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Energetic particle measurements from the *Ulysses*/COSPIN/LET instrument obtained during the August/September 2005 events

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Abstract. We report recent observations of energetic particles at energies 1–40 MeV/n made by the COSPIN/LET instrument onboard the *Ulysses* spacecraft during the period of intense solar activity in August/September 2005 during the declining phase of solar cycle 23. *Ulysses*, having started its climb to high southern latitudes for the third time, was located at ∼5 AU, at a helio-latitude of ∼30 degrees south. It detected the arrival of a solar wind compound stream resulting from the merging of a series of fast halo CMEs ejected from the Sun in late August and early September 2005 and their interaction with the pre-existing pattern of solar wind Stream Interaction Regions (SIRs) in the ambient medium through which they propagated. The heavy ion intensities are observed by COSPIN/LET to remain elevated for at least 20 days following the very intense X17.0/3B solar flare on 7 September and its associated very fast CME (plane of sky projected CME speed ∼2400 km s^{-1}). We carry out an analysis of the composition of the particle increases observed at the location of the spacecraft. Although the composition signatures were predominantly Solar Energetic Particle (SEP)-like, after the passage of the compound stream over *Ulysses*, in association with a characteristic forward and reverse shock pair, the observations showed evidence of an enhanced He content.

Keywords. Interplanetary physics (Energetic particles; Interplanetary magnetic fields; Interplanetary shocks)

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1 Introduction

Ulysses is the first spacecraft ever to fly over the poles of the Sun. Following aphelion passage in June 2004, it began its third climb to high southern heliographic latitudes, now during the declining phase of solar cycle 23. From the end of August through mid-September 2005, a remarkable series of energetic events occurred on the Sun including one of the most intense flares of the solar cycle (see Table 1). The *Ulysses* spacecraft was near 4.8 AU and about 30 degrees south of the heliographic equator, during this period. This phase of the *Ulysses* mission provides a unique opportunity to study the effects of solar activity from intermediate latitudes and a heliocentric distance of ∼5 AU. At this location in the heliosphere, individual transient solar wind disturbances resulting from multiple Coronal Mass Ejections (CMEs) at the Sun tend to coalesce to form larger, more complex structures (e.g. Richardson et al., 2005). If at the same time, the background solar wind is dominated by a more or less regular pattern of fast and slow streams that form Stream Interaction Regions (SIRs) or Corotating Interaction Regions (CIRs) (e.g. Forsyth and Marsch, 1999, and references therein; Gosling et al., 2001; Gosling and Pizzo, 1999), the result is often the formation of so-called compound streams (Burlaga et al., 1986). The focus of this study is the effects of such a compound stream on the populations of energetic particles accelerated by either CME-driven shocks or shocks associated with the stream interactions. In particular, as discussed below, we use composition data to investigate the characteristics of these populations.

Comparison of element abundances in Solar Energetic Particle (SEP) events and CIR-related events at 1 AU shows

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Table 1. Reported Solar Events relevant to the studied particle events from 22 August to 17 September 2005.

	Flare				CME[a]		
Date	X-ray onset	Flare Class	Hα location	NOAA AR	Time[b]	CME Width	V^{c}_{CME}
22 Aug	234/0044	M2.6/SF	S11 W54	0798	234/0131	Halo	1194
22 Aug	234/1646	M5.6/1N	S13 W65	0798	234/1730	Halo	2378
23 Aug	235/1419	M2.7/SF	S14 W90	0798	235/1454	Halo	1929
25 Aug	237/0431	M6.4/1N	N09 E80	0803	237/0454	146° (115[d])	1327
28 Aug	240/1017	M1.6/SF	N09 E36	0803	240/1056	76° (95)	1047
29 Aug	–	–	–	–	241/1054	Halo +	1600
31 Aug	–	–	–	–	243/2230	Halo +	1808
2 Sep	–	–	–	–	245/0030	Halo +	1384
3 Sep	–	–	–	–	246/0312	Halo +	1672
5 Sep	–	–	–	–	248/0948	Halo +	2326
7 Sep	250/1717	**X17.0/3B**	S06 E89	0808[e]	250/1726 [f]	– (105)	2400
8 Sep	251/2052	**X5.4/2B**	S11 E74	0808	No LASCO, MLSO observations		
9 Sept	252/0243	**X1.1**	S12 E68	0808	No LASCO, MLSO observations		
9 Sep	252/0532	M6.2/1F	S13 E71	0808	No LASCO, MLSO observations		
9 Sep	252/0942	**X3.6**	S11 E66	0808	No LASCO, MLSO observations		
9 Sep	252/1913	**X6.2/2B**	S11 E58	0808	252/1948	Halo	2257
10 Sep	253/0606	M3.7/2N	S11 E51	0808	253/0701	35° (149)	747
10 Sep	253/1634	**X1.1**	S11 E47	0808	–	–	–
10 Sep	253/1910	M4.1/1N	S12 E45	0808	–	–	–
10 Sep	253/2130	**X2.1**	S13 E47	0808	253/2152	Halo	1893
11 Sep	254/0229	M3.4/SF	S12 E42	0808	–	–	–
11 Sep	254/1244	M3.0/SF	S13 E42	0808	254/1300	Halo	1922
12 Sep	255/0837	M6.1/2F	S11 E25	0808	255/0912	22° (144)	511
13 Sept	256/1919	**X1.5**/2B	S09 E10	0808	256/2000	Halo	1866
13 Sep	256/2315	**X1.7**/1B	S10 E04	0808	–	–	–
14 Sep	257/1005	M4.6	–	0808	–	–	–
15 Sep	258/0830	**X1.1**/1B	S10 W15	0808	–	–	–
16 Sep	259/0141	M4.4/1B	S13 W26	0808	–	–	–
16 Sep	259/1918	M3.5/1F	S11 W37	0808	–	–	–
17 Sep	260/0558	M9.8/2N	S10 W39	0808	–	–	–

