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From the Sun's south to the north pole – Ulysses COSPIN/LET composition measurements at solar maximum

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Abstract. Based on elemental abundance ratios derived from the Ulysses COSPIN/LET measurements, we classified the energetic particle populations during and after the so-called Fast Latitude Scan – the time period during which the Ulysses spacecraft traveled from the highest helio-latitude south to maximum northern latitude, i.e. 27 November 2000 to 13 October 2001 – as being mixed between solar energetic particles (major component) and particles accelerated at stream interaction regions.

During the fast latitude scan, the Ulysses spacecraft made the first transit in helio-latitude from pole to pole during solar activity maximum conditions, providing a unique opportunity to acquire energetic particle composition data over a maximum range of helio-latitudes in the inner heliosphere. At low latitudes, based on our elemental abundance analysis, we found that while solar energetic particles dominated, there were indications for particle acceleration at single compression regions in a few instances.

In the high helio-latitude range the observed elemental particle compositions are mainly of the solar energetic particle type. Within the statistical errors, the observed abundance ratios were independent of latitude, and were characteristic of solar energetic particles. These observations raise an important question for the theories of particle propagation in the inner heliosphere. The daily elemental abundance ratios of S/O, Mg/O and Si/O shown here are the first measured ratios at high helio-latitudes in the energy range from 13.0 to 30.0 MeV/n.

Key words. Interplanetary physics (energetic particles; interplanetary shocks) – Solar physics, astrophysics and astronomy (flares and mass ejections)

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1 Introduction

Recently, the Ulysses spacecraft made the first transit in helio-latitude from pole to pole during solar activity maximum conditions. This provided a unique opportunity to acquire energetic particle data over this wide range of helio-latitudes. In November 2000, the Ulysses spacecraft reached its highest southern heliographic latitude during the solar maximum mission (80.2°), at a heliocentric radial distance of $\approx$ 2.27 AU. From 27 November 2000 (DOY 332) to 13 October 2001 (DOY 286), the spacecraft traveled from the highest southern helio-latitude to the highest northern helio-latitude during the so-called Fast Latitude Scan (FLS). After the FLS, Ulysses started its second journey from the northern solar pole to aphelion at the heliocentric distance of the Jupiter orbit. The spacecraft will reach aphelion in June 2004.

In earlier studies using energetic particle data from the solar polar passes (e.g. Hofer et al., 2001, 2002a; Marsden et al., 2001), we showed that the data from the high-latitude observations reflected the generally high level of solar activity present during that period. We found evidence that the observed particle populations from the southern and northern polar passages comprised predominantly solar energetic particles (SEPs) accelerated in association with coronal mass ejections (CMEs), rather than particles related to stream interaction regions (SIRs) (Gosling et al., 2001) or even the recurrent structure called corotating interaction regions (CIRs) (Hofer et al., 2002a). Tranquille et al. (2003) identified periods of enhanced helium isotopic abundance ratios, i.e. $^3He/^4He$ up to 48° helio-latitude in 2002. Both findings open the question about the propagation of energetic particles to high helio-latitudes, as also addressed in McKibben et al. (2001) and Dalla et al. (2003).

In this analysis, the daily averaged elemental abundance ratios based on Ulysses COSPIN/LET measurements from the end of 2000 to about mid 2002 are derived. The large latitudinal variation of the elemental composition values averaged during 11 selected events are investigated. With respect to the preliminary analysis of Hofer et al. (2003), the time in-

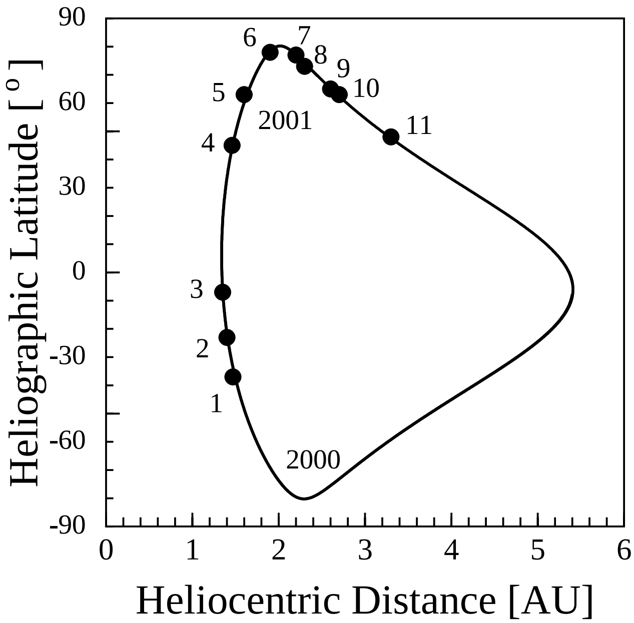

Fig. 1. The orbit of the spacecraft Ulysses. The second fast latitude scan from south to north during the solar maximum mission lasts from November 2000 to October 2001 (events 1–6). The circles represent the averaged helio-latitude and heliocentric distance of the spacecraft during the eleven selected time intervals.

terval was enlarged, elements with higher Z and observations in higher energy ranges were added.

