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DYNAMIC SIMULATION OF CORONAL
MASS EJECTIONS

The University
Of Alabama
In Huntsville

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THIS RESEARCH WORK WAS SUPPORTED BY THE
National Aeronautics and Space Administration
Contract NAS8-33216
UAMS Research Report No. 240

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Final Technical Report

This research work was supported by
the National Aeronautics and Space Administration
Contract NAS8-33216

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April 1980
Acknowledgements

This work was supported by the National Aeronautics and Space Administration under Contract NAS8-33216. The authors would like to thank Drs. Ernie Hildner, Steve Suess, Einar Tandberg-Hanssen, and Murray Dryer for many helpful discussions during the course of this work.

Acknowledgement is made to the National Center for Atmospheric Research, which is sponsored by the National Science Foundation, for the use of its computing facilities.

The manuscript was typed by Miss Lynn Breeding and Miss Karen Goodrowe, whose services are appreciated.
Summary

A model is developed for the formation and propagation through the lower corona of the loop-like coronal transients in which mass is ejected from near the solar surface to the outer corona. The mass ejections are simulated with numerical solutions of the time-dependent, two-dimensional, dissipationless, magnetohydrodynamic equations of motion. The objective is to obtain a better understanding of the physical processes responsible for and occurring in the mass ejections.

The main difference between this model and previous similar models is that we assume that the initial state for the transient is a coronal streamer. In previous models the initial state has been taken as a hydrostatic state with a force-free magnetic field. In the coronal streamer, the atmosphere is not stationary and the magnetic field is not force-free. A coronal streamer consists of closed magnetic field lines near the solar surface with overlying and adjacent open field lines. The plasma is stationary in the closed region and flows outward in the open region.

Coronal streamers are observed to last for long periods on the solar surface and, therefore, must represent a quasi steady-state solution to the complete time-dependent equations. Since a self-consistent analytic solution for coronal streamers does not exist, a numerical solution is constructed. The initial state for the streamer is a polytropic, hydrodynamic solution to the steady-state radial equation of motion coupled with a force-free dipole magnetic field. The numerical solution of the complete time-dependent equations then gradually approaches a stationary coronal-streamer configuration. The streamer configuration becomes the initial state for the coronal...
transient. The streamer and transient simulations are performed completely independent of each other. The transient is created by a sudden increase in the pressure at the base of the closed-field region in the streamer configuration. Both coronal streamers and coronal transients are calculated for values of the plasma beta (the ratio of thermal to magnetic pressure) varying from 0.1 to 100. We compare our results with similar results obtained using the previously-developed model mentioned above in which the initial atmosphere is stationary and the magnetic field is force-free. We also compare both our results and the previous results with the observed characteristics of loop-like, mass ejection coronal transients in order to evaluate the relative merits of the two models.
**TABLE OF CONTENTS**

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acknowledgements</td>
<td>1</td>
</tr>
<tr>
<td>Summary</td>
<td>11</td>
</tr>
<tr>
<td>I. Introduction</td>
<td>1</td>
</tr>
<tr>
<td>II. Equations and Solution Procedure</td>
<td>3</td>
</tr>
<tr>
<td>III. Coronal Streamers</td>
<td>6</td>
</tr>
<tr>
<td>A. Initial State and Boundary Conditions</td>
<td>6</td>
</tr>
<tr>
<td>B. Numerical Results</td>
<td>10</td>
</tr>
<tr>
<td>1. ( \beta = 4 )</td>
<td>10</td>
</tr>
<tr>
<td>2. ( \beta = 0.5 )</td>
<td>12</td>
</tr>
<tr>
<td>3. Coronal Streamer Structure</td>
<td>14</td>
</tr>
<tr>
<td>IV. Coronal Transients</td>
<td>16</td>
</tr>
<tr>
<td>A. Initial State, Boundary Conditions and Perturbation</td>
<td>16</td>
</tr>
<tr>
<td>B. Numerical Results</td>
<td>17</td>
</tr>
<tr>
<td>1. ( \beta = 4 )</td>
<td>17</td>
</tr>
<tr>
<td>2. ( \beta = 0.5 )</td>
<td>19</td>
</tr>
<tr>
<td>3. Other Pertinent Results</td>
<td>21</td>
</tr>
<tr>
<td>V. Comparison with Other Applicable Models</td>
<td>24</td>
</tr>
<tr>
<td>A. A Model with an Initially Stationary Atmosphere</td>
<td>25</td>
</tr>
<tr>
<td>B. Comparisons</td>
<td>26</td>
</tr>
<tr>
<td>VI. Comparison with Observations</td>
<td>29</td>
</tr>
<tr>
<td>A. Observed Characteristics of Coronal Transients</td>
<td>29</td>
</tr>
<tr>
<td>B. Comparisons</td>
<td>31</td>
</tr>
<tr>
<td>VII. Discussion and Conclusions</td>
<td>34</td>
</tr>
<tr>
<td>References</td>
<td>38</td>
</tr>
<tr>
<td>Table</td>
<td>40</td>
</tr>
<tr>
<td>Figure Captions</td>
<td>41</td>
</tr>
</tbody>
</table>
## Appendices

<table>
<thead>
<tr>
<th>Appendix</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Computer Code for Numerical Solution</td>
<td>71</td>
</tr>
<tr>
<td>B. Computer Code for Computer-Generated Plots</td>
<td>116</td>
</tr>
<tr>
<td>C. Sample Run</td>
<td>127</td>
</tr>
</tbody>
</table>
I. INTRODUCTION

Coronal mass ejections are transients or disturbances in the corona in which material appears to escape from the Sun. The data obtained during the Skylab mission, by both on-board and ground-based instrumentation, have contributed significantly to the understanding of coronal mass ejections. For several ejections the coverage was complete enough that observations of the coronal transient (seen in white light and radio) could be associated with observations related to the solar phenomena, usually eruptive prominences or flares (seen in XUV, EUV, H\textalpha and X-ray), responsible for the transient (Hildner et al., 1975a, b; Rust and Hildner, 1976; Dulk et al., 1976; Poland and Munro, 1976; Schmahl and Hildner, 1977). This complete data analysis and establishment of a cause-effect relationship are crucial in determining the physical processes in mass ejections. These associations are particularly informative for the purpose of developing dynamic models when the data can be used to infer the thermodynamic properties (temperature, density and pressure), velocities and magnetic fields of at least some portions or features of either the solar event or the transient. If the simulation can be made to reasonably reproduce the observed physical properties, then since all the above properties are included in the simulation, information will be obtained on the physics of the solar event and transient for which observations are not available.

Several models have been developed to simulate the dynamics of the transient (see, e.g., Nakagawa et al., 1975; Steinolfson and Nakagawa, 1976; Steinolfson et al., 1978; Wu et al., 1978). These models do clarify some basic physics of the observed features of mass
ejections; however, they are not able (by the very nature of the models) to simulate some other important features. The shortcomings of the current models (which will be discussed in Section V) are such that it is questionable whether they are capable of simulating the detailed structure of mass ejections; even though they may be applicable to other types of atmospheric transients. In this report we present a model which leads to a more realistic simulation of the observed features of mass ejections and, consequently, to a better understanding of the related physical processes. The particular class of ejections which we simulate is the loop-like mass ejections that tend to be associated with eruptive prominences (Hildner, 1977).

The equations used in the model and the procedure followed in solving the equations are discussed in Section II. The complete simulation consists of two parts. In the first part a coronal- or helmet-streamer configuration is established; this is discussed in Section III. A coronal-streamer configuration consists of closed magnetic loops on the solar surface that lie beneath and adjacent to an open-field region. In the second part a perturbation in the thermal pressure is introduced at the base of the closed loops which simulates the solar event. The numerical solution of the time-dependent equations then simulates the resulting coronal transient. The coronal transient is discussed in Section IV. The model is compared with a previous model in Section V and with observations in Section VI. The results are summarized and the conclusions that can be made from this study are discussed in Section VII.
II. EQUATIONS AND SOLUTION PROCEDURE

The solar atmosphere is assumed to behave as a single fluid with negligible dissipative effects. With these assumptions the time-dependent magnetohydrodynamic (MHD) equations that describe atmospheric flows in the meridional plane can be written in MKS units as follows:

\[
\frac{\partial \rho}{\partial t} + \frac{1}{r} \frac{\partial}{\partial r} (ru) + \frac{1}{\rho} \frac{\partial}{\partial \theta} (\rho v) = - \frac{2 \dot{\gamma} u}{r} - \frac{\rho v}{r} \cot \theta \quad (1a)
\]

\[
\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial r} + \frac{B_0}{\mu_0} \frac{\partial B_0}{\partial r} + \frac{1}{\rho} \frac{\partial}{\partial r} \left( \frac{v}{r} \frac{\partial v}{\partial \theta} - \frac{B_0}{\mu_0} \frac{\partial B_0}{\partial \theta} \right) = - \frac{C_H}{r^2} + \frac{v^2}{r} - \frac{B_0^2}{\mu_0 r} \quad (1b)
\]

\[
\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial r} - \frac{B_0}{\mu_0} \frac{\partial B_0}{\partial r} + \frac{v}{r} \frac{\partial v}{\partial \theta} + \frac{B_r}{\mu_0} \frac{\partial B_r}{\partial \theta} + \frac{1}{\rho} \frac{\partial}{\partial \theta} \frac{\partial p}{\partial \theta} = \frac{r v B_0}{\mu_0 r} - \frac{uv}{r} \quad (1c)
\]

\[
\frac{\partial B_r}{\partial t} - \frac{1}{r} \left( \frac{u B_0 - v B_r}{r} \right) = \frac{1}{r} (u B_0 - v B_r) \cot \theta \quad (1d)
\]

\[
\frac{\partial B_0}{\partial t} + \frac{1}{r} \left( \frac{u B_0 - v B_r}{r} \right) = - \frac{1}{r} (u B_0 - v B_r) \quad (1e)
\]

\[
\frac{\partial p}{\partial t} + \gamma p \frac{\partial u}{\partial r} + u \frac{\partial p}{\partial r} + \gamma p \frac{\partial v}{\partial \theta} + \frac{v}{r} \frac{\partial p}{\partial \theta} = - \frac{\gamma p}{r} (2u + v \cot \theta) \quad (1f)
\]

where the dependent variables are the density \( \rho \), radial velocity \( u \), meridional velocity \( v \), pressure \( p \), radial magnetic field \( B_r \), and meridional magnetic field \( B_\theta \). The independent variables are the radius \( r \) and the latitude \( \theta \). The constants are the polytropic index \( \gamma \), magnetic permeability \( \mu \), solar gravitational constant \( G \), and solar mass \( M_s \).
The region in which the solution to the above equations is desired is shown in Figure 1; i.e., the region bounded by the solar surface and 5 solar radii ($R_0$) in radial distance and by the equator and the pole in meridional distance. The solution is assumed to be symmetric about the equator. The equations are solved numerically using a modified Lax-Wendroff difference scheme given by Rubin and Burstein (1967). The grid spacings used are $\Delta r = 0.1 R_0$ and $\Delta \theta = 2.5$ deg. The time step is chosen to be the maximum allowable from the usual stability criterion for Eulerian difference schemes; i.e., $\Delta t = \min (\Delta t_r, \Delta t_\theta)$ where $\Delta t_r = \Delta r / |\lambda_r|$ and $\Delta t_\theta = r \Delta \theta / |\lambda_\theta|$ and $|\lambda_r| (|\lambda_\theta|)$ is the maximum eigenvalue (the sum of the fluid velocity and the characteristic velocity) in the radial (meridional) direction. A smoothing term suggested by Lapidus (1967) is used to reduce numerical oscillations. The amount of the smoothing is controlled by a constant. Lapidus used a value of 4; we use a value of 2. The initial conditions and the boundary conditions for this initial-boundary value problem for the coronal streamer and the coronal transient calculations are discussed in Sections III and IV, respectively.

When Equations (1) are written in conservation form, as they must be in order to solve numerically, they contain singularities at the pole due to terms of the form $v \sin \theta$ and $B_\theta \sin \theta$. Both the numerator and denominator of these relations vanish at the pole. In the numerical solution these singularities were overcome by setting the values of the above two relations at the pole (point 2 in Figure 1) equal to their respective values at the grid point next to the pole (point 3).

The above equations can be non-dimensionalized with respect to some selected reference values in such a way that the only parameters are $\gamma, \beta$ (the ratio of thermal to magnetic pressure), and a parameter $\Lambda$.
involving the reference temperature. We selected the reference values as the initial values at the solar surface at the equator. Since \( \gamma \) and the reference temperature are kept constant, the only parameter remaining in the equations is \( \beta \). A number of theoretical studies have demonstrated the importance of the value of \( \beta \) (see, e.g., Steinolfson and Dryer, 1978; Nakagawa et al., 1976; Steinolfson et al., 1978). The importance of \( \beta \) in the present problem is investigated by examining coronal-streamer and coronal-transient structures for \( \beta \) varying from 0.1 to 100. The results for \( \beta = 4 \) and \( \beta = 0.5 \) are discussed in the most detail.

A listing of the computer code used to numerically solve Equations (1) is included in Appendix A along with a description of the input variables for the code. A separate code is used to produce the computer-generated plots presented in this report, and this computer code and a description of the input variables for it are given in Appendix B. Appendix C contains a listing of a sample run for a coronal-streamer simulation. All of the computer simulations were performed on the CRAY-1 computer at the National Center for Atmospheric Research in Boulder, Colorado.
III. CORONAL STREAMERS

A schematic of the magnetic field lines in a coronal streamer is shown in Figure 2. The fluid velocity is essentially zero inside the closed-field region with all the outward flow occurring in the open-field region. A current sheet exists on the equator in the open region where the magnetic field reverses direction. Coronal streamers are long-lived structures (often lasting for days) and, hence, must represent, in some sense at least, a configuration approaching a solution to the steady state form of Equations (1). However, such a steady-state solution would be extremely difficult to obtain. Pneuman and Kopp (1971) have constructed a steady state solution, but they assumed that the field lines were known a priori and neglected the interaction between the field lines and the fluid. Our approach is to start with an initial state as close to a coronal streamer as feasible, numerically solve the time-dependent equations and let the solution relax with time to a coronal-streamer configuration. This approach was used by Endler (1971) and Weber (1978) for a constant temperature medium; an assumption which we do not make. The final coronal-streamer configuration serves as the initial state for the coronal transient discussed in Section IV.

