Persistent energetic ^{3}He in the inner heliosphere

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Abstract: Using data from the Solar Isotope Spectrometer on NASA's Advanced Composition Explorer spacecraft we have examined the time and energy dependence of the quiet-time ∼5–15 MeV/nuc ^{3}He intensity from 1998 through 2006 in order to establish the origin of these particles. We find a mixed population, with ^{3}He from impulsive solar energetic particle events dominating at the lower end of this energy interval and galactic secondary ^{3}He becoming significant at the high end.

Introduction

There are two well established sources of energetic ^{3}He in interplanetary space: ^{3}He-rich solar energetic particle (SEP) events and secondary ^{3}He produced by fragmentation of galactic cosmic ray (GCR) ^{4}He and adiabatically decelerated in penetrating to the inner heliosphere. These two populations have distinctly different energy spectra in the MeV range, with SEP intensities falling with increasing energy and GCR intensities rising. In addition, SEP intensities increase from solar minimum to solar maximum while GCRs vary in the opposite direction.

Studies of ^{3}He above 1 MeV/nuc during solar quiet times [4, 5] have found energy spectra that are decreasing functions of energy per nucleon and that have intensities that increase towards solar maximum. These authors conclude that small, unresolved impulsive (i.e., ^{3}He-rich) SEP events are the likely source of the quiet-time ^{3}He.

Since the launch of NASA'S Advanced Composition Explorer (ACE) spacecraft [6] in 1997, data from two of its instruments have been used to monitor the occurrence of ^{3}He-rich SEP events. The Solar Isotope Spectrometer (SIS) [7] covers the energy range 4.5 to 16 MeV/nuc for ^{3}He while the Ultra-Low-Energy Isotope Spectrometer (ULEIS) [3] covers 0.2 to 1 MeV/nuc. In investigations combining data from these two instruments [8, 9] we found that energetic ^{3}He was present in the inner heliosphere >60% of the time during solar maximum based on the observation of distinct increases of the ^{3}He intensity that could identified as SEP events. However in the same studies it was noted that there are periods during which there is a quasi-steady intensity of ^{3}He at a level too low to be identified as being related to distinct SEP events ([8] Figs. 1 and 2). As solar activity has been declining over the past ∼2 years, the number of distinguishable ^{3}He-rich events has decreased markedly while and the fraction of "quiet time" has increased correspondingly. In this paper we investigate the origin of the ^{3}He observed in the SIS energy range during solar quiet time periods from 1998 through 2006.

Helium Isotope Observations

Fig. 1 shows He mass spectrograms[1] for one solar rotation in 2006 (Bartels rotation 2359, 1–27 Jun 2006) in which there were no clearly-defined ^{3}He increases. In the two SIS energy ranges shown (SIS-L, 4.5–7.6 MeV/nuc; SIS-H, 7.6–16.3

1. http://www.srl.caltech.edu/ACE/ASC/DATA/level3/sis/heplots/he_plots.html

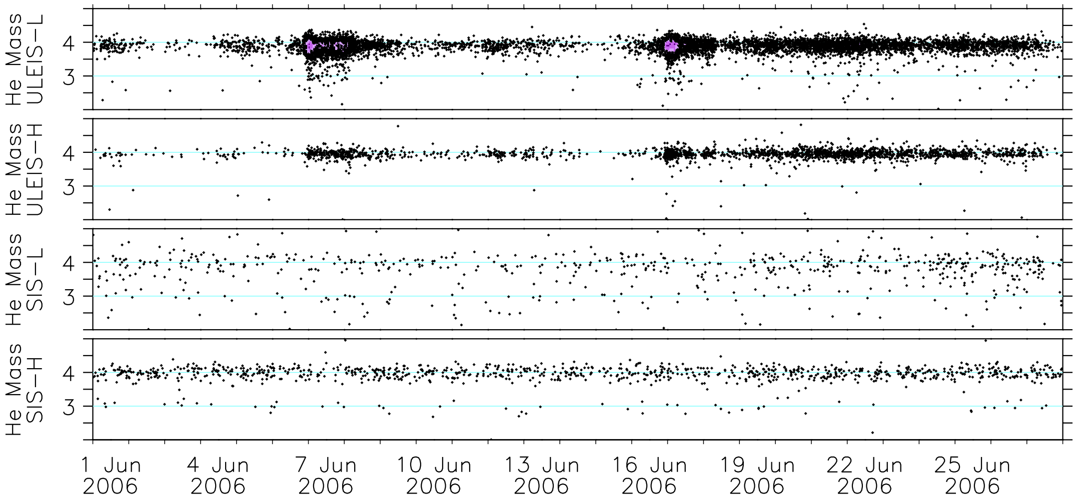

Figure 1: Mass spectrograms from ACE/ULEIS and ACE/SIS (see text for energy ranges) during Bartels rotation 2359. A quasi-steady intensity of ^{3}He is seen at the SIS energies with no indication of distinct ^{3}He-rich SEP events.