First, the intensity profiles for the most abundant species, i.e. proton and helium, are presented and discussed. The proton/alpha ratio is used to identify time intervals that are likely to be influenced by SIRs.

Second, the abundance ratios of the heavier elements with a wide range in Z from He/O up to Fe/O from about 4 MeV/n to 30 MeV/n are derived and compared with reference values.

Third, the elemental abundance ratios are averaged for each of the eleven selected time intervals and compared with the reference values of SEP and CIR/SIR populations (Mason and Sanderson, 1999).

Finally, the changes of the averaged composition measurements are discussed with respect to possible changes due to latitudinal effects or the level of solar activity.

2 Ulysses COSPIN/LET instrument and data

The low energy particle data used in this study are recorded by the Low Energy Telescope (LET), one of five telescopes of the Cosmic Ray and Solar Particle Investigation (COSPIN) instrument (Simpson et al., 1992), on board the Ulysses spacecraft. Ulysses is the first (and so far the only) mission to explore the out-of-ecliptic regions of the heliosphere up to high helio-latitudes. The spacecraft was launched in October 1990. The mission to date, therefore, covers a period of more than 12 years, providing the opportunity to follow the Sun's 11-year activity cycle, and part of the 22-year magnetic cycle.

The COSPIN/LET instrument records the flux and the composition of solar energetic particles and of low energy cosmic ray nuclei from hydrogen up to iron over a range of energies from $\approx$1 to $\approx$50 MeV/n, using four level-element solid state detectors surrounded by an anti-coincidence shield. The measurements are made based on the double dE/dX vs. E technique (e.g. Marsden et al., 1984; Simpson et al., 1992).

The times of the shock occurrences at Ulysses were derived by R. J. Forsyth based on solar wind and magnetic field data.

In Fig. 1, the Ulysses orbit in a heliolatitude-heliocentric distance diagram is shown. The locations of the spacecraft averaged during each of the 11 selected time intervals are presented by labeled circles. The events 1 to 6 belong to the so-called FLS. The events 1–9 take place in 2001 and the events 10 and 11 in 2002.

3 Composition analysis

The elemental particle composition can be used to identify the type of a given energetic particle population (Hofer et al., 2002c): SEP or SIR/CIR populations. Solar energetic particle and stream interaction regions have two different time scales. Large solar energetic particle events at 1.6 AU in the selected energy range last about 15 days (Hofer et al., 2002b), whereas CIR or SIR are known to be present for up to $\approx$3 days, only.

The proton-to-alpha flux ratios (energies around 1 MeV/n) help to identify SIR dominated time intervals. Sudden decreases in the proton to alpha ratio from $\approx$80 to $\approx$10 followed by a more gradual decrease are indicative of the presence of an SIR. The corresponding energetic particles are usually accelerated at the reverse shock associated with SIRs (e.g. Marsden et al., 1993; Lario et al., 2001, 2003; Hofer et al., 2002c).

In Fig. 2, the proton/alpha flux ratios and the 30 minutes averaged alpha flux (1.0–5.0 MeV/n) are shown from DOY 330 in 2000 to DOY 149 in 2002. The alpha flux profile is scaled for reasons of clarity by a factor of 0.05. The arrows at the bottom of the figure mark the times of the shock occurrences at Ulysses. The numbers indicate the 11 selected time intervals.

The highly variable flux profiles and the changes in the proton/alpha ratios reflect the high solar activity during the entire time interval. From DOY 56 to about DOY 178 in 2001 (including the intervals 1, 2, 3 and 4) large, short-term decreases are observed. Three of them are accompanied by almost simultaneous, large peaks in the alpha flux profile and an enhanced number of shock occurrences. This period has a high potential to contain at least one SIR. Before and mainly after this period, the amplitudes of large decreases in the proton/alpha ratios are smaller and the signal looks more noisy, i.e. high frequency variability dominates.

