Radial Interplanetary Mean Free Paths Inferred from Anomalous Cosmic Ray Observations in the Outer Heliosphere

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Abstract

We use two independent techniques to estimate the rigidity dependence of the interplanetary mean free path-length in the outer heliosphere in 1998: 1) inferences from gradients of anomalous cosmic rays (ACRs) between Voyagers 1 and 2 and 2) inferences from the shape of the ACR energy spectra. Both techniques indicate that the mean free path increases rapidly between $\sim$0.25 GV and 1 GV but is independent of rigidity above $\sim$1 GV, in agreement with the dependence used by Steenberg et al. (1999) to fit the 1998 ACR energy spectra using a full-drift, two-dimensional solution to the transport equation. The gradient method also yields an estimate of the magnitude of the mean free path, which is $\sim$2 $\pm$ 0.4 AU at 1.5 GV, the same as the value of 2.0 AU used by Steenberg et al. (1999). In addition, we find that the mean free path at 0.42 GV is 1.4 $\pm$ 0.8 from anisotropy measurements of 4-7.8 MeV/nuc ACR He from Voyager 1. This value is consistent with the estimate from the gradient method and from the Steenberg et al. fits. At 1.5 GV, the mean free path during the 1998 solar minimum is $\sim$10 times larger than that estimated for solar maximum in 1990, suggesting that for A$>$0, when particles drift from high to low latitudes, the radial gradient at low latitudes reflects the much smaller radial gradients theoretically expected (Zank et al. 1998) at higher latitudes.

1 Introduction:

The propagation of cosmic rays in the heliosphere is regulated by the processes of diffusion, convection, adiabatic deceleration, and drifts in the large-scale interplanetary magnetic field. The parameters for convection and adiabatic deceleration are reasonably well known, being related to the solar wind speed, which has now been measured to $\sim$60 AU as well as over the poles of the Sun. But whether drift or diffusion dominates the transport depends on the magnitude of the interplanetary mean free path (λ), which has been difficult to quantify.

At solar maximum, Stone & Cummings (1999) have argued that the drift effects are suppressed and have used a one-dimensional spherical model of particle propagation to estimate the diffusion coefficient in the outer heliosphere in the rigidity range $\sim$1.4 to 4 GV. At 1.5 GV, they find $\lambda \sim 0.15$ AU is required to explain the anomalous cosmic ray (ACR) oxygen gradient observed with instruments on the Voyager and Pioneer 10 spacecraft in 1990. This value is in excellent agreement with two theoretical models of λ (Zank et al. 1998, Bieber & Matthaeus 1997) at low latitudes ($\lesssim$30°).

For solar minimum, the quantification of λ is difficult because drift effects imply non-spherical effects and make the modelling more difficult. However, recently a new full-drift, two-dimensional study of the energy spectra of anomalous cosmic rays at Voyager 1 and 2 (V1 and V2) during 1998 at solar minimum has been undertaken by Steenberg et al. (1999). The authors could not find good fits to the data using diffusion coefficients as small as Stone & Cummings (1999) found at solar maximum. Steenberg et al. (1999) concluded that much larger values of λ were required.

2 Estimate of λ From Force-Field Model:

To estimate the interplanetary mean free path using the force-field solution, we followed the method described in Cummings & Stone (1997) in which:

$$\lambda = 3 <r><C> V/(c\beta G_r) \qquad (1)$$

where $<r>$ is the average radial position of V1 and V2 and $<C>$ is the average Compton-Getting factor for V1 and V2 energy spectra. C depends on the power-law index, γ, of the energy spectum and is given by

