Correlated solar wind speed, density, and magnetic field changes at Voyager 2

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[1] The character of the solar wind plasma data observed by Voyager 2 recently changed to a regime in which the speed, density and magnetic field magnitude are positively correlated. In the inner heliosphere, the density and speed are generally anti-correlated. As streams interact while propagating outward, this correlation weakens. Outside 65 AU, Voyager observed large, in-phase, fluctuations of speed, density, and magnetic field magnitude with time scales of 6–12 months. The dynamic pressure varies by a factor of ten in these fluctuations, which should produce motions in the termination shock. We use ACE data from 1 AU as input to a 1-D MHD model which includes pickup ions to model the radial evolution of the solar wind. The model reproduces the basic character (but not the details) of the observations, predicting correlated variations in speed, density, and magnetic field with time scales similar to those observed. *INDEX TERMS:* 2124 Interplanetary Physics: Heliopause and solar wind termination; 2134 Interplanetary Physics: Interplanetary magnetic fields; 2162 Interplanetary Physics: Solar cycle variations (7536); 2164 Interplanetary Physics: Solar wind plasma. **Citation:** 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*(23), 2207, doi:10.1029/2003GL018253, 2003.

1. Introduction

[2] Voyager 2 has observed the solar wind since it was launched in 1977; as of mid-2003 it was at a distance of 70 AU and a latitude of 25°S. In general the solar wind has behaved as predicted; the density has decreased as distance squared and the speed remained relatively constant until interstellar H slowed the solar wind in the outer heliosphere [*Richardson et al.*, 2003]. The temperature has increased since roughly 30 AU, probably due to energy transfer from pickup ions [*Richardson and Smith*, 2003]. The magnetic field magnitude is consistent with that predicted by the Parker model [*Burlaga et al.*, 2002].

[3] At 1 AU, the density and speed of the solar wind are strongly anti-correlated and the speed and proton temperature are correlated [*Hundhausen et al.*, 1970; *Burlaga and Ogilvie*, 1970; *Wolfe*, 1972]. Solar cycle variations have been observed in the solar wind speed and dynamic pressure [*Neugebauer*, 1975; *Bridge*, 1976; *Gosling et al.*, 1976; *Grzedzielski and Lazarus*, 1993; *Richardson et al.*, 2003]. The speed-density and speed-temperature correlations have a strong solar cycle dependence at 1 AU, with stronger correlations at solar minimum [*Richardson et al.*, 1996]. These data are from near Earth; at solar minimum the solar wind near Earth often alternates between high density, low speed, low temperature wind and low-density, high speed, high temperature wind giving strong correlations. At solar maximum the stream structure is not present so corotating streams are not dominant and correlations are relatively weak. The correlations weaken as the solar wind moves outward [*Richardson et al.*, 1996].

[4] Recent Voyager 2 data show a positive correlation between the speed, density, and magnetic field at 65–70 AU. We present these data and discuss their implications. We try to understand the origin of these data by comparing results from a model of solar wind propagation with the observations.

2. Data

[5] The Voyager plasma experiment observes solar wind protons simultaneously in three Earthward-pointing Faraday cups over an energy range of 10-5950 eV with an energy resolution $\Delta E/E$ of 3.6% [*Bridge et al.*, 1977]. The spectra are fit with convected isotropic Maxwellian distributions to determine the thermal proton velocity, density, and temperature.

[6] The Voyager magnetometer measures the magnetic field with two sensors mounted on a boom, one at the end of the boom and the other closer to the spacecraft [*Behannon et al.*, 1977]. At large distances from the Sun the magnetic field is very weak, making it difficult to measure accurately. We estimate that the standard deviation of the error in the magnetic field strength observations presented below is ±0.03 nT.

[7] Figure 1 shows 25-day running boxcar averages of the plasma speed, density, and dynamic pressure from 2001 through mid-2003 and of the magnetic field magnitude in 2002. Beginning in mid-2001, the character of the plasma data changes; after this time density and speed measurements generally occur in phase as is clear from comparison of the top two panels in Figure 1. This produces the quasi-periodic dynamic pressure variations shown in the third panel of Figure 1 which have an amplitude of a factor of 10 and a time scale of 6–12 months. The magnetic field magnitude, shown in the bottom panel, varies in phase with

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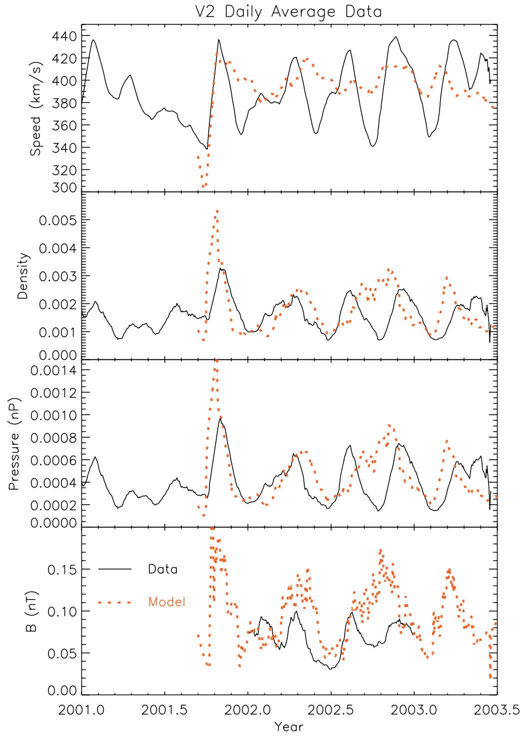

