Evolution of Coronal MHD Shocks into Interplanetary MHD Shocks

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ABSTRACT

One of the fundamental potential hazards to the "Fire" mission (Solar Probe) is the energetic particle environment near the sun. Heras et *al.*, *(1995)*, Sanahuja *et al. (1995)*, and Sanahuja and Lario (1995) have modeled shock acceleration of low energy particles (< 2 MeV) due to fast ejects from the sun, One critical problem in this model, at the present time, is that no one has modeled coronal and heliospheric shock strengths as a function of radial distances and ejects velocities. In this paper we take a normal ambient solar wind (with a coronal hole and helmet-streamer representative of solar minimum) and generate low velocity and high velocity ejects by imposing thermal pulses at the base of the helmet streamer. Our preliminary results show that the shocks formed at -2 R_s and their strengths (i.e. magnetosonic Mach number) increase as they propagate outward. These preliminary results will be very helpful in defining an energetic particle environment close to the sun.

1. INTRODUCTION

The energetic particle environment near the Sun, particularly during solar activity, is of major importance to the planning of a solar probe. It is not known if intensive fluxes are generated solely in the impulsive phase of flares or whether they are augmented by, or contained within, the coronal mass ejections and shock waves spatially preceding them. Heras *et al.* (1995) and Sanahuja *et al.* (1995) have successfully modeled the low-energy (≤ 2 MeV) proton flux caused by *in situ* shock acceleration; Sanahuja and Lario (1995) and Sanahuja *et al. (1995)* have demonstrated that this technique can be extended to -50 MeV. However, their work is based on a time-dependent MHD shock model (2D) that is initiated at 18 R_s (R_s = 1 solar radius = 6.9 x 10s km).

There is a single MHD shock study (concerned, in 3D, with the simulation of the June 1991 multiple flare events) that starts at the coronal base (Usmanov and Dryer, 1995). However, those workers did not provide the shock velocities or strengths (magnetosonic Mach Numbers, Ms) as a function of helioradial distance (from 1 R_s, cent inuously outward) or ejects velocities. Other studies for transient flows and shocks have been reviewed by Dryer (1 994) who pointed to the two subsets of MHD numerical simulations: those near the sun extending to about 10 R_s, and those that were initialized at about 18 R_s and were carried out to 1 AU and beyond. Except for the Usmanov and Dryer (1995) study, no other work has been done for a consistent "run" from 1 R_s outward to arbitrarily-large distances because of the mathematical and computational restrictions on the proper consideration of self-consistent, time-dependent, boundary conditions at the lower boundary (1 R_s). These restrictions have now been overcome (WU and Wang, 1987), and the model discussed here incorporates these essential features.

We will discuss the self-consistent evolution of coronal MHD shocks into interplanetary shocks. In this preliminary study, two representative ejects speeds, "low" and "high," are examined in order to study their shock strengths' evolution with distance. Detailed results will be given in a separate paper (WU *et al.,* 1995a). Section II describes the steady-state MHD model for a self-consistent coronal helmet-streamer and hole that extends from 1 R_s to 1 AU. Section 111 is a discussion of two pulse perturbations to this background-solar wind. Section IV gives the results of the helioradial evolution of these two shock strengths . A few preliminary conclusions are presented in Section V.

II. STEADY-STATE SOLAR WIND AND IMF MODEL

We use the time-dependent, 2D planar MHD model given by Wu et *al. (1995b).* These authors performed a study that provided a representative coronal hole and magnetic helmet-streamer topology for the solar wind plasma and interplanetary magnetic field (IMF). They demonstrated appropriate values of velocity and density at both the equatorial plane (within the streamer, or heliospheric current sheet) and at the poles. In the present case, we use a constant adiabatic exponent, y = 1.05, from 1-8 R_s and y = 1.67 from 18 R_s to 1 AU; a linear interpolation is used from 1.05 to 1.67 between 8-18& The steady-state solar wind and magnetic field values at 1 R_s (equatorial plane) and at 1 AU are given in Table 1.

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TABLE 1. STEADY-STATE SOLAR WIND PARAMETERS

PARAMETER	1 R_s (EQUATOR)	1 AU
Density, n_o (cm^{-3})	3.2X 10^8	64*
Velocity, V_o (km/sec)	0	315
Temperature, T_o (K)	1.65 X 10^6	1.46X 10^4
Magnetic Field, B_o (Gauss)	1.22	5 X 10^5

* Note that this value is higher than the representative density at 1 AU because the model is taken to be purely adiabatic from& (i.e., no thermal conduction nor wave damping, for example, are considered).

