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The effect of cosmic ray energy changes in the heliosphere on K-capture secondaries

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In an accompanying paper we give a re-assessment of cosmic ray energy changes in the heliosphere to determine the effects of acceleration at the solar wind termination shock and modulation in the heliosheath beyond that. In this paper we show that these effects have important consequences for the interpretation of secondary to primary ratios of cosmic rays at energies below 1 GeV, i.e. in the region where they are strongly modulated.

1. Introduction

The energy loss of cosmic rays in the radially expanding solar wind in the heliosphere is an integral part of the cosmic ray modulation, the other three processes being diffusion, convection and drift in the solar wind and the heliospheric magnetic field (HMF). In an accompanying paper [1], henceforth called Paper 1, it is shown that in a heliosphere surrounded by a solar wind termination shock and an extended heliosheath, the net energy loss is reduced, due to the fact that the shock accelerates particles, while in the heliosheath they are modulated without energy loss.

Spectral shapes determine cosmic ray properties, but at energies < 1 GeV these spectra are modified due to modulation. Energy losses play an important part in this modification. A good example is the ratio of secondary to primary cosmic rays which reflects the propagation, nuclear fragmentation and escape from the galaxy. The effects of these processes on the spectra must be unfolded to determine the shape of the cosmic ray spectra at the source. Such processes are best studied at low energies where the counting rates are high and good statistical accuracy can be achieved. To exploit this low energy region, one must know how to accurately demodulate the spectra observed in the vicinity of Earth.

A specific case is that of K-capture cosmic ray secondaries, as recently described by [2] and [3], using the high precision ACE observations. Cosmic ray nuclei attach electrons as they move through the galaxy. Typical attachment times are 10^5 y for 10 MeV and 10^9 y for 10 GeV particles. For a radioactive isotope such as ^{51}Cr that decays by electron capture, this time is comparable with typical nuclear decay and escape lifetimes at $T < 100$ MeV, and therefore it has a reasonable chance to occur. At high energies, however, most of the ^{51}Cr fragments or escapes before this can happen. After this attachment, the nucleus decays into ^{51}V with a mean-life of 27 days, and consequently the ^{51}V/^{51}Cr ratio in interstellar space should be strongly energy dependent, being much higher at low energies. [2] and [3] have studied the energy dependence of this process as modified by cosmic ray modulation. They observed that the ^{51}V/^{51}Cr ratio is less energy dependent at solar maximum conditions than at solar minimum. The authors interpret this as a signature of higher energy loss suffered by these $A/Z = 2$ particles at solar maximum conditions (≈ 400 MeV/n), than at solar minimum (≈ 200 MeV/n). They used the solution of the one-dimensional transport equation for their calculations. However, in Paper 1 it is shown that more complete solutions produce different amounts of energy loss, and here we explore how this may affect the secondary to primary ratio.

