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Final Report for NASA Contract NAS5-30930
MHD Shocks in Coronal Mass Ejections
R.S. Steinolfson, Principal Investigator

The primary objective of this research program is the study of the MHD shocks and nonlinear simple waves produced as a result of the interaction of ejected lower coronal plasma with the ambient corona. The types of shocks and nonlinear simple waves produced for representative coronal conditions and disturbance velocities have been determined. The wave system and the interactions between the ejecta and ambient corona have been studied using both analytic theory and numerical solutions of the time-dependent, nonlinear MHD equations. Observations from the SMM coronagraph/polarimeter provided both guidance and motivation for this study and are used extensively in evaluating the results. As a natural consequence of the comparisons with the data, the simulations have assisted in better understanding the physical interactions in coronal mass ejections (CMEs).

The general approach followed in this study was to begin with a sufficiently simple model corona and geometry such that the shock and wave formation processes could be studied in detail without extraneous complicating factors. When the shocks were well understood in this simplified model, a more realistic corona was used. Hence, the initial studies were carried out with a static atmosphere without gravity so the initial thermodynamic conditions were uniform. The results of these initial studies have been published in the following articles:

Steinolfson, R.S. and A.J. Hundhausen, Waves in low-beta plasmas: Slow shocks, *J. Geophys Res.*, **94**, 1222, 1989.

Steinolfson, R.S. and A.J. Hundhausen, MHD intermediate shocks in coronal mass ejections, *J. Geophys. Res.*, **95**, 6389, 1990.

Steinolfson, R.S. and A.J. Hundhausen, Concave-outward slow shocks in coronal mass ejections, *J. Geophys. Res.*, **95**, 15251, 1990.

Steinolfson, R.S. and A.J. Hundhausen, Coronal mass ejection shock fronts containing the two types of intermediate shocks, *J. Geophys. Res.*, **95**, 20693, 1990.

The last three papers listed above appeared during the period of this contract and are included here in an appendix. One of the main results of these studies was to demonstrate that all three MHD shocks (slow, intermediate, and fast) may form near the leading edge of CMEs for various parametric regimes. In general, slow shocks form in slower CMEs and intermediate and fast shocks form in the faster CMEs. For the cases with both slow and intermediate shocks, fast expansion waves travel out ahead of the shocks, and produce a large enough reduction in density (and thereby in white-light brightness) that it should be noticeable in the observations. Because of the simplified geometry and initial atmosphere, the types of shocks that form for various values of the parameters could be determined analytically. One of the most satisfying aspects of these early studies was to be able to confirm the analytically-predicted shock configurations with numerical simulations.

(NASA-CR-193418) MHD SHOCKS IN CORONAL MASS EJECTIONS Final Report, 25 May 1990 - 25 Nov. 1991 (Southwest Research Inst.) 10 p

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These initial studies have been expanded upon by using a more realistic coronal atmosphere. This atmosphere contains a coronal streamer with outflow along open field lines and no outflow within the closed-field region. Several of the physical variables in this ambient state are shown in Figure 1. The streamer was computed numerically using a relaxation procedure developed with previous support from the SMM Guest Investigator program (Steinolfson and Hundhausen, *J. Geophys. Res.*, **93**, 14261, 1988).

A disturbance (CME) was then produced in the streamer by increasing the magnetic flux within the closed-field region near the coronal base. Examples of simulations containing slow and intermediate shocks are given in Figures 2 and 3. The shock locations are indicated by the two parallel line segments drawn on the computer-generated plots of the velocity vectors and magnetic field lines. The leading edge of the entropy provides a good means by which the shock location can be determined. Note that expansion waves are formed ahead of both shocks. The distinctive flat-topped appearance of many observed CMEs may be a result of the formation of intermediate shocks. This work is currently being written up for submission to the *Journal of Geophysical Research.*