A. Initial State and Boundary Conditions

The thermodynamic variables and the velocity are given initially by a radial, hydrodynamic solution to the time-independent form of Equations (1); i.e., a Parker-type solution (Parker, 1963). The reference values for the thermodynamic variables in the initial state at 1 R\(_{\odot}\) are temperature \(T = 1.8 \times 10^6\) K and electron number density \(n = 2.25 \times 10^8\) cm\(^{-3}\), where \(\rho = nm\) and \(m_p\) is the proton mass. With these values the only solutions to the steady-state hydrodynamic equations with the critical
point beyond 1 \( R_\odot \) are obtained for \( 1 < \gamma < 1.1 \). The larger the value of \( \gamma \), the more rapidly \( \beta \) increases with distance. Since too large an increase in \( \beta \) with increasing distance is unrealistic and since \( \gamma = 1 \) implies that the temperature is constant, we used an intermediate value for \( \gamma \) of 1.05. The hydrodynamic solution then gives a value for the initial radial velocity at the solar surface of 8.2 km s\(^{-1}\). The initial meridional velocity is assumed to be zero.

The magnetic field is assumed to be force-free initially. The equations for the vanishing of the Lorentz force and the absence of free magnetic poles then determine the initial magnetic field configuration, which is given in terms of Legendre polynomials of order 1. The initial configuration selected is the dipole configuration obtained by using the Legendre polynomial of degree 1; i.e.,

\[
B_r = \frac{2 B_0 \cos \theta}{r^3}, \quad \quad B_\theta = \frac{B_0 \sin \theta}{r^3},
\]

where \( B_0 \) is the reference magnetic field. This configuration tends to restrain material ejected near the equator and consequently is referred to as a "closed field" configuration. The reference magnetic field is selected to obtain the desired value for \( \beta \). Values for the reference magnetic field of 0.83 G and 2.35 G at 1 \( R_\odot \) at the equator yield values for the plasma beta of 4 and 0.5, respectively. \( \beta \) increases with radius and decreases away from the equator. The initial value of \( \beta \) at 1 \( R_\odot \) at the pole is a factor of 2 less than at 1 \( R_\odot \) at the equator.
The above chosen initial state does not, of course, represent a steady-state solution to the complete two-dimensional equations. Hence, when used as the initial state, the time-dependent solution to Equations (1) will evolve until the solution relaxes to or approaches a steady-state solution (the coronal streamer).

The remaining quantities that must be specified for the numerical solution are the boundary conditions at the four boundaries in Figure 1. The solution is assumed to be symmetric about the equator, and hence, the boundary conditions there become (using the notation in Figure 1):

\[ u_1 = u_3 \quad p_1 = p_3 \quad B_{01} = B_{03} \]
\[ v_1 = -v_3 \quad p_1 = p_3 \quad B_{r1} = -B_{r3} \]

For the coronal-streamer calculation, the pole can also be considered as a symmetry boundary. The boundary conditions there then become the same as for the equator with the following exceptions:

\[ B_{01} = -B_{03} \quad B_{r1} = B_{r3} \]

Note that there is no flow across either of the above two boundaries. There is flow, however, across the remaining two boundaries at 1 \( R_e \) and 5 \( R_e \) (the inner and outer boundaries) and this makes their treatment somewhat more difficult. The reason can best be explained using the theory of characteristics. This has been done previously for one-dimensional, hydrodynamic flow by Nakagawa and Steinolfson (1976) and Steinolfson and Nakagawa (1976). We will briefly discuss the extension of their analysis to the present problem (see also Endler, 1971). Equations (1) are a hyperbolic system of equations, and therefore, the characteristics
for the equations are all real. In this case information from any point in the flow field can only propagate in the characteristic directions. In the radial direction, then, information propagates at the six velocities equal to the sum of the radial velocity and the radial component of each of the six characteristic velocities. At the outer boundary the flow is generally supersonic and super-Alfvenic, and hence, information from the outer boundary only propagates downstream, i.e., outside the region of interest. Another way of viewing this is that all six radial characteristic directions at the outer boundary are positive. This implies that the boundary conditions at 5 \( R_o \) can be specified arbitrarily. We choose to linearly extrapolate using the relation \( u_b = \Omega_n + \Lambda Q \) (notation as in Figure 1) where \( Q \) is any dependent variable and \( \Lambda Q \) is calculated at each time step from the values at the two radial grid points adjacent to the boundary. At the inner boundary two of the six radial characteristic directions are negative, and consequently, information from the region of interest propagates upstream to the boundary. In this case four dependent variables at the lower boundary can be specified arbitrarily, and two must be calculated from some form of compatibility relations (see Steinolfson and Nakagawa, 1976).

Strictly speaking, the compatibility relations are equations that can be derived from Equations (1) which must be satisfied by the dependent variables in each of the characteristic directions. Steinolfson and Nakagawa (1976) have shown that first-order or second-order (linear) extrapolation often works as well as using the more complex compatibility relations. We choose to hold the pressure, density and radial magnetic field at their initial values at the boundary and calculate the meridional velocity so that the total velocity and magnetic field are parallel at the boundary. The
radial velocity and meridional magnetic field are calculated from linear extrapolation. When the velocity approaches zero inside the closed-field region, the pressure and density at the boundary are allowed to increase accordingly by linear extrapolation.

B. Numerical Results

The initial-boundary value problem discussed above forms a well-posed problem, and the time-dependent equations are now solved numerically using the appropriate initial state and boundary conditions. It remains to select a criterion by which to determine when a steady-state, coronal-streamer configuration has been achieved. Admittedly this decision must be somewhat subjective. The criterion we used was to continue the time-dependent solution until the configuration did not change appreciably over a period of at least one hour of physical time. In general, the smaller the value of $\beta$, the more rapidly the solution evolved to a coronal-streamer configuration.

1. $\beta = 4$

The initial dipole magnetic field is shown in Figure 3(a). The field lines are spaced at 5 deg intervals at the solar surface. The curve consisting of long dashes represents the location where the radial flow velocity is equal to the sound speed (sonic curve). The radial flow velocity is equal to the Alfvén velocity based on the total magnetic field along the curve composed of short dashes (Alfvén curve). The evolving magnetic field is shown for three successive times in Figure 3. The numerical solution is changing so slowly with time after 24 hours that the solution at that time is selected as the final coronal-streamer configuration. Several of the dependent variables after 24 hours are shown in Figure 4. The nondimensional values given for the pressure and density are the values referenced to their respective initial values at
each point in the flow field. From Figures 3 and 4, it is easy to see the field lines evolving from a closed dipole field to a coronal-streamer configuration with the closed field lines lying beneath and adjacent to open field lines. The sonic curve is displaced inward in the final state, except for a small region around the equator, due to the general increase in velocity. The velocity decreases somewhat at the equator from that in the initial state and increases at the pole as shown in Figure 5. The changes in the pressure and density at the equator and pole referenced to their respective initial values at each point are also shown in the figure.

The top of the closed-field region in Figure 4(a) at the equator occurs at approximately the same radius at which the Alfven curve intersects the equator. The reason for this is that the magnetic field at the equator is approximately zero above the closed region, and the velocity is approximately zero in the closed region. There is one field line above the intersection of the Alfven curve with the equator that appears to be closed in Figure 4(a), but this is believed to be due to the interpolation between the relatively large grid spacing that we have used. The intersection of this field line with the equator is gradually moving outward.

The pressure and density are increased over their initial values and the velocity is approximately zero in the closed region as indicated in Figures 4 and 5. The temperature is proportional to the ratio of the pressure to the density, and hence, it is evident that the temperature also increases throughout the flow field. The increments in pressure and density between the contour lines in Figure 4 are equal so more tightly grouped curves denote larger gradients. The velocity vectors closely parallel the magnetic field lines in Figure 4 despite the relatively large value of $\beta$. The open field lines never become completely radial; not even the field lines next to the pole. Hence, assuming that the flow
does follow the field lines, the flow near the pole is in a region where the cross-sectional area of an infinitesimal flow tube increases more rapidly than as the radius squared. Several steady-state studies for flow in coronal holes where the cross-sectional area of a flow tube is specified to increase more rapidly than as the radius squared have appeared in the literature (see, e.g., Kopp and Holzer, 1976, and Steinolfson and Tandberg-Hanssen, 1977). These steady-state studies conclude that the velocity increases in coronal holes, but that the temperature and density decrease, which is in contrast with the present results. The reason for the discrepancy is not immediately apparent, but it is most likely related to the different boundary conditions applied at the solar surface in the two studies and to the inclusion of the meridional terms in the equations used in our study.

The results discussed above for $\beta = 4$ display several of the characteristics expected of coronal streamers (correct magnetic field configuration, higher pressure and density and zero velocity in the closed region, etc.) in spite of the fact that $\beta = 4$ is larger than would be expected in coronal streamers. We now consider a reference plasma beta almost an order of magnitude smaller ($\beta = 0.5$) which is a value more consistent with observations.

2. $\beta = 0.5$

The initial dipole magnetic field configuration and the location of the sonic curve are the same regardless of the value of the reference magnetic field as can be seen by comparing Figures 6(a) for $\beta = 0.5$ and 3(a) for $\beta = 4$. The only difference in the two figures is that the Alfven velocity increases with the magnetic field causing the Alfven curve to move outward as $\beta$ is decreased (magnetic field increased). As the magnetic field evolves in this case, as shown in Figure 6, the Alfven curve moves inward throughout the flow field as does the sonic curve except for a
small region around the equator. Some of the variables in the final coronal-streamer configuration are presented in Figure 7. The sonic curve intersects the equator in Figure 7(a) at approximately the same radius as for $\beta = 4$ in Figure 4(a) indicating that the sonic Mach number near the equator must be similar for the two cases. The radial velocities along the equator are about the same as can be seen by comparing Figures 5 and 8, and therefore, the temperatures along the equator must be similar. The temperature distribution along the pole is clearly quite different for the two values of $\beta$ with the temperature for $\beta = 0.5$ being considerably larger. The velocity in the open region near the pole for $\beta = 0.5$ is more than a factor of two larger than the velocity over the closed region near the equator. The velocity in the closed region is again approximately zero as would be expected, but the pressure and density in the closed region are increased considerably more for $\beta = 0.5$ than they were for the larger value of $\beta$.

The distribution of $\beta$ throughout the flow field is shown in Figure 9 for both the initial state and the coronal streamer. For the initial state $\beta$ increases from 0.5 (0.25) at the solar surface to 10.2 (2.6) at 5 $R_\odot$ along the equator (pole). In the coronal streamer the value of $\beta$ increases at the equator and becomes infinite along the neutral line above the closed region. Since $\beta$ is so large near the equator and since the incremental spacing between the curves in Figure 9(b) is fixed, the $\beta$ distribution is not shown within 10 deg of the equator in order to show the distribution in the remainder of the flow field. $\beta$ is decreased at the pole near the solar surface and increased at 5 $R_\odot$ at the pole compared to the corresponding values in the initial state. Throughout most of the flow field, $\beta$ is lower in the coronal streamer than for
the initial state. Because of this and since the thermal pressure is higher in the coronal streamer than initially, the magnetic pressure in the coronal streamer is also higher than the initial value throughout most of the flow field.

As for the previous example, the velocity flows more or less along the field lines. Also, none of the field lines becomes exactly radial. The radial location of the top of the closed field region is not changed appreciably from that for the higher value of $\beta$. The dimensions of the closed-field region are considered below for a wider range of $\beta$.

3. Coronal-Streamer Structure

As the magnitude of the reference magnetic field is increased in studies such as the above two, one would expect that the field lines would remain closed to a higher altitude in the solar atmosphere. That this indeed happens is illustrated in Figure 10 where the dimensions of the height and the base at the solar surface for the closed region are plotted as a function of $\beta$. The circles indicate values obtained from individual computer runs. A closed region is not achieved for $\beta = 100$. The base dimension of the closed region is relatively unaffected by the values of $\beta$ unless $\beta$ becomes larger than about 5. The maximum values of the pressure and density (referenced to their respective initial values at each point) in the closed region are plotted as a function of $\beta$ in Figure 11. The large increase in the pressure and density with decreasing $\beta$ is due partly to the increased Lorentz force which is directed inward on the closed region and partly to the increased magnetic field strength which increases the tensile strength of the field lines and makes it more difficult to open the closed field lines. This latter effect has been demonstrated by Steinolfson.
et al. (1978). Both of these effects must be balanced by an increase in thermal pressure in the closed region, and both effects also tend to compress the fluid in the closed region. For $\beta = 100$ the magnetic field is so weak ($B = 0.17$ G) that the solution remains essentially unchanged.

The velocity and the thermodynamic variables at 5 $R_\odot$ are presented as a function of meridional angle in Figures 12 and 13, respectively, for several values of $\beta$. The velocity is consistently larger over the pole than the equator with the velocity differential between the two regions increasing dramatically as $\beta$ decreases. The pressure and density are highest near the equator and the temperature is highest at the pole for each value of $\beta$. The temperature distribution for $\beta$ equal to 4, 10 and 100 are so close to being the same that the curves cannot be resolved in Figure 13. For the two lowest values of $\beta$ (0.5 and 0.1), the density decreases and the velocity increases from their respective initial values in the polar region in analogy with flow in coronal holes (Kopp and Holzer, 1976). However, according to the study of Steinolfson and Tandberg-Hanssen (1977) the temperature and pressure should also decrease in coronal holes, while in the present study both variables increase. Hence, although the open magnetic field in the present study is diverging as would be expected in coronal holes, it appears that the flows in the open regions in the present study are not analogous to previous steady-state studies of flows in coronal holes. As mentioned earlier, the discrepancy may be due to the different boundary conditions in the two studies, but it may also be partially due to the meridional gradients in the equations that we use which are neglected in the steady-state studies.
IV. CORONAL TRANSIENTS

The coronal-streamer configurations discussed in the previous section are long-lasting structures which may remain virtually unchanged on the solar surface for periods up to several days. These configurations are often observed to exist prior, both spatially and temporally, to the occurrence of mass ejections or, as they are often referred to, coronal transients. We now simulate a coronal transient by using the final state for the coronal streamer as the initial state for the coronal transient.

A. Initial State, Boundary Conditions and Perturbation

As mentioned above, the final state for the coronal streamer is used as the initial state for the coronal transient. The reference β referred to in this section (and all other reference conditions) is the reference value used for the coronal streamer. Naturally, all the dependent variables may have a different value in the final streamer simulation than they did in the corresponding initial state.

The boundary conditions applied at the equator, pole and 5 \( R_e \) for the coronal transient are the same as those used for the coronal streamer. At the solar surface a perturbation in the thermodynamic variables from their initial values (the final values for the coronal streamer) is introduced near the equator to simulate the solar event that produces the resulting coronal transient. The perturbation is assumed to occur instantaneously, to be symmetric about the equator, and to extend in the meridional direction over a total of 10 deg (5 deg on each side of the equator) or \( 1.22 \times 10^5 \) km. The perturbed values are maintained for the duration of the calculation. The magnitude of the perturbation varies with each simulation and is discussed along with the corresponding numerical results. The pressure and density are assumed to be constant throughout the perturbed region. Outside this region they are calculated from linear extrapolation as for the streamer.
simulation. The remaining variables at the solar surface are simply set equal to the value at the grid point next to the boundary at each time step; i.e., \( Q_b = Q_n \) (first-order extrapolation).

