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Possible role of transients on the energy spectra of energetic particles at the solar wind termination shock

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Abstract: We suggest that a series of merged interaction regions interacted with the solar wind termination shock for several years prior to its crossing by Voyager 1 in December 2004 and created the observed spectral shape of energetic particles. We also find that the charge-state of He with 3 to ~70 MeV/nuc and O with 1 to ~14 MeV/nuc is +1 and that the rigidity dependence of the diffusion coefficient from ~170 MV to ~2.7 GV is given by $\kappa \propto \beta R^{1.4}$.

Introduction

One of the puzzles that arose from the Voyager 1 (V1) energetic particle observations when V1 crossed the solar wind termination shock on 16 December 2004 [13] was the unexpected shape of the spectra of anomalous cosmic rays (ACRs). The consensus view prior to the shock crossing was that ACRs originate as interstellar neutral atoms that drift into the heliosphere, become ionized by either solar photons or by charge-exchange, and then are picked up by the expanding solar wind and accelerated at the solar wind termination shock [3] [11]. In a steady state, diffusive shock acceleration results in a power-law spectrum with an exponential roll-off at some high energies (see, e.g., [1]). This spectral shape was not observed at the shock; the spectra were deficient in intensities at middle to high energies. However, as V1 moved into the heliosheath, the spectra did begin to fill in towards the expected shape.

These observations sparked new suggestions for the origin and acceleration of ACRs. It was proposed that because of the geometry of the blunt shock (e.g., [14]) particles are accelerated to high energies along the flanks of the shock rather than near the nose where V1 crossed [8]. Another possibility is that the shock is more efficient at acceleration near the helioequator where there might be more turbulence or near the pole of the heliosphere where injection into the acceleration process might be easier [13]. Others recently investigated whether stochastic acceleration in the heliosheath could account for the observations [10] [15]. It was also considered whether a possible latitudinal dependence of the compression ratio across the shock and different solar wind speed variations with radius in the heliosheath could explain the spectral shapes [7].

In this paper we examine yet a different possibility proposed by Florinski and Zank [4]. These authors modeled the effects on the particle spectra at the termination shock of a merged interaction region (MIR) observed at Voyager 2 (V2) in early 2006. They found energy spectra which qualitatively resembled the V1 observations. They also found that the MIR would affect the spectrum for a considerable time, in excess of half a year. In the observations reported here we also find a remarkable scaling of the H, He, and O spectra that imply that the charge state of He with 3 to ~70 MeV/nuc and O with 1 to ~14 MeV/nuc is +1 and that the rigidity dependence of the diffusion coefficient from ~170 MV to ~2.7 GV is given by $\kappa \propto \beta R^{1.4}$.

Observations

In Figure 1 we show the series of MIRs that were present at V2 from 2001 to mid-2007. The frequency of MIRs is about 2-3 per year until mid-2004. After that, the MIRs are less intense with

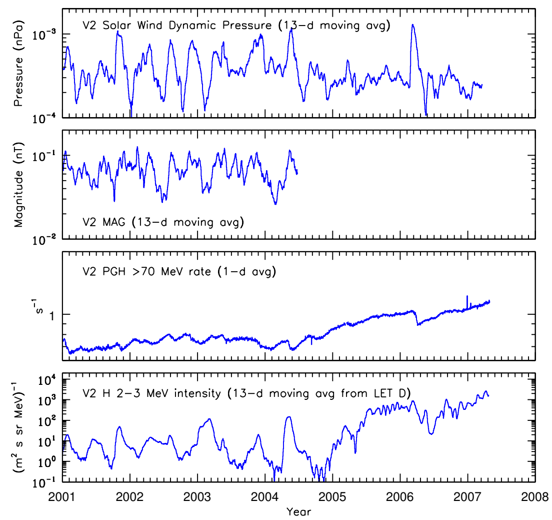

Figure 1: Voyager 2 observations of solar wind dynamic pressure, magnetic field magnitude, >70 MeV ion rate, and intensity of H with 2-3 MeV vs. time. Note the series of MIRs discussed in the text.

the last large one observed in early 2006 [12]. The solar wind instrument on V1 is not functioning, but the available magnetic field data suggest a similar series of MIRs was present at V1. If just one of the MIRs can affect the shape of the spectra at the termination shock for greater than 0.5 years [4], then this series could conceivably have kept the spectra in a disturbed state for several years.

The calculated temporal evolution of the disturbed spectra is shown in Figure 2 [4]. Energy spectra at the termination shock are shown in the right hand panels for times prior to the MIR reaching the shock (top) and afterwards (bottom 3 panels). The total time span covered by the four panels is 270 days. The MIR affects the energy spectrum most noticeably in the ∼2-70 MeV range, creating a dip in the spectrum.

