IPS OBSERVATIONS OF THE SOLAR WIND VELOCITY AND THE ACCELERATION MECHANISM

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ABSTRACT

Coronal holes are well known sources of high speed solar wind, however, the exact acceleration mechanism of the wind is still unknown. IPS observations indicate that the average velocity of 800 km s$^{-1}$ within several solar radii with large velocity fluctuations. However, the origin of the large IPS velocity spread below 10$R_{\odot}$ is unclear. We apply a previously developed coronal hole model with a more realistic initial state and numerically solve the time-dependent, nonlinear, resistive 2.5-D MHD equations. We find that nonlinear solitonic-like waves with a supersonic phase speed are generated in coronal holes by torsional Alfvén waves in the radial flow velocity. The outward propagating nonlinear waves are similar in properties to sound solitons. When these waves are present the solar wind speed and density fluctuate considerably on a time scale of an hour and on spatial scales of several solar radii in addition to the Alfvénic fluctuations. This is in qualitative agreement with the IPS velocity observations beyond 10$R_{\odot}$.

Key words: Solar Wind; IPS Observations; MHD simulation; Waves; Nonlinear phenomena.

1. Introduction

Coronal hole regions are well known sources of high-speed solar wind (Krieger, Timothy, and Roelof 1973; Neupert and Pizzo 1974; Wagner 1976; Nolte et al. 1976; Rickett et al. 1976; Coles et al. 1980). Recently, the Ulysses spacecraft has encountered continuous fast solar wind in the range 700-800 km s$^{-1}$ above the polar coronal holes at a distance of $\sim$1.6 A.U. (Phillips et al. 1995). Interplanetary Scintillation (IPS) measurements indicate that the average solar wind velocity of 800 km s$^{-1}$ is reached within a few solar radii of the Sun with a large spread in the range of 100-1000 km/s (Grall et al. 1996; Klinglesmith 1996). In the present study we propose that this spread may indicate the presence of large amplitude nonlinear waves in the radial flow velocity.

Thermal conduction alone as the acceleration mechanism is not sufficient to explain the observed flow speed of the high speed streams (e.g., Kopp and Holzer 1976; Holzer and Leer 1980; Leer and Holzer 1980; Davila 1985). To account for the observed properties of the solar wind Alfvén waves were suggested as a source of momentum and heat, and studied in the linear regime (e.g., Alazraki and Courtier 1971; Belcher 1971; Hollweg 1973; Jacques 1977; Davila 1985; Davila 1987; An et al. 1990; Ofman and Davila 1995). Alfvén waves were also suggested as the driving mechanism for stellar winds in late type stars (e.g., Belcher and Olbert 1975; Heinemann and Olbert 1980). At present there is no observational evidence that network activity at the base of the coronal hole can provide the necessary heat and momentum input for the fast solar wind.

Recently, Ofman and Davila (1997a) (hereafter, OD97) investigated the nonlinear effects due to Alfvén waves in coronal holes via numerical solution of the nonlinear 2.5-D resistive MHD equations in a spherical geometry with an $(r, \theta)$-inhomogeneous atmosphere and the hydrostatic initial state. They found that nonlinear longitudinal waves are driven by torsional Alfvén waves. These waves resemble solitons in their relation between the phase speed and amplitude. The nonlinear waves form when the steepening of longitudinal sound waves, driven by the Alfvén waves, is balanced by dispersive and dissipative effects in the inhomogeneous coronal hole structures. These waves, acting on a hydrostatic initial condition, may accelerate the solar wind to supersonic velocities. Ofman and Davila (1997b) suggested that the nonlinear solitonic-like waves may explain the apparent broadening of ion emission lines observed by the SOHO Ultraviolet Coronagraph Spectrometer (UVCS). Ofman and Davila (1997c) explored in detail the dependence of the solar wind velocity on the coronal parameters, such as, the temperature, background magnetic field, and Alfvén wave amplitude.

In the present study we use the 2.5D MHD model to explain the large solar wind velocity fluctuations inferred from the IPS observations. We use similar numerical technique and geometry as OD97, replacing the hydrostatic initial state with Parker's (1963) isothermal solar wind solution (as in Ofman and Davila 1997c). In particular, we find that low


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frequency Alfvén waves with a period of about an hour drive nonlinear waves in the radial flow velocity, which contributes significantly to the acceleration of the solar wind in coronal holes. The dynamical evolution and the spatial variability of the nonlinear wave driven wind are in good qualitative agreement with IPS observations for the region beyond 10 solar radii reported below.

