NASA-CR-204720

SELF-CONSISTENT AND TIME-DEPENDENT SOLAR WIND MODELS

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ABSTRACT

We describe the first results from a self-consistent study of Alfvén waves for the time-dependent, single-fluid magnetohydrodynamic (MHD) solar wind equations, using a modified version of the ZEUS MHD code. The wind models we examine are radially symmetrical and magnetized; the initial outflow is described by the standard Parker wind solution. Our study focuses on the effects of Alfvén waves on the outflow and is based on solving the full set of the ideal nonlinear MHD equations. In contrast to previous studies, no assumptions regarding wave linearity, wave damping, and wave-flow interaction are made; thus, the models naturally account for the back-reaction of the wind on the waves, as well as for the nonlinear interaction between different types of MHD waves. Our results clearly demonstrate when momentum deposition by Alfvén waves in the solar wind can be sufficient to explain the origin of fast streams in solar coronal holes; we discuss the range of wave amplitudes required to obtained such fast stream solutions.

Subject headings: MHD — solar wind — waves

1. INTRODUCTION

The fact that the solar wind can be divided into fast and slow streams has been known for many years. Fast streams are associated with solar coronal holes, velocities in the range $600-800$ km s^{-1}, and relatively uniform physical properties. Slow streams are associated with coronal sector boundaries, velocities in the range $300-500$ km s^{-1}, and highly variable physical properties. In this Letter, we restrict our attention to fast streams because the time-varying properties of slow streams suggest that the latter are not in equilibrium with the coronal base, an issue that is beyond the scope of this Letter.

The main difficulty with understanding fast solar wind streams is that their origin cannot be explained (e.g., Axford & McKenzie 1992) simply on the basis of the theory of thermally driven solar winds proposed by Parker (1958, 1965). An additional momentum deposition mechanism is required to account for the onset of such high-speed flows. It has been suggested that the additional force is supplied by Alfvén waves (Hollweg 1978). A number of calculations have already been made to investigate the behavior of Alfvén waves in the solar wind and to construct solar wind models based on Alfvén wave momentum deposition (Alazraki & Couturier 1971; Hollweg 1973; 1978; Jacques 1978; Heinemann & Olbert 1980; Leer, Holzer, & Flå 1982; MacGregor & Charbonneau 1994; Lau & Siregar 1996). Similar ideas have also been used to explain the acceleration of cool massive winds observed from late-type giants and to construct models of these winds (Belcher & Olbert 1975; Hartmann & MacGregor 1980, 1982; Holzer, Flå, & Leer 1983; Hartmann & Avrett 1984; An et al. 1989, 1990; Barkhudarov 1991; Rosner et al. 1991, 1995; Lou 1993; Velli 1993). The basic challenge for these solar and stellar models is that one must account for the onset of the mass loss, the mass-loss rate, and the terminal speed, and at the same time, explain the observed heating in the region of the atmosphere

where the wind originates. The obtained results demonstrat that, in general, it is possible to construct models based o wave heating and momentum deposition by Alfvén waves, bu as pointed out by Holzer et al. (1983), such models suffer fro the defect that the necessary wave-damping lengths are no only ad hoc, but also need to be extremely finely tuned i value. A possible resolution to this difficulty has been pr posed by An et al. (1990) and Rosner et al. (1991), wh suggested that reflection and trapping of non-WKB Alfvé waves in the solar and stellar atmospheres may lead to significant increase in the acceleration force, and that thi force may be sufficient to explain the acceleration of wind (see Rosner et al. 1995). However, recent numerical (Krogule et al. 1994; MacGregor & Charbonneau 1994) and analytic (Lou & Rosner 1994) results indicate that the push on th background medium exerted by non-WKB Alfvén waves i lower than the corresponding force exerted by WKB wave Similar results have been also reported by Ong, Krogulec, & Musielak (1995), who constructed the first purely theoretical self-consistent, time-dependent wind models based on mo mentum deposition by *linear* Alfvén waves.

