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The Time Variation of Energetic ^{3}He in Interplanetary Space from 1997 to 2005

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1. Introduction

The rare isotope of helium, ^{3}He, can be enhanced relative to ^{4}He by factors ranging to above 10^4 as the result of fractionation in impulsive solar energetic particle (SEP) events. At energies up to $\sim$ 10 MeV/nuc this is the dominant source of ^{3}He in the interplanetary medium at 1 AU over much, if not all, of the solar cycle. The interplanetary intensity of ^{3}He can vary greatly over time due to the episodic nature of impulsive events. At higher energies ($\gtrsim$50 MeV/nuc) galactic cosmic ray secondary ^{3}He dominates, but due to solar modulation the contribution of this component below $\sim$ 10 MeV/nuc near solar maximum is relatively insignificant.

Observations during the maximum of solar cycle 23 have shown that energetic ^{3}He is often present in the accelerated particle populations associated with gradual SEP events and interplanetary shock events with a much higher abundance relative to ^{4}He than the value ^{3}He/^{4}He$\simeq 5 \times 10^{-4}$ found in the solar wind, which was assumed to be the seed population from which these particles are accelerated. Mason et al. [1] suggested that the source of the extra ^{3}He could be suprathermals from numerous impulsive SEP events, which could be further accelerated with high efficiency by shocks.

Using data from the SIS and ULEIS instruments on the Advanced Composition Explorer (ACE) spacecraft, Wiedenbeck et al. [2] investigated how frequently ^{3}He from impulsive events was present at 1 AU during solar maximum and found that, on average, ^{3}He in the energy range ~ 0.2 to $\sim$16 MeV/nuc can be observed $\gtrsim 60\%$ of the time. Because solar activity has declined significantly since the 2002 maximum, one would expect a corresponding decline in the fraction of time that energetic ^{3}He is detected. In this paper we extend the study of Wiedenbeck et al. [2] through the first quarter of 2005.

2. Data Analysis

In our previous investigation [2] periods with energetic ^{3}He were identified by manually examining plots of detected He mass versus time of the sort shown in Figure 1. Each panel shows data from a different energy range, as indicated. Injections of ^{3}He from impulsive events can be seen as distinct intensity increases along the line corresponding to mass 3, such as on October 29. Note, however, that during periods of high ^{4}He intensities some points along this line can actually be attributable to ^{4}He spillover, such as on November 9.

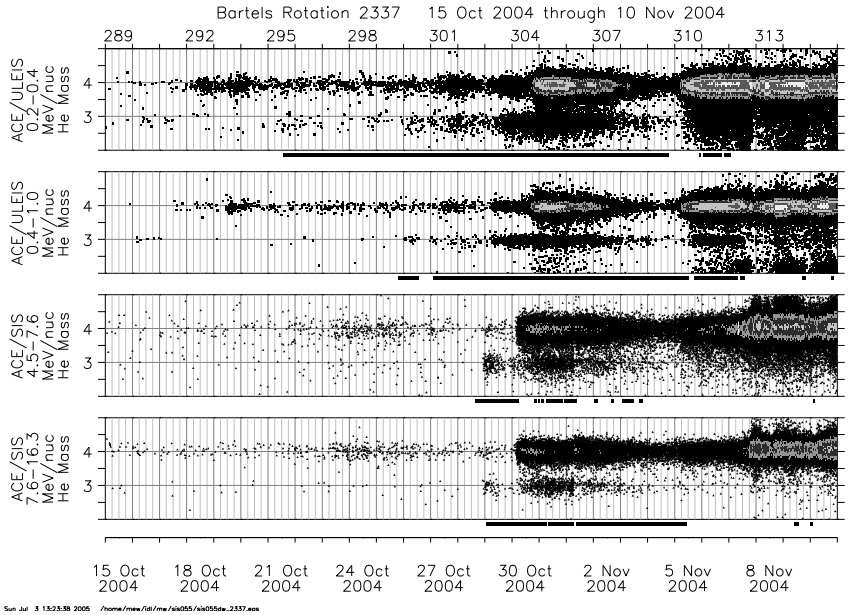

Figure 1. Mass of detected helium versus time in 4 energy intervals. Points indicate individual detected nuclei. In saturated regions of the plot a gray scale is used. For identification of times with impulsive ^{3}He injections, intervals of variable length were used so as to include a minimum of 10 ^{3}He events.

