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A survey of ^{3}He enhancements at 2–20 MeV/nucleon: Ulysses COSPIN/LET observations

C. Tranquille, R. G. Marsden, T. R. Sanderson, and M. Y. Hofer

Research and Scientific Support Department of ESA, ESTEC, 2200 AG Noordwijk, The Netherlands

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Abstract. We present the results of a survey of enhancements in the ratio of ^{3}He/^{4}He as measured by the COSPIN/LET instrument on board the Ulysses spacecraft in the energy range 2–20 MeV/n. In the context of this study, all ratios of ^{3}He/^{4}He above 0.05 are considered to be enhanced compared with the solar system value of ∼0.0004. Previous studies have shown that enhanced fluxes of ^{3}He are frequently associated with small, impulsive solar flare events in which the observer is well connected to the flare site. These events also often show enrichments in heavy ion composition compared with standard coronal values. Recent attention has also focused on ^{3}He enrichments as evidence for re-acceleration of remnant particle populations that are present in the inner heliosphere following periods of enhanced solar activity. For this study, we have examined the Ulysses data set from launch (October 1990) up to the present, representing a full solar cycle. The spatial coverage extends from 1–5.4 AU in heliocentric distance, and effectively includes the complete range of heliomagnetic latitudes from pole to pole. We have identified 12 periods of enhanced ^{3}He/^{4}He, occurring at heliocentric distances out to 5 AU, and helio-latitudes up to 48°. We investigate the characteristics of the events, many of which last for several days, in order to establish possible origins.

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

1 Introduction

The ambient solar system value for the ^{3}He/^{4}He ratio has been shown to be ∼0.0004 by studying helium abundances in the slow solar wind (Gloeckler and Geiss, 1998) and solar prominences (Hall, 1975). Early in situ observations of energetic ions indicated that a low value for the ^{3}He/^{4}He ratio was also valid for large solar energetic particle (SEP) events (Mewaldt et al., 1984). Such events are termed "gradual" because of their association with soft solar X-ray emission characterised by a slow onset and relatively long decay phase. The dominant acceleration processes for gradual events are CME (coronal mass ejection) driven shocks, which energize protons more efficiently than heavier ions. A second class of SEP event, termed "impulsive" because of a rapid, short-lived rise in solar X-ray activity and radio emissions, have been shown to provide enhanced ^{3}He populations (Reames et al., 1988), with the ratio to ^{4}He fluxes increasing by up to 10^4 times that of the solar system value. Impulsive events have in general smaller fluences than gradual events and are also characterised by elevated fluxes of heavier ions, most notably Fe (Mason et al., 1986). A review of the acceleration mechanisms and characteristics associated with both types of SEP events can be found in Reames (1999).

Recent measurements by more sensitive energetic ion spectrometers on board the Advanced Composition Explorer (ACE) spacecraft indicate that the above classification of ^{3}He populations in SEP events is not so rigid, and that enhanced ^{3}He/^{4}He ratios have also been measured during large SEP events (Wiedenbeck et al., 2000). A possible explanation for such observations requires the re-acceleration of a ^{3}He remnant population seeded in the interplanetary medium by an earlier impulsive SEP event (Mason et al., 1999; Desai et al., 2001).

In this study, we make a systematic survey of ^{3}He abundances at 2–20 MeV/n using COSPIN/LET measurements made by Ulysses throughout the complete mission, and attempt to correlate our results with features in the solar wind and magnetic field data, and heavy ion fluxes. A previous search for ^{3}He rich events using Ulysses HI-SCALE data (Biesecker, 1996) catalogued such events at low heliographic latitudes before the spacecraft embarked on the first pass of the southern solar polar regions. However, no evidence of ^{3}He enhancements was found at higher latitudes in corotating interaction regions in their study.