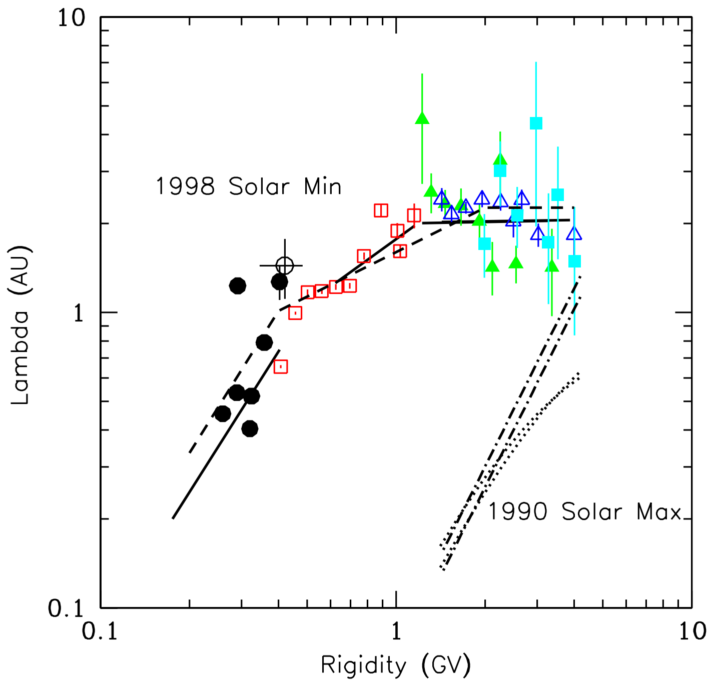

Figure 1: Estimate of the mean free path in the outer heliosphere during solar minimum in 1998 and for a solar maximum period in 1990. The open circle is from the anisotropy measurements of 4-7.8 MeV/nuc He at V1 in 1998. The remaining symbols are from the force-field technique based on the gradient of ACRs between V1 and V2 using different elements: H (solid circles), He (open squares), N (solid triangles), O (open triangles), and Ne (solid squares). The dashed line is from the fits of Steenberg et al. (1999) to the same energy spectra. The solid line segments are from the energy scaling method. The dotted curves represent the allowable range from fits to the ACR O energy spectra in the outer heliosphere in 1990, assuming λ is proportional to heliocentric radius. The dot-dash lines represent the allowable range from similar fits, except using a λ from Zank et al. (1998) which is independent of radius.

$C = (2-2\gamma)/3$. G_r is the radial gradient ($G_r = \ln(j_1/j_2)/\ln(r_1/r_2)$), determined from the V1 and V2 energy spectra in 1998 (Stone et al. 1999). We use only the observations from the Cosmic Ray experiment to minimize systematic uncertainties. V is the solar wind speed, which we took to be 500 km s^{-1}, and β is particle velocity in units of c. The average radial positions for V1 and V2 in 1998 were 70.7 and 55.2 AU, respectively.

The results are shown as the symbols in Figure 1 (except for the open circle which will be described later), representing estimates from five different ACR elemental energy spectra. Also shown for comparison in Figure 1 is the mean free path used by Steenberg et al. (1999) in fitting the same ACR energy spectra with a full-drift, two-dimensional solution to the transport equation. The λ from Steenberg et al. (1999) is in reasonable agreement with the force-field estimates, suggesting that diffusion/convection processes establish the radial intensity gradients in the outer heliosphere at solar minimum when A>0. The data indicate that λ increases rapidly from $\sim$0.25 to 1 GV but levels off at $\sim$2 AU above 1 GV.

3 Estimate of λ From Energy-Scaling of Spectra:

It is possible to deduce the power-law index α in the relation $\lambda \propto R^{\alpha}$, where R is rigidity, from the locations of the peak intensities of the ACR energy spectra as pointed out by Cummings et al. (1984) for propagation dominated by diffusion and for a power-law source energy spectrum at the shock. Steenberg (1998) found that the ACR species scaling was fairly robust and applied to solutions of the transport equation that involved self-consistent accelerated energy spectra at the shock that were not power laws and to cases where drifts were included in the solution to the transport equation.

The method is based on the energy-scaling relation:

$$f_E(Z, A) \propto (A/Z)^{-2\alpha/(\alpha+1)} \tag{2}$$

where A is the mass of the particle and Z is its charge. In the application here, we do not have the energy of the peak intensity in all the elemental spectra. However, we do find that there is enough curvature to the observed energy spectra in 1998 to yield reasonably well-defined energy scaling factors between elemental spectra.

We have determined four values of α in four rigidity ranges by fitting the energy spectra of ACRs sequentially. For example, we fit ACR He to ACR H and obtain an energy scaling value valid over the rigidity range of the ACR He observations. Then we fit ACR N to ACR He and find another value of α valid over the rigidity range of the ACR N. We repeat this for the pairs ACR O to ACR N and ACR Ne to ACR O.

The resulting power-law segments for λ vs. rigidity are shown in Figure 1 as the solid line segments. The method does not yield the absolute magnitude of λ, so in Figure 1 we have arbitrarily positioned the segments vertically as shown. As shown in Figure 1, this method yields a rigidity dependence for λ which is consistent with the force-field method and reasonably similar to the form used by Steenberg et al. (1999) in their fits.

4 Estimate of λ From Anisotropy Measurements:

Some deviation from isotropy is expected in the ACR particle flow at and above the energy of the peak intensities, and that anisotropy is related to the radial intensity gradient and the mean free path by

$$\delta_{diff} = \lambda G_r \tag{3}$$

The diffusive portion of the anisotropy differs from the observed anisotropy because of the Compton-Getting effect: $\vec{\delta_{diff}} = \vec{\delta_{obs}} - \vec{\delta_{cg}}$. The Compton-Getting anisotropy is in the radial direction and is given by $\delta_{cg} = 3VC/(\beta c)$ where V is the solar wind speed (taken to be 500 km s^{-1}), C is the Compton-Getting factor, and β is the average particle speed in units of the speed of light c. Thus, a measurement of the anisotropy permits another estimate of the mean free path of the particles.

