The Approach of Voyager 1 to the Termination Shock

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Abstract

From 2001 to 2002 the anomalous cosmic ray (ACR) He intensity at 52 MeV/nuc increased by a factor of $\sim$2.2 at Voyager 1. The increase was larger at lower energies, indicating that Voyager 1 was 7.5$\pm$2.2 AU closer to the termination shock in 2002. Since Voyager 1 moved outward 3.8 AU during this time, it appears the shock moved inward 3.7$\pm$2.2 AU following short term transient motions outward during solar maximum.

1. Introduction

The location of the termination shock is determined by the balance of the solar wind dynamic pressure and the interstellar pressure. The shock moves as the solar wind dynamic pressure varies on the long term with the solar cycle and on the short term due to transients such as merged interaction regions. Voyager 1 is at >88 AU and in the vicinity of the termination shock. ACRs are accelerated at the shock, and as the distance to the shock decreases the low energy ACR spectra will "unroll" as the intensity at lower energies increases rapidly on approaching the shock. By comparing the energy dependence of the increases of ACR He from 2001 to 2002 with the simultaneously observed radial gradients between Voyager 1 and 2 (V1 and V2), it is possible to estimate the distance the shock has moved inward after solar maximum.

2. Observations

As shown in Figure 1, the ACR He and O intensities reached a minimum in 2001 and were reasonably constant from 2001.6 to 2002.0. The ACRs then began to recover, reaching a steady level from 2002.6 to 2003.1. The recovery during the first half of 2002 appears to have been affected by transient increases at V2 and decreases at V1. Figure 1 also shows that a large enhancement of low energy He ions (2-3 MeV/nuc) [3] occurred at V1 during the same period in late 2002 when the ACR He had reached its maximum.

The spectra of He and O for the above two periods when there were minimal transient effects are shown in Figure 2 to illustrate the significant changes

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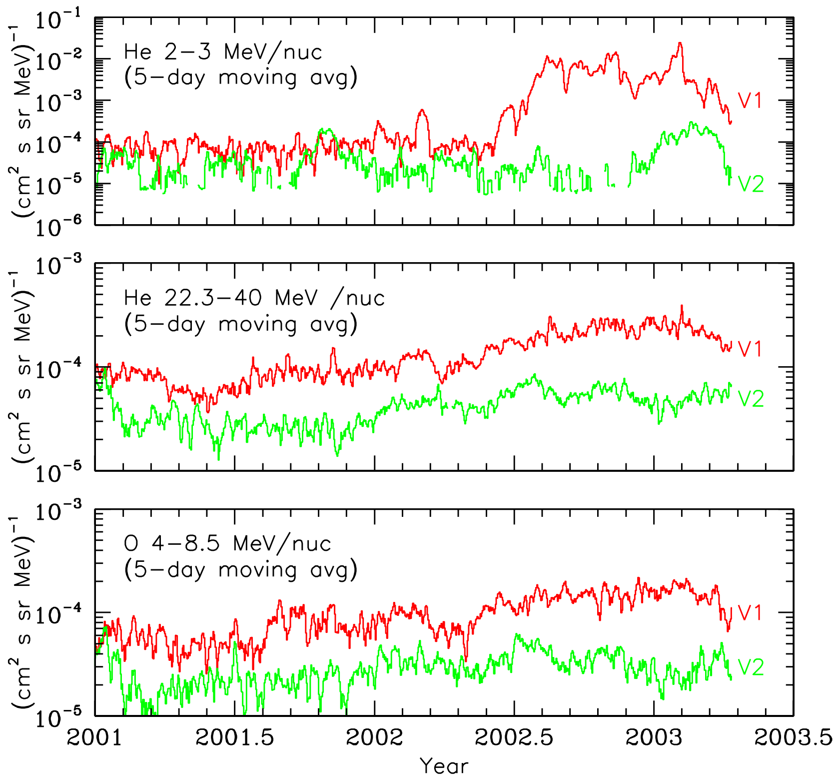

Fig. 1. Five-day moving averages of low energy He (2-3 MeV/nuc) ions and of the peak intensities of anomalous cosmic ray He and O. Maximum solar modulation of ACRs occurred in 2001, after which the intensities began to recover. The ACR intensities are relatively unaffected by transients during two periods: 2001.6 to 2002.0 and 2002.6 to 2003.1. In the latter period there is an unusual 100-fold enhancement of low energy He at V1 that was not observed at V2.

that occurred between late 2001 and late 2002. The new low energy component observed in late 2002 is apparent in the He spectrum below ~10 MeV/nuc. The intensity increased almost a factor of 100 at Voyager 1, with no significant increase at Voyager 2. At the same time there were small increases (~15%) in V1 galactic cosmic ray (GCR) He intensities (energies >80 MeV/nuc) as shown in the lower panel of Figure 2, indicating a modest change in the modulation of GCRs at V1.

