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Upstream and magnetosheath energetic ions with energies to ≈2 MeV

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Abstract. We present the first observations of ≈2 MeV ion bursts detected in the upstream region and the magnetosheath by the three-dimensional (3D) plasma and energetic particles instrument on the WIND spacecraft. This instrument measures the full 3D distribution of particles from a few eV to several MeV, and allows characterization of the upstream ions in both pitch angle and energy. The new feature observed is the presence of bursts of ions at energies extending up to ≈2 MeV, both upstream and in the magnetosheath. The observation of MeV ions has strong implications for the ion source and acceleration mechanisms.

Introduction

The WIND 3D plasma and energetic particle (3DP) experiment consists of electrostatic analyzers (ESA) and solid state telescopes (SST) which obtain 3D phase space distributions of electrons and ions with energies from a few eV to a few MeV [*Lin et al.,* 1995]. Upstream energetic ions can be observed even at the libration point L1, ≈230 R_E from the Earth [*Anderson,* 1981; *Sanderson,* 1983]. Two sources have been suggested for upstream energetic ions: (1) solar wind ions that have been accelerated by the Fermi mechanism at the bow shock [e.g. *Terasawa,* 1979; *Scholer et al.,* 1990], and (2) leakage of magnetospheric ring current particles [e.g. *Sarris et al.,* 1987; *Sibeck et al.,* 1988]. The same two mechanisms have been proposed for energetic particles in the magnetosheath [e.g. *Paschalidis et al.,* 1994].

The results presented here are the first observations of upstream and magnetosheath ion bursts at energies up to ≈2 MeV. These observations extend previous measurements, which have shown that upstream ions can have energies up to several hundred keV [e.g. *Lin et al.,* 1974; *Scholer et al.,* 1981]. The extension to ≈2 MeV places new requirements on the ion source since, as will be discussed below, it extends the burst energy from a range which is consistent with either a bow shock or magnetospheric source to a range which cannot be easily produced by Fermi acceleration. A different physical process may thus be required to produce these very high energy bursts. The purpose of this paper is to characterize the energy spectra and pitch angle distributions of the ≈2 MeV ions in the upstream and magnetosheath regions.

Observations

Figure 1 shows an eight hour example of the ion fluxes observed by the 3DP experiment from 1300–2100 UT on November 30, 1994. The bottom 9 lines in the figure are taken from the SSTs, and show ions from 30–7200 keV with 6 second time resolution. The top 8 lines show 0.96–32 keV ions from the ion ESA, measured with 48 second time resolution. Both data sets have been averaged over all angles, and are in the spacecraft reference frame. During this time period, WIND was moving toward the Earth nearly along the sun-Earth line from ≈21.4 R_E to 11.1 R_E. The satellite crossed the bow shock at ≈1920 UT at a distance of 13.6 R_E from the Earth, and the magnetopause at ≈2130 UT (not shown).

Many familiar features of upstream events are discernible in the display, for example, typical bursts of energetic ions lasting from a few minutes to a half hour. The bursts occur primarily at energies above 5 keV, and in some cases only at energies above 30 keV (e.g. from 1505–1525 UT). Most of the bursts extend no higher in energy than the 670–1370 keV channel, and many (e.g. 1810 UT, 1500-1600 UT) include ions up to only a few hundred keV. Some bursts show a "flat-topped" structure at energies from ≈13–85 keV, in which the ion flux increases rapidly, and then remains at a high level for several minutes. This structure is not due to detector saturation.

We call attention to bursts which extend into the 1.4–2.8 MeV energy channel, for example, the upstream bursts at ≈1355 UT and 1640 UT and the magnetosheath burst at ≈2040 UT. The average energy in this channel, as obtained from the energy spectra below, is 1.8 MeV, so we will refer to particles in this channel as "2 MeV ions". To the best of our knowledge, this is the first report of such high energy ion bursts in

