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Cosmic-ray helium intensities over the solar cycle from ACE

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Abstract: Observations of cosmic-ray helium energy spectra provide important constraints on cosmic ray origin and propagation. However, helium intensities measured at Earth are affected by solar modulation, especially below several GeV/nucleon. Observations of helium intensities over a solar cycle are important for understanding how solar modulation affects galactic cosmic ray intensities and for separating the contributions of anomalous and galactic cosmic rays. The Cosmic Ray Isotope Spectrometer (CRIS) on ACE has been measuring cosmic ray isotopes, including helium, since 1997 with high statistical precision. We present helium elemental intensities between ∼10 to ∼100 MeV/nucleon from the Solar Isotope Spectrometer (SIS) and CRIS observations over a solar cycle and compare these results with the observations from other satellite and balloon-borne instruments, and with GCR transport and solar modulation models.

Introduction

Helium nuclei in galactic cosmic rays (GCR) are the second most abundant species in cosmic rays next to protons and offer important clues to understanding GCR propagation, particularly since the isotope ^{3}He is generally believed to be of secondary origin. In addition, the abundance of helium at 1 AU is strongly influenced by solar modulation at low energies, and by the addition of the anomalous helium component during solar minimum conditions (see review [1]).

Comparisons of the time histories of helium intensities observed by spacecraft such as IMP 8 and Ulysses and the two Voyager spacecraft at different locations across the heliosphere show interesting modulation features that help to refine calculations of solar modulation [2]. Observations of helium intensities at 1 AU are rather limited, especially since IMP 8 has been operating with reduced coverage of ∼30-50% since 2001 and recently stopped transmitting data altogether. The Cosmic-Ray Isotope Spectrometer (CRIS) onboard ACE has been measuring abundances of nuclei with charges between $2 \leq Z \leq 30$ and energies 30-500 MeV/nuc at 1 AU continuously since 1997 with unprecedented statistical accuracy. ACE/CRIS observations are able to provide important coverage of helium intensities at 1 AU concurrent with the limited observations from IMP 8, with new observations from HET/LET on STEREO ([3], [4]), and finally with observations in the distant parts of the heliosphere from Ulysses and Voyager. We present the time history of helium GCR intensities derived from CRIS/ACE starting with the minimum of solar cycle 22 and ending well into solar cycle 23.

Data Analysis

The mass and charge of particles stopping within CRIS are identified using the dE/dx versus residual energy method [5]. The methods and selection criteria used to assign charge and mass to incident light nuclei have been described previously

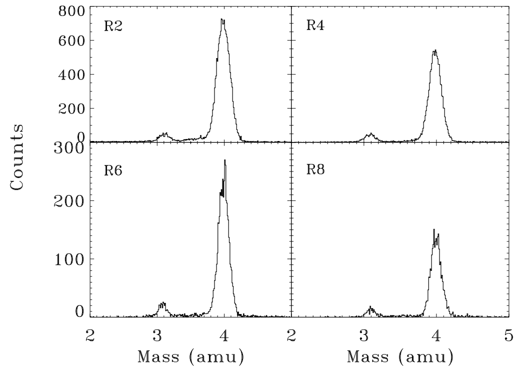

Figure 1: Mass histograms for helium in 4 energy ranges R2: 34-47 MeV/nuc, R4: 64-83 MeV/nuc, R6: 91-109 MeV/nuc, and R8: 113-131 MeV/nuc observed during solar minimum.

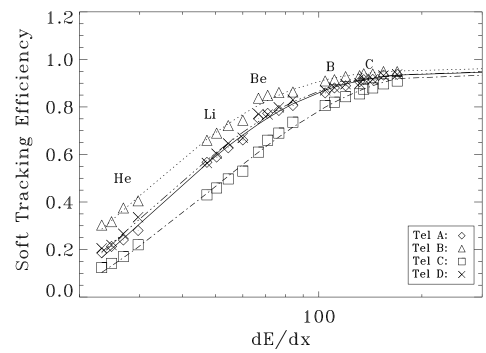

Figure 2: SOFT tracking efficiency derived for each of the 4 telescopes of CRIS. The symbols are larger than the statistical uncertainties.

