Statistical properties of the solar wind

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Abstract. This paper presents some new and some updated data on the variation of the solar wind with solar cycle and distance from the Sun. The dynamic pressure of the solar wind is a minimum at solar maximum, the same time the standard deviation in pressure is a maximum, so the crossing of the termination shock is most likely at the next solar maximum in 2001. The degree of correlation between plasma parameters maximizes at solar minimum, possibly because stream interactions are a minimum then. The standard deviations of the radial velocity decrease rapidly out to 20 AU, then flatten out. Standard deviations of the density and temperature decrease with distance less steeply than those of the speed.

Introduction

We are beginning to fill in our knowledge of the the spatial and temporal structure of the solar wind as spacecraft continue entering new regions of the heliosphere and extending data sets in time. We look at data from the Pioneer Venus orbiter (0.7 AU, 1978-1993), IMP 8 (1 AU, 1973-present), Voyager 2 (1-45 AU, 1977-present), Pioneer 11 (1-36 AU, 1973-1992), and Pioneer 10 (1-61 AU, 1972-present). These extensive data sets allow us to describe solar wind changes with time and radial distance.

Studies of the statistical properties of the solar wind have been undertaken since sufficient spacecraft data were available, most from spacecraft near Earth orbit [e.g., Wolfe, 1972]. Particular interest has been paid to correlations between plasma parameters and to solar cycle variations. Solar cycle variations have been observed in the solar wind speed and pressure [Neugebauer, 1975; Bridge, 1976; Gosling et al., 1976; Grzedzielski and Lazarus, 1993]. Solar wind speed and density are anti-correlated, speed and temperature are correlated, and azimuthal (but not polar) flows are correlated with speed [Hundhausen et al., 1970; Burlaga and Ogilvie, 1970; Wolfe, 1972]. In this paper we look at other solar cycle variations, radial distance variations, and look at standard deviations as well as the parameters themselves.

Solar Cycle Variations

Although the variations of velocity and dynamic pressure with solar cycle were discussed recently [Richardson et al., 1995, Gazis, 1995], the importance of the pressure in determining the location of the termination shock and heliopause justifies its inclusion. We also discuss variations of the standard deviations of this quantity which are not described elsewhere.

Figure 1 shows the dynamic pressure in nP observed by IMP 8 and PVO. Each point shows the average of six months of data. The dotted lines show six-month averages of the sunspot number. The pressure profiles generally exhibit minima at the solar maxima which occurred from 1979–1981 and 1989–1991, although the minimum in IMP 8 pressure in the latter maximum is very narrow. The maximum pressure generally occurs in the declining phase of the solar cycle roughly three years after solar maximum. The variation in pressure over a solar cycle is about a factor of two. For these two spacecraft, the standard deviations

Fig. 1. The IMP 8 and PVO dynamic pressures and standard deviations of pressure plotted versus time. The dotted line shows the sunspot number.
roughly follow the pressure profile except at solar minimum where it is small. Thus the standard deviation of pressure is low at solar minima and solar maxima in the inner heliosphere.

Considerable evolution of the solar wind occurs before plasma parameters are measured by Voyager 2, now at 46 AU. Figure 2 shows six-month averages of the pressure and standard deviation of the pressure observed by Voyager 2 versus time. The pressures are normalized to 1 AU by multiplying by $R^2$. The pressure profile looks very similar to that in the inner magnetosphere; the pressure profile has a minima at solar maxima and peaks in the declining phase of the solar cycle, with a total pressure variation of about a factor of two. The standard deviation evolves a relatively smooth profile in the outer heliosphere with a maximum at the minimum in pressure (which is at the solar maximum in 1991). This has important consequences for the motion of the heliopause and termination shock. As described by numerous authors [see Belcher et al., 1993], the location of the heliopause and termination shock vary as the square root of the pressure, so a factor of two change in pressure gives a 40% variation in the equilibrium position of these boundaries. The standard deviation is comparable to the pressure at this time, so much lower pressures than the average occur often, bringing the boundaries in even closer.

The degree to which the boundaries move in response to solar wind pressure changes is not known, but they may be far from their equilibrium positions. The location of the heliopause and termination shock depend on the pressure in the interstellar medium, which is poorly known. Assuming the external pressure is relatively constant, boundary position changes are thus determined by changes in the solar wind dynamic pressure. These data suggest that if the Voyager spacecraft are to cross the termination shock in the near future, the most likely time is during the next solar maximum in roughly 2002, when Voyager 1 will be at 83 AU and Voyager 2 at 66 AU.

Correlations

In this section we investigate the change in the relationship between plasma parameters over the course of a solar cycle. Figures 3 and 4 show the correlations between radial velocity and density, radial velocity and temperature, and density and temperature for IMP 8 and PVO, respectively. The data is again divided into 6-month bins and the correlations calculated for the data in each bin. The dotted lines show six-month averages of the sunspot number. The amplitude and axis direction of the sunspot plots are adjusted to facilitate comparison with the correlation data, as shown by the right axis.