MeV/nuc) there is no indication of discrete SEP events, with or without ^{3}He, other than possibly a small increase in the ^{4}He intensity during the last several days of the rotation. The flux of ^{4}He is dominated by anomalous cosmic ray (ACR) He, especially at the higher energy. A low rate of ^{3}He particles was detected throughout the rotation; in the SIS-H range it appears as a separate track on the plot, clearly resolved from ^{4}He, while in the SIS-L range the separation of the two tracks is not as clearly seen because of the poorer mass resolution. In the two ULEIS energy ranges (ULEIS-L, 0.2–0.4 Mev/nuc; ULEIS-H, 0.4–1 MeV/nuc) there are a number of small SEP events that dominate the ^{4}He during most of the rotation. No clear ^{3}He increases are evident, although events along the ^{3}He track during the highest-intensity ^{4}He periods (6–8 Jun, 16–17 Jun) could contain some ^{3}He in addition to spill-over from ^{4}He.

In Fig. 2 we have summed the data for this entire solar rotation to produce mass histograms. At ULIES energies the ^{3}He intensity is $<$1% of ^{4}He. In the SIS-L and SIS-H histograms the ^{3}He/^{4}He ratios are $\sim$20% and $\sim$6%, respectively, although these values are not directly significant because 1) the measurement are made over equal range intervals, which implies that the ^{3}He is coming from a slightly higher energy per nucleon than the ^{4}He, and 2) the ^{4}He is dominated by ACRs, which do not contribute to the ^{3}He.

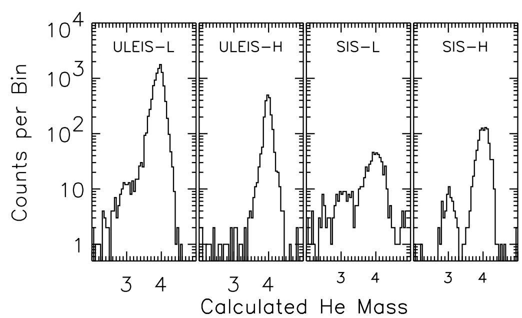

Figure 2: Helium mass histograms obtained by summing the data shown in Fig. 1.

Fig. 3 shows a cross plot of daily averaged isotope intensities in the lowest of SIS energy interval ($\sim$4.5–5.8 MeV/nuc ^{3}He; $\sim$3.8–4.9 MeV/nuc ^{4}He). The concentration of points along a diagonal line corresponding to a value ~ 0.04 for the ^{3}He/^{4}He ratio is due to spillover of ^{4}He events into the ^{3}He mass interval. For longer ranges the spillover fraction is lower because consistency checks among multiple mass measurements are possible for each detected particle. The clusters of points along horizontal lines for low ^{3}He intensities correspond to 1, 2, ... ^{3}He events observed in a day, spread somewhat by variations in the instrument livetime.

For the present study we have selected days in the region bounded by the solid line toward the lower left of the plot. This region encompasses days with average range-0 ^{3}He intensity $< 5 \times 10^{-6}$ (cm^{2}sr sec MeV/nuc)$^{-1}$ and a range-0 ^{3}He/^{4}He ratio >0.05. In Bartels rotation 2359 (Fig. 1) the average ^{3}He intensity is slightly less than 1/2 of the cut value and 26 of the 27 days are included in the quiet time data set. Fig. 4 shows the number of quiet days found in each year from 1998 through 2006.

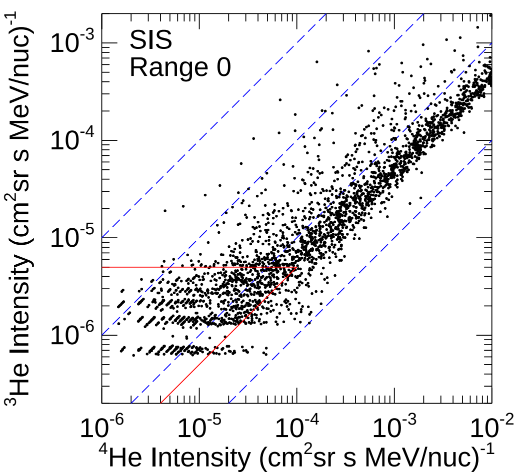

Figure 3: Distribution of daily average ^{3}He and ^{4}He from the lowest energy range measured in SIS. Dashed lines indicate ^{3}He/^{4}He of 0.01, 0.1, 1, and 10. Days falling in the lower left of region bounded by solid lines were selected as quiet days for this study.

