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Estimating Characteristics of the Heliosphere Using Anomalous Cosmic Ray Observations at Solar Maximum

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Abstract. Observations of the energy spectra of anomalous cosmic ray (ACR) oxygen were acquired in the outer heliosphere during the last solar maximum period in 1990 when the particle distributions are expected to be more nearly spherically symmetric than at solar minimum. Hence, we use a simple one-dimensional model of ACR acceleration and transport to fit the observed energy spectra at Voyagers 1 and 2 and Pioneer 10. The inferred interplanetary radial diffusion coefficient is remarkably consistent with recent theoretical estimates. The next solar maximum is expected to occur in the outer heliosphere in early 2001 when Voyager 1 will be ~80 AU from the Sun. We predict that the intensity of ACR oxygen and helium at Voyagers 1 and 2 will be sufficiently large, and the model uncertainties sufficiently small, that it should be possible in 2001 to determine the remaining distance to the shock to within ±1 AU if the shock is within ~5 AU, -3 to +6 AU if the shock is within ~15 AU, and -5 to +14 AU if the shock is within ~25 AU.

INTRODUCTION

Over the last several years it has been well-established that anomalous cosmic rays (ACRs) originate as interstellar neutral gas (5), which becomes ionized in the heliosphere, is swept up by the expanding solar wind, and accelerated at the solar wind termination shock (9). Because their source is at the solar wind termination shock and because they are strongly affected by interplanetary conditions (4, 8), ACRs represent an ideal tool to investigate characteristics of the heliosphere, such as the location of the shock, the strength of the shock, and the interplanetary diffusion coefficient.

At solar minimum, such studies require 2 or 3-dimensional models of cosmic ray transport that include gradient and curvature drifts. However, the complex magnetic topology at solar maximum disrupts large scale drifts, permitting the use of a simpler, spherically-symmetric model for transport.

In this paper, we predict the ACR energy spectra that will be observed by Voyagers 1 and 2 (V1 and V2) at the next solar maximum in 2001, using a simple one-dimensional model of ACR acceleration and transport (10) that is fit to the energy spectra of ACR O collected during the last solar maximum period in the outer heliosphere.

THE MODEL

The steady state model for the combined acceleration and modulation of ACRs is described in (10) and (7). In this one-dimensional model, the radial gradients depend on the interplanetary mean free path, about which little is known observationally in the outer heliosphere. Recently, the radial and rigidity dependence of the mean free path has been addressed theoretically (1, 12).

In order to bound the problem, we have selected two forms for the mean free path, one proportional to radial distance from (1) and one independent of radius from (12), which is based on their fully-driven formulation referred to in their paper as the "NP1" model. We refer to the diffusion coefficient from (1) as the "KAP1" model, where the "1" refers to the power-law index of the radial variation. The radially independent NP1 diffusion coefficient from (12) will be referred to as "KAP0". The KAP1 form is given by:

$$\kappa = \frac{\kappa_0 \beta r \kappa_S R^2}{1+(\kappa_S R)^2}\ \ \mathrm{cm^2 s^{-1}} \quad (\mathrm{r} \gg 1\ \mathrm{AU}) \qquad (1)$$

where $\kappa_0 = 1.13 \times 10^{21}$, κ_S is a scaling factor, β is particle speed in units of c, and R is rigidity in GV. This form for the radial and rigidity dependence of κ can be derived from the quasilinear formulation of the perpendicular diffusion coefficient from (1) and (2) in which $\lambda_\perp = R_L\Omega\tau/(1+\Omega^2\tau^2)$, where R_L is the Larmour radius ($\propto R/B_0$), Ω the gyrofrequency, τ the scattering time, and $\Omega\tau = [(2R_L)/(3\lambda_c)](B_0^2/\delta B_x^2)$. Following (1), we assume that the coherence length of the magnetic field scales as

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r ($\lambda_c \propto r$), that the root mean square field fluctuations are proportional to the mean field ($\delta B_x^2 \propto B_0^2$), and that $B_0 \propto r^{-1}$ for $r \gg 1$ AU. Since we are using only energy spectra measured beyond 32.5 AU in this analysis, where the diffusion perpendicular to the interplanetary magnetic field is expected to dominate the diffusion parallel to the field, we equate the radial diffusion coefficient with the perpendicular diffusion coefficient.