Figure 1. 25-day running boxcar averages of the plasma speed, density, dynamic pressure, and the magnetic field magnitude. Uncertainties are about 5 km/s for the speed, 0.0002 cm^{-3} for the density, and 0.03 nT for the magnetic field magnitude. The dotted lines show the model predictions for this time period.

the speed and density increases. The temperatures of the solar wind protons (not shown) are not strongly correlated with the other solar wind parameters.

[8] One way to quantify this change in the solar wind character is to calculate the correlations between density and speed as a function of distance (we neglect the magnetic field data for now as they are routinely available only through 1989 when Voyager 2 was near 30 AU). Figure 2 shows the correlations of speed and normalized density. We are looking for large scale correlations as observed in the data, so the correlations are calculated for 25-day (one solar rotation) running averages of the data. We use a 5 AU interval to compute the correlation and slide the interval 1 AU for each new determination of the correlation. The choice of a 5 AU interval was driven by the scale of the observed features, which have scale sizes of a few AU. Changing the box size by several AU does not significantly affect the results. The correlation coefficients for the data are shown by the solid line. The locations of solar maxima are shown by the hatched regions. The plot shows a strong solar cycle dependence of the correlations, with correlations negative near solar minimum and positive at solar maximum. The correlations in the solar maximum periods increase with radial distance, and are almost 0.7 during the current solar maximum. Thus the features shown in Figure 1 are qualitatively and quantitatively different from those observed nearer the Sun.

[9] These features are probably merged interaction regions (MIRs) formed from the merging of transient and co-rotating events of solar origin [*Burlaga et al.*, 1984; *Burlaga*, 1995]. The first density, dynamic pressure, and speed enhancement followed the October 2001 shock (2001.78); this shock was likely formed from the merging of the many CMEs observed in April and May of 2001 [*Wang and Richardson*, 2002]. If these are MIRs, their character has changed from that observed in the previous solar cycle in that the density and speed now change in phase, perhaps the result of further radial evolution. The other difference is that Voyager 2 is at a higher latitude, 25°S, whereas it was near the helioequator for both previous solar maxima.

3. Model

[10] We use a numerical model to propagate the solar wind observed at Earth to the position of Voyager 2. The 1-D MHD model includes the effect of pickup ions and is more fully described in *Wang et al.* [2000] and *Wang and Richardson* [2001]. We use an interstellar neutral density at the termination shock of 0.09 cm^{-3}; this density yields a solar wind speed decrease which matches the observations [*Wang et al.*, 2000; *Wang and Richardson*, 2003]. The effect of solar wind pickup of interstellar neutrals is important for the propagation out to the radial distance of Voyager 2 as it decreases the solar wind speed by about 50 km/s and heats the solar wind.

[11] The model is run with average solar wind parameters as input at 1 AU until a steady state heliosphere is reached. Then we use the hourly average solar wind values from ACE beginning at the start of 2001 as the solar wind input at 1 AU and follow the plasma outward. We interpolate across the data gaps in the ACE data. The dotted lines in Figure 1 show the model predictions for 25-day running boxcar averages of the solar wind speed, density, dynamic pressure, and magnetic field magnitude. The first event is the October 2001 shock which the model reproduces quite well. In general, we do not expect the model to replicate the

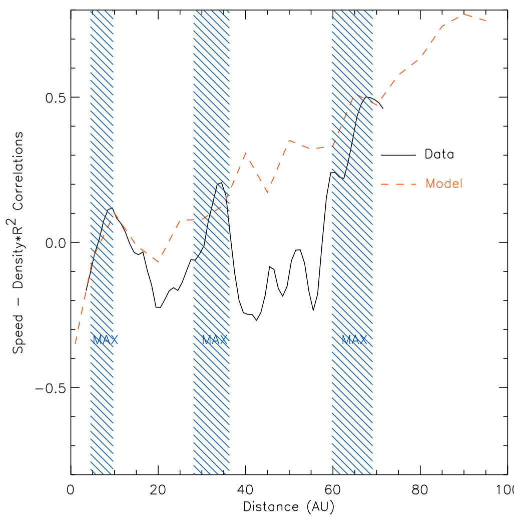

Figure 2. Correlations between the speed and density. Solid line shows correlations of 25-day running averages of the Voyager 2 data; the correlations were done over 5 AU intervals of data, one point/AU. The dashed line shows the equivalent model values.

observations feature by feature since ACE and Voyager 2 are at different latitudes and longitudes. Instead, we investigate whether the character of the data is the same. Figure 1 shows that the model does capture the character of the density, dynamic pressure, and magnetic field insofar as all these parameters show large, in-phase variations with time scales of 6–12 months. The model and data structures do not match in number or length, but we do not expect them to since the longitude and latitude of the model input and Voyager are different. In both the model predictions and data these enhancements are in phase. The amplitude of the model density and pressure variations are similar to those observed. The amplitudes of the model speed variations are only about half those observed and, in particular, the low speed, below 350 km/s, regions are not reproduced by the model. The model magnetic field has higher peak values than those observed. The model speed, density, and magnetic field magnitude vary in phase as observed.

