed previously we first studied the possibility that the AMI spectra were due to some instrumental effects. The experiment preparation lasted ~ 6 years and DOK-2 was tested and studied extensively during this time. No peak signatures were noticed in the spectra except the time when a pulse calibrator or isotope sources were applied. During 3 years of flight time the instrument operated as expected and con-

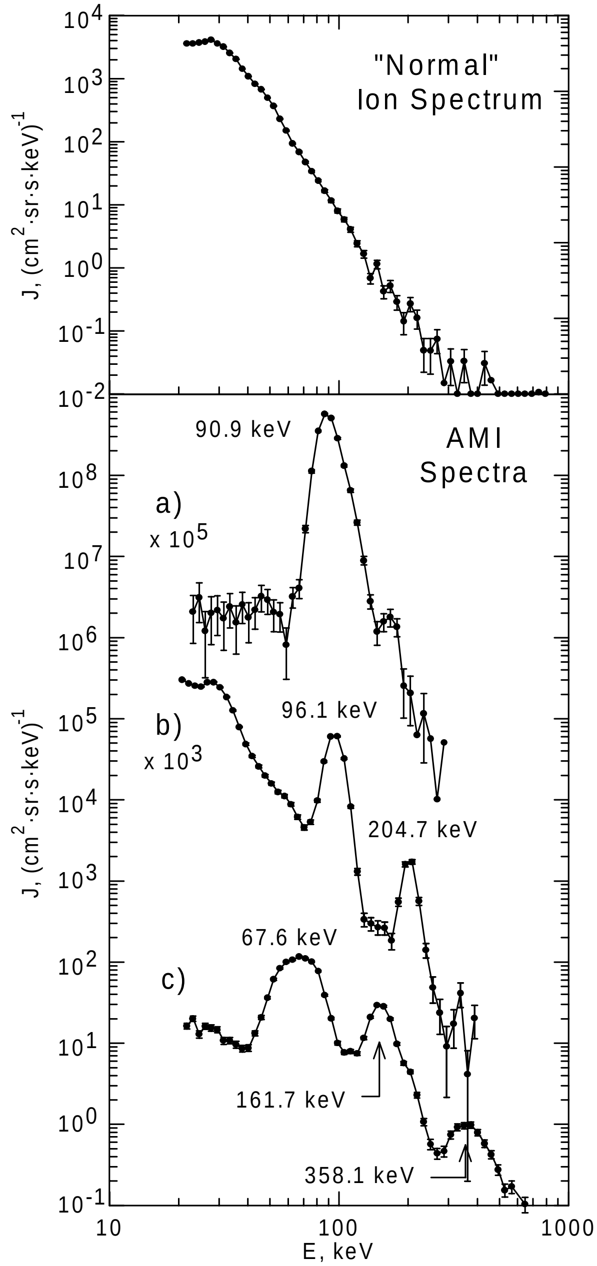

Figure 1. The upper panel shows the typical energetic ion spectrum of "normal" type measured by the 1p telescope of the DOK-2 instrument upstream of the bow shock on April 14, 1996 01:19:15 UT. The spacecraft GSE coordinates were X=14.04, Y=8.30, Z=12.91 R_E. The bottom panel shows examples of AMI spectra with one a), two b) and three c) peaks measured upstream of the bow shock. The telescope designation, the observation time, the spectrum accumulation time ΔT, GSE coordinates of the spacecraft (in R_E units) and the angle θ of the telescope axis with the X-axis of the spacecraft were: a) 1p, April 14, 1996, 02:57:56 UT, ΔT=6 s, X=15.27, Y=9.28, Z=13.05 and θ=180°; b) 2p, August 16, 1995, 01:45:38 UT, ΔT=658 s, X=4.30, Y=-28.32, Z=11.28 and θ=45°; c) 1p, May 5, 1996, 12:50:47 UT, ΔT=347 s, X=18.52, Y=6.83, Z=-2.44 and θ=180°.

served all regularly checked calibration parameters, which correspond to preflight values. In addition the following facts provide evidence that the AMI spectra cannot be a result of instrumental effects:

– The AMI peaks in DOK-2 spectra are smooth and consist of many points. The FWHM exceeds that from a pulser and has always values of 15–30%. Such a shape cannot be the result of some accidental disturbances, e.g. "Single Event Upsets" in memory cells from cosmic rays or some interference by data transmission.