We have derived energy spectra of ^{3}He averaged over the quiet days during 5 different time periods, as indicated in Fig. 5. The lowest energy points in these spectra must be regarded with caution because they correspond to the range-0 data that were used for selecting quiet days. The similarity of the intensities at this energy is and artifact of that selection. We have examined the effect of changing the limit on the range-0 ^{3}He intensity. Reducing

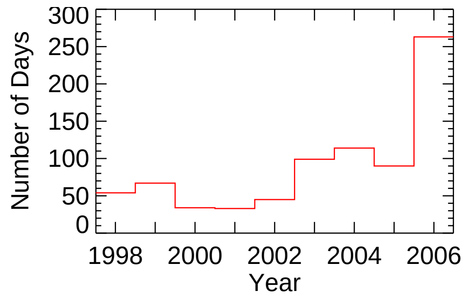

Figure 4: Yearly numbers of "He-quiet" days identified.

the limit to 2×10^{-6} resulted in small decreases in the range-1 intensities and had negligible effect at higher energies, but significantly increased the statistical uncertainties. We also tried increasing the lower limit on the ^{3}He/^{4}He ratio to 0.1 (with the ^{3}He limit held at 5×10^{-6}) and obtained results consistent with those shown in Fig. 5, within statistical errors.

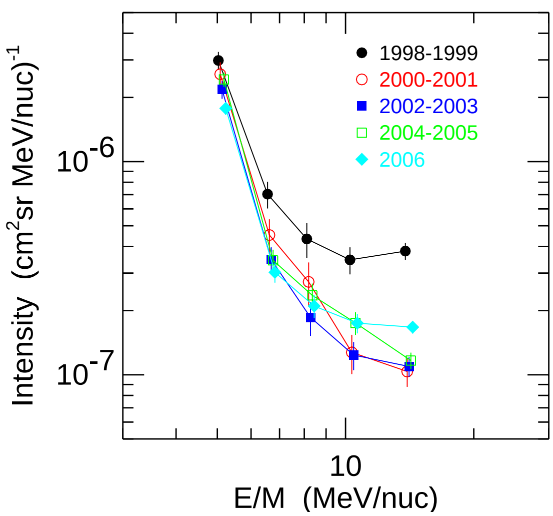

Figure 5: Energy spectra for ^{3}He for quiet days during 5 different periods.

Discussion

The ^{3}He spectra exhibit turn-ups below $\sim$10 MeV/nuc in all of the time periods studied. This suggests that the low-energy ^{3}He has a solar origin, possibly resulting from numerous ^{3}He-rich SEP events that are too small to distinguish, consistent with results from previous studies [4, 5]. However the spectra flatten towards higher energies and even have indications of a high-energy turn-up during solar minimum. This is not consistent with the superposition of energy spectra from many small ^{3}He-rich SEP events, each of which falls with increasing energy.

Comparing the 1998–99 spectrum from Fig. 5 with solar minimum spectra of GCR ^{3}He measured at higher energies [2, 1], we find the intensities that we obtain at ∼10–15 MeV/nuc appear to be reasonably consistent with an origin as secondary GCR ^{3}He.

The decrease of the 10–15 MeV/nuc ^{3}He after 1998–99 is consistent with a galactic origin since the level of solar modulation increased significantly in 2000 [9]. Although by the end of 2006 the solar modulation level was significantly less than at solar maximum, it still had not reached its 1998–99 level. The fact that in 2006 the 10–15 MeV/nuc ^{3}He intensity lies between the 1998–99 and the solar maximum levels also appears qualitatively consistent. We would expect that this level will further increase in 2007.

Thus our tentative conclusion is that ^{3}He near the orbit of Earth consists of a mix of solar and galactic ^{3}He. At solar minimum the ^{3}He intensity near 5 MeV/nuc is dominated by the solar component and near 15 MeV/nuc by galactic material. At solar maximum the galactic contribution is suppressed, but still appears to make a non-negligible contribution at 15 MeV/nuc.

There are several follow-up investigations that can be undertaken to further clarify the origin of the ^{3}He in this transition energy range. By selecting quiet-time intervals using independent data sets as done in [5] rather than using the SIS ^{3}He itself, one should be able to obtain a meaningful measurement of the solar cycle dependence of the quiet-time ^{3}He intensity at the lowest SIS energies. If our interpretation is correct, this intensity should increase going from solar minimum to solar maximum, in anitcorrelation with the 15 MeV/nuc intensity. It should also be possible to combine quiet time data from three ACE instruments, ULEIS, SIS, and CRIS, to understand in more detail the solar cycle variation of this two-component spectrum over a broad energy range, ~ 0.2 to ~ 120 MeV/nuc.

Finally, since the spatial and temporal scales for GCR variations tend to be significantly larger than those for SEP variations, statistical tests of the variations in the ^{3}He intensity could prove useful. For galactic particles observed over a period of several weeks or more one would expect to find a Poisson distribution whereas for SEPs larger fluctuations associated with changing magnetic connection to solar source regions are likely. Correlations between ^{3}He observations from the two STEREO spacecraft could also be useful: for GCRs one would expect little correlation on short (∼day) time scales, while for SEPs correlations could be significant during the present early part of the mission when the two spacecraft should have similar connection to solar source regions.

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