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MAGNETOHYDRODYNAMIC MODELLING OF SOLAR DISTURBANCES IN  
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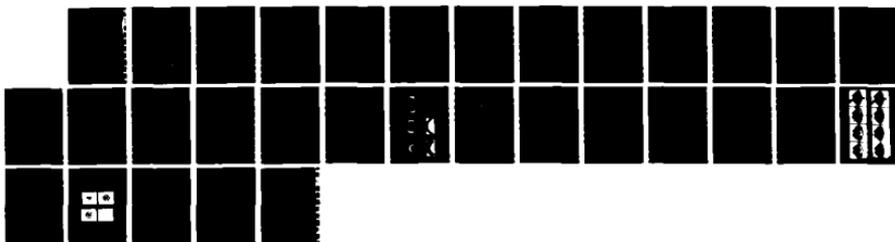
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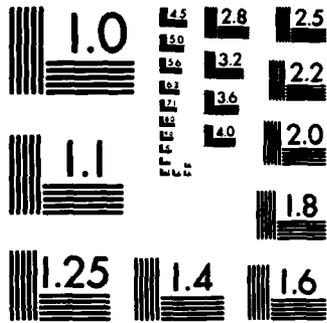
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Magneto-hydrodynamic Modelling of Solar Disturbances  
in the Interplanetary Medium

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December 1985

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**FOR THE COMMANDER**



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## ABSTRACT

We have scientifically constructed a series of interplanetary MHD models that comprise the foundations for a composite solar-terrestrial environment model. These models, unique in the field of solar wind physics, include both 2-1/2D as well as 3D time-dependent codes that will lead to future operational status. We have also developed a geomagnetic storm forecasting strategy, referred to as the Solar-Terrestrial Environment Model (STEM/2000), whereby these models would be appended in modular fashion to solar, magnetosphere, ionosphere, thermosphere, and neutral atmosphere models. We stress that these models, while still not appropriate at this date for operational use, outline a strategy or blueprint for the future. This strategy, if implemented in its essential features, offers a high probability for technology transfer from theory to operational testing within, approximately, a decade. It would ensure that real-time observations would be used to drive physically-based models that outputs of which would be used by space environment forecasters.

A Bibliography of papers is appended, with listing by first author for easy reference. A Summary comprises the balance of this Final Report in which the various papers are categorized with a description of their main points and conclusions. A set of representative figures, together with extensive descriptive captions, is also included for the reader interested in some additional details. This work was prepared with partial support from various AFGL project orders to NOAA's Space Environment Laboratory during Fiscal Years 1983 through 1985. This support is gratefully acknowledged and reported in each of the 22 papers that are now published, in press, or under consideration in various forums (refereed journals and symposia proceedings).

## SUMMARY

The papers listed in the Bibliography are divided into several categories followed by a short description of key points and conclusions.

The four categories are listed as follows:

- A. Basic solar wind studies.
- B. Magnetohydrodynamic, time-dependent models for the solar wind plasma and interplanetary magnetic field. [short title: MHD Modeling]
- C. Coronal mass ejection studies.
- D. Technology transfer for geomagnetic storm prediction studies [short title: Technology Transfer]

Some of the main points and conclusions found from the papers included under each category are given in the following sections.

## A. Basic Solar Wind Studies

The paper by Cuperman, Tzur, and Dryer (1984) is representative of a series of papers by the group led by Prof. S. Cuperman who has successfully developed a generalization of previously-used, "standard" solar wind equations. This work consists of the derivation—starting from the Boltzmann equation—of a higher order, closed system of equations for the moments of the particle distribution function,  $f_a$  for species  $a$ , for spherically symmetric systems. This paper uses full equations (rather than the Fourier heat flux expressions) for electron and proton thermal conductivities. A time-dependent, relaxation method is used to obtain steady solutions between the Sun and 5 AU. One of these solutions is shown in Figure 1. The goal of this research is to explore the additional physics, such as dissipative processes, that may become necessary to be incorporated into our 2-1/2D and/or 3D MHD codes when high spatial and temporal resolution may be required. This work is being extended to include electrostatic effects due to unequal proton and electron densities.

In a more operationally-oriented study, Yeh (1984) devised a quantitative model for a corotating solar wind stream. An algorithm was developed for the calculation of the correlation between two points in two disparate streams. Thermal conduction, assuming the commonly-used Fourier heat flux equation for protons only, was assumed to be the main heating along an interplanetary magnetic field (IMF) flux tube.

With the time-dependent magnetohydrodynamic (MHD) models in mind, Yeh and Dryer (1985) developed from first principles a constraint required at the lower boundary in MHD calculations. This constraint is necessary and sufficient for magnetic solenoidality. This is important because numerically-prescribed physical parameters at the lower boundary (say, close to the Sun) can introduce fictitious magnetic monopoles into a medium that was originally free of such monopoles. This constraint, based on Faraday's law, will be incorporated into our MHD modelling work.

