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WIND Observations of energetic ions far upstream of the Earth's bow-shock

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Abstract. During the first year of operation, the WIND spacecraft followed a complicated orbit which took it from the Earth to the upstream libration point and back again. During this time, a considerable number of upstream particle events were observed all the way out to the libration point. These events are typically of short duration (a few tens of minutes) and up until now have only been seen in the energetic protons (at energies of a few tens of keV, but extending up to several hundreds of keV). We present here new observations from the Three-dimensional (3D) plasma and energetic particle experiment on the WIND spacecraft of these upstream events, with particular emphasis on the uniqueness of the observations from this instrument: energy spectra measured over the range from a few keV to several hundreds of keV, and complete three-dimensional angular distributions covering the same range of energies. We present here for the first time a complete spectrum of these ions extending from a few eV to a few MeV. This spectrum, with a turnover at one or two keV, shows that the bulk of the energy density of the upstream ions is at around 1 keV. These are most likely the particles responsible for the low-frequency waves which are usually seen accompanying upstream events.

Introduction

Almost 20 years ago, the ISEE-3 spacecraft visited for the first time the region around the Earth's upstream libration point, discovering upstream events extending far upstream from the bow shock [Sanderson et al., 1979, Scholer et al., 1980, Anderson et al., 1981, Sanderson et al., 1981a, 1981b]. These events were seen all the way out to the libration point ~240 R_E from the Earth when the magnetic field provided a connecting path from the magnetosphere to the spacecraft [Sanderson et al., 1981a]. The events were characterised by sudden increases in the energetic ion counting rates. Onset times were often only a few tens of seconds, durations a few minutes up to a few hours. Increases were observed at energies up to a few hundreds of keV, with the largest increases being seen at a few tens of keV (the lower limit of the instruments capabilities on board ISEE-3). Spectra were power law, very steep, with power-law spectral indices of ~ - 6 to - 7, which implied that only a small part of the distribution was being observed.

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At the start of the events at the libration point ~240 R_E upstream, highly anisotropic beam-like distributions were often observed. Later on in the events, the distributions broadened as associated low-frequency wave activity increased. On ISEE-3 no instrumentation was available to measure below ~35 keV. Gosling at al. [1981] showed for the first time composite spectra from ISEE-3 extending from solar wind energies up to several hundred keV, but in the upstream direction there was a gap between a few hundred eV and around 35 keV. With the limited energy range on board ISEE-3, it was not possible to completely examine this wave-particle interaction.

From resonant conditions, it was expected from the ISEE-3 observations that the particles responsible for these interactions were ions with energies of only a few keV. In this paper we present first observations of upstream ions on the WIND spacecraft from the Three-dimensional (3D) plasma and energetic particle experiment, and using the considerably greater energy range capabilities of the instrument, re-examine the question which of the particles reaching the upstream libration point carry the bulk of the energy density. Observations from the same instrument of upstream events extending up to ~3 MeV, and of the modeling of these events are presented in two companion papers, Skoug et al. [1996] and Winglee et al. [1996].

Instrumentation

The observations presented here were made with the Three-dimensional (3D) plasma and energetic particle experiment on the WIND spacecraft [Lin et al., 1995]. This instrument is designed to make measurements of the full three-dimensional distribution of supra-thermal electrons and ions from solar wind plasma to low energy cosmic rays, with high sensitivity, wide dynamic range, good energy and angular resolution, and high time resolution.

At low energies, top-hat symmetrical spherical section electrostatic analysers with microchannel plate detectors are used to measure ions (PESA) and electrons (EESA) from ~ 3 eV to 30 keV. All these analysers have either 180^0 or 360^0 fields of view in a plane, $\Delta E/E \sim 0.2$, and angular resolution varying from 5.6^0 (near the ecliptic) to 22.5^0. Full 4π steradian coverage can be obtained in one-half or one spin. A large and a small geometric factor analyser are used to measure ions over the wide flux range from quiet-time supra-thermal level to intense solar wind fluxes. Similarly, two analysers are used to cover the wide range of electron fluxes.

