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Temporal and solar polar field effects on anomalous cosmic ray modulation at the termination shock and in the heliosheath

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Abstract: Anomalous cosmic ray spectra, observed by Voyager 1 at the solar wind terminatiuon shock crossing, were not of the form expected of first order Fermi (or shock) acceleration, but gave an indication that they were modulated relative to that form. Further data analysis reveals two other remarkable features, namely that the energy where the peak ACR intensity occurs is about four times higher than it was during the previous solar minimum in 1997, and that regression plots of low versus high energy cosmic rays, both of the anomalous and galactic species, behave differently across the shock than would be expected form standard acceleration theory. These phenomena are investigated in this paper with numerical solutions of the cosmic ray transport equation. The two main conclusions are that (a) the features of cosmic ray intensities that were observed during the shock crossing were dominated by temporal variations in the intensity as the heliosphere was resetting towards solar minimum conditions, and (b) the change in spectra with solar field reversal is not yet understood.

Introduction

Voyager 1 crossed the solar wind termination shock (SWTS) at 94 AU on 16 December 2004. The main results are described in [1], [3], [7]. The cosmic-ray observations held the surprise that the anomalous cosmic ray (ACR) kinetic energy spectrum was not of the form suggested by the theory of first order Fermi acceleration.

In this paper we investigate these unexpected ACR spectra, and point out that there are at least two other features of these spectra that need to be explained. The first is that the peak intensity occurs at about four times higher energy than it did in the previous solar minimum in 1997, and that this energy is approximately the same as the peak energy of the 1987 spectra. It is generally perceived that this type of effect, that switches from one solar minimum to the next, can be explained as due to oppositely directed drifts in consecutive solar cycles, but [6] showed that this is not necessarily so, and that one has to make special assumptions about diffusion mean free paths in the heliosphere. Here we show that a polar source for ACRs can explain this effect in principle, but not quantiatively. Second, the regressions of low versus high energy ACRs and galactic cosmic rays (GCRs) of [5] behave different from what is expected from the standard radial intensity profiles across the shock. This indicates that these regressions are strongly dominated by temporal effects, both due to the gradual demodulation to solar minimum conditions, as well as from significant short-term events passing by.

Observations

In this paper we use spectra and time histories of ACR Helium, as observed by the Voyager 1 and Voyager 2 spacecraft. Figure 1, from [5], traces the time histories of these particles at three energies during the solar cycle 23, from January 1997 to May 2006. They are plotted as regressions of low- and high-energy species against one another, which reveals rigidity (or rather βP) dependent effects in their modulation.

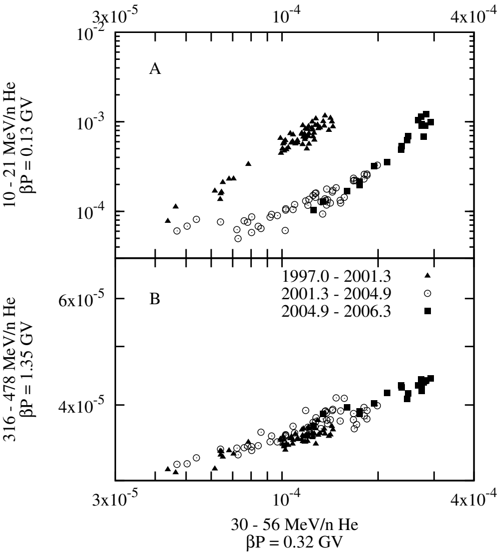

Figure 1: Regression plots of 10–21 and 316–478 MeV/n Helium against 30–56 MeV/n Helium observed on Voyager 1.

The regression line in panel A displays a significant hysteresis effect that sets in at solar maximum conditions in $\sim$ March 2001, such that low-energy particles lag in their recovery behind high-energy particles. The βP dependence of these loops is, however, not immediately clear from comparison of the two panels, because panel B shows that there is no significant hystersis between 316 - 478 MeV/n GCR He^{++} (βP = 1.3 GV) and 30-56 MeV/n ACR He^{+} (βP = 0.32 GV). Given the large difference in βP, this indicates that species differences between GCR and ACR play an important role in the modulation.

It is also significant that the shock crossing is not the dominant effect in these plots. Both panels do indeed show a perceptible kink at the crossing, with the post 2004.9 points on a somewhat steeper slope than before that. We will show, however, that these profiles are dominated by temporal, and not shock-crossing effects.