[6]. Valid events are required to trigger all three Scintillating Optical Fiber Telescope (SOFT) hodoscope planes. The hodoscope is used to obtain a particle trajectory before entering one of 4 stacks of solid-state detectors below SOFT. Shown in Figure 1 are the resulting mass histograms derived during solar minimum from CRIS. The isotopes of He are easily resolved and the number of events for each isotope is determined by summing the number of events under each peak. The present analysis is limited to events whose reconstructed trajectories have an opening angle of less than 30 degrees. Corrections to the derived intensities are applied to account for the probability of a particle surviving fragmentation within the instrument.

The derived charge dependent tracking efficiency with the SOFT [5] hodoscope is shown in Figure 2. A detailed study of the SOFT hodoscope has resulted in an improved understanding of the systematic uncertainties associated with the efficiency for tracking low Z nuclei. The tracking efficiency for each of the four CRIS telescopes was determined separately and the resulting fluxes for the light nuclei (He-C) for each telescope were compared for consistency. Based on these studies, overall systematic uncertainties were derived for charged particles from Li to Zn which ranged from 15% to better than 2%. The SOFT tracking efficiency for helium is more problematic since the tracking efficiency drops to $\sim$10-30% for He in the highest energy ranges covered by CRIS (Figure 2).

To understand the uncertainties associated with the SOFT tracking efficiency for He, we compare derived He intensities from CRIS with previous data. Figures 3, 4, and 5 show the He intensities derived from CRIS in three separate time ranges, a solar minimum period between Jan. 1 1998 and Jan. 1 1999, a solar maximum period between Jan. 1 2001 and Jan. 2004, and finally a recent solar minimum period from Jan. 1 2007 to Apr. 15 2007. Periods of intense solar activity have been removed using observations from the Solar Isotope Spectrometer (SIS) also on ACE. The open black triangles in these figures show the CRIS helium spectrum derived from the original derivation of the SOFT He tracking efficiency. Comparing the helium intensities with previous data, particularly the derived concurrent intensities from IMP 8 and the high energy data of BESS, suggests that the derived He efficiency for CRIS is over estimated, especially at high energies (or low values of dE/dx in Figure 2).

In order to determine an appropriate correction factor for the SOFT efficiencies, we adjust the SOFT efficiencies such that the CRIS helium data matches a modified power-law fit to previous and concurrent helium data during solar minimum conditions (period 1). The results of this fit are shown in Figure 3 as the red dot-dashed curve, which essentially overlies predictions from a transport model discussed below (solid black curves). The correction to the SOFT tracking efficiency ranges from a factor of 1 at the lowest energies to $\sim 1/2$

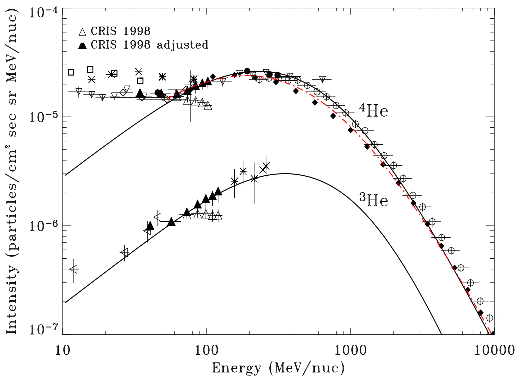

Figure 3: CRIS helium intensities during solar minimum conditions (Jan. 1 1998 to Jan. 1 1999). Observations include [7] (open circles), ACE/SIS (open squares), [8] (upsidedown triangles), [9] (solid diamonds), [10] (asterisk), [11] (thick asterisk and open diamonds), [12] (solid circles). Also shown are the GALPROP results with $\phi = 500$ MV.

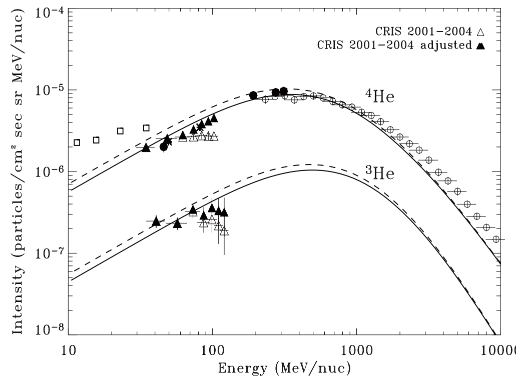

Figure 4: CRIS helium intensities during solar maximum conditions (Jan. 1 2001 to Jan. 1 2004) compared with the results from previous and concurrent experiments and results from GALPROP with an assumed ϕ of 1100 & 1200 MV.

at the highest energies. This correction introduces an additional systematic uncertainty, which we are still in the process of evaluating, and which depends to a large extent on the fit to previous helium data. The correction to the SOFT efficiency is a one-time correction determined from period 1. The resulting SOFT efficiency is then applied to periods 2 and 3 as well.