[a] CME classification and parameters extracted from the SOHO/LASCO CME catalogue at http://cdaw.gsfc.nasa.gov/.
[b] First appearance in the C2 coronagraph (>1.5 solar radii).
[c] Plane of sky projected CME speed in $km\,s^{-1}$.
[d] Position angle measured from solar north in degrees (counterclockwise). + indicates a backside halo CME event.
[e] Region 0808 is the return of old Region 0798 (as reported in the SEC *Preliminary Report and Forecast of Solar Geophysical Data* published online at http://sec.noaa.gov.weekly/ by the NOAA/SED and the AFWA).
[f] Data gap in LASCO, time disruption in the active region near the limb begins, CME observed with the Mk4 K-coronameter at Mauna Loa Solar Observatory (MLSO).

that the latter exhibit significant enrichments of helium and carbon relative to SEP events (Mason and Sanderson, 1999; Fränz et al., 1999; Richardson, 2004, and references therein). Particle composition measurements are important for understanding the origin of the seed particle population accelerated in association with CIRs. It has been suggested that the source is the suprathermal tail of the bulk solar wind distribution (Reames et al., 1991). Another possibility is that CIRs simply re-accelerate a background population of particles remaining from earlier SEP events (e.g. Maclennan et al., 1993; Richardson et al., 1998). A contribution from pick up ions is also a possibility (Gloeckler et al., 1994; Geiss et al., 1995). However, the contribution of "inner source" pickup ions as a substantial source for the observed enhancement in carbon associated with CIRs is an issue under debate. Recent results based on charge states of CIR-event ions (∼0.5 MeV/n) have shown that "inner source" pick up ions do not appear to be major contributors to the source material for CIRs even at 1 AU (Möbius et al., 2002; Mazur et al., 2002).

Hofer et al. (2003a, b) investigated the origin of the energetic particle populations during and after the second so-called Fast Latitude Scan (that occurred from 27 November 2000 to 13 October 2001) using elemental composition measurements from the *Ulysses*/COSPIN/LET. They classified the energetic particle populations during this period as being mixed between solar energetic particles (major component) and particles accelerated at SIRs or CIRs. CIRs are recurrent SIRs, i.e. compression regions that have a characteristic time difference of ∼26 days as viewed from Ulysses (e.g. Forsyth and Marsch, 1999, and references therein). In the present work, we present recent unique energetic particle measurements in the 1–40 MeV/n range obtained by the COSPIN/LET instrument onboard *Ulysses* during the August/September 2005 period of intense solar activity, observed during the declining phase of the solar cycle 23. Furthermore, we carry out a composition analysis which allows distinction between SEPs accelerated in transient events associated with CMEs and particles accelerated at SIRs.

2 Instrumentation

The particle data used in this study are from the Low Energy Telescope (LET) onboard the *Ulysses* spacecraft. LET is one of the five telescopes in the Cosmic Ray and Solar Particle Investigation (COSPIN). The COSPIN/LET instrument records the fluxes and the composition of solar energetic particles low energy cosmic ray nuclei from hydrogen up to iron over a range of energies from ∼1 MeV/ to 50 MeV/n using a four-element solid state detector telescope surrounded by an anti-coincidence shield (Simpson et al., 1992). The measurements are made using the double dE/dX vs. E technique. The magnetic field observations presented here were made with the *Ulysses* Magnetometer (Balogh et al., 1992), whilst the solar wind measurements were made with the ion sensor of the *Ulysses* Solar Wind Plasma experiment (Bame et al., 1992).

