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SLOW SHOCKS IN CORONAL MASS EJECTIONS

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ABSTRACT

The possibility that slow-mode shock compression may produce at least some of the increased brightness observed at the leading edge of coronal mass ejections is investigated. Among the reasons given for the possible existence of slow shocks are the following: (1) transient velocities are often greater than the upstream sound speed but less than the Alfvén speed, (2) the presence of a slow shock is consistent with the flat top observed in some transients, and (3) the lateral extension of slow shocks may be responsible for disturbing adjacent structures as also seen in the observations. It is shown that there may be some difficulties with this suggestion for transients originating inside the closed-field region at the base of a preexisting coronal streamer. First of all, slow mode characteristics have difficulty emerging from the closed-field region at the streamer base so they can merge to form a slow shock, unless a preceding, large-amplitude disturbance opens the field lines. In addition, a slow shock cannot exist at the center of the streamer current sheet. Finally, numerical simulations demonstrate that at least the last two (and possibly all) of the above reasons for slow shocks can be satisfied by a disturbance whose leading edge propagates at the local fast-mode speed without any shocks. The leading portion of the transient that would be seen in white-light coronagraphs propagates at a speed either less than or equal to the fast-mode speed.

I. Introduction

It is becoming commonly accepted that the interaction between the ambient atmosphere and the material and magnetic field ejected (or rearranged) in the solar-associated source of a coronal mass ejection form an integral part of the mass ejection phenomena. This realization is virtually independent of the driving mechanism and just recognizes the compressible nature of the corona. The presence of a strong magnetic field substantially complicates the atmospheric response and allows for the presence of slow-mode waves as well as fast modes.

Numerical simulations of the coronal reaction to a localized energy source usually contain enough physics to allow for the production of both wave modes. However, they have generally been limited to parameter regions where the leading edge speed exceeds all characteristic wave speeds with the resulting formation of fast-mode shocks [e.g., *Dryer et al.*, 1979; *Steinolfson*, 1982; *Wu et al.*, 1983]. Recent simulations by *Steinolfson and Hundhausen* [1988] add heating to the corona and thereby raise the fast speed enough that fast shocks do not form at typical mass ejection velocities.

Hundhausen et al. [1987] recently suggested that ambient coronal conditions may often be such that leading edge velocities of ~350 km/sec may be lower than the Alfvén velocity yet higher than the sound speed. In this case, it becomes possible that slow shocks may form. They also argued that the slow shock may be concave upward in which case the lateral extension of the slow shock (possibly just a slow wave) may be responsible for disturbing adjacent structures as often seen in observations. Finally, with a concave upward shape, the presence of a slow shock coincides with observed flat tops on some mass ejections.

The possibility of producing slow shocks is examined for the situation where the transient energy source originates inside the closed field region at the base of a preexisting coronal streamer. Some general considerations are discussed first followed by results from a numerical simulation.

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II. General Comments on Slow Shock Formation

Slow shocks form as a result of wave steepening and the ultimate intersection of slow-mode characteristics. In contrast to fast-mode waves, slow waves do not propagate across magnetic field lines. This is dramatically shown in Figure 1 which compares the location of the fast and slow wavefronts at several times in a streamer. The waves originated at (and propagate in straight lines away from) 0.25 $r_\odot$ above the surface at the equator inside the closed-field region at the base of the streamer. The details of this computation are given by *Steinolfson* [1988]. The slow-mode wavefront (lighter dashed curves) does not propagate at all along the equator and only moves very slowly away from it. The fast wavefront, on the other hand, is not hindered by field lines and, in fact, travels faster across them. For such an energy source, it becomes evident that the field lines must first be opened up before slow waves can escape and steepen to form a slow shock. This situation represents a rather extreme scenario. If, for instance, the energy source effectively raised the entire closed-field region, this may push upward on the overlying corona in a location where the field is not closed and both fast and slow waves could propagate.

