On the Energetic Particle Fluxes at 5 AU Associated with the April/May 1998 Solar Activity: Ulysses Observations

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Abstract. Located close to the ecliptic at 5.4 AU heliocentric distance, Ulysses observed energetic particle increases in April/May 1998 that were related to the second major episode of activity in the new solar cycle, the first being in November, 1997. In this paper, we report on the characteristics of the transient particle enhancements seen at Ulysses, including the compositional signatures, and suggest an interpretation in terms of the activity occurring at the Sun.

INTRODUCTION

The current phase of the ESA/NASA Ulysses mission offers a unique opportunity to study the onset of the new solar cycle (23) from a near-ecliptic vantage point at intermediate heliocentric distance, some 5 AU from the Sun (Figure 1). An additional point of interest in this regard is that Ulysses traversed this same region of the heliosphere 6.2 years earlier, in 1992, following its fly-by of Jupiter. At that time, however, conditions in the heliosphere were significantly different, corresponding to the post-maximum phase of the previous solar cycle. The main purpose of this paper is to present recent data from Ulysses covering the period late March through mid-May, 1998, at which time a complex series of energetic particle events was observed. Based on the signatures present in the data, we attempt to interpret the various transient particle enhancements seen at Ulysses in terms of the activity occurring at the Sun.

The energetic particle observations reported here were made with the Low Energy Telescope (LET), one of the five sensors of the Ulysses COSPIN experiment (1). The LET measures the intensity and composition of energetic nuclei in the energy range ~1-50 MeV/n (species dependent). Supporting data from the Ulysses Magnetometer (2) instrument and COSPIN Anisotropy Telescopes (ATs) have been used to facilitate the interpretation.

OBSERVATIONS

The top panel of Figure 2 shows the proton intensity measured by the LET in four energy channels, 0.9-1.2, 1.8-3.8, 3.8-8.0, and 9.0-19 MeV, for the 55-day period starting 21 March, 1998. Vertical lines indicate the times of arrival at Ulysses of forward (F) and reverse (R) shocks, while horizontal black bars denote the approximate duration of magnetic clouds identified in the magnetic field data. The middle panel shows

FIGURE 1. View from the north ecliptic pole in a coordinate system fixed with respect to the Sun-Earth line, showing the position of the Ulysses spacecraft at the times indicated during the period April/May 1998. Also shown are nominal heliospheric magnetic field lines (Vsw = 400 km/s) connecting Ulysses to the Sun at the longitudes shown.
FIGURE 2. (Upper panel) Intensity of protons at four energies in the range 0.9-19 MeV measured by the COSPIN/LET on Ulysses during the period 21 Mar-15 May (DOY 80-135) 1998. Vertical lines mark forward (F) and reverse (R) shocks identified in the Ulysses plasma and field data. (Middle panel) Proton/alpha ratio at two energies (1.8-3.8 and 3.8-8.0 MeV/n). Horizontal bars indicate periods of enhanced particle streaming. (Lower panel) Abundances of He, C, N, and O in the energy ranges shown, computed from 3-day averaged fluxes for the period 01 Jan-28 Jul (DOY 001-0240) 1998.
12-hour averages of the H/He ratio in two energy ranges (1.8-3.8 and 3.8-8.0 MeV/n). Also shown in Figure 2 are the peak times and locations on the solar disk of selected X-ray flares, as given in Solar Geophysical Data (inverted open triangles), and the times of selected coronal mass ejections (CME, where hCME denotes a halo event) observed by the LASCO experiment on SOHO (ftp://lasco6.nascom.nasa.gov/pub/lasco/status/LASCO_CME_List_1998). The horizontal lines connecting a number of CMEs to shocks represent our tentative associations (see Discussion). The horizontal bars in the middle panel indicate periods of enhanced field-aligned particle streaming as derived from a preliminary analysis of data from the COSPIN/ATS.

The energetic particle flux profiles at ~1-10 MeV seen at Ulysses during the period under study are dominated by two large-scale enhancements. The first increase started late on DOY 090 (30 March) and lasted in excess of 15 days, while the second onset occurred on DOY 111 (21 April) and continued until DOY 127 (7 April). Additional events of shorter duration were observed on DOY 082-090, DOY 105-111, and DOY 127-131. The first and third of these latter events were characterised by p/alpha ratios at 1.8-3.8 MeV/n that were significantly larger (~100 and ~150, respectively) than those of the long-duration events and the DOY 105 increase. In these cases, the p/alpha ratio at the same energy was typically 30-50. As can be seen in Figure 2, however, the measured ratios varied throughout individual increases, largely as a result of changes in the energy spectra of the two species. The complex series of forward and reverse shocks surrounding a magnetic cloud comprising the DOY 082-090 "event" will be the topic of a future study, and is not considered further here.