Thus to identify genuine impulsive SEP injections one must take into account both the ^{3}He rate (designated R_3) and a measure of spillover (designated S), for which we use the ratio of counts in the valley between the two mass peaks to counts in the ^{3}He peak.

For the present study we have automated the identification of time intervals containing impulsive ^{3}He injections. Intervals having $R_3 > R_3^0$ and $S < S^0$ are labeled as having impulsive ^{3}He and are indicated by the bars along the bottom of each panel in Figure 1. The threshold values R_3^0 and S^0 were selected by comparing the results for the period of our earlier study [2] with the original manual identifications and attempting to maximize the fraction of time that the two procedures assigned the same classification (^{3}He rich or not).

Thresholds were selected individually for each of the four energy intervals due to their differing resolutions and sensitivities, which influence the ability to clearly identify ^{3}He injections. With the selected thresholds the agreement was in the range $\sim$ 85–95% for each of the four energy bands. The automated procedure's consistent, quantitative criteria for identifying ^{3}He should provide a more reliable indication of how the fraction of time with ^{3}He present has been varying over the solar cycle.

3. Results and Discussion

Figure 2 shows the resulting fraction of time for which ^{3}He was observed. Time intervals were counted during which any of our four energy intervals contained significant ^{3}He. Because of energy spectra variations, velocity dispersion, changing magnetic connection, and differing fields of view for SIS and ULEIS it is not unusual to

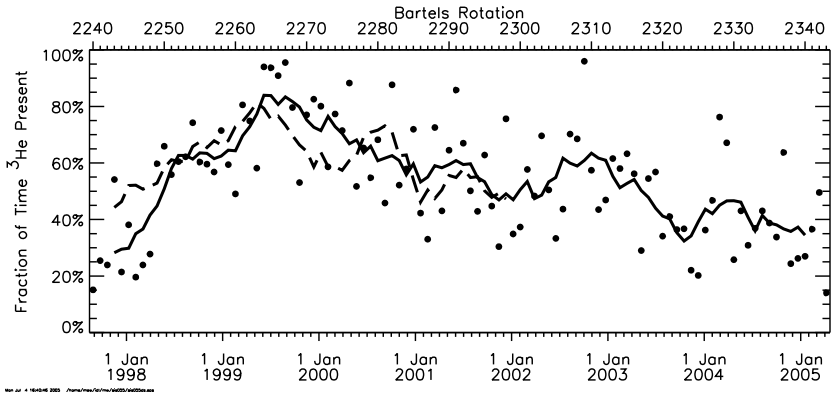

Figure 2. Time variation of the fraction of time when ^{3}He from impulsive SEP events is observed at 1 AU in any of the four energy intervals analyzed. The dashed curve is the smoothed result from our previous study [2] study. The solid curve is the smoothed result from the present study. The points indicate values obtained for individual Bartels rotations.

see a ^{3}He signature in some, but not all of the energy intervals (e.g., October 27 in Figure. 1). We hypothesize that the ^{3}He we are measuring is just the high-energy tail of a relatively-soft ^{3}He energy spectrum. In this case the seed particles that are accelerated by interplanetary shocks could mainly have energies below the 0.2 MeV/nuc at which our measurements start. The particles we are measuring would then be serving as a proxy for this unmeasured low-energy population.

The points in Figure 2 show values for individual Bartels rotations while the solid curve is a 7-point smoothed version of these same data. The dashed line is the smoothed result previously reported [2] based on the manual analysis.

As seen from Figure 2, the fraction of time with ^{3}He identified peaked at over 80% in late 1999. Since then the value has been gradually falling but was interrupted by a secondary peak in late 2002. At present (early 2005) ^{3}He is still observed about 35% of the time. These fractions are best regarded as lower limits, since it is quite possible that time periods in which spillover prevented the identification of a ^{3}He signal may still have had a significant amount of ^{3}He present.