– Many times, when it was possible to measure several successive spectra during an AMI event, these spectra resembled each other showing only smooth variations of the peak intensity and energy.

– The AMI events were observed only in certain regions: upstream of the bow shock, in the magnetosheath and were not observed in the outer magnetosphere near the magnetopause while conditions and particle intensities were about the same (see Figure 2).

– The AMI events were observed in the solar wind only when the spacecraft was connected with the bow shock by IMF.

– The AMI events were observed only by that of two ion telescopes which was directed closer to the connection point with the front part of the bow shock or the magnetopause.

– All of 200 registered AMI events have spectra measured with a very good statistical accuracy and have narrow lines. We rejected all cases with a poor statistics and those with peaks which are too wide and not certain.

Main Properties of AMI

Our analysis of AMI events allows to summarize their main properties as follows:

1. AMI events were observed in the magnetosheath and upstream of the bow shock during periods of magnetic field connection of the spacecraft with the magnetopause or with the bow shock by that of two energetic ion telescopes which was directed closer to the side of the connection. Figure 2 shows the spatial distribution of the observation points. In the solar wind it was 1p telescope looking antisunward while in the magnetosheath it was mainly 2p-telescope looking 62° to Sun direction. No AMI were observed in the outer magnetosphere inside of the magnetopause. Figure 2 does not allow us to determine definitively whether the AMI source is on the magnetopause or on the bow shock. More detailed analysis of the magnetic field direction and the AMI flux angular distribution for individual events may probably help to define the source position.
2. An important feature of AMI is the total absence of energetic electron fluxes exceeding background level during AMI events.
3. A typical event duration is $\sim$ 1 min.
4. Spectra of AMI consist of several narrow lines with a relative FWHM of 15–30%.
5. The line energies are rather constant during the event without evident signatures of time-of-flight dispersion. For different events they vary from 30 to 600 keV. An average energy of the first line in 2 and 3 lines spectra is of 78 keV.
6. In two peak spectra the energy values ratio was 1:2, in three peak ones the ratios were 1:2:(5–6). The scatter plot in Figure 3 illustrates this fact. The peak area ratios show significant spread with average values of 1:0.26:0.02. The coincidence of the energy ratio values for the first and the second peaks in both cases and similar values of the 1-st peak average energy led us to a conjecture that the 3 line spectra are the most common type. One and two peak spectra were possibly observed when some lines come out of the energy or intensity ranges of the instrument or were cut by