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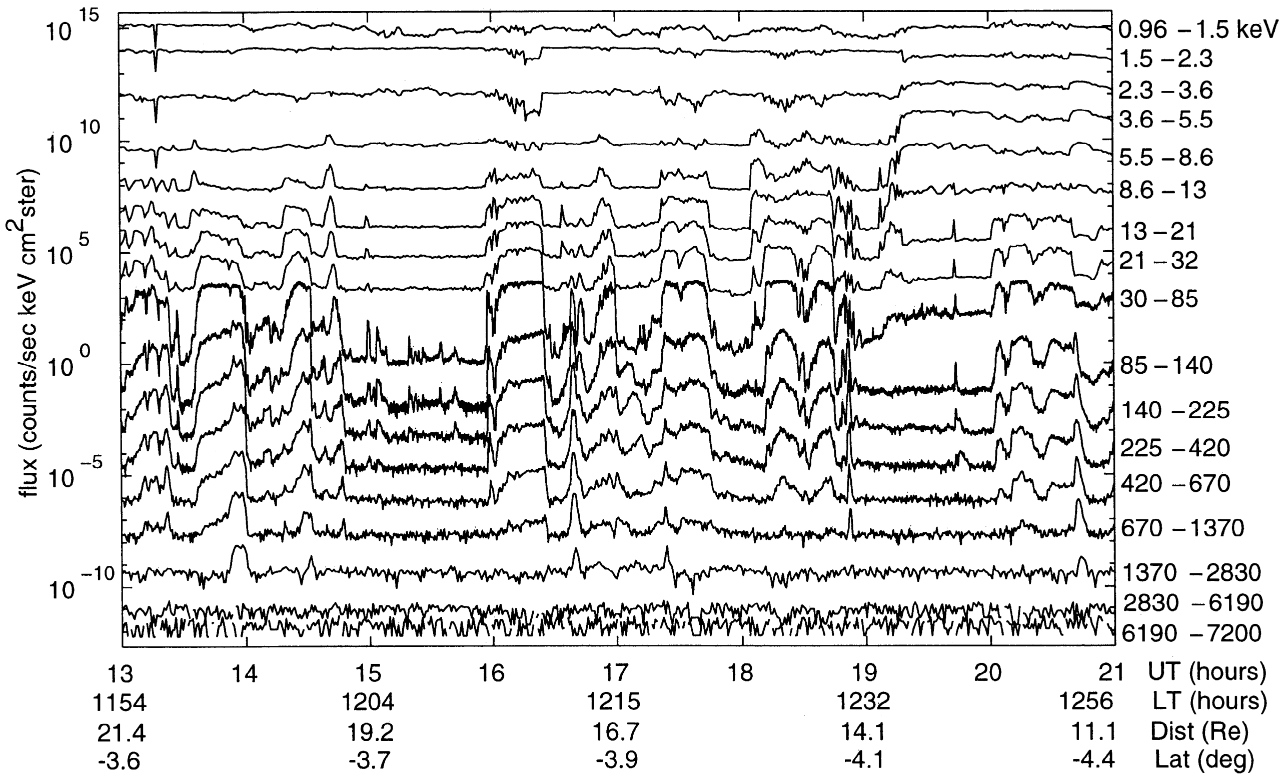

Figure 1. Eight hours of data from the ion ESA and SSTs. The data have been averaged over all angles. To clarify the display, each energy channel has been offset by a factor of 10 relative to the previous channel, i.e. 30-85 keV are actual fluxes, 21–32 keV are flux×10, 85–140 keV are flux/10, 140–225 keV are flux/100, etc.

these regions of space. The bursts in the 1.4–2.8 MeV channel last only a few minutes and are in general of much shorter duration than the corresponding bursts at lower energies. The 2 MeV particles can occur at either the trailing edge (1355 UT, 1445 UT) or the leading edge (1722 UT) of a low energy burst. In some cases (1640 UT), the burst is of short duration at all energies up to 2 MeV. Ion bursts including 2 MeV particles were also observed both upstream and in the magnetosheath during the other perigee passes of WIND.

Energy Spectra and Pitch Angle Distributions

Figures 2a and 2b show examples of the ion energy spectrum during the burst from 1335–1405 UT. Fig-