Correspondence to: C. Tranquille
(Cecil.Tranquille@esa.int)

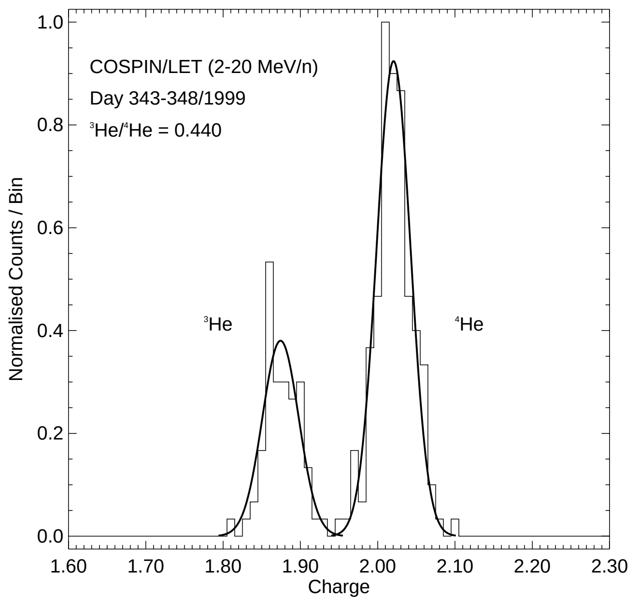

Fig. 1. An example of the charge histograms obtained from the D1:D2 pair of detectors for a ^{3}He rich event. The ^{3}He and ^{4}He populations are easily separated and are well-defined by standard Gaussian fits. Integrating the two Gaussian functions and taking their ratios yields the ^{3}He/^{4}He ratios used in this study. The histograms have been normalised to the maximum number of counts accumulated in a single charge bin during the complete event.

Table 1. The 12 periods of enhanced ^{3}He fluxes identified in this study with an event integrated ratio of ^{3}He/^{4}He exceeding 0.05. The table provides details of the date and location (heliocentric distance (R) and helio-latitude) of each event, and the derived ^{3}He/^{4}He ratio

Event	Year	Day of Year	R (AU)	Helio-Latitude	^{3}He/^{4}He
A	1990	300-302	1.03	4.98	0.110±0.010
B	1990	311-315	1.09	3.78	0.303±0.022
C	1990	332	1.24	1.84	0.197±0.084
D	1990	345-350	1.39	0.48	0.389±0.016
E	1990	359-363	1.53	-0.49	0.164±0.006
F	1991	051-055	2.16	-3.00	0.335±0.019
G	1991	080-081	2.46	-3.68	0.077±0.004
H	1999	096-097	5.02	-24.10	0.209±0.032
I	1999	343-348	4.25	-40.36	0.440±0.064
J	2000	007-009	4.13	-42.56	0.825±0.155
K	2001	086	1.49	-36.34	0.395±0.126
L	2002	106	3.25	48.45	0.170±0.050

2 Instrumentation

The data used in this analysis were obtained from the Low Energy Telescope (LET) of the Cosmic Ray and Solar Particle Investigation (COSPIN) flown on board the Ulysses spacecraft (Simpson et al., 1992). The LET instrument measures the flux, energy spectra and ion composition of solar energetic particles and low energy cosmic ray nuclei in the energy range of ∼1 MeV/n to ∼75 MeV/n. The instrument uses the standard dE/dX vs. E technique to provide pulse height analysis (PHA) information, allowing for the identification of the chemical species and the energy of individual particles. The telescope is also able to provide counting rate information of protons, alpha particles and groups of particle species in fixed energy channels. The present study will focus primarily on PHA data of 2–20 MeV/n helium ions, using the D1 and D2 pair of solid state detectors. Data from the Ulysses magnetometer (Balogh et al., 1992) and the solar wind instrument (Bame et al., 1992) have also been used in this study.

3 Observations and discussion

Soon after the launch of Ulysses, the COSPIN/LET instrument measured a ^{3}He rich event (Simpson et al., 1992), which was clearly seen in the D1:D2 pulse height matrix plot as a separate track from the ^{4}He track. The corresponding signature in the D1:D2 charge histogram also provided a clean separation between the two helium isotopes, with two well separated histograms, both allowing excellent fits to Gaussian profiles. This signature was used to systematically search the complete LET pulse height data set for elevated levels of the ^{3}He/^{4}He ratio, indicating enhanced ^{3}He populations. An example of the resolution of ^{3}He and ^{4}He using the charge histogram technique is shown in Fig. 1.

