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Cosmic ray energy loss in the heliosphere: Direct evidence from electron-capture-decay secondary isotopes

S. M. Niebur,[1,2] L. M. Scott,[1] M. E. Wiedenbeck,[3] W. R. Binns,[1] E. R. Christian,[2,4] A. C. Cummings,[5] A. J. Davis,[5] J. S. George,[5] P. L. Hink,[1,6] M. H. Israel,[1] R. A. Leske,[5] R. A. Mewaldt,[5] E. C. Stone,[5] T. T. von Rosenvinge,[4] and N. E. Yanasak[3,7]

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[1] Measurements by the Cosmic Ray Isotope Spectrometer (CRIS) on the Advanced Composition Explorer (ACE) spacecraft provide direct evidence that galactic cosmic rays lose energy as a result of their interactions with magnetic fields expanding with the solar wind. The secondary isotopes ^{49}V and ^{51}Cr can decay to ^{49}Ti and ^{51}V, respectively, only by electron capture. The observed abundances of these isotopes are directly related to the probability of attaching an electron from the interstellar medium; this probability decreases strongly with increasing energy around a few hundred MeV/nucleon. At the highest energies observed by CRIS, electron attachment on these nuclides is very unlikely, and thus ^{49}V and ^{51}Cr are essentially stable. At lower energies, attachment and decay do occur. Comparison of the energy dependence of the daughter/parent ratios ^{49}Ti/^{49}V and ^{51}V/^{51}Cr during solar minimum and solar maximum conditions confirms that increased energy loss occurs during solar maximum. This analysis indicates an increase in the modulation parameter ϕ of about 400 to 700 MV corresponding to an increase in average energy loss for these elements of about 200 to 300 MeV/nucleon. *INDEX TERMS:* 2104 Interplanetary Physics: Cosmic rays; 2162 Interplanetary Physics: Solar cycle variations (7536); 7536 Solar Physics, Astrophysics, and Astronomy: Solar activity cycle (2162); 2134 Interplanetary Physics: Interplanetary magnetic fields; *KEYWORDS:* Cosmic ray isotopes, solar modulation, adiabatic energy loss, electron-capture decay

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1. Introduction

[2] The flux of galactic cosmic rays observed near Earth varies over the eleven-year solar cycle in anticorrelation with solar activity. This modulation of the flux of cosmic rays in the solar system is understood to be the result of diffusion, convection, drifts, and adiabatic energy loss of cosmic rays in the magnetic field of the outflowing solar wind, the changing level of modulation resulting from changing characteristics of the solar wind over the solar cycle.

[3] Some early calculations of solar modulation considered only the diffusion of the cosmic rays through the irregularities of the solar wind magnetic field and the outward convection of those irregularities. However, it soon became apparent that features of the spectra and temporal variations of cosmic rays also required inclusion of the adiabatic energy loss of the cosmic rays as they diffused in the expanding solar wind. *Rygg and Earl* [1967] demonstrated that this adiabatic energy loss gave a ready explanation for their observation that below about 250 MeV/nucleon galactic cosmic ray components display a differential flux, dJ/dE, simply proportional to E, the kinetic energy. Further evidence for energy loss came from observing differences in the amount by which species with different spectral shapes are modulated [*von Rosenvinge and Paizis*, 1981].

[4] Adiabatic energy loss of galactic cosmic rays as they are scattered among magnetic irregularities moving outward with the expanding solar wind was demonstrated by calculations with a spherically symmetric Fokker-Plank equation [*Goldstein et al.*, 1970]. When the effects of cosmic ray transport in the heliosphere are calculated using the spherically symmetric model of *Gleeson and Axford* [1968], the variations of spectra of various components of the galactic cosmic rays are well described in a model characterized by a parameter, ϕ. For the form of the interplanetary diffusion coefficient used here, which is proportional to velocity times rigidity, the quantity $e\phi Z/A$ is approximately the mean loss

[1]Department of Physics and McDonnell Center for the Space Sciences, Washington University, St. Louis, Missouri, USA.
[2]Now at NASA Headquarters, Washington, D. C., USA.
[3]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA.
[4]NASA Goddard Space Flight Center, Greenbelt, Maryland, USA.
[5]Space Radiation Laboratory, California Institute of Technology, Pasadena, California, USA.
[6]Now at Burle Industries, Lancaster, Pennsylvania, USA.
[7]Now at Department of Psychology, University of Georgia, Athens, Georgia, USA.

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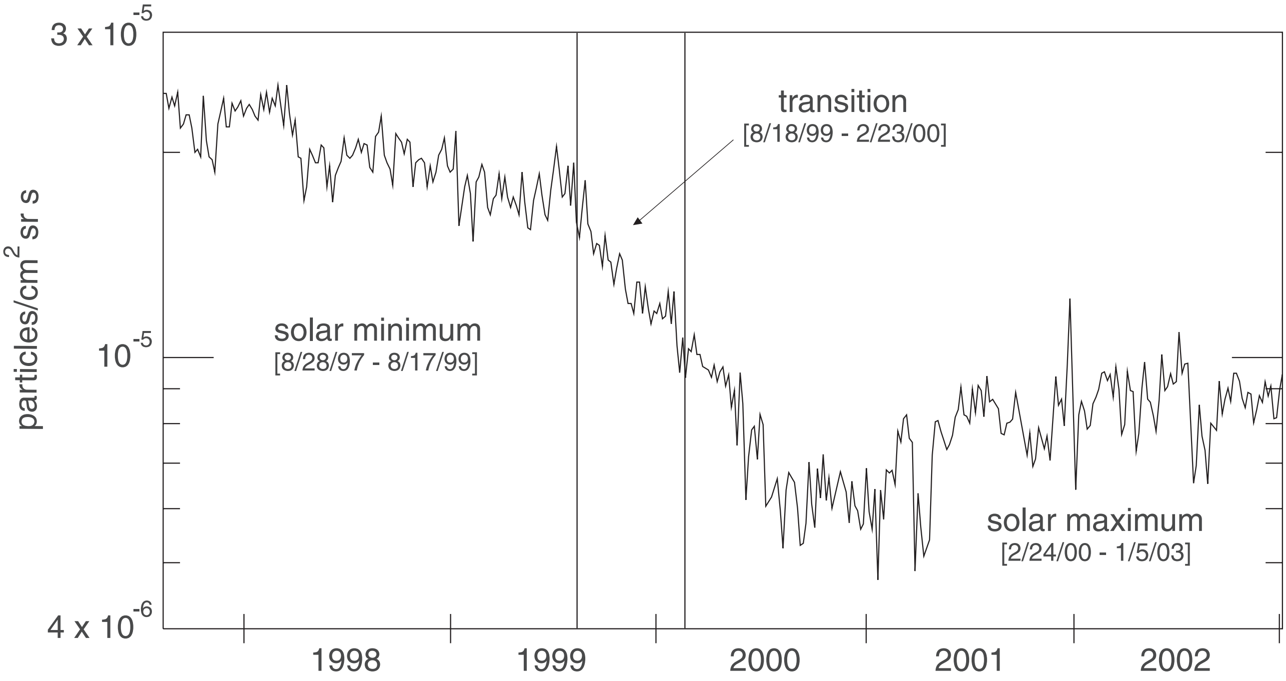

