JOINT *ULYSSES* AND ACE OBSERVATIONS OF A MAGNETIC CLOUD AND THE ASSOCIATED SOLAR ENERGETIC PARTICLE EVENT

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Abstract. On day 49 of 1999 a strong interplanetary shock was observed by the ACE spacecraft located at 1 AU from the Sun. This shock was followed 10 hours later by a magnetic cloud (MC). A large solar energetic particle (SEP) event was observed in association with the arrival of the shock and the MC at ACE. The Ulysses spacecraft, located at 22° S heliolatitude and nearly the same ecliptic longitude as ACE, observed a large SEP event beginning on day 54 that peaked with the arrival of a solar wind and magnetic field disturbance on day 61. A magnetic cloud was observed by *Ulysses* on days 63–64. We suggest a scenario in which both spacecraft intercepted the same MC, although sampling different regions of it. We describe the effects that the MC produced on the streaming of energetic particles at both spacecraft.

At the end of February 1999, the ACE spacecraft (at 1 AU) and the *Ulysses* spacecraft (at ∼5 AU and 22°S heliolatitude) were at nearly the same longitude. Large-scale solar wind structures expanding out from the Sun near Central Meridian had a chance, during that time, of being observed by both spacecraft. Figure 1 shows energetic ion, magnetic field and solar wind data from day 47 to day 68 of 1999 as measured by ACE and *Ulysses*. A SEP event (labeled T_1) was observed by ACE in association with the arrival of an interplanetary shock at 02:11 UT on day 49 (i.e., 49/02:11 UT). No coronagraph observations were available at that time, but an isolated M3.2 X-ray flare with maximum at 47/03:12 UT and located at S23W14, was most likely related to the solar event origin of this intense SEP event. The shock was followed by a plasma structure crossing the ACE spacecraft from 49/∼12:00 UT to 50/∼12:00 UT. This structure, characterized by an enhanced, quiet and slowly decreasing magnetic field (IMF) intensity; a rotation of the IMF orientation through ∼70°; a low solar wind plasma density and proton temperature; enhanced solar wind helium abundances and counterstreaming solar wind electron fluxes (not shown here), is commonly associated with a magnetic cloud (Gosling, 1997). We label this structure MC in Figure 1.

At the time of the flare on day 47, the nominal magnetic field connection for the *Ulysses* spacecraft was behind the east limb of the Sun. No SEP event was observed at that time. A forward-reverse shock pair associated with a recurrent corotating interaction region (CIR) was seen at *Ulysses* on day 52–56 with a small energetic

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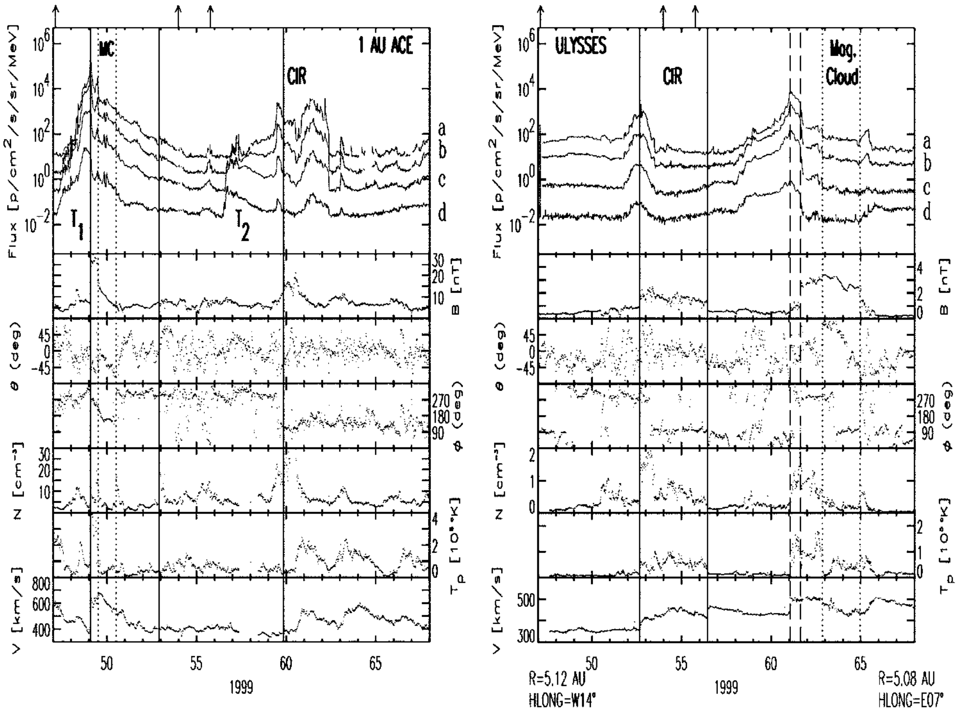