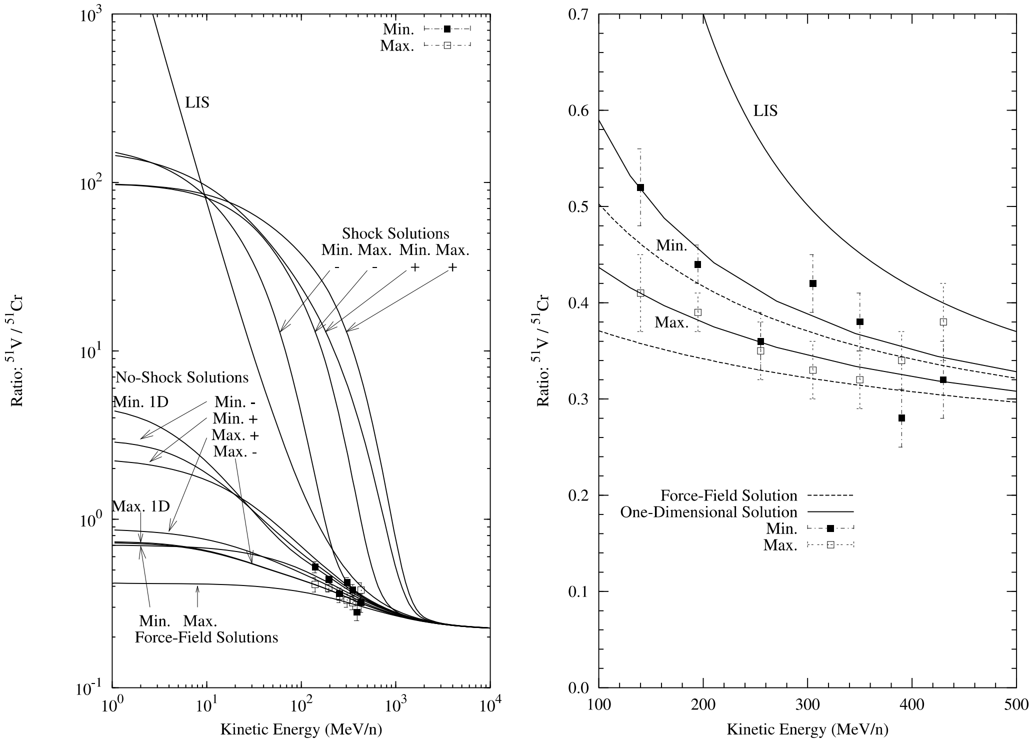

Figure 1. The ^{51}V/^{51}Cr ratio. The thick line is the interstellar ratio, and the data points the observations at 1 AU from [2]. Calculated ratios at Earth are for the Force-Field approximation, and for no-shock and shock-heliosheath models of the heliosphere, for both drift states. Typical solar minimum and solar maximum values are shown. The right panel is a zoomed version to show the observations better, together with the Force-Field, and a repeat of the one-dimensional calculations of [2] and [3].

2. Calculations

We calculate ^{51}V/^{51}Cr ratios in a variety of models for cosmic ray modulation, ranging from a simple Force-Field solution of the transport equation to one that contains drift effects in a heliosphere with a wavy neutral sheet, a termination shock where acceleration occurs, and a heliosheath that provides additional modulation.

We demonstrate the calculations with an LIS for ^{51}Cr of the form $j_{Tb} = 1.075T^{-2.8}/(1 + 3.91T^{-1.09} + 0.9T^{-2.54})$ with T in GeV/n. (This spectrum was derived by [4] for He; the precise form is not important for our demonstration calculations.) According to [2], however, the secondary ^{51}Vr LIS is much steeper, and we fit the shape of that spectrum by multiplying the ^{51}Cr spectrum with $0.22{+}0.061/T{+}0.007/T^2$ to represent the interstellar ^{51}V/^{51}Cr ratio given in their Figure 3. The results are shown in the left panel of Figure 1. The steep solid line is the fit to the Niebur *et al.* value of the ^{51}V/^{51}Cr ratio in the LIS. The two solutions marked FF near the bottom are the modulated ratios for a Force-Field solution with Force-Field potentials of 400 and 800 MV, to represent solar minimum and solar maximum conditions. The calculation is repeated for the one-

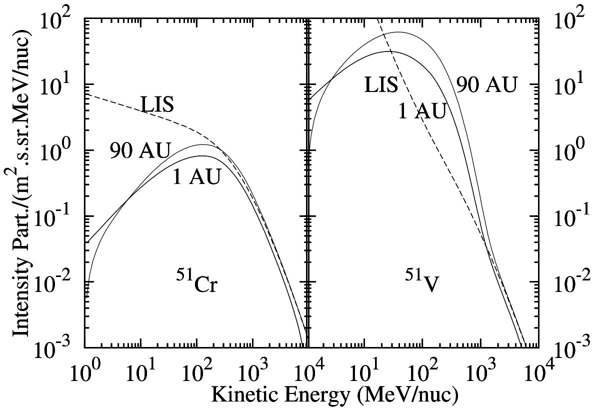

Figure 2. Spectra of ^{51}Cr and ^{51}V at 150 AU (input), at 90 AU (the termination shock) and at 1 AU (Earth), to demonstrate the very different acceleration and modulation effects on LIS inputs of different form.

dimensional steady-state solution of the transport equation with the same parameters. In this case there is less energy loss, leading to a stronger energy dependence of the ratio. These two calculations are also shown in the right panel, which is a zoomed version, in the same format as Figures 8 and 9 of Niebur *et al.* This shows that the solid-line one-dimensional solutions are the same as theirs.

