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Solar cycle phase, and streaming of energetic particles in and around the magnetosphere

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Abstract. Flux levels and anisotropy patterns of electrons, protons, and other nuclei are variable both in space and in time. IMP-8 data provide the longest-term near-Earth baseline for comparison with various heliospheric missions, including the Helios probes, Ulysses, and the Voyagers. The anisotropy data of IMP-8 protons at sub-MeV and even at MeV energies show that magnetospheric effects cannot be neglected in the local SW, and the spatial extent and degree of the contamination change considerably with the level of solar activity. While anisotropy is sensitively affected even upstream of the mean position of the bow shock, omnidirectional fluxes depend less on geocentric position than on the phase of the solar cycle. This preliminary analysis is focussed on the year-to-year changes of the anisotropy pattern experienced along the IMP-8 orbit. MeV directional distributions are affected by the the breakdown of anticoincidence cups of some IMP-8 instruments. For 0.29 to 0.5 MeV ions, however, relatively clean and consistent results are obtained over the whole period.

1 Introduction

Data measured by IMP-8, active since late 1973, have provided the long-term 1 AU baseline for all major heliospheric missions, and have also provided upstream boundary conditions for several missions on lower Earth orbits. As IMP-8 spends about half of its life either inside the terrestrial magnetosphere or magnetosheath, or at least in the close vicinity of the bow shock, it is important to know to what extent the data provided by IMP-8 instruments are contaminated by magnetospheric and other upstream effects. Here we focus on the dependence of long-term levels of contamination on the position of IMP-8 relative to a model magnetosphere. Because of the nearly lognormal distribution of particle intensities, medians or logarithmic means of omnidirectional and sectored fluxes provide statistically better results than means of the intensities themselves.

Long-term averages are also affected by changing instrumental background and by gradual or sudden breakdown of anticoincidence shielding. Such instrumental effects are particularly important for quiet-time periods. An extensive comparison and interpretation of quiet-time data has been done during an 1997 guest investigator team project at ISSI (Bern), which contributed to the present investigation. Background effects and in some cases also poor counting statistics tend to smooth out flux variations during quiet-time periods, and the true extent of MeV and sub-MeV variation is still very poorly known (Király, 1999). At sub-MeV energies, however, count rates are sufficiently high, so that zero-count hourly periods do not cause a major problem. Also, the anticoincidence shield is more important for MeV than for sub-Mev protons.

A recent paper by Paularena and King (1999) presented a nice overview of the then 25-year old IMP-8 mission. Orbital parameters and their variations were described in some detail, and instrumentation discussed. Extreme apogee and perigee distances were 45 R_E and 22 R_E, respectively, but the geocentric distance was mostly in the 30 to 40 R_E range. Eccentricity also varied around a mean of 0.12. Inclination also changed with a several-year period, being typically not very far from the ecliptic, but rarely also reaching maxima higher than 50 degrees. Some orbital plots are also given in the paper. It is important to call attention to the fact that the IMP-8 spacecraft was turned upside-down on 4 December, 1973, thus some changes are needed when using pre-flip software for the interpretation of directional data. The rotation axis is nearly perpendicular to the ecliptic; the rotation time is slightly more than 2 s. The orbital period of IMP-8 is somewhat above 13 days.

One of the most successful energetic particle instruments aboard is the CPME (Charged Particle Measurements Experiment, current PI is Robert Decker) detector, the data of which are widely accessible and much used. Although its anticoincidence shield did cause some problems before breaking down in 1989, the low-energy directional hourly proton data (0.29 to 0.5 MeV energy, 8 directional sectors) provide

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a reasonably consistent set of data for our investigations over the whole period. For protons of higher energies and for heavier nuclei the statistics is poorer, but results are mostly similar. Electron anisotropies are expected to be smaller because of their high velocities, but on account of their small gyroradii sharper positional dependence is expected. Electrons will not be further discussed in this paper.

2 Variation of intensity and anisotropy of low-energy ions

In interplanetary space at 1 AU both energetic proton fluxes and anisotropies vary widely, depending on the solar, CME or CIR origin of the particles actually detected, and also on the position of the spacecraft with respect to the central line of the high-flux streams. In periods characterized by moderately low fluxes it was found by Marshall and Stone (1978) that 1.3 to 2.3 MeV protons in 1972 and 73 tended to stream outward in the spacecraft frame, but inward in the SW frame. How should that streaming depend on the phase of the solar cycle, on energy, and on the proximity to the bow shock? Here we consider the behaviour of a lower energy ion population over an extended time, classified according to spacecraft position with respect to Earth. As positions extend over the whole IMP-8 orbit, no frame co-moving with the plasma can be reasonably introduced. All anisotropy data refer to the spacecraft frame. Although the low-energy CPME ions are expected to be predominantly 0.29 to 0.5 MeV protons in the SW, this might not be the case at certain times and in certain positions inside the magneosphere. As the ion energy is inferred from energy deposition in a single solid state detector, different ions cannot be distinguished.

