Direct Evidence of Energy-Loss in Electron-Capture-Decay Secondary Isotopes in the Heliosphere

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Abstract

We report direct evidence of the energy loss of galactic cosmic rays as they diffuse in magnetic irregularities expanding with the solar wind. Using the Cosmic Ray Isotope Spectrometer (CRIS) on the Advanced Composition Explorer (ACE), we report on the energy-dependence of the electron-capture decay of the secondary isotopes ^{49}V and ^{51}Cr. At the highest energies observed by CRIS, where electron attachment is unlikely, ^{49}V and ^{51}Cr are essentially stable; at lower energies the timescale for electron attachment is much shorter and substantial decay does occur. Comparing the energy dependence of the daughter/parent ratios ^{49}Ti/^{49}V and ^{51}V/^{51}Cr during periods of solar minimum and maximum demonstrates that the solar modulation parameter ϕ is about 400 to 700 MV higher during solar maximum than at minimum. Absolute values of ϕ inferred from these electron-capture-isotope data agree well with values inferred from comparison of the observed elemental energy spectra with model calculations.

1. Introduction

It has long been known that the flux of cosmic rays near Earth varies with the eleven-year solar cycle, due to the effects of convection and diffusion in the outwardly flowing solar wind. The necessity of including adiabatic deceleration was made clear when it was demonstrated that this process explained the observed low-energy flux of cosmic rays being linear with energy [8]. These effects can be modeled well using a spherically symmetric Fokker-Planck equation, which accounts for convection, diffusion and adiabatic energy loss of cosmic rays in the heliosphere [4]. The resultant modulation of cosmic rays in the heliosphere can be characterized by a parameter, ϕ, which denotes the average amount by which the rigidity of a particle is decreased as compared to the value in the interstellar

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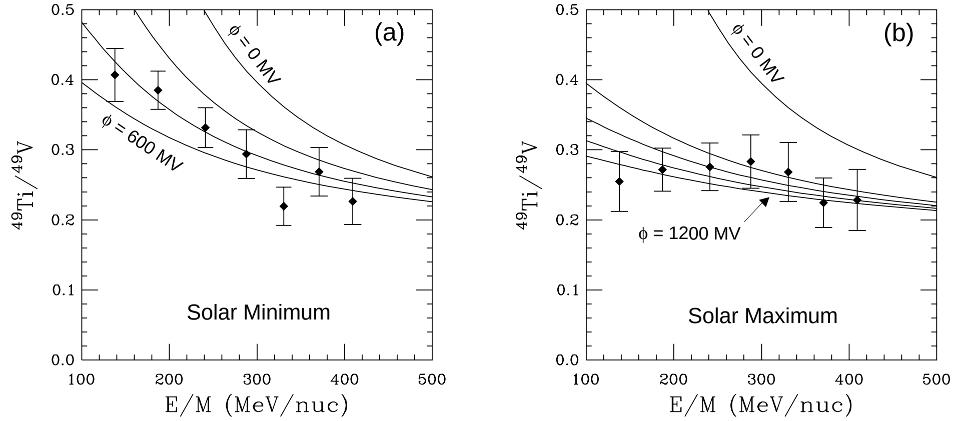

Fig. 1. ^{49}Ti/^{49}V abundance ratio near Earth. (a) at solar minimum with calculated curves for (top to bottom) $\phi = 0$, 200, 400, 600 MV. (b) at solar maximum with calculated curves for (top to bottom) $\phi = 0$, 600, 800, 1000, 1200 MV.

medium. We present here direct evidence of energy loss in cosmic rays due to solar modulation [6] using data from the Cosmic Ray Isotope Spectrometer (CRIS) [10] on board the Advanced Composition Explorer (ACE) spacecraft [11].

2. Electron-capture decay

We probe solar modulation using electron-capture-decay isotopes, which are fully stripped and essentially stable at high energies but which decay when propagating at lower energies where the cross section for electron attachment is much higher. The use of electron-capture decay isotopes to quantify the effects of solar modulation was first proposed by [7]. The electron-capture-decay isotopes ^{49}V, which decays to ^{49}Ti with a laboratory half-life of 337 days, and ^{51}Cr, which decays to ^{51}V with a laboratory half-life of 27.7 days are good for probing the effects of solar modulation since these half-lives are short compared to the time scales for fragmentation or escape from the Galaxy, and the spectral features expected from their electron-capture decay are well within the energy range of CRIS.