In Figure 3 we compare the fraction of time with ^{3}He present in the four individual energy intervals. The upper dashed curve is identical to the solid curve in Figure 2 but plotted with a logarithmic vertical axis. The four solid curves correspond to our four energies, with the curve thickness decreasing with increasing energy. The bottom dashed curve shows the fraction of time that impulsive ^{3}He was seen in all four energy intervals. Comparing the various curves one sees the following: First, ^{3}He is observed a significantly larger fraction of the time in the two ULEIS energy ranges than it is at the SIS energies. The overall result obtained by including times when ^{3}He is present in any of the four energy intervals does not differ greatly from what one would find by requiring only that ^{3}He be present in ULEIS. The sizable difference between the ULEIS and SIS curves (in spite of the fact that the SIS geometrical factor is $> 30\times$ that of ULEIS) is probably due to the soft energy spectra of impulsive SEP events combined with the significantly lower energy range of ULEIS (0.2–1 MeV/nuc vs. >4.5 MeV/nuc for SIS). Second, all of the energy intervals exhibit qualitatively similar overall trends: a rise from 1997–1999, a global maximum in 1999–2000, a secondary peak in late 2002, and a decline from 2003-2005. The curves in Figure 3 suggest a larger relative variation over time for SIS than for ULEIS. However this may simply be because ULEIS was already observing impulsive ^{3}He material a very

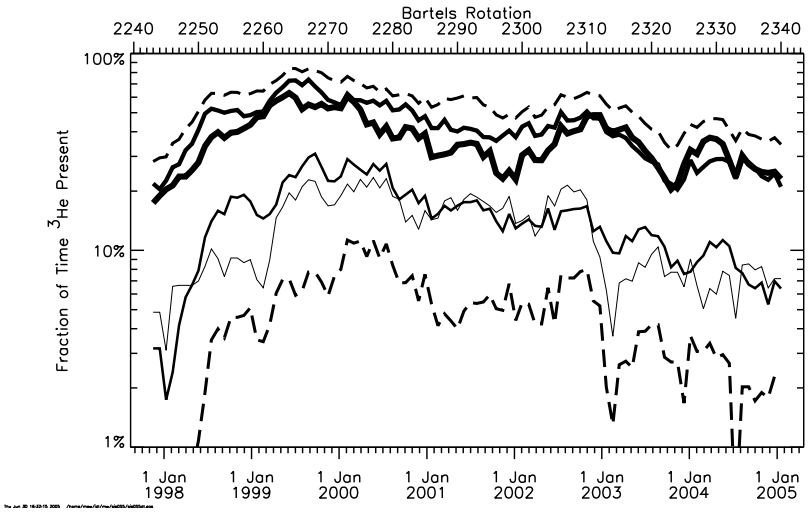

Figure 3. Time variation of the fraction of time when ^{3}He was present in the individual energy ranges (solid curves, with curve thickness decreasing with increasing energy). The upper (lower) dashed curve shows the fraction of time that ^{3}He was present in any (all) of the energy intervals.

large fraction of the time during during solar maximum. Future work should extend the analysis to include a determination of the actual intensity of the measured ^{3}He, which could help clarify the energy dependence of the trends we are observing.

Examination of a period not identified as ^{3}He-rich in Figure 1 (October 15-19) reveals the clear presence of ^{3}He in at least 3 of the energy intervals. Such periods, which we frequently observe, are not classified as ^{3}He rich simply because the measured intensities are too low to distinguish individual impulsive events. One possibility is that the ^{3}He seen during such periods could be coming from many impulsive events that are much smaller than those studied to date. If this is the case, the previous determination [3] that there are $\sim$1000 impulsive events per year on the solar disk could be a significant underestimate.

During the solar minimum of 1986, energetic particle observations around 1 MeV/nuc on ISEE-3 [3] provided upper limits on the rate of ^{3}He rich events that indicated a drop by a factor > 50 [3] from the solar maximum value. With the high sensitivity that ACE has for detecting ^{3}He injections it will be interesting to investigate the actual level to which impulsive ^{3}He drops when solar activity reaches its minimum.

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