The preliminary results reported by Ong et al. (1995 demonstrate that momentum deposition by linear Alfvér waves can lead to a slow secular increase in wind velocity However, although the cumulative wave effects can be seer clearly, they are not prominent, and the maximum increase ii the wind velocity in such models only reaches $\approx 10\%$ of it initial value before the solution approaches a steady state Therefore, we can conclude that small-amplitude (linear Alfvén waves cannot contribute enough momentum to th solar wind to explain the observed properties of fast streams This indicates that models must be extended to treat finite amplitude, nonlinear Alfvén waves. Unfortunately, such ar extension cannot be done in a one-dimensional approach, bu instead requires (at least) two-dimensional numerical calcula tions. In this Letter, we report on our first theoretical self-consistent, time-dependent wind models based on mo mentum deposition by *nonlinear* Alfvén waves. The detailec procedure for constructing these models is described in § 2.

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2. WIND MODELS

To calculate our wind models, we start with a standard Parker model of thermally driven winds (Parker 1958) and treat it as the initial flow. The structure of an atmosphere computed with this initial flow is then perturbed by radially propagating toroidal Alfvén waves of a finite amplitude. The interaction between these waves and the flow is treated self-consistently; e.g., the structure of the wind and atmosphere is modified by the waves and, in turn, the wave behavior is influenced by this newly modified structure. The physical parameters describing the background medium are recorded (as they fluctuate on timescales of the Alfvén wave period) and then time-averaged over the Alfvén wave crossing time in order to obtain estimates for the corresponding parameter values of the flow on timescales long when compared to the Alfvén wave period.

In order to perform these calculations, we modified the original ZEUS code (Stone & Norman 1992a, 1992b; see also Ong 1997), and we use it to solve the full set of ideal single-fluid compressible MHD equations in two-dimensions; we consider a single magnetic flux tube along which the field decreases radially. At the lower boundary of our computational domain the field line is perturbed in such a way that toroidal ($\partial/\partial\phi = 0$) Alfvén waves are continuously generated. The upper boundary is transparent, which means that the wind and waves freely leave the computational domain. Since we are solving the single-fluid MHD equations without any further simplifications, processes such as wave reflection, nonlinear coupling between the various MHD waves, and shock formation are automatically accounted for. For any given solar wind model, it is necessary to specify the strength of the ambient (background) magnetic field, B_0, the wind temperature, T_0, and wind density, ρ_0, at the base of the coronal ($r = 1R_\odot$), and to prescribe the initial flow. The results presented in this paper have been obtained using $B_0 = 10$ G, $T_0 = 1.0 \times 10^6$ K, and $\rho_0 = 1.3 \times 10^{-15}$. The initial flow's velocity is $V = 0.2$ km s^{-1} at $r = 1R_\odot$, becomes supersonic at $r = 37.8R_\odot$, and reaches a velocity of $V = 418$ km s^{-1} at $r = 91R_\odot$. A source of Alfvén waves is located at the base of the corona; we assume that this source generates continuous, monochromatic, sinusoidal waves with period of 1 hr. We considered four different values of the wave amplitude, corresponding to three different wave amplitude regimes: the essentially linear case (8 km s^{-1}); the weakly nonlinear, finite amplitude case (20 km s^{-1}, 40 km s^{-1}); and the fully nonlinear case (75 km s^{-1}). In all of these cases, the computational domain extended from $r = 1R_\odot$ (the base of the corona) to $r = 91R_\odot$; the calculations were continued for 278 hr, sufficient time to allow the waves to interact with the initial flow and to change its physical properties. We note again that the results we show are time averages of the wind velocity over timescales long when compared to the Alfvén wave period.