CORONAL STREAMER

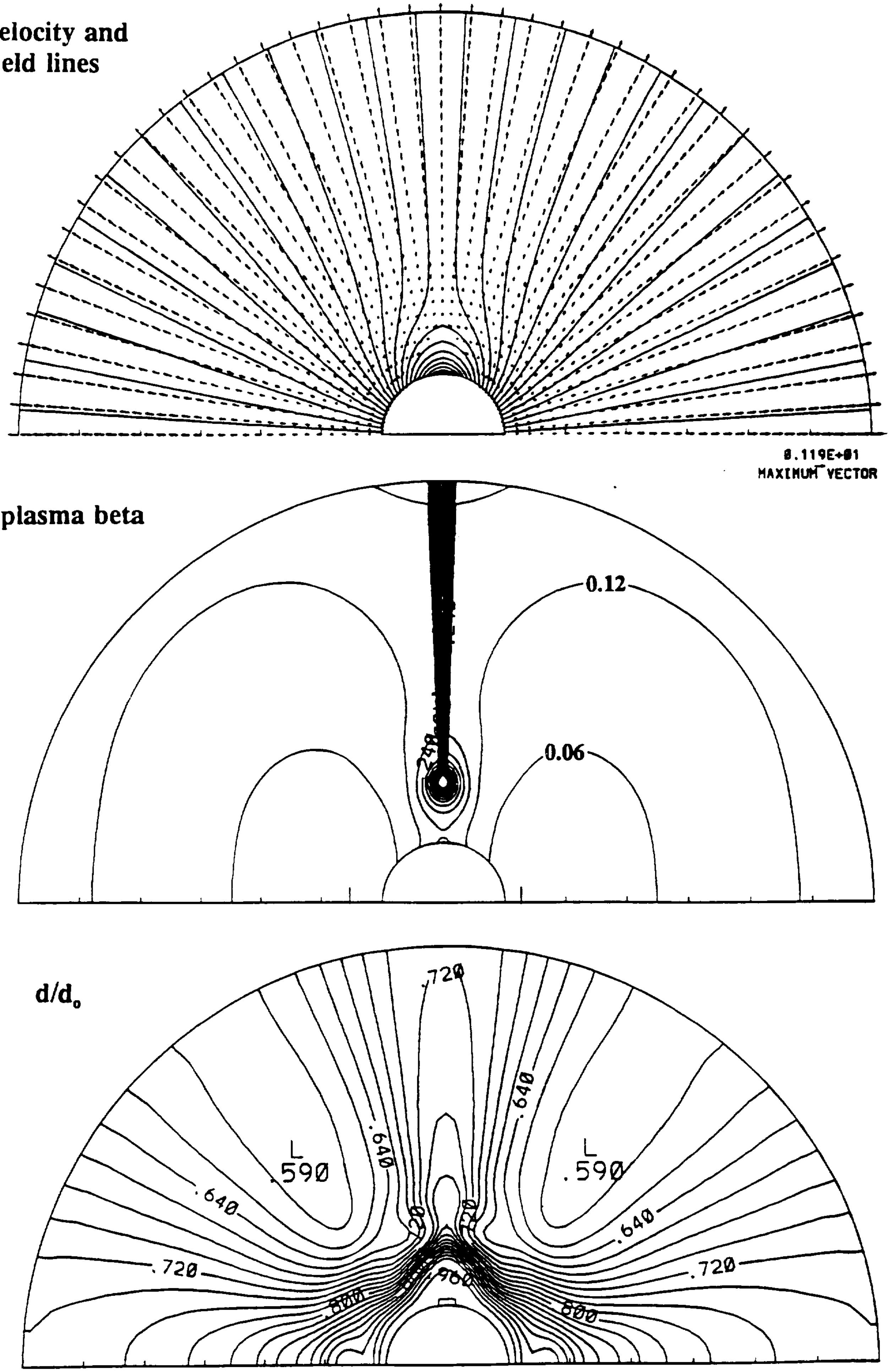