3 Observations and data analysis

Ulysses data analyzed in this paper cover the period from mid-August to the end of October 2005. *Ulysses* had begun its third orbit and its ascent to high southern latitudes and during this period was located at ∼30 degrees south of the solar equator, at a heliocentric radial distance of ∼4.8 AU from the Sun and traveled in heliolongitude from 160 degrees east to 126 degrees west of the Sun-Earth line.

3.1 Heliospheric structure and solar activity

Corotating Interaction Regions are regions of compressed plasma formed at the leading edges of corotating high-speed solar wind streams originating in coronal holes as they interact with the preceding slow solar wind (Balogh et al., 1999). They are particularly prominent features of the solar wind during the declining and minimum phases of the 11-year solar cycle. At low heliographic latitudes, such CIRs are typically bounded by forward and reverse waves on their leading and trailing edges, respectively, that steepen into

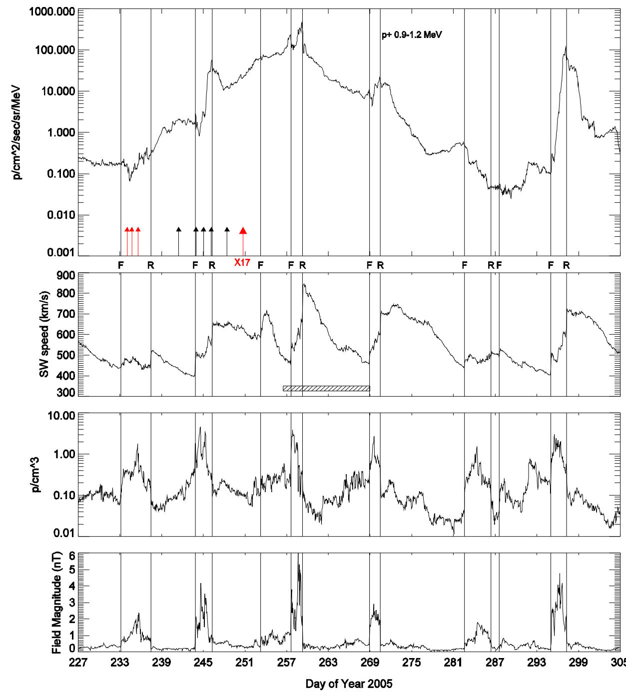

Fig. 1. Overview of the 0.9–1.2 MeV energetic proton intensities as measured by the *Ulysses* COSPIN/LET instrument, solar wind velocity, plasma ion density and IMF magnitude from 15 August till the end of October 2005 (DOY 227–305). The hatched horizontal bar in the second panel denotes a period with ICME characteristics. Upward pointing red and black vertical arrows indicate solar events that occurred during this period (see Table 1).

shocks at heliocentric distances beyond 1 AU (e.g. Forsyth and Gosling, 2001).

Figure 1 shows from top to bottom an overview of the energetic proton profile in the energy interval 0.9–1.2 MeV as measured by the COSPIN/LET instrument onboard *Ulysses*, as well as solar wind velocity, density and Interplanetary Magnetic Field (IMF) magnitude observations in the period from 15 August till the end of October 2005 (Days of Year (DOY) 227–305). The solid vertical lines in Fig. 1 correspond to the passage of Forward (F) and Reverse (R) shocks/waves during this period. The Forward shocks are distinguished by an abrupt increase in density, temperature, flow speed, magnetic field strength and total pressure. The Reverse shocks are distinguished by an abrupt decrease in density, temperature, magnetic field strength and total pressure and an increase in flow speed.

The occurrence of stable sources of high speed solar wind streams (i.e. coronal holes) are expected in the descending phase of the solar cycle. As noted above, stable streams of fast solar wind interacting with slow solar wind streams can lead to the formation of compression regions, SIRs or CIRs. During *Ulysses*' first orbit, in June 1992 while traveling south at ∼13° S *Ulysses* encountered a stable high-speed solar

