NASA-CR-190664

115676

p. 6

SOUTHWEST RESEARCH INSTITUTE
FINAL TECHNICAL REPORT FOR NASA GRANT NO. NAGW-2087
SwRI PROJECT NO. 15-3619

DYNAMICS AND ENERGETICS OF THE SOLAR CORONA

Principal Investigator:

R. S. Steinolfson

Dr. R.S. Steinolfson, Staff Scientist
Southwest Research Institute
6220 Culebra Road
San Antonio, TX 78238-5166
E-mail: rich@solar.space.swri.edu, swri::rich
(512) 522-2822

Period Covered: September 1989 - August 1992

ABSTRACT

The primary objective of this research program is to improve our understanding of the dynamics and energetics of the solar corona both in the quiescent dynamic equilibrium state when coronal structure is dominated by the equatorial streamer belt and in the eruptive state when coronal plasma is ejected into the interplanetary medium. Numerical solutions of the time-dependent magnetohydrodynamic (MHD) equations and comparisons of the computed results with observations form the core of the approach to achieving this objective. Some of the specific topics that have been studied are: (1) quiescent coronal streamers in an atmosphere dominated by a dipole magnetic field at large radii, (2) the formation of coronal mass ejections (CMEs) in quiescent streamers due to the emergence of new magnetic flux and due to photospheric shear motion, (3) MHD shock fomation near the leading edge of CMEs, (4) coronal magnetic arcade eruption as a result of applied photospheric shear motion, and (5) the three-dimensional structure of CMEs. The main results from each of these studies are summarized below.

PUBLICATIONS

Publications resulting from research supported by this NASA grant are listed below. Copies of those marked with an abstract are included with this final report. Reprints for the first three were sent with earlier semi-annual reports, and the last two are currently being prepared.

1. R.S. Steinolfson and A.J. Hundhausen, MHD Intermediate Shocks in Coronal Mass Ejections, *J. Geophys. Res.* **95**, 6389, (1990).
2. R.S. Steinolfson and A.J. Hundhausen, Concave-Outward Slow Shocks in Coronal Mass Ejections, *J. Geophys. Res.* **95**, 15251 (1990).
3. R.S. Steinolfson, Dynamics of Axisymmetric Loops, in *Physics of Magnetic Flux Ropes* (C.T. Russell, E.R. Priest, and L.C. Lee, Eds.), Geophysical Monograph 58, 211-218, 1990.

*4. R.S. Steinolfson and A.J. Hundhausen, Coronal Mass Ejection Shock Fronts Containing the Two Types of Intermediate Shocks, *J. Geophys. Res.* **95**, 20,693-20,699 (1990).

*5. R. S. Steinolfson, Coronal Evolution Due to Shear Motion, *Astrophys. J.* **382**, 677-687 (1990).

*6. R.S. Steinolfson, MHD Modeling of Shear-Induced Coronal Evolution and MHD Shocks, in *Max '91/SMM Solar Flares: Observations and Theory* (R.M. Winglee and A.L. Kiplinger, Eds.) 123-138, 1990.

*7. S. Koutchmy, J.B. Zirker, R.S. Steinolfson, and J.D. Zhugzda, Coronal Activity, in *The Solar Interior and Atmosphere* (A.N. Cox, W.C. Livingston, and M.S. Matthews, Eds.) University of Arizona Press, Tucson, pp. 1044-1086, 1991. (invited review)

*8. R.S. Steinolfson, Models of Material Ejection, in *Flares 22, Dynamics of Solar Flares* (B. Schmieder and E.R. Priest, Eds.) Observatorie dE Paris, DASOP, 171-183, 1991.

*9. R.S. Steinolfson, Coronal Shock Waves, in *Proceedings of the 26th ESLAB Symposium on the Study of the Solar-Terrestrial System*, Killarney, Ireland, 16-19 June 1992, in press, 1992. (invited review)

*10. R.S. Steinolfson, The Three-Dimensional Structure of Coronal Mass Ejections, *J. Geophys. Res.*, **97**, 10,811-10,824 (1991).

11. R.S. Steinolfson, The Eruption of Coronal Arcades Due to Shear Motion, *Astrophys. J.* in preparation, 1992.
12. R.S. Steinolfson, MHD Shock Formation Near the Leading Edge of Coronal Mass Ejections Propagating Through Streamers, *J. Geophys. Res.*, in preparation, 1992.