## B. MHD Modeling

We have followed a very conservative "learning curve" in the construction and testing of our time-dependent computer simulation codes. The modeling has attacked the problem in the classical way: the simultaneous solution of the governing mathematical equations (conservation of mass, momentum, and energy coupled to Maxwell's equations for an electrically-conducting plasma) subject to prescribed initial and boundary conditions. The physics that go into these equations are currently fairly simple: single-fluid electrically neutral, polytropic plasma; no dissipation (except at shocks); and gravitational attraction by the Sun. Additional physics has been developed in a parallel track as mentioned in Section A above and in the papers given in the Bibliography (as well as in various review papers by participants in this project: M. Dryer, S. Cuperman, and S.T. Wu). Such additional physics will be incorporated into future extensions of our models.

We have continued to utilize the computers available to us, starting with CDC 6600, then moving to the CDC 7600, followed by CYBER's 650, 750, and now

the CYBER 840 (all in Boulder). In addition, we have utilized the CRAY-1 (NCAR/Boulder) and, now, the CYBER 855/205 (NOAA/NBS/Gaithersburg, MD). Developmental work is also currently being accomplished on an APOLLO microcomputer. An NCAR graphics package, together with several routines of our own design, has been helpful. Additional machines (PDP VAX and UNIVAC) have also been used by several of our contractors (Tennessee Technological University and Engineering International, Inc.) as part of our focused study.

With the physics and mathematics combined and with the usage of the computers, we have utilized the approach of the initial boundary value problem of mathematical physics. That is, with initial configurations as specified above, various lower boundary conditions have been imposed to generate the disturbances. These lower boundary conditions are chosen to simulate a variety of solar conditions, such as flares, prominence eruptions, coronal mass ejections, etc. Figures 2, 3, and 4, together with their captions, illustrate some of our basic studies with the 2-1/2D MHD model. Sensitivity studies with varying pulse strengths and durations are given in the Bibliography. As time progresses, we hope that the evolutionary plasma properties will reflect reality as closely as possible. The need for observational comparisons is obvious, and we have indeed made several comparisons of this kind. One must keep in mind that no analytic solutions are available for the problems that confront us, namely varying conditions at the Sun that cause compound evolutionary changes in an inhomogeneous steady-state heliospheric medium. A single caveat should be stated: use of similarity theory has proved useful and instructive in simple situations such as the blast wave and constant velocity piston-driven cases.

The question of geometry is important. We obviously must live in a three-dimensional universe. But insight must come along the "learning curve" by progressing from one to two, then to three dimensional, time-dependent simulations. We have followed this course and have now achieved the fully-3D stage. However, we continue, on occasion, to fall back on the 2D, 2-1/2D (three components of IMF and solar wind velocity are considered on the ecliptic plane), and even the 1-1/2D (two components along a fixed helioradial direction) models. This approach is essential whenever we have found complete sets of data from two radially-aligned spacecraft or from widely-separated spacecraft within (or close to) the ecliptic plane. We have successfully completed the former case (1-1/2D solution with Pioneer 10 and 11 spacecraft) as indicated by Smith, Dryer, and Steinolfson (1984a, and references therein).

Most of our work has been done in the 2D and 2-1/2D area with the simulation of solar flare shocks, high-speed coronal hole streams, and combinations of these forms of solar activity. The latter work is described by Dryer and Smith (1986) and Dryer et al. (1986) who attempted to simulate the interplanetary response to more than 10 days of substantial activity on the Sun during STIP Interval VII (August 1979); the results were mixed. Figures 5, 6, 7, and 8 are representative of this study of a series of an eruptive prominence that was superimposed on a low-speed stream that was bracketed by higher-speed coronal hole streams. The figures, supported by the material in the figure captions, will give the interested reader the flavor for the simulated response in the ecliptic plane as well as at Earth (actually, ISEE-3) following a series of five solar flares, several of which

were followed by coronal mass ejections that were observed by P78-1's SOLWIND coronagraph. We gained a greater respect for the need to observe and analyze the solar and near-sun conditions needed to drive the model. A study of isolated solar flare shocks was made by Dryer et al. (1984) to demonstrate the model's use as a prediction module for prediction of solar wind "geoeffective" parameters,  $v$  and  $VB_z$ . A time series of one such example is shown in Figure 9 for three hypothetical locations of Earth relative to a single solar flare-generated shock wave. Improvements to the numerical algorithm are described by Han et al. (1984b). The influence of a pre-existing inhomogeneity in the solar wind on a flare-generated shock wave response in the interplanetary medium was studied by Gislason et al. (1984). The pre-existing inhomogeneity was found by simulating an equatorially-fluctuating heliospheric current sheet. A review of some of this work is given by Dryer (1984) who also discussed the pioneering aspects of our 3D work.