![Fig. 2. The Voyager 2 dynamic pressure and standard deviation of pressure plotted versus time. The dotted line shows the sunspot number.](image)

![Fig. 3. The correlation between plasma parameters observed by IMP 8 (crosses) and the sunspot number (dotted line).](image)

Figures 3 and 4 show similar results for IMP 8 and PVO. The level of correlation (or anti-correlation) is strongest at solar minima (1976 and 1986) and weakest at solar maxima (1980 and 1990). Velocity and density are anti-correlated with correlation coefficients of -0.5 to -0.6 at solar minimum but only -0.2 (IMP 8) and -0.4 (PVO) at solar maximum. The variation of the correlation of velocity and temperature and of density and temperature also show a very clear solar cycle dependence. A possible explanation is that stream-stream interactions are more important at solar maximum when the Sun’s magnetic configuration is less ordered and
CME's more common. The stream-stream interactions may cause the solar wind to evolve enough by the time it reaches Venus and Earth that the correlations imposed at the source are diminished. At solar minimum, when the Sun's magnetic configuration is more structured, stream-stream interactions are less important.

The correlation coefficients decrease with distance from the Sun. Figures 3 and 4 show that even between Venus and Earth the correlation coefficients decrease significantly, particularly at solar maximum. Figure 5 shows the correlations observed by Voyager 2 as a function of distance from the Sun out to 20 AU. The data are divided into 1 AU bins, i.e., the first point is calculated from data obtained between 1 and 2 AU. The velocity-density anti-correlation is gone by the 3-4 AU bin. The temperature correlation with velocity decreases with distance and is small outside 10 AU. We conclude that evolution of the solar wind acts quickly to remove the correlations present at the source of the solar wind near the Sun, more quickly at solar maxima than solar minima.

The density and temperature profiles (not shown) do not exhibit solar cycle variations. The non-radial solar wind velocity components do show variations, especially in the standard deviations of the flow angles [Richardson et al., this volume].

**Radial Distance Effects**

An early study of Pioneer 10 data by Collard et al. [1982] shows that the standard deviation of the radial velocity falls off as a power law between 1 and 15 AU. Projecting this result outwards, they concluded that the solar wind would be smooth and essentially featureless outside 30-40 AU. This is not the case; very clear solar rotation signatures are still observed at 45 AU [Richardson et al., 1995]. Figure 6 shows why this prediction failed. We plot the standard deviation of the radial velocity for Pioneers 10 and 11 and Voyager 2, where the velocity is divided into 1 AU bins. The standard deviations decrease from roughly 80 km/s to 20 km/s as the spacecraft move from 1 to 20 AU, which was the basis of the Collard et al. [1982] result. Outside 20 AU, the character of the profile changes and it becomes nearly flat. Some scatter is present, but the standard deviations outside 20 AU are generally on the order of 20 km/s and never fall below 10 km/s. The smoothing of the solar wind velocity profile with distance is usually ascribed to shock processing, with the shocks forming at the boundaries between fast and slow streams. This at least qualitatively explains the decrease in standard deviations in the inner heliosphere. We don’t understand why the decrease stops; perhaps the speed differences in the wind are too small or the shocks too weak for efficient inter-stream momentum transfer to occur.

Figure 7 shows the density and temperature profiles measured by Voyager 2 as it moves outward and the standard deviations of these quantities. The data is again divided into 1 AU bins. The density decreases as $R^{-1.93 \pm 0.04}$.

Fig. 4. The correlation between plasma parameters observed by PVO (crosses) and the sunspot number (dotted line).

Fig. 5. The correlation between plasma parameters observed by Voyager 2 as it moved from 1 to 20 AU.

slightly less than expected for spherical expansion of the solar wind. The standard deviations decrease as $R^{-2.15 \pm 0.05}$ so the smoothing of the density profile by solar processing is as rapid as for the speed as pointed out by Richardson et al. [1995]. The temperature decreases as $R^{-0.46 \pm 0.06}$, and is very similar to the Pioneer 10 profile [Richardson et al., this volume]. The standard deviation decreases at a similar rate,
Fig. 6. Standard deviations of the solar wind speed versus distance for Voyager 2, Pioneer 10, and Pioneer 11.

as $R^{-0.56\pm0.09}$. To make the comparison more clear, by 40 AU the standard deviations of speed decrease by a factor of 4, those of the density decrease by a factor of 2.3, and those of temperature decrease by a factor of 1.4.

Fig. 7. The density, temperature, and standard deviations of these quantities measured by Voyager 2 from 1 to 45 AU. Also shown are the best fits of a power law to the data.

Summary

We have described changes in the solar wind which occur as a function of solar cycle and/or distance from the Sun. The solar wind dynamic pressure is a minimum at the same time the standard deviation peaks, both occurring at solar maximum. Since Voyager 1 is approaching the predicted distance of the termination shock, the next solar maximum is a preferred time for Voyager to cross this boundary. The degree of correlation between solar wind parameters varies over the solar cycle with the best correlation at solar minimum. The standard deviation of the radial velocity declines out to 20 AU, then flattens out, so we expect to see substantial structure in the solar wind parameters until the termination shock is encountered.

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