SUMMARY OF RESEARCH

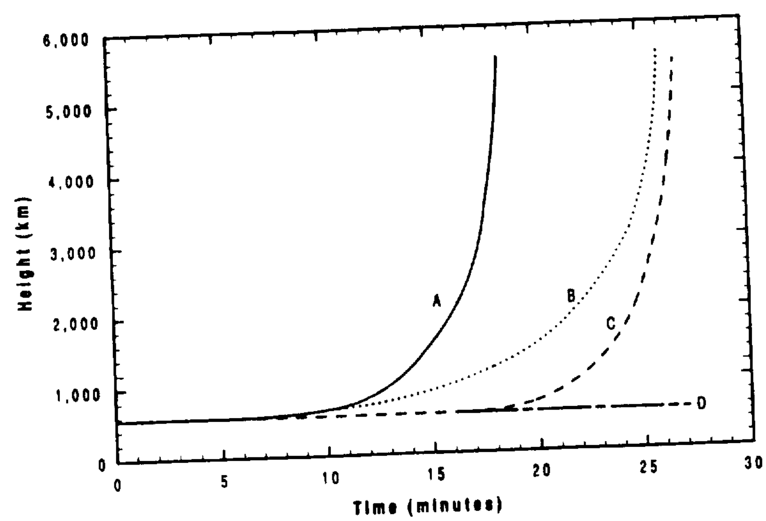
The formation of MHD shocks near the leading edge of CMEs is discussed in papers 1, 2, 4, 6, 9, and 12 above. The general approach followed in this study was to begin with a sufficiently simple model corona and geometry that the shock and wave formation processes could be studied in detail without unnecessary complicating factors. When the shocks were well understood in this simplified model, a more realistic corona was used. The initial studies, then, were carried out with a static atmosphere without gravity so the initial thermodynamic conditions were uniform. The use of this simple model atmosphere offered the additional advantage that the types of shocks that should form for various values of the parameters could be determined analytically. One of the main results to emerge from this study was to demonstrate that all three types of MHD shocks (slow, intermediate, and fast) may form near the leading edge of CMEs for various parametric regimes. As would be expected, slow shocks form at the lowest CME speeds, and fast shocks for the highest speeds. For CMEs with either slow or intermediate shocks, fast expansion waves travel out ahead of the shocks and produce a large enough reduction in density (and therby in white-light brightness) that it should be noticeable in the observations. Numerical simulations confirmed the predictions of the analytic studies. Both the analytic and numerical work for this model predict that (1) a slow shock front should be concave upward (away from the solar surface), (2) a configuration containing intermediate shocks should also be concave upward near the center of the CME and concave downward at some distance from the vertical CME centerline, and (3) a fast shock configuration should be concave downward.

The above studies using a static atmosphere were extended to the use of a more realistic coronal atmosphere containing a streamer with outflow along open field lines and no outflow within the closed-field region. An important feature of this streamer is that it was constructed so as to contain physical conditions similar to observed values, and, in particular, the plasma beta (ratio of thermal pressure to magnetic pressure) is less than unity throughout the streamer except within the narrow current sheet above the closed-field region. The streamer was computed numerically using a relaxation procedure developed with previous NASA support (Steinolfson and Hundhausen, *J. Geophys. Res.*, **93**, 14,261, 1988) and is discussed in more detail in papers 9, 10, and 12. By examining the characteristic wave speeds in this ambient streamer, it was estimated that the different shock configurations predicted from the above simpler model should form for CME speeds within the following speed increments: slow shocks, 200-300 km/sec; intermediate shocks, 300-900 km/sec; fast shocks, >900 km/sec. These estimates were substantiated with numerical simulations of CMEs produced in the streamer as a result of an increase in magnetic flux within the closed-field region at the streamer base. Consequently, for most typical CME speeds, intermediate shocks should form near the leading edge. The distinctive flat-topped or concave-upward appearance of many observed CMEs may be a result of the formation of intermediate shocks. These more recent results are presented in an abbreviated form in paper 9 of the above list, and a more thorough discussion is in preparation (paper 12).

Another topic involves the simulation of the evolution of coronal magnetic structures in response to slow photospheric shear motion of the field line foot points, which is discussed more in papers 5, 6, and 11. The most important result from this portion of the research is to show that a single isolated magnetic arcade can be sheared slowly until it eventually erupts *providing* the coronal field lines are forced to move with the applied shear motion. In a number of studies by other investigators of the same problem, this condition was not applied, and the arcade did not erupt. In these latter studies, the field lines did not track the shear, thereby resulting in the build-up of what has been referred to as a resistive boundary layer at the shear boundary. For a typical result from the study in paper 5 the applied maximum shear speed is 2.6 km/sec or 0.005 times the reference Alfvén speed. In this case the sheared field moves out very little for the first 16 hours and then begins moving out slowly at first until it ultimately erupts outward. This type of behavior is precisely what is found when the outward motion of identifiable features in observed CMEs are followed in time. It is also shown that if the field is allowed to resistively slip as in other studies, the field does not erupt.

