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Evolution of the Energy Spectra of Anomalous Cosmic Rays in the Outer Heliosphere and the Distance to the Solar Wind Termination Shock

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Abstract

Using data from the Voyager 1 and 2 (V1 and V2) spacecraft, we examine the energy spectra of anomalous cosmic rays (ACRs) for three time periods in 1993 - 1994. We use a spherically-symmetric model of the propagation of ACRs in the heliosphere to derive the energy spectrum of ACRs at the solar wind termination shock and the shock's location. We find that in late 1994 the shock strength has a value of 2.40 ± 0.12 and is located at 84.2 (-2.2, +2.6) AU.

1. Introduction

Anomalous cosmic rays (ACRs) are thought to be accelerated from a pool of pick-up ions at the solar wind termination shock [1]. The pick-up ions [2,3] originated as interstellar neutrals [4] which flow into the heliosphere before becoming ionized in the interplanetary medium. Recently, a study of their gradients has suggested that the solar wind termination shock was at 67 ± 5 AU in 1987 during the last period of minimum solar activity [5]. Other recent estimates of the location of the termination shock based on dynamic pressure balance [6,7,8,9], hydrogen Lyman-α resonant scattering [10], and kilohertz radio emissions [11,12] range from 60 to 105 AU.

Cummings et al. [5] based their estimate of the location of the termination shock in 1987 on a model in which positive particles were drifting into the inner heliosphere along the Sun's neutral sheet. During the current segment of the solar cycle, after the solar magnetic field reversed in 1990, the ACR particles are expected to drift downward onto the heliographic equator from the polar regions [13]. The cosmic ray intensity is expected to be less responsive to the changes in the tilt angle than in the $qA < 0$ period [14], and hence we do not use the same technique of extrapolation to the shock that was employed for the 1987 data.

In the current study we have used another technique, similar to that used by [15], for estimating the energy spectrum of ACRs at the solar wind termination shock and its location that is valid for ~1993 onward during periods without large transient disturbances. We employ a spherically-symmetric model of solar modulation to fit the energy spectra at V1 and V2.

2. Observations

In a companion paper [16] we show the evolution of the He energy spectra at V1 during 1992 - 1994. We also show the latitudinal and radial gradients of ACR He with energies ~10-22 MeV/nuc during that time interval. We find that the intensity gradient between V1 and V2 has a steady mean value but exhibits substantial deviations from the mean due to transient disturbances (see [16]). In this paper we will derive the shock spectrum and the location of the shock by making fits to the V1 and V2 ACR energy spectra with a spherically-symmetric model of the propagation of these particles. This implies that: 1) we need to pick time periods that are not affected by transient disturbances so that the V1/V2 intensity gradient is close to the mean value and 2) we must correct for the small latitudinal gradients so that a spherically-symmetric model is appropriate.

The small positive latitudinal gradient, 0.77%/deg [16], means that the spectrum observed out of the heliographic equatorial plane at a given radius corresponds to that which would be observed at a somewhat larger "effective radius" in the equatorial plane. We use the following equation to estimate the effective location of a particular spacecraft:

$$\ln(r') - \ln(r) = \frac{G_\Theta \Theta}{G_0} \qquad (1)$$

where r' is the effective location, r is the actual location, G_Θ is the average latitudinal gradient, Θ is the average latitude of the spacecraft, and where we have used a model in which the radial gradient in the flux f is proportional to 1/r, with $G_r \propto (1/f)(\partial f/\partial r) = G_0/r$. In this work we assume the particle distributions are symmetrical about the heliographic equator [17], so we use the absolute value of the spacecraft latitude in all cases.

The most recent 52-day period for which the V1/V2 gradient is close to the mean value (~5.3 %/AU) is 1994/157-209 and the energy spectra of ACR He at V1 and V2 for this period are shown in Figure 1, along with model calculations. The model assumes that the diffusion coefficient is proportional to r and also to $\beta R^{1.8}$, where r is heliocentric radial distance, β is particle velocity, and R is rigidity. The rigidity dependence is inferred from studies of the composition of ACRs [18]. There are four free parameters in the model: the shock location (R_S), a scaling factor (K_0) for the ratio of diffusion coefficient to solar wind velocity, the power-law index (γ) of