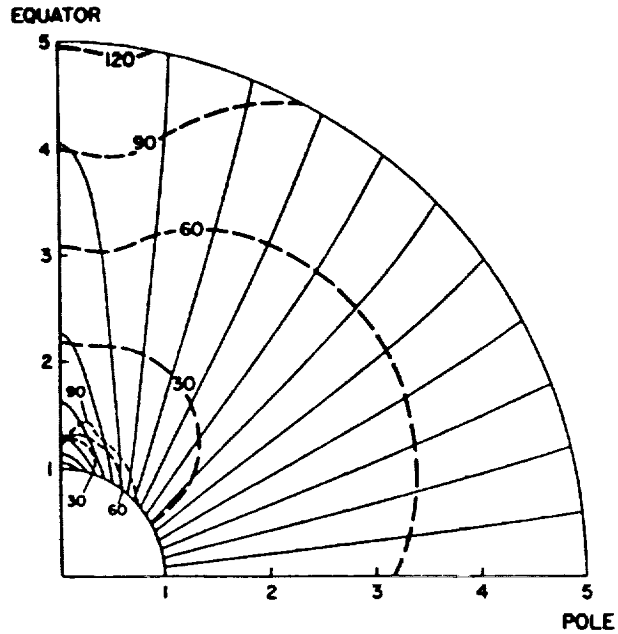

Fig. 1. Fast- (heavy dashed curves) and slow-mode (light dashed curves) wavefront locations at various times overlain on the magnetic field lines in a streamer configuration.

Another issue has to do with the presence of the streamer current sheet. Slow shocks cannot exist at the exact center of the sheet since the field either vanishes there or has only a component perpendicular to the streamer plane. Actually, there is some finite region about the sheet center in which slow shocks are excluded. To quantify the extent of this region, a simple computation shows that, if the current has a cosine dependence through the sheet and thermal pressure forces maintain equilibrium, a slow shock is prohibited from forming in more than half the current sheet width for a plasma beta outside the sheet of 0.1.

Although current sheets often appear as very narrow structures on eclipse photographs, the merging of an assumed slow shock outside the sheet to some other form of disturbance in its interior must be accounted for. The importance of this point can be illustrated by noting the substantially different effects produced by fast and slow shocks with identical velocities as shown in Figure 2. The shocks have

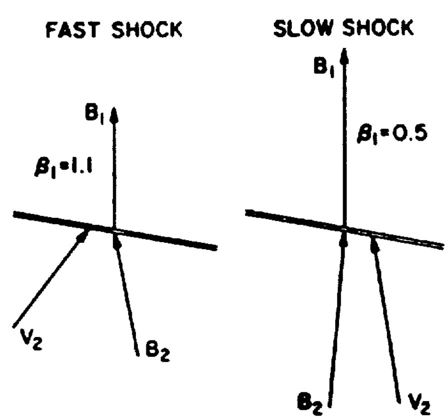

Fig. 2. Example of the large difference in jump conditions across fast and slow shocks with the same velocity.

velocities of 220 km sec^{-1} and are propagating at an angle of 10° with respect to the ambient field at locations in the current sheet where the upstream β is 0.5 for the slow shock and 1.1 for the fast shock. The much different downstream field direction and flow velocities for the two shocks seem to preclude a smooth transition from one to the other.

A final point is that the presence of a fast-mode disturbance ahead of the proposed slow shock must be taken into consideration. The fast wave may alter the ambient corona in such a way that slow shocks no longer form or, at least, they may resolve the apparent problem with the lack of a slow shock inside the current sheet. The neglect of the preceding fast-mode disturbance in the study of *Wolfson* [1987] makes the application of his results to the present problem questionable.

One way to resolve the above comments on the influence of the preceding fast wave and the effect of the current sheet is to do a parametric numerical study of shock formation in a current sheet, which (to the author's knowledge) has not been done. Some results for the simulation of a mass ejection in a heated streamer (with a poorly defined current sheet) in the following section indicate that some of the reasons for suggesting the presence of slow shocks may be removed without them.