For the streamer simulation the computation had to be carried out for the entire flow regime at each time step. In this section we only compute the solution from the solar surface to the leading edge of the coronal transient.

B. Numerical Results

The coronal transients for the two values of \( \beta \) used in the previous section \((\beta = 0.5, 4)\) are investigated. The transient for the lower value of \( \beta \) is examined in more detail since, as will be shown later, it agrees more closely with observations. Some of the more important results for other values of \( \beta \) are also discussed.

1. \( \beta = 4 \)

The thermal pressure in the perturbation is increased by a factor of 2.6 above the initial value at the solar surface for the streamer calculation which, as discussed in the previous section (see Figure 5), remained unchanged throughout that calculation. The pressure increase results from a factor of 2 increase in temperature and a factor of 1.3 increase in density. Some of the variables in the resulting coronal transient are shown in Figure 14 after 60 minutes and in Figure 15 after 120 minutes. The corresponding variables for the initial state for the transient are those in Figure 4. The time is now referenced to the start of the transient simulation. The pressure and density are referenced to their initial values for the streamer calculation at each point in the flow field.
The large velocity that develops at the solar surface in the vicinity of the perturbed region causes the flow to become super-Alfvenic there after 60 minutes and both supersonic and super-Alfvenic after 120 minutes as seen in Figures 14(a) and 15(a). The coronal transient is preceded by an MHD shock which has the characteristics of a fast shock since it increases the meridional component in both the velocity and magnetic field. It is not clear from the figures that the shock normal (or the direction of shock propagation) lies directly along the magnetic field, except, of course, when the shock propagates into the open region along the equator. Note that a meridional velocity component cannot be produced by the shock along the equator because of the boundary conditions there. When the shock normal and magnetic field are parallel for some finite length of the shock, the fast shock becomes a switch-on shock since it produces a meridional component in the magnetic field and velocity when neither was present ahead of the shock. The numerical shock is necessarily spread over a few grid points due to the relatively large grid spacing that we used. Hence the shock location shown in the figures is selected to be approximately at the midpoint of the jump in the dependent variables produced by the shock. The shock has not completely formed at large meridional angles near the pole after 60 minutes. The shock velocity along the equator increases from 306 km s\(^{-1}\) at 2 \(R_\odot\) to 584 km s\(^{-1}\) at 4 \(R_\odot\) implying that the shock travels considerably faster in the initially open region than it does in the initially closed region. One reason for this is that there is an ambient outward flow in the open region which tends to increase the shock velocity in the laboratory frame.

The contact surface separates the initial coronal plasma from that which has been emitted from the perturbed region. The maximum increase in pressure lies along the equator below the contact surface while the maximum increase
in density is between the contact surface and the shock. Due to the relatively large value of $\beta$ used for this simulation, the magnetic field does not have a large effect on guiding the outward-propagating plasma and is, to a large extent, essentially carried along with the plasma. As can be seen in the figures, the contact surface travels outward both radially and meridionally. It appears from the figures that the fluid is propagating across the field lines (which should not occur due to the infinite conductivity) since the contact surface at 120 minutes encloses more field lines than at the earlier time. That this is not actually happening is a result of the method used to calculate the field lines. The field lines are calculated by starting at the same location on the solar surface at each time step and using the magnitude and direction of the magnetic field at that time as the starting values. Since the magnitudes of both components of the magnetic field at the solar surface are allowed to change with time, different field lines may be traced out from each starting location at each time.

2. $\beta = 0.5$

The thermal pressure in the perturbation is increased by a factor of 10, the temperature by a factor of 5, and the density by a factor of 2. All of these increases are with respect to the corresponding final values at the solar surface for the streamer calculation. Some of the variables in the coronal transient produced by this perturbation are shown in Figure 16 after 80 minutes and in Figure 17 after 180 minutes. The corresponding variables for the initial state for this transient are given in Figure 7.

The relatively low velocities and large magnetic field prevent the flow from becoming either supersonic or super-Alfvenic at the solar surface near the perturbed region as it did for $\beta = \frac{1}{2}$. The transient
is again preceded by a fast MHD shock which may, over a portion of its extent, be a switch-on shock. The shock velocity along the equator increases from 397 km s\(^{-1}\) at 2 \(R_e\) to 517 km s\(^{-1}\) at 4 \(R_e\). Hence, as for the results at \(\beta = 4\), the shock travels faster in the initially open region than in the initially closed region. However, the shock velocity is now larger at 2 \(R_e\) and smaller at 4 \(R_e\) than it was for \(\beta = 4\). The shock velocities for these two values of \(\beta\) and for other values of \(\beta\) will be discussed in more detail later.

The contact surface does not travel as far in the meridional direction as for \(\beta = 4\). This is due to the larger magnetic field in this case which tends to restrict the meridional movement of the plasma. Along the equator the maximum increase in pressure again occurs below the contact surface and the maximum increase in density between the contact surface and the shock. This is shown better in Figure 18 which gives the radial profiles of the radial velocity, pressure and density along the equator initially and at two subsequent times. The mass excess initially in the closed region of the coronal streamer (illustrated by the increase in density between 1 and 2 \(R_e\) in the figure) is at the later times distributed between the shock and the contact surface.

The fluid ahead of the contact surface (including the fluid initially in the closed region) has been heated, compressed and accelerated by the shock. This figure also demonstrates how the shock is spread over a number of grid points. At \(t = 80\) minutes, the shock, which should be a sharp discontinuity, extends approximately from 3.75 \(R_e\) to 4.25 \(R_e\).

The curves consisting of the dark shorter dashes in Figures 16 (d) and 17 (d) enclose a region in which the density is higher than in the adjacent regions in the meridional direction. That is, in a scan from
the equator to the pole at a fixed radius, an increase in density would be found in this region. This is illustrated by the meridional scans of pressure and density at 4 R\(_e\) for three times in Figure 19. The density has a definite peak at approximately 30 degrees at 180 minutes where the scan is now through the "leg" of the high density region in Figure 17 (d). At the previous times the scans are partially through the top of the high density region. The pressure, on the other hand, does not have a peak away from the equator at 180 minutes and decreases more or less monotonically for all three times from the equator to the pole. The curves with the dark longer dashes in Figures 16 (d) and 17 (d) represent the approximate locations of the maximum in the high-density region. The importance of this dense region will be discussed in the following sections.

The distribution of \(\beta\) throughout the flow field (except near the equator, since \(\beta\) again becomes very large there) for the two times in Figures 16 and 17 are given in Figure 20. The initial distribution of \(\beta\) is shown in Figure 9 (b). The \(\beta\) contours are very similar to those of the pressure -- especially after 180 minutes when the magnetic field is almost radial. These plots illustrate that for the region shown, \(\beta\) remains relatively small during and following the passage of the coronal transient.

3. Other Pertinent Results

The shock velocities along the equator at various values of \(\beta\) are shown in Figure 21. A wide range of perturbations in the thermodynamic variables was used to obtain these results as shown in Table I. The
shock velocities for the $\beta = 4$ and $\beta = 0.5$ studies discussed above are represented by the dashed curves. There are several important results that should be noted from the figure. First of all, despite more than an order of magnitude change in both $\beta$ and the magnitude of the pressure perturbation, the shock velocities for all simulations do not vary that much in magnitude; at 4 $R_\odot$, the velocities are all within 200 km s$^{-1}$ of each other. Note also that at a fixed $\beta$, a reduction in the magnitude of the pressure perturbation reduces the shock velocity although the shape of the curve remains generally the same. This is true for both $\beta = 4$, where both runs have the same density perturbations, and $\beta = 0.5$, where the two runs have different density perturbations. One would expect that if the density perturbation was varied over a wide range this result may be altered. Finally, as $\beta$ is decreased, the shock velocity curves tend to become flatter until for $\beta = 0.1$ the shock velocity is essentially constant over the radius range considered. If the results had been extended to a larger radius, the curves for $\beta = 4$ would certainly approach a constant velocity also although the final velocity in this case may be somewhat larger.

The fact that a larger pressure perturbation was used to obtain the results in Figure 21 as $\beta$ decreases is not coincidental. In fact, at each value of $\beta$ there is a value of the magnitude of the pressure perturbation (at a fixed value of the density perturbation) below which a physically realistic solution (in the sense that the flow along the equator is outward) is not obtained. This would be expected since the perturbation is in a closed-field region, and a certain pressure force is required to open the field lines so the fluid can flow outward. As the strength of the magnetic field increases ($\beta$ decreases), one would expect that a larger
force would be required. The approximate minimum pressure perturbation for a fixed density perturbation of 1.3 is shown in Figure 22 for the range of $\beta$ used for the results in Figure 21. The circles indicate the runs used to obtain the curve. Hence, it is clear that as $\beta$ is decreased below 0.5, the required pressure perturbation increases very rapidly.
V. COMPARISON WITH OTHER APPLICABLE MODELS

The other models which we will consider here are those which are similar to the one we have developed in the sense that they consider the transient to be the coronal response to a simulated solar event near the solar surface. That is, the driving force responsible for the transient originated and remains near the solar surface. We do not consider the magnetically-driven model proposed by Mouschovias and Poland (1978) and further studied by Anzer (1978). They assume that the driving force is the magnetic force produced by the interaction of currents flowing in the loops with their self-induced magnetic fields. Yeh and Dryer (1980) have attempted to show that coronal loop transients cannot be driven by such magnetic forces.

All similar models that have appeared in the literature which purport to be applicable to the formation and propagation of coronal transients in the lower corona (with the inner boundary inside the critical points near the solar surface) in either the meridional or latitudinal plane and including the magnetic field have assumed that the atmosphere is initially stationary. On the surface this appears to be a reasonable assumption since the kinetic energy in the inner corona is certainly less than either the thermal or magnetic energies. It is definitely simpler to assume an initially stationary atmosphere since an analytic planar solution including the magnetic field (other than a purely radial field, which is unrealistic in the lower corona) and finite velocity has not been obtained for the lower corona to the author's knowledge. In addition to including the velocity in the initial streamer for the transient in the present study, the magnetic field in the streamer decreases with radius similar to a dipole field. This offers the
advantage of producing a reasonable increase in $\beta$ with radius. For any higher order field $\beta$ increases too rapidly with radius to be reasonable. We first present some results for an initially stationary atmosphere and then compare these and other similar results from the literature with our results obtained using a coronal streamer as the initial state.

A. A Model with an Initially Stationary Atmosphere

The initial state for this model is taken to be an initially hydrostatic atmosphere for the thermodynamic variables and a dipole magnetic field. This initial state represents a solution to the steady-state form of the complete set of time-dependent equations (Equations (1)). The reference conditions for the thermodynamic variables and the magnetic field are the same as used for the streamer simulations. Again we will consider the $\beta = 4$ and $\beta = 0.5$ simulations. The boundary conditions, grid spacings and spatial distribution of the perturbation are also the same as used above. Hence the simulations considered here are in every way as close as possible to the same as those done for the coronal transients in the previous section.

The spatial distribution of some of the variables for the coronal transient for $\beta = 4$ are shown in Figure 23 after 120 minutes. The magnitudes of the pressure and density perturbations used for this simulation are the same as those used in the previous section for $\beta = 4$. Similar results for $\beta = 0.5$ are presented in Figure 24 after 80 minutes. The pressure in the perturbation is now increased by a factor of 6 and the density by 1.3, which is not the same as those used in the previous...
section for $\beta = 0.5$. The corresponding results obtained when the initial atmosphere is a coronal streamer are given in Figure 15 for $\beta = 4$ and in Figure 16 for $\beta = 0.5$. The pressure and density along a meridional scan at $4^\circ$ for the present simulation with $\beta = 0.5$ are illustrated in Figure 25. These results are analogous to those in Figure 19 for the streamer initial configuration. All the above results for the initially stationary atmosphere will now be discussed vis-à-vis the results from the previous section.

B. Comparisons

For convenience, the results obtained in this section and other previously published results for an initially stationary atmosphere will be referred to as the "stationary" results, while those in the previous section for an initial atmosphere consisting of a coronal streamer will be referred to as the "streamer" results. The figure numbers of the results presented in this paper will only be referred to when some confusion may arise.

Since the perturbations are identical for both the stationary and streamer results for $\beta = 4$ and since the magnetic field in this case is relatively small, a comparison of the results should be similar to what one would expect from a similar hydrodynamic study. Indeed they are, as will soon become apparent. The shock travels more rapidly and the fluid velocity is larger for the streamer results due to the initial fluid velocity. The shape of the shock curves in Figure 23(a) and 15(a) are also similar, which would be expected since the shock velocity in a lab-
oratory frame depends to a large extent on the characteristic speeds in the ambient medium through which it is propagating (in addition to its dependence on the velocity in the ambient medium). As the magnetic field is relatively small in this case the sound speed dominates, and, of course, this speed is approximately the same for the two sets of results. The separation between the shock and contact surface is larger in the stationary results since the velocity of the contact surface depends entirely on the fluid velocity which is smaller for the stationary results. The general shape of the pressure and density profiles for the two cases are quite different with the higher pressure and density values being confined to a region closer to the equator for the streamer results. The maxima of the pressure and density are larger for the streamer results because of the increased values in the initial closed magnetic field region near the equator and the solar surface.

The magnetic field would be expected to have a larger effect on the results for $\beta = 0.5$. Note that a larger pressure pulse was used for the streamer results when $\beta = 0.5$ than for the stationary results. This difference is not expected to affect the comparisons. The shock travels faster along the equator (despite a smaller pressure perturbation) and slower at the pole for the stationary results as compared to the streamer results (Figures 24 (a) and 16 (a)). This result is reasonable since shocks with a given initial strength always travel faster across field lines than along them. This effect is not important for $\beta = 4$ since the field is so small. The other results mentioned above for $\beta = 4$ remain much the same at the lower $\beta$. It is important to note that the high pressure and density region near the equator for the streamer results is even more exaggerated at $\beta = 0.5$. 

27
The curves consisting of heavy short dashes in Figure 24 (d) enclose the high density region that would be observed in a meridional scan at a fixed radius in analogy with the similar curves in Figures 16 (d) and 17 (d). A curve with heavy longer dashes again identifies the approximate center of the maxima of this high-density region. The density peaks away from the equator for the stationary results show up on the meridional scans at 4 R_0 in Figure 25; however, they are much further from the equator than for the streamer results in Figure 19.