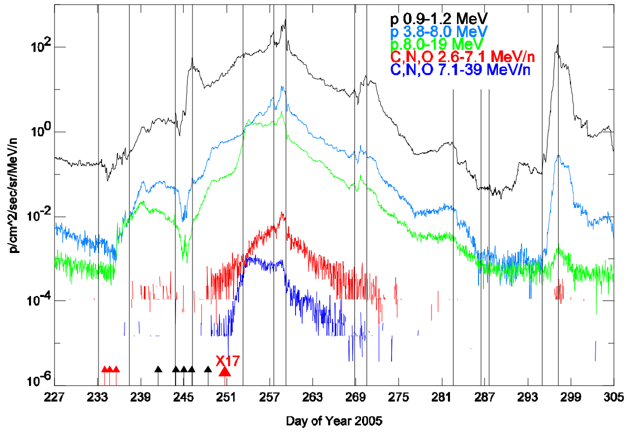

Fig. 2. From top to bottom: Overview of the 0.9–1.2 MeV, 3.8–8.0 MeV and 8.0–19.0 MeV energetic proton intensities and the heavy ion intensities in the 2.6–7.1 MeV/n and 7.1–39 MeV/n energy intervals for the charge group C,N,O as measured by the *Ulysses* COSPIN/LET instrument during the period presented in Fig. 1.

wind stream recurring for about 14 rotations through June 1993 at ~34° S (Bame et al., 1993). McComas et al. (2006) examined solar wind observations from *Ulysses*' third solar orbit and concluded that transient disturbances (ICMEs) continued to be observed and that a regular stable stream structure of the kind seen in the first orbit was not recurrently observed at least below ~37° S. Note that Ulysses finally remained immersed in the southern polar coronal hole high-speed solar wind flow at 39° S. Nevertheless, Fig. 1 shows that during the period presented, one or more SIRs/CIRs were present (see also Lario and Roelof, 2007). Magnetic field compression regions were clearly observed. The principal stream interaction region passed over the spacecraft around DOY 244 (F-shock on DOY 243 and R-shock on DOY 246). Later occurrences were around DOY 270 (F-shock on DOY 268 and R-shock on DOY 270) and 296 (F-shock on DOY 295 and R-shock on DOY 297). Therefore, these 3 sequences were separated by ~26 days and constitute a short-lived sequence of CIR events. Weaker SIRs are observed around DOY 235 and 285. A structure with unusually high solar wind speed (~850 km/s) and unusually high magnetic field magnitude was observed by *Ulysses* around DOY 258. As discussed later in Sect. 3.2, this structure has characteristics of interplanetary counterpart of a CME (i.e. ICME). Forward and Reverse shocks were also observed within the structure, suggesting that the SIRs that passed the spacecraft around DOY 235 and 285 were most likely originated by the same solar wind interaction that produced the forward and reverse shocks in front of this structure (F-shock on day 257 and R-shock on day 259). The difference is that now, the recurrent structure interacted with the ICME resulting in the formation of a compound stream.

Table 1 contains an extensive list of the major solar events (M3.0 or greater flares; CMEs faster than 1000 km s^{-1}) and their characteristics for the period 22 August (DOY 234) to 17 September 2005 (DOY 260). These events are considered as possible sources of energetic particles observed at *Ulysses*. For completeness, in Table 1 we also associate flares and CMEs (when observed) for each major event. Association between solar flares and CMEs is based upon their temporal proximity, the longitude of the flare site and the direction of propagation of the CME. The many X-class events during this period of isolated but intense solar activity are highlighted using bold-faced type. The solar flares are as reported in the Solar Geophysical Data (http://sgd.ngdc.noaa.gov/sgd/jsp/solarindex.jsp), whereas CME identification and parameters were obtained from the SOHO/LASCO CME catalogue compiled by Yashiro and G. Michalek (available at http://cdaw.gsfc.nasa.gov). The CME on 7 September 2005, for which no LASCO images are available, is identified from the list of CMEs observed with the Mk4 K-coronameter at Mauna Loa Solar Observatory (MLSO). The details of CME identification and measurements by MLSO are available at http://mlso.hao.ucar.edu/cgi-bin/mlso_logs.cgi.

3.2 Energetic particle observations

Figure 2 focuses on the energetic particle observations and shows an overview of the energetic proton profiles in three energy intervals in the range 0.9–19 MeV and the heavy ion intensities in the 2.6–7.1 MeV/n and 7.1–39 MeV/n energy intervals for the charge group C,N,O as measured by the COSPIN/LET instrument onboard *Ulysses* during the same period presented in Fig. 1. The instrument configuration is such that, at quiet times, the COSPIN/LET 8–19 MeV proton channel responds mainly to galactic cosmic rays, but when the level of solar activity increases, it also responds to protons in the nominal energy range 8–19 MeV. Protons of this energy are normally only observed by the LET in association with large solar energetic particle events. These high-energy particle observations (green trace in Fig. 2) show that there were basically three large enhancements at *Ulysses* during this period.