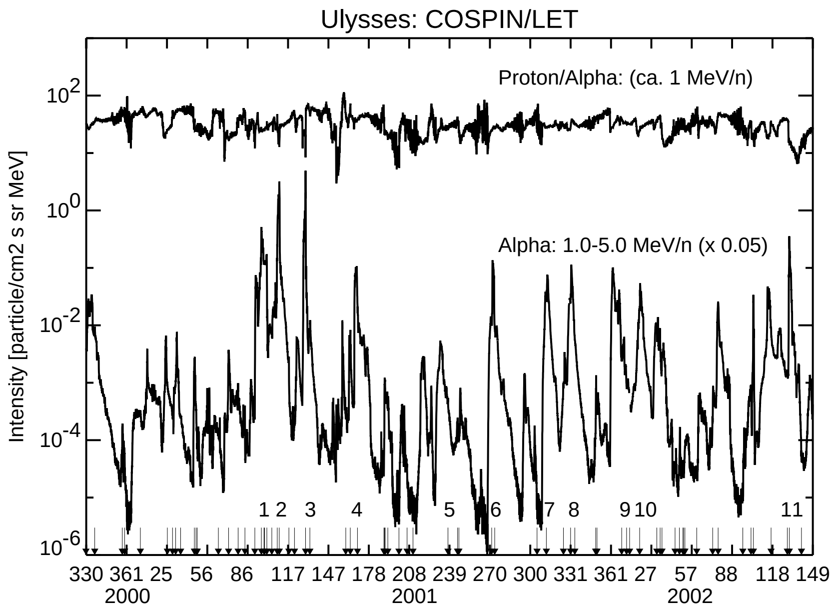

Fig. 2. The 30-min proton (1.2–3.0 MeV)/alpha(1.0–5.0 MeV/n) and the alpha intensity profiles from DOY 330 in 2000 to DOY 149 in 2002 are represented by solid lines. The arrows at the bottom of the panel mark the times of the shock occurrences at Ulysses.

The elemental abundances of heavier elements with respect to oxygen can also be used to distinguish between solar energetic particles (SEP) and particle populations associated with SIR or CIR. For the analysis we divide the elemental abundance ratios X/O by a reference value for solar energetic particles. 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. The mean Fe/O value varies by a factor of 3 in the higher energy range. In this analysis we use the reference values from Mason and Sanderson (1999), which refer to Mazur (1993), for both selected energy ranges, i.e. (4.25–7.5) MeV/n and (13.0–30.0) MeV/n.

In Fig. 3, the three panels show the 30-min averaged proton flux, and the daily elemental abundance ratios with respect to the corresponding reference SEP value (Mason and Sanderson, 1999) in the lower and the higher energy range, as indicated from November 2000 to May 2002. For the current analysis 11 time intervals with good statistics for MeV particles were selected. The selected time intervals can easily be found by focusing on the columns with various symbols in Fig. 3. During the gaps, no MeV particles have been registered. The abundance ratios of He/O were present during the longest duration. Therefore, the boundaries of the events were set at the edges of the non-zero He/O abundance ratios.

In the upper panel of Fig. 3, the 30-min averaged proton flux (1.2–3.0 MeV) is shown for reference using a solid line. The selected events are labeled from 1 to 11. In the middle panel of Fig. 3, we show the daily averaged elemental abundance ratios He/O, C/O, N/O, Ne/O and Fe/O for the energy range 4.25 MeV/n to 7.5 MeV/n with respect to the corresponding SEP reference values. In the third panel of Fig. 3, the daily averaged elemental abundance ratios Ne/O, Mg/O, Si/O, S/O and Fe/O for the energy range 13–30 MeV/n also with respect to the corresponding reference SEP value (Mason and Sanderson, 1999) are shown. For the selected time interval 1, there are no data available in the higher energy range (third panel).

The majority of the abundance ratios in the middle and the third panels are close to unity and are, therefore, compatible with an SEP type. Four daily He/O/SEP ratios (events 1, 3, 4 and 11) are larger than two. The averaged value for the event 2 is enhanced. In the next paragraph, we have a closer look at the events 1–4.

In Fig. 4, the abundance ratios during the time interval from day 84 to day 184 in 2001 are shown. The upper panel presents the corresponding proton to alpha ratio and the alpha flux profile (1.0–5.0 MeV/n). In the lower panel the corresponding daily abundance ratios with the He/O errors and the proton flux (1.2–3.0 MeV) are plotted.

On day 92 in 2001 (interval 1), a small decrease in the proton/alpha ratio and a shock are observed at Ulysses. The corresponding He/O and C/O with respect to the reference SEP values are enhanced. This is a clear indication for an SIR. The second decrease in the proton/alpha ratio occurs on day 109 (interval 2). It is accompanied by a spike in the particle flux embedded in a shock pair. The corresponding He/O and C/O elemental abundance ratios increase after the shock pair. On day 127 (interval 3) another decrease in the proton/alpha ratio is found. Shortly after day 129 spikes in the proton and alpha flux are followed by a shock and again enhancements of the He/O elemental abundance ratios are measured. During interval 4 (around day 172), several He/O ratios are larger than unity. The corresponding spike in the alpha flux is similar to that of interval 1. Nevertheless, the proton/alpha ratio (light elements) shows no significant variation. Event 4 follows a period of more than 25 days without an interplanetary shock and a large decrease in the proton to alpha ratio around day 154.