2. IPS Observations

The IPS method of estimating the solar wind velocity is indirect and subject to several possible biases. However it can provide velocity estimates where direct measurements have not been made, and it can provide an estimate of the velocity distribution averaged over a “scattering volume”. In this method a distant radio source is observed at a time when the radio path passes near the Sun. The radio wave is phase modulated by the electron density fluctuations near the Sun. As the modulated wave continues to propagate to the Earth, the smaller scale phase modulation is converted to intensity modulation by diffraction. The dominant scale of the intensity diffraction pattern is the radius of the first Fresnel zone, about 70 km for most of the observations shown here.

The velocity of the density fluctuations can be estimated by measuring the resulting intensity fluctuations with a pair of separated antennas. The time series measured at the two antennas are similar but one is delayed by the transit time. The transit time provides a measure of the mean speed. The decorrelation between the two time series is a measure of the range of velocities which has contributed to the diffraction pattern.

The two time series are compared with a correlation analysis. If the cross correlation is simply a delayed version of the autocorrelation, then the pattern can be characterized by a single velocity. However in practice there is a range of velocities caused by the spherical divergence of the solar wind. In addition there may be other causes of a velocity spread. The two most obvious causes of velocity spread have quite distinctive effects on the cross correlation. A range of radial velocities causes a characteristic skew because both the width and the delay of the cross correlation are inversely proportional to the velocity. The higher speeds cause narrow cross correlations near the origin, whereas the slower speeds add broad wings with long time lags. The effect of outwards propagating Alfvén waves is also distinctive because they cause the apparent flow direction to fluctuate. If the density fluctuations are field aligned, one can also see the effect of fluctuations in the field orientation.

The accuracy of the transit-time speed estimation is linearly proportional to the separation of the antennas, and the accuracy of the measurement of the spread of velocity depends quadratically on the antenna separation. Thus the observations reported here, which have been made with baselines a factor of 10 longer than earlier work, are much more accurate in both respects.

IPS measurements were recently reported as close as 10 \( R_\odot \) (Grall et al. 1996) using a wavelength of 32 cm. We have extended these observations inwards to 2.4 \( R_\odot \), using two telescopes of the Very Long Baseline Array, a radio telescope operated by the National Radio Astronomy Observatory, at shorter wavelengths. In Figure 2 we show the range of radial velocities necessary to fit IPS observations (vertical bars). The two bars at each distance represent the extremes of a family of satisfactory model fits obtained by integrating over an observing time of 10 minutes with typical total observing time of 2 hours. The bars are plotted at a distance corresponding to the closest point of approach of the line of sight to the Sun. The mean distance of the scattering volume probed by the IPS observation is 1.27 times this distance. The two dotted lines indicate the maximum and minimum velocity inferred from the Ulysses spacecraft observations at the same time and latitude range.

The new results confirm the early measurements, that the mean IPS speed does not decrease as the Sun is approached, even as close as 2.4 \( R_\odot \). They also show that the range of speeds present along the line of sight \( \delta v_r \) increases rapidly as the Sun is approached, approximately as does the Alfvén speed. There are no other observations supporting \( v_r \sim 1000 \text{ km/s} \) at 2.4\( R_\odot \). There are Doppler dimming observations by the SOHO UVCS which suggest \( v_r = 250 \pm 100 \text{ km/s} \) (Kohl et al. 1996). However, we have not been able to match the IPS data without invoking a very wide range of \( v_r \) at or inside of 10\( R_\odot \).

The IPS observations do not show much time variability during the several hours of an observation, nor from one observation to another. This suggests that the inhomogeneities which cause the range of radial speeds are always present, and of relatively small scale compared with the size of the scattering volume (which subtends an angle of about 70° at the Sun).

The most important biases in the IPS observations are due to the line of sight integration and the possible presence of traveling density waves. The correlation analysis compensates for the line of sight integration and the effect of linear Alfvén waves, but the apparent IPS velocity is that of the density fluctuations. If the density fluctuations are caused by static pressure-balance structures, as appears to be the case outside of 80 \( R_\odot \), then the IPS speed is equal to the flow speed. However, if the density fluctuations near the Sun are caused by propagating density waves, then the IPS velocity is the sum of the flow speed and the group velocity of the density waves.