The proton intensities started to increase gradually on day 235. This increase can be attributed to the solar events from active region AR 0798 occurring on days 234 and 235 on the Western Hemisphere of the Sun as seen from the Earth (Table 1). We indicate the occurrence of these solar events by thin upward pointing red vertical arrows in Fig. 2. These events most likely started filling the heliosphere with energetic particles. On day 245, before the fluxes have returned to background levels, a new event sets in. The likely source for this particle enhancement is one or more of the fast backside halo CMEs observed between days 241 and 248. The black upward pointing vertical arrows in Fig. 2 indicate the occurrence of these events. These backside CMEs have been associated with the old active region AR 0798 (ftp://lasco6.nasom.nasa.gov/pub/lasco/status/LASCO_CME_List_2005). An increase with statistically significant heavy ion intensities in the 2.6–7.1 MeV/n energy interval for the charge group C,N,O (red line in Fig. 2) is also seen in association with this solar activity.

Figure 3 shows the position of *Ulysses* with respect to the fixed Sun-Earth line, projected onto the solar equatorial plane as viewed from the north (top) and on a plane perpendicular to the solar equator as viewed from the Earth toward the Sun (bottom) at the beginning, middle and after the end of the period of major solar activity. The ideal Archimedes spiral magnetic field lines connecting *Ulysses* to the Sun are also shown, calculated using the measured solar wind speed at *Ulysses* on the three days indicated. As shown in Fig. 3, given that *Ulysses* was separated by almost 180° in longitude with respect to the Earth's position, it is highly likely that CMEs that impact *Ulysses* originate on the backside of the Sun and do not affect Earth.

Intermittently during the period denoted by a hatched horizontal bar in the 2nd panel from top in Fig. 1, a characteristic coherent rotation of the magnetic field direction, low variance magnetic field, enhanced He^{++}/H^{+} density ratios, increased O^{7+}/O^{6+} charge-state ratios and high iron charge states are observed (see http://helio2.estec.esa.int/ulysses/). This provides evidence that material exhibiting ICME characteristics is observed by *Ulysses* and strongly suggests that during this period, *Ulysses* detected a system of solar wind transient flows that resulted from the interaction and merging of the fast backside halo CMEs ejected from the Sun from 29 August (DOY 241) till 5 September (DOY 248) 2005 (Table 1). The arrival time of this system of ICME material at the spacecraft is consistent with the times of ejection of the backside halo CMEs at the Sun. As noted in Sect. 1, these ICMEs should merge by the time they reach 5 AU. Interaction and coalescence of the transient flows with pre-existing stream interaction regions in the ambient medium through which they propagate can lead to the formation of a compound stream. Forward and Reverse shocks are usually observed at various points during the passage of such compound streams over spacecraft at such heliocentric distances (e.g. Burlaga et al., 1986). As discussed in Sect. 3.1, this is also the case here.

When AR 0798 re-appeared on the east limb of the Sun (as viewed from the Earth) on 7 September (DOY 250) it was numbered AR 0808. At ∼17:17 UT on this day it produced one of the largest flares of the solar cycle 23, a very intense X17.2/3B solar flare which had an associated fast east limb CME (plane of sky projected CME speed $\sim$2400 km s^{-1}). As shown in Fig. 2, in response to this high level of solar activity an additional rise in the 8–19 MeV particle intensities is observed at ∼08:00 UT on 9 September (DOY 252) superposed upon the already enhanced proton intensities. Associated increases in the low-energy proton intensities and the 2.6–7.1 MeV/n C,N,O group are not observed, however,