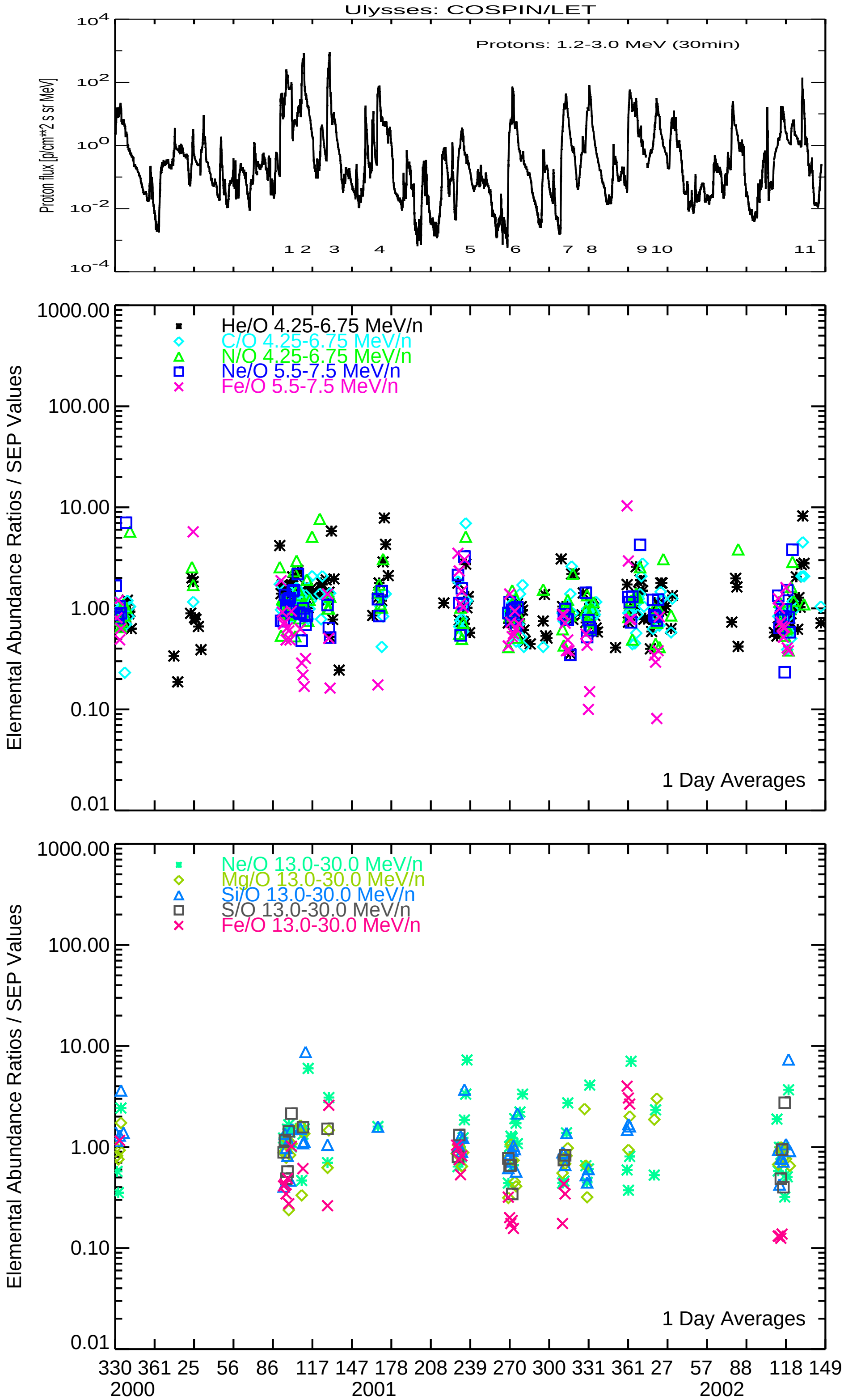

Fig. 3. The 30-min averaged proton flux, and the daily averaged elemental abundance ratios in the lower and the higher energy range from November (DOY 330) 2000 to May (DOY 149) 2002 divided by the corresponding reference SEP values (Mason and Sanderson, 1999) as recorded by the Ulysses COSPIN/LET instrument. In the upper panel the 30-min averaged proton intensity profile (1.2–3.0 MeV) is plotted using a solid line. The selected events are labeled from 1 to 11. The elemental abundance ratios in the energy ranges (4.25 to 7.5 MeV/n) and (13 to 30 MeV/n) are shown in the middle and the lower panel.