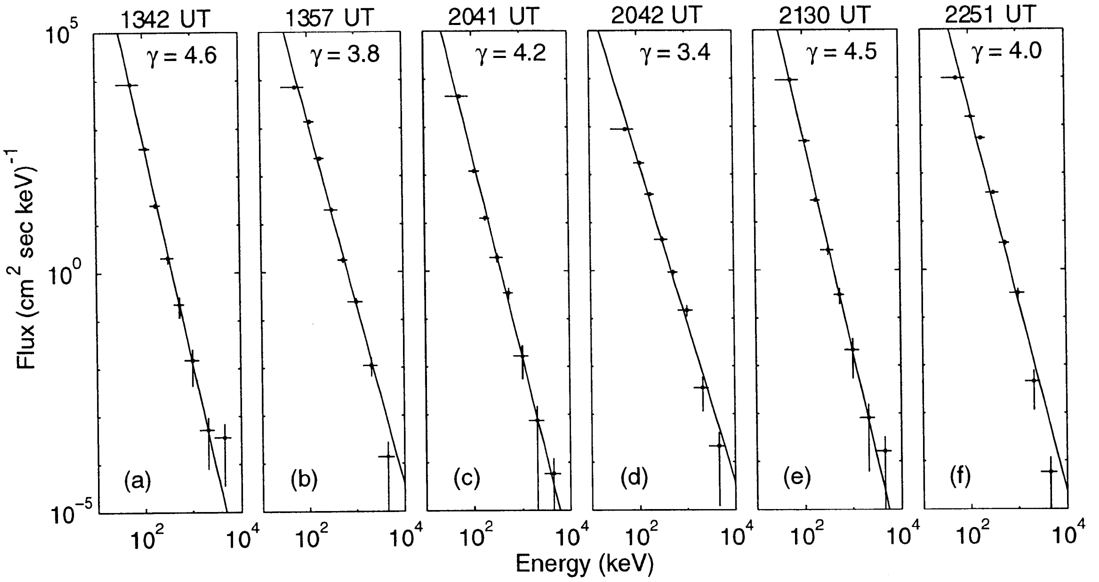

Figure 2. Six examples of the energy spectrum measured by the ion SSTs. The spectra in 2a-c and 2e-f are 48 second averages, and the spectrum in 2d is a 150 sec average. Panels a and b show the spectrum during an upstream burst, panels c and d show the spectrum during a magnetosheath high energy ion burst, and panels e and f show the spectrum inside the magnetosphere.

ure 2a shows the energy spectrum during the initial portion of the burst (prior to the appearance of the 2 MeV ions) at 1342 UT. Figure 2b shows the spectrum during a later portion of the burst, at 1357 UT, which includes the 2 MeV ions. The initial spectrum can be well described by a power law form, $dj/dE \propto E^{-\gamma}$, with $\gamma = 4.6$ over the energy range shown. The spectrum which includes the 2 MeV ions is harder, but can also be fit by a power law form with $\gamma = 3.8$.

The same power law behavior characterizes the magnetosheath burst. Figure 2c shows the spectrum during the early portion of this burst, before the 2 MeV ions were detected. This spectrum, similar to the spectrum in the upstream region (1342 UT), is fit by a power law form with $\gamma = 4.2$. Figure 2d shows a spectrum during the portion which includes the 2 MeV ions. This magnetosheath burst showed strong inverse velocity dispersion, with both the leading and trailing edges of the burst occuring at earlier times for lower energy particles. This dispersion produced complex energy spectra, and thus 150 sec of data were used to produce a spectrum. This spectrum is very hard, and is fit by a power law distribution with $\gamma = 3.4$.

Figure 3 shows examples of the phase space distributions of 50 keV–3.3 MeV ions during the upstream burst at 1357 UT and the magnetosheath burst at 2043 UT. These distribution contours are shown in the solar wind frame of reference. The upstream distribution (Figure 3a) is quite anisotropic in the parallel direction, with more particles traveling along the magnetic field direction. Since, at this time, the magnetic field pointed primarily Earthward, the majority of the high energy particles were traveling sunward.

The magnetosheath burst at 2040 UT also included more parallel than anti-parallel ions prior to the detection of the 2 MeV ions (not shown). The magnetic field during this burst pointed dawnward, hence the flow was duskward. At the time when the highest energy ions were detected, however, Figure 3b shows that the distribution evolved to a loss-cone type, with more particles at 90° pitch angle. The beam of ions parallel to the field at $\approx 8 \times 10^3$ km/s (330 keV) shows the inverse velocity dispersion.

Discussion

The 3DP instrument on the WIND satellite has detected for the first time bursts of ions in the upstream region and in the magnetosheath with energies up to ≈ 2 MeV. To identify the source of the upstream ions, we first note that the lower energy bursts in our data are similar to the upstream ion events previously observed by *Scholer et al.,* [1981; 1990]. The energy spectra for these lower energy bursts ($>$ 30 keV) are not well fit by either a power law or an exponential form. *Scholer et al.,* [1990] have suggested that these ions are solar wind ions accelerated by the Fermi mechanism at the bow shock. The Fermi mechanism can accelerate particles to produce low energy ion bursts, up to a few hundred keV [*Scholer et al.,* 1990] but cannot be responsible for the 2 MeV ions unless they are in high charge states, as discussed below.