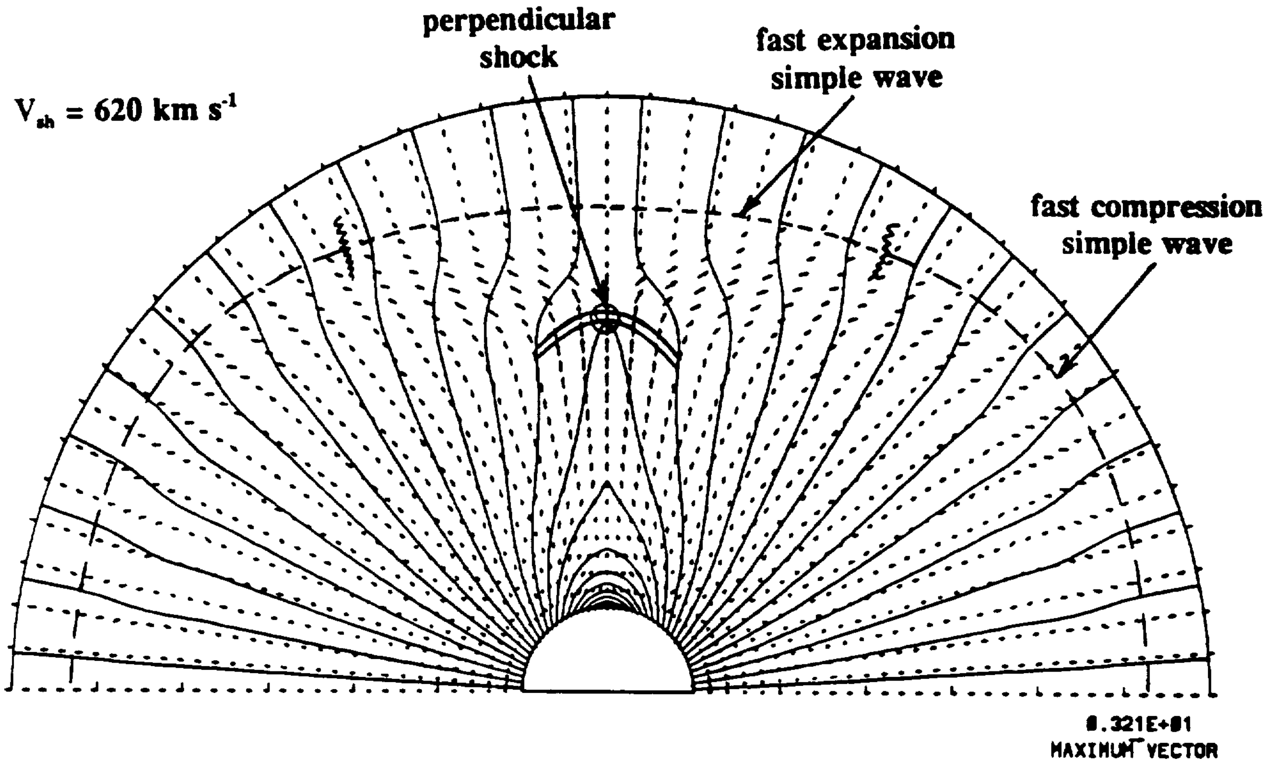


