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Solar energetic proton intensity profiles at 5 AU from the Sun

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Abstract. We compare Ulysses particle measurements for two large gradual solar energetic particle (SEP) events, which took place on 24 August 1998 and 20 January 1999. At these times the Ulysses spacecraft was close to the ecliptic plane and at ∼5.2 AU from the Sun. The two events are characterised by similar time intensity profiles for 40–100 MeV protons, both at Ulysses and at Earth orbit. However the profiles at Ulysses in the 1.3–2.2 MeV proton energy range are remarkably different, showing on 24 August 1998 a smooth long duration event, and on 20 January 1999 two small intensity enhancements. We use particle data from the Ulysses/COSPIN KET and ATs instruments, and from the IMP8/CRNC instrument. We discuss the possibility that the differences in intensity profiles in the ∼MeV range may be a spatial effect and analyse the role of sector boundaries and the spacecraft's magnetic connection to the corona in shaping them.

1 Introduction

Solar energetic particle (SEP) fluxes have been measured for many years by detectors on board spacecraft. The intensity enhancements associated with solar activity are thought to be the result of two distinct processes: acceleration at the shock driven by a coronal mass ejection (CME) close to the Sun for the so-called gradual events and flare-acceleration in the lower corona for impulsive events (Reames *et al.*, 1996).

SEPs propagate through interplanetary space and can be detected at large distances from the Sun. Particles can also be locally accelerated in the interplanetary medium at shock fronts. In this paper we focus on measurements made at 5.2 AU by the Ulysses spacecraft, at times when it was close to the ecliptic plane.

A typical approach in the analysis of particle enhancements in 1 AU data consists in looking for parent solar events in time association with the particle enhancement. Many important results were discovered in this way, for example, the dependence of the rise time of a particle event on the heliographic longitude of the associated activity. Already at 1 AU, however, a large number of particle events cannot be associated with any solar activity.

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The interpretation of particle measurements at 5 AU from the Sun is generally not straightforward. Looking at ∼1 MeV proton data, for many enhancements at 5 AU it is not possible to find a corresponding one at 1 AU (Lario *et al.*, 2000), making it difficult to establish which is the parent solar event. However in an earlier paper we have shown that for the much less frequent cases where proton fluxes in the 40–100 MeV range were detected at 5 AU, a corresponding event at 1 AU could be identified (Dalla *et al.*, 2001). A comparison between fluxes at lower energies can then be attempted.

In this paper we focus on two large SEP events characterised by similar particle intensity profiles at 1 AU and in the high energy proton range at 5 AU. For ∼1 MeV particles at 5 AU, however, the profiles are very different, showing in one case a smooth long duration (∼30 day) event, and in the second one a depletion in flux 5 days after the flare onset, followed by another flux increase. We discuss the possibility that the depletion in flux might be a spatial effect and the implications that this would have on the interpretation of 5 AU data for MeV particles.

2 Observations

Two large SEP events were observed following solar events which took place on 24 August 1998 and 20 January 1999. On both days intense (X1.0 and M5.2) long duration flares were observed, and a halo CME was reported for the second date by the Manua Loa Solar observatory, with no SOHO observations available for either event (Dalla *et al.*, 2001).

Fig. 1 shows hourly averages of SEP fluxes and local solar wind parameters at the time of the events, at a distance of 1 AU from the Sun, as measured by instruments on board the ACE and IMP8 spacecraft. Data displayed cover 38 days.