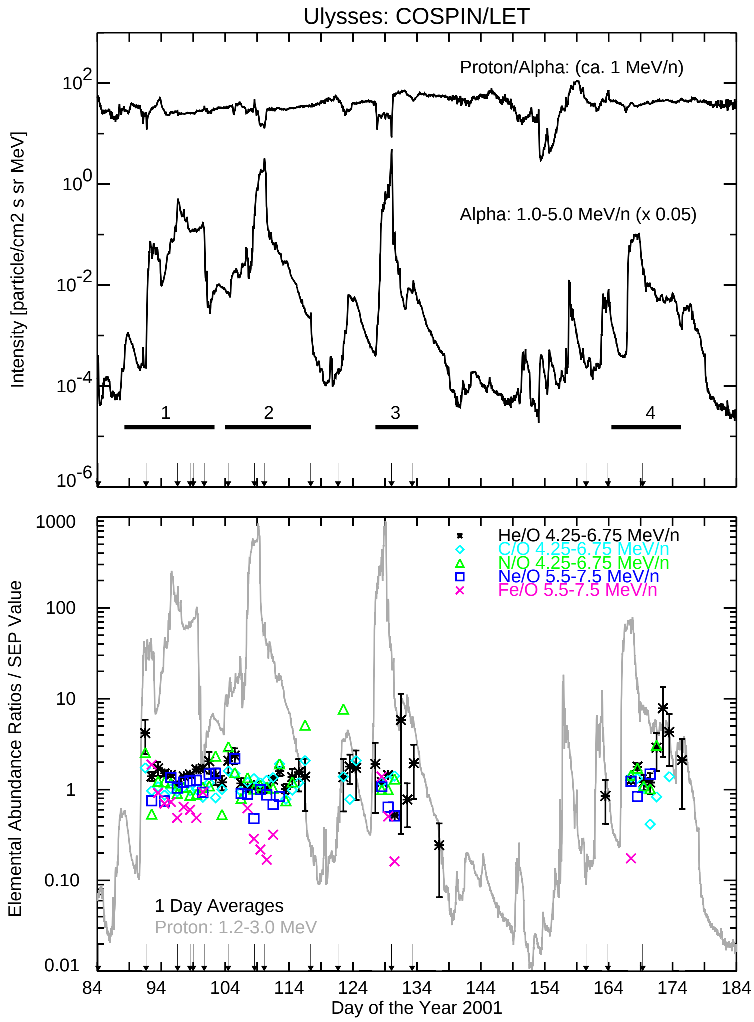

Fig. 4. Proton and alpha flux and elemental abundance ratios with respect to the corresponding reference SEP values as recorded by the Ulysses COSPIN/LET instrument from day 84 to day 184 in 2001.

Based on the characteristic decreases in the proton/alpha ratio, on the enhancements in the He/O and C/O ratios, and on the relative smoothness of the alpha flux profiles, we conclude that the energetic particle populations sampled at low helio-latitude during the intervals 1–3, and possibly 4, comprise some material accelerated at SIRs that were observed in the plasma and magnetic field measurements at Ulysses. The SIRs did not show a recurrent pattern, i.e. they were not CIRs in the strict sense.

In Tables 1 and 2, the event averaged elemental abundance ratios (X/O) are listed. The averages were taken over the available values of the element *X* with respect to oxygen, (X/O), within the selected time intervals. The values resulting from a single count rate were not taken into account for the calculation of the averages. The given error is the standard deviation of the observed values in the selected time interval. The last six rows contain SEP and CIR reference values (Mason and Sanderson, 1999; Gloeckler et al., 1979), the derived CIR/SEP ratios and their errors for comparison.

In Fig. 5, the event averages as listed in Tables 1 and 2 now with respect to the corresponding reference SEP values, are plotted for two energy ranges (left and right) and five different elemental composition ratios (panels 1–5), resulting in 10 panels. The left column contains averages based on observations in the low energy range (4.25 MeV/n–7.5 MeV/n) and the right column contains the values of the high energy range (13 MeV/n–30MeV/n). The two horizontal lines mark the reference value for an SEP population (i.e. unity), and a CIR population for the corresponding element, i.e. CIR/SEP, as listed in the last six rows of the Tables 1 and 2.

In panels 1 and 2 in the left column, (He/O and C/O), the two dashed horizontal reference lines are well separated. These abundance ratios can, therefore, be used to distinguish as SEP from a CIR or SIR signature. In panel 3, (N/O), no large separation of the reference values is given. Nevertheless, the measured N/O abundance averages lay close to the double line.

