Voyager Observations of Anomalous Cosmic Ray Gradients and the Role of Diffusion and Drifts in the Outer Heliosphere

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Abstract

We find that the diffusion mean free path at 1.5 GV inferred from the gradient of anomalous cosmic rays (ACRs) observed by Voyager 1 and 2 (V1 and V2) has an approximately linear radial distance dependence at solar maximum. At solar minimum the mean free path is a factor of 10 or more larger than at solar maximum. We find that the expected dependence on current sheet tilt of the ACR O V1/V2 gradient has not become evident as of early 2003, likely because the tilt has yet to decrease below $\sim 40°$. It appears that from mid-2000 up to day 104 of 2003 diffusion is the dominant particle transport mechanism in the far outer heliosphere at 1.5 GV.

1. Introduction

In previous work [2] we have presented inferred energetic particle mean free paths in the rigidity interval 0.4 to 4 GV based on V1/V2 radial gradients from 1990 thru day 104 of 2001. We have extended this study to day 104 of 2003. The primary technique, which is based on the zero streaming approximation of the cosmic ray transport equation, is described in [2]. The new data includes the recent solar maximum that began in mid-2000 in the outer heliosphere and the new A<0 period of the solar magnetic cycle.

2. Observations

The mean free path in the rigidity interval 0.4 to 4 GV for intervals from 1990 to the second 52-day interval of 2003 are shown in Figure 1. The onset of significant solar modulation of these particles in the outer heliosphere is evident in the 3rd and 4th 52-day periods of 2000 [3]. By the 5th 52-day interval of 2001, the rigidity dependence has returned to what it was during the solar maximum of 1990, except the magnitude is larger by the ratio of the radial locations. Except for deviations due to transients, the same rigidity dependence is observed for the remainder of the intervals through the end of the data set.

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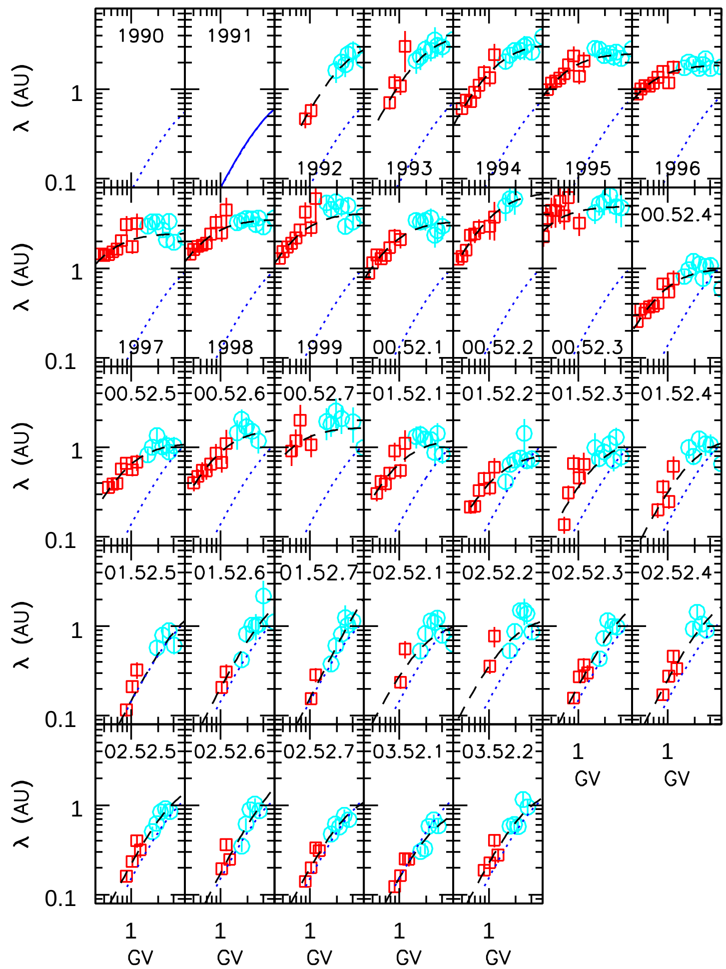

Fig. 1. Mean free path inferred in 33 time periods. For 1990 and 1991, the results are from fits to the energy spectra of ACR O using an assumed location of the termination shock of 90 AU, similar to results shown in [2] and [6]. The points in the other panels show inferred mean free paths from the gradient of ACR He (open squares) and O (open circles) between V1 and V2 (see [2] for technique). Some points with large uncertainties have been excluded from the fits and are not shown. The dashed lines are a fit to the data as described in [2]. The dotted lines in each panel represent the 1990 result scaled linearly with distance. For 1992 through day 156 of 2000, the actual mean free paths are somewhat higher than shown owing to a small positive latitudinal gradient that is likely present but not accounted for. Mean free paths are based on yearly averaged spectra except starting in 2000 when 52-day averaged spectra were used.