The maxima of the high density region (the curves consisting of the heavy longer dashes in Figures 16 (d), 17 (d), and 24 (d) are shown for several times for β = 0.5 and for both the stationary (dashed curves) and streamer results in Figure 26. The maxima for the streamer results are contained within 30 deg of the equator, while the maxima for the stationary results extend to the pole. A plot similar to that in Figure 26 is shown in Figure 27 for only the streamer results for β = 0.1. This plot demonstrates that as β is decreased below 0.5 the angle of confinement of the density maxima decreases. The variation of the density along a meridional scan at 4 R_0 for β = 0.1 corresponding to the results in Figure 27 is presented in Figure 28. This result is in comparison with that in Figure 19 and shows that as β decreases the density peak becomes more prominent. The importance of these results will be discussed in comparing the results with observations in the following section.
VI. COMPARISON WITH OBSERVATIONS

Among the several classes into which coronal transients in general tend to be grouped (Hildner, 1977), the type we have attempted to simulate is the loop-like transients in which mass is ejected from near the solar surface to the outer corona. The major observed characteristics of this type of transient will first be discussed followed by a comparison with the calculated results. We concentrate on attempting to simulate just the characteristics for this single class of transient since it is extremely difficult to simulate all observed aspects of one particular transient (due to inhomogeneities, non-planar effects, dissipative effects, etc.). One would also expect that different physical processes are involved in the different classes of transients.

A. Observed Characteristics of Coronal Transients

The velocity of the leading edge of a transient is a relatively simple quantity to determine from the white-light observations. These velocities generally lie in the range of 100-1200 \( \text{km s}^{-1} \) with an average value of 470 km s\(^{-1}\) (Gosling et al., 1976). The velocity tends to increase or remain about constant between approximately 2.5 - 5 \( R_\odot \).

The reason that coronal transients are observed by the white-light coronagraph is that the density in the transients exceeds that in the surrounding medium. Hence it is necessary that the simulated transient produce a density enhancement similar to that observed. It should be pointed out that the coronagraph only observes the projection of the...
transient in the meridional plane so it is certainly possible that they do not lie in that plane. For the purpose of the following discussion we will assume that the observed transients do lie in or near the meridional plane. As shown by Hildner (1977), the observed transient tends to take the shape of a loop, with the loop extending from near the solar surface, out to some maximum height (which increases with time) in the atmosphere, and back to the solar surface. The northern and southern edges (the legs) of the loop generally remain stationary so the loop just stretches outward with time. The centers of the loops usually lie within 40 deg of the equator, with a symmetrical distribution about a maximum at the equator. The latitudinal extents of the transients are usually less than 65 deg.

The coronal magnetic field cannot be measured directly so other means are necessary to infer its value. Dulk et al. (1976) used data from type IV radio bursts along with white-light data to calculate the magnetic field for the loop-shaped mass ejection of 15 September 1973. They calculated a value of 2.6 G at a height of 3.1 R\(_s\) and a \(\beta\) at that height of 0.007. Further evidence for expecting relatively large fields near transients is due to the observations that at least three-quarters of the transients occur over active regions (Hildner, 1977) where the magnetic field is larger than elsewhere on the sun. Mass ejections also tend to be associated with magnetic phenomena (flares, eruptive prominences, etc.) which occur near lines on the solar surface which separate uni-polar regions of the photospheric magnetic field.

The mass associated with a mass ejection generally lies in the range 1 - 24 \(\times 10^{15}\) g with an average of 6.2 \(\times 10^{15}\) g while the energy ranges from 1.6 - 69.8 \(\times 10^{30}\) erg with an average of 11.9 \(\times 10^{30}\) erg (Hildner, 1977).
In order to obtain these values it is necessary to make some rather speculative assumptions concerning the size of the transient.

B. Comparisons

The radial velocity of the leading edge of the transient can be easily simulated by the model proposed herein, as shown in Figure 21, or by any of the previous models which do not use the streamer configuration as the initial state. Larger velocities than those in Figure 21 can be obtained in our present model by increasing the magnitude of the pressure perturbation. The observed increase in velocity with radius, however, is generally between that shown in Figure 21 for $\beta = 0.5$ and $\beta = 0.1$, implying that the lower $\beta$ results are more realistic in this sense.

The fact that previous models also reproduce the observed velocities (as demonstrated by the one-dimensional study by Steinolfson and Nakagawa, 1977, and the two-dimensional study by Dryer et al., 1979) makes the leading-edge velocity a poor quantity by which to judge the relative merits of various models.

One observed characteristic that previous models cannot adequately simulate (at least not for any of the results published to date) is the shape of the loop as given by the density enhancement. This is seen quite clearly for the calculations presented in Section V for a non-streamer, stationary initial state (see Figures 23(d) and 24(d)). The enhanced density region moves both radially and laterally away from the simulated solar event similar to the motion of an expanding bubble. Similar results for a non-streamer, stationary initial state have been obtained in all previous two-dimensional studies (see eg. Dryer et al., 1979; and Nakagawa,
Wu and Han, 1978). These previous results are obtained regardless of whether the initial magnetic field configuration is assumed to be closed over the location of the simulated solar event (as for the initial dipole configuration for the streamer calculation in Figure 3(a)) or open (as if the configuration in Figure 3(a) was rotated 90 deg so the configuration originally at the pole was at the equator). The edges of the loop do not move laterally in the present model as seen in Figures 16(d) and 17(d). The most graphic comparison of the present model with previous models is shown in Figure 26 which shows the outward motion of the high density regions near the outer edge of the transient. The latitudinal extent of the transient for the present model is 60 deg which lies within the observed latitudinal extent of 65 deg. The results in Figure 27 show that if \( \beta \) is decreased the latitudinal extent of the transient decreases. Hence it is obvious that the present model agrees considerably better than the previous models with the observed density enhancement which is certainly one of the more important observed characteristics.

Since the coronal magnetic field cannot be measured directly, a direct comparison cannot be made between observed and calculated magnetic field magnitudes at various points in the flow field. The inferred value of the magnetic field of 2.6 G at 3.1 \( R_e \) made by Dulk et al. (1976) agrees closely with the values at that height in our model for the \( \beta = 0.1 \) calculation. Dulk, however, obtained a \( \beta \) of 0.007 at that height which is about an order of magnitude less than what we calculated indicating a difference in thermal pressure. Although the magnetic field cannot be measured, it is reasonable to expect that if the \( \beta \) is relatively small (as observations indicate it should be) it may be important in guiding
the fluid; that is, in determining the shape of the expanding loop.
Thus it is logical to assume that the magnetic field prevents the lateral expansion of the loop, as has been done by several authors. This assumption would agree with our model since it is the magnetic field that contains the lateral expansion in Figures 26 and 27. The fact that mass ejections generally originate near lines separating uni-polar regions on the solar surface implies that previous studies using open field lines do not apply to mass ejections.

We have not attempted to calculate the mass or energy associated with the mass ejections in our simulations. Due to the assumptions that must be made for the dimensions of the transient both in the observations and in the simulation, it is not felt that a direct comparison of the absolute magnitudes would be meaningful.
VII. DISCUSSION AND CONCLUSIONS

The main objective for developing self-consistent models such as the one we have presented herein is to attempt to gain a better understanding of the physical mechanisms occurring in and responsible for observed coronal transients. As such, it is necessary that the simulations reproduce the available observations as well as possible in order that valid conclusions regarding the behavior of transient quantities that are not observed can be made from the simulations. From the previous section it is apparent that the present model does reproduce the observations better than similar models published previously. Again we should point out that the only other models we are considering here assume that a sudden disturbance near the solar surface produced the transient.

The major difference between the present models and previous ones is the initial state for the coronal transient. While previous models simply use a stationary atmosphere with a force-free magnetic field, we have used a coronal-streamer configuration in which the atmosphere is not stationary (except in the closed-field region) nor is the magnetic field force-free. Coronal streamers are frequently observed in the lower solar corona and are observed to occur over uni-polar regions of the photospheric magnetic field. As mentioned previously, this is the region in which mass ejections commonly originate. We should also mention that the class of transients which we are concerned with is the loop-like transient in which mass is ejected to the outer corona. Although it does not appear likely that previous models apply to these transients, they may certainly be applicable to other classes of transients or other solar
phenomena.

The magnetically-driven models studied by Mouschovias and Poland (1978) and Anzer (1978) may also merit some consideration as the mechanism involved in mass ejections. However, the simplifications made in their analysis and the fact that their study is confined to just the top of the loop limit the application of their results. A more complete study of magnetically-driven models may prove worthwhile.

In the present and previous similar models, the radially-propagating, leading edge of the transient is a shock wave. This shock wave certainly agrees with observations in that it travels radially outward and produces the necessary density enhancement. The fact that both type II and type IV radio bursts (which are indicative of shocks) are often observed in transients substantiates the possibility that the leading edge may be a shock. Other than the frequent observation of radio bursts there is no a priori reason why the leading edge should be a shock. In fact, in the magnetically-driven models, it is not. The lateral edges of previous models are also shock waves (which travel laterally as well as somewhat radially), while in the present model they are due to plasma confinement by the magnetic field. Since the lateral edges of observed transients do not travel laterally, they, of course, cannot be shocks.

The available observations imply that the magnetic field associated with mass ejection coronal transients would be expected to be relatively large. The plasma beta is certainly less than one and may be one or two orders of magnitude smaller. This conclusion being due to the usual occurrence of mass ejections over active regions and their association with
magnetic phenomena. The present study supports this view since the best agreement with the well-observed, leading-edge velocities of transients is obtained for $\beta \leq 0.5$. The lower beta results in the simulation also produced better lateral confinement of the edges of the transient.

As $\beta$ is decreased, the more the simulated coronal transients with a coronal streamer initial state differ from those with an initially stationary, force-free initial state - as shown in the results in Section V. One reason for this is that - as discussed in Section III - the coronal streamer diverges more from the initially stationary, force-free state with decreasing $\beta$. For the coronal streamer as $\beta$ decreases the following changes occur in the variables: (1) the pressure and density in the closed-field region increase, (2) the velocities increase throughout the open region and the gradient in the velocities between the values at $4 \, R_\odot$ at the equator and at the pole increases, and (3) larger changes occur in all the thermodynamic variables and, as for the velocity, the gradients in all the thermodynamic variables between the values at $4 \, R_\odot$ at the equator and at the pole increase. Hence the meridional inhomogeneities in the streamer increase with decreasing $\beta$.

For a constant reference temperature, as we have assumed, the only other parameter in our model besides $\beta$ is the polytropic index $\gamma$. We used a value of 1.05 which is not much different than the constant temperature value of 1. From the results in Sections III and IV it appears that the temperature does not change much in our simulation of either the streamer or transient providing $\beta \geq 1$. Hence for a large $\beta$, the constant temperature solution should not be much different than ours.
However, as $\beta$ is decreased below 1, the temperature changes more and more from the steady-state value indicating that a constant temperature solution is no longer valid.

The mass that is contained in the expanding loop in our model (i.e.; the enhancement that would be observed by a white-light coronagraph) is entirely composed of mass which was in the corona prior to the occurrence of the solar event responsible for the transient. Part of the mass was initially in the closed region and part in the open region of the coronal streamer. In this respect our model contrasts with other more approximate one-dimensional models where the mass is assumed to initially reside in a loop without any consideration given to how the mass-filled loop was formed (Mouschovias and Poland, 1978; and Anzer, 1978). The transient in these simplified models consists of an expansion of the top section of the initial loop outward through the corona, while in our model both the formation and propagation of the loop are calculated self-consistently throughout the meridional plane.
REFERENCES


Table I. Perturbation parameters used to obtain the results in Figure 21.

<table>
<thead>
<tr>
<th>$\beta$</th>
<th>curve</th>
<th>$\delta_p$</th>
<th>$\delta_P$</th>
<th>$\delta_T$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>solid</td>
<td>2.0</td>
<td>1.3</td>
<td>1.54</td>
</tr>
<tr>
<td>4</td>
<td>dashed</td>
<td>2.6</td>
<td>1.3</td>
<td>2.0</td>
</tr>
<tr>
<td>1</td>
<td>solid</td>
<td>5</td>
<td>1.3</td>
<td>3.85</td>
</tr>
<tr>
<td>0.5</td>
<td>solid</td>
<td>8</td>
<td>1.3</td>
<td>6.15</td>
</tr>
<tr>
<td>0.5</td>
<td>dashed</td>
<td>10</td>
<td>2</td>
<td>5.00</td>
</tr>
<tr>
<td>0.1</td>
<td>solid</td>
<td>30</td>
<td>1.3</td>
<td>23.10</td>
</tr>
</tbody>
</table>
FIGURE CAPTIONS

1. A schematic of the portion of the meridional plane in which the solution is calculated. The grid spacings are also sketched (not to scale) along with the nomenclature used for the boundary conditions.

2. A schematic of the magnetic field lines in a coronal streamer.

3. The evolution of the coronal magnetic field for $\beta = 4$. The sonic curve is represented by the curve with long dashes and the Alfvén curve by the curve with shorter dashes.

4. Planar maps of several of the dependent variables in the coronal streamer for $\beta = 4$. The maximum values given are the maximum values throughout the regions shown. The velocity vectors point in the direction of the velocity at their base and their length is proportional to the magnitude of the velocity. The pressure and density are referenced to their respective initial values at each point in the flow field.

5. Radial distributions of the density, pressure, and radial velocity initially (solid curve) and in the coronal streamer for $\beta = 4$ (Figure 4) at the pole (shorter dashes) and equator (long dashes).

6. The evolution of the coronal magnetic field for $\beta = 0.5$. See the caption for Figure 3.

7. Planar maps of several of the dependent variables in the coronal streamer for $\beta = 0.5$. See the caption for Figure 4.

8. Radial distributions of the density, pressure, and radial velocity initially (solid curve) and in the coronal streamer for $\beta = 0.5$ (Figure 7) at the pole (short dashes) and at the equator (long dashes).

9. Planar maps of the plasma beta for the $\beta = 0.5$ simulation initially and in the coronal streamer.

10. The dependence of the dimensions of the closed region on the reference beta. A closed region is not obtained for $\beta = 100$.

11. The dependence of the maximum pressure and density in the closed region on the reference beta.

12. The meridional distribution of the radial velocity at $5 R_e$ as a function of the reference beta.

13. The meridional distribution of the thermodynamic variables at $5 R_e$ as a function of the reference beta.

14. Planar maps of several dependent variables in the coronal transient for $\beta = 4$ after 60 min. The approximate locations of the shock (double lines) and contact surface (heavy dashed lines) are indicated. See the caption for Figure 4.
15. Planar maps of several dependent variables in the coronal transient for $\beta = 4$ after 120 min. See the caption for Figure 4.

