Location of the Termination Shock at Solar Maximum

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Location of the Termination Shock at Solar Maximum

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Abstract. During the recent solar maximum, Voyager 1 was beyond 80 AU. Extrapolation of the small gradients of anomalous cosmic rays at solar minimum and the larger gradients at solar maximum indicate that the solar wind termination shock is at $\lesssim$ 92 AU at the beginning of 2002.

INTRODUCTION

Various estimates of the location of the solar wind termination shock suggest a distance in the range of 90±10 AU (see summary in [1] and [2]). During the recent solar maximum in 2001, Voyager 1 and 2 (V1 and V2) were at distances of >80 AU and >63 AU, respectively. During this time the radial mean free path for 1.5 GV anomalous cosmic ray (ACR) O was a factor of ten smaller than during the most recent solar minimum period [3]. The resulting differences in the radial gradients of ACRs between periods of minimum and maximum solar modulation can be used to estimate the distance to the termination shock where ACRs are accelerated.

EXTRAPOLATION OF LARGE SCALE, LONG TERM GRADIENTS

Since they were launched twenty-five years ago, the two Voyager spacecraft have been observing changes in the modulation of ACRs, as did Pioneer 10 and 11 for much of this period. As shown in Figure 1, the Voyager observations now span three periods of maximum solar modulation. With Pioneer and Voyager, it is possible to determine both the latitudinal and radial gradients. As shown in Figure 1, the radial gradient at solar minimum is much smaller than during periods of solar maximum, although at solar maximum in 1990-91 individual gradient measurements are affected by propagating transients. The small radial gradient beyond ~10 AU at solar minimum for the positive solar magnetic polarity (A>0) is also reflected in the nearly identical flux observed by Pioneer 10 in 1978 and 1996 when it was at ~15 and ~64 AU [4, 5].

To illustrate the large scale variation more directly, the ACR O flux is shown in Figure 2 as a function of the heliocentric distance at the time of the observation. Although the observed fluxes are affected by latitudinal as well as radial gradients, latitudinal gradients are small at solar maximum when the solar magnetic field is reversing polarity. The intensity minima marking periods of maximum modulation at the three spacecraft show a strong radial dependence corresponding to a large scale gradient of ~7.5%/AU from ~10 to 80 AU.

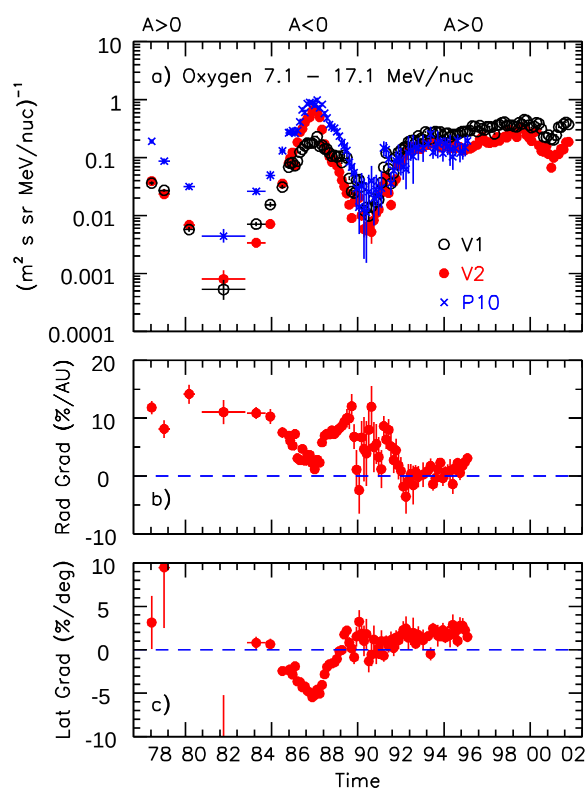

FIGURE 1. a) Intensity of ACR O with 7.1-17.1 MeV/nuc versus time at three spacecraft. b) Radial gradient of ACR O versus time. c) Latitudinal gradient of ACR O versus time.

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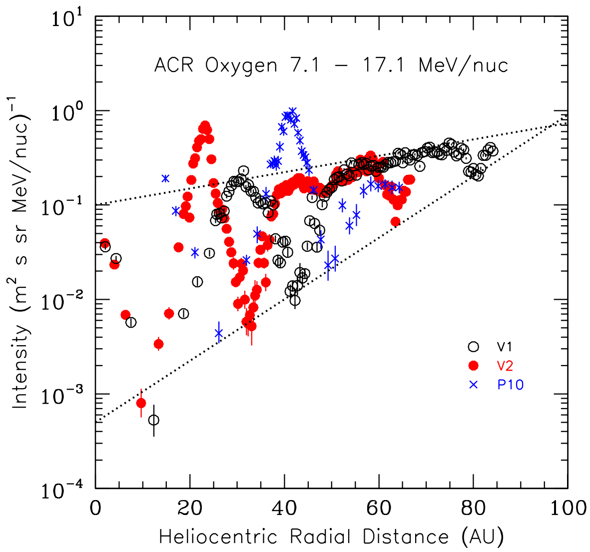

FIGURE 2. ACR O intensities shown in Figure 1 plotted versus radial distance of the observation. The two dotted lines show the intensity variation for gradients of 2%/AU (solar minimum) and 7.5%/AU (solar maximum).

