POSSIBLE SIGNATURES OF NONLINEAR MHD WAVES IN THE SOLAR WIND: UVCS OBSERVATIONS AND MODELS


1 Hughes STX and NASA/Goddard Space Flight Center, Mail code 682, Greenbelt, MD 20771, USA
2 Department of Astronomy and Space Science, University of Florence, Largo Fermi 5, 50125 Florence, Italy
3 NASA/Goddard Space Flight Center, Mail code 682, Greenbelt, MD 20771, USA
4 Arcetri Observatory, I-50125 Florence, Italy
5 Harvard-Smithsonian Center for Astrophysics, 60 Garden st, Cambridge, MA 02138, USA

ABSTRACT

Recent UVCS White Light Channel (WLC) observations indicate quasi-periodic variations in the polarized brightness (pB) in the polar coronal holes. Fourier power spectrum of the pB time series shows significant peaks at about 6 minutes and possible fluctuations on longer time scales (20-50 minutes). These preliminary observations may result from density fluctuations caused by compressional waves propagating in polar coronal holes. We stress that our results are preliminary and we plan future high cadence observations in both plume and inter-plume regions of coronal holes. The motivation for these observations is the result of 2.5 MHD model that predicts the presence of nonlinear compressional waves in the fast solar wind. Recently, Ofman and Davila (1997) found that Alfvén waves with an amplitude of 20 – 70 km/sec at the base of the coronal hole can generate nonlinear high amplitude compressional waves that are similar to sound solitons. These waves may contribute significantly to solar wind acceleration in open magnetic field structures.

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

1. INTRODUCTION

Coronal hole regions are well known sources of high-speed solar wind that can reach 800 km s⁻¹ near earth orbit (Krieger, Timothy, & Roelof 1973; Neupert & Pizzo 1974; Wagner 1976; Nolte et al. 1976). 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 ~ 1.6 A.U. (Phillips et al. 1995). Thermal conduction alone is not sufficient to explain observed flow speed of the high speed streams (e.g., Kopp & Holzer 1976; Holzer & Leer 1960; Leer & Holzer 1980; Davila 1985) or the observationally inferred large velocity fluctuations.

Recently Ofman and Davila (1997) have developed a self-consistent nonlinear 2.5D MHD model of solar wind acceleration and found that nonlinear compressional MHD waves are generated in a model coronal hole via Alfvén waves. The nonlinear wave shape and phase-amplitude relations are similar to that of sound solitons. These waves contribute to solar wind acceleration and can account for the additional energy input required to obtain the high-speed solar wind.

A viable observational goal is to test the above model by detecting the presence (or absence) of compressional waves in the solar wind. This can be accomplished by detecting time-dependent density fluctuations and propagation of these fluctuations with a phase speed and amplitude consistent with the model predictions. Here, we present the first results from the SOHO UVCS White Light Channel (WLC) (Kohl et al. 1995) that indicate the presence of density fluctuations in a polar coronal hole – a possible signature of compressional waves. We plan to perform additional observations in order to determine whether these fluctuations are propagating and what is their phase speed.

2. OBSERVATIONS

The detection of nonlinear compressional waves in the polar coronal holes can be accomplished by UVCS through time resolved observations with the UVCS White Light Channel (WLC). The WLC is a polarimeter, which measures the polarized brightness (pB) in the 450 to 600 nm band, over a 14×14 square arc-second area, located at the center of the instantaneous UVCS field of view. Because the UVCS field of view can be rotated about the Sun center, the WLC can look at different position angles. This allows us to test adjacent regions, investigating both the high density and low density coronal structures (i.e., plumes and interplumes).