3. RESULTS AND DISCUSSION

The results of our numerical simulations are presented in Figure 1, which shows the distribution of the time-averaged wind velocity with distance. It is clearly seen that *linear* Alfvén waves, with amplitudes comparable to, or smaller than, 10 km s^{-1}, add very little momentum to the initial flow; the resulting wind velocity at $r = 91R_\odot$ is 423 km s^{-1}, which is only 4 km s^{-1} higher than the thermally driven initial flow. It must be noted that a higher wind velocity is obtained when a time-averaged WKB wind type of model is used (e.g., MacGre-
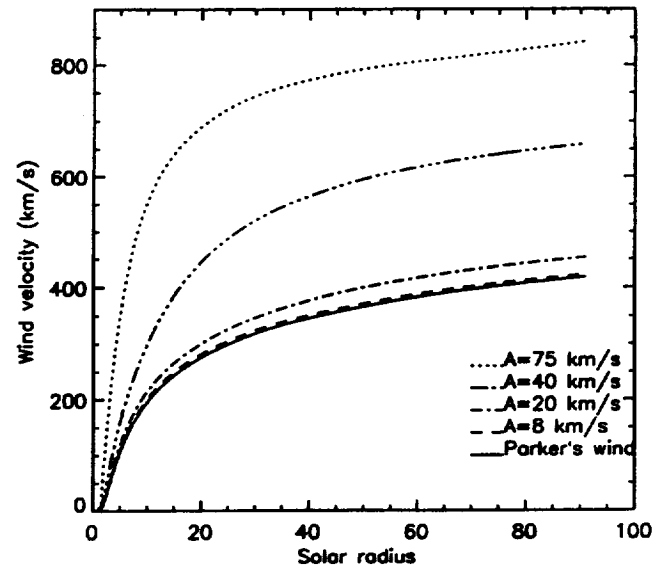

Fig. 1.—Time-averaged wind velocity profiles for four different solar wind models. In each model, the initial flow is assumed to be the thermally driven (Parker) wind. Alfvén waves with the same period (1 hr) but different amplitudes, A, are generated at the base of each model (corresponding to the base of solar coronal holes) and allowed to interact with the initial flow for 278 hr. After this time, the resulting time-averaged wind velocity profiles are calculated. The obtained results show that the presence of Alfvén waves with amplitudes ranging from 40 to 75 km s^{-1} is required in the solar wind in order to explain the origin of fast streams.

gor & Charbonneau 1994). The difference can be explained by the presence of non-WKB effects for Alfvén waves with period of 1 hr considered in our calculations. Much more momentum is deposited by *finite* amplitude Alfvén waves; waves with amplitude 20 km s^{-1} increase the wind velocity at $r = 91R_\odot$ to 453 km s^{-1} (34 km s^{-1} above Parker's wind solution), while waves with amplitude 40 km s^{-1} increase the wind velocity at $r = 91R_\odot$ to 660 km s^{-1}, which is 241 km s^{-1} above the velocity of the thermally driven background flow. Finally, the results shown in Figure 1 demonstrate that *nonlinear* Alfvén waves can deposit enough momentum to increase the velocity of the initial outflow at $r = 91R_\odot$ to 845 km s^{-1}, which is 427 km s^{-1} above Parker's wind solution. This is an interesting result, since it shows that Alfvén waves with amplitudes ranging from 50 to 80 km s^{-1} can, in principle, account for the observed velocities of fast streams in the solar wind.

The results presented in this Letter lead to two important conclusions. By constructing theoretical self-consistent, time-dependent solar wind MHD models based on momentum deposition by Alfvén waves, we have shown that, first, models based on momentum deposition by small-amplitude (linear) Alfvén waves cannot account for the basic observational properties of fast streams in the solar wind; and second, that in order to explain the observed range of the wind velocities of fast streams (600–800 km s^{-1}), one has to assume Alfvén wave amplitudes ranging from 40 to 75 km s^{-1} at the coronal base of the solar wind. This range of required Alfvén wave amplitudes seems to be in agreement with observations of line broadening of Mg coronal emission lines (Hassler et al. 1990) and with more recent *Ulysses* observations (e.g., Phillips et al. 1995).

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