

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

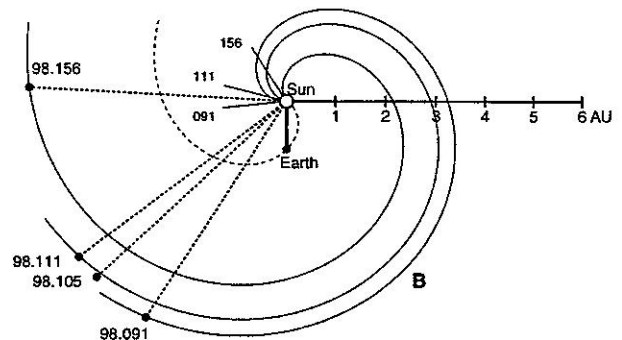


FIGURE 1. View from the north ecliptic pole in a coordinate system fixed with respect to the Sun-Earth line, showing the position of the Ulysses spacecraft at the times indicated during the period April/May 1998. Also shown are nominal heliospheric magnetic field lines ($V_{sw} = 400$ km/s) connecting Ulysses to the Sun at the longitudes shown.

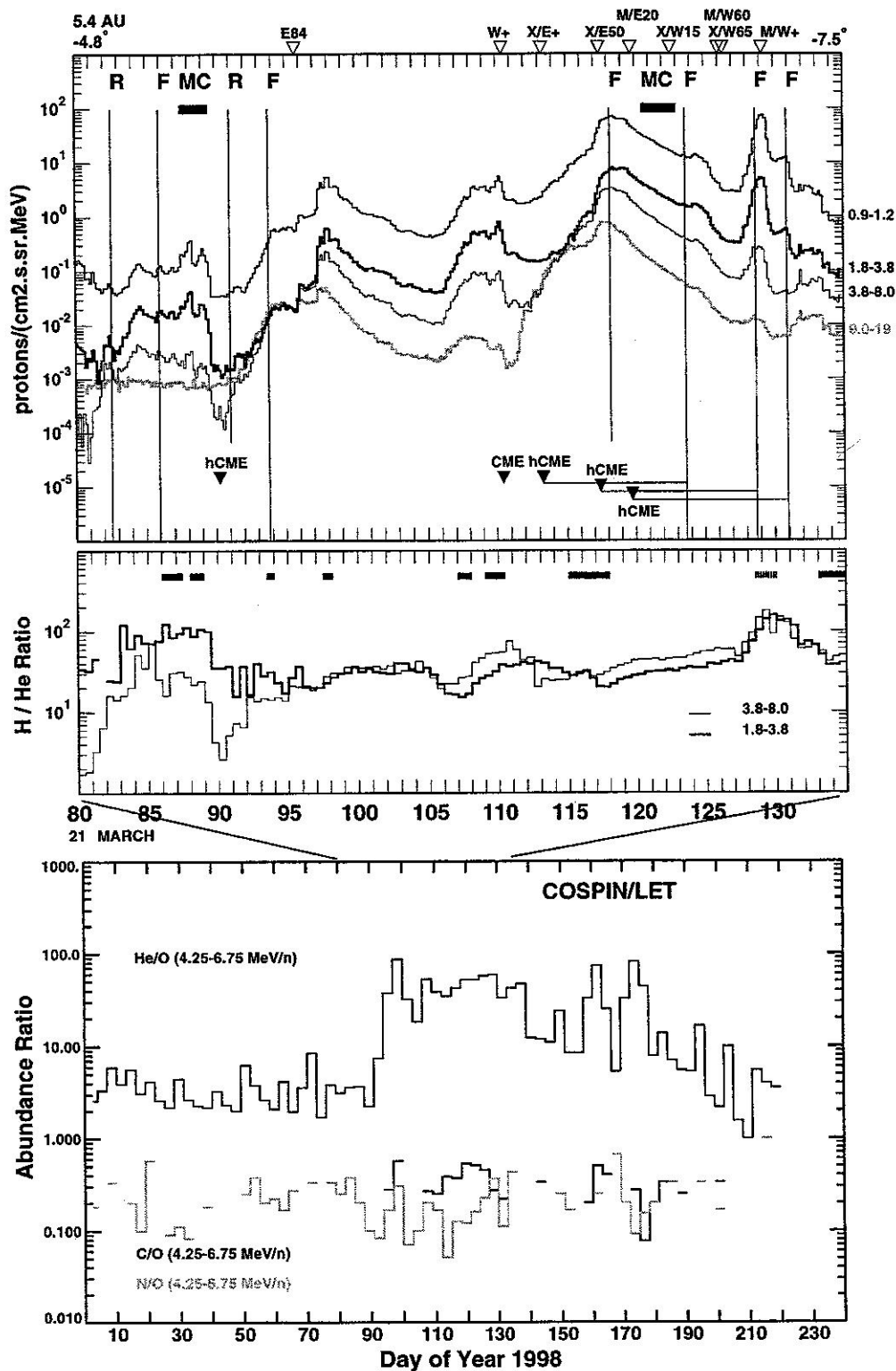


FIGURE 2. (Upper panel) Intensity of protons at four energies in the range 0.9-19 MeV measured by the COSPIN/LET on Ulysses during the period 21 Mar-15 May (DOY 80-135) 1998. Vertical lines mark forward (F) and reverse (R) shocks identified in the Ulysses plasma and field data. (Middle panel) Proton/alpha 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 is clearly seen in Figure 3, where we show the energy spectra of (a) He and (b) O for 3 periods, DOYs

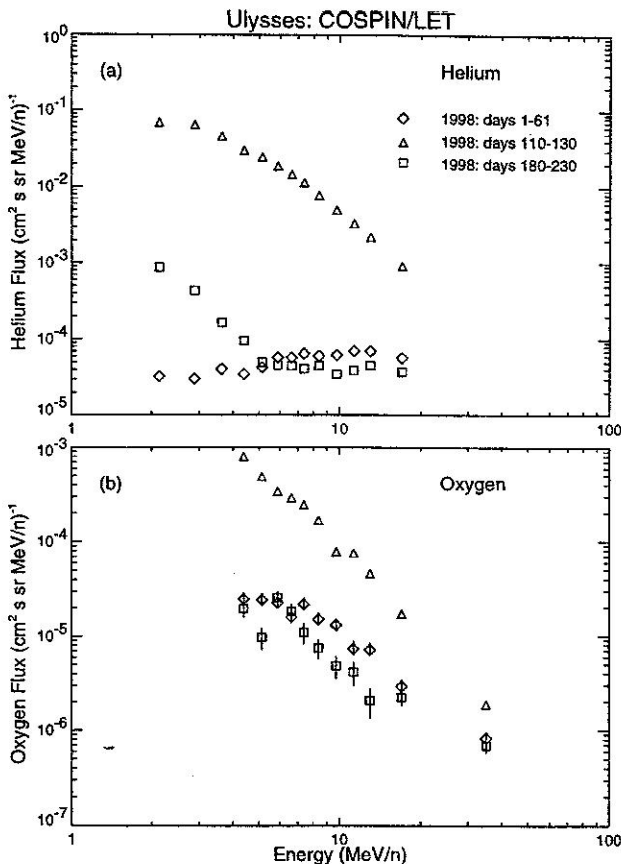


FIGURE 3. Energy spectra of (a) Helium, and (b) Oxygen for three intervals in 1998: DOY 001-061, 110-130, and 180-230. Unless shown, error bars are smaller than the symbols.

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

