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PLASMA OBSERVATIONS FROM VOYAGER 2

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ABSTRACT

Voyager 2 is now beyond 75 AU and observing the descending phase of the solar cycle. Voyager 2 is the spacecraft in best position to predict the plasma conditions at Voyager 1 (whose plasma instrument failed). We show that some of the Voyager 1 energetic particle events are associated with plasma changes observed at Voyager 2. Voyager currently observes low speeds, near 400 km/s, suggesting coronal hole flow is not observed. Since the latitudinal speed gradient which occurs in the inner heliosphere at solar minimum has not yet developed, we can use the speed decrease from Earth to Voyager 2 to determine the solar wind slowdown due to interaction with interstellar H and thus the interstellar H density at the termination shock. We find that the observed slowdown implies a larger H density than previous results.

1. INTRODUCTION

Voyagers 1 and 2 are traversing the edges of the heliosphere. In mid-2005 Voyager 1 was at roughly 96 AU and Voyager 2 at 77 AU. Voyager 1 crossed the termination shock in December 2004 and is now in the heliosheath (Stone, 2005). Voyager 2 has been observing the effects of the interstellar pickup ions for many years, as evidenced by pressure-balanced structures (Burlaga et al., 1994), the increase in temperature of the solar wind outside 30 AU (Richardson and Smith, 2003), and a slowing of the solar wind speed (Wang and Richardson, 2003). The Voyager 1 plasma experiment (PLS) is no longer returning useful data, so the Voyager 2 data must be extrapolated to the distance of Voyager 1 to understand the effects of solar wind changes on the termination shock and shock-related phenomena.

In this paper we touch on several solar wind plasma topics. The last determination of the solar wind slow down used solar maximum (near 2000) data; recent data suggest that latitudinal gradients of speed have not yet been established at Voyager 2 (as they usually are near solar minimum) so that we can make a new determination of the solar wind slowdown at 75 AU. The solar wind dynamic pressure at Voyager 2 can be used as a proxy for the pressures at Voyager 1. We use these pressures and the location of the Voyager 1 termination shock crossing to calculate the position of the termination shock as a function of time. These termination shock positions and the pressure changes observed in the solar wind at Voyager 2 are compared to the Voyager 1 data to show that these solar wind changes affect the energetic particle fluxes.

2. SOLAR WIND OBSERVATIONS

The Voyager plasma experiment consists of four Faraday cup detectors which take a set of solar wind spectra in the outer heliosphere every 192 s. Data are received only for the times that the Deep Space Network is tracking Voyager, roughly 40% of the time. The spectra are fit with isotropic convected Maxwellian distributions to determine the plasma velocity, thermal proton density, and thermal proton temperature.

Fig. 1 shows the recent hourly average data from Voyager 2. The speeds vary from 310 to 560 km/s and many structures with time scales of months are apparent. Densities range from 0.3-5$\times 10^{-3}$ cm^{-3} and the density structure is dominated by successive merged interaction regions (MIRs) with high density. The temperatures show a lot of scatter but on the large scale track the speed profile.

2.1. Solar Wind pressures

Fig. 2 compares the solar wind pressures observed by Voyager 2 with the Voyager 1 CRS >0.5 MeV counting rates. The solar wind pressure varies in a similar manner at all heliolatitudes and longitudes (Richardson

