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Drift Calculations on the Modulation of Anomalous Cosmic Rays During the 1998 Solar Minimum Period

C.D. Steenberg, A.C. Cummings, and E.C. Stone
Space Radiation Laboratory, California Institute of Technology, Pasadena, CA 91125, USA

Abstract

We present full-drift solutions of the two-dimensional cosmic ray transport equation in an ongoing study to explain ACR observations made in the outer heliosphere. Calculated spectra are compared to 1998 ACR H, He, O, N, and Ne observations from Voyager 1 and 2. It is found that the modulation is dominated by diffusion at the spacecraft positions and that the spectra of all the above species can be reasonably explained using a single set of modulation parameters. These include diffusion mean free paths with a magnitude significantly smaller at the shock than at the spacecraft positions.

1 Introduction:

The Voyager 1 and 2 deep space probes continue to provide differential energy spectra of anomalous and galactic cosmic rays of different species. The extreme radial distances (70 AU and 55 AU in 1998, respectively) at which these observations were made provide an opportunity to probe the structure and modulation conditions in the outer heliosphere.

The experimental effort must, however, be matched by a theoretical effort to extract the maximum scientific benefit from the observations. In this contribution we will make use of numerical solutions of the cosmic ray transport equation (TPE) to look for a set of modulation parameters that can explain the observations.

2 Observations

We make use of the H, He, O, N, and Ne spectra for the whole of 1998 that are discussed in more detail in a companion article by Stone et al. (1999). In this period, V1 was at an average position of 70 AU, 34° N, while V2 was at 55 AU, -19° S (heliographic coordinates).

The observations clearly show the dominance of ACRs at low energies and GCRs at high energies. In the cases of H, He, and O, the ACR spectral peaks are clearly resolved at ≈ 32, ≈ 5.5, and ≈ 1.2 MeV/nuc, respectively, while the N and Ne data do not extend to low enough energies to resolve the peaks.

A prominent feature of this solar minimum period is the very small ACR radial gradients of $\approx 2\%$/AU, calculated by assuming a latitudinal gradient of 1.5%/AU. More refined calculations of the 1998 gradients will be shown in the results section.

3 The Model

The Steenkamp (1995) modulation model solves the cosmic ray transport equation in an axisymmetric spherical heliosphere with a simulated neutral sheet, tilted by 10° in this case. A Jokipii & Kóta (1989) modified Parker spiral magnetic field, with a magnitude of $B_e = 5$ nT at earth was specified. Shock spectra are self-consistently generated at a discontinuous, strong (compression ratio $s = 4$) shock placed at $r_s = 90$ AU, while a modulation boundary was placed at $r_b = 120$ AU. A polar (θ) grid interval of 3° was used, assuming latitudinal symmetry around the equatorial plane. A radial (r) grid of 140 intervals was used, with the interval varying between a minimum of 0.01 AU at the shock, and a maximum of 4 AU for the interval just inside the boundary, r_b.

A rigidity grid of 264 logarithmically-spaced intervals was used for all 5 singly charged species. Since the rigidity ranges covered by the observations vary between species, slightly different upper and lower limits were used for their respective rigidity grids. In the case of H, the range is $0.09 \leq P \leq 4$ GV; for the other species the range is $0.19 \leq P \leq 10$ GV. A source of particles of arbitrary magnitude was injected at r_s at a rigidity of 0.1 GV in the case of H, and 0.2 GV for the other species. The magnitude of the source controls the vertical normalization of each solution, or the particle abundance of the species.