16. Planar maps of several dependent variables in the coronal transient for $\beta = 0.5$ after 80 min. The short dashed curves in (d) enclose the maximum density region and the curve with longer dashes traces out the approximate location of the maximum density in this region. See the caption for Figure 4.

17. Planar maps of several dependent variables in the coronal transient for $\beta = 0.5$ after 180 min. See the captions for Figures 4 and 16.

18. Radial distributions of the density, pressure, and radial velocity initially and at two later times in the coronal transient for $\beta = 0.5$.

19. Meridional distribution at $4R_e$ of the pressure and density in the coronal transient for $\beta = 0.5$ at three times.

20. Planar maps of the plasma beta for the coronal transient for $\beta = 0.5$ after 80 and 180 min.

21. The variation of the shock velocity along the equator with radius for several values of the reference beta.

22. The magnitude of the pressure perturbation required to produce a mass ejection coronal transient for a fixed value of the density perturbation as a function of the reference beta.

23. Planar maps of several dependent variables in the coronal transient for $\beta = 4$ after 120 min for an initially stationary atmosphere with a force-free magnetic field. See the caption for Figure 4.

24. Planar maps of several dependent variables in the coronal transient for $\beta = 0.5$ after 80 min for an initially stationary atmosphere with a force-free magnetic field. See the captions for Figure 4 and 16.

25. Meridional distributions at $4R_e$ of the density and pressure at three times in the coronal transient for $\beta = 0.5$ for an initially stationary atmosphere with a force-free magnetic field.

26. The maxima of the high density regions at several times in the coronal transient with $\beta = 0.5$ for an initial state consisting of a coronal streamer (solid curves) and an initially stationary, force-free atmosphere (dashed curves).

27. The maxima of the high density regions at several times in the coronal transient with $\beta = 0.1$ for an initial state consisting of a coronal streamer.

28. Meridional distributions at $4R_e$ of the density at two times in the coronal transient for $\beta = 0.5$ for an initial state consisting of a coronal streamer.
Figure 3

MAGNETIC FIELD LINES ($\rho = 4$)

(a) $t = 0$

(b) $t = 6$ hrs

(c) $t = 12$ hrs

(d) $t = 16$ hrs
CORONAL STREAMER \((t = 24 \text{ hrs, } \beta = 4)\)

(a) MAGNETIC FIELD LINES

(b) PRESSURE \(P_{\text{max}} = 1.0\)

(c) VELOCITY VECTORS \(v_{\text{max}} = 233 \text{ km s}^{-1}\)

(d) DENSITY \(\rho_{\text{max}} = 1.5\)

Figure 4
Figure 5
MAGNETIC FIELD LINES ($\rho=0.5$)

(a) $t=0$

(b) $t=4$ hrs

(c) $t=8$ hrs

(d) $t=12$ hrs

Figure 6
Figure 7
Figure 8
Figure 9

BETA DISTRIBUTION ($\beta = 0.5$)

(a) $t=0$

$\Phi_{max} = 10.2$

(b) $t=16$ hrs

$\Phi_{max} = 3.6$
Figure 10

DIMENSIONS OF CLOSED REGION (m x 10^{-5})

HEIGHT

BASE

BETA

0.1 1 10 100

Figure 10
Figure 11

MAXIMUM VALUES IN
THE CLOSED REGION

NON-DIMENSIONAL

BETA

PRESSURE

DENSITY
Figure 12

VELOCITY AT 5 $R_0$

$\beta = 0.1$

INITIAL VELOCITY

VELOCITY (km s$^{-1}$)

EQUATOR

POLE

THETA (DEGREES)

0 30 60 90

200 400 600 800 1000

0.5 1 10 4
Figure 13
CORONAL TRANSIENT (t = 60 min, \( \theta = 4 \))

(a) MAGNETIC FIELD LINES

(b) PRESSURE
\( \rho_{\text{max}} = 7.4 \)

(c) VELOCITY VECTORS
\( v_{\text{max}} = 376 \text{ km s}^{-1} \)

(d) DENSITY
\( \rho_{\text{max}} = 4.3 \)

Figure 14
CORONAL TRANSIENT (t=120 min, $\rho = 4$)

(a) MAGNETIC FIELD LINES

(b) PRESSURE
$\rho_{\text{max}} = 18.8$

(c) VELOCITY VECTORS
$V_{\text{max}} = 525 \text{ km s}^{-1}$

(d) DENSITY
$\rho_{\text{max}} = 2.0$

Figure 15
CORONAL TRANSIENT (t=80 min, $\rho=0.5$)

(a) MAGNETIC FIELD LINES

(b) PRESSURE
\(P_{\text{max}} = 17.8\)

(c) VELOCITY VECTORS
\(v_{\text{max}} = 500 \text{ km s}^{-1}\)

(d) DENSITY
\(\rho_{\text{max}} = 9.5\)

Figure 16
CORONAL TRANSIENT \( t = 180 \text{ min}, \theta = 0.5 \)

(a) MAGNETIC FIELD LINES

(b) PRESSURE \( P_{\text{max}} = 17.5 \)

(c) VELOCITY VECTORS \( v_{\text{max}} = 100 \text{ km s}^{-1} \)

(d) DENSITY \( \rho_{\text{max}} = 3.0 \)

Figure 17
Figure 18

Radial Velocity (km s$^{-1}$)

Pressure (non-dimensional)

Density (non-dimensional)

Contact Surface

$t = 0$

$40$ min

$80$ min

$V_s = 517$ km s$^{-1}$

$V_s = 430$ km s$^{-1}$
Figure 19
Figure 20
Figure 21
CORONAL TRANSIENT ($v=0$ at $t=0$, $t=120$ min, $\rho=4$)

(a) MAGNETIC FIELD LINES
(b) PRESSURE
   $\rho_{max} = 8.6$
(c) VELOCITY VECTORS
   $v_{max} = 460$ km s$^{-1}$
(d) DENSITY
   $\rho_{max} = 4.5$

Figure 23
CORONAL TRANSIENT \( \nu = 0 \) at \( t = 0, t = 80 \) min, \( \rho = 0.5 \)

(a) MAGNETIC FIELD LINES
(b) PRESSURE \( p_{\text{max}} = 0.3 \)
(c) VELOCITY VECTORS \( v_{\text{max}} = 320 \) km \( s^{-1} \)
(d) DENSITY \( \rho_{\text{max}} = 3.2 \)

Figure 24
Figure 25

- Pressure
  - $\rho = 0.5$
  - $v = 0$ at $t = 0$
  - $t = 160$ min

- Density
  - $t = 80$ min
  - $t = 160$ min
  - $t = 120$ min
Figure 28

At 4 R₀

Non-Dimensional Values

Density

θ = 0.1

t = 80 min

t = 160 min
APPENDIX A. COMPUTER CODE FOR NUMERICAL SOLUTION

The simulations of the coronal streamer and the coronal transient are performed in two separate computer runs. The numerical solutions for the streamer simulation at each value of $\beta$ are output to mass storage devices at selected time intervals. These solutions can then be recalled by the plotting routine in Appendix B and plotted in various formats by the computer. The streamer simulation at the last time for which it is calculated is then used as the initial state for the transient simulation. The transient solutions are also output to mass storage devices at selected time intervals, and plots can again be produced.

As an example of the computer time required, the streamer simulation for $\beta = 0.5$ required 6 min and 45 sec on the CRAY-1 computer to simulate 16 hrs of physical time. The transient simulation for $\beta = 0.5$ required 40 sec on the same computer to simulate 2 hrs of physical time.

Since the codes for the streamer and transient simulations are essentially identical, only the code for the streamer simulation is presented here. The variables that must be input to the code are given first followed by a listing of the code.
Description of Input Variables for Computer Code MHDHS*(CRAY-1)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Columns</th>
<th>Definition</th>
<th>Comments</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>RN</td>
<td>1-4</td>
<td>Run number</td>
<td>Right-adjusted integer</td>
<td></td>
</tr>
<tr>
<td>Title</td>
<td>5-80</td>
<td>Run title</td>
<td>Any alphanumeric information</td>
<td></td>
</tr>
<tr>
<td>RØ</td>
<td>1-8</td>
<td>Reference radius</td>
<td>a. The time-dependent solution is computed for $r \geq RØ$</td>
<td>solar radius</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>b. The values of the remaining variables on this card must be the values at this radius</td>
<td></td>
</tr>
<tr>
<td>T</td>
<td>9-16</td>
<td>Temperature</td>
<td></td>
<td>K</td>
</tr>
<tr>
<td>D</td>
<td>17-24</td>
<td>Electron (or proton) density</td>
<td></td>
<td>no/cm³</td>
</tr>
<tr>
<td>PI</td>
<td>25-32</td>
<td>Polytropic index</td>
<td>Constant everywhere $(1 &lt; PI \leq 5/3)$. If input as 0, set to 5/3.</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>33-40</td>
<td>Magnetic field</td>
<td>The reference value at RØ and theta = 90°.</td>
<td></td>
</tr>
<tr>
<td>TAU</td>
<td>1-8</td>
<td>Pulse duration</td>
<td></td>
<td>minutes</td>
</tr>
<tr>
<td>DMG(I),</td>
<td>9-16</td>
<td>Determine the dependent variables in the pulse at RØ.</td>
<td>The values input depend on the type of pulse being considered - see IPULS on the option card</td>
<td></td>
</tr>
<tr>
<td>I = 1,9</td>
<td>17-24</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*This code is two-dimensional and is applicable to the meridional or $r-\theta$ plane in spherical coordinates. The azimuthal components of the velocity and magnetic field are neglected. This code does not use the large core memory.
<table>
<thead>
<tr>
<th>Variable</th>
<th>Columns</th>
<th>Definition</th>
<th>Comments</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>REND</td>
<td>1-8</td>
<td>Maximum radius</td>
<td>Steady State</td>
<td>solar radii</td>
</tr>
<tr>
<td>DR</td>
<td>9-16</td>
<td>Grid spacing in radial direction</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DTT</td>
<td>17-24</td>
<td>Grid spacing in theta direction</td>
<td></td>
<td>degrees</td>
</tr>
<tr>
<td>DRT</td>
<td>25-32</td>
<td>Grid spacing in radial direction</td>
<td></td>
<td>solar radii</td>
</tr>
<tr>
<td>TMAX</td>
<td>33-40</td>
<td>Maximum distance in theta direction</td>
<td></td>
<td>degrees</td>
</tr>
<tr>
<td>RMAX</td>
<td>41-48</td>
<td>Maximum distance in radial direction</td>
<td></td>
<td>solar radii</td>
</tr>
<tr>
<td>DTTP</td>
<td>49-56</td>
<td>Theta increment at which solution printed out</td>
<td></td>
<td>degrees</td>
</tr>
<tr>
<td>DRTP</td>
<td>57-64</td>
<td>Radial increment at which solution printed out</td>
<td></td>
<td>solar radii</td>
</tr>
<tr>
<td>TMAX</td>
<td>65-72</td>
<td>Time limit</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DTP</td>
<td>73-80</td>
<td>Time increment at which solution printed out</td>
<td></td>
<td>minutes</td>
</tr>
<tr>
<td>DTPT</td>
<td>1-8</td>
<td>Time increment at which solution is written out on a plot file</td>
<td></td>
<td></td>
</tr>
<tr>
<td>STBY</td>
<td>9-16</td>
<td>Stability constant</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Numerical Solution Parameters (Cards 5 and 6)

**Card 5**

- **REND**: 1-8
  - Maximum radius

- **DR**: 9-16
  - Grid spacing in radial direction

- **DTT**: 17-24
  - Grid spacing in theta direction
  - It is best to select DTT such that R*DIT is about equal to DRT at (RMAX+RΘ)/2

- **DRT**: 25-32
  - Grid spacing in radial direction

- **TMAX**: 33-40
  - Maximum distance in theta direction
  - The solution is computed from the equatorial plane (theta = 90°) to TMAX > 90°.

- **RMAX**: 41-48
  - Maximum distance in radial direction
  - The solution is computed from RΘ to RMAX.

- **DTTP**: 49-56
  - Theta increment at which solution printed out

- **DRTP**: 57-64
  - Radial increment at which solution printed out

**Card 6**

- **TMAX**: 65-72
  - Time limit

- **DTP**: 73-80
  - Time increment at which solution is written out on a plot file

- **DTPT**: 1-8
  - Time increment at which solution is written out on a plot file