III. Numerical Simulation Results

A mass ejection is produced in the streamer with the magnetic configuration shown in Figure 1 by a localized source of thermal energy inside the closed-field region near the coronal base. (See *Steinolfson and Hundhausen* [1987] for more information on this simulation.) Contours of equal values of coronal brightness at two times during the ejection are shown in Figure 3. The thick dashed lines indicate the fast mode wavefront location from Figure 1. Note that the transient leading-edge travels outward at approximately the fast-mode speed with no apparent wave steepening.

This ejection has the characteristic flat top often observed and the lateral extension of the fast wavefront may be responsible for disturbing adjacent structures. The transient speed is approximately 380 km sec^{-1} along the equator. The sound and Alfvén speeds at 20 degrees from the equator and at 4 $r_{\odot}$ are 220 and 400 km sec^{-1}, respectively. Hence, the equatorial leading-edge is travelling slightly slower than the Alfvén speed away from the equator.

As shown in Figure 1, the current sheet is not well-defined in this simulation in the sense that there is a relatively large latitudinal component of the magnetic field inside it. Based on the arguments in the

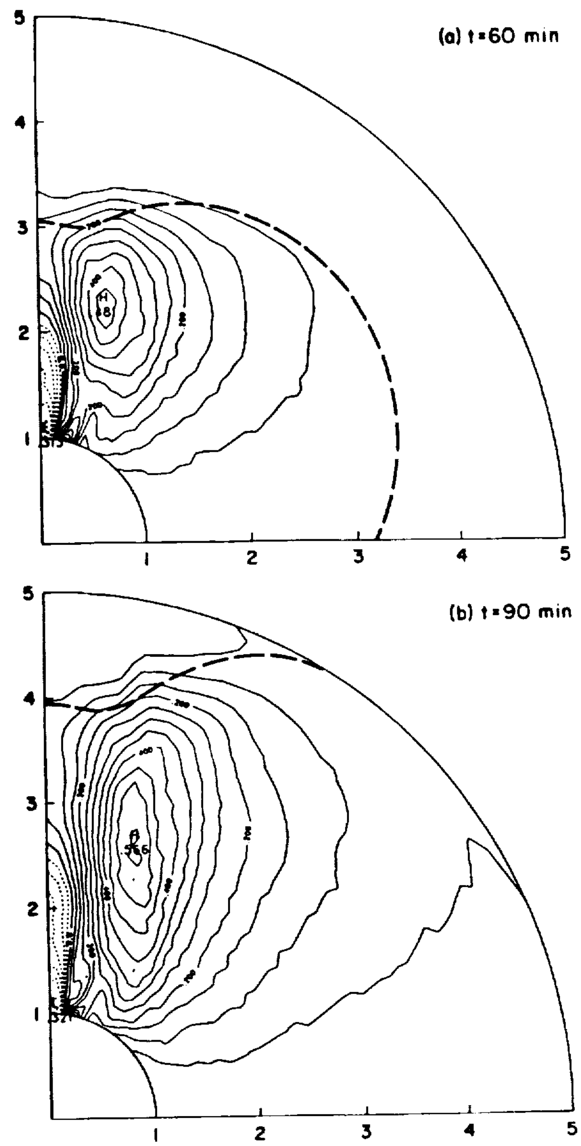

Fig. 3. Simulation of a "flat-top" mass ejection without any shock waves.

preceding section, this would tend to retard slow wave steepening and thereby bias this simulation against formation of slow shocks.

IV. Discussion

Some suggestions are given for why there may be problems with the formation of slow shocks in mass ejections originating within the closed-field region at the base of a streamer. In addition, results from a numerical simulation demonstrate that at least some the reasons given for the possible occurrence of slow shocks may be satisfied without their presence and, in fact, without the necessity of any shocks. The possibility remains, however, that some transients may travel considerably slower than the Alfvén speed. The overall conclusion is that the possible role of slow shocks and their configuration in the mass ejection phenomena remains an open question and awaits more quantitative simulations and further data analysis.

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