2.1 IMP-8 orbits and 1D parametrization

In Fig. 1 a crude sketch of the magnetopause and bow shock are presented together with the region covered by IMP-8 orbits. In the geocentric solar ecliptic (GSE) coordinate system the X axis points towards the Sun, the Y axis towards dusk in the ecliptic (thus opposing the motion of Earth around the Sun). We neglect the deviation of the shapes of both the magnetosphere and of the bow shock from rotational symmetry. Both the model magnetopause and bow shock are represented by ellipsoidal surfaces. An interpolating parameter p_M called magnetospheric parameter is introduced, so that its value is 1 for the magnetopause, 2 for the bow shock, and the value is intermediate between them.

The parameter p_M is then extended by extrapolation both inward and outward. Values from 0 to 1 represent positions inside the magnetosphere, those above 2 refer to positions upstream of the model bow shock, in the SW. The larger the value of p_M, the farther upstream is the spacecraft position. A signed version P_M of the magnetospheric parameter is also introduced, the sign being that of the GSE Y coordinate. Thus a 1D ordering of spacecraft positions is defined, representing their relationship to the magnetopause and bow shock. Negative values of the parameter refer to the dawn side, positive ones to the dusk side. The actual parametrization used here is of course somewhat arbitrary. In view of the preliminary nature of this paper, we omit further details. For more extensive discussions on the shapes of the magnetopause and bow shock and on their dependence on SW parameters see e.g. Shue et al. (2000) and Peredo et al. (1995).

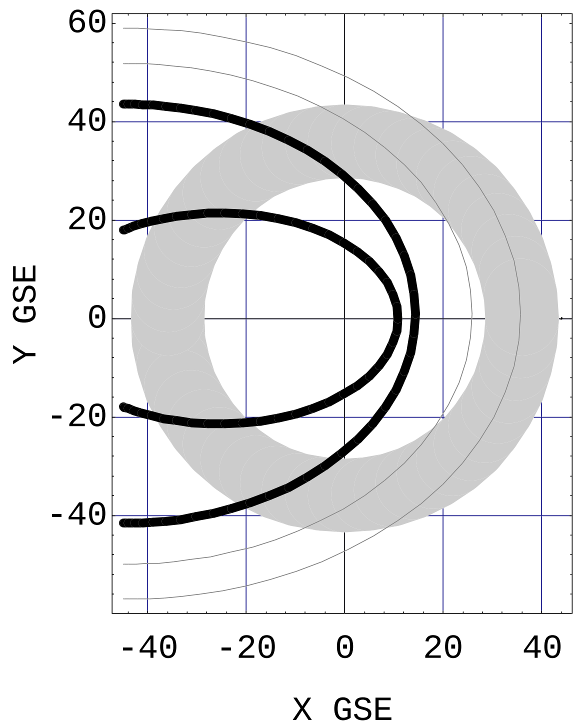

Fig. 1. Approximate range of IMP-8 orbits, rotated into the ecliptic plane (shaded). Magnetopause and bow shock ($p_M = 1$ and $p_M = 2$) are given by thick lines, while the intersection of the ecliptic with two upstream surfaces ($p_M = 3$ and $p_M = 4$) by thin lines. Earth is at the centre, Sun to the right, dusk side at top, dawn side at bottom. GSE X and Y coordinates are used, distances are given in Earth radii (R_E).

2.2 Variation of intensity and anisotropy with P_M

Hourly total and sectored intensity data of 0.29 to 0.5 MeV ions, measured in a particular year, are first collected in bins of P_M, calculated from the orbital positions. By averaging each subset logarithmically, the 'typical' changes of those characteristics with P_M, i.e. with the position relative to the magnetosphere can be studied. This appears a better procedure than to use orbital phase as the ordering parameter, because IMP-8 orbits change considerably even in one year. Differences between solar minimum and solar maximum periods provide then some indication on how magnetospheric effects change with the solar cycle. Error bars are hard to define because variations with solar rotation and with irregular CME activity have no proper statistical model. The consis-