[12] We compare the density-speed correlations from the model and from the data by looking at the model parameters every 5 AU from 5 to 95 AU. The correlation coefficients are calculated over 550 days of model output, and we again perform the correlation calculations on 25-day running averages of each solar wind parameter. The 550-day interval was chosen because that is roughly the time it takes Voyager 2 to travel 5 AU in the outer heliosphere, so that we can compare these results with the correlations of the data shown in Figure 2.

[13] The dashed line in Figure 2 shows the model results which are based on input for a period just after solar maximum. At the three solar maxima, shown by the hatched areas, the model and observed speed-density correlations agree. The model predicts that the correlations will increase with distance out to 95 AU. The data and model correlations do not agree well between the solar maxima. This result is not surprising as we use solar maximum data at 1 AU as the model input, so the model results are only applicable at solar maximum. However, we also ran the model using data from the 1996–1997 solar minimum as input. The model profile of the correlations for this input data set for this period is nearly identical to that at solar maximum outside of 10 AU. At solar minimum fast, tenuous streams at >20° latitude and slow, dense streams near the equator are the dominant plasma structures and result in anti-correlated speeds and temperatures. This deviation from the spherical symmetry implicitly assumed in the 1-D model may lead to the discrepancies between model and data at times other than solar maximum. We will continue to try to understand discrepancy between the model and the data at solar minimum.

[14] We can also use the model to look at the correlations between the plasma speed and density and the magnetic field magnitude. Figure 3 shows that the model predicts that the correlation between the magnetic field magnitude and speed changes from slightly negative at 1 AU to 0.4 at 10 AU, then decreases to below 0.2 at 20 AU, then increases with distance. Due to the low values of the magnetic fields at large heliocentric distances, we have continuous magnetic field data only inside 30 AU. The V-B and B-N correlations observed in the data are shown, as well as the correlation for 2002. The model results are consistent with the V-B correlations both inside 30 AU and at 67 AU. The correlation between density and magnetic field decreases with distance from 0.6 near Earth to near zero at 30 AU, but was up to 0.64 in the 2002 data at 67 AU. The model shows a high correlation between B and N throughout the heliosphere, but this high value probably results from the 1-D nature of the model which forces B and N changes to occur synchronously.

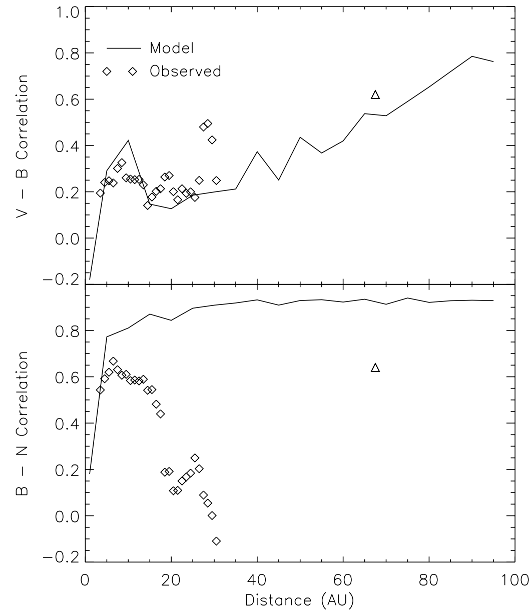

Figure 3. Correlations between the speed and magnetic field magnitude and between the density and the magnetic field magnitude using 25-day averages of the model results and of the data (when available).

4. Discussion and Summary

[15] The recent solar maximum period observed by Voyager 2 near 70 AU is characterized by a new phenomenon, in-phase fluctuations of the plasma density, speed, dynamic pressure and magnetic field magnitude. These result in order of magnitude increases in the dynamic pressure of the solar wind every 6–12 months.

[16] These dynamic pressure changes are predicted by a 1-D MHD model. Using 1 AU data as input for the model results in correlated speed, density, and magnetic field profiles and order of magnitude dynamic pressure variations similar to those observed. The model predicts that these effects will continue to become more pronounced with distance during solar maxima. The model also predicts similar correlated features at solar minimum which have not been detected to date. Both the solar cycle dependence and the evolution predictions for these events will be tested as Voyager 2 moves outward.

[17] The observed large fluctuations of the dynamic pressure can have a significant impact on the structure of the heliosphere. *Zank and Muller* [2003] show that large dynamic pressure pulses can produce heliospheric disturbances which persist for nearly a solar cycle. A succession of such events such as those observed would drive multiple shocks through the heliosheath, creating a very dynamic and complicated plasma and magnetic field environment in that region.

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