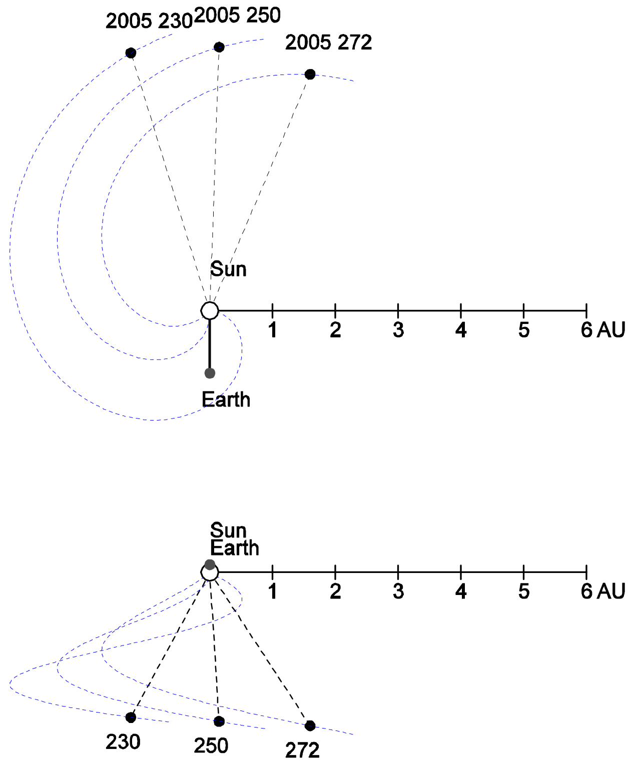

Fig. 3. The position of Ulysses on DOY 230, 250 and 272 of 2005 with respect to the fixed Sun-Earth line, projected **(a)** on the solar equatorial plane as viewed from the north (top), and **(b)** on a plane perpendicular to the solar equator as viewed from the Earth toward the Sun (bottom) is shown. Also shown as dashed blue lines are the ideal Archimedes spiral magnetic field lines connecting Ulysses to the solar surface, calculated using the measured solar wind speed.

most likely due to the high pre-event ambient intensities that mask the onset of the event at these channels. The associated onset is more clearly observed in the heavy ion intensities in the 7.1–39 MeV/n energy range for the charge group C,N,O (blue line) which start to rise gradually at ∼20:00 UT on 8 September (DOY 251) with the same slope as the corresponding profile of the 8–19 MeV protons. It is noteworthy that only the X17 solar flare on 7 September produced increases in the C,N,O intensities in the 7.1–39 MeV/n energy range. This is most likely the result of the flare intensity and/or a better magnetic connectivity between *Ulysses* and the Sun during this period. Using the solar wind velocity of 600 km/s^{-1} measured by the *Ulysses*/SWOOPS experiment at the time of the event the Parker spiral magnetic field line connecting *Ulysses* to the Sun, is computed to be ∼8.86 AU long. Assuming the first arriving particles were accelerated near the Sun in association with the solar events on the 7 September, the earliest expected onset time for directly arriving particles propagating from the Sun along the field using the velocity of the highest energy ions contributing to this channel would be ∼4.3 h after the events. Comparison

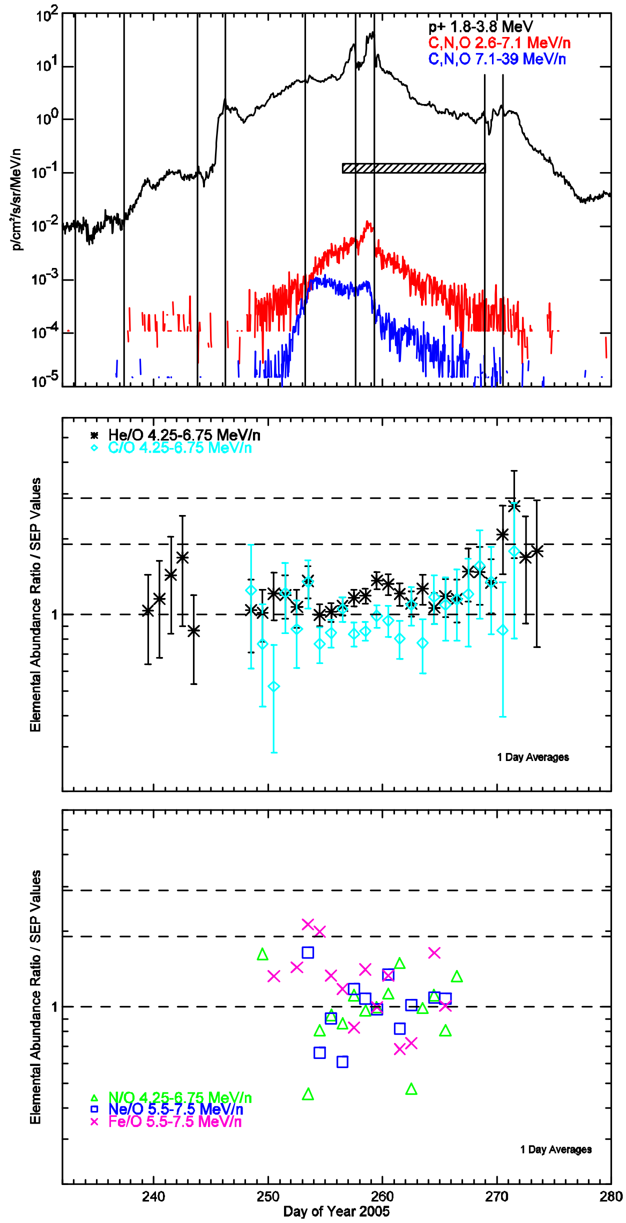

Fig. 4a. (Top panel) The three traces from top show 1.8–3.8 MeV proton intensity and the heavy ion intensities in the 2.6–7.1 MeV/n and 7.1–39 MeV/n energy intervals for the charge group C,N,O as measured by the COSPIN/LET for the period DOY 232–280. (Middle and bottom panels) Heavy ion abundance ratios (1-day averages) in the energy range 4.25 MeV/n to 7.5 MeV/n for helium, carbon, nitrogen, neon and iron with respect to oxygen, all normalized to the SEP composition given by Mason and Sanderson (1999).