Figure 1. CRIS measurement of the time dependence of the flux of cosmic ray iron between 115 and 560 MeV/nucleon. The data begin 28 August 1997, 3 days after ACE launch.

of energy per nucleon experienced by the particles in penetrating to 1 AU. (The mean loss of energy per nucleon is often denoted by Φ.) In fact, since the energy loss is a stochastic process, particles of a given energy outside the solar system have a range of energies at 1 AU [*Goldstein et al.*, 1970; *Labrador and Mewaldt*, 1997].

[5] We present here new direct evidence for energy loss having a significant role in solar modulation of galactic cosmic rays. Our results demonstrate that cosmic rays observed near Earth during solar maximum have experienced substantially greater energy loss than those observed during a period of solar minimum. We examine electron-capture-decay isotopes whose daughter/parent ratios between 100 and 500 MeV/nucleon have a distinct energy dependence during solar minimum. During solar maximum the ratios are flat and similar in value to the ratios at the highest energies observed during solar minimum.

[6] We use data from the Cosmic Ray Isotope Spectrometer (CRIS) [*Stone et al.*, 1998a] on the Advanced Composition Explorer (ACE) spacecraft [*Stone et al.*, 1998b], which is near the L1 Lagrange point, 0.01 AU sunward of the Earth. CRIS measures the isotopic composition of cosmic rays with atomic number (Z) from Z = 2 to Z ~ 28. The energy interval varies with Z - from about 30 to 150 MeV/nucleon for Z ~ 3, and from about 100 to 600 MeV/nucleon at Z ~ 28. During the first 2 years of ACE operation, the Sun was near its cyclical minimum of activity, and the cosmic ray intensity near Earth was close to its maximum. Preliminary analysis of these data for solar minimum was reported by *Niebur et al.* [2000, 2001]. Since February 2000 the Sun has been near its maximum activity, and the cosmic ray intensity near Earth has been close to its minimum. Figure 1 shows the variation in the intensity of cosmic ray iron since the launch of ACE. In this report we compare measurements made during the period marked "solar minimum" with those made during the period marked "solar maximum".

2. Electron-Capture-Decay Isotopes as Energy Markers

[7] Several isotopes found in the cosmic rays have radioactive decay modes requiring capture of an orbital electron. Secondary cosmic ray nuclei, formed by fragmentation of heavier cosmic rays in interactions with nuclei of the interstellar medium, are created as bare nuclei. If their only decay mode is by electron capture, these secondary nuclei are stable unless they attach an atomic electron from the interstellar medium. The cross section for electron attachment is strongly energy dependent. At high enough energy the electron-attachment cross section is much smaller than the nuclear-interaction cross section, and these nuclei are generally lost to nuclear fragmentation, or they escape from the Galaxy, before they attach an electron and decay. At lower energy the attachment cross section becomes significant, and electron-capture decay becomes likely. The use of electron-capture-decay isotopes to probe energy-dependent effects in cosmic rays, including the effect of solar modulation, was proposed by *Raisbeck et al.* [1973].

[8] In this report we examine two isotopes for which the transition from likely to unlikely electron-capture decay occurs in the energy interval to which CRIS is sensitive, and the abundance ratio of decay product to radioactive isotope is strongly energy-dependent during the solar minimum period. ^{51}Cr decays to ^{51}V by electron capture with a laboratory half-life of 27.7 days, and ^{49}V decays to ^{49}Ti with a laboratory half-life of 337 days. With just one attached electron the electron-capture-decay half-life would be approximately twice that measured in the laboratory. For

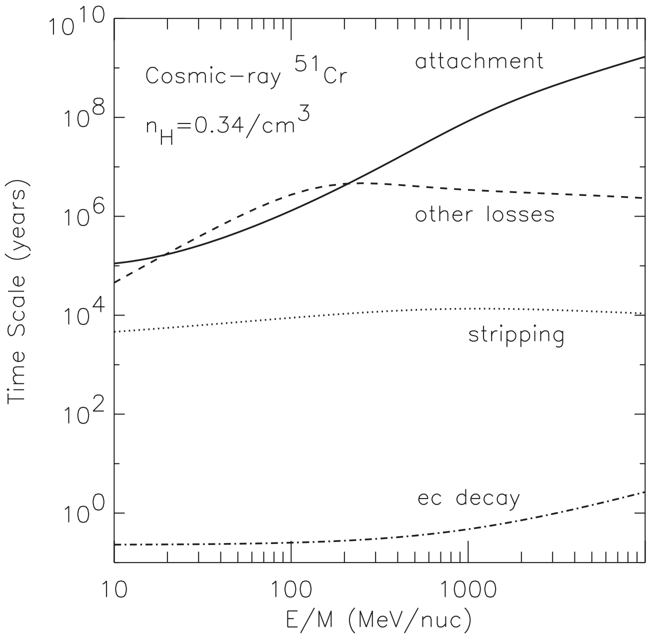

Figure 2. Energy dependence of timescales for various processes affecting ^{51}Cr nuclei as they propagate in an interstellar medium in which the density of ambient hydrogen is 0.34 cm^{-3} [*Yanasak et al.* 2001]: Solid curve, attachment of an atomic electron. Dashed curve, other losses (fragmentation in a nuclear collision, and escape from the Galaxy). Dotted curve, stripping of an atomic electron after it is captured. Dot-dashed curve, electron-capture decay of the nucleus with a single atomic electron attached.

both these decays the half-life is very short compared with other pertinent times. (In principle, we could use the same sort of analysis of the decay of ^{44}Ti to ^{44}Ca; however, the abundance of ^{44}Ti is very low, giving poor statistics, and only a small fraction of the observed ^{44}Ca comes from this decay.)