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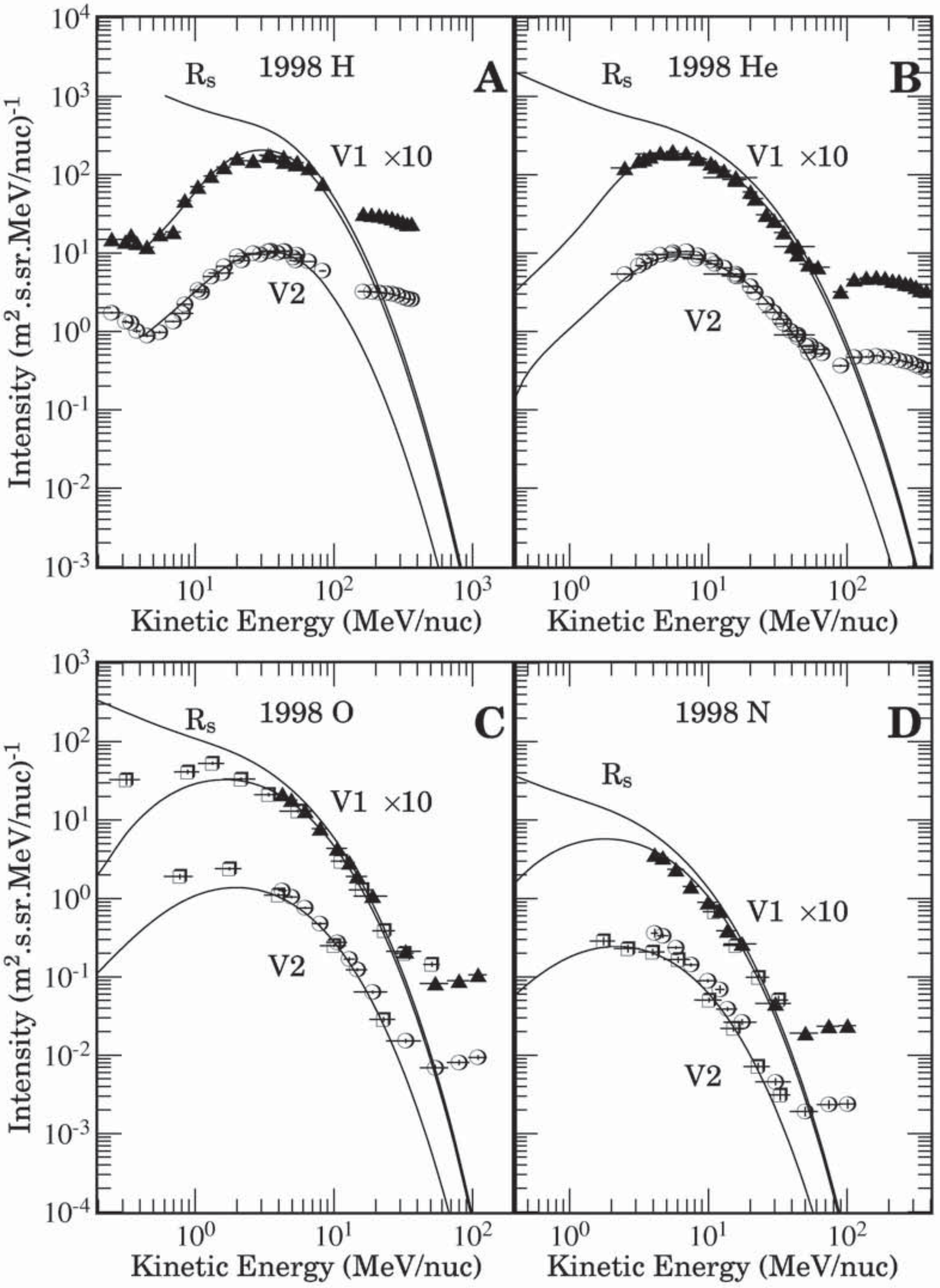

Figure 1: Observed ACR and GCR (points) and calculated singly charged (lines) Voyager 1 and 2 He, H, O, and N spectra. Open squares (N,O) are from LECP, other points are from CRS. The shock spectrum at $r_s = 90$ AU at the latitude of V1 is also shown for each species. The Voyager 1 and shock spectra are shifted upward by a factor of 10.

Steenberg (1998) and Moraal et al. (1998) determined that the peak energy of modulated ACR spectra is primarily determined by the energy of the cutoff from a power law form of the accelerated shock spectrum. This cutoff occurs at the energy where $\kappa_{rr(shock)} \approx 10V_s r_s$, with V_s the solar wind speed at the shock, and $\kappa_{rr(shock)}$ the radial diffusion coefficient at the shock. In this study we used a solar wind speed of 400 km.s^{-1} in the ecliptic, increasing to 800 km.s^{-1} over the poles.

Fitting the radial gradients between 55 AU and 70 AU required the magnitude of $\lambda_{rr} = 3\kappa_{rr}/v$, with v denoting particle speed, to be 1.6 AU at 1 GV. If this value was used at the shock, however, it resulted in accelerated spectra with a cutoff at energies below what is required to fit the data.

For this reason a radial form of λ_{rr} was used which, at 1 GV, had the value 1.60 AU for $r \leq 80$ AU, and 0.40 AU for $80 < r \leq 90$ AU. The radial independence of λ_{rr} for $r < 80$ AU is motivated by recent theoretical results of Zank et al. (1998). They showed that for several different diffusion models, λ_{rr} should increase slowly with r in the outer heliosphere. These results also indicate that the magnitude of λ_{rr} may be substantially larger than 1 AU at a rigidity of 445 MV. The decrease in λ_{rr} near the shock could be the result of increased turbulence in the upstream region close to the shock, although this has not been observed.