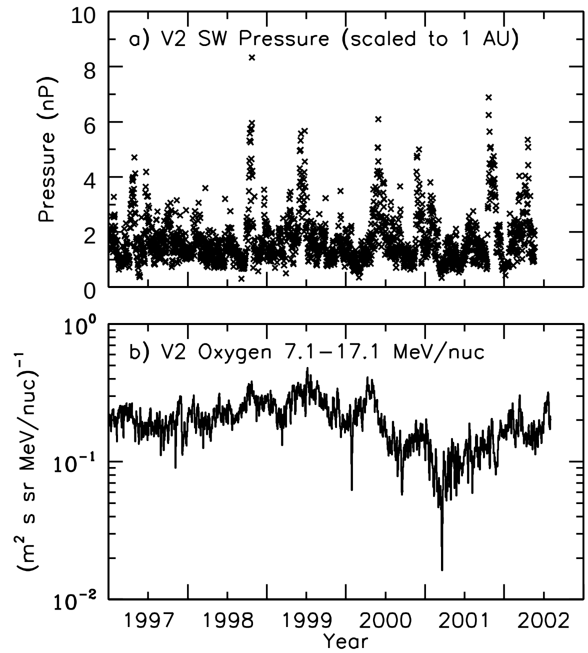

FIGURE 3. a) V2 solar wind pressure scaled by r^2 versus time, where r is the radial distance of the observation in AU. b) Five-day moving averages of the intensity of oxygen with 7.1-17.1 MeV/nuc observed at V2 versus time.

During solar minimum periods, latitudinal as well as radial gradients contribute to the differences in intensities at the three spacecraft. However, the latitude of V1 changed by only 1° while moving from 50 to 80 AU, so the long term intensity change was dominated by the radial gradient of ~2%/AU shown in Figure 2.

The converging intensity gradients in Figure 2 are an indication of the distance of the shock from V1 during periods of solar maximum when the heliosphere is smallest [see, e.g., 6]. Extrapolation of the gradients in Figure 2 indicates a shock location at ~95 AU at solar maximum, assuming that the shock location and source intensity of ACR O at the latitude of V1 did not change between 1999 and 2001.

EXTRAPOLATION OF INSTANTANEOUS, LOCALIZED GRADIENTS

The extrapolation in Figure 2 is based on determinations of the large scale gradients measured over long periods of time and assumes there is no evolution of the radial profile or changes in the shock location. To allow for such changes, radial gradients for specific epochs and radial intervals can be estimated using simultaneous V1 and V2 observations. However, gradient measurements for individual epochs around solar maximum can be significantly affected by outward propagating disturbances that affect V1 and V2 at different times.

Figure 3 illustrates some of the transient effects at V2. The increases in solar wind dynamic pressure indicate the arrival of merged interaction regions (MIRs). These are barriers to cosmic rays that can also act as a snowplow producing an enhanced intensity [see, e.g., 7]. This effect is especially apparent with the arrival of the large global merged interaction region (GMIR) in 2000.4, but is also seen for some of the other MIRs. To be useful for extrapolating outward, gradients must be measured during periods without such large transient increases. In addition, GMIRs serve as barriers, producing a transient decrease in ACR intensity while propagating between the observation point and the termination shock [8].

As shown in Figure 4, the projected arrival time at 95 AU of the GMIR observed at V2 in 2000.4 was 2000.8. The intensity remained depressed until a subsequent GMIR passed 95 AU about six months later. Subsequent MIRs appear to have had little effect on the high energy ACR O intensity, suggesting that the gradients observed in the most recent five 52-day periods in Figure 4 can be used to extrapolate from V1 out to the shock, as shown in Figure 5. Note that the gradients in Figure 5 are of the form $j \propto r^{\alpha}$, as would result from a diffusion mean free path proportional to r as indicated by Voyager data [3].