A ratio of counts between the two helium isotopes exceeding 0.05 and the ability to fit the histograms to Gaussian functions with centre lines in the expected location, were used as criteria to define periods of enriched ^{3}He. A total of 12 such events were found during the complete Ulysses mission. Figure 2 shows the spatial distribution of these events (labelled A to L) along the Ulysses orbit, and Table 1 summarises their dates, positions and the derived ^{3}He/^{4}He ratios. Colour coded along the trajectory is the PHA derived 4–6 MeV/n helium intensity, which is used to indicate the level of solar activity. The in-ecliptic transit to Jupiter took place near solar maximum and seven ^{3}He rich events (A–G) were seen. After early 1991, enhanced levels of ^{3}He were not seen again until the next peak in the solar activity cycle, indicating a clear solar cycle dependence. The remaining out of ecliptic events (H–L) all occur in the southern heliosphere, with the exception of the last event (L) which was recently recorded in the Northern Hemisphere as Ulysses made its way back down to the ecliptic plane. This is most likely due to the phasing of the Ulysses mission with the solar cycle, as opposed to any underlying asymmetry between the two solar hemispheres. What is apparent from Fig. 2 is that the ^{3}He rich events identified in this study generally do not occur during large events with high helium and proton intensities (e.g. Hofer et al., 2003). This would indicate a preference for the impulsive class of events. It may be that for the more intense events, the signature of ^{3}He ions is masked in the spill over of the dominant ^{4}He histogram contribution.

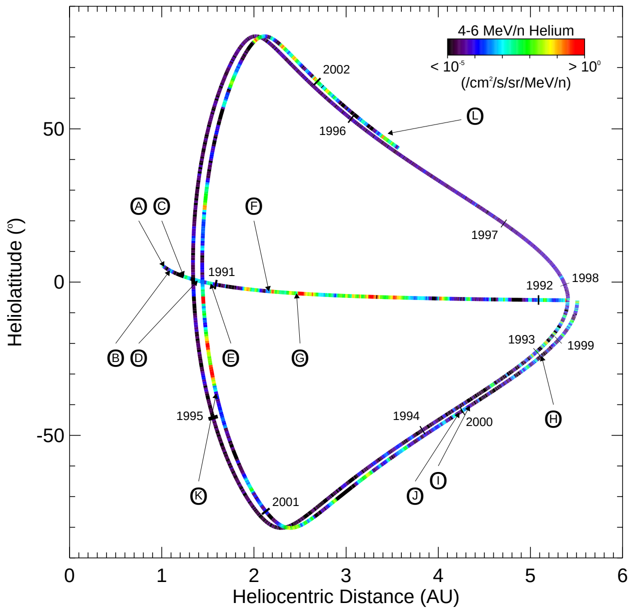

Fig. 2. The Ulysses trajectory plotted as a function of heliocentric distance and helio-latitude from launch in (October 1990) to May 2002. The second orbit is slightly displaced from the true orbit, in order to separate it from the first pair of polar passages for clarity. Colour-coded along the Ulysses trajectory is the PHA derived 4–6 MeV/n helium intensity measured by the COSPIN/LET instrument. The 12 periods of ^{3}He enrichments identified in this study have been labelled as events A to L on this diagram. Events A–G took place during the in-ecliptic transfer to Jupiter (launch to February 1992), and the remaining events (H–L) were during the high-latitude phase of the mission.

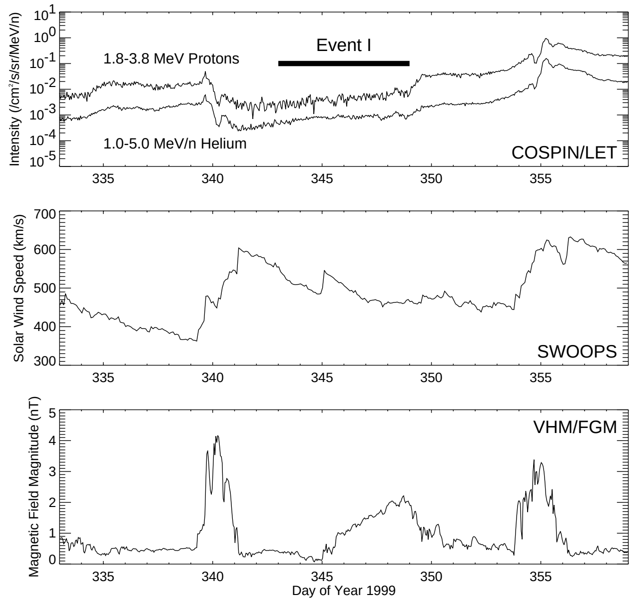

Fig. 3. The top panel shows 1.8–3.8 MeV protons and 1–5 MeV/n helium intensities (obtained from rate channels of the LET instrument) for a 26-day period centred about event I in 1999. The middle panel shows the solar wind speed variations as measured by the solar wind instrument (SWOOPS), and the bottom panel shows the magnetic field magnitude obtained from the magnetometer (VHM/FGM) on board Ulysses.