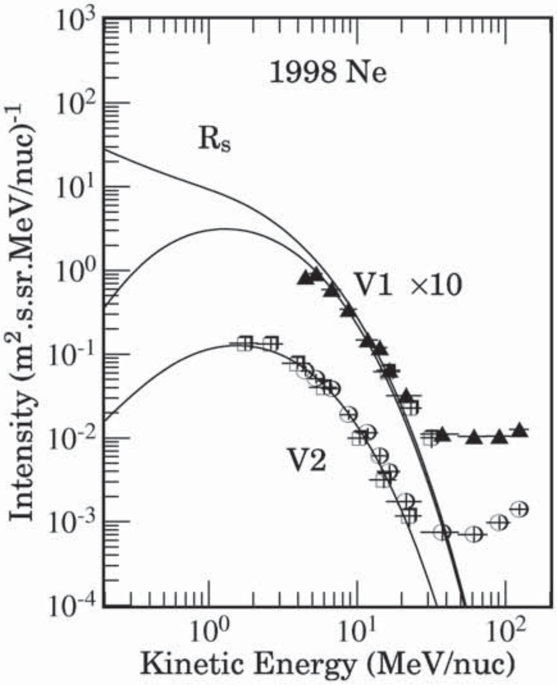

Figure 2: ACR Ne observations and calculated spectra in the same format as Figure 1.

The value of $\lambda_{\theta\theta}$ was set equal to λ_{rr} everywhere, with both of these parameters given a latitudinal dependence identical to that of the solar wind. A model time of 4.8 years, divided in 8000 equal steps was used, resulting in a saturated time-asymptotic solution. The rigidity dependence of the diffusion parameters are $\lambda_{rr,\theta\theta} \propto P^{1.6}$ for $P \leq 0.4$ GV, $\lambda_{rr,\theta\theta} \propto P^{0.5}$ for $0.4 < P \leq 2.0$ GV, and $\lambda_{rr,\theta\theta} \propto P^0$ for $P > 2.0$ GV. The constraint on these rigidity dependences is the species scaling, or relative energies of the modulated ACR spectral peaks (see also Steenberg & Moraal, 1997). The magnitude and rigidity dependence of λ_{rr} at different rigidities are consistent with results obtained by Cummings & Stone (1999) with the same data, using a force-field model, species scaling, and anisotropy measurements.

Using the above diffusion parameters, the solution of the TPE is dominated by diffusion, with $\lambda_{rr,\theta\theta}$ always larger than the drift element of the diffusion tensor, $\lambda_T = P/Bc$, with P particle rigidity, B the magnetic field, and c the speed of light. Drift effects are largest at the shock, in the ecliptic plane, and over the poles, where drift speeds are large.

4 Results

ACR spectra calculated using the model and parameters above are presented in Figures 1 (He, H, O, and N) and 2 (Ne). To first order, the calculated spectra provide a good description of the ACR observations. At sufficiently high energies the contribution of GCRs becomes noticeable, increasing the observed intensities significantly above the calculated ACR spectra, as is expected. The biggest difference between the calculated and observed spectra can be found in ACR O (panel C of Figure 1), where the calculated spectra are up to 50% below the LECP data points at the spectral peaks.

Taking ACR O (panel C, Figure 1) as an example, we find that the latitudinal gradients between 0° and 30° at 70 AU is 2.0%/deg (1.6%/AU) and 0.64%/deg (0.67%/AU) at 55 AU for 10 MeV/nuc particles. That is, for energies above the ACR O spectral peak, the latitudinal gradient is positive in the outer heliosphere, as expected in the current positive drift cycle, and becomes smaller from the outer to the inner heliosphere. The radial gradient in the ACR O solution for 10 MeV/nuc between 55 AU and 70 AU is 1.6%/AU in the ecliptic and 2.2%/AU at 30° latitude. Between 55 AU and 90 AU (the shock) these gradients are 0.45%/AU and 2.3%/AU respectively. The smaller radial gradients near the ecliptic are predicted by standard drift theory for the positive drift cycle.

These calculated gradients are generally in agreement with values calculated by Cummings et al. (1995) using V1/2, Pioneer 10, SAMPEX, and Ulysses, namely radial and latitudinal gradients of 1.3 ± 0.4%/deg at 30 AU, and 2.2 ± 0.8%/AU between 1 AU and 58 AU for 10 MeV/nuc O in 1993. Another recent calculation using data from these three spacecraft resulted in average gradients of ~ 1.8%/deg and ~ 3%/AU for $10 - 22$ MeV/nuc He during the first half of 1996 (Cummings & Stone, 1998).

5 Conclusions

We obtained reasonable fits to observed V1 and V2 ACR spectra for five different particle species in 1998. In order to fit both the intensity gradients between V1/V2 and the spectral shapes of the observed spectra, it was neccessary to use a value for λ_{rr} that is four times smaller at the shock than at the position of V1.

We find that even though the model solutions are diffusion dominated, drift effects are responsible for suppressing ecliptic radial gradients in the outer heliosphere and causing latitudinal gradients to be positive. This conclusion is similar to earlier ones made using the same model (Steenberg, 1998, Steenberg & Moraal, 1999).

We emphasize that the parameters used to obtain the model solutions may be only one possible combination that can explain the observations. In particular, the distance to the termination shock, the compression ratio of the shock, and the ratio of latitudinal diffusion to radial diffusion were not optimized in obtaining these results, even though they may influence the solutions.

In the future, this study will be extended to include calculations of GCRs and also spectra from more particle species.

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