From the MHD model we expect the density fluctuations due to nonlinear solitary-like waves to become most evident when the solar wind is supersonic and exhibits large amplitude parallel velocity fluctuation modulated on top of an average solar wind velocity, in phase with significant density fluctuations ($\rho_{\text{max}}/\rho_{\text{min}} \sim 2.5$ at $5R_\odot$). Below the sonic point the effect of solitary waves is less apparent, but, still significant with a predicted $\rho_{\text{max}}/\rho_{\text{min}} \sim v_{\text{max}}/v_{\text{min}} \sim 1.2$ at $2R_\odot$, where $\rho_{\text{max,min}}$ and $v_{\text{max,min}}$ are the maximal and minimal densities and velocities, respectively. These fluctuations

compare favorably with the signal to noise ratio of the pB measurements.

We have made a set of preliminary observations at several heights in the range of 1.9–2.2\(R_\odot\). In Figure 3 we show the observations made at a height of 1.9\(R_\odot\) with a count rate of approximately 300 counts per second. The top panel shows significant fluctuations of the pB on a time scale of 6 minutes with additional fluctuations on longer and shorter time scales. The dashed lines indicate the error bars derived from Poisson statistics. The fluctuations in pB may indicate possible periodicities consistent with the presence of nonlinear compressional waves. However, to establish the wave origin of these fluctuations with higher confidence we need longer duration measurements for power spectrum analysis, and we need to determine their phase speed.

We use the Fast Fourier Transform (FFT) spectral data analysis of the time-series to determine the frequency content of the fluctuations in pB. In the middle panel we show the raw power spectrum of the pB time series. The largest peak appears at a frequency of 2.7 \(\pm 0.1 \times 10^{-3}\) Hz or a period of about 6.2 \(\pm 0.3\) minutes and additional smaller peaks at about 20 and 50 minutes. In order to test for statistical significance of the peaks we have applied a running average of 5 points to the power spectrum and determined the \(\pm\)standard error interval. The 6.2 minute peak is still apparent in the lower panel figure. However, the larger time scale (lower frequency) fluctuations have lower statistical significance. We hope that longer duration observation will allow to establish these lower frequency peaks with higher statistical confidence.

3. CORONAL HOLE MODEL

In this section we present briefly the coronal hole model developed by Ofman and Davila (1997) in order to model the nonlinear self consistent solar wind acceleration by waves. They solved the following set of the nonlinear, compressible, resistive MHD equations in 2.5D (i.e., three dimensional with azimuthal symmetry):

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0, \tag{1}
\]

\[
\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla) \mathbf{v} = -\frac{E_u}{\rho} \nabla p - \frac{1}{\rho} \mathbf{J} \times \mathbf{B} + \frac{J \times \mathbf{B}}{\rho^2}, \tag{2}
\]

\[
\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) + S^{-1} \nabla^2 \mathbf{B}, \tag{3}
\]

\[
\left( \frac{\partial}{\partial t} + \mathbf{v} \cdot \nabla \right) \frac{p}{\rho^2} = 0. \tag{4}
\]

The above equations are normalized as follows: \(r \rightarrow r/R_A, t \rightarrow t/\tau_A, \mathbf{v} \rightarrow v/v_A, B \rightarrow B/k, \rho \rightarrow \rho/\rho_0, p \rightarrow p/p_0\). The physical parameters are \(S = \tau_r/\tau_A\), the Lundquist number, \(\tau_r = 4\pi \alpha^2/v_c^2\) the resistive time scale, \(\tau_A = a/v_A\) the Alfvén time scale, \(F_r = \nu \tau_A/R_A/(GM_\odot)\) Froude number, \(E_u = \rho_0/\rho_0 v_A^2 = c_s^2/v_A^2\) Euler's number (\(\equiv \beta/2\)), and \(c_s = \sqrt{\gamma p_0/\rho_0}\) the sound speed. In the present study we use \(\tau = 1\).

Figure 1. The \(\theta\)-dependence of the initial density and the magnetic field components for the non-radial case (\(f_e = 10\)) at \(r = 1R_\odot\) to the right of the symmetry axis.