The ACR portions of the spectra (10 to 80 MeV/nuc He and 4 to 50 MeV/nuc O) in Figure 2 show the strong energy dependence of the recovery. The middle panels show that the strong energy dependence of the gradients, as indicated by the ratio of intensities at V1/V2, was essentially the same in 2001 and 2002, even though the intensities had increased by up to a factor of 3. This is consistent with little change in the rigidity dependence of the diffusion mean free path [2]. Although the mean free paths are the same for the two periods, the spectra steepen as they recover, yielding somewhat larger Compton-Getting

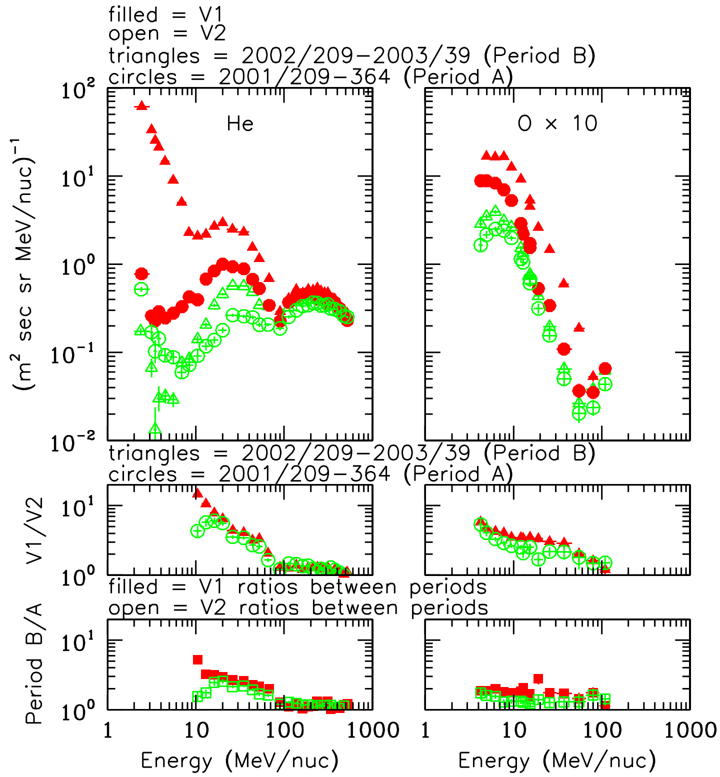

Fig. 2. The top panels show the evolution of the spectra of He and O observed by V1 and V2 between Period A in 2001 and Period B in 2002. Anomalous cosmic rays dominate He from ∼10 to 80 MeV/nuc and O below 50 MeV/nuc. The middle panels show the ratio of the intensities observed by V1 and V2, illustrating the similarity of the energy dependence of the gradients in 2001 and 2002. The lower panels show the ratio of the V1 intensities in Periods A and B and the similar ratios for V2, illustrating that the energy dependence of the increase was similar at V1 and V2. For He, only the ratio at energies >10 MeV/nuc are shown.

factors that result in a ∼30% larger gradient in 2002.

The radial gradients are given by $G_r = \ln(\mathrm{V1/V2})/\Delta r_{12}$, where Δr_{12} is the difference in the radial distance of V1 and V2 from the Sun. For 20 MeV/nuc He, $G_r(20) = 0.105 \pm 0.002$ and 0.100 ± 0.005 %/AU in 2002 and 2001, respectively, while at 52 MeV/nuc the gradients $G_r(52) = 0.068 \pm 0.003$ and 0.055 ± 0.004. The gradient change with energy is essentially the same in 2001 and 2002 and is $\Delta G_r(20, 52) = G_r(20) - G_r(52) = 0.041 \pm 0.006$ %/AU.

This energy dependence in G_r can be used to estimate how much closer V1 was to the shock in '02 than in '01. Assuming that V1 was Δr closer to the shock in '02, the V1 intensities at 20 and 52 MeV/nuc should have increased according to

$$\ln(\mathrm{V1('02)/V1('01)})_{20} = G_r(20) \cdot \Delta r \qquad (1)$$

$$\ln(\mathrm{V1}(\text{'02})/\mathrm{V1}(\text{'01}))_{52} = G_r(52) \cdot \Delta r \tag{2}$$

As seen in Figure 2, the increase at 20 MeV/nuc is 1.36±0.11 times that at 52 MeV/nuc, so $(\mathrm{V1}(\text{'02})/\mathrm{V1}(\text{'01}))_{20} = 1.36 \cdot ((\mathrm{V1}(\text{'02})/\mathrm{V1}(\text{'01}))_{52}$. Combining with Equations 1 and 2 gives

$$\ln(1.36 \pm 0.11) = \Delta G_r(20, 52) \cdot \Delta r \tag{3}$$

Thus $\Delta r = (\ln(1.36 \pm 0.11))/(0.041 \pm 0.006) = 7.5 \pm 2.2$ AU

3. Discussion

The unrolling of the low energy ACR He spectrum following solar maximum modulation levels in late 2001 suggests that by late 2002 the shock was 7.5±2.2 AU closer to V1. Since V1 moved outward 3.8 AU during that time, the shock must have moved inward 3.7±2.2 AU. This suggests that the shock was returning inward during 2002 after having been pushed outward by a series of global merged interaction regions at solar maximum (see e.g. [4]). In particular, the decrease in ACRs at V1 following 2001.25 (Figure 1) resulted from a GMIR that also produced a decrease in GCRs [1] and likely pushed the shock outward several AU.

The unusual enhancement of much lower energy ions in late 2002 may also be an indication of the proximity of V1 to the termination shock. Because there was residual ACR He modulation below ∼20 MeV/nuc, it does not appear that V1 encountered the shock in late 2002. However, these results suggest that there may be short term transient motions of the shock of several AU in addition to the larger changes in the shock location driven by the longer term changes in solar wind dynamic pressure associated with the solar cycle. Thus, during the next five years Voyager 1 may be surfing along a shock that is dynamically driven on both shorter and longer time scales.

4. Acknowledgements

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5. References

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