Figure 1

SLOW SHOCK

velocity and field lines



d/d$_{st}$

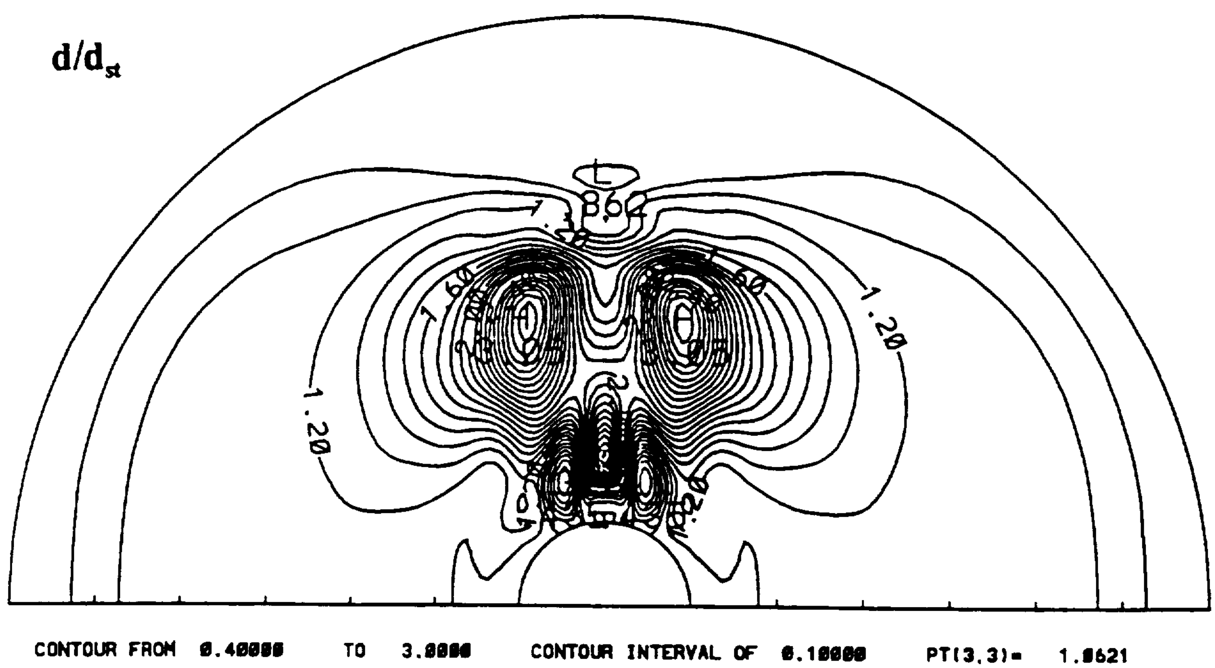


Figure 2a

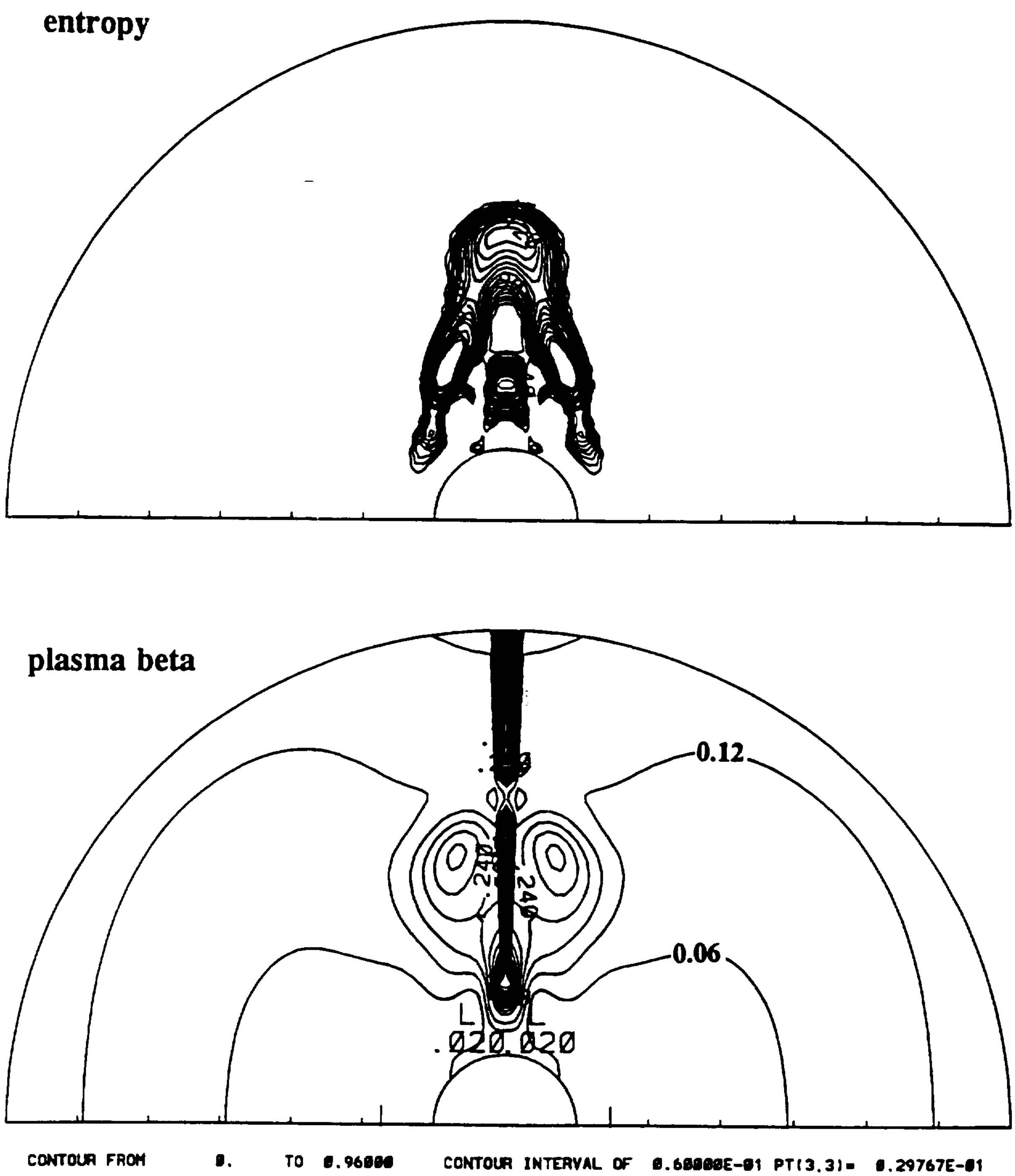
