Latitudinal distribution of the solar wind properties in the low- and high-pressure regimes: Wind observations

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Abstract. The solar wind properties depend on $\lambda$, the heliomagnetic latitude with respect to the heliospheric current sheet (HCS), more than on the heliographic latitude. We analyse the wind properties observed by Wind at 1 AU during about 2.5 solar rotations in 1995, a period close to the last minimum of solar activity. To determine $\lambda$, we use a model of the HCS which we fit to the magnetic sector boundary crossings observed by Wind. We find that the solar wind properties mainly depend on the modulus $|\lambda|$. But they also depend on a local parameter, the total pressure (magnetic pressure plus electron and proton thermal pressure). Furthermore, whatever the total pressure, we observe that the plasma properties also depend on the time: the latitudinal gradients of the wind speed and of the proton temperature are not the same before and after the closest HCS crossing. This is a consequence of the dynamical stream interactions. In the low pressure wind, at low $|\lambda|$, we find a clear maximum of the density, a clear minimum of the wind speed and of the proton temperature, a weak minimum of the average magnetic field strength, a weak maximum of the average thermal pressure, and a weak maximum of the average $\beta$ factor. This overdense sheet is embedded in a density halo. The latitudinal thickness is about 5° for the overdense sheet, and 20° for the density halo. The HCS is thus wrapped in an overdense sheet surrounded by a halo, even in the non-compressed solar wind. In the high-pressure wind, the plasma properties are less well ordered as functions of the latitude than in the low-pressure wind; the minimum of the average speed is seen before the HCS crossing. The latitudinal thickness of the high-pressure region is about 20°. Our observations are qualitatively consistent with the numerical model of Pizzo for the deformation of the heliospheric current sheet and plasma sheet.

Key words: Interplanetary physics (solar wind plasma)

1 Introduction

Observations of the latitudinal distribution of the solar wind properties (velocity, density, temperatures) are necessary to test models of the solar wind, and models of the heliospheric plasma sheet (HPS) which surrounds the heliospheric current sheet (HCS). The exploration by Ulysses of the heliographic latitude range $-80^\circ \leq \lambda_G \leq 80^\circ$ (N) yielded the density and the speed of the wind as functions of $\lambda_G$ (Phillips et al., 1995; Issautier et al., 1997). Latitudinal models of the solar wind have been compared with the Ulysses data averaged over the 26 days of a solar rotation (Lima and Tsynganos, 1996; Suess et al., 1996). In these models the HCS, i.e. the magnetic equator, is assumed to be in the plane of the heliographic equator; the axis of the dipolar solar magnetic field is along the solar rotation axis. These axisymmetric models neglect the dynamical interactions between the fast and the slow streams of the wind. They also assume north-south symmetry. These models can be fitted to the Ulysses data, in which the density $N_p$ is about 2.7 times larger and the speed $V_{sw}$ 1.8 times smaller at $\lambda_G = 0^\circ$ than at $|\lambda_G| = 80^\circ$. $N_p$ and $V_{sw}$ averaged over a solar rotation may thus be considered as controlled by $\lambda_G$. On the other hand, the high-resolution measurements of $N_p$ and $V_{sw}$ display several peaks and troughs for $-40^\circ \leq \lambda_G \leq 20^\circ$ (Phillips et al., 1995). The occurrence of these peaks and troughs is not related to $\lambda_G$. Thus, the non-averaged density and speed are not controlled by $\lambda_G$.

As shown for instance by Zhao and Hundhausen (1981), the solar wind properties at 1 AU are more closely dependent on the heliomagnetic latitude $\lambda$ than on the heliographic latitude $\lambda_G$. These authors assumed that the HCS was a plane tilted at about 30° to the solar heliographic equator; $\lambda$ is the latitude with respect to this planar HCS, counted in an heliographic meridian plane. However, the HCS is generally not a plane. Bruno et al. (1986) avoided this hypothesis: they derived the shape of the warped and tilted HCS close to the Sun

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from the maximum brightness curve at 1.75 solar radii observed in the solar corona by the HAO K-coronameter. They did not determine the latitude \( \lambda \) of the spacecraft with respect to the HCS but its angular distance \( \delta \) from the HCS, in a direction perpendicular to it. Bruno et al. (1986) only considered solar wind regions without stream interactions. In 1976 and 1977, close to a minimum of solar activity, they found a clear dependence of \( V_{sw} \), \( N_p \) and the proton temperature \( T_p \) on \( \delta \): \( V_{sw} \) and \( T_p \) were minimum, and \( N_p \) was maximum at low \( \delta \). The latitudinal profiles of \( N_p \) and \( T_p \) were symmetrical about the HCS; \( V_{sw} \) was less symmetrical.