Estimates of the radial gradient for three years of solar minimum are also indicated in Figure 5. Yearly averages

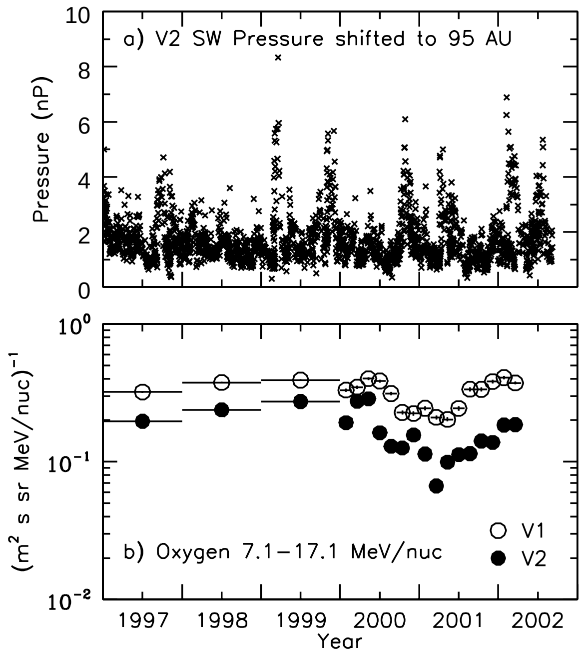

FIGURE 4. a) Same as Figure 3a except the observations have been shifted to 95 AU assuming the solar wind speed measured at V2. b) Intensity of ACR O at V1 and V2 versus time.

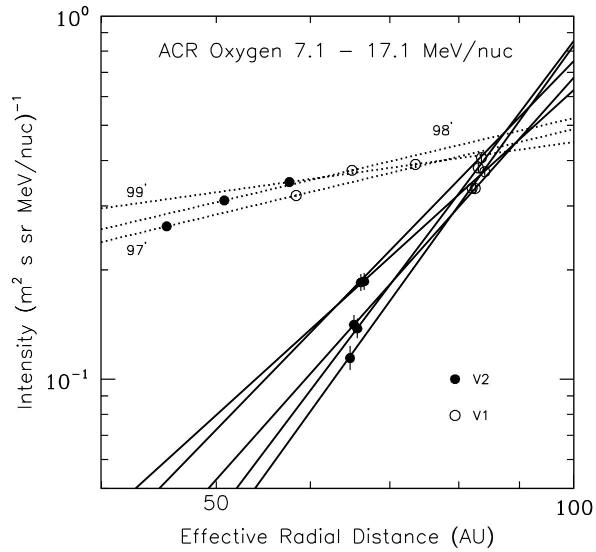

FIGURE 5. Same as Figure 4b, except plotted versus effective radial distance of the observations. The effective radial distances differ from actual radial distances only for 1997, 1998, and 1999 and the procedure is described in the text. The lines connect V1 and V2 data measured at the same time.

have been used in order to reduce the effects of transients on the derived gradients. During solar minimum, the gradient between V1 and V2 is also affected by a latitudinal gradient. To estimate the radial gradient, the V2 intensity has been adjusted to the latitude of V1 by 1.9%/degree, the average latitudinal gradient observed between mid-1994 and mid-1996 when Pioneer 10 was operational (see Figure 1).

The intensities in 1997, 1998, and 1999 are also affected by changes in the location of the termination shock. MHD calculations (Whang and Burlaga, personal communication; see also [6]) indicate that relative to the beginning of 2002, the average location of the shock in 1997, 1998, and 1999 was at increased distances of $\Delta r_s \approx$ 14.5, 8.2, and 1.1 AU, respectively. The increased distance results in a corresponding decrease in flux according to $j(r) = j_s(r/r_s{}')^{\alpha}$, where j_s is the intensity at a shock located at $r_s{}' = r_s + \Delta r_s$ and r_s is the (unknown) shock location in 2002. From this relationship, it follows that the flux $j(r)$ for a shock at $r_s{}'$ is the same as the flux $j(r')$ for a shock at r_s and an effective radial location r' if $r' = kr$, where the scaling factor is $k = (r_s/r_s{}')$. The scaling factor k is relatively insensitive to the exact values of r_s. For $90 \leq r_s \leq 100$ AU, k = 0.87, 0.92, and 0.99 to within 0.01 for 1997, 1998, and 1999, respectively. These factors have been applied to the radial positions of the solar minimum intensities in Figure 5.

As in Figure 2, the gradients in Figure 5 exhibit a strong difference between solar minimum and solar maximum. The intersections of the extrapolated intensities provide estimates of the location (r_s) of the shock in 2002, assuming that the intensity at the shock was the same for all of the epochs. The systematic differences among the five radial profiles for solar maximum profiles give some indication of the variability from epoch to epoch due to systematic uncertainties from residual transient effects. The intersections correspond to a shock location of $\lesssim$ 92 AU in early 2002.

CONCLUSION

It is possible that before Voyager 1 reaches 95 AU in 2005, it will encounter the shock. If the shock is beyond that distance, however, Voyager 1 may not reach it before the onset of increased solar wind pressure pushes the shock outward ahead of the spacecraft for several more years.

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