This spectral shape is similar to those in Figure 3, which shows the evolution of the 52-day averaged H, He, and O spectra at V1 from just prior to the crossing of the termination shock to 1.75 years after the crossing. The H and O energy spectra in Figure 3 are scaled by factors of 0.2 and 5.0, respectively, in energy/nuc, and by factors of 1.2 and

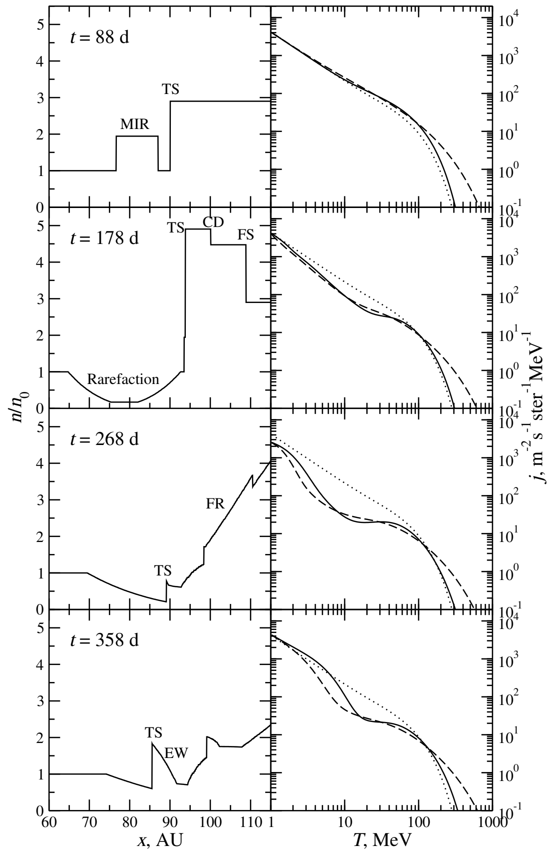

Figure 2: Model calculations of effect on energy spectrum of H of MIR interacting with termination shock (from [4]). Relative solar wind density is on the left and energy spectra are on the right. The dotted line shows the unperturbed original energy spectrum and the solid and dashed lines represent two different methods of modeling the MIR.

1.4, respectively, in intensity. This scaling results in a remarkably good match to the He energy spectrum from ∼3 to ∼70 MeV/nuc and implies that the charge-state of the particles is +1 and that the rigidity dependence of the diffusion coefficient is $\kappa \propto \beta R^{1.4}$ (see analysis in [2]). It also suggests that the particles with rigidity from ∼170 MV to ∼2.7 GV are all part of one component, the ACR component.

V2 is approaching the termination shock and its energy spectra have been evolving as well as shown in Figure 4. The same scaling factors in energy/nuc

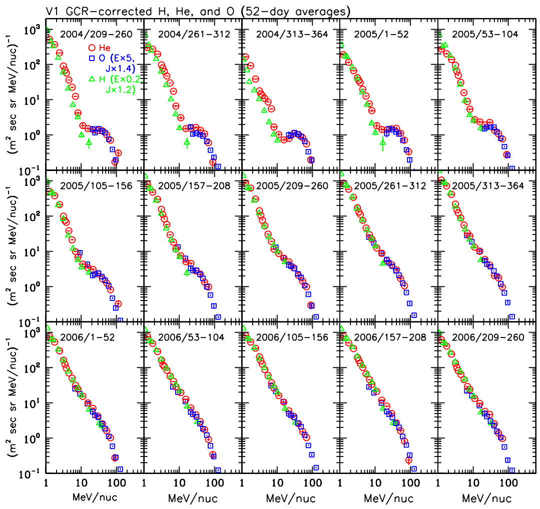

Figure 3: Energy spectra of H, He, and O at V1 for fifteen 52 day periods. The observed spectra have been corrected for galactic cosmic rays (GCRs) based on the observed C energy spectrum. V1 crossed the shock on day 351 of 2004. The H and O energy spectra have been scaled by factors in energy/nuc and intensity as shown in the figure.