with observations shows that the onset at *Ulysses* is considerably delayed. In this very disturbed period it is more than likely that the actual field lines are significantly distorted from ideal Parker spirals. Furthermore, the observed delay may also result from delayed injection of particles onto IMF lines connecting the particle sources (e.g. CME-driven shocks) to *Ulysses*.

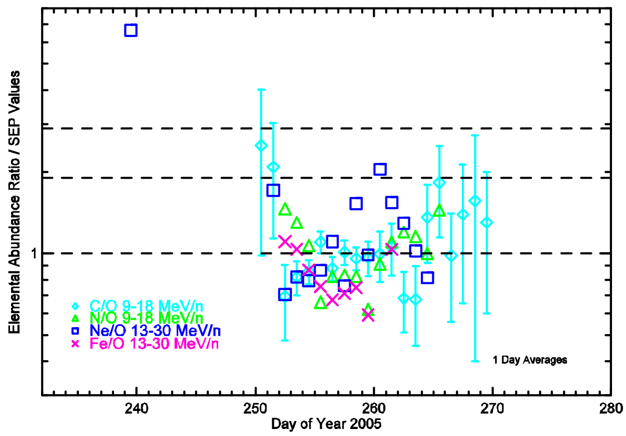

Fig. 4b. Daily averaged elemental abundance ratios C/O and N/O for the energy range 9–18 MeV and Ne/O and Fe/O in the energy interval 13–30 MeV/n also normalized to the reference composition given by Mason and Sanderson (1999).

The 8–19 MeV proton intensity (green line in Fig. 2) and the intensity of heavy ions in the 7.1–39 MeV/n energy interval for the C,N,O charge group (blue line in Fig. 2) are observed to exhibit a plateau after they reach a maximum on day 253, while the lower energy heavy ion intensities are observed to still increase gradually. After the passage of the Reverse Shock over the spacecraft on day 259 the particle intensities at all energy channels exhibit a smooth decay. From 7–18 September, (days 250–261) 2005 during its passage on the visible disk of the Sun, AR 0808 produced 26 M-class and 10 X-class flares. (Table 1 showing only the flares above M3). This sustained and intense solar activity contributed to the build-up and maintenance at high levels of the particle fluxes at *Ulysses*.

3.2.1 Composition analysis

We now examine the elemental composition of the energetic particle fluxes recorded by the COSPIN/LET instrument onboard *Ulysses* in association with the August/September 2005 events. The elemental abundances of heavier elements with respect to oxygen can be used to distinguish between SEPs and particle populations associated with SIRs or CIRs (Mason and Sanderson, 1999). For the analysis we divide the measured elemental abundance ratios by a reference value for SEPs. In this analysis we use the reference values as reported by Mason and Sanderson (1999), which refer to Mazur et al. (1993), for both selected energy ranges, i.e. (4.25–7.5) MeV/n and (9.0–30.0) MeV/n. According to Mazur et al. (1993), the reference value for He/O is nearly the same in the energy interval 0.6–1.0 MeV/n and ∼4.9–22.5 MeV/n. As reported by Mason and Sanderson (1999), the largest CIR to SEP ratio is obtained for He/O (2.9). Furthermore, the C/O ratio given by these authors (1.9) could also be used to distinguish between CIR and SEP-related populations. Since there is no large separation of the reference values for the other elements, their elemental abundance ratios are less optimal than He/O and C/O to identify the type of population.