[9] The mean electron-attachment time of ^{51}Cr propagating through the interstellar medium is strongly energy dependent (Figure 2). Below a few hundred MeV/nucleon this electron-attachment time is comparable to the mean time for loss of Cr to other processes (nuclear fragmentation and escape from the galactic confinement region). At higher energies, attachment is unlikely before the Cr is lost to fragmentation or escape. Figure 2 also shows that the mean time to strip an orbital electron from Cr is much longer than the electron-capture decay time; so after the ^{51}Cr nucleus attaches an orbital electron it is almost certain to decay to ^{51}V. (The corresponding figure for ^{49}V would be almost identical, except for the electron-capture decay time, which is still much shorter than any of the other relevant times.) As a result of the electron attachment and subsequent decay, the daughter/parent ratio in the interstellar medium is strongly energy dependent. This calculated energy dependence is shown by the solid curve in Figure 3. (The calculation is described in more detail in section 4, below.) If the same calculation is carried out without permitting electron-capture decay, the dotted curve of Figure 3 results; without this decay, the ^{51}V/^{51}Cr ratio in the interstellar medium would be almost independent of energy.

[10] The energy scale of Figure 2 refers to the energy of the cosmic rays as they propagate in the interstellar medium. Because of adiabatic energy loss in the solar wind, an observer near 1 AU finds the transition from likely to unlikely electron-capture decay at a lower energy and less sharply defined but still apparent (dashed curve of Figure 3).

[11] It is possible that other energy-changing processes could be acting. For example, we cannot rule out the possibility that some degree of distributed reacceleration could be altering the spectra of secondary nuclides after they are produced [*Silberberg et al.*, 1983, 1998a; *Letaw et al.*, 1993; *Heinbach and Simon*, 1995]. However, it appears that nearly all the cosmic-ray spectra and composition observations can be accounted for without requiring such processes, and recent calculations by *Webber et al.* [2003] compare well with the preliminary report of our solar minimum electron-capture-isotope data [*Niebur et al.*, 2001] without requiring reacceleration. Thus although some uncertainty remains in the absolute values of the modulation parameters that we derive (see section 4), these values should provide useful indications of the modulation levels.

[12] In an earlier attempt to study the effects of electron-capture decay in the cosmic rays, *Soutoul et al.* [1998] examined the relative abundance of the isotopes ^{49}V and ^{51}V using a combination of data from the Voyager and ISEE 3 spacecraft. That investigation was hampered by poor isotopic resolution and limited statistics that did not allow study of the energy dependence of these abundances. Subsequently, the ^{49}Ti, ^{49}V, ^{51}V, and ^{51}Cr isotopes were studied in Ulysses data; those data displayed well-resolved isotopes, but limited statistics prevented study of energy dependence

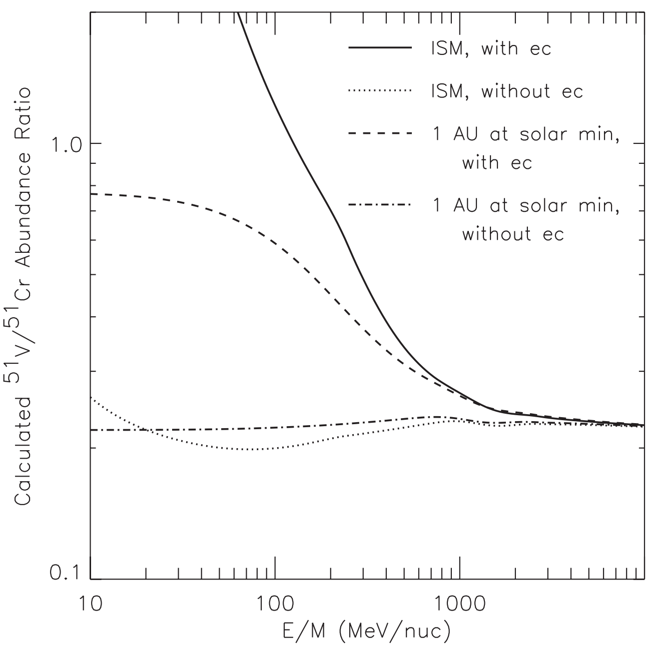

Figure 3. Calculated energy dependence of the daughter/parent abundance ratio, ^{51}V/^{51}Cr, including (top curves) and omitting (lower curves) electron-capture decay of ^{51}Cr. Solid and dotted curves, in the interstellar medium. Dashed and dot-dashed curves, after entering the heliosphere and reaching 1 AU, at solar minimum with ϕ = 400 MV.