At higher energies, three arrays, each consisting of a pair of double-ended semi-conductor telescopes (SST), each with two or three closely sandwiched passivated ion implanted silicon detectors, measure electrons and ions above ~ 20 keV. One side of each telescope is covered with a thin foil which absorbs ions below 400 keV, whilst on the other side the incoming <400 keV electrons are swept away by a magnet so that electrons and ions are cleanly separated. Higher energy electrons (up to ~ 1 MeV) and ions (up to ~ 11 MeV) are identified by the two double ended telescopes which contain an extra third detector. The telescopes provide energy resolution $\Delta E/E \sim 0.3$, angular resolution of $22.5^0 \times 36^0$, and full 4π steradian coverage in one spin (3s). In this paper we use ion data from both the PESA and SST sensors.

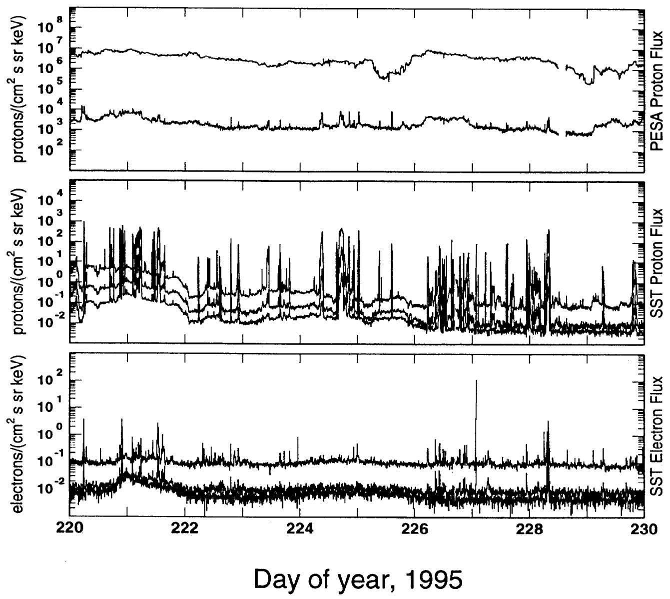

Figure 2. From top to bottom, proton fluxes measured by the PESA, proton fluxes measured by the SSTs, and electron fluxes measured by the SST's for the 10-day period commencing on 8 August 1995 (day 220) when the spacecraft was moving out from X_{gse}= 73.2 R_E, Y_{gse} = -12.6 R_E, to apogee at X_{gse}= 82.3 R_E, Y_{gse} = -1.3 R_E and back again to X_{gse}= 44.7 R_E, Y_{gse} = 19.1 R_E.

Observations

In Figure 1 we show the projection in the X_{gse}/Y_{gse} plane of the orbit of the WIND spacecraft from the time it left the magnetosphere until late in 1995. The spacecraft was launched in November 1994, and after a few highly elliptical orbits with an apogee of ~80 R_E, used a lunar swing-by to start its journey to the libration point. Upon returning to the Earth, another lunar swing-by was used to put the spacecraft into orbit around the Earth again, orbiting the Earth with an apogee of ~ 80 R_E.

In Figure 2 we show a summary of data from the PESA and the SST for the 10-day period starting on 8 August 1995 (day 220), when the spacecraft was close to the apogee of ~82 R_E of one of the highly-elliptical orbits around the Earth. This covers the period shown with the thick line in Figure 1.