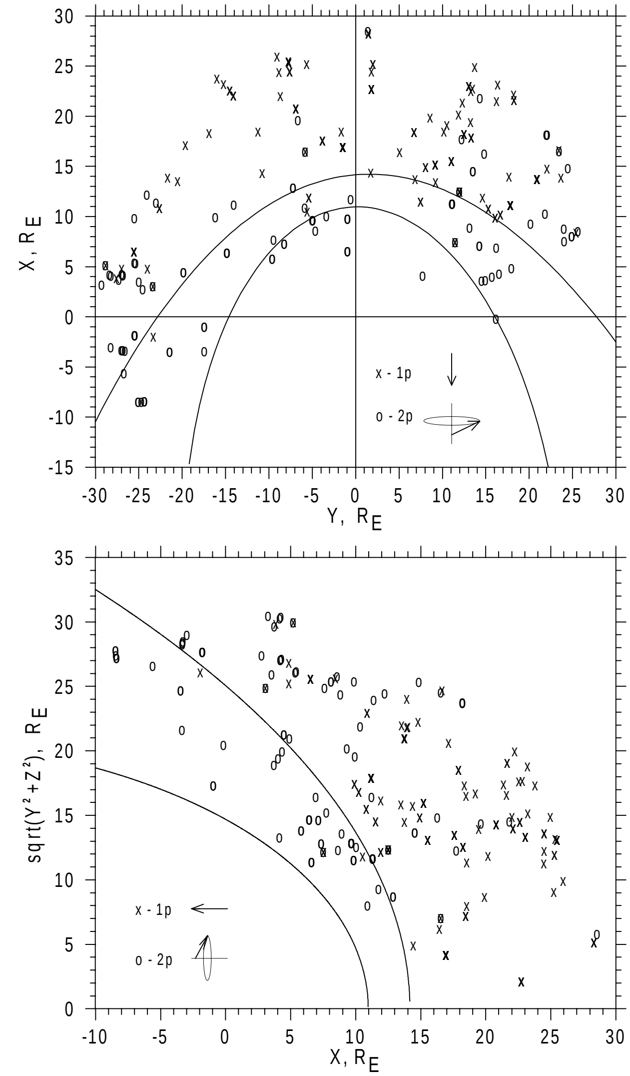

Figure 2. The spatial distribution of AMI event observation points and the average position of the magnetopause and the bow shock according to V. Formisano model [*Formisano*, 1979; *Formisano at al.*, 1979]. The angles of 1p telescope (crosses) and 2p telescope (circles) axes with the spacecraft X-axis directed to the Sun were 180° and 62° (45° before November 1, 1995).

some natural velocity filter like $\bar{E} \times \bar{B}$ drift in the solar wind. Characteristics of AMI spectra in the solar wind and in the magnetosheath are similar.

7. The widths of the first and the second peaks are well correlated $\Delta E_2 = 2 \cdot \Delta E_1$. The third peak is always broader and possibly consists of several unresolved peaks.

8. The absolute intensity of AMI has a great spread from 0.3 to 10^4 cm^{-2} sr^{-1} s^{-1} keV^{-1}.

9. So far we have not found any special conditions and disturbances in the solar wind and interplanetary magnetic field before and during AMI events. Our estimates show that interplanetary media parameters changes in the AMI observation point should be very small and hardly measurable. Indeed, the magnetic field from the most intensive AMI beam with E=100 keV, ΔE=20 keV, J=10^4cm^{-2} sr^{-1}s^{-1}keV^{-1} and the beam radius R=$5 \cdot 10^8$ cm will be from 0 to 1 nT depending on the distance from the beam axis. The plasma waves excited by such an AMI beam will be effectively damped by solar wind plasma electrons which thermal velocities ($3.2 \cdot 10^8$ cm/s at E=30 eV) are close to the AMI velocity ($4.3 \cdot 10^8$ cm/s at E=100 keV).

Possible Origin of AMI

The fact of existence and main properties of AMI cannot be explained in the framework of currently accepted models of particle acceleration and propagation in the magnetosphere. It is possible, in principle, under special conditions to select a rather narrow interval from a "normal", continuous spectrum by such natural velocity filters as time-of-flight and $\bar{E} \times \bar{B}$ ion drift in the solar wind. Our analysis shows that although such filters can modify AMI spectra they cannot explain all of their features. The observed line structure of AMI spectra should be created by a process of ions acceleration.

The line energy ratios in 2 and 3 peak spectra suggest that AMI may be explained as H^+, He^{++} and $(C,N,O)^{+(5-6)}$ solar wind ions accelerated in a burst of electrostatic field to energies proportional to their charges q. This hypothesis can be checked by direct ion mass analysis experiments. The intensity ratios of accelerated ions show an enrichment by heavy components in comparison with the solar wind composition. This fact and the absence of energetic electrons can be explained if we suppose that the acceleration takes place in a region with perpendicular electric and magnetic fields in which the scale size d along the electric field direction is smaller then the width of an ion cycloid trajectory and is greater then that for an electron trajectory. In such a small region electrons are totally magnetized and will be swept by $\bar{E} \times \bar{B}$ drift without acceleration. Ions which are not magnetized can pass through the region and gain the energy $q \cdot E \cdot d$. By the same reason the relative number of He^{++} and $(C,N,O)^{+(5-6)}$ ions involved in the acceleration will be greater then for H^+ what explains the observed enrichment.