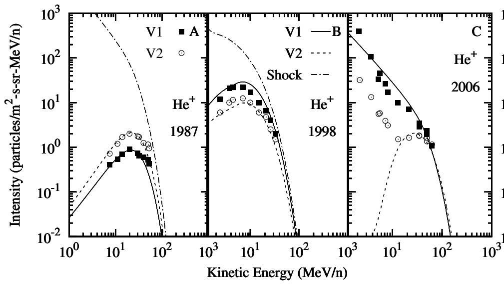

Figure 2: Fit to ACR part of the spectra during the 1987 and 1998/9 solar minima, as well as in 2006.

ACR spectra in consecutive solar cycles

To model the observations, intensity spectra were calculated from numerical solutions of the cosmic ray transport equation. The details of the model appear in [2]. A shock with compression ratio $s =$ 3 was put at r_s = 94 AU, with the outer boundary at r_b = 180 AU.

Figure 2 shows model fits to the Voyager 1 and 2 ACR observations during the solar minimum periods of 1987 and 1998, and also for 2006, which apporaches the next solar minimum..

The main, and puzzling, feature of this fit is that it can only be achieved in a standard model if the diffusion mean free paths in 1998 (Panel B) are $\sim$ 10 larger than in 1987 and 2006. In 1987 and 2006 $\kappa_{rr} = 2.4\text{x}10^{22}\beta P(\text{GV})\ \text{cm}^2\text{s}^{-1}$ inside the shock, dropping with a factor s in the heliosheath, while $\kappa_{\theta\theta}$ is 10% of κ_{rr}. Apart from this drop across the shock, both κ's are independent of position. At $P < 0.4$ GV both are $\propto \beta$. These solar minima were in qA<0 drift cycles, and a neutral sheet tilt angle of 10° was used.

The 1997 qA>0 solution has the same parameters as the 1987 one, except that κ_{rr} is 10 times larger, $\kappa_{\theta\theta}$ is 20% of κ_{rr}, and the source strength, Q, is 7 times smaller. The larger diffusion coefficients are needed to shift down the roll-over of the spectrum that is accelerated on the shock by a factor of $\sim$ 4. These higher diffusion mean free paths, however, cause significantly less modulation relative to the shock spectrum, which must be compensated

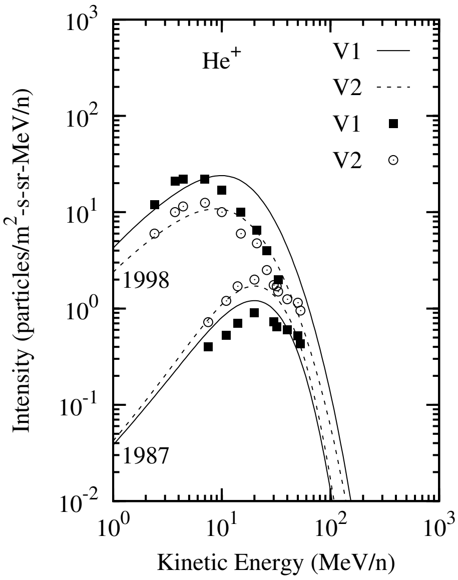

Figure 3: Fit to the 1987 and 1998/9 ACR-I spectra by using a source/injection mechanism limited to within 20° off the poles to demonstrate that this scenario does lead to significant shifts in peak energy as observed.

for by a weaker source function. We note that Q is actually the combination of source strength and injection efficiency at the shock. This injection efficiency is, in turn, determined by magnetic field topology and its connection with the shock, so that both the higher κs and lower Q seem to be related to the properties of the HMF. In agreement with [6], we consider these differences from one solar cycle to the next as fundamental.

There is an interesting way to reduce the big differences in transport coefficients needed to explain the spectra in the qA>0 and qA<0 solar cycles. This is based on an old idea of [4] to limit the source function to the polar regions. As discussed above, this also reflects the efficiency of the injection mechanism, which may be quite different in the quasi-radial HMF configuration above the poles than at other positions on the shock. Accordingly, Figure 3 shows the observations and solutions for 1987 and 1997 when the source of particles on the shock is limited to polar angles of $\leq$ 20°. The diffusion mean free paths for these solutions are the same, and intermediate to the two sets used in Figure 2. This does provide the required shift in peak energy predicted by [4] in a straightforward way. It happens because in the qA<0 cycle the particles are efficiently accelerated as they drift from the poles to the ecliptic along the shock. In the qA>0 cycle the acceleration is much less efficient because there are little or no source particles near the ecliptic plane to be accelerated. The source particles injected at the poles therefore have to be cycled throughout the entire heliosphere first, before they become available for acceleration on the shock, leading to lower overall efficiency. This natural explanation comes at the expense, however, of having to use a source function that is 10^5 times higher in the qA>0 than in the qA<0 cycle. This is even more porblematic than the different mean free paths used in Fig. 2 for the different drift states. This solution also produces latitudinal intensity distributions in the inner heliosphere that are not observed. Thus, we conclude that the shift in ACR peaks in consecutive solar cycles is a fundamental effect that is presently not understood.