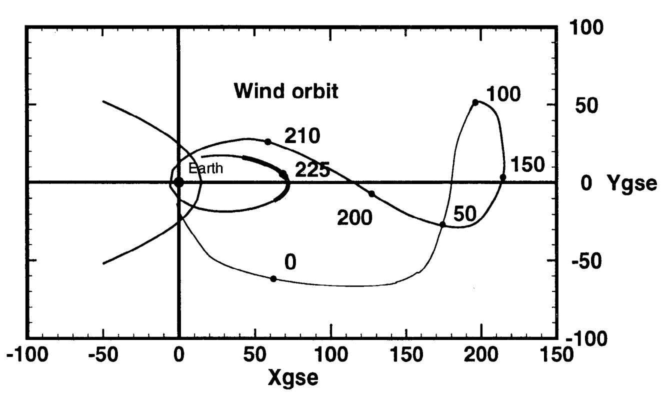

Figure 1. The orbit of the WIND spacecraft, projected onto the X_{gse}/Y_{gse} plane. After launch, the spacecraft performed several orbits around the Earth (not shown here), before using a lunar swing-by to travel out to the upstream libration point. After reaching the libration point, the spacecraft returned to the Earth, performing again several orbits around the Earth. Data from the thick part of the orbit is shown in Figure 2, whilst data from day 225 is shown in Figures 3 and 4.

The top panel of Figure 2 shows two energy ranges from the PESA instrument, 1.3 to 7 keV, and 8 to 30 keV. The second panel shows three proton ranges from the SST, 20 to 58 keV, 58 to 126 keV, and 115 to 400 keV. The bottom panel shows three electron energy ranges from 20 - 48 keV, 43 - 138 keV, and 127 - 225 keV from the SST's. Several upstream events can be seen as vertical spikes lasting typically only a few minutes to a few hours in the 8 - 30 keV proton channel of the PESA, the 20 - 58, 58 - 126 and 115 - 400 keV proton channels from the SSTs, and in the 20 - 48 and 48 - 138 keV electron channels of the SSTs, superimposed upon a small longer-lasting solar event. There are periods when many upstream events are observed (e.g., days 226 and 227) and other periods when very few events are observed (e.g., day 229). This behaviour is seen throughout the mission, and is most likely due to changes in the long-term average direction of the magnetic field.

In Figure 3 we show a typical short upstream event, as observed on 13 August 1995 (day 225) when the spacecraft was close to the Sun-Earth line, at an upstream distance of around 80 R_E (X_{gse}= 79.1 R_E, Y_{gse} = 5.4 R_E). At this distance it is well outside the free escape region of Mitchell et al. [1983], and so is typical of events seen all the way out to the libration point.

In the top panel we show data from the 14 PESA channels, covering the energy range, from top to bottom, from ~100 eV to ~27 keV. In the lower panel we show data from 9 channels from the SST open detectors, covering the range 56 keV to 7.14 MeV. The upstream event starts at ~14:15 UT and lasts for around 25 minutes. Here we have averaged the PESA data over one-quarter of spin to include only those particles coming from the direction of the Earth. In this way, we can reject the solar wind particles, and so see the event down to energies of ~ 1 keV. The event is seen in the 1.0, 1.8, 2.7, 4.5, 7, 12, 18 and 27 keV quarter-spin-averaged channels of the PESA, and also in

