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Cosmic ray and solar particle composition measurements in the southern solar polar region.

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Abstract. This analysis is based on energetic particle measurements covering the energy range $4-20$ MeV/n recorded by the COSPIN/LET instrument on the Ulysses spacecraft. Around the end of the year 2000 the Ulysses spacecraft was above the southern polar region at less than 2.5 AU radial distance from the Sun. A preliminary analysis has shown that the abundance ratios He/O and C/O are lower than during the in-ecliptic passage around the last solar maximum and more than ten times higher than during the last southern solar passage. In this work we discuss the abundances measured during three major events at high southern solar latitudes and compare with in-ecliptic and other findings. The elemental abundances of the selected events are consistent with particles having solar energetic particle (SEP) origin. One possible scenario for the production of SEPs is that the particles are accelerated by a CME driven shock, but the most of the corresponding flares of the selected events observed during the southern solar polar region passage occur in the northern solar hemisphere. Furthermore, we found that different periods in the selected time intervals might be characterized by average C/O ratios.

1 Introduction

The Ulysses southern solar passage is defined as the time interval September 2000 to January 2001. Following aphelion passage in 1998 the spacecraft began its second climb to high southern heliolatitudes, reaching its maximum latitude of 80.2° in November 2000. In May 2001 perhelion was reached. During the southern solar passage the spacecraft's heliocentric distance changes from ∼2.9 to ∼1.8 AU (Marsden et al., 2001). In contrast to the first southern solar polar passage in 1994 (e.g. Simpson et al., 1995; Sanderson et al., 1995), which took place as the level of solar activity was approaching the minimum in cycle 22, the recent high-latitude observations correspond to near-maximum solar activity conditions with a large number of transient phenomena.

Composition measurements can be used to identify particle populations accelerated at various interplanetary magnetic structures. A proton to alpha ratio decrease approaching 10 is often used for the identification of particles accelerated at corotating interaction regions (CIR) (Marsden et al., 1993) or stream interaction regions (SIR) (Gosling et al., 2001). At the beginning of solar energetic particle events (SEPs) the $^{3}He/^{4}He$ and the Fe/O ratios are often found to rise as a result of resonant wave-particle interaction in the solar flare plasma (e.g. Reames, 1999; Reames et al., 2000a). The temporal evolution of the abundance ratios can give some insight in the ongoing acceleration process. A preliminary analysis using Ulysses COSPIN/LET data (Hofer et al., 2001) showed for selected events in June 1999 and in July 2001 that the averaged abundance ratios He/O and C/O are lower than during the in-ecliptic transfer around the last solar maximum and more than ten times higher than during the last southern solar passage in 1994.

For this analysis three major events in July and November 2000, and in April 2001 are selected. The abundance ratios of the famous 'Bastille event' in July 2000 are shown using a higher time resolution than in Hofer et al. (2001) in order to get an overview over the entire southern solar polar region. Furthermore, we compare the ratios of the abundances of the selected events at high southern latitudes as far as available with in-ecliptic values and with other findings.

2 Description of the Data

The low energy particle data used in this study is from the Low Energy Telescope (LET), one of the five telescopes in the Cosmic Ray and Solar Particle Investigation (COSPIN) instrument onboard the Ulysses spacecraft (Simpson et al., 1992). The COSPIN/LET instrument records the fluxes and the composition of energetic particles and of low energy cosmic ray nuclei from hydrogen up to iron over a range of energies from ∼1MeV/n to 75 MeV/n (Tranquille et al., 2001).

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The times of shock occurrences are taken from available shock lists (private communication, R.J. Forsyth). The corresponding locations of the flares for the end of the year 2000 are listed in McKibben et al.(2001), for April 2001 in Marsden et al.(2001) and are also obtained from the Solar Geophysical Data Archives (2000, 2001).

3 Ulysses Second Southern Solar Polar Passage

In Figure 1 the proton intensity observed in the energy range $1.2 - 3.0$ MeV (upper curve), the alpha intensity (middle curve, $8.4-19$ MeV/n) and the $\sim$1 MeV proton to alpha ratio (lower curve) are shown from July 2000 to April 2001. Three large events with onset in July (interval 1) and November 2000 (interval 2), and in April 2001 (interval 3) are selected for the analysis, labeled and marked by horizontal lines.