- **STBY**: 9-16
  - Stability constant
    - a. STBY ≤ 1.0
    - b. Recommend using a value as near 1.0 as possible without numerical instabilities developing.
<table>
<thead>
<tr>
<th>Variable</th>
<th>Columns</th>
<th>Definition</th>
<th>Comments</th>
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<td>SMTH</td>
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<td>Smoothing constant</td>
<td>a. Removes some numerical instabilities.</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>b. Recommended using SMTH = 1.0 if possible.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>c. Only used if ISMTH = 1 and ICROX = 0.</td>
<td></td>
</tr>
<tr>
<td>TSTR</td>
<td>25-32</td>
<td>Times at which solution written on mass storage</td>
<td>The solution can then be used as the initial state for restart in a separate program.</td>
<td>Minutes</td>
</tr>
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<td>Variable</td>
<td>Columns</td>
<td>Definition</td>
<td>Value</td>
<td>Description</td>
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<td>---------</td>
<td>-----------------------------------</td>
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<td>------------------------------------------------------------------</td>
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<td>ISTST</td>
<td>1-4</td>
<td>Steady-state solution</td>
<td>1</td>
<td>Isothermal solar wind.</td>
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<td></td>
<td></td>
<td></td>
<td>2</td>
<td>Polytropic solar wind.</td>
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<tr>
<td>IPULS</td>
<td>5-8</td>
<td>Pulse</td>
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<td>The pulse depends on the particular study being conducted. The</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>types of pulses currently available are the following (all</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>symmetrical about theta = 90°):</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td>Pulse in temperature and density. DMG(L)=TM (Meridional extent</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>of pulse in degrees), DMG(2)=δT, DMG(3)=δp. The maximum pulse</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>in T and ρ is at theta = 90°, and it falls off sinusoidally to</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>ambient values at theta = TM. See IPULS = 2 also.</td>
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<td></td>
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<td>2</td>
<td>Pulse in the magnetic field. DMG(1) as for IPULS=1, DMG(2)=(B_p)</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>p gauss, DMG(3)=(B_r)p where (B_p) and (B_r) are the maximum</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>values of the latitudinal and radial components, respectively,</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>in the pulse. Input 0 if no pulse desired in one of the</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>components. The theta dependence is the same as for IPULS=1.</td>
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<td>For both IPULS=1 and =2, DMG(4)=DTI where DTI is the time in</td>
</tr>
<tr>
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<td></td>
<td></td>
<td></td>
<td>minutes for the pulse to reach maximum magnitude. The pulse</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>increases linearly in magnitude with time.</td>
</tr>
<tr>
<td>ICHCK</td>
<td>9-12</td>
<td>Time-dependent solution check</td>
<td>0</td>
<td>Do not check the time-dependent solution.</td>
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<td></td>
<td></td>
<td></td>
<td>1</td>
<td>Check the time-dependent solution by starting it with the</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>steady-state solution. The space terms are handled properly</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(and the steady-state solution is correct) if the time-dependent</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>solution does not deviate appreciably from the steady-state</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>solution after a sufficiently long time.</td>
</tr>
<tr>
<td>IBDRY</td>
<td>13-16</td>
<td>Boundary treatment at RØ</td>
<td></td>
<td>The boundary treatment depends on the type of pulse (IPULS)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>being used. See the subroutine BDHY. The current options are:</td>
</tr>
<tr>
<td>Variable</td>
<td>Column</td>
<td>Definition</td>
<td>Value</td>
<td>Description</td>
</tr>
<tr>
<td>----------</td>
<td>--------</td>
<td>-------------------------------------------------</td>
<td>-------</td>
<td>-------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>IMAGF</td>
<td>17-20</td>
<td>Steady-state magnetic field calculation</td>
<td>1</td>
<td>No boundary treatment</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0</td>
<td>$v_r$ and $v_\theta$ at R0 set to value at adjacent radial grid point (R0+DRT).</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td>Closed dipole</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2</td>
<td>Open quadrupole</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3</td>
<td>Open dipole</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4</td>
<td>Closed hexapole</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>5</td>
<td>Open hexapole</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>6</td>
<td>Closed decapole</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>7</td>
<td>Open decapole</td>
</tr>
<tr>
<td>IFWCS</td>
<td>21-24</td>
<td>Contact surface calculation</td>
<td>0</td>
<td>If IMAGF = 1, 4 or 6 (2, 3, 5 or 7), the option IBDX0 is set to 2(3) internally.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td>Follow the contact surfaces along $r$ at $\theta = 90^\circ$</td>
</tr>
<tr>
<td>IPTFL</td>
<td>25-28</td>
<td>Print out radii at which sound and Alfvén Mach numbers are one initially and at each time print out solution</td>
<td>1</td>
<td>Do not follow the contact surfaces along $r$ at $\theta = 90^\circ$</td>
</tr>
<tr>
<td>IPTVR</td>
<td>29-32</td>
<td>Dependent variable plots</td>
<td>0</td>
<td>Print out</td>
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<td>ISTSL</td>
<td>33-36</td>
<td>Store solution at time TSTR on mass storage for restart</td>
<td>1</td>
<td>No plots of the dependent variables</td>
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<tr>
<td>ISMTH</td>
<td>37-40</td>
<td>Smoothing</td>
<td>0</td>
<td>Produce plots of the dependent variables (CAH)</td>
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<td>Produce plots of the dependent variables (NCAR)</td>
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<td>NTMSM</td>
<td>41-44</td>
<td>Smoothing</td>
<td>0</td>
<td>No smoothing applied.</td>
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<td>1</td>
<td>Lapidus smoothing method applied.</td>
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<tr>
<td>IBDX0</td>
<td>45-48</td>
<td>Boundary treatment at $\theta = 90^\circ$.</td>
<td>1</td>
<td>The input value minus one is the number of time cycles that are skipped before smoothing. Only used if ISMTH = 1.</td>
</tr>
</tbody>
</table>

The nomenclature is: $I_1 = \text{value at 90-DTT}$, $I_2 = \text{value at 90+DTT}$. For all cases $I_1 = I_2$, $p_1 = p_3$, $u_1 = u_3$, $v_1 = -v_3$, $B_{t1} = B_{t3}$, $r_1 = -r_3$
<table>
<thead>
<tr>
<th>Variable</th>
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<th>Value</th>
<th>Description</th>
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<tr>
<td>IBDXM</td>
<td>49-52</td>
<td>Boundary treatment at TMAX</td>
<td>2</td>
<td>$u_1 = -u_3, \ v_1 = v_3, \ B_{\theta 1} = B_{\theta 3}, \ B_{r 1} = -B_{r 3}$</td>
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<tr>
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<td>3</td>
<td>$u_1 = -u_3, \ v_1 = v_3, \ B_{\theta 1} = -B_{\theta 3}, \ B_{r 1} = B_{r 3}$</td>
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<td>The nomenclature is: $(\cdot)_1 = \text{value at TMAX-DTT}, (\cdot)_2 = \text{value at TMAX}, (\cdot)_3 = \text{value at TMAX+DTT.}$</td>
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<td>0</td>
<td>No boundary treatment, calculation stops when reach TMAX.</td>
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<td>$Q_3 = Q_2$, where Q is any dependent variable</td>
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<tr>
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<td>2</td>
<td>$Q_3 = 2Q_2 - Q_1$, where Q is any dependent variable</td>
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<td>$Q_3 = Q_1$, where Q is any dependent variable</td>
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<td>IBDYM</td>
<td>53-56</td>
<td>Boundary treatment at RMAX</td>
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<td>No boundary treatment, calculation stops when reach RMAX.</td>
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<td>$Q_3 = 2Q_2 - Q_1$, where Q is any dependent variable</td>
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<td>$Q_3 = Q_1$, where Q is any dependent variable</td>
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<td>IRDTN</td>
<td>57-60</td>
<td>Radiation-Not included in these codes</td>
<td>0</td>
<td>Neglect radiation</td>
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<tr>
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<td>1</td>
<td>Calculate radiation (Cox-Tucker), but don't allow it to effect the solution</td>
</tr>
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<td>2</td>
<td>Calculate radiation (Cox-Tucker) and include it in equations.</td>
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<tr>
<td>ILWBM</td>
<td>61-64</td>
<td>Application of numerical differencing procedure</td>
<td>0</td>
<td>Use usual method with equations in conservation form.</td>
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<td>1</td>
<td>Use modified method. This method is often necessary when $\beta$ is small ($\beta \approx 0.1$) and the magnetic field is essentially radial.</td>
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<td>Options: All right-adjusted integers (Card 2):</td>
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<td>Pulse Parameters (Card 4):</td>
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<td>Numerical Solution Parameters (Card 6):</td>
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Note: The text is not legible in some parts due to the quality of the scan.
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*Note: The table continues with similar entries.*
740.  00  IF(1012)
741.  00  RSE1=Y(J-1)+Y1*(1.-RPS1)/(RMS2-RMS1)
742.  00  90  GO TO (91,52),1661
743.  00  21  IF(IAES=1)
744.  00  25  IF(-X2?L,J=J+1)
745.  00  29  IF(-X2?L,J=J+1)
746.  00  33  IF(-X2?L,J=J+1)
747.  00  37  IF(-X2?L,J=J+1)
748.  00  41  IF(-X2?L,J=J+1)
749.  00  45  IF(-X2?L,J=J+1)
750.  00  49  IF(-X2?L,J=J+1)
751.  00  53  IF(-X2?L,J=J+1)
752.  00  57  IF(-X2?L,J=J+1)
753.  00  61  IF(-X2?L,J=J+1)
754.  00  65  IF(-X2?L,J=J+1)
755.  00  69  IF(-X2?L,J=J+1)
756.  00  73  IF(-X2?L,J=J+1)
757.  00  77  IF(-X2?L,J=J+1)
758.  00  81  IF(-X2?L,J=J+1)
759.  00  85  IF(-X2?L,J=J+1)
760.  00  89  IF(-X2?L,J=J+1)
761.  00  93  IF(-X2?L,J=J+1)
762.  00  97  IF(-X2?L,J=J+1)
763.  00  101  IF(-X2?L,J=J+1)
764.  00  105  IF(-X2?L,J=J+1)
765.  00  109  IF(-X2?L,J=J+1)
766.  00  113  IF(-X2?L,J=J+1)
767.  00  117  IF(-X2?L,J=J+1)
768.  00  121  IF(-X2?L,J=J+1)
769.  00  125  IF(-X2?L,J=J+1)
770.  00  129  IF(-X2?L,J=J+1)
771.  00  133  IF(-X2?L,J=J+1)
772.  00  137  IF(-X2?L,J=J+1)
773.  00  141  IF(-X2?L,J=J+1)
774.  00  145  IF(-X2?L,J=J+1)
775.  00  149  IF(-X2?L,J=J+1)
776.  00  153  IF(-X2?L,J=J+1)
777.  00  157  IF(-X2?L,J=J+1)
778.  00  161  IF(-X2?L,J=J+1)
779.  00  165  IF(-X2?L,J=J+1)
780.  00  169  IF(-X2?L,J=J+1)
781.  00  173  IF(-X2?L,J=J+1)
782.  00  177  IF(-X2?L,J=J+1)
783.  00  181  IF(-X2?L,J=J+1)
784.  00  185  IF(-X2?L,J=J+1)
785.  00  189  IF(-X2?L,J=J+1)
786.  00  193  IF(-X2?L,J=J+1)
787.  00  197  IF(-X2?L,J=J+1)
788.  00  201  IF(-X2?L,J=J+1)
789.  00  205  IF(-X2?L,J=J+1)
790.  00  209  IF(-X2?L,J=J+1)
791.  00  213  IF(-X2?L,J=J+1)
792.  00  217  IF(-X2?L,J=J+1)
793.  00  221  IF(-X2?L,J=J+1)
794.  00  225  IF(-X2?L,J=J+1)
795.  00  229  IF(-X2?L,J=J+1)
796.  00  233  IF(-X2?L,J=J+1)
C  CALCULATE INITIAL ENERGIES AND PASS

A1 = 0.0
A2 = 0.0
A3 = 0.0
A4 = 0.0

IMX = IMX - 1
B2 = B2*(2,1,1) + 2*B1*(2,1,1) + 2
B1 = (B1 + 1)/(B1 + 1) + 2*B1*(2,1,1) + 2
B2 = B2*(2,1,1) + 2*B1*(2,1,1) + 2

C1 = C1*(1.0,1.1,1.0) + 2*C1*(1.0,1.1,1.0) + 2
C2 = C2*(1.0,1.1,1.0) + 2*C1*(1.0,1.1,1.0) + 2

ARE1 = ARE1 + 5*(C1 + C2)*DY

ARE2 = ARE2 + 5*(C1 + C2)*DY

ARE3 = ARE3 + 5*(C1 + C2)*DY

ARE1 = ARE1 + 5*(B1 + B2)*DY

ARE2 = ARE2 + 5*(B1 + B2)*DY

ARE3 = ARE3 + 5*(B1 + B2)*DY

ARE1 = ARE1 + 5*(A1 + A2)*DY

ARE2 = ARE2 + 5*(A1 + A2)*DY

ARE3 = ARE3 + 5*(A1 + A2)*DY

RETURN
END
00 SIGREC=T
00 IF (REC.I,MT,LT,0,0) SIGREC=1.
00 CHARMT=SIGREC*(I+J,N1)+CHARTY
00 IF (CHARMT.-.CHARZ) CHARBY=CHARYT
00 CONTINUE
00 IF (X-DEP.=.0) GO TO 39
00 PRINT ST,NSEN
00 NSEN=0
00 IF (XPRE.>.0) GO TO 40
00 PRINT 5,NPRE
00 XPRE=0
00 C SMOOTHING
00 40 IF (ISKRRK.EQ.0) GO TO 56
00 NTKSRK=NTKSRK+1
00 IF (NTKSRK.LT.NTKSRK) GO TO 56
00 NT=SKRSK
00 CALL LAPSE-(IL,MAX)
00 56 DTA=DIT
00 57 CHARX=DTX/CHARAX
00 CHARY=DTX/CHARA
00 DTX=AINT(C-APTX,CHARAY)*STY
00 C SMOOTHING
00 58 CHARX=DTX/CHARAX
00 59 CHARY=DTX/CHARA
00 56 DTA=DIT
00 DTX=AINT(C-APTX,CHARAY)*STY
00 C SMOOTHING
00 60 IF (I+J.2) GO TO 29
00 LG 12 J=1,LSUB
00 62 RAOTHC(I,J)=RAFAR(P(I,J,N1)+TO/D(I,J,MT))*(D(I,J,N1)+TO)*CRADE
00 64 LG 12 J=1,LSUB
00 66 LSKD=CLSSY*(J-1)
00 67 LG 12 J=1,LSUB
00 68 15 K=1, LSUB
00 70 K=AADTC(1,J)=RAFATC(1,J)
00 71 LSKD=CLSSY*(K,LSUB)+1
00 72 LG 12 J=1,LSUB
00 74 KG 15 J=1,LSUB
00 76 K=1, LSUB
00 78 K=1, LSUB
00 80 IF (K.1) GO TO 12
00 82 N=1
00 M1=2
00 CG TO 12
00 84 LG 12 J=2
00 86 A1=1
00 88 LG 12 RETURN
00 C END
00 SUBROUTINE LAPSE-(IL,MAX)
00 PARACR Ker (I+79,J+75)
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<th>Code</th>
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<td>U1=E(I1,1)</td>
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<td>00</td>
<td>U1P=E(I1,2)</td>
</tr>
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<td>U2=E(I1,3)</td>
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<td>00</td>
<td>DP=ABS(V(I1,34))</td>
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<tr>
<td>1244</td>
<td>00</td>
<td>C SMOOTHING IN X DIRECTION</td>
</tr>
</tbody>
</table>
| 1245 | 00   | DT=TOX*SIN
| 1246 | 00   | JX=0
| 1247 | 00   | DC*Z(TJ,LOT5)*
| 1248 | 00   | IF (LOT5=Y(I1,10,5)) JMAX=LOT5+Y(I1,10
| 1249 | 00   | DC*Z(I1,5)
| 1250 | 00   | JMAX=LOT5
| 1251 | 00   | DC 3 J=2,JX
| 1252 | 00   | U1=U(I1,1)
1367.00 17 FORMAT (10D17.4)  
1368.00 12 FORMAT (/5X'7=DEG'11X'7=DT'12X'BB')  
1369.00 $ FORMAT (1$4,2$)  
1370.00 8 FORMAT (1G15.3)  
1371.00 4 FORMAT ('SECD',E10.3,'T','E=$1P'T','S',16X'PULSIN*')  
1372.00 1 '3 FORMAT (1S40=';SELD LARGER THAN IN PULSIN ****')  
1373.00 16 FORMAT (1D16.6)  
1374.00 C 4OTE - IF PUT IN TIME-DEPENDENT PULSE, NEED CHANGES IN BBRY  
1375.00 C  
1376.00 CHARID=3.E-10  
1377.00 CHARIDY=3.E-10  
1378.00 PIE = 2,14159  
1379.00 XAP=1.07433  
1380.00 ABO2=AB0**2  
1381.00 C3=PI/ENG**2  
1382.00 DINC=2*MP1/110  
1383.00 I=NULL  
1384.00 WHITE (10,3)  
1385.00  
1386.00 DENTAL  
1387.00 GO TO (5,6,9,10)  
1388.00 8 WRITE (10,12)  
1389.00 9 PRINT 15  
1390.00 15 XMP=(XMP-G00)*APGF  
1391.00 IF (IPULS.EQ.,3) GO TO 2  
1392.00 20  
1393.00 20 PRINT 15  
1394.00 15 IF (IPULS.EQ.,3) GO TO 2  
1395.00 25  
1396.00 25 XCP=(1+XCP)/(2)  
1397.00 VCP=XCP-(XCP-2)/2  
1398.00 C1=CLSPE+XCP/(XCP-2)  
1399.00 VC=(XCP-1)/2  
1400.00 IF (C1LPE.LT.,2) VCPE=VC+C1  
1401.00 IF (C1LPE.LT.,2) VCPE=VC+C1  
1402.00  
1403.00 12 CONTINUE  
1404.00 20  
1405.00 30 DO 20 I=1,15  
1406.00 15 XTP=XTP-(XTP-30)  
1407.00 IF (XTP.LT.1.1) TC=74  
1408.00 40  
1409.00 40 ALPHAS=15 SIN(XTP/10)  
1410.00 PHI=IHT+PI/2-ALFA  
1411.00 IF (COS(IHTA)<LT.1.-DEG)) PHI=IHTA-PI/2-ALPA  
1412.00 50 PHI=IHT+PI/2+PHI  
1413.00 60  
1414.00 60 XLAST=2.61+PHI  
1415.00 70  
1416.00 XCP=XCP/XAP+G00  
1417.00 PRINT 4,XCP,2XT-3AR  
1418.00 20 CONTINUE  
1419.00 10 PRINT 22  
1420.00 22 CONTINUE  
1421.00 IF (C1LPE.LT.,2) GO TO 24  
1422.00 24  
1423.00 SC TO SC
IF (ISNRY.EQ.0, AND, ISNBDY.EQ.0) RETURN