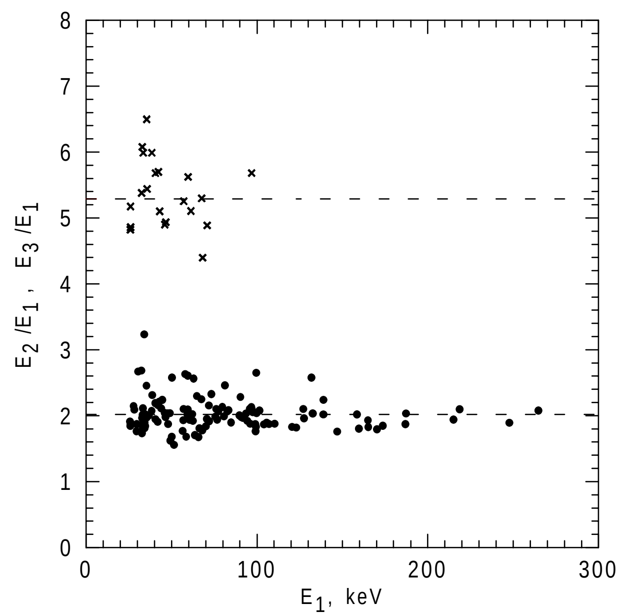

Figure 3. Ratios of peak energies E_2/E_1 (circles) and E_3/E_1 (crosses) for AMI spectra with 2 and 3 peaks. Average ratio values (dashed lines) are 2.02±0.25 (points number N=126) and 5.21±0.75 (N=24).

The most probable place for the AMI acceleration region is the magnetopause however, as it was stated above, the bow shock cannot be excluded. Our estimates show that by B=20 nT, the electric field magnitude of 50–100 mV/m and E=100 keV the scale of the region d should be of several thousands km. The average value of the first peak energy in AMI spectra is approximately equal to the total potential difference on the magnetopause due to the solar wind convection electric field ($\sim$100 keV). If the convective electric field is the initial cause of the AMI then some mechanism should exist which leads to a concentration of this great potential difference across a small acceleration region.

Conclusions

A new class of energetic particle events — Almost Monoenergetic Ion beams near Earth's magnetosphere boundaries was discovered by the DOK-2 experiment on board of the Interball-1 spacecraft. Our study of AMI properties suggests that they are solar wind ions accelerated in a burst of a strong, perpendicular electrostatic field in a region which dimension along the electric field direction is lower than the ion cycloid trajectory width and is greater then the electron one.

Acknowledgments. Very important comments and constant encouragement by Dr. L.M. Zelenyi are greatly appreciated. We are grateful to Dr. E.T. Sarris, Demokritos University of Xanthi, Greece, for his contribution in development of DOK-2 device and to J. Rojko, IEP SAS, for his great role in the DOK-2 design and the experiment preparation. This work was supported for V.N.L. by grants INTAS 96-2346, RFFI 96-15-96723, 96-05-64534 and for K.K. by grant of Slovak Academy of Sciences 2/5137.

References

Decker R.B., Computer modeling of test particle acceleration at oblique shocks, *Space Sci. Revs., 48,* 195–262, 1988.

Formisano V., Orientation and shape of the Earth's bow shock in three dimensions, *Planet. Space Sci., 27,* 1151–1161, 1979.

Formisano V., V.V. Domingo, K.-P. Wenzel, Three-dimensional shape of the magnetopause, *Planet. Space Sci., 27,* 1137–1149, 1979.

Kudela, K., D.G. Sibeck, R.D. Belian, S. Fischer, V.N. Lutsenko, Possible leakage of energetic particles from the magnetosphere into the upstream region on June 7, 1985, *J. Geophys. Res., 95,* 20825–20832, 1990.

Lee M.A., Coupled hydromagnetic wave excitation and ion acceleration upstream of the bow shock, *J. Geophys. Res., 87,* 5063–5080, 1982.

Lutsenko V.N., J. Rojko, K. Kudela, T.V. Gretchko, J. Balaž, J. Matišin, E.T. Sarris, K. Kalaitzides, N. Paschalidis, Energetic Particle Experiment DOK-2 (INTERBALL Project), *INTERBALL, Mission and Payload, RSA, SRI, CNES,* p. 249–255, 1995.

Lutsenko V.N., K. Kudela, E.T. Sarris, The DOK-2 experiment to study energetic particles by Tail Probe and Auroral Probe satellites in the Interball project, *Cosmic Research, 36,* 93–102, 1998.

V. Lutsenko, Space Research Institute, Russian Academy of Sciences, Profsoyuznaya 84/32, 117810 Moscow, Russia. (e-mail: vlutsenk@volt.iki.rssi.ru)

K. Kudela, Institute of Experimental Physics, Slovak Academy of Sciences, Watsonova 47, 04353 Košice, Slovakia. (e-mail: kkudela@kosice.upjs.sk)

(Received May 25, 1998; revised December 7, 1998;
accepted December 23, 1998.)