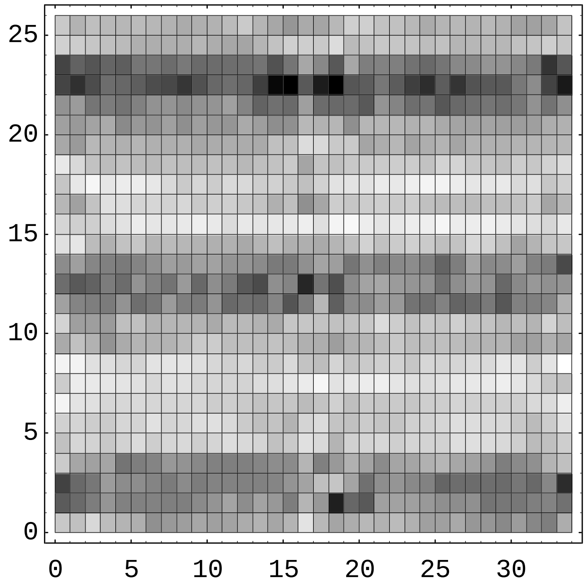

Fig. 2. Density plot of logarithmically averaged ion fluxes from 1974 (year 1, below) to 1999 (year 26, top). High flux is bright, scaling is non-linear (4th root). Position bins go from the upstream dawn side (position 1, left) along the IMP-8 orbit, to the upstream dusk side (position 34, right). It is important that intenisties do not change much with position.

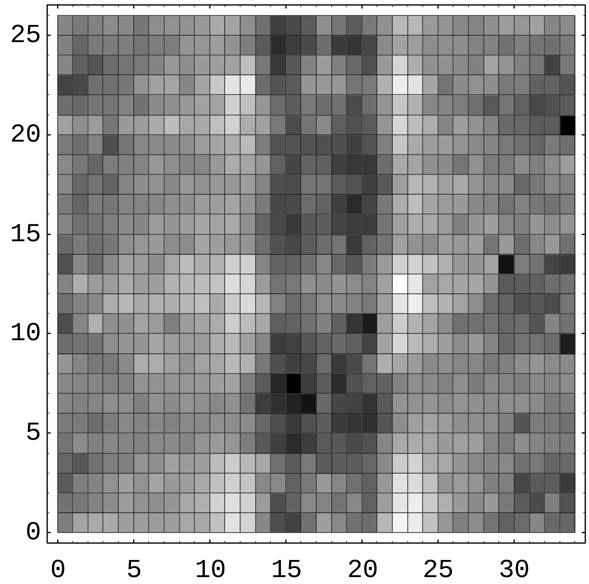

Fig. 3. Density plot of 1st harmonic anisotropy amplitudes in a similar form to Fig. 2. In contrast to intensities, anisotropy amplitudes do change with position. The dark vertical stripe corresponds to positions in the magnetosphere.

tency of yearly patterns, however, provides confidence in the method.

The total range of P_M parameter values extends from about -5 to 5. As extreme values are not reached in each year, larger bins are used for far upstream positions (-5 to -4 and 4 to 5), while between -4 and 4 the bin size is 0.25. Altogether, 34 P_M bins were thus formed. The first and last 9 bins refer to the SW (upstream of the model bow shock), bins 10 to 13 and 22 to 25 to the magnetosheath, and 14 to 21 to the magnetotail. Numbering starts on the dawn side.

The natural logarithm of the hourly intensities was averaged for each position bin and for 8 directions in each year from 1974 to 1999. Positional information (P_M, 3 coordinates, and distance from the Sun-Earth axis multiplied by the sign of P_M) were also averaged, so as to get positions for each year and bin. For the 1D results, the P_M bin number was used as the only positional information. For 2D results, the average X coordinate and the signed distance from the Sun-Earth axis were used. The 8 directional data in each bin were Fourier transformed to get data on anisotropies; here we discuss only 1st harmonics.

2.3 Some long-term 1D results

The results are represented as 'density plots' in Fig. 2 and 3, where bright regions indicate high intensity and large 1st harmonic amplitude, respectively. Data are arranged in 26 rows (from 1974 to 1999, starting from below), and 34 columns, in increasing order of P_M. Mean logarithmic intensities change with the phase of the solar cycle, having maxima at solar maxima. There is no obvious variation with P_M, except for a faint feature at the middle, close to the plasma sheet.

Figure 3 displays a much more dramatic change of 1st harmonic amplitudes with P_M and also with solar activity. The portion of the orbits inside the model magnetosphere, between bin numbers 13 and 20, is clearly marked by low mean anisotropies, while the neighbouring magnetosheath by high ones. Solar maxima and minima show different patterns. There is also some difference between the dawn and dusk sides. It is also clear that anisotropies of magnetospheric origin extend well into the SW.