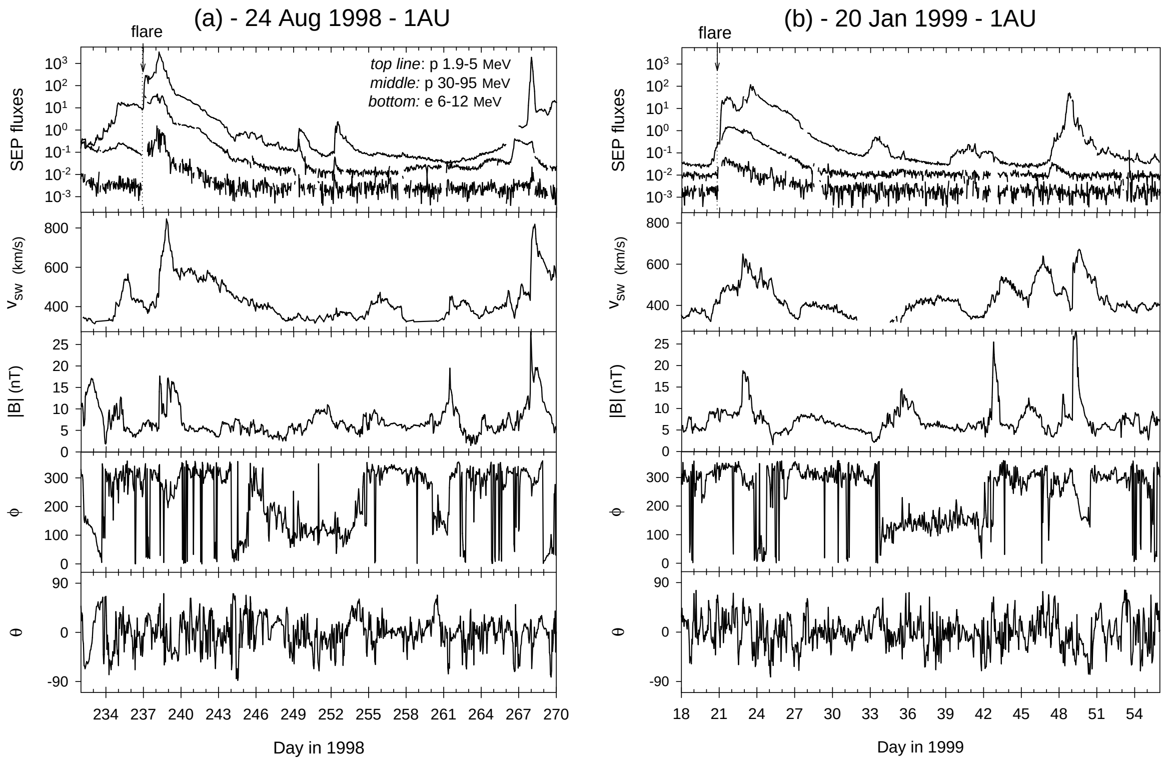

Fig. 1. Measurements of SEPs at 1 AU from the Sun for the events on 24 Aug 1998 (a) and 20 Jan 1999 (b). The format is the same for (a) and (b), as follows. Top panel: from top to bottom curves: fluxes of 1.9–5 MeV protons (ACE/EPAM); 30–95 MeV protons (IMP8/CRNC) and 6–12 MeV electrons (IMP8/CRNC). Second panel: solar wind speed (ACE/SWEPAM). Remaining panels: magnetic field magnitude $|B|$, meridional angle ϕ and azimuth θ (ACE/MAG). Each tick on the x-axis is one day. Particle fluxes are in $(\mathrm{cm}^2\,\mathrm{s}\,\mathrm{sr}\,\mathrm{MeV})^{-1}$.

In both cases the solar event was sufficiently energetic to produce relativistic electrons and high energy protons, as can be seen from the bottom and middle plots in the top panels of Fig. 1 (data gaps are present in the IMP8/CRNC channels at the start of both events). The solar wind and magnetic field data show the arrival of a large shock 32 hours after the flare onset on 24 Aug 1998 and after 48 hours on 20 Jan 1999. The fluxes of 1.9–5 MeV protons show a large increase in correspondence with both shock passages. Local shock acceleration can be seen also at higher energies, less clearly for the January 1999 event.

We observe that the two events have a very long duration, of approximately 7 days in the relativistic electron channel. The timescales are very similar in the two cases.

Fig. 2 shows the measurements made by the Ulysses spacecraft at ∼5.2 AU from the Sun and close to the ecliptic plane, during the same time periods. In both panels large flux enhancements are seen for protons of energies from the 1.3–2.2 MeV range (COSPIN-ATs channel) to the 38–125 MeV range (COSPIN- KET channel). Relativistic electrons are detected only for the January 1999 event.

SEP events of this type are quite rare at 5 AU: in fact only four main flux enhancements were detected at Ulysses in the 38–125 MeV proton channel during the whole of 1998 and 1999. These data show a statistically significant recurrence every ∼140 days (Dalla *et al.*, 2001). The events of 24 August 1998 and 20 January 1999 are part of the recurrent sequence.

From a comparison of Figs. 1 and 2, we associate the measurements at 1 and 5 AU for both (a) and (b). At 5 AU, we observe that the overall time intensity profile in the ATs 1.3–2.2 MeV channel is very different in the two events. The 24 Aug 1998 event is characterised by a smooth particle flux with very slow decay, lasting a total of 30 days. In the 20 Jan 1999 event a drop in the ATs intensity is seen, starting on day 26. The intensity continues to decrease until day 32 of 1999, when another enhancement peaking on day 37 is seen. The 5.4–25 MeV proton flux also shows a similar profile, with the second peak less pronounced.