In panels 1–3 in the right column, averaged elemental abundance ratios of Mg/O, Si/O, S/O are the first elemental abundance ratios measured at high helio-latitudes in the energy range from 13.0 to 30.0 MeV/n. The two horizontal lines show that these element abundance ratios are less

Table 1. The elemental abundance ratios averaged during 11 selected periods from the beginning of 2001 to day May in 2002 measured by Ulysses COSPIN/LET in the lower energy range. The last six rows contain SEP and CIR values (Mason and Sanderson, 1999), the CIR/SEP ratios and their errors for comparison (He/O, C/O, N/O: 4.25–6.75 MeV/n; Ne/O, Fe/O: 5.5–7.5 MeV/n)

	He/O	C/O	N/O	Ne/O	Fe/O
2001:					
1: 88-103	94.6	0.49	0.16	0.17	0.13
	±11.9	±0.03	±0.02	±0.01	±0.02
2: 104-118	76.4	0.6	0.17	0.15	0.05
	±6.5	±0.04	±0.02	±0.03	±0.01
3: 127-134	71.9	0.62	0.14	0.11	0.11
	±13.2	±0.03	±0.01	±0.03	±0.05
4: 164-176	161.6	0.48	0.17	0.18	0.28
	±51.2	±0.08	±0.02	±0.03	±0.02
5: 225-240	60.9	0.45	0.09	0.19	0.3
	±11.9	±0.09	±0.02	±0.04	±0.07
6: 268-285	48.4	0.44	0.12	0.14	0.12
	±2.8	±0.05	±0.02	±0.08	±0.02
7: 309-320	71.0	0.47	0.11	0.13	0.04
	±13.8	±0.04	±0.01	±0.01	±0.01
8: 324-337	50.2	0.45	0.12	0.12	0.05
	±3.6	±0.02	±0.01	±0.01	±0.02
9: 360-9	72.0	0.41	0.18	0.17	0.24
	±7.7	±0.05	±0.04	±0.02	±0.12
2002:					
10: 13-27	55.3	0.44	0.1	0.15	0.07
	±7.3	±0.05	±0.02	±0.02	±0.02
11: 108-125	45.1	0.40	0.13	0.14	0.05
	±2.7	±0.03	±0.03	±0.02	±0.01
SEP	55.2	0.48	0.13	0.15	0.16
	±3	±0.02	±0.01	±0.01	±0.02
CIR	159	0.89	0.14	0.17	0.097
	±1.01	±0.036	±0.014	±0.016	±0.011
CIR/	2.88	1.85	1.08	1.13	0.6
SEP	±0.16	±0.1	±0.14	±0.13	±0.1

Table 2. The elemental abundance ratios averaged during 11 selected periods from the beginning of 2001 to day May in 2002 measured by Ulysses COSPIN/LET in the higher energy range. The last six rows contain SEP and CIR values (Mason and Sanderson, 1999), the CIR/SEP ratios and their errors for comparison Ne/O, Mg/O, Si/O, S/O, Fe/O: 13.0–30.0 MeV/n)

	Ne/O	Mg/O	Si/O	S/O	Fe/O
2001:					
1: 88-103	0.19	0.18	0.14	0.039	0.07
	±0.01	±0.02	±0.02	±0.009	±0.016
2: 104-118	0.33	0.25	0.19	0.055	0.1
	±0.15	±0.06	±0.02	±0.02	±0.03
3: 127-134	0.28	0.22	0.16	0.05	0.23
	±0.18	±0.09	±0.06	±0.03	±0.18
4: 164-176	0.24	-	-	-	-
	±0.08	-	-	-	-
5: 225-240	0.14	0.18	0.16	0.03	0.12
	±0.02	±0.02	±0.01	±0.005	±0.01
6: 268-285	0.22	0.15	0.13	0.02	0.03
	±0.04	±0.03	±0.01	±0.018	±0.01
7: 309-320	0.17	0.16	0.14		0.05
	±0.06	±0.01	±0.02	-	±0.01
8: 324-337	0.22	0.23	0.08	-	-
	±0.13	±0.13	±0.03	-	-
9: 360-9	0.09	0.21	0.24	-	0.18
	±0.02	±0.12	±0.01	-	±0.02
2002:					
10: 13-27	0.08	0.51	-	-	-
	±0.02	±0.12	-	-	-
11: 108-125	0.17	0.18	0.12	0.05	0.02
	±0.05	±0.01	±0.01	±0.02	±0.001
SEP	0.15	0.21	0.15	0.035	0.16
	±0.01	±0.01	±0.01	±0.004	±0.02
CIR	0.17	0.14	0.1	0.05	0.097
	±0.016	±0.014	±0.012	±0.008	±0.011
CIR/	1.13	0.67	0.67	1.43	0.6
SEP	±0.13	±0.07	±0.09	±0.28	±0.1

optimal than C/O and He/O to identify the type of population. Within the given available statistical accuracy, we are not able to assign likely source populations in these cases, since the averages are scattered between the two reference lines.