On the other hand, the energy spectra of the 2 MeV bursts are well fit by a power law form. Some previous upstream observations at lower energies also have shown power law type energy spectra [*Anderson et al.,* 1981; *Sarris et al.,* 1987]. *Sibeck et al.,* [1988] have suggested that this type of burst may have a magnetospheric origin, and we now test this possibility. Figure 2e shows the spectrum measured at 2130 UT, just after WIND crossed the magnetopause at a distance of 10.3 R_E. This spectrum has a power law form with

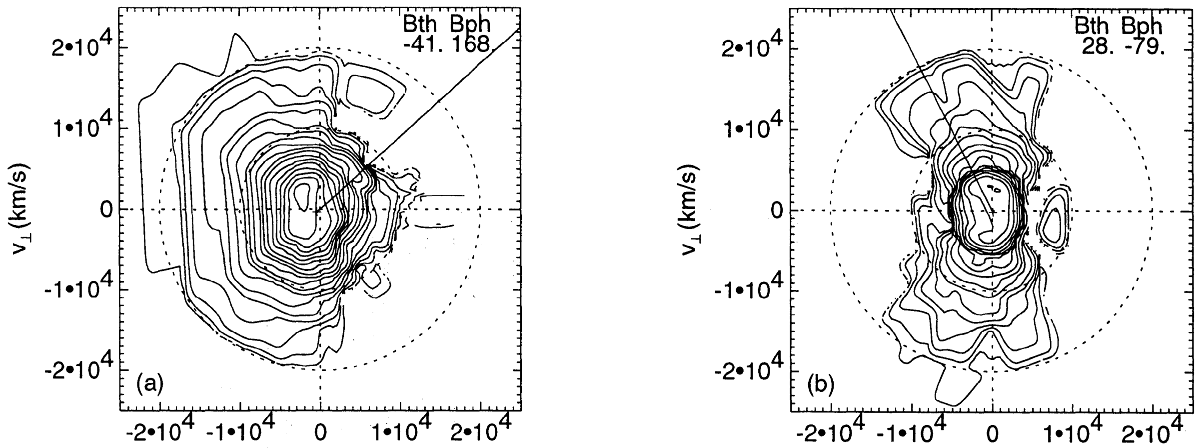

Figure 3. The pitch angle distribution of 50–3300 keV (3×10^3–2.5×10^4 km/s) ions during bursts which include 2 MeV ions. Panel a is taken from the upstream burst at 1357 UT, and Panel b from the magnetosheath burst at 2043 UT. The measured 3D distribution was transformed to the solar wind frame, and then folded into the plane containing V_{SW} with B along the x-axis. Information about the sign of V_y was retained to preserve non-gyrotropic features. The contours were produced by interpolating the data onto a regular grid. Contours which pass inside the low energy cutoff of ≈ 50 keV (3×10^3 km/s) are due to this interpolation and do not represent actual data. The line indicates the solar wind flow direction, and the plot also shows the magnetic field direction (GSE θ and ϕ). Contours are shown with a spacing of $10^{0.4}$ from 5×10^{-22}–2×10^{-14} (cm^3 (cm/s)^3 ster)$^{-1}$.

$\gamma = 4.5$, and is nearly identical to both the upstream spectrum shown in Figure 2a and the magnetosheath spectrum in Figure 2c (no 2 MeV ions). Figure 2f shows a spectrum observed deeper inside the magnetosphere (at ≈ 8 R_E) at 2251 UT. This spectrum fits a power law distribution with $\gamma = 4.0$, and is very similar to the upstream spectrum at 1357 UT (after the 2 MeV particles arrive). The energy spectra of the high energy ion bursts and of particles in the magnetosphere are similar, suggesting that the magnetosphere may be a source of these particles. However, note that the magnetosheath spectrum which includes the 2 MeV ions (Figure 2d) is harder than both the upstream and magnetospheric spectra. Note also that the pitch angle peaks at 90° during the magnetosheath burst, supporting this conclusion, although the sunward flow observed upstream indicates either a magnetospheric or bow shock source.

Finally, note that a bow shock source for the 2 MeV ions is not ruled out if the ions we detected are oxygen. However, since the Fermi mechanism is limited to acceleration of ions to a few hundred keV/charge, it would require that the oxygen be in a higher charge state (e.g. O^{+6}). Although the ion composition experiment on WIND did detect fluxes of oxygen during the 2 MeV bursts [*Glenn Mason, personal communication,* 1995], the charge state experiment on WIND had not been activated on November 30, 1994. Thus we are not able to determine at this time whether the O^{+6} accompanied the 2 MeV events. Other WIND perigee passes which include the ion composition data are now being studied which should yield more definitive information on the source of these high energy ions.

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