The heliomagnetic latitude \( \lambda \) (or \( \delta \)) is not a local quantity which could be measured by a spacecraft; it can only be estimated using models of the HCS at 1 AU, relying on different observations in the photosphere and in the corona (see the comparative analysis of these models made by Neugebauer et al., 1998). The HCS model is always assumed to be a warped but continuous surface all around the Sun, from a few solar radii to several AU. In the present work, we shall start from the classic model of the HCS (Hoeksema et al., 1983) described in Sect. 2, but we shall fit it to the sector boundary crossings observed on Wind over 70 days in 1995. With this fitted HCS, we obtain the fitted heliomagnetic latitude \( \lambda_f \) of Wind, which varies between \(-20^\circ\) and \(30^\circ\) during the interval considered. This relatively large interval of \( \lambda_f \) justifies the use of the data of Wind for a study of latitudinal effects in the solar wind.

We find that \( N_p \), \( V_{sw} \) and \( T_p \) observed at 1 AU on Wind are indeed functions of the heliomagnetic latitude \( \lambda_f \), but these functions are different in two kinds of wind: the low-pressure wind, where the total pressure (magnetic pressure plus electron and proton thermal pressure) is below about \( 5 \times 10^{-11} \) Pa, and the high-pressure wind. A clear minimum of \( V_{sw} \) and \( T_p \) at low latitudes is seen only in the low-pressure wind. In both kinds of wind, we find that the profiles of \( N_p \), \( V_{sw} \) and \( T_p \) display a crude north-south symmetry. But we show in Sect. 5 that the latitudinal gradients of \( V_{sw} \) and \( T_p \) are not the same before and after an HCS crossing: even in the low-pressure wind there are indications of the part played by the fast stream-slow stream interactions. We show that our observations are qualitatively consistent with the MHD model of Pizzo (1994). In this model the stream interactions are taken into account, and the deformations of the HCS and of the HPS are calculated (at 5 AU).

We shall particularly address the question of the latitudinal distribution of the density in the solar wind. Borrini et al. (1981) (see also Gosling et al., 1981) analysed several tens of magnetic sector boundaries or HCS crossings. They found two types of overdense regions in the ecliptic plane: (1) the stream-free overdensities which are found close to the HCS even if the HCS crossing is not followed by a fast stream within 24 h; (2) overdensities observed just before fast streams, and due to dynamical interactions in the wind. These two kinds of overdensities are often superimposed close to the HCS. We shall consider all the solar wind regions in the ecliptic plane where \( N_p \) measured by Wind is significantly enhanced over a time period devoid of magnetic clouds or strong interplanetary shocks. Over this continuous interval of 70 days we can test whether there is always an overdensity at the sector boundary. The existence and the strength of this overdensity are important parameters for studies of the propagation of low-frequency radio waves in the interplanetary medium (Steinberg et al., 2000).

2 The data

The proton density \( N_p \) on Wind is measured by the SWE experiment (Ogilvie et al., 1995), the magnetic field by the MFI experiment (Lepping et al., 1995), and the temperatures \( T_e \) and \( T_p \) by the 3D-plasma experiment (Lin et al., 1995). We used the key parameters (KP) data of these three experiments: they have a time resolution of \( \approx 15 \) min (930 points per day). We also used the detailed electron distribution functions measured by the 3D-plasma experiment up to about 1 keV. We integrated these electron distribution functions to calculate the electron heat flux vector every 1.5 min. All the KP data and the calculated quantities have been smoothed and resampled to give only 125 points per day (averages over about 10 min).

The interval chosen is close to the solar cycle minimum. It extends from May 15, 1995, to July 23, 1995, i.e. from 135.0 to 205.0 decimal days of the year. It was selected because no transient, magnetic cloud or strong interplanetary shock was observed over the 70 days (Sanderson et al., 1998). Until the end of June, Wind was around the Lagrange point, more than 200 Earth radii (\( R_E \)) away from the Earth; in July, Wind went back towards the Earth, and it was at about 100\( R_E \) away from it on July 24. From day 157.6 to 161.6, there are frequent and large data gaps in the electron distribution functions, so that the calculated averages of the electron heat flux can be biased. From day 185.1 to 187.6, neither the distribution functions nor the KP data were completely corrected for the effect of the photoelectrons. During the rest of the interval (days 135.0 to 185.1, days 187.6 to 205.0), the perturbations to the distribution functions due to the photoelectrons can be neglected in the calculation of the heat flux.

The basis of our determination of the heliomagnetic latitude of Wind at 1 AU is the classic model of Hoeksema et al. (1983) for the HCS, which is available on line and used in several studies (Sanderson et al., 1998; Ma et al., 1999). In this model, the position of the neutral line of the photospheric magnetic fields is deduced from the observations of the Wilcox Solar Observatory. The resolution of the synoptic charts of the photospheric field is \( 5^\circ \) in latitude and in longitude. Above the photosphere, the magnetic field is assumed to be potential and is calculated up to 2.5 solar radii. Higher up the magnetic field is assumed to be radial, so that the heliographic latitude \( \lambda_{hcs} \) of the neutral line (the HCS) at 1 AU is the same as at 2.5 solar radii, with a time delay of 5 days. The delay of 5 days, corresponding