LSDUM = SDM

LSTY = 15777

ST2 = LTZ

C = C + 1

CHZDRYF = E - 10

CHZDRYF = 1.0 + C

LSTY = 15777

IF (ISNRY.EQ.5) GO TO 17

IF (I = 1, I = 2, 16, 1, 10, 23, 23) IF (IVR = 1

GO TO 7

GO TO 17

GO TO 17

GO TO 17

GO TO 17

GO TO 17

IF (ISNRY.EQ.4) IF (IVR = 7

GO TO 17

IF (ISNRY.EQ.4) IF (IVR = 17

GO TO 17

IF (ISNRY.EQ.4) IF (IVR = 17

GO TO 17

IF (ISNRY.EQ.4) IF (IVR = 17

GO TO 17

IF (ISNRY.EQ.4) IF (IVR = 17

GO TO 17

IF (ISNRY.EQ.4) IF (IVR = 17

GO TO 17

IF (ISNRY.EQ.4) IF (IVR = 17

GO TO 17

IF (ISNRY.EQ.4) IF (IVR = 17

GO TO 17

IF (ISNRY.EQ.4) IF (IVR = 17
1821. 00  EX(1,J,NJ)=3*FX(1,J,NJ)
1822. 00  EX(2,J,NJ)=0.0
1823. 00  EX(3,J,NJ)=BY(3,J,NJ)
1824. 00  C  SUMMARY AT X=N
1825. 00  17 IF(C1(NX,EX/EX,EX,IPNX,EX,0) GO TO 16
1826. 00  LSUP = LDISMX+1
1827. 00  LSB2 = LDISMX+1
1828. 00  SUB = LDISMX
1829. 00  24 GO TO (Z1,17,17)
1830. 00  VELSUB2, J, N1) = V(VELDISM, J, N1)
1831. 00  DELSUB2, J, N1) = D(VELDISM, J, N1)
1832. 00  BY(VELSUB2, J, N1) = M(VELDISM, J, N1)
1833. 00  VELSUB, J, N1) = F(VELDISM, J, N1)
1834. 00  25 GO TO 16
1835. 00  13 DO 15 JMT, LSUP
1836. 00  VELSUB, J, N1) = U(VELDISM, J, N1) - VELSUB, J, N1)
1837. 00  VELSUB2, J, N1) = V(VELDISM, J, N1)
1838. 00  DELSUB2, J, N1) = D(VELDISM, J, N1)
1839. 00  BY(VELSUB2, J, N1) = M(VELDISM, J, N1)
1840. 00  VELSUB, J, N1) = F(VELDISM, J, N1)
1841. 00  15 GO TO 16
1842. 00  16 RETURN
1843. 00  END
1844. 00  SUBROUTINE SOLVE (AC,TS,VELDISM, VELSUB, LSUP)
1845. 00  5 FORMAT (** CONVERGENCE FOR V0 AT CRITICAL POINT - I =
1846. 00  112,12X V = C ***)
1847. 00  11 FORMAT (/ X 'CRITICAL POINT ITERATION / 4X 'N' 5X 'K' 5X 'F(X)' /
1848. 00  13 FORMAT (I2,12X,A5)
1849. 00  19 FORMAT (/ X 'NO SUESONIC CRITICAL POINT SOLUTION - I =',I3,
1850. 00  110X V = 0 ***)
1851. 00  19 FORMAT (5X 'X' = F10.2,1X 'Y' = F10.2)
1852. 00  10 FORMAT (/ X 'CRITICAL POINT/5X' X = F10.2,1X 'SOLAR RADIU '/5X
1853. 00  1867,00  PRINT=0
1854. 00  IF (IPHT, EX,1) PRINT=11
1855. 00  EX = 1.70E-16
1856. 00  PH = 1.70E-24
1857. 00  RC = 0.057E-16
1858. 00  SUM = 1.70E-16
1859. 00  LVA = 6.0E-8
1860. 00  ITM1
1861. 00  CC = 1.
1862. 00  CC = 2.0E-20
1863. 00  VGT
1864. 00  C  ITERATION = SECANT METHOD ONCE SOLUTION ISOLATED
1865. 00  DO 1 = 1, 200
1866. 00  GO TO (15, 14, 16), 1 IT
1867. 00  16 VVEL=0.
1868. 00  IF (VVEL = 0) GO TO 16
1869. 00  PRINT 19, 1
1870. 00  GO TO 16
1871. 00  RETURN
1872. 00  10 SIGMA(SUM)=2**2*1.1E0+AS)
1994. 00  C: A=3, E=6
1995. 00  N: A=14
1996. 00  DO 10 U=1*2, L=10
1997. 00  J=1
1998. 00  X: A=R2*3*(1.0,1.0)+D*(1.0,1.0)
1999. 00  X: A=R2*(1.0,1.0)+D*(1.0,1.0)
2000. 00  ABY=ABY2*XY(J,J,11)+2/S(1.0,1.0)
2001. 00  ARG=ARO1*ARO2*ABY2
2002. 00  GO TO 12
2003. 00  C: ABY=1
2004. 00  SIGN=1
2005. 00  IF(U=(1.0,1.0),L=1*0) SIGN=-1.
2006. 00  X: ABY=ABY*XY(J,J,11)+2/S(1.0,1.0)
2007. 00  IF(CHARX*GT.CHARX) CHARX=CHARX
2008. 00  IF(CHARX*LT.CHARX) CHARX=CHARX
2009. 00  CONTINUE
2010. 00  C: ABY=ABY*XY(J,J,11)+2/S(1.0,1.0)
2011. 00  SIGN=1
2012. 00  IF(U=(1.0,1.0),L=1*0) SIGN=-1.
2013. 00  X: ABY=ABY*XY(J,J,11)+2/S(1.0,1.0)
2014. 00  IF(CHARX*GT.CHARX) CHARX=CHARX
2015. 00  GO TO 10
2016. 00  J=1
2017. 00  X: A=R2*3*(1.0,1.0)+D*(1.0,1.0)
2018. 00  ABY=ABY2*XY(J,J,11)+2/S(1.0,1.0)
2019. 00  ARG=ARO1*ARO2*ABY2
2020. 00  C: ABY=ABY*XY(J,J,11)+2/S(1.0,1.0)
2021. 00  SIGN=1
2022. 00  IF(U=(1.0,1.0),L=1*0) SIGN=-1.
2023. 00  X: A=R2*3*(1.0,1.0)+D*(1.0,1.0)
2024. 00  IF(CHARX*LT.CHARX) CHARX=CHARX
2025. 00  IF(CHARX*GT.CHARX) CHARX=CHARX
2026. 00  CONTINUE
2027. 00  C: ABY=ABY*XY(J,J,11)+2/S(1.0,1.0)
2028. 00  SIGN=1
2029. 00  IF(U=(1.0,1.0),L=1*0) SIGN=-1.
2030. 00  IF(CHARX*LT.CHARX) CHARX=CHARX
2031. 00  IF(CHARX*GT.CHARX) CHARX=CHARX
2032. 00  CONTINUE
2033. 00  C: ABY=ABY2*XY(J,J,11)+2/S(1.0,1.0)
2034. 00  IF(CHARX*GT.CHARX) CHARX=CHARX
2035. 00  STICK=STICK(J,CHARX,CHARY)*STICK
2036. 00  IF(STICK*GT.DT) RETURN
2037. 00  PRINT 10, DT, STICK
2038. 00  DT=DT+STICK
2039. 00  HI=1
2040. 00  EN1
2041. 00  EN2

END END  ERRORS: NO.1, TIME: 79.429 SEC. IMAGE COUNT: 2041

ART: S SAMPLE
FURUR 239T, U1 E33 57411 06/12/65 09:31:22
APPENDIX B. COMPUTER CODE FOR COMPUTER-GENERATED PLOTS

One outstanding advantage of a computing facility such as that at the National Center for Atmospheric Research in Boulder, Colorado, which is where these simulations were performed, is the capability of quickly producing multi-dimensional plots of the physical variables. A listing of the code we used to obtain computer-generated plots (some of which are presented in this report) is given here along with a description of the variables that must be input to the code. The routines in the listing that actually generate the plots are, in general, unique to the NCAR Computing Facility; however, the remaining logic should be applicable to any facility.

Since the plots are placed on microfilm, this introduces the possibility of producing computer-generated movies. We have produced movies of the evolving magnetic field lines for the streamer and transient simulations for both $\beta = 0.5$ and $\beta = 4$. 

116
Description of Input Variables for Plot Routine PLTPTS for Codes MDH5 and MDCT (CRAY-1)

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<th>Variable Columns</th>
<th>Definition</th>
<th>Comments</th>
<th>Units</th>
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<td>NDS 1-4</td>
<td>Number of data sets to be plotted</td>
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<td>ANGH 1-8</td>
<td>Angular orientation of surface plots</td>
<td>See NCAR manual &quot;NCAR Software Support Library, Vol. 3&quot; for write-up on Subroutine SRFACE.</td>
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Options (Card 2)

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<td>IPS1</td>
<td>17-20</td>
<td>Surface plots of non-dimensional pressure, density, velocity magnitude and temperature</td>
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<td>Produce plots - see write-up on SRFACE in above manual.</td>
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<td>IPHT</td>
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<td>Half-tone plots of non-dimensional density, temperature and pressure</td>
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<td>IPVV</td>
<td>25-28</td>
<td>Velocity vect x plot</td>
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<td>IPFL</td>
<td>29-32</td>
<td>Contour plots of magnetic field lines and the non-dimensional density less the ambient value</td>
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<td>Produce plots - see write-up on COMREC in above manual.</td>
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<td>IPRN</td>
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<td>Half-tone plots of total radiation (Cox-Tucker) and the total radiation minus the background value</td>
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<td>Only do calculated field line contour polar plot.</td>
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<td>Use flash buffers if making a movie.</td>
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# FORTRAN CODING FORM

**ANALYST**       R. S. Steinolfson  
**ENGINEER**       ______________________  
**JOB NO.**        PLTPT. Input Format - 25 April 1980  
**COST CONTROL NO.**

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Right-adjusted integers.
Listing of Computer Code PLTPTS

CRTL.IDL .SAMPLE,STOP
ELT BRT 5740TC 04/25/80 11:18:44 -->0
1. 00 *JOB,5346,55811000,STENOLFSON
2. 00 +FORTRAN,D=PLIB,0N=PLTCY2,AF,FL
3. 00 PROGRAM PLTPTS
4. 00 C 1. II.AND.JJ.. MUST BE AT LEAST AS LARGE AS ARRAYS_READ ON_TAPE,
5. 00 C 2. DIMENSIONS OF Z MUST BE EQUAL TO ACTUAL NUMBER OF POINTS PLOTTED,
6. 00 C 3. M7 AND N7, M7=IMXP, N7=JMPX
7. 00 C 4. IMXP=2+JNPX*JMPX+JNPX**2+1, JJV=INXP/2+1
8. 00 C 5. NNPFL=1+IMPX
9. 00 PARAMETER (IXT=37, IYI=41, IMXP=37, JMPX=41, INX=2614, INY=19, JJV=21,
10. 00 1NNFL=123)
11. 00 REAL LXX, LXY
12. 00 DIMENSION P(IXT, IYT), D(IXT, IYT), V(IXT, IYT), U(IXT, IYT), B(IXT, IYT),
13. 00 1BY(IXT, IYT), X(IXT, IYT), Y(IXT, IYT)
14. 00 2ST(IYJ, DACTY), RACT(IYJ)
15. 00 DIMENSION Z(INXP, INXP), WORK(INXP), YU(IYN, JJV), VVXXV(JJV), SJVX(JJV)
16. 00 1LAXV(5), LAB(6), ZC(JMPX, INXP), ZZ(JMPX, INXP), YUCC(JJV, JJV),
17. 00 YV1(JJV, IYN), XLX(IYJ), YYLX(IYJ), XXUX(IYJ), YYUX(IYJ), VU(IYN, JJV),
18. 00 3VU(JJV, IYN), XXP(NNPFL), YYP(NNPFL)
19. 00 COMMON /TRAN/Y1,Y2,X1,X2
20. 00 56 FORMAT ('*** INCREASE NNPFL ***')
21. 00 4 FORMAT ('INPUT =/5X'NDS ="14 /
22. 00 3 FORMAT ('INPUO =/5X'NPS =",13 / 3X'IPSU =",13 / 3X'IPHT =",13 / 3X'IPHT =",13)
23. 00 31 FORMAT ('TIME =",1PE10.3," MIN. ,')
24. 00 SPX(1)=0.0
25. 00 20 IF (2*IMXP-LT,INXP, IMXP=IMXP+1
26. 00 2MPX=JMPX/2
27. 00 2IF (2*IMXP-LT,IMPX,IMXP=IMXP+1
28. 00 IF (2*IMXP-LT,JMPX, JMPX=JMPX+1
29. 00 C PLOT OPTION - WATCH Z_DIMENSION
30. 00 YJ=1.0
31. 00 10 M9ST=1
32. 00 PIEC=3.1415926
33. 00 RLTC=.08
34. 00 PRPDG=.0174533
35. 00 READ (10) TIME,M,N,((PCI,J),O(1,J),UCI,J),YCI,J),B(1,J),BY(J,J),
36. 00 TX=1.0, Y(1),Z(1),X(1),Y(1),Z(1),Y(1)
37. 00 21=1,M),Y(1),Z(1),Y(1),Z(1),Y(1)
38. 00 Y1=Y(1)
39. 00 Y2=Y(JMXP)-Y1
40. 00 ARP=Y1+Y2
41. 00 DO 49 J=1,IMXP
42. 00 49 X(J)=X(J)+RAPP
43. 00 XIX(J)=Y(J)+COS(PIECX(J1))
44. 00 YXX(J)=Y(J)+SIN(PIECX(J+1))
45. 00 XX(J)=Y(J)+COS(PIECX(J1))
46. 00 52 YJ(J)=Y(JMXP)+SIN(PIECX(J1))
47. 00 YXX(J)=Y(J)+SIN(PIECX(J1))
48. 00 53 Y1=Y1+Y2
49. 00 54 X2=X(2IMXP)-X(1)
50. 00 X1=0.0
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</table>
C HALFTON PLOTS