In the upper panel of Fig. 4a, the 40-min averaged proton intensity in the energy interval 1.8–3.8 MeV/n and hourly averages of the C,N,O ion intensities in the 2.6–7.1 MeV/n and 7.1–39 MeV/n energy intervals are shown from top to bottom as measured by the COSPIN/LET for the period 20 August–7 October 2005 (DOY 232–280). The solid vertical lines in this panel mark the time of passage of Forward and Reverse shocks/waves at the *Ulysses* spacecraft. The hatched horizontal bar denotes the CME/CIR combination observed by *Ulysses* during this period. In the middle and bottom panels of Fig. 4a, we show the daily averaged elemental abundance ratios for helium, carbon, nitrogen, neon and iron with respect to oxygen for the energy range 4.25 MeV/n to 7.5 MeV/n all normalized to the corresponding SEP reference values. Figure 4b shows the daily averaged elemental abundance ratios C/O and N/O for the energy range 9–18 MeV and Ne/O and Fe/O in the energy interval 13–30 MeV/n also normalized to the reference composition given by Mason and Sanderson (1999). Statistically significant data available for each element are presented in Fig. 4 (data for each element are shown for which errors are smaller than the elemental abundance ratio value). In order to aid a visual comparison horizontal lines have been drawn at unity, representing the reference SEP value for all elements and at 2.9 and 1.9 marking the reference CIR to SEP value for He/O and C/O respectively. The plotted error bars for He and C take the statistical error and the error of the reference values into account. Data with good statistics for particles in the higher energy range are more limited (Fig. 4b). The normalized elemental abundance ratios plotted in Fig. 4 show that the majority of the particle populations recorded during this period have an SEP elemental composition signature i.e. in Fig. 4 the majority of points lie within the error bars close to a measured-to-SEP ratio at unity for all elements in the energy ranges presented. However, well into the decay phase of the particle event on days 270 and 271, although a quite large scatter in the values making up the daily averages is observed, the normalized He/O ratio is apparently enhanced, close to the reference CIR/SEP value. The (C/O)/SEP ratio in both energy ranges shown does not exhibit a corresponding enhancement but, within the error bars, is close to unity throughout the period presented. On days 268 and 270, *Ulysses* observed a Forward-Reverse shock pair associated with a recurrent CIR (Fig. 1).

4 Discussion and conclusions

We report on unique observations obtained from the COSPIN/LET instrument onboard the *Ulysses* spacecraft at an intermediate latitude of 30° S and ∼5 AU heliocentric distance during the recent August–September 2005 period of intense solar activity which occurred during the declining phase of the solar cycle 23. *Ulysses* observes the arrival of a compound stream resulting from the merging of individual transient flows generated by a series of solar events in late August and early September 2005 and their interaction with the pre-existing pattern of stream interaction regions in the ambient medium. A delayed particle onset more clearly observed in the heavy ion intensities in the 7.1–39 MeV/n energy range for the charge group C,N,O is detected following the very intense X17.0/3B solar flare on 7 September and its associated very fast east limb CME. A possible explanation of the observed delay is a delayed injection of particles onto IMF lines connecting the particle sources to *Ulysses*. The energetic particle intensities remained elevated at Ulysses for at least 20 days following this intense solar activity.

In our analysis, we have derived the daily averaged elemental abundance ratios based on measurements from the COSPIN/LET instrument. The elemental composition signatures are used to investigate the characteristics of the particle increases observed at the location of the spacecraft. During the CME/CIR combination observed by *Ulysses* in September 2005 the composition analysis identifies the energetic particles, within the statistical errors, as an SEP population and therefore transient related. Previous elemental abundance analyses at low latitudes with *Ulysses* (e.g. Hofer et al., 2003a) have shown that while solar energetic particles dominated in the cases studied, there were also indications for particle acceleration at compression regions in a few instances.

As shown in Fig. 4a an enhancement in the He/O ratio is observed after the passage of the compound stream trailing edge over the spacecraft. No corresponding increase in the C/O ratio is observed. The He enhancement follows a characteristic recurrent Forward and Reverse shock pair that was observed in the plasma and magnetic field measurements at *Ulysses*. The He data recorded in this time interval is apparently influenced by this compression region and shows evidence of reverse shock acceleration (Marsden et al., 1993; Richardson et al., 2004). The observation of a more strongly enhanced helium abundance of the reverse shock particles relative to SEP abundances than particles detected at the forward shock is in agreement with current results in CIR research and literature (e.g. Richardson, 2004, and references therein) according to which more efficient particle acceleration occurs in the vicinity of the CIR Reverse shock. We believe that the most plausible origin for the enhanced He content observed in our paper in association with the CIR is CIR-accelerated pick up helium originating as interstellar neutrals (Simnett et al., 1995). The fact that the enhanced He/O values do not reach the CIR/SEP value indicates that Ulysses does not observe a pure CIR effect (e.g. Richardson, 2004) and suggests the existence of a background SEP population of He. The non-observation of an enhancement in carbon by *Ulysses* may be due to a lack of "inner source" pickup carbon at that location or suggests that the bulk of the particles observed were dominated by the ambient SEP population. Another possibility is that the CIR reverse shock has simply reaccelerated a preexisting population of SEPs or particles of this species from the solar energetic particle events themselves.

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