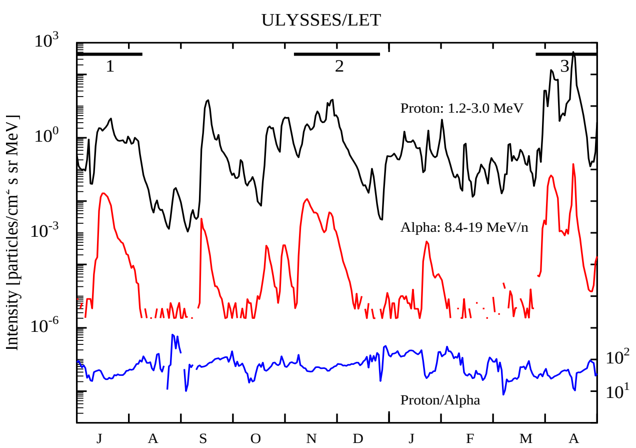

Fig. 1. The daily proton ($1.2 - 3.0$ MeV, upper curve) and alpha ($8.4 - 19$ MeV/n, middle curve) intensities and the $\sim$1 MeV proton to alpha ratio (lower panel) from July 2000 to April 2001. The horizontal, labeled lines in July and November 2000, and in April 2001 mark the selected time intervals.

During the entire time interval the particle intensities are highly variable. Most of the events last longer than one month. The $\sim$1 MeV proton intensity varies from about 10^{-3} up to more than 10^2 protons/(cm^2 s sr MeV). The largest amplitude is measured in April 2001.

The $\sim$1 MeV proton to alpha ratios are plotted to identify particles accelerated at CIRs or SIRs. A value below 10 selects CIR dominated time intervals (Marsden et al., 1993). The shown proton to alpha ratios indicate that during the southern solar passage few events were due to SIRs or CIRs. Particularly, during the three selected time intervals there is only one short-term decrease in the proton to alpha ratio approaching a value of 10 in mid April 2001.

4 Elemental Abundance Ratios of Heavier Species

In Figures 2-4 the hourly proton intensity ($1.2 - 3.0$ MeV) and the daily abundance ratios of carbon, nitrogen, neon and iron with respect to oxygen are shown for the selected time intervals and energy ranges as indicated. The ratios are represented in all the figures by symbols and the corresponding errors by vertical lines. In case of a very small minimum error the lower part of the error bar is not drawn. The black downward arrows at the bottom of the figures mark the times of shock occurrences as determined from magnetic field and solar wind parameters (private communication R.J. Forsyth). The corresponding major solar flares are represented in the figure by triangles. Their maximum amplitudes can be found in the caption.

The He/O ratios turned out to be almost constant during the selected time intervals are therefore not plotted. Even the C/O ratios do not vary very much during periods in the selected time intervals. The N/O and the Ne/O ratios show more substructure. Highly variable profiles are present in the Fe/O ratios. Most of the Fe/O ratio are less or equal than 0.2. Three very high Fe/O values are found on day 199 (July 17, 2000), on day 320 (November 15, 2000) and on day 92 (April 1, 2001).

In Figure 2 the July 2000 event is shown from day 190 to 230 (interval 1). The second of three X-class flares has a maximum amplitude of X5.7. The corresponding active region is in the northern solar hemisphere. The proton intensity time profile in Figure 2 increases fast and is followed by a longer lasting decrease. The entire event lasts more than one month. During the time interval, 6 shocks were identified (marked by arrows) with related slight changes in the intensity. The Ne/O ratio is maximum on day 194 (July 12) where the major increase of the event starts. A moderately high Ne/O ratio is observed on day 205 a day before a small increase in the proton intensity occurred. On day 217 a second very high Ne/O value is found with a simultaneous increase in the proton intensity. Around day 200 the Fe/O ratios start to decrease for at least four days. On days 203

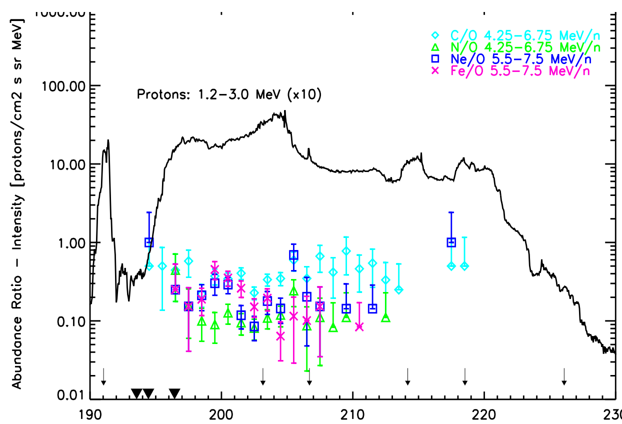

Fig. 2. The hourly proton (1.2-3.0 MeV) intensity and daily averaged values of the abundances of carbon, nitrogen, neon, and iron with respect to oxygen from day 190 to 230 in July 2000 (period 1). The triangles at the bottom of the figure mark the time of the flare (X1, X5.7, X1.9) and the arrows the times of shock occurrences (R.J. Forsyth, private communication)

and 206 two shocks are observed, one before and one after the time with the highest proton intensity.