In the case of the KAP0 diffusion coefficient, (12) show that λ_{rr} beyond about 20 AU is approximately independent of radius and proportional to the square of the rigidity. Accordingly, for KAP0 we use a diffusion coefficient of the form:

$$\kappa = \kappa_0 \beta R^2 \ \ \mathrm{cm^2 s^{-1}} \quad (r \gg 1 \text{ AU}) \qquad (2)$$

There are four free parameters in the KAP1 and KAP0 models: the shock location (r_{TS}), the diffusion coefficient scaling factor (κ_S for KAP1 and κ_0 for KAP0), the shock strength (s), and the intensity scaling factor (j_0) of the ACR O shock spectrum. We assume the solar wind velocity, V, is constant at 435 km $\mathrm{s^{-1}}$, the approximate average value at V2 for 1990/105-313 [*Richardson*, private communication, 1995].

FITS TO THE THE MODEL

The code that calculates the energy spectra at the three spacecraft is put into a loop and parameters are varied until a best-fit is determined. In addition, the confidence limits on each parameter are determined by iteratively changing and fixing the value of one parameter and re-fitting until we find the value of the parameter where χ^2 had increased by 1 (see (11), pp.551-553).

Since the shock location was a poorly determined parameter in the fits to the ACR O energy spectra of 1990/105-313 for either choice of the interplanetary mean free path, we fixed the shock location at several values ranging from 80 to 120 AU. Example fits for these two extremes are shown in Figure 1 for the KAP1 model. The fits using the KAP0 model were similar. The average heliocentric radial positions of the V1, V2, and P10 spacecraft for the data of Figure 1 are 42.0, 32.5, and 49.6 AU, respectively. The heliographic latitudes of the three spacecraft are 31.1° N, 0°, and 3.3° N, respectively, for V1, V2, and P10. However, the latitudinal information is not used in the fits because of the assumption of spherical symmetry.

The radial mean free path derived from parameters of the fits in Figure 1 (KAP1 model) for a radial position of 40 AU (the approximate average location of V1, V2, and P10) is shown as a function of rigidity in Figure 2a along with the theoretical estimate from (1). The agreement between the ACR determinations of λ_{rr} and the theoretical

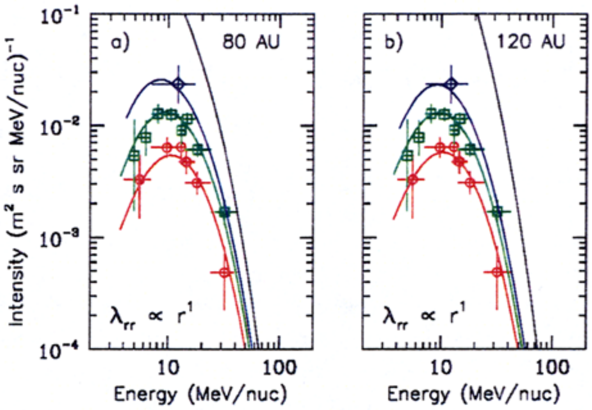

FIGURE 1. a) Model fit to ACR O energy spectra for 1990/105-313 from V2 (open circles), V1 (open squares), and P10 (open diamond) for a shock location of 80 AU using the KAP1 form of the diffusion coefficient (Eq. 1). The χ^2 of the fit is 6.0. b) Same as a) except for a shock location of 120 AU. The χ^2 is 5.4.

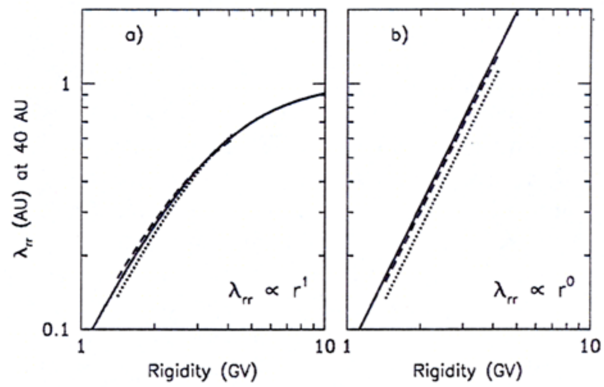

FIGURE 2. a) Radial mean free path at 40 AU vs. rigidity from the parameters of the model fits shown in Figures 1a (dotted line) and 1b (dashed line), respectively. The solid line is the mean free path at 40 AU using the quasilinear theory parameters in (1). b) Same as a) except using the KAP0 form of the diffusion coefficient. The solid line is the mean free path at 40 AU from the NP1 model of (12).

estimate of (1) is excellent. The radial gradient in intensities between the spacecraft sets the magnitude of λ_{rr} and hence it is relatively insensitive to the shock location. For the KAP0 model, a similar comparison of the best-fit mean free paths for the 80 AU and 120 AU fits and the NP1 model of (12) shows similar agreement as shown in Figure 2b.