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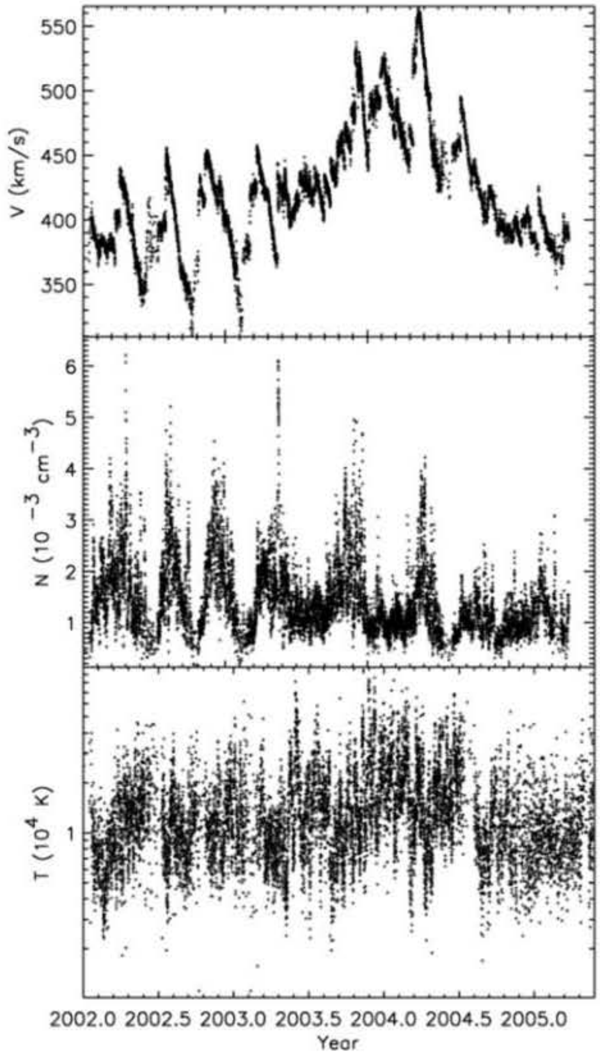

Figure 1. Hourly average solar wind speeds, densities, and temperatures

and Wang, 1999), so we time-shift the Voyager 2 data to the location of Voyager 1 using the observed solar wind speeds. The termination shock particle (TSP) events are labeled on the top of the plot. The pressure has large variations associated with the MIRs in Fig. 1. The termination shock, however, probably moves in response to larger term solar wind dynamic pressure changes; thus we also show the 200-day average pressures in the figure. The pressures slowly rise, on average, from before the start of the TSP1 event to midway through TSP2. The pressures then decrease, with the termination shock crossing at the start of TSP 3 resulting from this inward motion.

The Voyager 2 pressures have been used as input to the 2-D model including pickup ions described in Wang and Belcher (1999). The model predicts the shock moves between 85 and 100 AU with the local interstellar medium (LISM) parameters N(H^+)=.07 cm^{-3}, N(H) = .14 cm^{-3}, T(H^+)=T(H)=1.09 $\times 10^4$ K, and V=26 km/s. The model predicts the shock location to be at 97.3 AU at the time of the Voyager 1 crossing; since the crossing occurs at 94 AU the interstellar pressure must be about 6% higher than the for the LISM values listed above. We shifted the shock distance profile in Fig. 3 so that the termination shock crossing time and distance are those observed. The profile suggests that Voyager 1 has been surfing the shock since about 2000 and was very close to the shock from mid-2003 to 2004. Although there is not a close correspondence between the TSP event and the predicted termination shock position, the hypothesis that the first 2 TSP events resulted from connection of Voyager 1 and the termination shock seems reasonable.