In Figure 3 a part of the long-lasting November 2000 SEP event observed from day 310 to day 350 (interval 2) is plotted. As visible in Figure 1, two peaks in the intensity occur before the selected time interval. Therefore, the initial proton intensity is already enhanced. At the beginning around day 314 two M-class flares and two shocks are observed. Around day 330 another group of X-class flares occurs that divides the event in two parts. The C/O ratios change from a first to second constant value (0.53-0.42). Around day 338 higher Fe/O and Ne/O are correlated with the onset of a small, but sharp increase in the proton intensity. At the end of the November 2000 event the abundance ratios increase to the maximum N/O values found in this analysis.

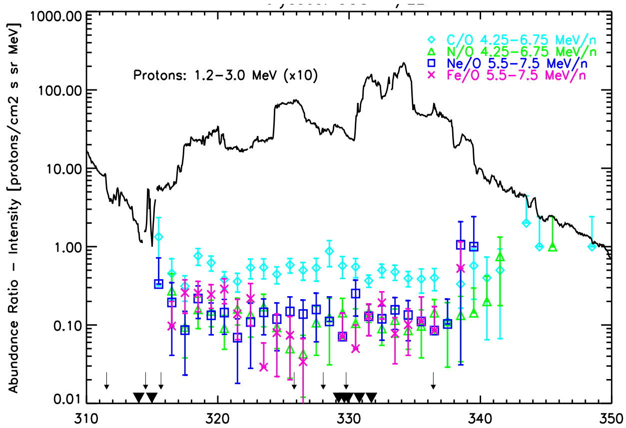

Fig. 3. The hourly proton (1.2-3.0 MeV) intensity and the daily averaged values of the abundances of carbon, nitrogen, neon, and iron with respect to oxygen from day 310 to 350 in November/December 2000 (period 2). The triangles at the bottom of the figure mark the times of flare (M7.4, M7.4, (X20,X2.3,X1.8), X1.9, X4.0) occurrences.

In Figure 4 the recent event in April 2001 from day 80 to day 120 (interval 3) is shown. This major increase in the particle intensity marks the end of a period with low flare activity that started at the beginning of the year 2001. On April 1, 2001 (day 91) the proton intensity increases dramatically by almost three orders of magnitude. This increase is accompanied by high abundance ratios. One day later a very strong flare is observed with a corresponding location of the active region on the northern solar hemisphere (Marsden et al., 2001). This initial time interval is followed by a period of about 10 days with almost constant C/O values. On day 101 the proton intensity decreases again by about a factor of 100. On day 107 a second increase to the highest proton intensity of this event seen on day 110 begins. The corresponding increase is accompanied by a decrease in the Fe/O ratios during about four days. The subsequent decrease in the proton intensity from almost 1000 to 0.1 protons/(cm^{2}s sr MeV) lasts about 10 days. During the last part of this time interval the N/O abundance ratios increase from 0.3 to 2.0 and the average C/O ratio steps to a slightly higher value.

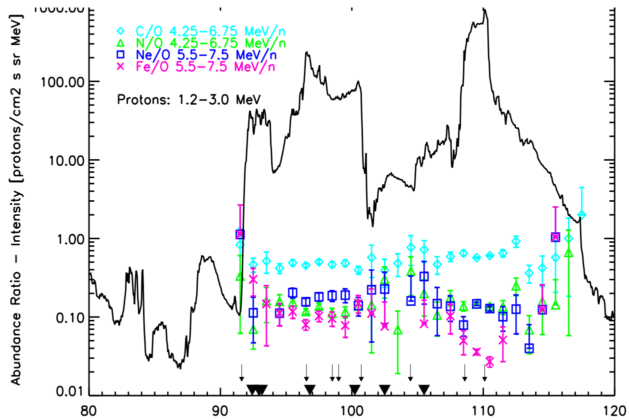

Fig. 4. The hourly proton (1.2-3.0 MeV) intensity and the daily averaged values of the abundances of carbon, nitrogen, neon, and iron with respect to oxygen from day 80 to 120 in April 2001 (period 3). The triangles at the bottom of the figure mark the times of the flare((X1.4,X20), X1.2, X5.6, X2, X2, X14) and the arrows the times of shock occurrences (R.J. Forsyth, private communication)

The selected time intervals can be divided in different periods based on the the measured abundance ratios. In Table 1 the number of the time intervals and the periods in days are given in the first column. The averaged values of the elemental abundances within a period in the selected time interval of helium, carbon, nitrogen, neon and iron with respect to oxygen are listed. The corresponding standard error is given in parentheses.