In Figure 2 we show the radial mean free path estimated at 1.5 GV from the data of Figure 1 plotted versus time and the tilt angle to indicate phase of the solar cycle. Periods of small tilts in the Figure correspond to the A>0

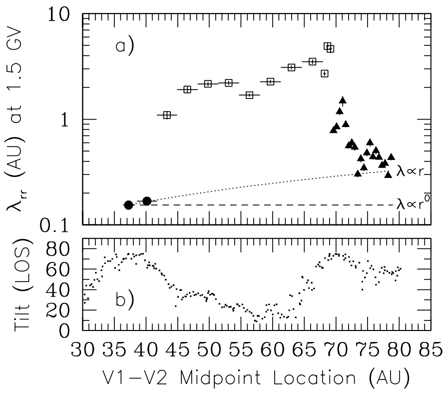

Fig. 2. (a) Mean free paths inferred at 1.5 GV from the data in Figure 1 vs. V1/V2 mid-point location. The filled symbols use a solar wind speed in the calculations based on V2 data. The open squares assume a solar wind speed of 750 ± 50 km s^{-1}. (b) Tilt (line-of-sight method) of current sheet shifted by the solar wind speed to the mid-point of V1/V2.

solar minimum period when positive particles drift from high latitudes to the lower latitudes of observations. Thus the larger mean free paths inferred during this time likely reflect the less turbulent conditions at high latitudes during solar minimum. Periods of large tilts correspond to solar maximum periods and the mean free path is small reflecting the greater turbulence at all latitudes. It appears that the mean free path at solar maximum varies approximately linearly with radial distance in accordance with the theoretical model of Bieber and Matthaeus [1].

We estimate that by the beginning of 2002, the entire region inside the termination shock experienced the Sun's magnetic field reversal ([see [3]). During the A<0 solar minimum in ∼1987, positive particles were entering the heliosphere via rapid drift along the current sheet [5]. We observed a strong dependence of the radial gradient of ACRs with tilt of the current sheet for tilts <30° [4], as expected. During the A>0 solar minimum of the 1990s, particles were drifting down from the poles onto the heliographic equator and the tilt dependence was much reduced [4], again as expected. We now have the opportunity to observe this dependence in a new A<0 period when the spacecraft are much further out in the heliosphere. In Figure 3 we show the tilt dependence of the V1/V2 gradient of ∼10 MeV/nuc ACR O for the preceding A<0 and A>0 periods as well as the new A<0 period starting in the beginning of 2002. In previous work [4] we used data from Pioneer 10 (P10) to remove the latitudinal gradient. Since P10 ceased returning useful data in mid-1996, we now show the V1/V2 gradient for all periods to facilitate comparison. The new A<0 period does not show a strong tilt dependence; however, gradients of 4 to 10%/AU are consistent with the earlier

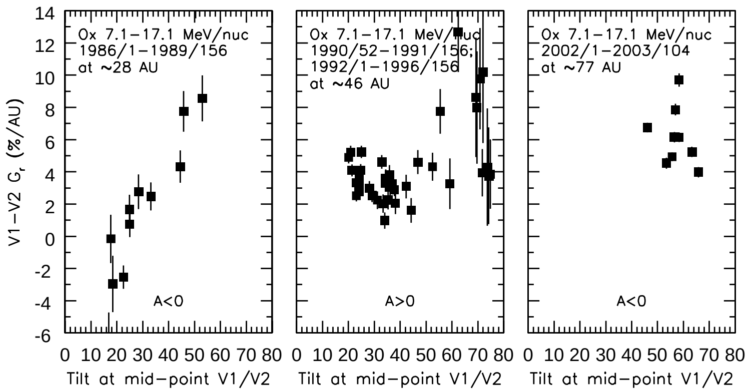

Fig. 3. V1/V2 radial gradient of 7.1-17.1 MeV/nuc ACR O for three time periods as described in the text.

period for tilts $> 40°$.

3. Discussion

The mean free path at solar minimum in the 1990s was much larger than at present, reflecting less turbulent conditions at high latitude and the importance of drifts in particle transport during solar minimum. It appears that diffusion is the dominant particle transport mechanism at >70 AU after mid-2000. As the tilt becomes smaller during the next few years we expect to once again observe a dependence of the gradient on tilt, unless V1 crosses the termination shock. The tilt angle at which this dependence sets in may tell us about the relative roles of drift and diffusion in the far outer heliosphere during an A<0 period.

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