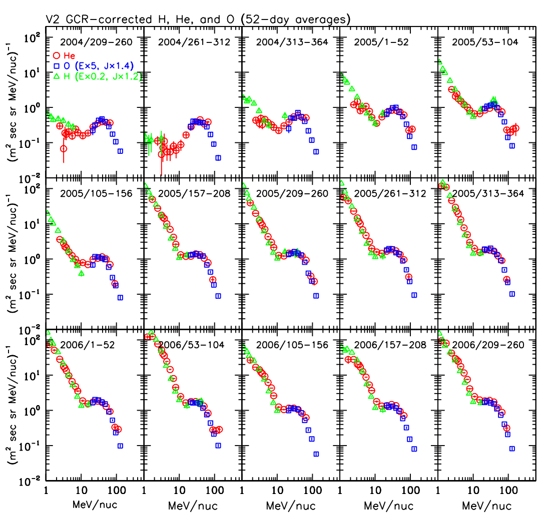

Figure 4: Same as Figure 3 except for V2.

and intensity for H and O that were used in Figure 3 for V1 have been used in each of the V2 panels. The spectral agreement of H and O with He is striking. From the first panel (2004/209-260) to the last (2006/209-260) in Figure 4 the intensity at 10 MeV/nuc has increased by about a factor of 10, the same factor of increase that occurred at V1. Thus the filling in of the V1 energy spectrum that happened after V1 crossed the termination shock may be a temporal effect and not a spatial one. This temporal effect could be caused by the decreasing frequency of MIRs and a resulting recovery of the spectrum of energetic particles at the termination shock.

Discussion and Conclusions

In the scenario presented here, the energy spectrum at V1 in the heliosheath is the near-instantaneous spectrum at the point on the termination shock where V1 crossed. This would be consistent with the original models of ACRs. The spectrum at V2, which is upstream of the termination shock, would reflect the source spectrum on the nearby region of the shock ahead of it plus some solar modulation effects as well. If the MIRs continue to decrease in frequency, as expected with the continuation of solar minimum conditions, the energy spectrum in both the north and south parts of the nose region of the heliosphere might be expected to become the same. Thus, in this case, the energy spectrum at V2 would be expected to fill in considerably as it approaches the termination shock. The most recent four 52-day averaged energy spectra at V1 and V2 are shown in Figure 5. Some filling in of the V2 energy spectra is already apparent in these panels, the intensity at ∼10 MeV/nuc having increased by a factor of ∼2 from beginning to end. If the V2 spectrum at the shock resembles that observed by V1 in the heliosheath, that would favor a dynamical model for the spectrum observed by V1 at the shock. However, if the V2 spectrum at the shock is similar to the one V1 observed when it crossed in late 2004, that would favor a model with the source along the flanks of the termination shock or one including stochastic acceleration in the heliosheath.

The agreement of the scaled H and O energy spectra with the He spectra in Figures 3, 4, and 5 is

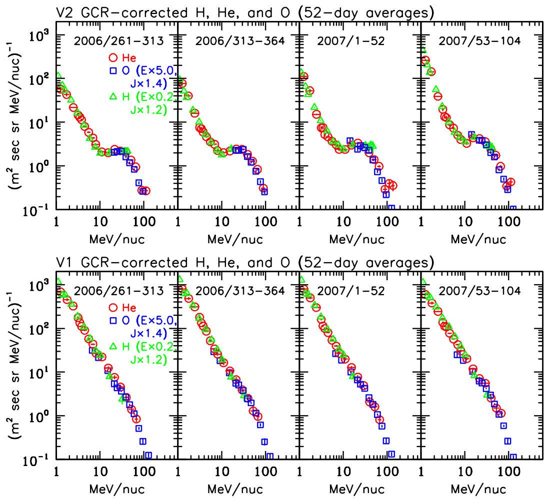

Figure 5: Same as Figures 3 and 4 except for the time periods.

remarkable. A similar scaling was used to deduce that the ACR component was primarily singly-charged [2], which was later shown more directly with SAMPEX observations [5] [9]. The new result here is that He ions at lower energies, down to 3 MeV/nuc, and O ions down to 1 MeV/nuc, heretofore referred to as part of the termination shock particle component [13], now show evidence of being singly ionized. This is consistent with the conclusion of Krimigis et al. [6] who showed the C/O ratio at ∼1 MeV/nuc was consistent with an interstellar pickup ion origin.

In addition to charge-state information, the energy scaling yields information on the rigidity dependence of the diffusion coefficient. The scaling in energy lines up features where the diffusion coefficient is the same for each species. Assuming that the diffusion coefficient is proportional to particle velocity times rigidity to a power, the value of the energy scaling factor of 5 for O to He and 0.2 for H to He corresponds to a power-law index of 1.4. It is remarkable that the same scaling works so well for the energy spectra at both V1 and V2 for more than the two years shown in this paper. We suggest that this supports the idea that the particles at the rigidities from ∼170 MV to ∼2.7 GV are from a common source location. In this view, the original concept of the acceleration of ACRs might well apply, with the addition of modifications of the energy spectra caused by the MIRs.

Acknowledgements

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