The adjusted ^{3}He and ^{4}He intensities are shown in Figures 3, 4, and 5 as the solid black triangles. During solar minimum conditions, the ^{4}He intensity is strongly affected by anomalous helium, causing the well known flattening of the helium spectrum at low energies [1]. A better indication of the spectral shape can be obtained from the ^{3}He intensity, where there is no contamination from anomalous helium. The derived CRIS ^{3}He intensities in Figure 3 are consistent with previous observations at lower and higher energies.

In addition, solar maximum data should be relatively free of contamination from anomalous helium (see Figure 4). As one can see from Figures 4 and 5, the helium intensities that were adjusted using data from the 1998 solar minimum conditions, are also in agreement with previous and concurrent data taken during periods when the effects of solar modulation were quite different. Finally, the adjusted helium intensities also agree well with the predictions of GALPROP (shown as the black solid lines) [13]. This version of GALPROP is a diffusive reacceleration model that agrees well with CRIS/ACE Li, Be, and B observations. Details of the model and the assumptions for the effects of solar modulation can be found in [14] and [15]. The levels of solar modulation adopted for the three time periods used in this study correspond to a ϕ of 500 MV, 1200 MV, and 700 MV, respectively.

Observations

Given an improved estimate of the SOFT tracking efficiency for helium, we can present the time history of helium intensities over the solar cycle (see Figure 6). The He time histories (black squares in top two panels) are compared with IMP 8 in overlapping energy ranges. Since the highest CRIS energy range is from 113-131 MeV/nuc, we fit the CRIS energy spectrum at each time interval, and project the value of the CRIS intensity in the energy range covered by IMP 8 (134-250 MeV/nuc). The two data sets observe the same overall trends in solar modulation. The bottom panel in Figure 6 shows the ratio of CRIS to IMP 8 in the two energy intervals explored.

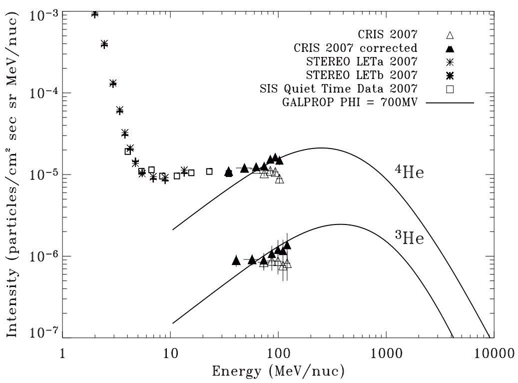

Figure 5: CRIS helium intensities during recent solar minimum conditions (Jan. 1 2007 to April 15 2007) compared with the results from concurrent observations of ACE/SIS (open squares), [4] (asterisks). Also shown are the predictions from GALPROP with $\phi = 700$ MV.

Summary

One-time adjustments to the CRIS He SOFT tracking efficiencies have brought good agreement between ACE and other observations taken at 1 AU. CRIS has observed He intensities over the entire solar cycle, which will be useful in studying trends in solar modulation over time, and in deriving radial and latitudinal gradients with data from Ulysses and Voyager. We also plan to investigate the ^{3}He intensity and ^{3}He/^{4}He ratio over the solar cycle.

Acknowledgements

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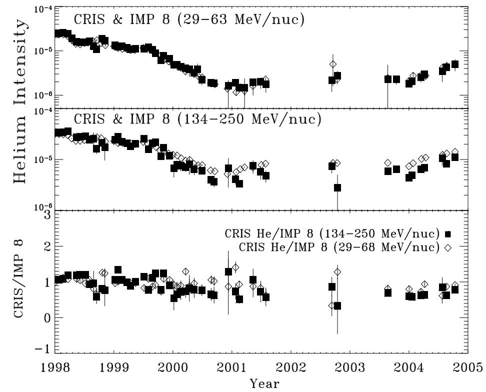

Figure 6: Top two panels: CRIS He intensities versus time in two separate energy intervals for the entire solar cycle (black squares) compared with the results from IMP 8 (open diamonds).Bottom panel: The ratio of CRIS/IMP 8 for both energy intervals.

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