Using the parameters of the model fits for a shock location of 120 AU for the KAP1 model (Figure 1b) and for the KAP0 model, we have calculated the radial dependence of the intensity of ACR O with energies 7.1-17.1 MeV/nuc. This dependence is shown in Figure 3. We have plotted the curves only at distances greater than 20

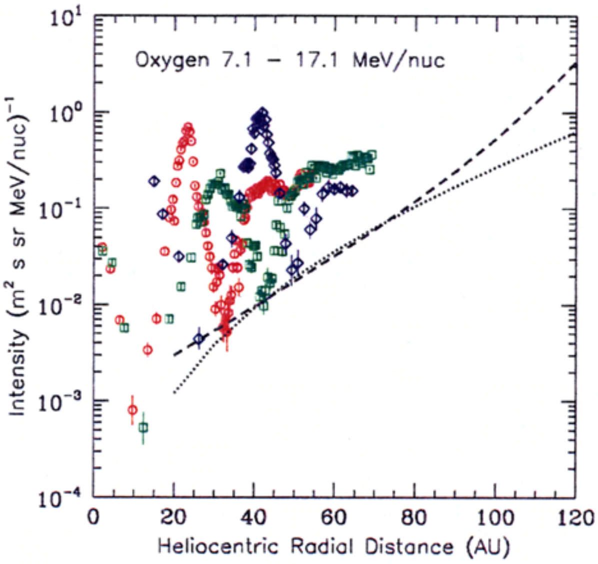

FIGURE 3. Intensity of ACR oxygen with 7.1-17.1 MeV/nuc vs. heliocentric radial distance. Open circles are from V2, open squares from V1, and open diamonds are from P10. The dotted and dashed lines represent radial dependences from the parameters of the model fits for solar maximum using the KAP1 diffusion coefficient (Figure 1b) and the KAP0 diffusion coefficient, respectively.

AU, because the forms we have used for the interplanetary mean free path are valid only in the outer heliosphere.

PREDICTIONS FOR 2001

Predicted Spectra of ACR O, He, and H

Although the location of the shock is not well-determined from the fits to the 1990 energy spectra of ACR O, the situation at the next solar maximum in 2001, when V1 will be at ~80 AU, should be greatly improved because the intensities are expected to increase as the spacecraft moves closer to the shock (see Figure 3).

The predicted energy spectra of ACR O at V1 in 2001 are shown in Figure 4 for various possible shock locations between 80 and 120 AU. Also shown for reference are the energy spectra measured during the present solar minimum period and during the last solar maximum period. The energy spectrum is expected to be at least a factor of 10 larger in intensity than observed during the last solar maximum and may approach within a factor of ~2 of the intensity level of the current solar minimum. The unrolling of the energy spectrum at low energies as the spacecraft to shock distance decreases is evident in Figure 4. However, because the observations will extend

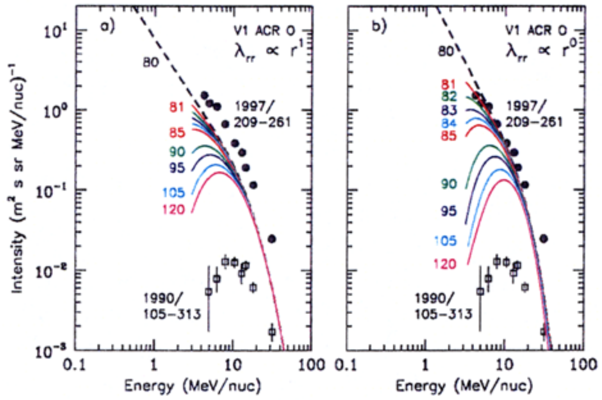

FIGURE 4. a) Predicted V1 energy spectra of ACR O at the next solar maximum in 2001 for various shock locations using the parameters from model fits that used the KAP1 form of the diffusion coefficient (Eq. 1). The dashed line shows the spectrum if the shock is located at the position of V1 in 2001 (80 AU). The solid lines are labeled with the shock location in AU. The three unlabeled lines between 81 and 85 AU are each 1 AU apart. The solid circles show the energy spectrum of ACR O at V1 for 1997/209-261. The open squares show the energy spectrum for 1990/105-313, the last solar maximum period. b) Same as a) except for the KAP0 form of the diffusion coefficient.