Figure 1. Left: 30-min averages of (a) 68–115 keV, (b) 195–321 keV, (c) 587–1060 keV and (d) 1.9 –4.8 MeV ion fluxes as observed by EPAM/LEMS120 (Gold *et al.*, 1998); magnetic field magnitude and orientation in RTN coordinates as observed by ACE/MAG (Smith *et al.*, 1998); and solar wind density, proton temperature and speed as measured by SWEPAM (McComas *et al.*, 1998). Right: 30-min averages of (a) 77–130 keV, (b) 210–340 keV, (c) 0.6–1.12 MeV and (d) 1.87–4.8 MeV ion fluxes as observed by HISCALE/LEMS120 (Lanzerotti *et al.*, 1992); magnetic field magnitude and orientation in the *Ulysses* RTN coordinate system (Balogh *et al.*, 1992); and solar wind density, proton temperature and speed as measured by SWOOPS instrument (Bame *et al.*, 1992). The vertical solid lines show the arrival of shocks, dotted lines the boundaries of the MC at both spacecraft, and dashed lines solar wind and magnetic field discontinuities at *Ulysses*.

ion enhancement at the forward shock. The study of this recurrent CIR at *Ulysses* and its observation at ACE on days 59–62 is descibed in Lario *et al.* (2001). High-energy (>4 MeV) proton fluxes and low-energy electron fluxes started increasing again on day 54 (not shown here). Low-energy ion fluxes (Figure 1) started increasing gradually on day 55. At the end of day 57 the increase became more pronounced, reaching a peak at 61/01:25 UT and coinciding with a discontinuity of the solar wind plasma parameters (first dashed line in Figure 1). Energetic ion intensities showed an abrupt depression at 61/15:36 UT coinciding with an increase of the IMF magnitude (second dashed line). From 62/∼20:50 UT to 64/∼23:00 UT *Ulysses* observed a region characterized by an enhanced and smooth magnetic field, a rotation of the IMF orientation, counterstreaming solar wind electron fluxes, and enhanced solar wind helium abundances (not shown here). The spacecraft align-

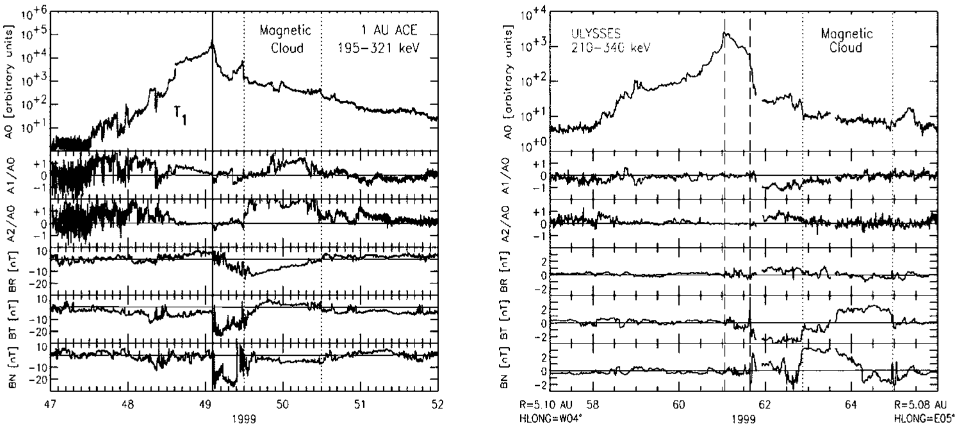

Figure 2. Anisotropy components for the two SEP events at ACE (left panel) and *Ulysses* (right panel). A_0 is the omnidirectional component, A_1/A_0 the first-order anisotropy along the magnetic field and A_2/A_0 the second-order anisotropy. Also the magnetic field components in RTN coordinates for ACE (left panel) and in the *Ulysses* RTN coordinate system (right panel). Averaging time is 96 s for ACE and 15 min for *Ulysses*.

ment, the site of the associated solar event, the scarcity of other solar events, and the average transit speed from the Sun to both spacecraft suggest that both spacecraft observed the same solar wind structure (i.e., the same magnetic cloud). However, *Ulysses* and ACE sampled different portions of this cloud. We believe that *Ulysses* intercepted the cloud near its axis (as shown by the complete rotation of IMF) and near its direction of propagation, while ACE crossed only a portion of the cloud through one of its flanks and far from its axis (shown by the partial rotation of the IMF caused by the decreasing intensity of its radial component across the cloud). The evolution of the cloud itself (still expanding at 1 AU) and the different sample of cloud taken by both spacecraft led also to different plasma signatures at ACE and *Ulysses* (not discussed here).