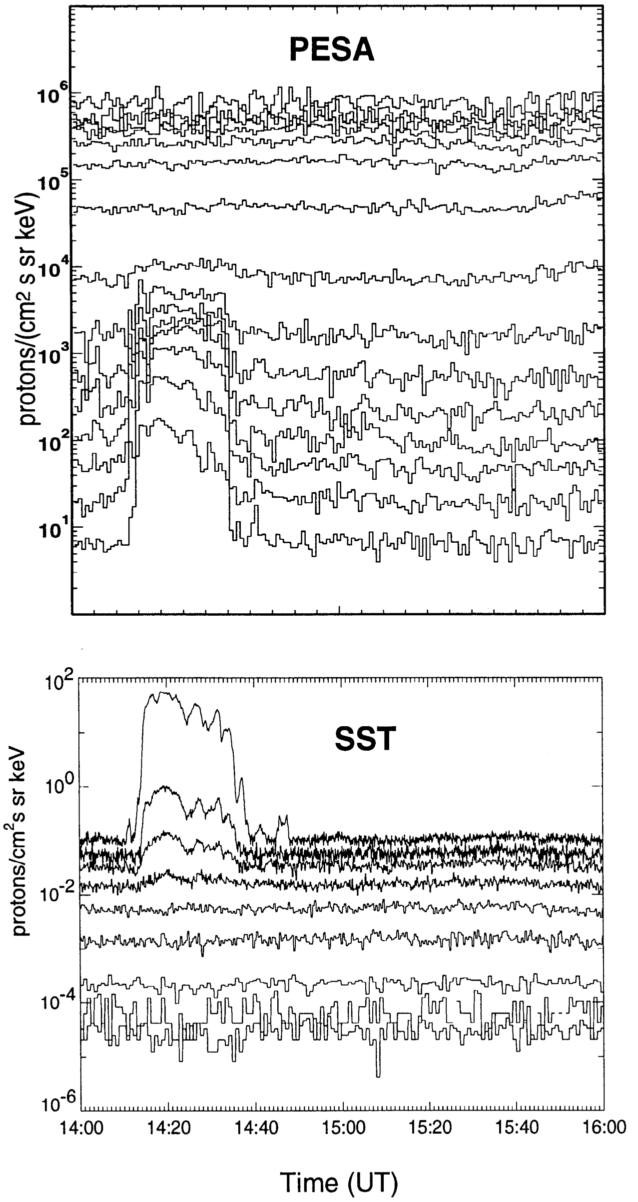

Figure 3. The upstream event of 13 August, 1995 (day 225) when WIND was at X_{gse}= 79.1 R_E, Y_{gse} = 5.4 R_E. The top panel shows the proton intensity from the PESA, covering the energy range, from top to bottom, 100 eV to 27 keV, averaged over one quarter of a spin (particle directions coming from the Earth), whilst the bottom panel shows the spin averaged intensity from the SST's, covering, from top to bottom, the range 56 keV to 7.14 MeV.

the 20 - 56, 56- 112, 112 - 196, and 196 - 392 keV spin-averaged channels of the SST's.

In Figure 4 we show composite proton spectra using data from 14 PESA channels, (ranging from an energy of 300 eV to 27 keV) and 23 SST channels (covering an energy range of 56 keV to 7.14 MeV). Spectra from 14:20 UT, in the middle of the event, are shown with solid lines, whilst spectra before the event, 14:00 UT, are shown with dashed lines. Each PESA spectrum is averaged over one-quarter of a spin, whereas each SST spectrum is averaged over one full spin. The PESA spectra show particles coming from the Earth, the dusk direction, and the dawn direction, whereas the 4 SST spectra are from different telescopes of the SST.

The upstream particles are seen in the solid traces as a bulge starting at around 1 keV, extending up to around 300 keV. The spectrum is very steep at energies greater than a few tens of keV, as observed previously on ISEE-3 [Sanderson et al., 1983]. Here we see for the first time the far-upstream spectrum at energies lower than a few tens of keV. The spectrum starts to flatten at an energy of a few keV, possibly turning over at around 1 keV. The exact point at which the spectrum turns over is difficult to observe because of the background flux at lower energies. The shape of this spectrum is such that the bulk of the energy density of the particles is carried by particles with energies of around 1 keV.