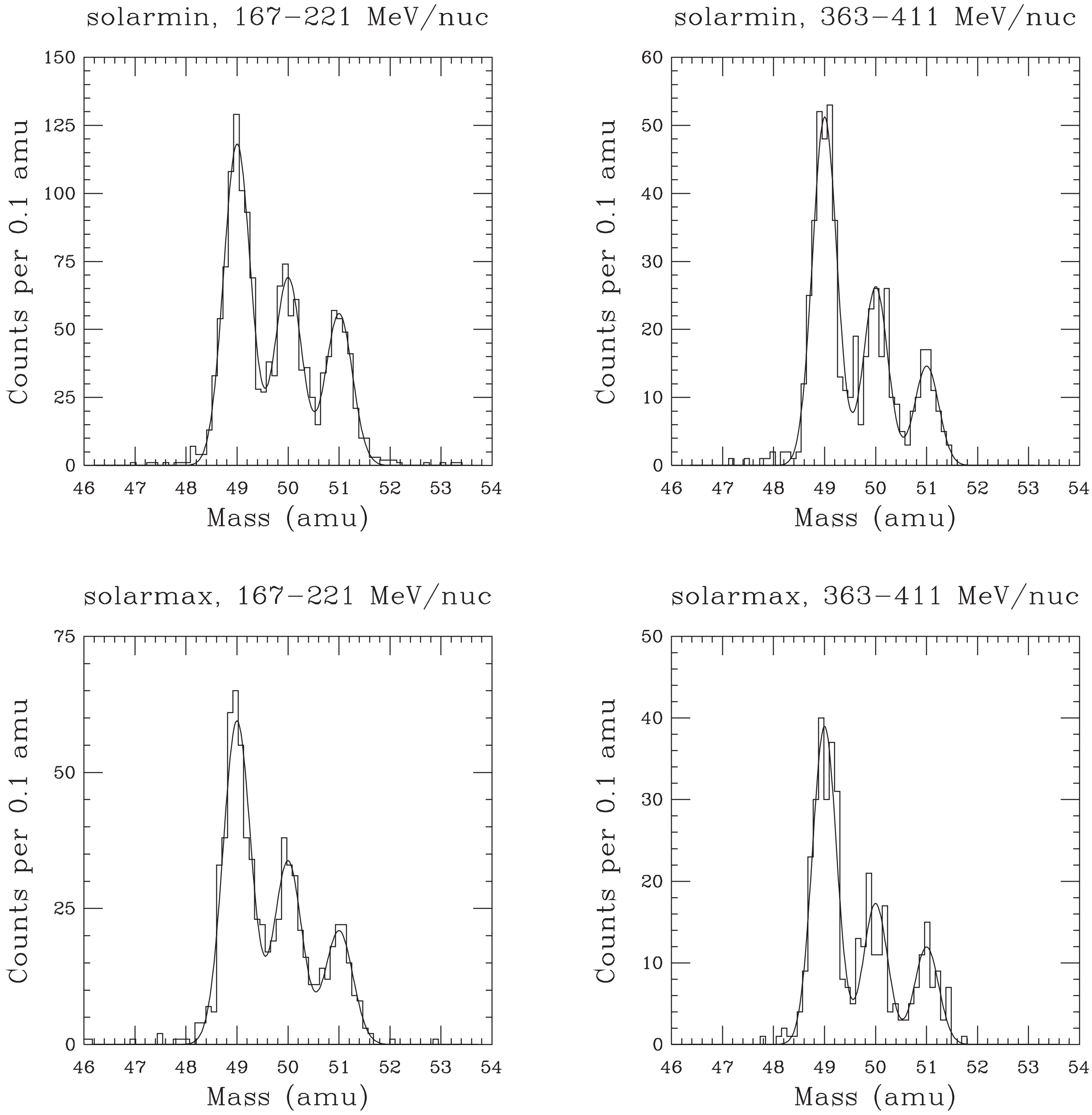

Figure 4. Histograms of mass of V nuclei with incident angle less than 30°. The smooth curves are the maximum-likelihood fits to the histograms. Left column, energies 167–221 MeV/nucleon. Right column, energies 363–411 MeV/nucleon. Top row, solar minimum. Bottom row, solar maximum.

or time dependence of these abundances [*Connell and Simpson*, 1999; *Connell*, 2001]. Our data from the CRIS instrument are the first to display well-resolved isotopes and sufficient statistics to investigate the energy dependence of their abundances.

3. CRIS Observations of Electron-Capture-Decay Isotopes

[13] We take the interval from 28 August 1997 through 17 August 1999 as our "solar minimum" and the interval from 24 February 2000 through 5 January 2003 as our "solar maximum" (Figure 1). During each of these intervals we excluded periods during which high fluxes of low-energy protons and helium from the Sun created large dead time in the instrument. Excluding these periods also ensures that we are looking only at galactic cosmic rays. Thus, during our 720-day solar minimum interval we excluded 38.75 days; and during our 1047-day solar maximum interval we excluded 121.28 days.

[14] Figure 4 shows histograms of the measured mass of V events in two energy intervals at solar minimum and at solar maximum. The individual isotopes are clearly resolved, with mass resolution characterized by an RMS deviation $\sigma \sim 0.24$ amu. Similar resolution is apparent for all the other energy intervals. The abundances of the individual isotopes are derived from the histograms by maximum-likelihood fitting of Gaussian peaks; the smooth

