Ulysses HET Measurements of Electron-capture Secondary Isotopes: Testing the Role of Cosmic Ray Reacceleration

J. J. Connell[1] and J. A. Simpson[1,2]
[1] *Laboratory for Astrophysics and Space Research, The Enico Fermi Institute, The University of Chicago, Chicago, IL 60610, USA*
[2] *Also Department of Physics, The University of Chicago*

Abstract

In recent publications, we have reported consistent cosmic ray Galactic confinement times from *Ulysses* HET measurements of ^{10}Be, ^{26}Al and ^{36}Cl. The abundances of other secondary radio-isotopes, specifically electron-capture isotopes such as ^{49}V and ^{51}Cr, are a crucial test of cosmic ray reacceleration. Reacceleration is implicit in interstellar shock or MHD acceleration models, but its significance for interstellar propagation is largely unknown. Electron-capture is suppressed during interstellar propagation. However, if cosmic rays experience significant reacceleration, nuclei will have spent time at lower energies where electron pick-up, and hence electron capture, is more likely than at higher energies. Thus, electron capture secondary isotopes would be less abundant (and their daughters, more abundant) than otherwise predicted. We show that the abundance ratio of ^{49}V to ^{51}V is a particularly sensitive test of this effect. For the first time in the literature we present evidence of reacceleration using *Ulysses* High Energy Telescope (HET) data.

1 Introduction:

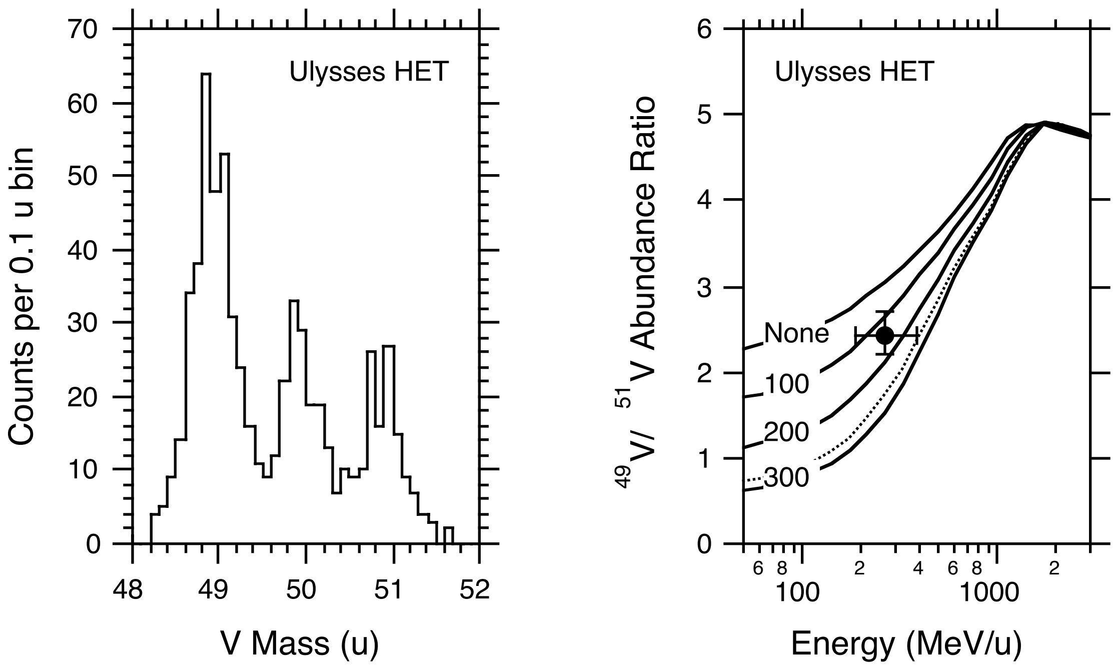
One of the most elusive questions involving cosmic ray propagation in the Galaxy is the role and significance of cosmic ray reacceleration (for early references, see Silberberg, Tsao & Shapiro 1998). If, as is generally believed, cosmic rays with energies up to at least 10^{14} eV are accelerated by supernova shocks, then reacceleration must take place. Reacceleration can also arise from interstellar turbulence (e.g. Seo & Ptuskin 1994). Whether reacceleration plays a major part in cosmic ray propagation, or is so insignificant that it can be ignored, is largely unknown. Strong reacceleration is ruled out by the decline in the primary to secondary elemental ratios at high energy (Hayakawa, 1969). Weak reacceleration is not ruled out, and could explain the decrease in the secondary to primary elemental ratios, such as B/C, at low energy (Silberberg, Tsao & Shapiro 1998). While reacceleration, as compared to otherwise more ad-hoc approaches, is theoretically more satisfying, there is no evidence in the literature to distinguish among these effects. To date, modeling efforts have been unable to break the degeneracy between reacceleration parameters and other physical parameters, often represented (but not explained) by an energy dependence in the diffusion coefficient (e.g. Strong & Moskalenko 1998) or pathlength distribution (e.g. Garcia-Munoz et al. 1987).