The very different intensity profiles in the ∼1 MeV range seen at Ulysses are the focus of this paper. Looking at ∼1 MeV data only, one would classify the two enhancements taking place between day 20 and day 52 of 1999 as two separate particle events. However we argue that both are associated to the same solar event, taking place on Jan 19. The justification for this assertion lies in the comparison of the

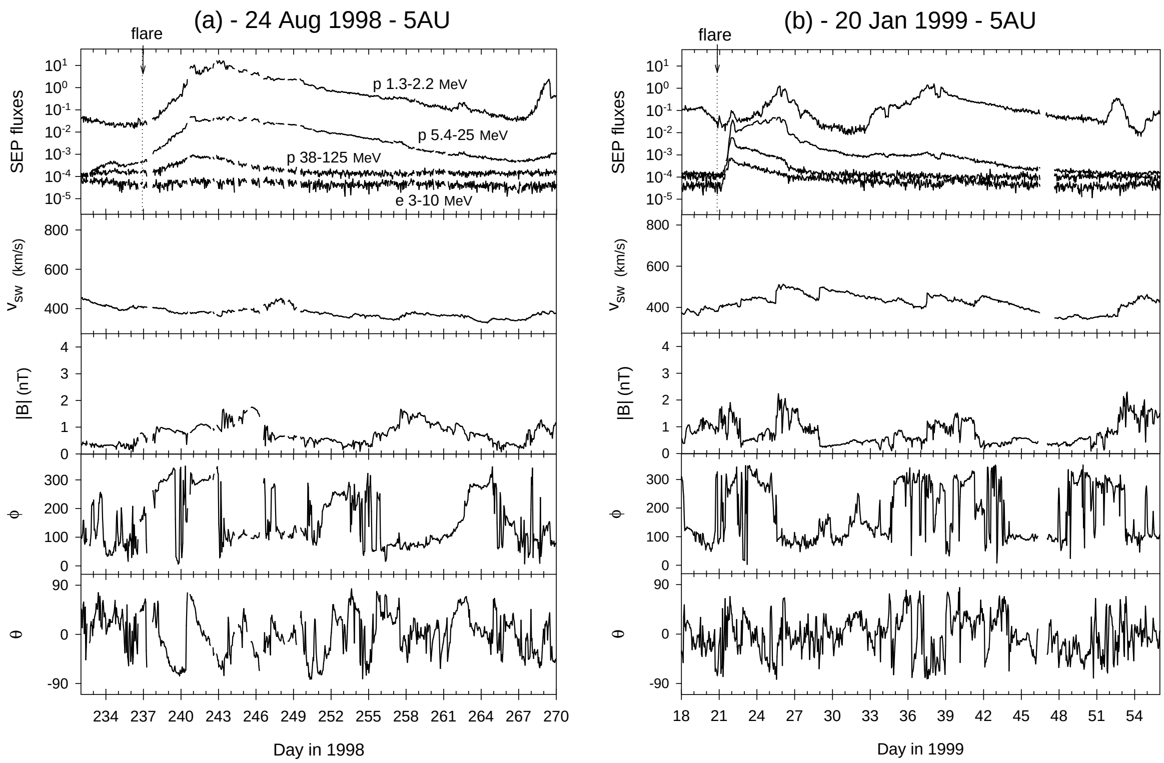

Fig. 2. Measurements at 5 AU from Ulysses instruments, for the same time periods as in Fig. 1. The format is the same for (a) and (b), as follows. Top panel: from top to bottom curves: fluxes of 1.3–2.2 MeV protons (COSPIN-ATs); fluxes of 5.4–25 MeV protons and 38–125 protons (COSPIN-KET); count rates of 3–10 MeV electrons, divided by a factor 100 (COSPIN-KET). Fluxes are in $(\mathrm{cm}^2\,\mathrm{s}\,\mathrm{sr}\,\mathrm{MeV})^{-1}$ and count rates in s^{-1}. Second panel: solar wind speed (SWOOPS). Remaining panels: magnetic field magnitude $|B|$, meridional angle ϕ and azimuth θ (magnetometer).

January 1999 data with the August 1998 one. Superimposing the ATs 1.3–2.2 MeV fluxes for these time periods, one can see that the timescales in the two periods become very similar if one assumes that both enhancements in 1999 are associated to the same event, and that some most likely spatial effect is causing the depletion in flux centered around day 31 of 1999.

Other facts point towards the second enhancement in the Ulysses ATs data in 1999 not being associated with a separate solar event. Analysis of the 1.9–5 MeV proton data from ACE/EPAM in Fig. 1 does not show a two-peak structure. Also, analysis of flare catalogues in Solar Geophysical Data shows that, besides the flare on 20 January, the only other long duration flare in the period displayed in Figs. 1 and 2 was a C5.1 flare on day 35 of 1999, after the ∼MeV flux in the ATs instrument had already started to increase. We observe that at the beginning of 1999 the Ulysses footpoint was well visible from the Earth.