Next, the calculation is repeated for the solution of the two-dimensional steady-state transport equation in the qA>0 and qA<0 drift states, once again for solar minimum and solar maximum conditions. The two solar minimum solutions are for the same parameters as the two drift solutions in Figure 2b of Paper 1 - the parameters are given there. We point out that this model does not have a termination shock and that the supersonic solar wind extends up to the modulation boundary at 150 AU. These ratios are significantly higher than those for the Force-Field and one-dimensional solutions, reflecting even smaller energy losses, as found in Paper 1. This result implies that to fit the observations, the propagation parameters and/or the interstellar input spectra must be revised.

Finally, the two drift calculations are repeated with the time-dependent shock-heliosheath model, i.e. the supersonic solar wind extends only to 90 AU where there is a strong shock, with a heliosheath beyond that up to the boundary at 150 AU. Once again, the two solar minimum solutions are the same as those in Figure 2c of Paper 1. The effect of this shock on the ratio is dramatic, and it actually increases above the LIS value for $T > 10$ MeV. This is due to very strong acceleration of the secondary ^{51}V spectrum by the termination shock (compression ratio s = 4), whereas it only has a moderate acceleration effect on the primary ^{51}Cr spectrum.

These different acceleration effects on the two spectra are demonstrated in Figure 2. The left panel shows spectra of ^{51}Cr. The dashed line is the assumed LIS ($j_{Tb} = 1.075T^{-2.8}/(1 + 3.91T^{-1.09} + 0.9T^{-2.54})$, while the other two are the spectra at 90 AU (at the shock) and at 1 AU. The same spectra are shown for ^{51}V in the right panel. There is a very large excess of ^{51}V on the shock spectrum because of the acceleration. Because of the multiplication factor of 0.22 +0.061/T+0.007/T^2 with the ^{51}Cr spectrum, this spectrum has a low energy form $j_T \propto T^{-2.26}$. According to the standard theory of shock acceleration a strong shock will accelerate such a soft spectrum to the form $T^{0.5(s+2)/(1-s)}$(T^{-1} for s = 4; $T^{-1.5}$ for s = 2.5 at non-relativistic energies). This acceleration cuts off at a maximum energy determined by the shock radius. In the present model this is at $\approx$ 100 MeV. At this point there is an extremely steep fall-off to the original LIS. The acceleration on

^{51}Cr is much less because there the low-energy limit of the LIS is $j_T \propto T^{-0.26}$. Such a hard spectrum is not significantly accelerated. This LIS is typical for primary cosmic ray species, and this is one of the reasons why [5] concluded that shock/heliosheath effects on galactic cosmic ray modulation are only moderate. The current example shows, however, that this statement is subject to the form of the LIS inputs.

The case shown here is extreme because it has the strongest possible shock (s = 4), and should not be regarded as realistic. A value of s = 2.5 may be more realistic. It is used, however, to demonstrate the extreme range of sensitivity of this ^{51}V/^{51}Cr ratio to modulation and acceleration conditions. Even if the shock does not accelerate galactic cosmic rays, the no-shock solutions show that this ratio is a sensitive diagnostic tool of the modulation/acceleration process.

3. Conclusions

The energy dependent ^{51}V/^{51}Cr ratio turns out to be sensitive to modulation and acceleration conditions in the outer heliosphere. In particular, the amount of acceleration at the solar wind termination shock has an extreme influence on this ratio.

In [5] we concluded the opposite, namely that observations at Earth are generally not sensitive to modulation and acceleration conditions in the distant heliosphere. It was found there that the modulation integral $M = \int (V dr/\kappa)$, or equivalently the Force-Field potential ϕ, which is related to M, is the most important parameter that determines the amount of modulation and spectral shapes deep inside the heliosphere. This meant that the distribution of the modulation/acceleration processes throughout the heliosphere was found not to be important, and that only the integral value matters. The current conclusion is different because of the difference in spectral shape of the secondary and primary species involved. This difference causes large differences in the amount of acceleration and modulation of these species.

The net result is that two-dimensional drift models, especially shock models, produce too little energy loss for a given amount of modulation to explain the K-capture ratios. This implies that more modulation may take place beyond the termination shock, and that interstellar spectra may be flatter below a few hundred MeV/n than currently thought. We therefore conclude that K-capture secondary cosmic rays observed at 1 AU provide an important diagnostic tool for modulation and acceleration studies of cosmic rays in the distant heliosphere, which needs to be investigated in greater detail.

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