One crucial test of reacceleration is to measure the abundance of electron capture secondary isotopes in cosmic rays. Electron capture decay is strongly suppressed during cosmic ray propagation because the high energy nuclei are effectively stripped of their electrons. Electron capture is only possible by electron pick-up during propagation. This process is highly energy dependent, with low energy nuclei far more likely to pick-up an electron and decay than high energy nuclei (Crawford 1979). Thus, if cosmic rays experience significant reacceleration, the observed cosmic ray nuclei will have spent some time at lower energies during propagation, and electron capture isotopes will be less abundant than otherwise expected while their daughters will be correspondingly more abundant.

2 Measurements:

The *Ulysses* spacecraft (a joint NASA and ESA mission) carries the University of Chicago High Energy Telescope (HET) as part of the COsmic and Solar Particle INvestigation (COSPIN) experiment described in detail in Simpson et al. (1992). The measurements in this paper are for quiet time data over the period from launch (October 1990) to the end of 1997.

The high mass resolution measurements reported here are based on our technology of position-sensitive semi-conductor detector arrays in the HET to determine the trajectories of the cosmic rays. In brief, the HET consists of two sets of three position sensing Si detectors (PSD's) of ~1100 μm thickness arranged to determine the trajectory of incident particles. Six 5000 μm Si detectors (K's) provide mass and charge determination by the multiple dE/dx versus residual energy method for events stopping in the second through sixth K. A Si detector (A) identifies penetrating events while a scintillator shield (S) identifies side penetrating events. Consistency requirements were made on the energy loss in the PSD's (2.5 σ cut) and in the mass determinations in the K detectors (2.0 σ cut). Figure 1 (A) shows mass histograms for the vanadium isotopes. The mass resolution is σ = 0.24 amu (hereafter, u) and there are 652 events shown with an average energy of 267 MeV/u. This is the first time in the literature that the V isotopes have been clearly separated. The Cr and Ti data have similar resolution.



(A) (B)

Figure 1. (A) *Ulysses* HET mass histogram for vanadium isotopes. (B) Model predictions for the isotopic abundance ratio $^{49}V/\,^{51}V$ with no reacceleration ("None"), and with 100, 200 and 300 MeV/u "boosts" as indicated. Dotted curve is for 300 MeV/u with no adjustment to the pathlength distribution. Point with error bars is the isotopic abundance ratio derived from *Ulysses* HET data.

3 The Propagation Model:

The basic propagation model used in this paper is the weighted-slab technique detailed in Garcia-Munoz et al. (1987), as updated in DuVernois, Simpson & Thayer (1996). These model calculations include nuclear spallation, radioactive decay and ionization energy loss. Electron pick-up and electron capture decay are also incorporated in the program (Letaw, Silberberg & Tsao 1984). The pathlength distribution (PLD) is a single exponential, thus closely approximating a simple homogenous "leaky box" model. The mean of the PLD varies with energy so as to simultaneously fit the measured secondary to primary ratios of both B/C and sub-Fe/Fe over the observed energy range. The interstellar medium (ISM) is taken as 93.7% H and 6.3% He by number with an average interstellar density of 0.25 atom/cm^3 which is consistent with our ^{10}Be (Connell 1998), ^{26}Al (Simpson & Connell, 1998) and ^{36}Cl (Connell, DuVernois & Simpson 1998) measurements.

A spherically symmetric solar modulation model was applied to the resulting interstellar spectra to obtain spectra inside the heliosphere. Particular consideration (detailed in Connell 1998) was given to the wide range of solar conditions since the launch of *Ulysses*. Modulation parameters (Φ) were found by simultaneously fitting the carbon spectra from the University of Chicago instruments on IMP-8 and *Pioneer* 10.

While a variety of models for reacceleration have been proposed (e.g. Silberberg, Tsao & Shapiro 1998 and references therein), we have used the simplest possible approach to test for the effects of reacceleration. The output of the interstellar propagation model were "boosted" in energy (per nucleon) before being modulated. The pathlength was adjusted for each energy boost (100, 200 and 300 MeV/u) to match the secondary to primary ratios (B/C and sub-Fe/Fe) with no reacceleration. While this model is not physically correct, it is indicative of the significance of reacceleration. This approach may also be more intuitive for the non-specialist. It should be noted that since reacceleration takes place, in effect, only at the boundary of the solar system rather than throughout propagation, this calculation exaggerates the effect.