Energetic ion observations were obtained from the LEMS telescope of EPAM on ACE and HI-SCALE on *Ulysses*. These sensors accumulate ion data in 12 fixed look directions. The total of 12 measurements were transformed into a frame of reference moving at the solar wind velocity. Defining a coordinate system with the z-axis along the instantaneous IMF direction, we use a reduced second-order spherical harmonic analysis to derive a series expansion for the ion intensity distribution (see Sanderson *et al.,* 1985, for details). The first-order harmonic consists of three components with amplitudes A_1, A_{11} and B_{11}. The ratio A_1/A_0 (where A_0 is the isotropic component) represents, in the solar wind frame, the first-order anisotropy resolved along the IMF direction (its sign is defined with respect to the IMF direction). A_{11} and B_{11} (not shown here) represent the flow transverse to the IMF and are small compared with A_1. The quantity A_2/A_0 represents the second-order harmonic distribution (forced to be symmetric about the magnetic field). A positive ratio of A_2/A_0, when the first-order coefficients are close to zero, represents a bidirectional flux along the IMF. Figure 2 (left) shows the evolution of the anisotropy coefficients in the solar wind frame for the event T_1 at ACE. The onset of this event was characterized by an antisunward flow of particles. The antisunward first-order anisotropy slowly decreased to zero as the shock approached. Just after the shock passage, there was a change in the sign of the anisotropy, indicating that particles were flowing away from the shock back towards the Sun. Bidirectional ion flows were clearly observed inside the MC structure. Figure 2 (right) shows the evolution of the anisotropy for the SEP event at *Ulysses*. Energetic particles showed intermittent weak unidirectional antisunward streaming until one day before the arrival of the first discontinuity when they reached isotropy. After the second discontinuity they showed a strong sunward flow (note the change in the IMF direction on day 61). The entrance into the MC shows a drop of the particle intensity and a weak sunward flow which evolves to isotropic.

The particle intensity enhancement seen before the arrival of the cloud at *Ulysses* suggests the possibility that the same transient solar wind disturbance was responsible for both particle events at ACE and *Ulysses*. However, the onset of the particle event at *Ulysses* and the observation by ACE of the SEP event labeled T_2 in Figure 1, suggest that other solar events might have contributed to the particle intensity at *Ulysses*. Two partial-halo CMEs (indicated by arrows in Figure 1) occurred at 53/23:26 UT and at 55/18:26 UT from behind the east and west limb of the Sun, respectively (http://lasco-www.nrl.navy.mil/cmelist.html). We suggest that as the cloud propagated out en route to *Ulysses*, it decelerated; consequently, the driven shock gradually weakened and the sheath region between the shock and MC became only a small interplanetary disturbance that was able to trap energetic particles coming from the event T_1 and other possible solar events. Particles flowing away from this region of high particle intensity (between the two dashed lines in Figure 1) constituted the SEP event at *Ulysses*.

References

Balogh, A. *et al.*: 1992, *Astron. Astrophys.* **92**, 221.
Bame, S. J. *et al.*: 1992, *Astron. Astrophys.* **92**, 237.
Gold, R. E. *et al.*: 1998, *Space. Sci. Rev.* **86**, 541.
Gosling, J. T.: 1997, 'Coronal Mass Ejections', *AGU Geophys. Monograph* **99**, 9.
Lanzerotti, L. J. *et al.*: 1992, *Astron. Astrophys.* **92**, 349.
Lario, D. *et al.*: 2001, *Space Sci. Rev.* **97**, 249–252 (this issue).
McComas, D. J. *et al.*: 1998, *Space. Sci. Rev.* **86**, 563.
Sanderson, T. R. *et al.*: 1985, *J. Geophys. Res.* **90**, 19.
Smith, C. W. *et al.*: 1998, *Space. Sci. Rev.* **86**, 613.