The forth panels in the second last row (left and right) contain the elemental abundance ratio of Ne/O in the lower and the higher energy range. In the left panel the Ne/O looks very variable from event to event. Comparing the left and right panel, the higher the energy range, the larger the uncertainty and variability.

The fifth panels of Fig. 5 (Fe/O) show a large variability of the averages of individual events. The variability is very large in both panels. The Fe/O ratio is often found to be enhanced at the beginning of the event and decreases afterwards in a step-like fashion, as can be seen in Figure 4 around day 109 (e.g. Hofer et al., 2001). Reames et al. (2001) explain the variation of abundance ratios, e.g. Fe/O, in terms of differential scattering of Fe and O by proton-generated Alfvén waves.

In Fig. 6, the average elemental abundance ratios He/O and C/O with respect to the reference SEP ratio (as listed in Tables 1 and 2) are plotted as a function of the helio-latitude. For the time interval 1 only, the normalized He/O is above the reference SEP line. In both panels, it can be seen that the values for the time intervals 2 and 3 are above the corresponding SEP reference line. These three selected time intervals take place during the FLS and are accompanied by the above-mentioned short-term decreases in the proton to alpha ratios. Taken together, these pieces of evidence suggest that these intervals can be identified as SIR-influenced. Otherwise, there is only one other averaged value indicative for an SIR or CIR influence, the He/O/SEP ratio for interval 4, although this has a large error bar. The rest of the averaged

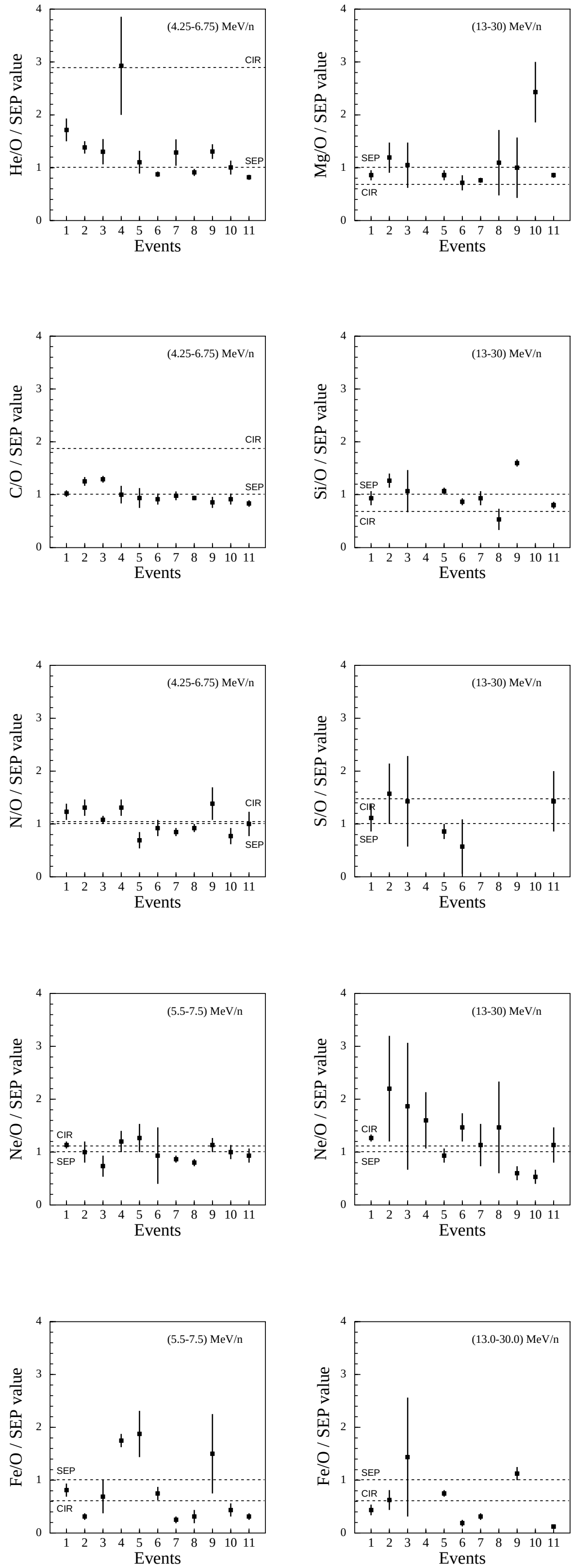

Fig. 5. Elemental abundance ratios with respect to the corresponding reference SEP values as recorded by the Ulysses COSPIN/LET instrument averaged during eleven selected time periods during the solar maximum mission from the solar polar passages in 2000/2001 to May in 2002 (left: energy range 5.5–7.5 MeV/n; right: 13.0–30.0 MeV/n).