For the radial case the initial density profile is given by

\[
\rho_0(\theta, r) = \left[1 - (1 - \rho_r) e^{-[(r - r_f)/r_s]^4}\right] \rho(r)/\rho_r, \tag{5}
\]

where \(\rho_r = 0.111\), \(\rho(r, t = 0)\) and the initial solar wind flow \(v_r(r, t = 0)\) are given by Parker's (1963) solution. The initial magnetic field is radial: \(\mathbf{B} = B_0/r^2 \mathbf{e}_r\).

The maximal divergence rate is defined as \(f_e = 1/(B_0/\rho)^2\) at the symmetry axis (\(\theta = \pi/2\)). For non-radial divergence a quadrupole field is added to the radial field such that \(f_e = 10\) and the \(\theta\)-dependence of the initial density structure is determined from pressure balance in \(\theta\) (Figure 1).

At \(r = 1\) the boundary conditions are incoming characteristics approximated by zero order extrapolation (Steinolfson & Nakagawa 1976) with \(v_r > 0\) and

\[
B_\phi(1, \theta) = v_d/v_A(1, \theta) \cos \omega t, \tag{6}
\]

\[
B_r(1, \theta) = B_{r,0}, v_\theta = B_\theta = 0. \tag{7}
\]

Ofman and Davila solved equations (1)–(4) using the 4th order Runge-Kutta in time and 4th order differences in space method. In addition an upwind differencing of the density in \(r\) with a 4th order Chebyshev smoothing term (artificial viscosity) were utilized to improve stability.

In Figure 4 we show the result of a run of the coronal hole model with \(v_d = 46\) km/s, \(B = 7\) G, \(T = 1.4 \times 10^6\) K, \(f = 2.2\) mHz, \(\rho_0 = 10^8\) cm\(^{-3}\) and an expansion ratio \(f_e = 10\). The spatial dependence of \(B_\phi/\rho^{3/2}, v_\phi, v_r, v_\theta\), and \(\rho\) are given at \(t = 255\) \(\tau_A = 32.5\) hrs. Nonlinear solitary-like waves are evident in \(v_r\) and \(\rho\) with highest amplitude near the center of the coronal hole. The Alfvén waves are evident in \(v_\phi\) and in \(B_\phi/\rho^{3/2}\) that are \(180°\) out of phase. Here we use a single frequency driver to generate the Alfvén waves. The frequency of the density fluctuations that we obtained from the present run is about 20 minutes. This value depends on the frequency of the Alfvén waves that drive the nonlinear solitary-like
waves in the model and on other coronal hole parameters (Ofman & Davila 1998). In the solar corona we expect that a spectrum of frequencies will be present in the Alfvénic fluctuations and the resulting temporal (and spatial) spectrum of the density fluctuations due to the nonlinear waves will be more complex than in the present model.

In Figure 2 we show the results of the parametric study of the maximal solar wind velocity dependence on the driving amplitude of the Alfvén waves at the base of the coronal hole. For the radially divergent magnetic field structure \( f = 2.78 \text{ mHz} \) for the super-radial case \( f = 0.35 \text{ mHz} \). Without Alfvén waves \( (v_A = 0) \) Parker’s solar wind speed is recovered. When the amplitude of the Alfvén waves is increased the solar wind velocity at \( 32 R_\odot \) increases gradually to about 600 km/s with about 60 km/s Alfvén waves at \( r = R_\odot \) and \( f = 2.78 \text{ mHz} \). When the magnetic field configuration diverges at faster then radial rate \( (f_s = 10) \) and \( f = 0.35 \text{ mHz} \) the solar wind speed increases at a faster rate with \( v_A \). The solar wind speed is 800 km/s at \( 32 R_\odot \) with a reasonable coronal Alfvén wave amplitude of \( v_A \approx 46 \text{ km/s} \). The solar wind speed at \( 32 R_\odot \) increases when \( f \) decreases (Ofman & Davila 1998). Thus, for the radial magnetic field case with \( f = 0.35 \text{ mHz} \) the solar wind speed is larger than both the radial case with \( f = 2.78 \text{ mHz} \) and the non-radial case.