2.4 2D results on 1st harmonic anisotropy

A more detailed picture emerges in the 2D representation. Fig. 4 and 5 provide examples of anisotropies for a solar maximum (1980) and a solar minimum (1986) year. Arrows represent 'typical' 1st harmonic anisotropy at a certain spot and in a given year. While the meaning of the directions is clear (that of streaming relative to the orbital plane), arrow lengths are not directly proportional to the amplitude of the anisotropy, because of the huge range they cover. Thus the 4th root of the genuine amplitude has been used instead. In 1980, the far upstream anisotropy is hardly influenced by the effects of the terrestrial magnetosphere and bow shock, while in 1986 there is even sunward streaming at the same positions. Similar dependence on position and solar activity is also seen on plots for all other years. The combination of 1D plots and the 2D case studies should provide a reasonable overview.

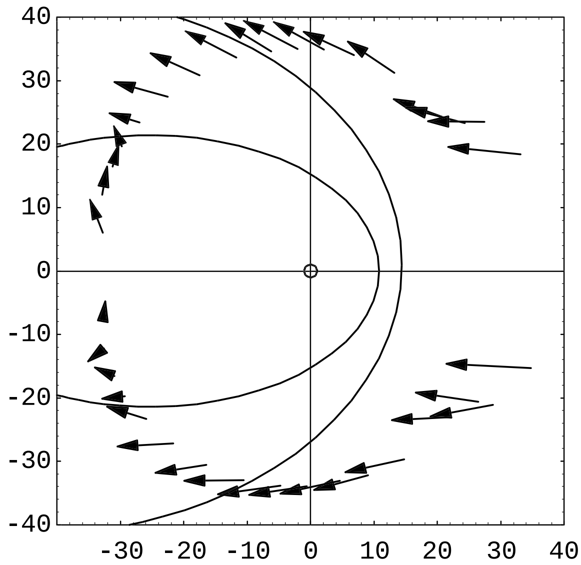

Fig. 4. First harmonic anisotropy amplitudes in the solar maximum year 1980. No strong effects of the magnetosphere and bow shock are seen far upstream.

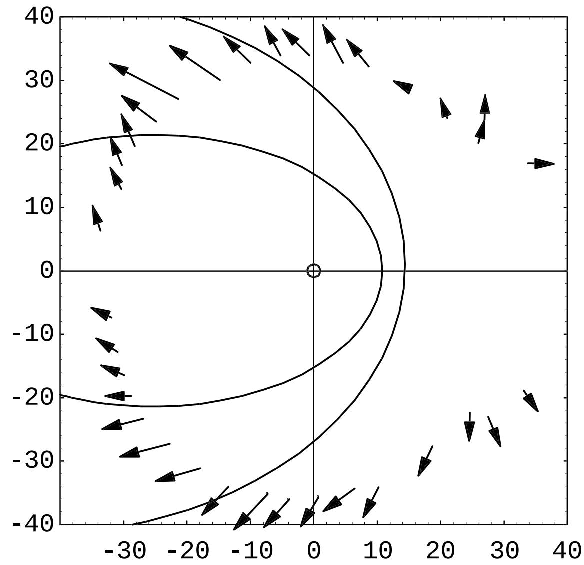

Fig. 5. Same as in Fig. 4, but for the solar activity minimum year 1986. Upstream effects are much stronger.

3 Discussion and conclusions

It is well known that upstream particles coming from the magnetosphere or accelerated in the bow shock occasionally reach eneregies of several hundred keV, although the majority of upstream ions is of much lower energy (see e.g. in Lee, 1982). The foreshock, extending upstream on the dawn side, along the interplanetary field, is also the site of intensive MHD and plasma waves. It is less known, how typical those events are, and whether the energetic particles are mostly accelerated in the bow shock or leak out of the magnetosphere. Particles of one order of magnitude lower energies in both the magnetosheath and SW have recently been studied e.g. by Kudela et al. (2000). Upstream ion bursts of higher energy particles, up to 0.5 Mev, have also been discussed by Anagnostopoulos et al. (2000) and by Sarafopoulos et al. (2000). Their conclusion is that magnetospheric leakage plays a major part, and that particles in our energy range (290 to 500 keV) show a broader distribution in local time, to some extent covering the dusk side as well. They also claim that such upstream ions of magnetospheric origin occur fairly often, up to one third of the time.

The present survey confirms some of those conclusions, and also calls attention to the intricate pattern of the variation of upstream ion anisotropy with solar activity. 2nd harmonic anisotropy, not discussed here, also yields interesting results. It is important that Fig. 2 does not show much variation of the intensity with position, thus a major role of magnetospheric acceleration may be in doubt. A directional re-distribution of pre-existing SW ions by magnetospheric processes may thus be of importance. As our survey is not based on individual bursts, but on a logarithmic averaging process, it provides 'typical' characteristics for a variety of positions along the IMP-8 orbit, and over the whole duration of the mission. Protons of higher (MeV) energy, He fluxes, and electron streaming are also being studied by the same techniques, and an important new approach to an old problem appears to emerge.

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