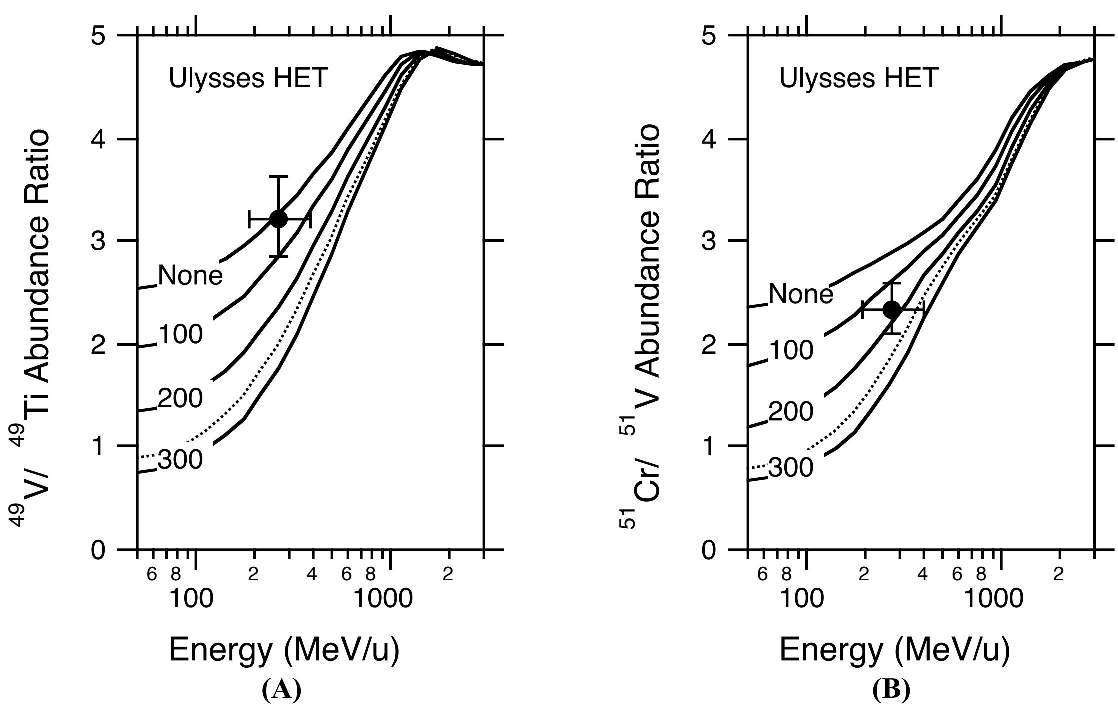


Figure 2. Model predictions for the isotopic abundance ratio ^{49}V/ ^{49}Ti (A) and ^{51}Cr/ ^{51}V (B) with no reacceleration ("None"), and with 100, 200 and 300 MeV/u "boosts" as indicated. Dotted curves are for 300 MeV/u with no adjustment to the pathlength distribution. Points with error bars are the isotopic abundance ratio derived from *Ulysses* HET data.

4 Results:

Figure 1 (B) shows the results of these propagation calculations for the $^{49}V/^{51}V$ isotopic abundance ratio. The curve marked "None" is with no reacceleration, while the curves marked 100, 200 and 300 are for calculations in which the cosmic rays are "boosted" by those energies (in MeV/u) before entering the solar system as described above. ^{49}V decays solely by electron capture to ^{49}Ti ($t_{1/2}$ = 331 d) while ^{51}V is the daughter of the electron capture nuclide ^{51}Cr ($t_{1/2}$ = 27.7 d), so this ratio is particularly sensitive to reacceleration. (Note, the half-lives quoted are for neutral atoms—for a single pick-up electron the half-lives are slightly more than twice as long.) As noted above, the pathlengths have been adjusted for each energy boost. The dotted curve shows the result with an uncorrected pathlength boosted by 300 MeV/u: the effect on the secondary to secondary $^{49}V/^{51}V$ ratio is small, even though the primary to secondary ratios (B/C and sub-Fe/Fe) are highly discrepant (~25% low at these energies) without adjusting the pathlength. The point with error bars is the ratio derived from the HET data, 2.4 ± 0.3, corrected for energy intervals in the instrument and spectral shape. Figure 2 shows similar plots for the parent to daughter isotopic abundance ratios $^{49}V/^{49}Ti$ (A) and $^{51}Cr/^{51}V$ (B). The measured ratios are 3.2 ± 0.4 and 2.3 ± 0.2 respectively. It can be seen that the results are consistent among all four isotopes. It should also be noted that the measured V/Ti and Cr/V elemental abundance ratios (not shown) are consistent with the model.

5 Conclusions:

Based on our measurements of the electron capture secondary isotopes ^{49}V and ^{51}Cr and their daughters, ^{49}Ti and ^{51}V, we conclude that weak reacceleration of galactic cosmic rays is indicated. The agreement among the four isotopes, and the consistency of the V/Ti and Cr/V elemental abundance measurements with our model, gives added confidence to this conclusion. This conclusion is relatively robust, as demonstrated by the insensitivity of these ratios to changes in pathlength distribution. Although our analysis shows evidence of reacceleration, it will be absolutely essential to study other electron capture nuclides as further tests before we can be certain of the significance of reacceleration in cosmic ray propagation. Cr, V and Ti have the advantage that they are mainly direct spallation products of ^{56}Fe, whereas many other potentially interesting electron capture isotopes (e.g. ^{37}Ar) have significant contributions from the spallation of other secondaries, thus complicating the problem of interpretation.

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