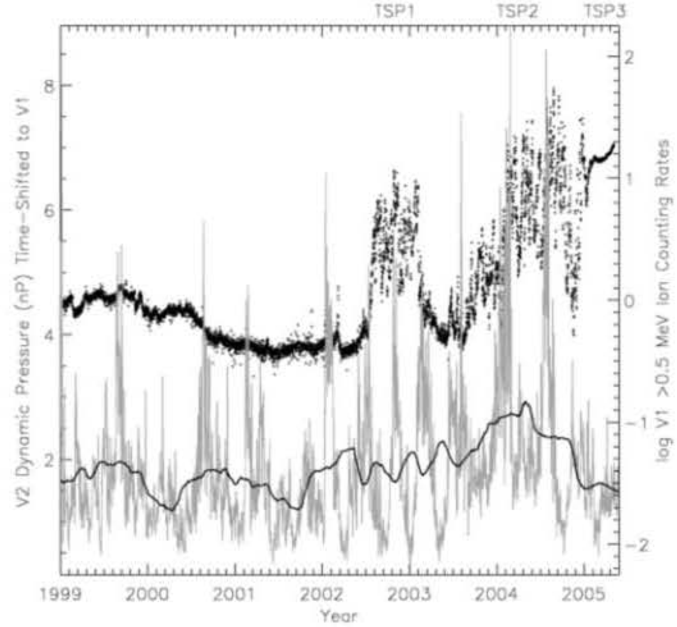

Figure 2. Hourly average solar wind dynamic pressures (dotted line), 200-day running averages of the dynamic pressure (solid line), and CRS >0.5 MeV counting rates (+'s).

2.2. MIRs at Voyager 1

Although the small scale solar wind pressure features may not have a large effect on the average termination shock position, they may effect the connection of Voyager 1 to the termination shock or have other effects. Merged interaction regions form when an ICME or series of ICMEs compresses a region of enhance magnetic field and usually density. As noted above, in the outer heliosphere these regions are characterized by enhanced speed, density, pressure, and magnetic field magnitude and are often preceded by an interplanetary shock. Fig. 4 compares the Voyager 2 daily average pressure profile time-shifted to the Voyager 1 location to the Voyager 1 CRS >0.5 MeV counting rates (Richardson et al., 2005). The vertical lines highlight the effect the MIRs appear to have on the energetic particle fluxes when they pass Voyager 1.

MIR 1 ends just before the onset of TSP1. MIR 2 coin-

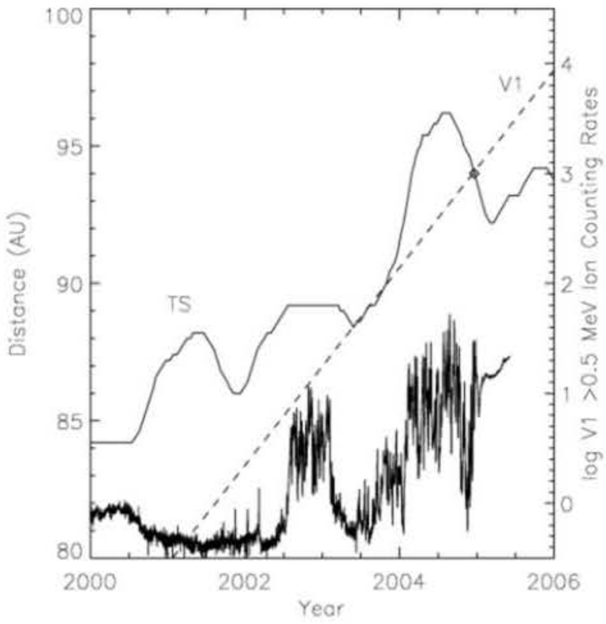

Figure 3. Location of the termination shock as a function of time using the dynamic pressure observed by Voyager 2 as input to a 2-D model. Also shown are the position of Voyager 1 and the Voyager 1 CRS >0.5 MeV counting rates. The location of the shock is shown by the diamond.

