SURVEY OF MEV PROTON ANISOTROPIES MEASURED BY *ULYSSES*

SILVIA DALLA and ANDRÉ BALOGH
The Blackett Laboratory, Imperial College, London, SW7 2BW, U.K.

Abstract. The Anisotropy Telescopes (ATs) instrument, part of the COSPIN experiment on board *Ulysses*, measures fluxes and anisotropies of protons in the MeV range. We survey data from this instrument throughout the *Ulysses* mission, with particular emphasis on solar maximum, when large particle intensities were measured. The only significant fluxes detected by the ATs during solar minimum are those associated with corotating interaction regions. We focus on events characterised by very large first-order anisotropies, indicating beam-like streaming along the magnetic field lines, and also on times of unusually low and constant anisotropies. We describe the parameters associated with these events and put forward possible physical explanations of the extreme anisotropies observed.

1. Introduction

The Anisotropy Telescopes (ATs) instrument is a two-telescope particle detector on board the *Ulysses* spacecraft. It comprises two identical solid state detectors mounted at angles of 60° and 145° to the spin axis. Counts are binned into 8 sectors per telescope allowing reconstruction of particle flows by spherical harmonic analysis as follows.

We indicate as $J(\mathbf{e}_v)$ the measured differential flux along the direction identified by the unit vector $\mathbf{e}_v$, taken as pointing towards the centre of the sector under consideration. We assume that $J(\mathbf{e}_v)$ can be fitted by a reduced 2nd-order spherical-harmonic expansion as follows:

$$J(\mathbf{e}_v) = J_0\left[1 + \mathbf{A}_1 \cdot \mathbf{e}_v + A_2\,(3\mu^2 - 1)/2\right], \tag{1}$$

where $\mu = \cos\theta$ and θ is the angle between the magnetic field and the vector $\mathbf{e}_v$, and we have assumed the second order harmonics to be gyrosymmetric about the field direction. We call J_0 the omnidirectional flux, $\mathbf{A}_1$ the first order anisotropy vector and A_2 the second order anisotropy. We examine the anisotropies in the solar wind frame by subtracting the bulk flow Compton–Getting anisotropy.

In this paper we focus on data from the sectored channels detecting 1.3–2.2 MeV protons.

2. Selection of Extreme Anisotropy Events

We survey ATs data for the time period from day 310 of 1997 to day 209 of 2000, during the rising phase of solar cycle 23. Prior to day 310, no particle fluxes were

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TABLE I

Large anisotropy events and zero anisotropy events. For each event a label, the onset date, *Ulysses*' range R and heliographic latitude α are given

	Date	R (AU)	α (°S)		Date	R (AU)	α (°S)
(L1)	116/1998	5.41	6.4	(Z1)	335/1998	5.25	17.3
(L2)	200/1998	5.38	10.6	(Z2)	21/2000	4.07	43.7
(L3)	238/1998	5.36	12.4	(Z3)	142/2000	3.48	55.5
(L4)	355/1998	5.22	18.4	(Z4)	203/2000	3.12	63.1
(L5)	24/1999	5.16	20.2				

detected by the ATs for the whole of 1997. We calculate hourly averages of the anisotropy coefficients J_0, $\mathbf{A}_1$ and A_2 defined in Equation (1), starting from 512 s averages of sectored counts.

We find that the component of $\mathbf{A}_1$ perpendicular to the magnetic field is negligible with respect to the component along the field, in agreement with the results of Richardson (1999). Consequently we focus on the component along the magnetic field direction, which we indicate as A_1. Positive values of A_1 correspond to anti-sunward particle flow, and negative values to sunward flow. A large A_2 generally indicates bidirectional flow. However, when A_2 and A_1 are simultaneously enhanced with $A_2 \approx A_1$, the net effect is still of a one-directional flow.

We select extreme anisotropy events using the following criteria:

– *Large anisotropy events (LAEs):* $|A_1| > 1$ for at least 9 consecutive hours; A_2 any, but not much larger in magnitude than $|A_1|$.

– *Zero anisotropy events (ZAEs):* $|A_1| < 0.05$ and $|A_2| < 0.05$ for at least 7 consecutive hours.

Physically, LAEs are characterised by long duration intense particle streaming along the magnetic field lines, and ZAEs by long duration particle isotropy.

A search for events with the above characteristics found 5 LAEs and 4 ZAEs in the survey period, as detailed in Table I. The dates in this table indicate the onset of the extreme anisotropy phase, rather than the start of the associated particle event. We observe that 4 LAEs took place in 1998 and 1 at the beginning of 1999, i.e. at times when *Ulysses* was at small heliographic latitudes. The longest duration ZAE took place in November 1998 and was the subject of a previous detailed study (Dalla and Balogh, 2000). The survey identified another 3 such events, all of them in 2000, i.e., at heliographic latitudes >42° S.