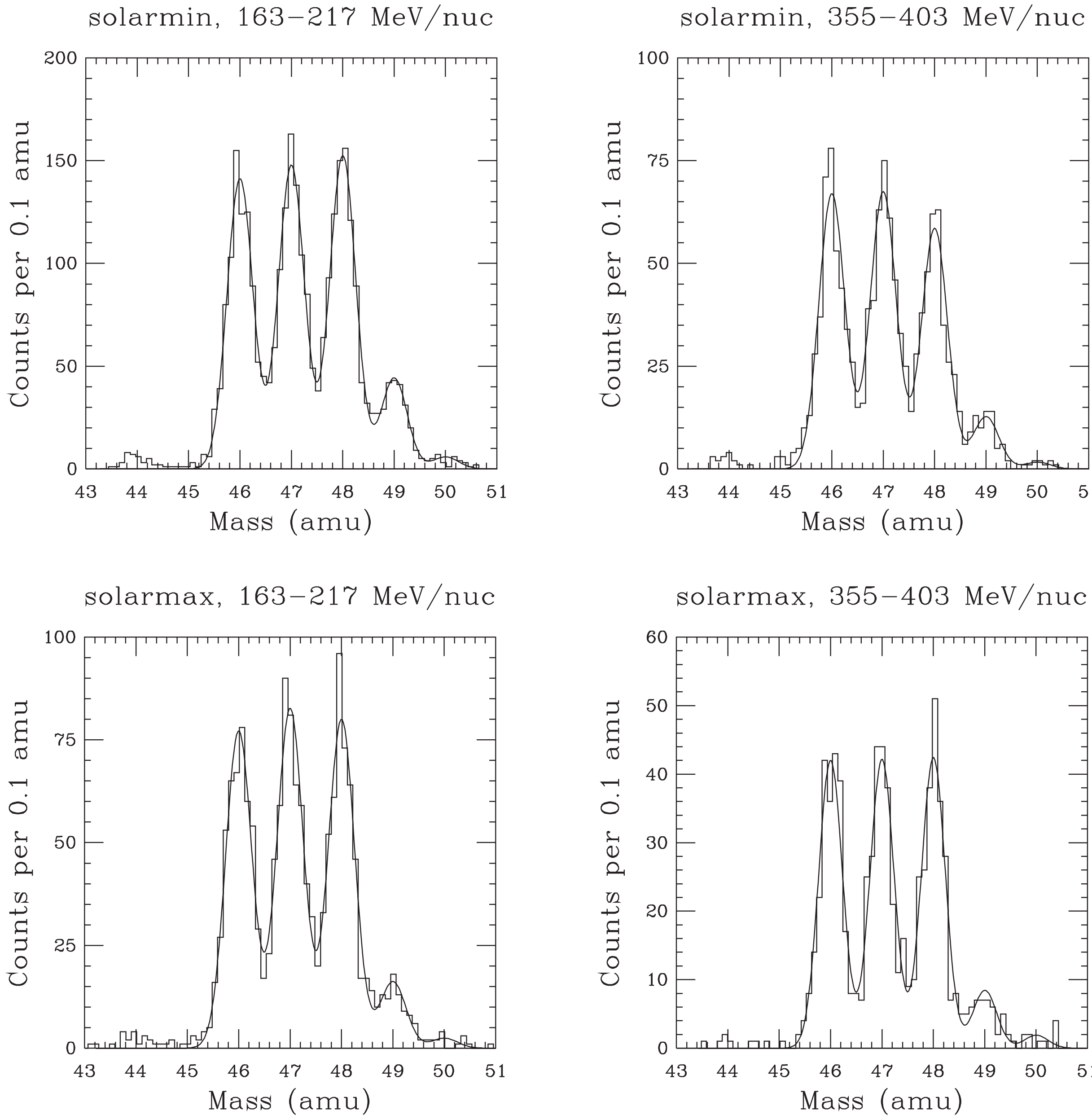

Figure 5. Histograms of mass of Ti nuclei with incident angle less than 30°. The smooth curves are the maximum-likelihood fits to the histograms. Left column, energies 163–217 MeV/nucleon. Right column, energies 355–403 MeV/nucleon. Top row, solar minimum. Bottom row, solar maximum.

curves through these histograms show the results of these fits. Figure 5 shows similar histograms for Ti, which have essentially the same resolution as V. In Ti the isotope of interest for this paper is ^{49}Ti. In spite of its low abundance compared with ^{48}Ti, the ^{49}Ti peak is resolved, and we have confidence in the derived abundance of this isotope. In our analysis used to obtain the histograms in Figures 4 and 5, and the derived ratios discussed below for ^{49}Ti/^{49}V, we restricted the data to events incident at angles less than 30° to the detector normal. For the ratio ^{51}V/^{51}Cr we increase our statistics by expanding the acceptance to angles less than 45°. The resulting small degradation in mass resolution, to $\sigma \sim 0.26$ amu, has an imperceptible effect on our ability to derive accurate abundances of the individual mass-51 isotopes, which have comparable abundance to adjacent isotopes.

[15] During solar minimum the ^{49}Ti/^{49}V ratio (Figure 6a) is observed to increase by a factor of about 1.8 as the energy decreases from about 400 to about 120 MeV/nucleon. This increase of the ratio is qualitatively as expected: At the higher energies electron attachment of the ^{49}V is unlikely. At the lower energies there is a substantial possibility of ^{49}V-to-^{49}Ti decay, so the ^{49}Ti/^{49}V ratio is substantially higher.

[16] During solar maximum (Figure 6b) the ^{49}Ti/^{49}V ratio has essentially the same value as it had above 300 MeV/nucleon during solar minimum. The direct inference is that the nuclei observed as low as 120 MeV/nucleon during

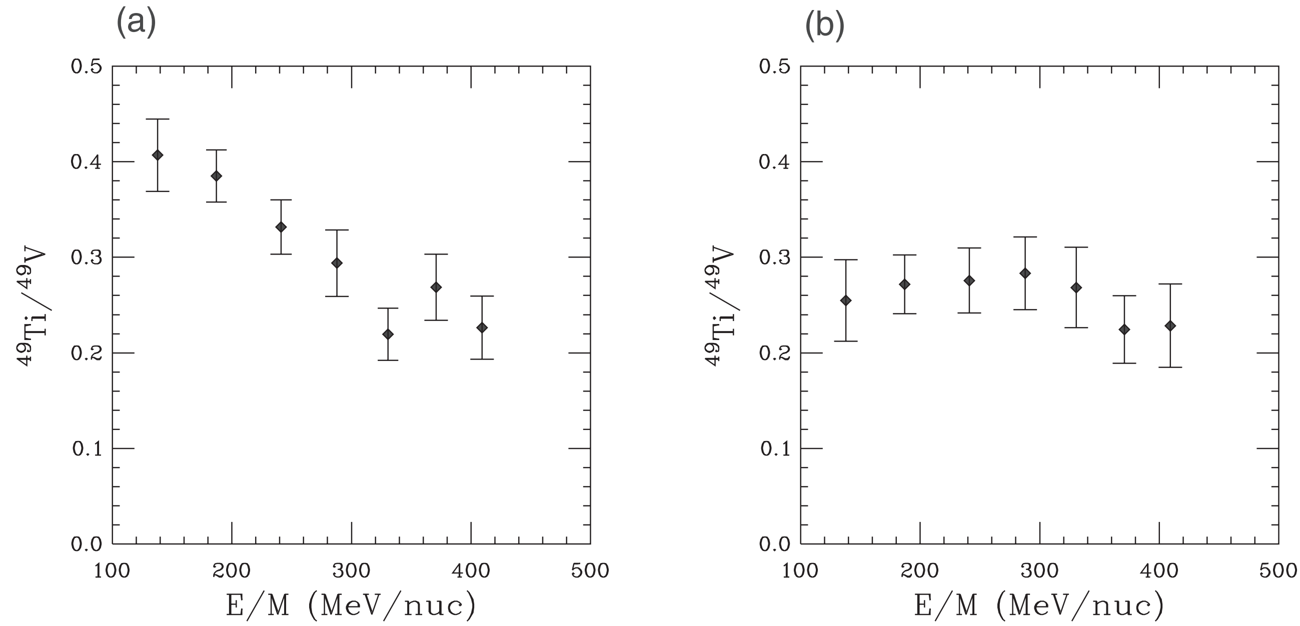

Figure 6. The $^{49}Ti/^{49}V$ abundance ratio, incident angle less than 30°. (a) Solar minimum, (b) solar maximum.

solar maximum must have come from the population that was above 300 MeV/nucleon during solar minimum. In other words, the mean energy loss in the solar system was higher during solar maximum than during solar minimum by at least 180 MeV/nucleon, corresponding to an increase by at least 400 MV in the modulation parameter, ϕ.