The Low Energy Telescope (LET) system on the Voyager 1 Cosmic Ray experiment consists of 4 identical sensors with orthogonal bore sights which permit the derivation of the first-order anisotropy, δ. In order to minimize systematic uncertainties from possible threshold differences among the telescopes, we have chosen a flat portion of the energy spectrum of ACR He in which to derive δ. The energy range is 4-7.8 MeV/nuc which encompasses the peak of the ACR He energy spectrum at V1 (Stone et al. 1999). This energy range corresponds to the rigidity range 0.35 - 0.48 GV with $< \beta >= 0.112$. For 1998, we find $\delta_{diff} = 0.061 \pm 0.014$. The overall He intensity gradient between V1 and V2 is 4.25 ± 0.05%/AU, derived at 6 MeV/nuc from Figure 3 of Stone et al. (1999). Using Eq. 3, we find $\lambda = 1.44 \pm 0.32$ AU. This point is indicated on Figure 1 as the open circle and is reasonably consistent with the other data near 0.4 GV.

5 Discussion:

Several lines of investigation now seem to converge on the rigidity dependence and magnitude of the mean free path shown in Figure 1 for 1998, which is a period of minimum solar modulation. For the previous solar maximum in $\sim$1990, Stone & Cummings (1999) found the mean free paths as a function of rigidity shown by the lower set of curves in Figure 1, which are much lower in magnitude than at solar minimum at rigidities of $\sim$1-3 GV.

In Figure 2a, we show the estimate of λ at 1.5 GV for 5 time periods from one in 1990 to the end of 1998 based on this and previous work. The increase in λ by a factor of $\sim$10 from 1990 to 1998 is unlikely to result from the $\sim$50% increase in radial positions of the spacecraft. More likely, the increased λ is associated with the increased role of drifts from higher latitude as the current sheet tilt decreases (see Figure 2b).

At solar maximum, when drift effects should be small, the radial mean free path of ∼0.15 AU at 1.5 GV agrees well with the theoretical estimates for low latitudes by Zank et al. (1998). Their model also predicts a much larger λ_{rr} at higher latitudes. For example, at latitudes above 60° they predict $\lambda_{rr} \sim 0.15$ to 5 AU at 0.445 GV depending on latitude and the correlation length associated with 2-D fluctuations in the magnetic field. The range of these theoretical estimates encompasses the estimated λ shown in Figures 1 and 2 for solar minimum conditions at lower latitudes. This suggests that during periods of reduced current sheet tilt ($\lesssim$35°) with A>0 when particles drift from high to low latitudes, the radial gradients at low latitudes reflect the smaller radial gradients predicted for higher latitudes. When the current sheet tilt is large during solar maximum, drifts are inhibited and the radial gradients at low latitudes would be much larger, reflecting the much shorter mean free paths at low latitudes. This and other possible explanations for the inferred changes in λ during the solar cycle should be investigated with 2-dimensional drift models.

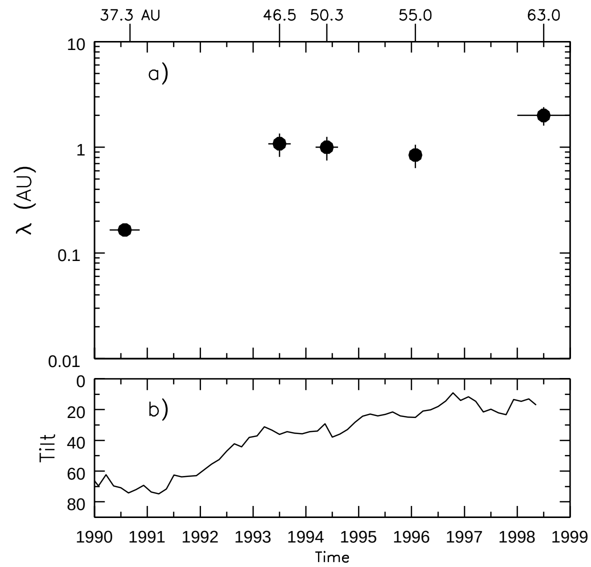

Figure 2: a) Estimated mean free path at 1.5 GV for 5 periods between solar maximum in 1990 and the end of 1998. The point in 1990 is from Stone & Cummings (1999). The points in 1993, 1994, and 1996 are from Cummings & Stone (1997). The point for 1998 is from this work. The average mid-point radial position between V1 and V2 for each period is indicated at the top of the figure. b) Tilt angles (line-of-sight method) of the heliospheric current sheet from the Wilcox Solar Observatory shifted to the mid-point of V1 and V2 using measured V2 solar wind velocities (Richardson, private communication).

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