13 IF (IPHT.EQ.1) GO TO 15
15    DO 2 MM=1,3
2       DO 5 I=1,IFXP
5       DO 5 J=1,JXMP
8       GO TO (11,12,243,PM)
11       Z(I,J)=B(I,J)/DA(J)
12       GO TO 5
12       Z(I,J)=P(I,J)/(DA(I,J)+TA(J))
24       5 CONTINUE
25       GO TO (37,38,39),MM
37       LAB(4)=4HD/80
38       LAB(5)=1H
39       LAB(6)=1H
40       GO TO 40
38       LAB(6)=1H/TO
40       GO TO 40
41       CALL PWDY(136,1008,LAB,48,2,0,2)
42       CALL EZHFTA(2,1MXP,1MPX)
43       2 CONTINUE
44       C RADIATION PLOTS
15 IF (IPRN.EQ.1) GO TO 26
16    DO 27 MM=1,2
27       DO 28 I=1,IMXP
28       DO 29 J=1,JMPX
29       GO TO (29,303,MM)
30       Z(I,J)=RADXNP(I,J)*TO/D(I,J)*DO**2*CRADH
31       GO TO 28
32       28 CONTINUE
33       GO TO (41,42),MM
41       LAB(4)=8HRADIATION
42       LAB(5)=1H
43       LAP(6)=1H
44       GO TO 43
45       LAB(5)=8HM - AMBI
46       LAB(6)=5HEAT
47       CALL PWDR(136,1008,LAB,48,2,0,2)
48       CALL EZHEMP(2,1IMX,MXP)
49       27 CONTINUE
50       C VELOCITY VECTOR PLOTS
26 IF (IPVX.EQ.3) GO TO 10
51       KI=1
52       DO 19 I=1,1MXPV
19       KI=KI+2
53       KJ=7
54       DO 19 J=1,1MXPV
55       KJ=KJ+2
56       YMP(I)=X(KI)
57       VV(I,J)=VV(KI,KJ)
58       19  VV(I,J)=VV(KI,KJ)
59       DO 48 I=1,1MXPV
60       DO 48 J=1,1MXPV
61       VV(X,J)=VV(I,J)
5360 TO 59

DO 58 J = 1, JMXPV
DO 59 I = 1, IMXPV

XX = IMXPV + I

58 VUC(J, I) = VUC(J, K)
DO 59 J = 1, JMXPV
DO 59 I = 1, IMXPV

IF (VUDD(J, I), LT, 1.E-4, AND, VUDD(J, I), LT, 1.E-4) GO TO 60
IF (VUDD(J, I), LT, 1.E-4, VUDD(J, I)) GO TO 67

ALP = 0.0

60 GO TO 68

67 IF (VUDD(J, I), LT, 1.E-4, + VUDD(J, I)) GO TO 69

ALP = PIEC / 2.

69 ALP = ATAN(ABS(VUDD(J, I)) / VUDD(J, I))

68 IF (VUDD(J, I), LE, 0.0) PHI = PIEC - XX*(I) + ALP
IF (VUDD(J, I), LE, 0.0) PHI = PIEC - XX*(I) - ALP

VUC(J, I) = CFI*COS(PHI)
VUC(J, I) = CFI*SIN(PHI)

60 VUC(J, I) = VUC(J, I)
61 VUC(J, I) = VUC(J, I)

59 CONTINUE

72 CALL EZVEC (VVC, VUC, JMXPV, IMXPV)

73 CALL EZVEC (VVC, VUC, JMXPV, IMXPV)

74 CONTINUE

72 CALL EZVEC (VVC, VUC, JMXPV, IMXPV)

73 CALL EZVEC (VVC, VUC, JMXPV, IMXPV)
227. 00 81 LAB(4)=4HP/PO
228. 00 LAB(5)=1H
229. 00 LAB(2)  
230. 00 GO TO 85
231. 00 82 LAB(4)=4ND/DO
232. 00 GO TO 85
233. 00 83 LAB(4)=8HAMMER EXEC
234. 00 LAB(5)=SHESS (D= 
235. 00 LAB(6)=2HD
236. 00 GO TO 85
237. 00 84 LAB(4)=HMJ/TO
238. 00 LAB(5)=1H
239. 00 LAB(6)=1H
240. 00 85 CALL PWY(46,1008,LAB,45,2,0,2)
241. 00 CALL SET (.05,.95,.95,.0,AB,0,0,AB,1)
242. 00 DO 99 I=1,2
243. 00 CALL LINE (.0,.0,.0,AB,0,0)
244. 00 CALL LINE (.0,.0,.0,0,AB)
245. 00 89 CONTINUE
246. 00 DO 86 I=2,15
247. 00 R=I
248. 00 IF (RI GE AB-1.E-5) GO TO 87
249. 00 CALL LINE (RI,0,0,RI,RLTIC)
250. 00 CALL LINE (RI,0,0,RI,RLTIC,RI)
251. 00 86 CONTINUE
252. 00 87 CALL CURVE(XXL,YXL,IMXP)
253. 00 CALL CURVE (XXL,YXL,IMXP)
254. 00 CALL EZCENTRIC,IMXP,IMXP)
255. 00 IF (IPTO.E1.0) GO TO 88
256. 00 76 CONTINUE
257. 00 88 IFPL1=1
258. 00 CALL PWY(46,1008,LAB,45,2,0,2)
259. 00 CALL SET (.05,.95,.95,.0,AB,0,0,AB,1)
260. 00 DO 99 I=1,2
261. 00 CALL LINE (.0,.0,.0,AB,0,0)
262. 00 CALL LINE (.0,.0,.0,0,AB)
263. 00 90 CONTINUE
264. 00 DO 86 I=2,15
265. 00 R=I
266. 00 IF (RI GE AB-1.E-5) GO TO 62
267. 00 CALL LINE (RI,0,0,RI,RLTIC)
268. 00 CALL LINE (RI,0,0,RI,RLTIC,RI)
269. 00 61 CONTINUE
270. 00 62 CALL CURVE(XXL,YXL,IMXP)
271. 00 CALL CURVE(XXL,YXL,IMXP)
272. 00 GO TO (71,72),IFPL1
273. 00 71 DL=Y(2)-Y(1)
274. 00 DO 50 L=1,IMXP
275. 00 DO 50 J=1,IMXP
276. 00 BX(I,J)=BX(I,J)
277. 00 BY(I,J)=BY(I,J)
278. 00 LAB(4)=8MAGNETIC
279. 00 LAB(5)=6K FIELD L
280. 00 LAB(6)=4HINES
281. 00 IMXP1=IMXP-1
282. 00 DO 70 L=4,IMXP1,2
283. 00 R1=Y(1)
DO 51 K=2,NPFL

IF (BR1.LT.0.0) DR=-DR

IF (ABS(BR1).LT.1.0E-5) DT=ABS(BR1)/BT1/R1

R1=R1+DR

T1=X(T1)

IF (X(J).LT.R1) GO TO 55

IF (KY(J).GT.R1) GO TO 55

54. CONTINUE

53. J=J+1

52. CONTINUE

IPI=I+1

DO 54 J=2,JXP

IF (Y(J).GT.R1) GO TO 55

55. CONTINUE

51. CONTINUE

PRINT 56

57 CALL CURVE (XXM,YM,KK)

50. CONTINUE

70. CALL FRAME

IF (IPTO.EQ.0) GO TO 56

NDST=NDST+1
341. 00  IF (NDST.LT.NDS) GO TO 16
342. 00  END
343. 00  END
344. 00  FUNCTION RADFN(TS)
345. 00  DIMENSION T(49), Q(49)
346. 00  DATA T/9.2E3, 1.8E4, 1.5E4, 2.6E4, 1.4E4, 1.8E4, 2.4E4, 2.2E4,
347. 00   12.3E4, 2.0E5, 3.5E4, 4.7E4, 6.9E4, 8.0E4, 6.7E4, 1.0E5, 6.5E4,
348. 00   3.1E5, 1.0E5, 1.9E5, 2.1E5, 2.4E5, 2.8E5, 3.2E5, 3.5E5,
349. 00   33.9E5, 4.7E5, 5.6E5, 6.2E5, 6.9E5, 7.4E5, 8.0E5, 9.0E5, 1.0E6, 1.3E6,
350. 00   41.7E6, 2.2E8, 3.1E8, 4.3E8, 7.0E8, 9.8E8, 1.2E9, 2.3E9, 3.7E9,
351. 00  DATA Q/370, 326, 353, 345, 342, 337, 355, 350, 348, 346
352. 00  DATA Q/1.1E-24, 3.6E-24, 8.05E-24, 1.65E-23, 3.5E-23, 5.8E-23,
353. 00  18.15E-23, 23.1E-23, 22.1E-22, 22.9E-22, 9.5E-23, 8.0E-23, 22.1E-22,
354. 00  1.4E-22, 22.9E-22, 21.1E-22, 22.1E-22, 22.1E-22, 22.1E-22,
355. 00  41.7E6, 2.2E8, 3.1E8, 4.3E8, 7.0E8, 9.8E8, 1.2E9, 2.3E9, 3.7E9,
356. 00  57.1E-23, 6.3E-23, 5.7E-23, 5.5E-23, 4.9E-23, 23.25E-23, 23.25E-23,
357. 00  61.7E-23, 2.0E-23, 2.25E-23, 2.9E-23, 2.3E-23,
358. 00  3 FORMAT (2X***, 15.6F1, 1.3D, _RADIATION_ _EXTRAPOLATED_ _***)
359. 00  IF (TS.GE.T(1)) Go To 1
360. 00  RADFN=0.0
361. 00  RETURN
362. 00  IF (TS.LT.T(49)) Go To 2
363. 00  PRINT 3
364. 00  RADFN=Q(47)*Q(469)-Q(47)*(TS-T(47))/ (T(49)-T(47))
365. 00  RETURN
366. 00  2 DO 4 I=1,48
367. 00  4 CONTINUE
368. 00  IF (TS.GE.T(I) AND TS.LT.T(I)) Go To 5
369. 00  4 CONTINUE
370. 00  5 RADFN=Q(I)*(Q(I)-Q(I-1))*(TS-T(I))/(T(I)-T(I-1))
371. 00  RETURN
372. 00  END
373. 00  END

END ELT. ERRORS: NONE. TIME: 3.532 SEC. IMAGE COUNT: 373

GPRTS SAMPLE
FURPUR 28RT.1 U1 E35 S74711 06/25/80 11:18:46.
APPENDIX C. SAMPLE RUN

A listing of a typical computer run for a coronal streamer simulation is presented. The input variables are listed first followed by the initial ambient atmosphere and the time-dependent solution. The time-dependent solution is given at selected time intervals along radial lines at selected meridional increments. For this example the solution is only shown for the first time increment.
INPUT

RUN IDENTIFICATION
RUN NUMBER = 1
HELMET STREAMER SIMULATION

ITUS = 3
IGUS = 3
ITULS = 3
IGUS = 3
ITOMY = 6
ITOE = 1
IFGMO = 0
ITOLE = 2
ITDI = 2
ITDI = 2
ITLH = 6
ITLH = 6
ITREI = 2
ITREI = 2
ITLH = 6
ITLH = 6
ITDI = 2
ITDI = 2

STEADY-STATE PARAMETERS AT T0
PG = 1.000000E+06 SLS.24 = ACII
T = 1.000000E+24 DEGREES
J = 2.000000E+35 ELECTRON/CM
ET = 1.000000E+24 MILLI
B = 5.250000E+24 GAUSS

PALE PARAMETERS
TAU = 1.425000E-02 MINUTES
TM = 1.000000E+24 DEGREES
DT = 0.000000E+00 BALANCE
DQ = 7.000000E+00 K
DT = 0.000000E+00 MINUTES

STEADY-STATE SOLUTION PARAMETERS
REM = 5.000000E+21 SOLAR RADII
DR = 1.000000E+21 SOLAR RADII

TIME-DEPENDENT SOLUTION PARAMETERS
OTT = 2.500000E+00 DEGREES
OBT = 1.000000E-21 SOLAR RADII
THA = 1.500000E+23 SOLAR RADII
TRX = 2.500000E+23 SOLAR RADII
TP = 2.500000E+23 SOLAR RADII
THA = 1.440000E+23 MINUTES
DIP = 1.220000E+12 OMEGA
TP = 1.220000E+12 MINUTES
STB = 0.000000E+00
SM = 0.000000E+00
TST = 1.000000E+13 MINUTES

OUTPUT

*******************************************************************************
  TOTT = 1.200000E+00 OMEGA
*******************************************************************************
### REVISED VALUES OF THAX AND ENAX

**THAX = 1.48°C = 2 DEGREES**

**PHAX = 5.39°C = 2 SOLAR RADI**

**LAV = 22**

**LAV = 41**

### VALUES AT YO

- **P = 1.376E+00**
- **Q = 1.75E+02**
- **R = 6.666E+01**
- **N = 1.39E+03**
- **S = 5.00E+02**
- **A = 1.56E+02**
- **NPA = 1.34E+02**
- **ORA = 3.53E+03**
- **V = 3.26E+00**

### CRITICAL POINT

- **R = 4.366E+00**
- **V = 1.53E+02**

### SOLUTION OF STEADY-STATE EQUATIONS

#### NON-DIMENSIONAL VARIABLES

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