[17] The corresponding data for the $^{51}V/^{51}Cr$ ratio (Figure 7) indicate a similar increase in ϕ between solar minimum and solar maximum as was indicated by the $^{49}Ti/^{49}V$ ratio. At solar minimum the $^{51}V/^{51}Cr$ ratio increases by a factor of about 1.6 as the energy decreases from about 400 to 120 MeV/nucleon, while at solar maximum the ratio is essentially independent of energy at about the same value as it had above about 300 MeV/nucleon during solar minimum.

4. Comparison With a Model of Interstellar Propagation and Solar Modulation

[18] The data presented above demonstrate that galactic cosmic rays entering the solar system lose more energy during solar maximum than during solar minimum. They

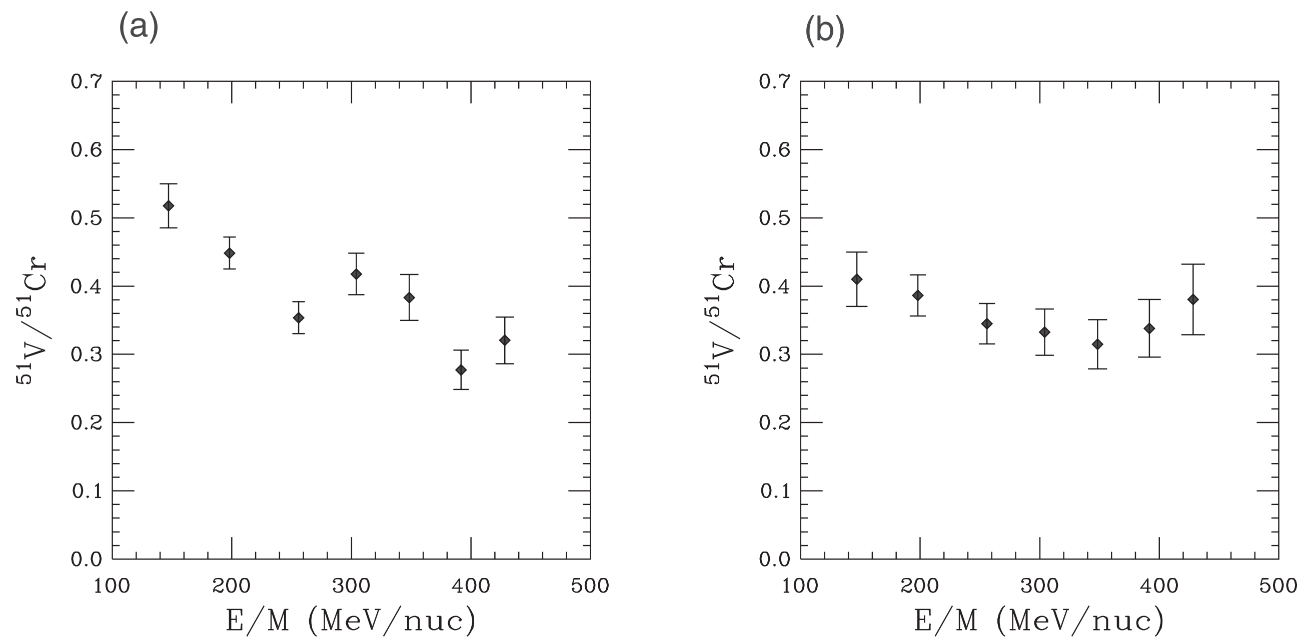

Figure 7. The $^{51}V/^{51}Cr$ abundance ratio, incident angle less than 45°. (a) solar minimum, (b) solar maximum.

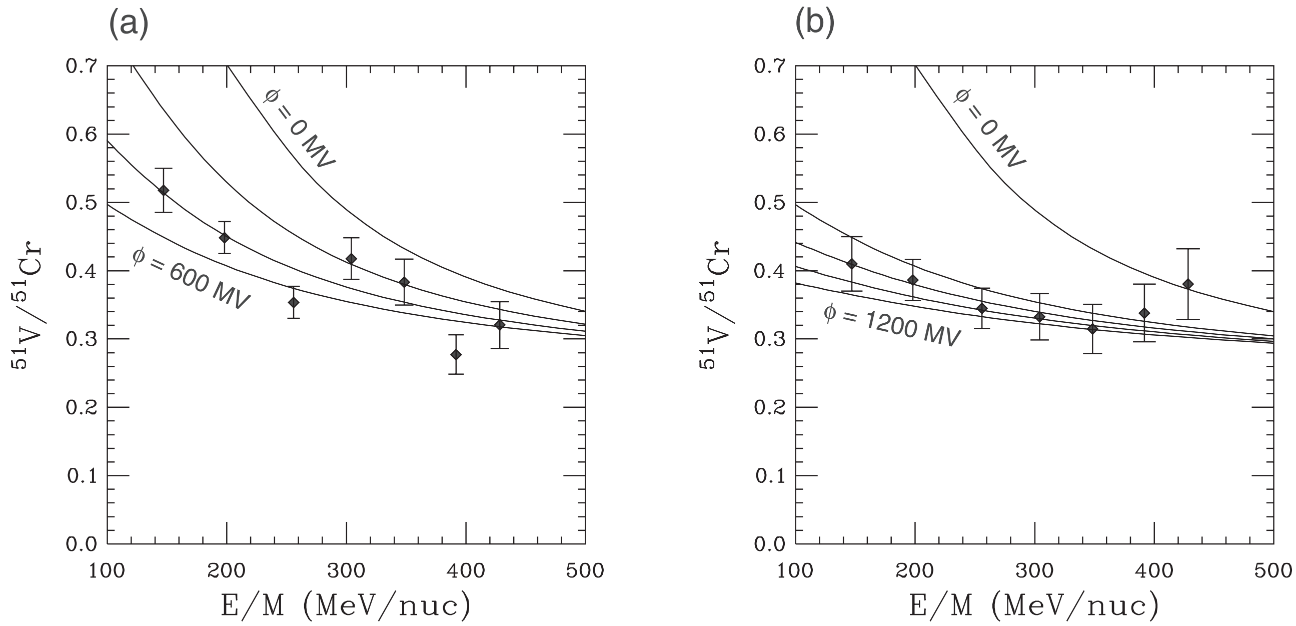

Figure 8. The $^{51}V/^{51}Cr$ abundance ratio. (a) At solar minimum with calculated curves for (top to bottom) $\phi = 0$, 200, 400, 600 MV. (b) At solar maximum with calculated curves for (top to bottom) $\phi = 0$, 600, 800, 1000, 1200 MV.