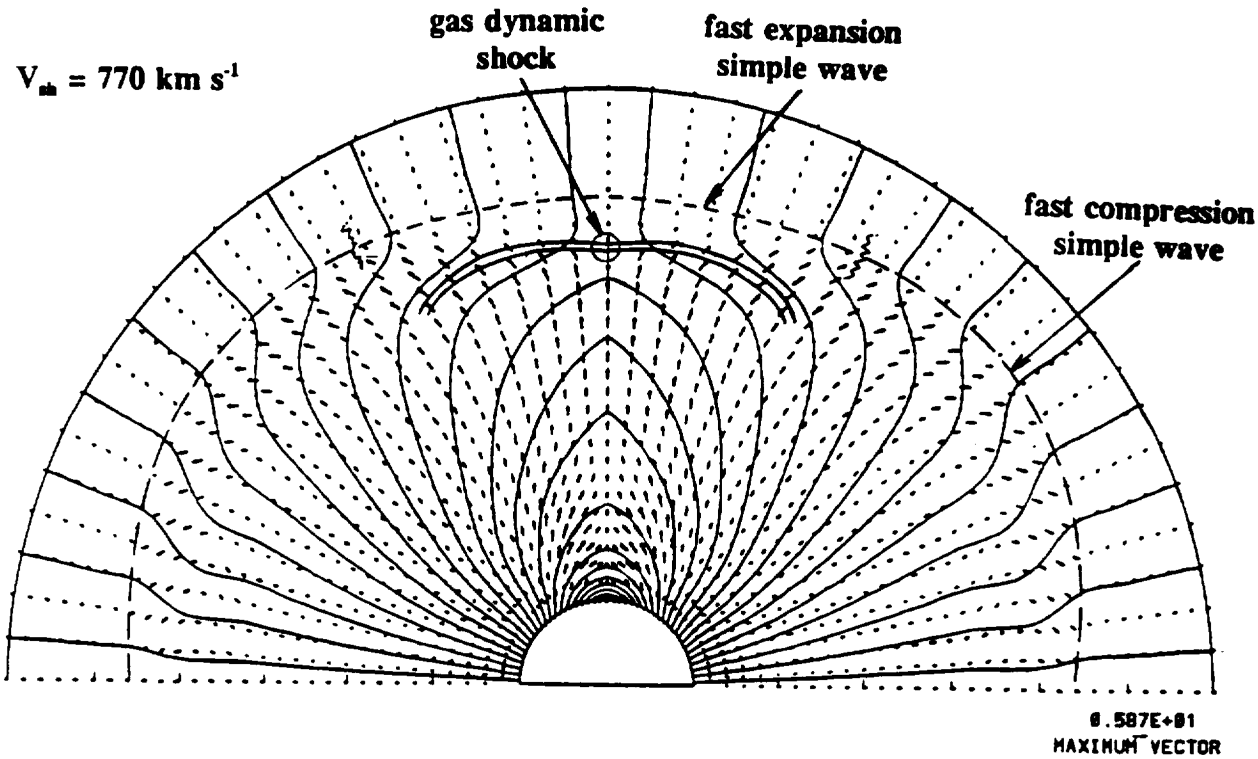

entropy
plasma beta
0.12
0.06
.240
.240
.020
.020
CONTOUR FROM 0. TO 0.96000 CONTOUR INTERVAL OF 0.60000E-01 PT(3,3)= 0.29767E-01