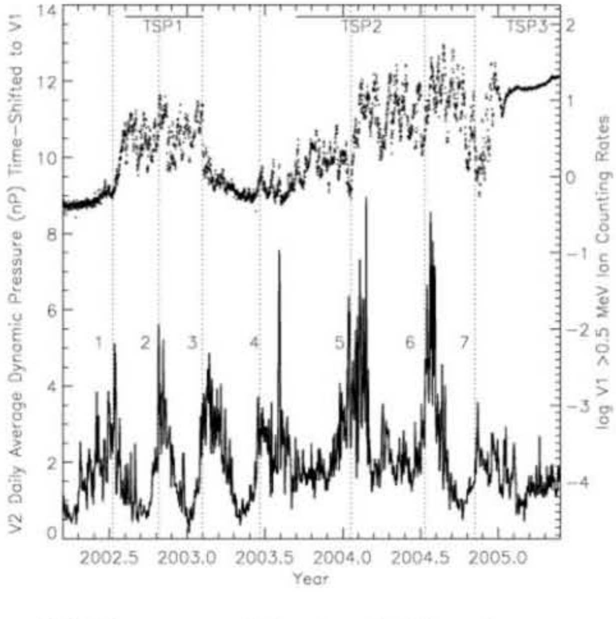

Figure 4. Daily averages of the solar wind dynamic pressure observed by Voyager 2 propagated to the distance of Voyager 1 (line) compared to six-hour averages of the CRS >0.5 MeV/nuc counting rates (points). The onset of the MIRs are indicated by the vertical dashed lines and the MIRs are numbered in order of occurrence. The TSP events are labeled at the top of the plot.

cides with an increase of the energetic particle flux. MIR 3 is associated with a short jump in the energetic particle flux followed by the end of TSP 1. The end of MIR 4 corresponds to the start of TSP2. MIRs 5 and 6 coincide with energetic particle flux increases, and MIR 7 to the end of TSP2. Every MIR is associated with changes in the energetic particle flux but the responses vary greatly. In the two cases (MIRs 1 and 4) when the TSP event begins at the end of the MIR, even though increasing pressure should drive have driven the shock farther away, the magnetic field direction could change producing a connection to the shock. Energetic particles pile up ahead of enhanced magnetic field regions (McDonald et al, 2000) because the enhanced field is a barrier to particle transport. Shocks can energize particles are they propagate. These two effects could account for the energetic particle flux increases associated with MIRs 2, 3, 5, and 6. The two MIRs, 3 and 7, which end TSP 1 and 2, could produce this effect by either pushing the termination shock shock outward and/or by heralding a change in the magnetic field direction, thus severing Voyager 1's connection to the termination shock.

3. SOLAR WIND SLOWDOWN

The solar wind interacts with the neutrals in the LISM; these neutrals become ionized in the solar wind and heated and accelerated to the solar wind energy. The roughly 2 keV of energy gained by each picked up proton comes from the bulk flow energy of the solar wind, so the solar wind slows with distance. The solar wind structure observed at 1 AU from 2002-2004 looks very similar to that observed at Voyager 2 from 2003-2005. The latitudinal speed gradients prevalent near solar minimum are not yet evident, so we estimate the slowdown of the solar wind by using a 1-D MHD model including pickup ions to propagate the solar wind from 1 AU to the distance of Voyager 2. We use the ACE data at 1 AU as input for the model and take the density of H at the termination shock to be 0.09 cm^{-3}, which gave good fits to the data for a similar comparison near solar maximum (Wang and Richardson, 2003).

Fig. 5 shows the predicted and observed solar wind speeds and thermal proton densities. The predicted speeds are clearly higher than those observed by tens of km/s. The densities predicted are comparable to those observed. If a latitudinal speed gradient were present in the solar wind, Voyager 2 at higher heliolatitudes should observed higher speeds; thus this explanation cannot account for the discrepancy. One possibility is that the termination shock H density changes with the solar cycle as the boundaries of the heliosphere breathe. Another is that the LISM density fluctuates. A third is that latitude differences are important, perhaps not because of coronal hole distributions but because of ICME strength. In 2006, Ulysses and Voyager 2 will be at the same latitudes and we will try to verify the increased slowing compared to predictions.