suggest a minimum of 400 MV change in the modulation parameter, ϕ, between solar minimum and solar maximum. For a better estimate of the change in ϕ, in Figures 8 and 9 we compare our data with calculated values for these ratios based on an interstellar propagation model in which no reacceleration is assumed. This "leaky-box" model, as described by *Meneguzzi et al.* [1971], takes into account the effects of production and loss of nuclei by nuclear spallation in collisions with interstellar gas atoms and of ionization energy loss. The nuclear spallation cross sections were obtained from the semi-empirical formulas of *Silberberg et al.* [1998b] and *Tsao et al.* [1998], scaled to measured cross sections when available [*Webber et al.*, 1990, 1998]. In addition, it includes the attachment and loss of electrons from the interstellar medium and decay of radioactive nuclides, including electron-capture decays by those nuclei that have attached an orbital electron. Abundances near Earth are calculated from the interstellar spectra using the formalism

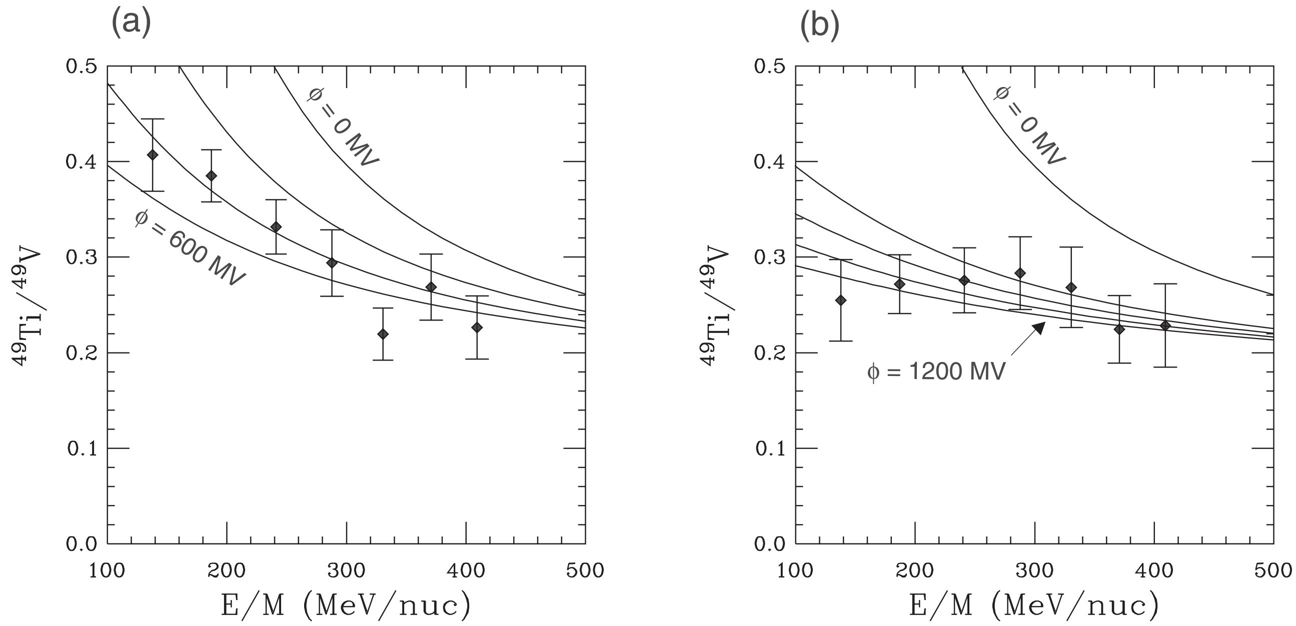

Figure 9. The $^{49}Ti/^{49}V$ abundance ratio. (a) At solar minimum with calculated curves for (top to bottom) $\phi = 0$, 200, 400, 600 MV. (b) At solar maximum with calculated curves for (top to bottom) $\phi = 0$, 600, 800, 1000, 1200 MV.

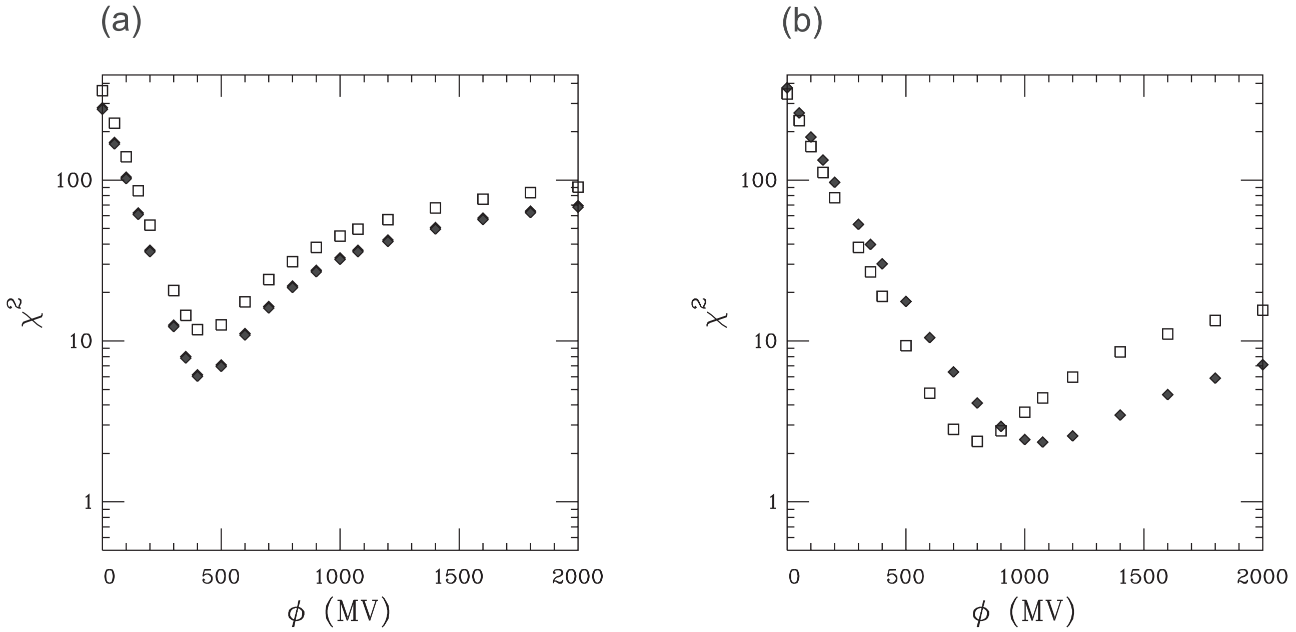

Figure 10. Chi-squared from fit of calculated energy-dependent abundance ratios for various values of ϕ to observations of $^{51}V/^{51}Cr$ (open squares) and $^{49}Ti/^{49}V$ (solid diamonds). (a) Solar minimum and (b) solar maximum.

of *Fisk* [1971], which includes the effects of convection, diffusion, and adiabatic deceleration.