111. GENERATION OF CORONAL SHOCKS: PERTURBATIONS

We employ both temporal and spatial distributions of two basic thermal pulses, A and B, to provide the “low” and “high” velocity ejects. For Case A, the coronal base temperature is linearly increased (for 1 hour) from its value (T_o) in Table 1 to $4T_o$, held constant at this value for 1 hour, and then is decreased over the third hour to its original value. The required self-consistent boundary conditions required the velocity to be (also) linearly ramped at 1 R_s to 100 km/sec for the first hour, remaining constant thereafter to simulate photospheric/chromospheric ejects. The magnetic field was similarly ramped over the first hour to a value twice that given in Table 1. Spatially, the velocity and temperature changes at 1 R_s were linearly ramped downward, at each moment, from their instantaneous values at the equator ($\theta = 90°$) to zero at $\theta = 60°$ and 120°. The magnetic field was also changed as $B_o(\theta,t) = \alpha B_o(\theta,0)$, where $\alpha = 2$ and 2.67 for Cases A and B, respectively. Case B was similar in its temporal and spatial variation except that the maximum value of T(t) was taken to be 8 To and was increased linearly for 2 hours from its original value, then held constant at this value for 2 hours and then is decreased linearly to its original value T_o for an additional 2 hours. Concerning the perturbed quantities of velocity and magnetic field, the magnitudes of these quantities are 100 km/sec and 2.67 Gauss, respectively, and they are increased to the maximum values for the first two hours, remaining constant thereafter, similar to Case A.

We are able to estimate the excess thermal and total energies released by these simulated eruptions by assuming an influenced depth (recalling that our model is only 2D) of 0.1 R_s and integrating over time and the affected solar surface. The results are given in Table 2.

TABLE 2. THERMAL AND TOTAL ENERGY IN EJECTA

CASE	THERMAL ENERGY	TOTAL ENERGY
A	1.70 X 10^{32} ergs	1.78 X 10^{32} ergs
B	6.20 X 10^{32} ergs	6.44 X 10^{32} ergs

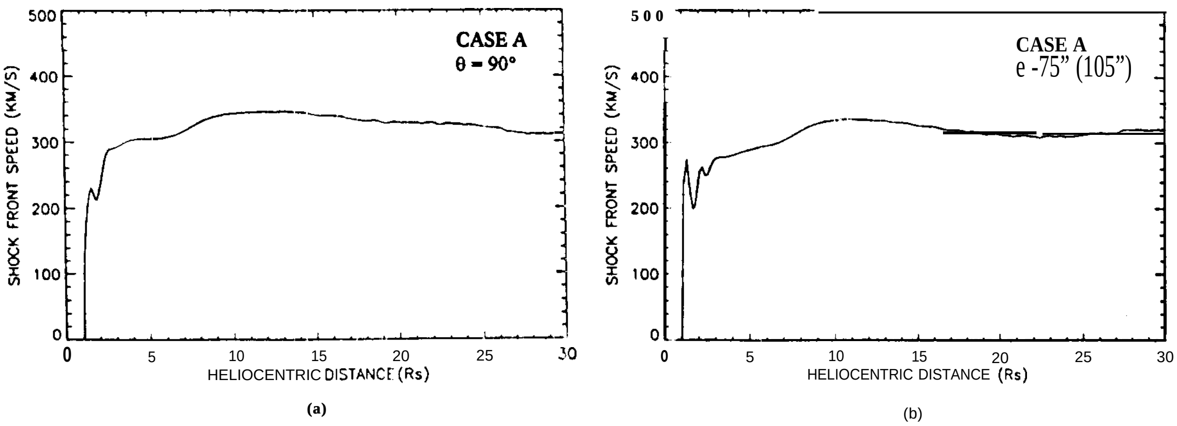

Figure 2. Case A: Shock front speed in the inertial frame from 1-30 R_s. (a) $\theta = 90°$; (b) $\theta = 75°$ (1050). Note that the shock speeds differ significantly at these two radial “cuts” only close to the Sun within the helmet stream. Quasi-sphericity of the shock is, therefore, indicated beyond the ejected “Gold tongue”. No reconnection takes place in the model due to the assumption of zero resistivity.

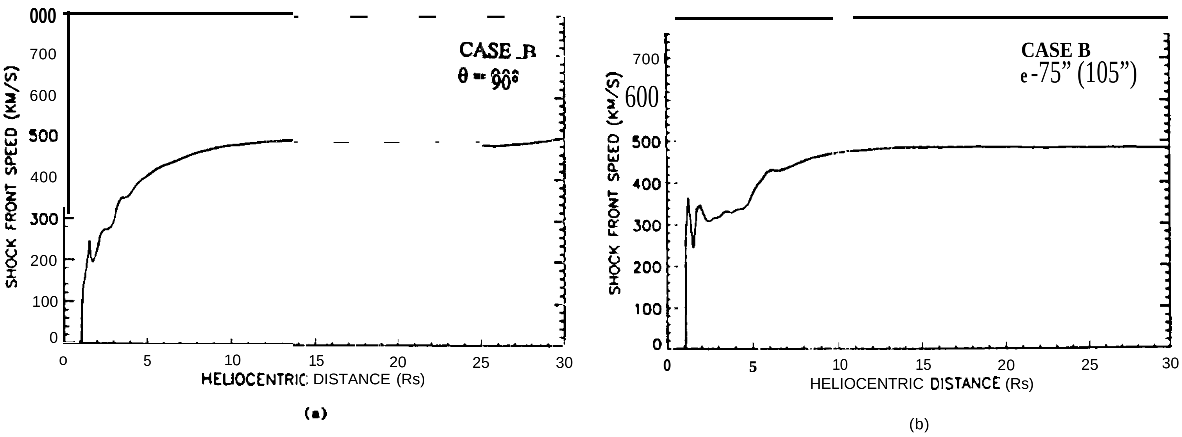

Figure 3. Case B: Shock front speed in the inertial frame from 1-30 R_s. (a) $\theta = 90°$;) $\theta = 75°$ (1050).