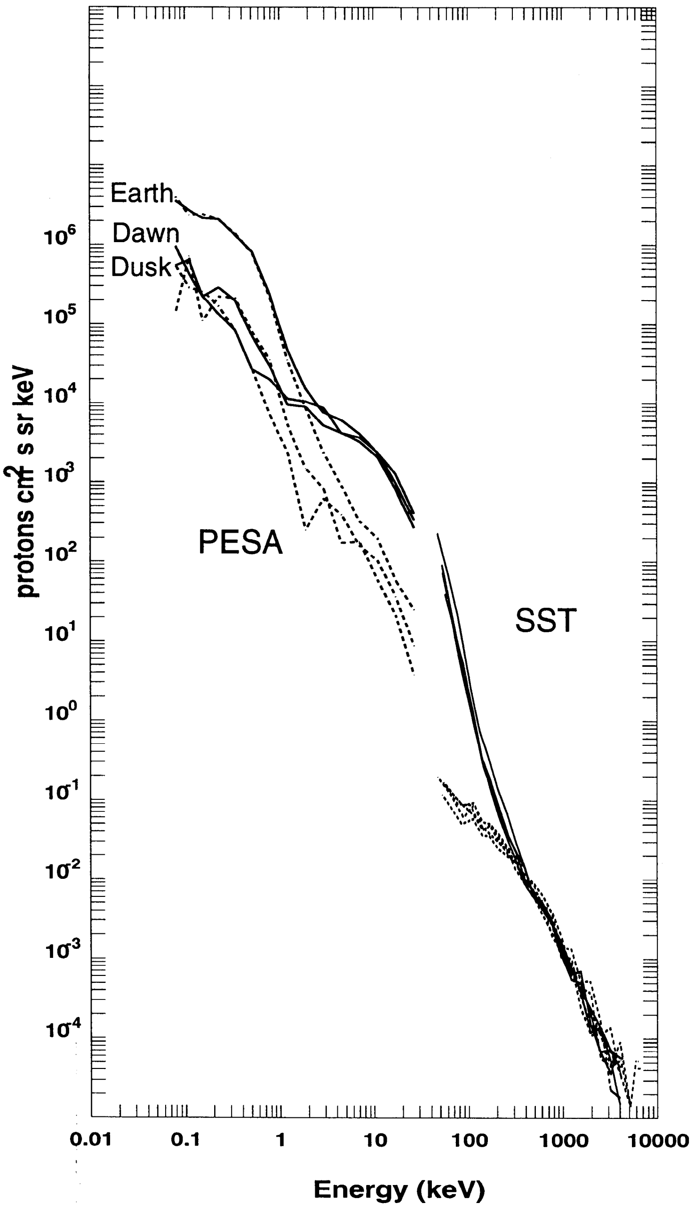

Figure 4. Composite proton spectrum measured by the PESA and SST during the event of 13 August 1995 (day 225). The dashed lines are spectra measured at 14:00 UT (before the event) whilst the solid lines are spectra measured at 14:20 UT (during the event). The PESA traces show ions coming from the Earth, dawn and dusk directions. The 4 SST spectra are spin-averaged. The spectra measured during the event shows evidence of a flattening and a possible turnover at around 1 keV.

In our ISEE-3 paper [Sanderson et al., 1983] on correlated observations of low-frequency waves in the magnetic field and energetic protons we calculated that the bulk of the particles should have an energy of ~ 1 keV, on the the assumption that the waves, with period ~30s, were caused by a resonant interaction between particles streaming away from the Earth. We were unable to verify this, since the lower energy limit of our instrument (the low-energy proton experiment, DFH) was ~35 keV, and there was no instrumentation on board to cover the gap between the solar wind instrument and the energetic particle instrument in the upstream direction.

The launch of the 3-D plasma and energetic particle instrument on the WIND spacecraft, with its capability to measure for the first time in all directions the energy range from solar wind energies to several MeV presents us now with the opportunity to observe these particles extending down to a few keV. Our observations confirm our predictions of 1983, that the bulk of the energy density carried by the upstream particles, even far upstream, is being carried by particles with energies of ~ 1 keV.

Conclusions

We have presented here first observations from the WIND spacecraft of upstream protons observed far upstream from the Earth. Our observations are considerably more comprehensive than those from ISEE-3, currently the only other spacecraft to go to the upstream libration point. We observe that the upstream events are seen at all positions of the orbit, all the way out to the libration point, and at all locations in the orbit around the libration point. The intensity does not appear to drop off with increasing upstream distance, implying a large mean free path. The events have short duration, can switch on and off very rapidly, can be seen at energies up to several hundreds of keV, and have very steep spectra at energies above a few tens of keV.

The instrumentation on board WIND is considerably more capable than that on ISEE-3. We have used some of these capabilities to measure parts of the spectrum never before observed in this region of space. We have observed, for the first time in these upstream particles evidence for a peak in the proton spectrum at around 1 keV. These ~1 keV particles carry the bulk of the energy density of the upstream protons, and are most likely responsible for the low-frequency waves which usually accompany such events. This wave-particle interaction will be the topic of a future paper

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