2000	He/O	C/O	N/O	Ne/O	Fe/O
1:195-207	49	0.42	0.14	0.21	0.19
	(3.4)	(0.03)	(0.03)	(0.05)	(0.03)
1:208-213	70	0.46	0.10	0.14	0.08
	(6.8)	(0.07)	(0.07)	*	*
2:316-328	61	0.53	0.13	0.14	0.16
	(3.5)	(0.04)	(0.02)	(0.01)	(0.03)
2:329-337	46	0.42	0.11	0.13	0.10
	(1.6)	(0.05)	(0.01)	(0.02)	(0.02)
2:338-341	52	0.45	0.31	1.06	0.53
	(5.5)	(0.05)	(0.15)	*	*
2001	He/O	C/O	N/O	Ne/O	Fe/O
3: 92-101	86	0.48	0.13	0.15	0.13
	(4.4)	(0.01)	(0.01)	(0.02)	(0.02)
3:102-108	82	0.58	0.2	0.15	0.08
	(10.8)	(0.05)	(0.04)	(0.03)	(0.01)
3:109-114	67	0.6	0.15	0.11	0.06
	(5.4)	(0.08)	(0.02)	(0.02)	(0.02)

Table 1. Averaged elemental abundance ratios during periods in the selected time intervals in 2000 and in 2001. (He/O, C/O, N/O: 4.25 - 6.75 MeV/n; Ne/O, Fe/O: 5.5-7.5 MeV/n). (*: only one or two values.)

The averages of the C/O and N/O ratios are different between the first and the second period for the time intervals 2 and 3 as listed in Table 1. This fact is supported by the different shape of the proton intensity profiles. The averages of the Fe/O and Ne/O ratios are significantly different between the first and the second period in the interval 1 and 3. The abundance ratios He/O, C/O, N/O are rather high and Fe/O is rather low during the period day 102-108 corresponding to the interval when the proton intensity is increasing upto the highest peak.

5 Discussion

The Fe/O abundance ratios for SEP and CIR events given by Mason and Sanderson (1999) are 0.16 ± 0.02 and 0.097 ± 0.011, respectively and have been derived prior the launch of Ulysses. Each selected event has at least three Fe/O values above the 10 percent level, indicating a SEP source.

High Ne/O values in combination with high Fe/O values indicate a scenario related to impulsive flares (Reames, 1999). For all three events we find enhanced values Ne/O with amplitudes around 1.0 almost systematically at the beginning and towards the end of the events. Slightly enhanced values are sometimes found between different regimes.

In constrast, the C/O and the N/O ratios seem to be almost constant during the periods in the time interval as defined in Table 1. The averages change from one period to another and might be used for characterizing the corresponding particle populations.

The July 2000 event is also observed by instruments on the WIND spacecraft (Reames et al., 2000b). The abundance ratios of both analyses are, within the errors, consistent. In particular, for day 199 in 2000 a high Fe/O value is derived which could be associated with the shock on day 203. During the following 10 days the values decrease. Reames et al.(2000b) interpret the initial rise as the evolution of a non-Kolmogorov Alfven wave spectra.

The solar activity in November 2000 and in April 2001, and correlated changes in the COSPIN observations are discussed in McKibben et al.(2001) and Marsden et al.(2001), respectively.

6 Summary and Conclusions

The conditions encountered by the Ulysses spacecraft during its second passage over the southern pole were clearly different from the first southern solar polar passage in 1994. Throughout the recent southern solar pass, enhanced solar activity gave rise to a large number of transient particle events, observed up to highest southern latitudes. As already mentioned in Hofer et al.(2001) major events were observed above the southern solar polar region. The November 2000 event was observed at a rather spectacular location, the highest latitude reached by the spacecraft, i.e. above the southern solar pole at $80.2°$.

The abundances of all selected events discussed here are consistent with particles having an SEP origin. One possible scenario for the production of SEPs is that the particles are accelerated by a CME driven shock, but most of the corresponding flares of the selected events observed during the southern solar polar region passage occur in the northern solar hemisphere. Using COSPIN/LET data, we have found no clear evidence for significant local acceleration at CME shocks at the highest latitudes. We have to assume that these SEP particles are most probably accelerated at lower latitudes. This would also be supported by the fact that the initial abundances found with the Ulysses instruments for the July 2000 event are within the errors equal to the in-ecliptic values. If the acceleration occurs at lower latitudes, the particles still have to propagate to the higher latitudes.

During the selected time intervals different particle populations were found using COSPIN/LET composition data. The ratios C/O and also N/O seem to be almost constant for one regime. The average C/O ratio might be used to characterize the particle populations seen during different periods in the selected time intervals.

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