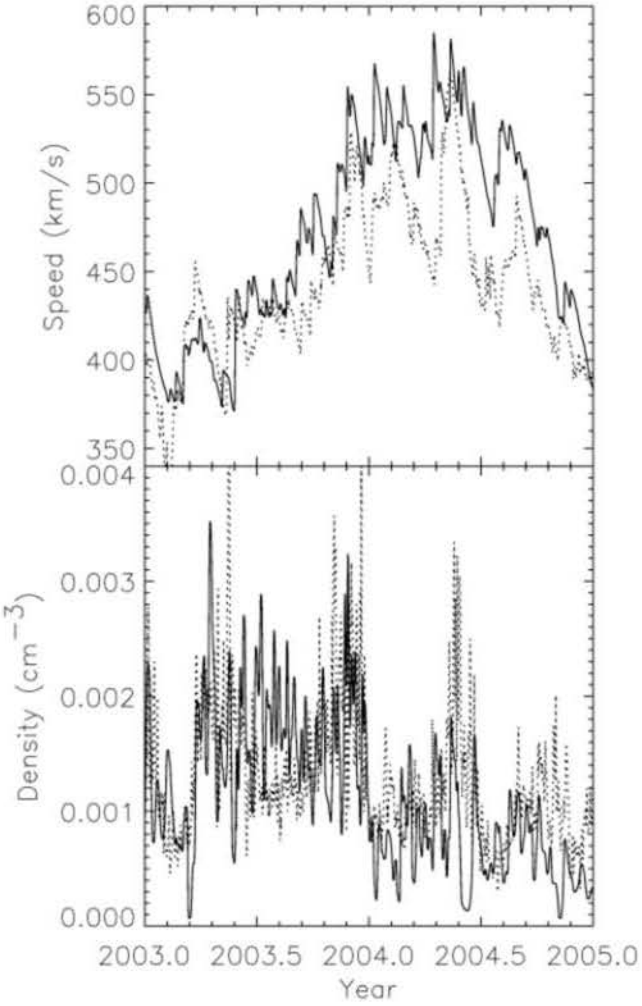

Figure 5. The solar wind speed and density at Voyager 2 predicted by the model based on ACE data (solid lines) and the actual speeds and densities observed by Voyager 2 (dotted lines)

4. SUMMARY

The Voyager spacecraft continue to explore the outer heliosphere, providing valuable information on the evolution of the solar wind and its interaction with the LISM. Voyager 2 data can be used to assess the likely plasma conditions at Voyager 1. All the MIRs observed at Voyager 2 seem to have an effect on the Voyager 1 CRS fluxes and the general pressure changes observed are consistent with the time of the termination shock crossing. The slowdown of the solar wind in the past few years is larger than expected; we need to determine if this is a solar cycle effect or has another cause.

ACKNOWLEDGMENTS

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REFERENCES

Burlaga, L. F., N. F. Ness, J. W. Belcher, A. Szabo, P. A. Isenberg, and M. A. Lee, Pickup protons and pressure-balanced structures: Voyager 2 observations in merged interaction regions near 35 AU, *J. Geophys. Res. 99*, 21,511, 1994.

McDonald, F. B., L. F. Burlaga, R. E. McGuire, N. F. Ness, The onset of long-term cosmic ray modulation in cycle 23 coupled with a transient increase of anomalous cosmic rays in the distant heliosphere *J. Geophys. Res., 105* , 20,997-21,004, 2000.

Richardson, J. D., and C. Wang, The global nature of solar cycle variations of the solar wind dynamic pressure, *Geophys. Res. Lett. 26*, 561-564, 1999.

Richardson, J. D., and C. W. Smith, The radial temperature profile of the solar wind, *Geophys. Res. Lett. 30*, 10.1029/2002GL016551, 2003.

Richardson, J. D., C. Wang, and L. F. Burlaga, Correlated solar wind speed, density, and magnetic field changes at Voyager 2, *Geophys. Res. Lett., 30*, 2207 10.1029/2003GL018253, 2003.

Richardson, J.D., F.B. McDonald, E.C. Stone, C. Wang, and J. Ashmall, The relation between the solar wind dynamic pressure at Voyager 2 and the energetic particle events at Voyager 1, *J. Geophys. Res*, in press, 2005.

Stone, E. C., Voyager in the Vicinity of the Termination Shock, Eos Trans. AGU, 86(18), Jt. Assem. Suppl., Abstract SH22A-01, 2005.

Wang, C., and J. W. Belcher, The heliospheric boundary response to large scale solar wind fluctuations: A gas dynamic model with pickup ions, *J. Geophys. Res., 104*, 549, 1999.

Wang, C., and J. D. Richardson, Determination of the solar wind slowdown near solar maximum, *J. Geophys. Res., 108, 10.1029/2002JA009322, 2003.*