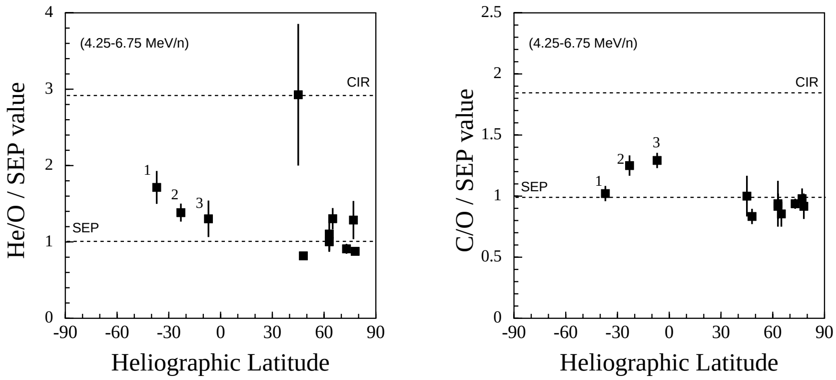

Fig. 6. Elemental abundance ratios He/O and C/O with respect to the corresponding reference values (Mason and Sanderson, 1999) averaged during eleven selected time periods from the solar polar passages in 2000/2001 to May in 2002 as a function of the helio-latitude. The elemental composition measurements were made by the Ulysses COSPIN/LET instrument (4.25–6.75 MeV/n).

values for the intervals 5–11 seem to be fully compatible with an SEP origin, and show, within the errors, no dependence on helio-latitude (not even for the high-latitude events 6, 7 and 8).

4 Discussion and conclusions

The variability of the proton and alpha intensity time profiles reflect the high solar activity from November 2000 to May 2002. Most of the events overlap, and, therefore, some MeV flux increases do not decay entirely before the following particle events take place (e.g. Hofer et al., 2003). Nevertheless, the events with statistically significant heavy ion fluxes are sufficiently well separated to allow for an event-by-event study of the kind performed here. The measurements reported here represent the first-ever determination of energetic particle composition up to high helio-latitudes in the ≈5–30 MeV/n range at solar maximum.

We have used the measured elemental abundance ratios to examine the possible origin of the populations recorded in these previously unexplored regions of the heliosphere. In the majority of the cases, the measured composition is within the statistical errors consistent with an SEP type.

The low-latitude observations during the FLS show the reappearance of SIRs. There are several lines of evidence that support this. As discussed above, the measured He/O and C/O abundance ratios with respect to reference SEP values can be used as discriminators between SEP and SIR/CIR populations. Based on the observed He/O and C/O ratios with respect to the reference values being greater than unity, the short-term decrease in the proton to alpha ratio, and the simultaneous peak in the alpha profiles, three time intervals are identified as being influenced during a few days by SIRs. The SIRs did not show a recurrent pattern, i.e. they were not CIRs in the strict sense. After the solar activity maximum, the level of solar activity decreases, the current sheet tilt decreases, and even more recurrent compression regions can be expected (e.g. Hofer et al., 2002c; Hofer and Storini, 2003).

The tolerance and the variability of the averaged Ne/O ratios of individual events is larger in the higher energy range, as also reported in Mazur et al. (1993). The abundance ratios of S/O, Mg/O and Si/O are the first such measurements at high helio-latitudes in the energy range from 13.0 to 30.0 MeV/n. The reference SEP and CIR values of S/O, Mg/O and Si/O are not optimal for the distinction between the two types of particle populations. The statistical accuracy of these abundance ratios does not permit a firm conclusion concerning the source population. Their average values are consistent with either of the reference compositions (SEP or SIR/CIR).

Within the statistical errors, there is no change in the SEP particle composition signatures with helio-latitude. McKibben et al. (2003) identified for selected particle events and the corresponding flare location before and during the southern solar passage. Most of the corresponding active regions, at least those above the southern solar polar region, were located on the northern solar hemisphere, whereas the Ulysses spacecraft recorded significant particle increases above the southern solar polar region. This raises an important question for the theory of the particle propagation in helio-latitude.

One of the solutions could be the fast filling of the inner heliosphere with energetic particles, as discussed by several authors (e.g. Roelof, 2002; McKibben et al., 2003). Other groups suggest cross-field diffusion (e.g. Zhang et al., 2001). Another possibility would be a field-aligned propagation along complex magnetic structures, e.g. magnetic clouds. The third process would also well support the very large onset times at high helio-latitudes of the solar energetic particles events, as reported in Dalla et al. (2003). With the results of this paper we cannot distinguish between these proposals.

Based on the elemental abundance ratio recorded by the Ulysses COSPIN/LET instrument, we identified the particle population during the FLS until about mid 2001 as a mixture between the major component of solar energetic particles and a few instances with particles accelerated at about four single compression regions, i.e. SIRs.

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