Conversely, we see no evidence for enhanced fluxes of heavy ions in the COSPIN/LET data during the identified events, as might be expected in the impulsive model. This observation could be due to the fact that the events were relatively weak, thereby producing heavy ion intensities that were too low for the sensitivity of the LET instrument. Furthermore, the energy threshold of the instrument increases for heavier ions (approximately 3 MeV/n and 4 MeV/n for oxygen and iron, respectively). Increased heavy ion fluxes are, however, clearly seen during large SEP events (Hofer et al., 2003).

The 12 events do not seem to correspond to any salient features in the solar wind or magnetic field observations which, if present, might indicate particle confinement or association with local travelling shocks. As an example, Fig. 3 shows solar wind and magnetic field data for a 26-day period centred about event I, together with proton and helium data obtained from the rate channels of the LET instrument. There are no significant features in any of the profiles during the period of enhanced ^{3}He. This observation is generally true for all of the ^{3}He rich events identified in this report. A careful analysis of the exact onset time of the ^{3}He enhancements may provide some correlation with small-scale features in the solar wind or magnetic field which have been missed in this study. An attempt to associate the ^{3}He rich events with solar X-ray or radio emissions remains a future task and may provide direct evidence of a coronal origin for the ^{3}He.

In Fig. 4 we plot the derived ^{3}He/^{4}He ratios as a function of helio-latitude (top panel). There appears to be an increase in the ratio of the two isotopes with increasing helio-latitude. We are, however, aware that this tentative observation suffers from a relatively small sample of valid events. Furthermore, previous in-ecliptic measurements of the ratio have recorded values greater than 10 and show the variability of ^{3}He populations. No correlation is seen if the ^{3}He/^{4}He ratios are ordered according to heliocentric distance (bottom panel).

4 Conclusions

The COSPIN/LET instrument provides good resolution of 2–20 MeV/n ^{3}He and ^{4}He isotopes, allowing for the identification of 12 distinct ^{3}He rich events during the Ulysses mission to date. These events are spatially distributed across the complete heliocentric distance range of the Ulysses mission, and span to moderately high helio-latitudes, providing the first in situ observations of non-ecliptic energetic ^{3}He populations. There is a tentative correlation between events having a high ^{3}He/^{4}He ratio and increasing helio-latitude, although this may be a consequence of the relatively low number of events identified. However, there is no apparent indication of the origin of the ^{3}He populations from signatures in the solar wind or magnetic field.

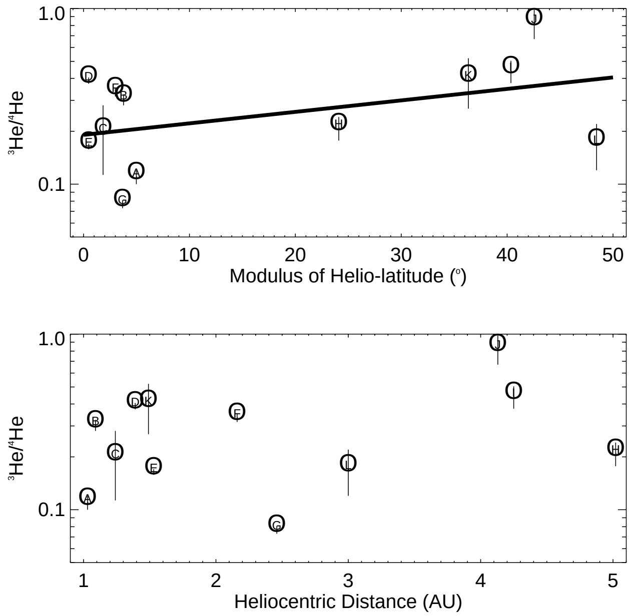

Fig. 4. Values of the derived ^{3}He/^{4}He ratio for each of the 12 events plotted against helio-latitude (top panel) and heliocentric distance (bottom panel). Statistical errors for each of the two isotope populations are combined to give an estimation of the error in the ^{3}He/^{4}He ratio. There is an indication that higher values occur with increasing helio-latitude. The straight line drawn in this figure is a least-squares fit to all the data points and has a chi-square value of 0.72.

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