3. Coronal Hole Model

Here, we use the OD97 model of normalized resistive, isothermal, 2.5D MHD equations, assuming azimuthal symmetry (i.e., \( \frac{\partial}{\partial \theta} = 0 \)). The coronal hole is modeled by a cone in spherical geometry confined between \( \pi/2 - \theta_0 < \theta < \pi/2 + \theta_0 \), with \( \theta_0 = 0.375 \), the pole of the Sun at \( \theta = \pi/2 \), and 1 \( \leq r/[R_\odot] \leq 40 \) (see OD97 for details on the model). The simulations are initiated with the background density profile

\[
\rho_0(r, \theta) = \left[ 1 - (1 - \rho_\infty) e^{-(\theta - \pi/2)/\theta_0^2} \right] \rho(r)/\rho_\infty,
\]

where \( \rho_\infty = \frac{1}{3} \), and \( 2\theta_0 = 0.4 \) is the angular extent of the low density region in the center of the
The initial radial dependence of the density and radial velocity is determined by Parker (1963) isothermal solar wind solution with the pressure at \( r = 1 \) given by the angular part of \( \rho \) (OD97 used a hydrostatic initial state). The background magnetic field is taken to be radial: \( B_0 = B_0(\theta) \rho^{-2} r \).

As in OD97 we use the following boundary conditions at \( r = 1 \) to generate Alfvén waves: \( B_0(1, \theta) = \nu_A(1, \theta) \cos \omega t \), with \( B_0(1, \theta) = B_{r,0} \), \( \nu_A(1, \theta) = B_0(1, \theta) = 0 \), and \( \nu_r(1, \theta) \geq 0 \). The boundary conditions for the remaining variables must be determined by the incoming characteristic equations. Near the solar surface the solar wind is sub-sonic and sub-Alfvénic, thus there are 3 incoming and 4 outgoing characteristics. At \( r = 1, \theta = 0 \), and \( \theta = \pi/2 \) we assume symmetry and solve the 2.5D-MHD equations in the domain \( (\pi/2, \pi/2 + \theta_0) \times (1, 40) \), using the Runge-Kutta method with 4th order accuracy in space and time. In addition a 4th order smoothing term (i.e., numerical viscosity) and an up-wind radial derivative of the density is used to make the solution more stable. Up to 64\times1024 uniform grid points are used, with the time step determined by the Courant-Friedrichs-Lewy (CFL) condition.

4. Numerical Results

In the present study we use the following coronal hole parameters at the base of the coronal hole (\( r = 1 \), \( \theta = \pi/2 \)): \( \rho_0 = 10^{10} ~ \text{cm}^{-3} \), \( B_0 = 7 \) G, which yields the Alfvén speed \( v_A = 1527 \text{ km s}^{-1} \) and the Alfvén time \( \tau_A \approx 458 \text{ s} \), with \( v_A = 0.02 v_A \approx 30.5 \text{ km s}^{-1} \) (consistent with the observed nonthermal velocities in the corona (Hassler et al. 1990)), \( \omega = \tau_A^{-1} \approx 3.47 \times 10^{-4} \text{ Hz} \), Froude number \( F_r = c_A^2 R_\odot / GM \approx 12.9909 \) and the Euler number \( E_u = c_A^2 / \gamma \approx 9.91424 \times 10^{-3} \) that corresponds to \( T_0 = 1.4 \times 10^9 \text{ K} \) and the sound speed \( c_s = 152 \text{ km s}^{-1} \). We have found that \( v_r \) and \( \delta v_r \) discussed below increase when \( v_A \) or \( B \) are increased, or when \( T \) is decreased. We also found that higher frequency Alfvén waves lead to smaller solar wind acceleration. A detailed parametric study of this model was recently performed by Ofman and Davila (1997c).

In Figure 3 we show the radial dependence of the velocity components \( v_r \) and \( v_\theta \) in units of \( v_A \) in the center of the coronal hole (\( \theta = \pi/2 \)) at time when the simulation has reached a steady state (\( \sim 600 \tau_A \)). The presence of the nonlinear waves is evident in the large radial variations of \( v_r \) and the non-sinusoidal variations of \( v_\theta \) (the outward propagating Alfvénic velocity component). The nonlinear waves in \( v_r \) propagate outwards on top of an average non-zero radial flow with a supersonic phase velocity. The spatial wavelength of the solitary-type waves is \( \sim 3.9 R_\odot \) and the period is \( \sim 8.6 \tau_A \) which yields a phase speed of \( 0.45 v_A \approx 692 \text{ km s}^{-1} \). In the present case the solitary wave phase speed is larger than the solitary wave phase speed obtained by OD97 with hydrostatic initial state. This can be understood as the effect of the Doppler shift of the average zero wave that is determined only on the solitary waves. It is interesting to note that the difference between the average flow in the region \( R > 20 R_\odot \) and the nonlinear wave phase speed is slightly above the sound speed.