4. CONCLUSIONS

Preliminary results from the UVCS WLC channel indicate that the density in a coronal hole at 1.9 \( R_\odot \) fluctuates on a time scale of about 6 minutes with possibly longer time scale fluctuations. These observations are consistent with the predictions of the nonlinear solitary-like wave model developed by Ofman and Davila (1997). It is not possible to determine based on present observation alone whether there are nonlinear compressional waves in solar coronal holes as predicted by the model. For this purpose one need to establish whether the fluctuations are propagating, what is their phase speed, and preferably what is the relation between the phase speed and other parameters of the plasma. The phase speed is an important indicator of the nature of the waves if the plasma parameters such as density, temperature and magnetic field are known (or if a reasonable range could be estimated). We plan to perform more observations with UVCS that may help to establish the nature of these density fluctuations. Also, other SOHO instruments such as LASCO and EIT might help to determine whether compressional nonlinear waves are present in coronal holes.

Using the 2.5D self consistent nonlinear MHD model developed by Ofman and Davila (1997) we study the effect of the coronal hole parameters on the solar wind acceleration by waves. Ofman and Davila (1998) found that the solar wind velocity fluctuations and magnitude increases when the amplitude of the input Alfvén waves at the base of the coronal hole increases. For coronal hole temperatures of \( 10^6 \text{ K} \) and \( B=5-10 \text{ G} \) the maximal solar wind speed driven by solitary-like waves, excited by the Alfvén waves is enhanced by a factor of two over the standard Parker’s solar wind model at \( r = 8 R_\odot \).

For radial field divergence and \( f = 2.78 \text{ mHz} \) the maximal solar wind speed at \( 32 R_\odot \) is \( \approx 600 \text{ km/s} \) when \( v_A \approx 60 \text{ km/s} \) and increases linearly with \( v_A \). When the driving frequency is decreased to \( f = 0.35 \text{ mHz} \), and the magnetic field diverges super-radially \( (f_s = 10) \) with \( v_A = 46 \text{ km/s} \) the solar wind speed is 800 km/s at \( 32 R_\odot \) and increases at a faster rate with \( v_A \) then with the radially divergent field. Thus, low frequency Alfvén waves drive nonlinear waves in a super-radially divergent coronal hole magnetic field structures that contribute significantly to the fast solar wind acceleration.

This work was supported by the NASA SOHO Guest Investigator Program, Space Physics Theory Program, and HPCC program. The JPL/Caltech Cray Supercomputer used in this investigation was provided through funding by the NASA Offices of Mission to Planet Earth, Aeronautics, and Space Science.

REFERENCES

Kohl, J.L. et al. 1995, Solar Physics, 162, 313
Figure 3. Time variation of the polarized brightness (top panel) with error bars (dashed line), the raw power spectrum (middle panel) and the smoothed power spectrum showing the ±standard error interval. The UVCS/WLC was pointed at 1.9 \( R_E \) in the south solar coronal hole with 60 s integration time. The polarized brightness units are given relative to the Sun center brightness integrated over the WLC wavelength bandpass (450-600 nm).
Figure 4. The result of a run of the coronal hole model with \(v_x = 46\) km/s, \(B = 7\) G, \(T = 1.4 \times 10^6\) K, \(f = 2.2\) mHz, \(\rho_0 = 10^8\) cm\(^{-3}\) and an expansion ratio \(f_x = 10\). The spatial dependence of \(B_\phi/\rho^{0.5}\), \(v_\phi\), \(v_x\), and \(\rho\) are given at \(t = 255\tau_A = 32.5\) hrs. Nonlinear solitary-like waves are evident in \(v_x\) and \(\rho\). The Alfvén waves are evident in \(v_\phi\) and \(B_\phi/\rho^{0.5}\) that are \(180^\circ\) out of phase.