The results in paper 5 are for a global-scale magnetic structure and demonstrate the feasibility of causing a single arcade to display eruptive behavior as a result of shear motion - providing the coronal field moves with the applied shear motion. It was speculated that the eruption did not occur due to an instability or a loss of equilibrium, but rather began gradually at first and eventually became more rapid when energy due to the shear motion was put into the corona (by Poynting flux through the surface) at a rate faster that the corona could adjust and maintain a quasi-static equilibrium. This behavior should be differentiated from a loss of equilibrium because there are equilibrium states consistent with the boundary conditions at each instant in time, but the corona simply does not have time to attain those equilibrium states before more energy is dumped into the corona and the boundary conditions are changed. The problem essentially reduces to a question of how rapidly the corona can find an equilibrium when the boundary conditions are changed.

Since no further evidence (beyond a limited parametric study) was given in paper 5 to support the above interpretation, an attempt was made to provide some supporting results by more detailed examination of the shearing of active region-sized arcades similar to those used in previous studies by others, as opposed to the global arcades considered above. Some of the important results from this study are shown in the figure below (more complete results are given in paper 11), which shows the outward trajectory of a relevant field line rooted near the edge of the shear region for several different cases. In every case the maximum shear velocity is 0.5 km/sec or 0.001 times the reference Alfvén speed. For case A the shear is applied continuously, and, as is obvious in the figure, the field erupts outward. Although the time scales are much different now (with respect to the above global simulation) due to the drastically different physical scales (about 2 orders of magnitude smaller), the physics involved in the two studies should be similar. Even though the shear is removed after 10 minutes for case B, the field still erupts, although at a slightly slower rate. The fact that the field erupts even though the shear is removed suggests that a cumulative feedback between the shear and the boundary conditions does not artificially generate the eruption. The shear is removed after 5 minutes for case C, and the field does not erupt. For case D the shear is removed after 5 minutes and then reapplied after being off for 10 minutes, and the field then erupts in a manner almost identical to that for case A where the shear is applied continuously. One interpretation of these results is that when the shear is applied for a short enough time and the field is not too highly stressed, the corona can find an equilibrium. However, when the shear is applied continuously or when the field is initially in a highly stressed state and the shear is then applied even for a relatively short time, the corona cannot find a quasi-static equilibrium and erupts outward in an attempt to find an equilibrium. Note that since the rate of energy input due to the shear motion depends linearly on the sheared component of the magnetic field, even the smallest shear speed has the potential of eventually putting energy into a highly stressed corona so rapidly that it loses quasi-static equilibrium (it just takes longer).



Additional studies discussed in paper 11 include putting in a model transition region and applying the shear in the high beta portion of the lower solar atmosphere (photosphere). Once again the shear leads to an eruption of the coronal arcade. Another study involved putting a shear viscosity term in the momentum equation as in some of the other studies of this problem. The viscosity delayed the eruption, but the shear eventually drove the arcade until it erupted. For a third problem the coronal resistivity was changed by two orders of magnitude (from a magnetic Reynolds number of 10^4 to 10^2) at a fixed distance above the shear surface. If the field slipped through one of the two resistive regions, then this would show up as a kink in the field lines at the location of the changing resistivity (i.e., a resistive boundary layer would form). There was absolutely no indication of the formation of a resistive boundary layer or any kink in the field lines. The field lines simply passed smoothly through the changing resistivity. This lends support to the method of applying the boundary conditions in which the field lines are forced to move with the shear motion without any slippage.

Due to the currently restricted observational view of CMEs, limited to plane-of-the-sky images as viewed from Earth, one of the major unresolved issues has been whether they have the shape of an expanding loop (arcade) with a finite extent perpendicular to the plane-of-the-sky or are more in the shape of a rapidly inflating bubble. Additionally, the change in the observed CME shape as it originates further from the limb is largely unknown.

Some insight into the 3-D structure of CMEs has been provided by the study presented in paper 12 for one typical case. The emergence of new magnetic flux into a finite longitudinal extent of a quiescent equatorial streamer belt is considered. In order to more directly relate the results to observations, the equations for Thomson scattering were used to convert the computed 3-D density distribution to the white-light signatures that would be recorded in a particular coronagraph. The results indicate that the CME has the same basic shape in the plane of the sky as it occurs further from the limb, but it becomes dimmer as the distance from the limb increases. This simulated CME is shaped more like an expanding arcade than a bubble.