[19] We observe in Figure 8 that our data for $^{51}V/^{51}Cr$ are in reasonable agreement with the calculated model for $\phi \sim$ 400 MV at solar minimum and for $\phi \sim$ 800 MV at solar maximum. Similar comparisons between our $^{49}Ti/^{49}V$ data and results of the same propagation model (Figure 9) give similar results. In this case, the propagation model used fragmentation cross sections for production of ^{49}Ti that had all been decreased by 15% independent of energy from the scaled cross sections described above. Without this scaling of the cross sections the calculated values of $^{49}Ti/^{49}V$ exceeded the measured ratios by ~15%, although the shapes of the energy dependences calculated for both solar minimum and solar maximum were reasonably consistent with the observations. This discrepancy in absolute magnitude is not surprising, given that uncertainties in fragmentation cross sections tend to be ~10–20%. (Checking the absolute production of ^{49}Ti, using the CRIS $^{49}Ti/^{56}Fe$ data, confirms the need for this 15% reduction, while the absolute production of ^{49}V requires no such adjustment of the cross sections. Adjustments similar to that for ^{49}Ti are needed to account for the absolute production of ^{51}Cr and ^{51}V, although in this case no significant discrepancy is found in the production ratio between the two isotopes.)

[20] Figure 10 displays chi-squared goodness-of-fit tests of our data against each of the curves of Figures 8 and 9 and other similar curves for other values of ϕ. While the chi-squared minima are not sharply defined because of limited statistics, at solar minimum the best fit is at about ϕ = 350 to 400 MV, while at solar maximum it is at about ϕ = 800 to 1100 MV. That the chi-squared minima for the two isotope ratios are not quite at the same value of ϕ probably reflects residual errors in production cross sections. Improved statistics combined with improved measurements of the relevant cross sections should improve the determination of ϕ by this method. These data do make clear that ϕ is larger at solar maximum than at solar minimum by about 400 to 700 MV, corresponding to a greater mean energy loss for these elements of about 200 to 300 MeV/nucleon.

[21] The values of ϕ derived here are consistent with those derived from comparisons of CRIS energy spectra for major elements with model calculations [*Davis et al.*, 2001a, 2001b]. The latter values are statistically more precise, but they depend on model assumptions about the shape of the cosmic ray source spectra and the energy dependence of the mean-free-path for escape from the Galaxy. The ϕ values obtained from the present analysis do not depend strongly on such assumptions, since our analysis relies on abundance ratios between pairs of nuclides that are produced by the fragmentation of the same parent species.

[22] The modulation model we have used here, which characterizes modulation by a single parameter ϕ, ignores particle drifts due to curvature of magnetic field lines and other effects that depart from spherical symmetry; however, we expect that use of a more complex modulation model would not alter our basic result, that the differences we observe between solar minimum and solar maximum give direct evidence for energy loss of cosmic rays in the solar system. It will be possible to test whether drifts have observable effects on the energy dependences of the ratios used in this study by remeasuring these ratios over the next several years as the heliosphere returns to solar minimum conditions with the polarity of the solar magnetic field reversed.

[23] Our interstellar propagation model did not include possible effects of reacceleration of cosmic rays during their propagation in interstellar space. Such reacceleration would be an additional source of change in energy between

production and observation; however it would provide the same change regardless of the phase of the solar cycle and so would not have a significant effect on our conclusions regarding the differences we observe between solar minimum and solar maximum. Indeed, the fact that our observations at solar minimum agree with our calculations using a reasonable value of the modulation parameter ϕ (Figures 8a and 9a) is evidence that any effects of interstellar reacceleration are relatively small.

5. Conclusions

[24] The isotopic abundance ratios $^{51}V/^{51}Cr$ and $^{49}Ti/^{49}V$ display an energy dependence during a period of solar minimum as expected from the energy dependence of electron attachment in the interstellar medium. At solar maximum the energy dependence of these ratios is markedly different, and the difference is directly explained by the increased amount of adiabatic energy loss experienced by these particles as they move through the solar system from the interplanetary medium to the vicinity of the Earth. While these observations do not give precise values for the modulation parameters, they do give direct evidence for the energy loss of cosmic rays resulting from solar modulation.

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W. R. Binns, M. H. Israel, and L. M. Scott, Department of Physics and McDonnell Center for the Space Sciences, Washington University, St. Louis, MO 63130, USA. (wrb@howdy.wustl.edu; mhi@wuphys.wustl.edu; lscott@hbar.wustl.edu)

E. R. Christian, Code SS, NASA Headquarters, Washington, DC 20546, USA. (erc@cosmicra.gsfc.nasa.gov)

A. C. Cummings, A. J. Davis, J. S. George, R. A. Leske, R. A. Mewaldt, and E. C. Stone, Space Radiation Laboratory, California Institute of Technology, Pasadena, CA 91125, USA. (ace@srl.caltech.edu; ad@aegir.srl.caltech.edu; george@aegir.srl.caltech.edu; ral@aegir.srl.caltech.edu; rmewaldt@aegir.srl.caltech.edu; ecs@aegir.srl.caltech.edu)

P. L. Hink, Burle Industries, Lancaster, PA 17601, USA. (HinkP@burle.com)

S. M. Niebur, Code SE, NASA Headquarters, Washington, DC 20546, USA. (sniebur@hq.nasa.gov)

T. T. von Rosenvinge, NASA Goddard Space Flight Center, Code 661, Greenbelt, MD 20771, USA. (tycho@milkyway.gsfc.nasa.gov)

M. E. Wiedenbeck, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA. (mark.e.wiedenbeck@jpl.nasa.gov)

N. E. Yanasak, Department of Psychology, University of Georgia, Athens, GA 30602, USA. (yanasak@srl.caltech.edu)