Regression profiles through the shock

The second surprising feature of both the ACR and GCR components is that their recovery from solar maximum conditions in 2001 has been remarkably similar in the supersonic solar wind inside the shock and in the heliosheath. Standard models of the ACR modulation predict an entirely different behavior, as can be seen as follows.

Figure 4a shows the radial distribution of 16 and 43 MeV/n ACR intensities, calculated with the same parameters as those used for the spectra in Figure 2c. Inside the shock these intensities show the typical modulation depletion which leads to positive radial gradients, the magnitude of which increases with decreasing energy. The intensities reach a maximum at the shock, however, with negative radial gradients in the heliosheath. These negative radial gradients increase with increasing energy, because the particles are convected and scattered away from their source.

The intensity variations of Figure 1 are produced by two effects, namely the motion of the spacecraft at $\sim$ 3 AU/yr, as well as temporal modulation ef-

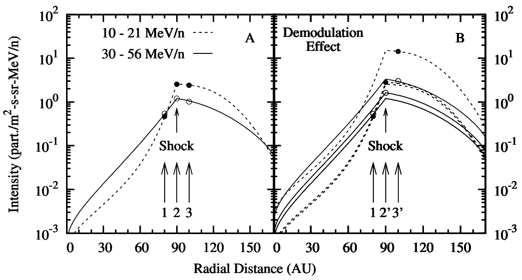

Figure 4: Panel A shows the radial distribution of ACRs at 16 (dashed) and 43 MeV/n (full) MeV/n. In panel B the solutions are lifted up to simulate demodulation towards solar minimum conditions.

fects. These temporal effects can both be due to the gradual reset to solar minimum conditions and the passage of shorter-term modulating events. With radial gradients as high as $\sim$ 100 %/AU (at MeV energies) the effect of the outward motion can easily be 300%/yr, or a factor of $\sim$ 100 over the recovery phase of a solar cycle. The unprimed numbers 1, 2, and 3, connected by the dashed line in Figure 5 show the calculated regression line due to the corresponding spacecraft positions 1, 2, and 3 in Figure 4a. Point 1 represents a measurements several AU inside the shock, point 2 on the shock, and point 3 well into the heliosheath. Due to the large gradients inside the shock, there is a large excursion from point 1 to point 2, but due to the intensity maximum at the shock and the much smaller negative gradient in the heliosheath there is a sudden turnaround and almost a stagnation from point 2 to point 3. This turnaround and stagnation is, however, not observed in the regression of the intensities in these two energy intervals, nor in any other combination of regressions that we have examined. If, on the other hand, there is a significant demodulation during the period of observation, the intensities will be sampled from the positions 1, 2', and 3' in Figure 4b, which produces the full line 1, 2', 3' in Figure 5. This is much nearer to the observed regression, which is a clear indication that the intensity variations observed by Voyager 1 during the SWTS crossing were dominated by demodulation effects, both gradual and episodic, obscuring the typical shock effects.

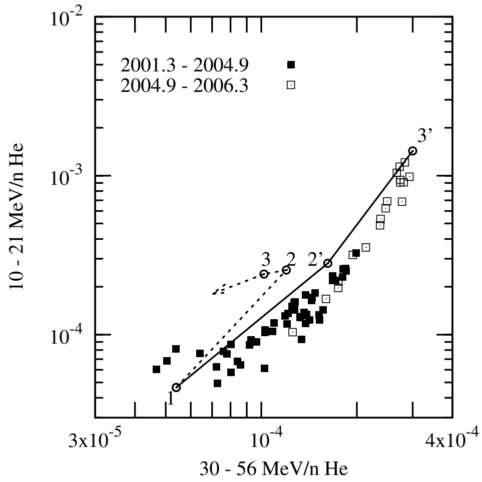

Figure 5: Regression line of the bottom half of Figure 2a together with three solutions of the transport equation, for conditions in 2001 (point 1), 2004 (points 2 and 2', and 2006 (points 3 and 3') in Figure 4.

Acknowledgements

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