The shock strengths, however, as determined by their magnetosonic Mach Numbers, must be obtained in the frame of the local steady-state solar wind and its characteristic speeds as discussed above. Figure 4, then, gives the results for Cases A and B ate = 90°. The results for $\theta = 75°$ (105°) in each case, respectively, are nearly the same and, therefore, are not shown. In all cases, it is seen that M_S reaches the shock stage ($M_S = 1.0$) within 2 R_s and increases monotonically because of the declining characteristic wave speeds (fast and sound) as shown in Figure 1.

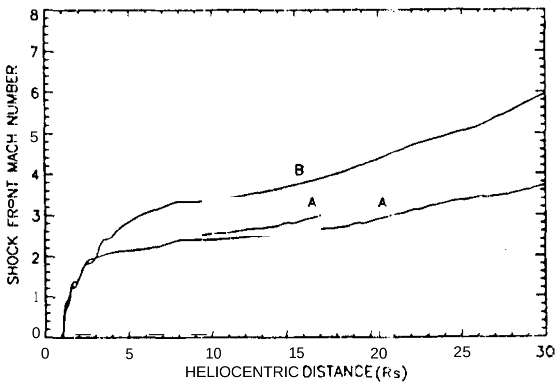

Figure 4. Magneto sonic Mach Numbers for the shocks in Cases A and B. Note the development of the considerably-higher M_S for Case B because of the higher energy input compared to Case A (see Table 2).

V. REMARKS

We have shown a preliminary result for the evolution of a disturbance, first into a coronal shock and then evolving into an interplanetary shock enroute to 1 AU. A self-consistent, time-dependent, 2D planar MHD model was used for a representative, steady-state coronal hole and helmet-streamer magnetic topology and solar wind which includes combined sub-sonic and sub-Alfvénic flows that change to supersonic and super- Alfvénic flows. Accordingly, appropriate time-dependent boundary conditions have to be made (Wu and Wang, 1987) in order to prevent non-physical reflections at the inner boundary of 1 R_S. Simulations of both "low" and "high" ejects speeds were used via a thermal pulse over a time span of 3 and 6 hours for Cases A and B, respectively. We do not specify if this disturbance is relative to either a flare or to a helmet-streamer destabilization in this exploratory study.

The results given by these two cases show that the MHD fast shocks were developed in the lower corona (i.e. within the height of $2R_s$). The development of a corona MHD fast shock at this early stage is due to the perturbation which we have prescribed for this simulation. Physically, we speculated that this may likely correspond to flare events. On the other hand, the same model was used to study the destabilization of a coronal streamer by prescribing a filament (line current) as the perturbation (Wu, Guo and Wang, 1995b; Guo, Wu and Tandberg-Hanssen, 1995) which shows the development of MHD fast shocks in a much later stage (i.e. 3-15 R_s). In some cases, there are only large amplitude MHD fast waves that form without steepening into a shock, As shown in Figure 4, the magnetosonic fast Mach number is increasing monotonically as the shock propagates outward. There is no indication of the acceleration of the MHD fast shock's acceleration; thus the M_S increase is due to the decreasing characteristic sonic and MHD fast mode speeds as shown in Figure 1. The cause of the decrease of these two characteristic, speeds is due to the pre-event solar wind properties.

By examining Figures 2 and 3, we notice, for both cases, that the fastest acceleration of the shock front speed is in the region between 1 to 3 R_s, then, a slow acceleration appearsupto-15 R_s; finally, it becomes almost constant propagating outward t 01 AU, with spreads of 320 and 500 km/s for cases A and B, respectively. This acceleration character resembles the perturbation which we have prescribed for these two cases as discussed in Section 111,

We find that the two cases of energy release, or, equivalently, ejects speeds (as noted above) produce shocks within 2 R_s. The magneto sonic Mach numbers of these shocks increase proportionately according to their respective energy releases. A valid question is: how close to reality are the pulses that were used here? Will other drivers (impulsive flares, impulsive plus post-eruption energetic flares, filament eruptions, destabilization of helmet-streamers caused by footpoint shearing, etc.) produce similar results? The thermal pulse used here must be compared with other drivers such as these just noted. These preliminary results, however, will be very helpful in defining the energetic particle environment close to the Sun,

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