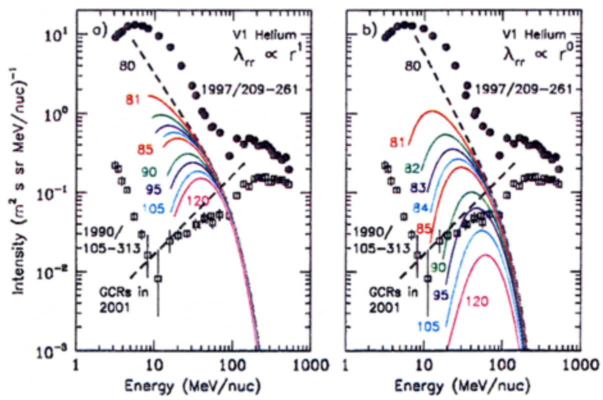

FIGURE 5. a) Same as Figure 4a except for helium. The dashed line shows the expected GCR intensity in 2001. b) Same as a) except for the KAP0 form of the diffusion coefficient.

down to only ~4 MeV/nuc, it may be difficult to use the shape of the ACR O spectrum as an indicator of shock proximity.

A much better opportunity may be afforded by using the observed helium spectrum at V1 in 2001. In Figure 5 we show the predicted V1 ACR He energy spectra in 2001 for shock locations between 80 and 120 AU. We used the mean free path from the fits to the 1990/105-313 ACR O energy spectra and scaled the O intensity by the factor 13.3 in accordance with the ACR composition results in (3). To estimate the GCR energy spectrum in 2001 we estimated the radial gradient between 40 and 80

AU at 2%/AU from Figure 7 of (6). We applied this gradient to the 1990/105-313 V1 observed He energy spectrum at 42 AU to estimate the expected He spectrum in 2001 at 80 AU. We then approximated the 10 to 100 MeV/nuc portion of the energy spectrum by $j_{He} = 1.67 \times 10^{-3}E$ where E is energy per nucleon. This curve is shown as the dashed line in Figure 5.

Whereas there were no significant contributions of ACR He in the observed He energy spectrum during the last solar maximum in 1990/105-313 at V1, if the diffusion is governed by the KAP1 diffusion coefficient, ACRs should be dominant below ~50 MeV/nuc in 2001, even if the shock is 40 AU from V1. The changing shape of the calculated energy spectrum as a function of distance to the shock shown in Figures 4 and 5 will be used below to establish shock distance indicator parameters.

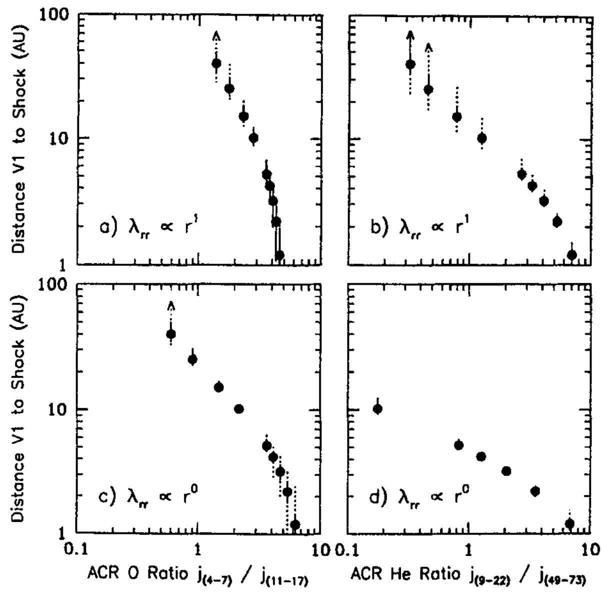

FIGURE 6. a) Estimated distance to the shock from V1 in 2001 as a function of the ACR O intensity ratio using the KAP1 form of the diffusion coefficient. Statistical uncertainties are shown as the solid lines and modeling uncertainties are shown as the dotted lines. b) Same as a) except for ACR He. c) Same as a) except for the KAP0 form of the diffusion coefficient. d) Same as c) except for ACR He.

Distance to the Shock

To form a shock distance indicator parameter based on an observable, we use the ratio of intensities in two energy intervals from the calculated ACR He and ACR O spectra. The two energy intervals are 9-22 MeV/nuc and 49-73 MeV/nuc for He and 4-7 MeV/nuc and 11-17 MeV/nuc for O.

Figure 6 shows the estimated shock locations as a function of the intensity ratios for both ACR He and ACR O for both forms of the diffusion coefficient. Both statistical and modeling uncertainties are shown for each point. It should be possible to use the intensity gradients between V1 and V2 in 2001 to determine which of the diffusion coefficient models best fits the data. If the shock is within ~25 AU of V1 in 2001, i.e., located at $\leq$105 AU, the intensity ratio should indicate that distance. The determination is to less than $\pm$1 AU if the shock is within ~5 AU, -3 to +6 AU if the shock is within ~15 AU, and -5 to +14 AU if the shock is within ~25 AU.

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