For a more detailed interpretation of the measurements of Figs. 1 and 2 we need to consider the location of the spacecraft and the longitude of the associated flare. This information is given in Fig. 3, also showing the Parker spiral field line through Earth and Ulysses calculated using the solar wind speed measured at the start of the two SEP events.

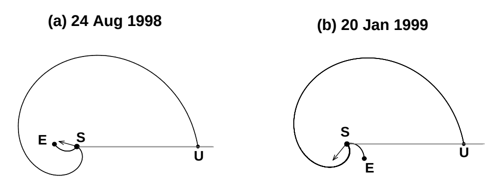

Fig. 3. Connection of Earth orbit spacecraft and Ulysses to the Sun at the start of the two SEP events. The arrows indicate the solar longitude of flares associated to the events.

We observe from Fig. 3 that the footpoint of the magnetic field line through Ulysses has a much smaller longitudinal separation from the flare site in the event of 20 Jan 1999 than for 24 Aug 1998. This results in a much faster rise time for the former event. The rise time at Ulysses for the 3–10 MeV electrons is ∼10 hours, indicating good connection to the acceleration source. Analysis of the onset in Fig. 2 (b) shows that the rise time is also small in the ATs 1.3–2.2 MeV channel, being of ∼20 hours. The time a 2 MeV proton takes to reach Ulysses by travelling along a Parker spiral of length 14 AU can be calculated to be about 30 hours. We conclude therefore that some contamination from higher energy particles is the most likely cause of the small peak starting on day 21 in the ATs 1.3–2.2 MeV channel and possibly in the KET 5.4–25 MeV channel. Analysis of the ATs anisotropies shows strong anti-solar streaming during the onset phase of the two events (in January 1999 after the small peak described above). These large anisotropies are maintained for over 4 days in each event.

Regarding the solar wind and magnetic measurements at Ulysses, we observe that on 24 Aug 1998 Ulysses and Earth are separated in longitude by 174°, and we do not expect any correlation in the local parameters at the two spacecraft. On 20 Jan 1999 their longitudinal separation is 40°. Association of shocks and magnetic field structures at the two spacecraft is uncertain.

Looking in detail at Fig. 2 (b), we searched for temporal coincidence between the start and end of the depletion zone and changes in the solar wind speed or magnetic field. We observe that a decrease in particle flux is seen not only in the ATs channel, but also in the KET 5.4–25 MeV and 38–125 MeV proton channels. The onset of the decrease appears to be around 4:00 UT on day 26. The solar wind and magnetic field data are characterised by the arrival of three shocks: on day 25 (at 11:45 UT), day 28 (at 22:43 UT) and day 37 (at 11:57 UT) (R.J. Forsyth, private communication). The first of these shocks arrives at Ulysses ∼16 hours prior to the start of decrease in particle fluxes observed in the ATs and KET proton data, thus not in time coincidence. There is no detectable change in intensities close to the second shock, while the arrival of the third shock, on day 37, is in time coincidence with the end of the depletion phase in the ATs intensities. There appears to be no correlation between changes in the magnetic polarity and changes in particle intensities.

3 Discussion

The issue of which factors cause sudden changes in energetic particle profiles in interplanetary space has long been debated in the literature. Within the paradigm of CME shock acceleration, changes in energetic particle intensities occur because the detecting spacecraft becomes connected to different (more/less efficient) portions of the shock front at which particles are produced. In this framework, Reames *et al.* (1996) have interpreted some abrupt changes in particle intensities as the result of large variations in solar wind speed, causing a sudden change in connection. Other work has suggested that particle intensities might be influenced by sector boundary crossings (Kallenrode, 1993). However a study of the influence of sector boundary crossings on the timescales and rise phases of particle events has concluded that these do not affect particle profiles (Kahler *et al.*, 1996).

Our analysis of the profiles of ∼MeV protons at 5 AU from the Sun has shown that the depletion in particle intensities observed on 20 Jan 1999 is not associated with local abrupt changes in the solar wind speed or the magnetic field polarity. In fact, our data show a remarkable degree of decoupling of the particle fluxes from the local solar wind conditions. As far as sector boundary crossings are concerned, this is expected since the coronal magnetic fields do evolve on the Sun over the time scales necessary for the magnetic polarity to be carried out to 5 AU.

When comparing the solar wind conditions during the two SEP events, we observe that many more stream interaction regions are present in January 1999, when compared to the vary flat solar wind speed time profile of August 1998.

It has been suggested in the literature that during periods of sustained high solar activity the inner heliosphere acts as a reservoir for low energy particles (Roelof *et al.*, 1992). Within this interpretation, the depletion in ∼1 MeV fluxes observed in January 1999 could be related to the three-dimensional structure of the reservoir, with the drop in flux taking place as connection to it is lost.

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