Figure 2b

INTERMEDIATE SHOCK

velocity and field lines



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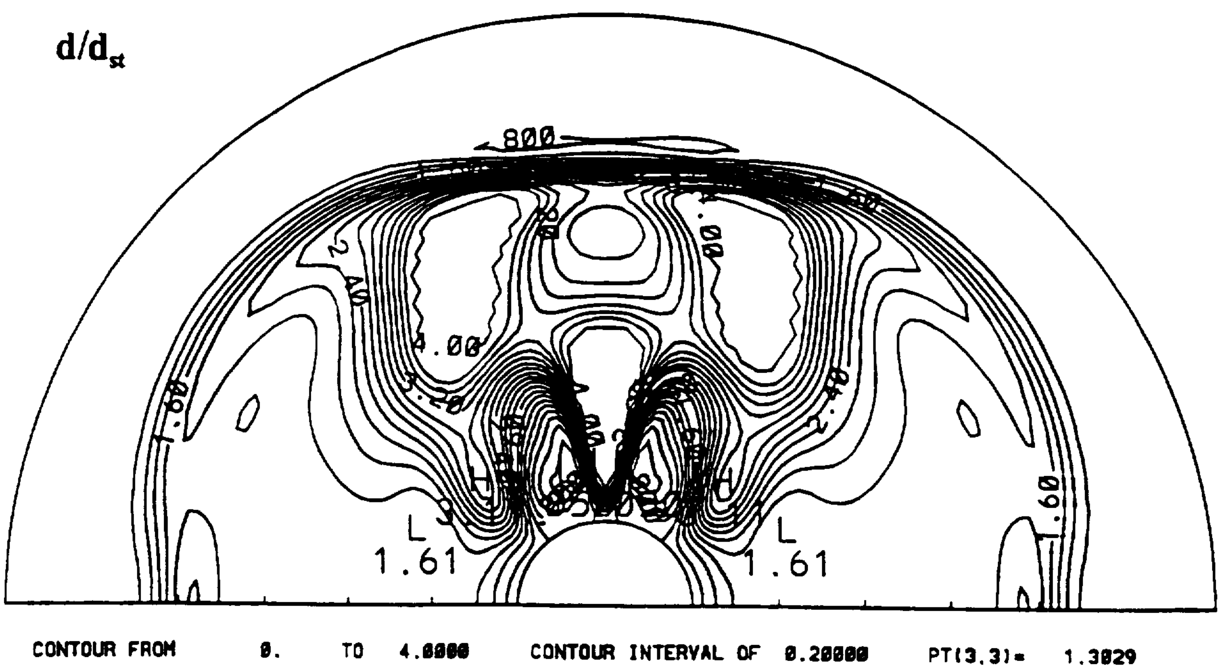
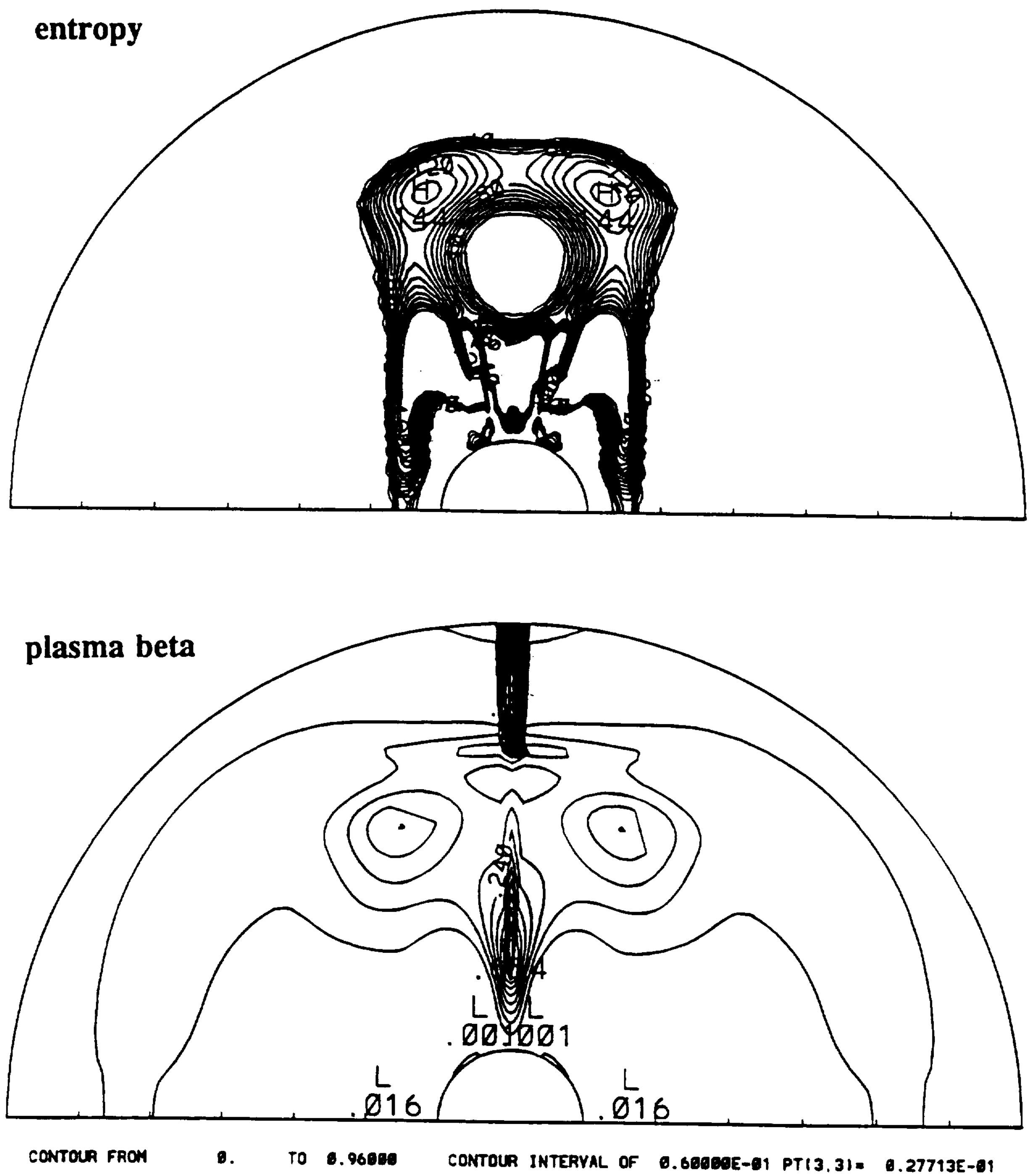


Figure 3a


entropy
plasma beta
L L
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CONTOUR FROM 0. TO 0.96000 CONTOUR INTERVAL OF 0.60000E-01 PT(3,3)= 0.27713E-01

Figure 3b

APPENDIX

Papers that appeared in print during the period of this contract.

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Report Documentation Page

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16. Abstract

The primary objective of this research program is the study of the MHD shocks and nonlinear simple waves produced as a result of the interaction of ejected lower coronal plasma with the ambient corona. The types of shocks and nonlinear simple waves produced for representative coronal conditions and disturbance velocities have been determined. The wave system and the interactions between the ejecta and ambient corona have been studied using both analytic theory and numerical solutions of the time-dependent, nonlinear MHD equations. Observations from the SMM coronagraph/polarimeter provided both guidance and motivation for this study and are used extensively in evaluating the results. As a natural consequence of the comparisons with the data, the simulations have assisted in better understanding the physical interactions in coronal mass ejections (CMEs).

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