3. Procedure

The data were collected during two distinct periods during the present solar cycle: 681.25 days between August 28, 1997 and August 17, 1999, defined as "solar minimum," and 925.72 days between February 24, 2000 and January 5, 2003, defined as "solar maximum." Data were excluded during large solar events where high flux of low-energy particles may have degraded isotopic resolution in CRIS. The daughter-to-parent abundance ratios during solar minimum demonstrate the effects of electron-capture decay at lower energies. Figures 1a and 2a show an

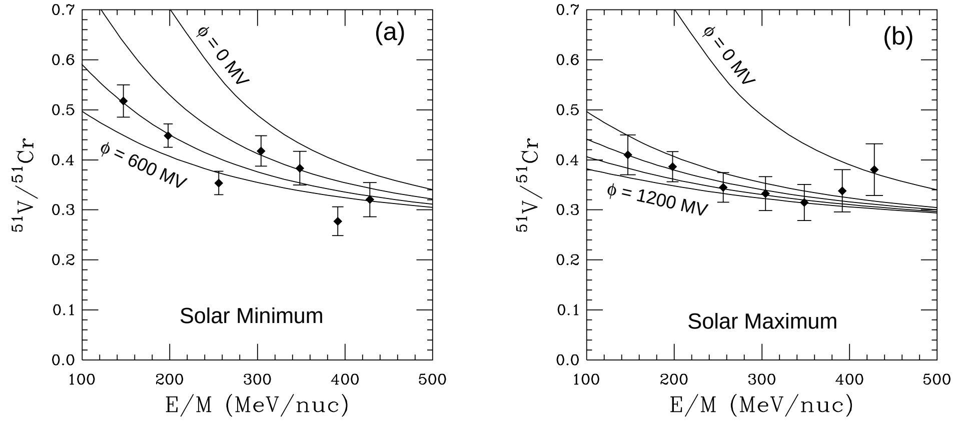

Fig. 2. Same as figure 1 but for ^{51}V/^{51}Cr.

upturn below ∼ 300 MeV/nucleon for both ^{49}Ti/^{49}V and ^{51}V/^{51}Cr, which is indicative of the decay of low-energy ^{49}V and ^{51}Cr to ^{49}Ti and ^{51}V, respectively. Figures 1b and 2b, however, show that at solar maximum, these ratios are much flatter, displaying at all energies the values characteristic of the higher energies at solar minimum.

4. Discussion

Using a "leaky-box" model of interstellar propagation based on [5], changes in the flux and energy of these cosmic-ray nuclei due to spallation with interstellar gas atoms and ionization losses are taken into account. The attachment and loss of electrons, and the effects of radioactive decay are included. The method of [3] is applied to account for diffusion, convection and adiabatic energy loss in the heliosphere. Performing this calculation using different levels of solar modulation (different values of ϕ) shows a decrease $\Delta\phi \sim 400$ MV between solar minimum and maximum in both cases. To quantify the change in ϕ for these nuclei in the heliosphere, a chi-squared fit was applied on each set of data to the curves of various ϕ. This resulted in $\phi \sim 350$ - 400 MV in both cases for solar minimum and $\phi \sim 800$ - 1100 MV for solar maximum. In the case of ^{49}Ti/^{49}V, the fragmentation cross sections for production of ^{49}Ti were decreased by 15% from the cross sections obtained from [9, 12, 13, 14], since the calculated values of ^{49}Ti/^{49}V exceeded the measured ratios by ∼ 15%. Given uncertainties in these cross sections of 10 - 20%, this discrepancy can be expected.

Another way to infer ϕ values involves comparing spectral fits to low-energy CRIS data for major elements with model calculations [1, 2]. These values are statistically more precise as they allow ϕ to be observed on time scales as short as a solar rotation, but they depend on model assumptions about the shape of the cosmic-ray source spectra and the energy dependence of the mean-free-

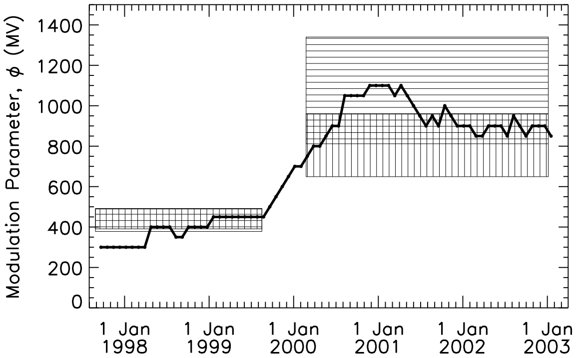

Fig. 3. Time dependence of ϕ for oxygen (line) from solar minimum through maximum. Values of ϕ using the electron-attachment feature in the energy dependence of daughter-to-parent ratios for pure-electron-capture secondary nuclides are shown (horizontal shading: ^{49}Ti/^{49}V; vertical shading: ^{51}V/^{51}Cr).

path for escape of cosmic rays from the Galaxy. The ϕ values obtained from the electron-capture secondaries do not depend strongly on such assumptions, since these results rely on abundance ratios between pairs of nuclides that are produced by fragmentation of the same parent species. We use oxygen in Figure 3 to demonstrate the consistency and accuracy of these two ways of determining ϕ; spectral fits using other major elements give similar results.

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5. References

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