For comparison we show in Figure 3 the Parker's isothermal solar wind flow speed (\( v_r, \), Parker). This flow speed with the corresponding density serves as the initial state for our model. It is evident that the nonlinear waves contribute significantly to the solar wind acceleration, which results in an average radial flow speed of about 600 km/s at 40 \( R_\odot \) and a peak radial velocity of about 700 km/s. The magnitude of the radial velocity fluctuations is in qualitative agreement with the velocity fluctuation determined by the IPS observations beyond 10 \( R_\odot \) (see Figure 2). However, the present model does not reproduce the large radial velocity close to the Sun (in the region \( r < 10 R_\odot \)) inferred from the IPS observation. At present there is no additional observational support for the large velocities near the Sun, and it is not clear whether it is possible to reproduce these features with our model.

5. Discussion and Conclusions

IPS observations suggest that the solar wind has a transient and dynamical nature with large spatial and temporal inhomogeneities on angular scales of a few degrees or less (subtended at the Sun). The peak to peak velocity range is about 900 km s\(^{-1}\) at 10 \( R_\odot \) and decrease farther from the Sun. In qualitative agreement with these observations, we show with the 2.5D MHD model that when solitary waves dominate the solar wind speed and density fluctuates considerably in addition to the Alfvénic fluctuations.

The interpretation of the IPS observations below 10 \( R_\odot \) is more complex than the interpretation of IPS observations farther from the Sun (Klinglehoffer 1996). We believe that the large spread in the measured IPS velocity close to the Sun is the combination of compressional wave phase velocity (such as fast
Figure 2. The range of radial velocities that fit IPS observations is indicated by the vertical bars. The two bars at each distance represent the extremes of a family of satisfactory model. The bars are plotted at a distance corresponding to the closest point of approach of the line of sight to the Sun. The mean distance of the scattering volume probed by the IPS observation is 1.27 times this distance. The two dotted lines indicate the maximum and minimum of the Ulysses speeds measured in the same time and latitude range.

Figure 3. The radial dependence of the solar wind velocity components as obtained from the 2.5D MHD simulations at the center of the model coronal hole. The radial component \( v_r \), and the Alfvénic velocity component \( v_\phi \) are shown (\( v_\phi \) is an order of magnitude smaller). For comparison, the Parker’s isothermal solar wind solution (\( v_{r\text{Parker}} \)) for the same parameters is shown.
magnetosonic waves), outflow velocity, and an uncertainty in the velocity fit to the observations. Far from the Sun ($r > 10R_\odot$) the determination of the IPS velocity is more certain, and the spread in the observed velocity is probably dominated by spread in the radial flow velocity in the observed volume.

We model the nonlinear evolution of MHD waves in a nonhomogeneous coronal hole by solving the 2.5-D MHD equations. We find that nonlinear longitudinal waves are generated by torsional Alfvén waves. The nonlinear waves are similar to sound solitons in their form and the relation between their phase speed and amplitude. The nonlinear waves accelerate the wind to supersonic velocities with large temporal and spatial fluctuations in qualitative agreement with IPS observations beyond $10R_\odot$.

It is important to keep in mind that the Alfvén waves in the present model were driven at a single frequency, and produced nonlinear waves with multiple harmonic spectrum. In the solar corona it is reasonable to assume that a spectrum of the Alfvén waves will be present. This Alfvén wave spectrum will drive a complex spectrum of nonlinear waves. This spectrum might resemble turbulent spectrum due to production of multiple harmonics that decrease in amplitude with frequency with a Kolmogorov type power law.

It is interesting to note that the longitudinal wave amplitude is of the same order of magnitude as the transverse torsional Alfvén wave amplitude despite the fact that the plasma is low-$\beta$. Nonlinearly, the transverse magnetic motions are coupled to the longitudinal motions that leads to the generation of the solitary-like waves. The longitudinal waves are very effective in concentrating the energy in small spatial scales in the radial direction and may dissipate effectively.

The radial velocity fluctuations calculated with the 2.5D MHD model are $\delta v_r \sim 150 - 430$ km s$^{-1}$ in the region $10R_\odot < r < 40R_\odot$, with the parameters used in the model. Ofman and Davila (1997c) found in a detailed parametric study of the MHD model that $v_r$ and $\delta v_r$ increases when $v_r$ or $B$ are increased, or when $T$ is decreased. They also found that higher frequency Alfvén waves lead to smaller solar wind acceleration. The frequency spectra of the fluctuations are complex with many harmonics induced by the nonlinear interactions of various modes. Their model results are in much better agreement with IPS observations than the thermally driven and WKB Alfvén wave solar wind models (for a review see Marsch and Schwenn 1991) that predict smooth and steady solar wind flow.

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