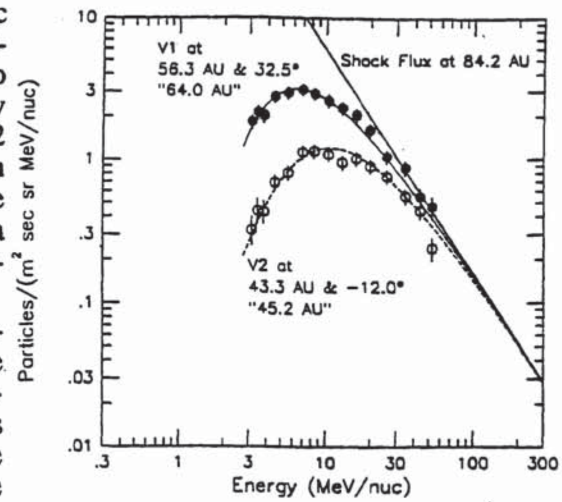

Figure 1. Energy spectra of ACR He at the positions of V1 and V2 spacecraft for the period 1994/157-209. The positions of the spacecraft are shown along with the effective radial locations (in quotes) appropriate for use with a spherically-symmetric model. The curves represent the 4-parameter best-fit energy spectra at the solar wind termination shock, V1, and V2, as described in the text.

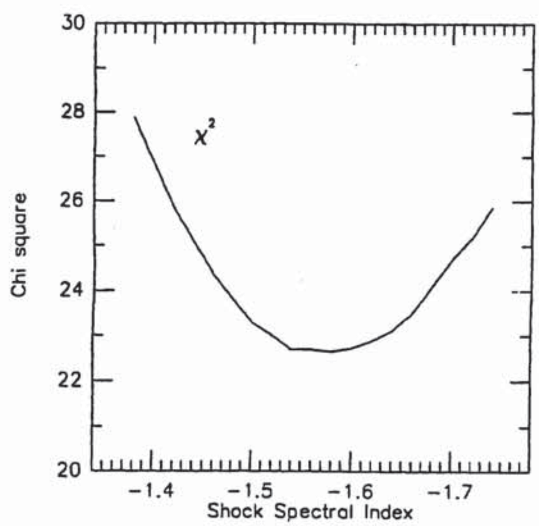

Figure 2. χ^2 versus power-law index of the energy spectrum at the shock.

the energy spectrum at the shock, and the flux scaling factor (A) of the shock spectrum. The χ^2 of the four-parameter best fit to the 30 data points in Figure 1 is 22.6.

We investigated the range of variation for the spectral index parameter, γ, by performing 3-parameter fits at fixed values of γ. Figure 2 shows a plot of χ^2 versus γ. The best-fit value is -1.57 ± 0.09. The shock strength (see, e.g., [19]), s, is related to the spectral index by: $s = (2\gamma-2)/(2\gamma+1)$ where the shock flux is given by $dJ/dT = AT^{\gamma}$, and T is energy/nuc. The inferred strength of the shock is 2.40 ± 0.12. The shock is therefore not a strong shock ($s = 4$; $\gamma \doteq -1$) and it may be modified by cosmic rays. We estimate that the shock location is 84.2 (-2.2, +2.6) AU during this period.

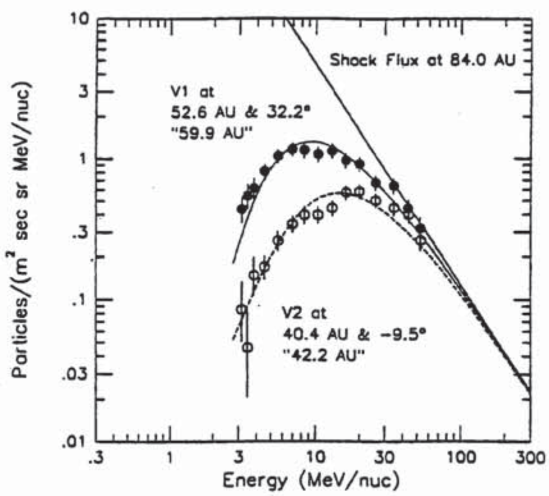

Figure 3. Same as Figure 1 except for the period 1993/157-209 and the shock power-law spectral index is fixed at -1.57.