In the lower panel of Figure 2 we show the elemental abundances of He, C, and N, relative to O, at 4.25-6.75/5.5-7.5 MeV/n as measured by the LET for an extended period beginning 1 January, 1998, up to the most recent data (DOY 240, 28 August). The early part of this period (DOY 001-080) is dominated by the Anomalous Cosmic Ray (ACR) component (3), as evidenced by the He/O ratio of ~3-5. The abundance ratios of other ACR species have limited statistics when plotted as 3-day averages, with the possible exception of N/O (~0.2). The period dominated by the series of transient particle events discussed above is characterised by a factor ~10 increase in He/O, consistent with the solar origin of the ions. The transition from ACR-dominated to solar-dominated fluxes in clearly seen in Figure 3, where we show the energy spectra of (a) He and (b) O for 3 periods, DOY's 001-61, 110-130, and 180-230. The spectra of both species in the first period are characteristic of ACRs, while those for the second period have a form typical of SEPs (e.g., (4)). In the case of He, the third period, following the extended episode of transient activity, is ACR-like at the higher energies (above ~5 MeV/n), but shows a clear turn-up at low energies, indicating a residual non-ACR contribution.

**DISCUSSION**

After an initial "flare-up" in late 1997 (e.g., (5)), followed by a period of relative calm, the next episode of moderate-to-high solar activity in the current cycle occurred in April and May 1998. In particular, active region 8210 produced several X-class flares, and was associated with a large number of bright CMEs and
solar proton events at 1 AU (Solar Geophysical Data). As discussed above, this transient activity also gave rise to a sequence of solar energetic particle events and solar wind disturbances at Ulysses, located at 5.4 AU. Taking into account appropriate propagation delays, and the relative location of the spacecraft with respect to the observed activity at the Sun, we have made tentative associations between the principal particle events and their progenitors as follows:

1. The particles responsible for the onset on DOY 090 were most likely accelerated near the Sun in association with the halo CME on 090/04:59 ("Mother-of-all-halos" according to the LASCO list).

2. Similarly, the particles giving rise to the onset on DOY 111 were most likely accelerated near the Sun in association with the bright CME on 110/10:07. Given the probable source region of the CME (behind the West limb as seen from the Earth), and the nominal magnetic connection to the spacecraft (footpoint ~ 100E), this implies a significant extent for the (coronal) shock of at least 135 deg. in longitude.

3. The DOY 127 event appears to be associated with a forward shock arriving at Ulysses on DOY 128/16:13, which in turn we associate with a halo CME observed on DOY 117/09:26 together with an X1/E50 flare. A notable feature in the particle data for this event is the steeper energy spectrum compared with, e.g., the DOY 111 increase. Note also that the subsequent shock late on DOY 130, which we associate with another halo CME from the same active region (8210), is much less effective, presumably owing to the less favourable geometry.

4. The origin of the onset on DOY 105 is uncertain.

In the case of the DOY 090 and DOY 111 events, particle flux profiles at higher energies (not shown here) display features suggestive of velocity dispersion, indicating that the particles travelled a significant way along the spiral field prior to reaching Ulysses. On the other hand, the fact that the onsets lasted several days, even at >10 MeV, argues against direct propagation from near the Sun out to 5 AU. Some confinement and gradual leakage, perhaps at the CME shock as it travels outward, would be consistent with the observations. The unusual spectral flattening seen in the low-energy protons on DOY 094-095 is probably a more local effect.

As a final remark on the energetic particle profiles during the April/May episode, it is interesting to note that fewer individual enhancements are seen at Ulysses than at 1 AU (Solar Geophysical Data). Although a detailed comparison of the events at 1 AU with those at 5 AU is beyond the scope of this paper, it seems likely that the processes occurring in the interplanetary medium which produced the long rise-times at Ulysses could also act to integrate the effects of the more numerous increases seen at 1 AU, as was the case in the November 1997 events (5).

A clear effect in both sets of spectra in Figure 2 is the decrease in ACR flux by at least a factor of 2 when comparing the pre- and post-transient periods. This decrease shows no sign of recovery up to the present time, and appears to be a significant contributor to the onset of solar modulation in cycle 23, at least for the ACR component. The initial onset in the galactic cosmic ray component occurred earlier, perhaps as early as September, 1997 (R.B. McKibben, private communication).

CONCLUSION

The episode of solar activity in April/May 1998 gave rise to significant transient enhancements in MeV particle fluxes at Ulysses, 5.4 AU from the Sun. The sequence of CMEs associated with the activity apparently produced effects that were sufficiently global to cause a step-like decrease in the ACR flux, marking the onset of solar modulation in cycle 23.

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REFERENCES