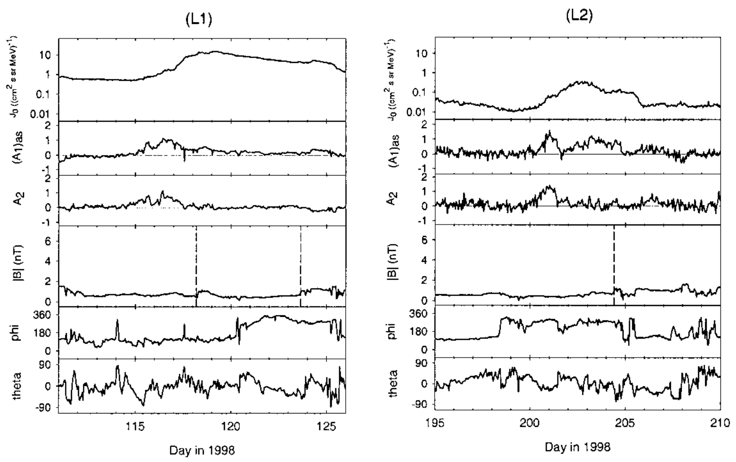

Figure 1. Large anisotropy events L1 and L2. From the top panel: J_0, A_1, A_2, the magnetic field magnitude $|B|$, meridional angle ϕ and azimuth θ. The dashed lines indicate interplanetary shocks.

3. Features of Extreme Anisotropy Events

All 5 LAEs are characterised by a positive A_1, i.e., a large antisunward flow. The five LAEs can be grouped into two classes: the first one comprising events L1, L3, and L5, which are characterised by large ATs fluxes and have a strong signature at higher proton energies (e.g., in the $\sim$30–100 MeV proton channel of the COSPIN/KET instrument); the second one consisting of events L2 and L4, both characterised by much lower ATs fluxes and with no signature at higher energies. An example of an event from each class is given in Figure 1.

We observe that the events in the first class are part of the $\sim$140-day recurrence in particle fluxes reported by Dalla *et al.* (2001). All LAE events are associated with flares/CMEs at the Sun and not with acceleration at interplanetary shocks.

The four ZAEs occur at times of constant omnidirectional flux J_0. Two of these events are shown in Figure 2. The first one is the November 1998 event, where an isotropic population was maintained for a 3.5 day period, characterised by very low constant magnetic field magnitude. This was interpreted by Lario *et al.* (2000), as resulting from a population of energetic particles being trapped in the region bounded by the two interplanetary shocks indicated by dashed lines in the figure. One problem with this interpretation is that the isotropic phase is maintained only in part of the region between the shocks. The second event took place in 2000 and again shows very low constant anisotropy in a region of almost constant particle fluxes. Here the onset of the isotropic phase seems to precede both a period of quiet magnetic field and a shock.

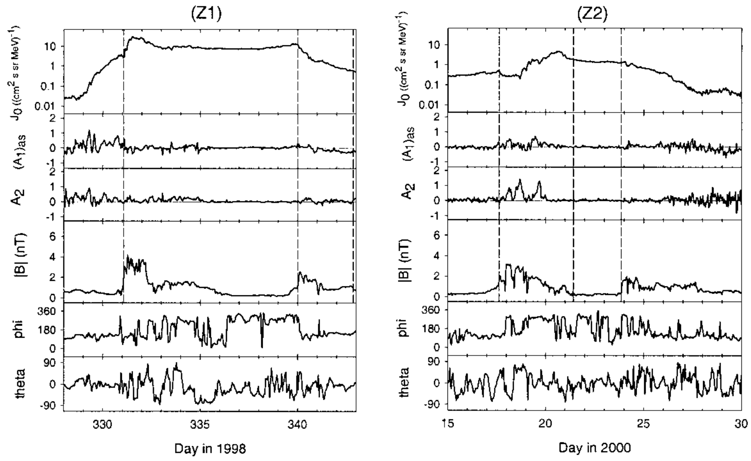

Figure 2. Zero anisotropy events Z1 and Z2. The format is the same as in Figure 1.

4. Conclusions

Our survey of ~MeV proton anisotropies measured by the *Ulysses* ATs instrument during the rising phase of solar cycle 23 has shown that strong long duration particle streaming along magnetic field lines is only seen close to the ecliptic plane.

In contrast, the second type of extreme anisotropy event observed, characterised by long duration isotropy, is seen most frequently at high latitudes and in correspondence with constant particle fluxes.

The large anisotropy events are interpreted as the result of intense activity close to the Sun resulting in very efficient particle acceleration. The physical mechanisms behind the measured zero anisotropies are less clear, one possibility being the existence of regions in which particles remain trapped for a long time resulting in isotropic distributions due to scattering by waves. For the November 1998 event, preliminary analysis has shown the presence of waves at the first harmonic of the ion cyclotron frequency (T. S. Horbury, private communication, 1998).

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