One year earlier is another 52-day period which has a V1/V2 intensity gradient for He at 10-22 MeV/nuc which is also near the mean value and is therefore likely free of transient effects. In Figure 3 we show the ACR He spectra at V1 and V2 for this period along with a 3-parameter model fit. We held the shock spectral index fixed at -1.57. The fit indicates that the shock distance has not changed appreciably over the year despite the fact that the peak intensity at V1 has increased by a factor of ~3. This intensity increase is apparently due to a combination of three effects: 1) V1 and V2 have moved closer to the shock, effectively 4 AU closer for V1, 2) the ratio of the diffusion coefficient to solar wind velocity has increased by ~40%, and 3) the best-fit shock flux scaling parameter increased by ~25%.

The V1 ACR He composite energy spectrum for the period 1994/157-365 [18] was formed by shifting the energy spectra of ACR H, N, O, and Ne to represent ACR He by using appropriate scaling factors in energy and intensity. This method is used in deriving the composition of the parent interstellar neutral gas and it also has the advantage of extending the effective energy spectrum of ACR He to a much larger energy range, ~1.2 to 200 MeV/nuc. This V1 composite energy spectrum is reproduced in Figure 4, along with a similarly-produced energy spectrum for V2 and a 4-parameter model fit. The best-fit spectral index and shock location were -1.54 and 85.5 AU, very similar to the values we derived for 1994/157-209. The fits were performed only over the energy range ~3 to 85 MeV/nuc. At low energies, the points are ACR H scaled to He and indicate that the rigidity dependence of the diffusion coefficient may be departing at rigidities below ~300 MV from the power law we assumed. Above ~85 MeV/nuc, the spectra of V1 and V2 converge and drop below the approximate power law they exhibit in the 20-80 MeV/nuc energy range. The convergence of the spectra indicates that there is little modulation above ~85 MeV/nuc and at those energies we are observing the actual shock spectrum. The rolloff or break in the energy spectrum above ~85 MeV/nuc is consistent with that expected in diffusive shock acceleration if the shock has a finite radius of curvature. Such a rolloff is predicted to occur when VR_S/K is of order unity (see, e.g, [19]), where V is the solar wind velocity, K is the diffusion coefficient in the vicinity of the shock, and R_S is the shock radius.

3. Discussion

We will continue to monitor the evolution of the energy spectra of ACRs at V1 and V2 and look for further clues to the strength of the shock and its location. The energy of the peak intensity should continue to decrease as the spacecraft approaches the shock. As the modulation lessens, the convergence of the V1 and V2 spectra should continue to lower energies and we will obtain a better estimate of the shock spectrum spectral index. As solar activity increases from the solar minimum conditions in 1998, the shock may move rapidly inward from its position at ~84 AU (see, e.g., [8]) and perhaps "overrun" the positions of the V1 and P10 spacecraft, which will both be at ~72 AU, some 5 AU beyond the estimated location of the shock 11 years earlier [5].

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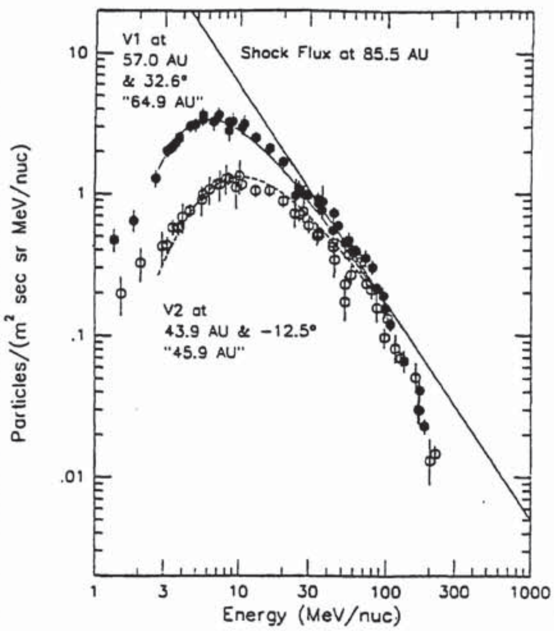

Figure 4. Same as Figure 1 except for period 1994/157-365 and the fit is to the composite energy spectra formed from ACR He and other ACR elements as described in the text.

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