One of our studies (Smith, Dryer, and Han, 1985b) was directed to a question frequently asked by forecasters: given a series of solar events, such as flares and/or disappearing filaments, why do some of them have geophysical consequences and the others do not? Figure 10 illustrates a case of interplanetary pressure contours produced by a series of three individual pulses. The first one produces a forward shock wave that, presumably, would produce a SSC if Earth were located along any of their radial rays labeled 1-5. The second one, however, produces a shock that is strongly attenuated by its interactions with the disturbed flow in their wake of the first shock. Hence, in this scenario, the Earth (at any of the radial rays, 1-5) would not experience a SSC from the second pulse. Indeed, even a third pulse (see  $T=30$  hr. in Figure 10) produces a shock that is also strongly attenuated by the time of its arrival twenty hours later, particularly at 1 AU along ray paths 1 and 5.

Moving into the 3D area has highlighted the need for the supercomputer (CRAY-1 and/or CYBER 855/205). We have considered to date a computational domain from 18 solar radii (0.08 AU) to 1.1 AU in the helioradial direction and  $90^\circ$  in both the heliolongitudinal and heliolatitudinal directions, the latter being  $45^\circ$  on each side of the solar ecliptic plane. In keeping with our conservative approach, both scientifically and from a computer usage viewpoint, we have studied thus far a single shock whose central axis is located in the ecliptic plane. Figures 11, 12, and 13 show some of the results of this work that was performed on the CRAY-1. The outer limit for this simulation was 76 solar radii when these figures were prepared but has since been extended to 1.2 AU for this  $90^\circ \times 90^\circ$  solid angle, the lower half of which is symmetrical to the upper half. In this first case, we have as yet not utilized the capability of the southern hemispherical domain. The basic study is described in detail by Han et al. (1984a) and by Han, Wu, and Dryer (1986); shorter summaries are given by Dryer (1984) and by Dryer, Wu, and Han (1986) for the earlier and most recent results, respectively. A major new feature is the large-scale twisting of the IMF, a discovery that may be relevant to the "magnetic cloud" observations as well as to future forecasting algorithms.

### C. Coronal Mass Ejection Studies

Magnetic stresses have been proposed as one of the physical mechanisms that drive coronal loops, such as prominences, away from the Sun. Yeh (1985) has described these stresses in the more general context of hydromagnetic buoyancy. This paper provides the mathematical explanation in a detail not covered by earlier proponents of the so-called "magnetically-driven" coronal mass ejections (CMEs).

A complementary description of the CME phenomenon has been proposed by our group. We have suggested the use of MHD modeling as a tool for understanding the coronal response to an arbitrarily-prescribed input at the coronal base. Thus far, our models have been in the 2D and 2-1/2D mode only as part of our fundamental approach toward a 3D capability. Some of our early results (circa 1977-78) has been criticized by several experimenters. Our comments on their work are given by Dryer and Wu (1985) who pointed to the authors' bias in their choice of a limited, white-light, data sample and their neglect of our other numerical results in arriving at their conclusions about their observation/model study.

We have also continued our collaboration with a large group of observers of coronal transients for specific cases. Some of this work is given by Harrison et al. (1985) and Maxwell, Dryer, and McIntosh (1985). This work demonstrates the acceptance of our MHD modeling by a larger group of observers who have considered many diagnostics (radio, H-alpha, X-ray images, and in situ spacecraft data) in addition to white-light imagery.

### D. Technology Transfer

Work by Air Force Geophysical Laboratory scientists in the area of flare shocks' times-of-arrival at Earth has stimulated several possible extensions as proposed by Pinter and Dryer (1985a, b). These suggest that the Type IV diagnostic feature may be relevant to the piston-driven phase of a flare-generated shock. That is, the duration of this radio emission for the most energetic flares might be used in place of the soft X-ray duration. They also suggested that the integrated energy flux in the soft X-rays (say, 1-4Å) could be correlated with the flare energy output and the time for the shock to reach Earth. A summary result of this work on the average kinematic property of flare-generated shocks is given in Figure 14 with additional details provided in the figure caption.

A much more general study has been developed for the transfer of verified research into an operationally-oriented forecast strategy. This work by Dryer et al. (1985) is aimed toward development of a "solar-terrestrial environment model" as a key strategic element for an operational geomagnetic storm forecasting tool for the late 1990s when operational SIMPL and SAMSAT spacecraft could provide more solar corona and solar wind data to drive MHD models. The strategy is clearly 3D-oriented with photospheric, coronal, interplanetary, magnetospheric, ionospheric, thermospheric, and even neutral atmosphere models as individual modules placed end-to-end. An example computation is given from the photosphere to the auroral ionosphere (following a coronal mass ejection that is preceded by a shock) by Wu, Dryer, and Han

(1985). We have decided to call this global concept STEM-2000, with the hope that all elements will be in place by that date. This concept, or strategy, is outlined in Figure 15 (and its caption) in several block diagram formats, the upper half relative to the sun/interplanetary connections and the lower half relative to the interplanetary/magnetosphere/ionosphere connections. Clearly, a further connection (not shown here) should be made to the thermosphere and its coupling to the neutral atmosphere.

#### CONCLUDING REMARKS

This Final Report consists of a brief outline of the work described in 22 publications. The scope of work is suggested in four major categories: (a) basic solar wind studies, (b) MHD modeling, (c) coronal mass ejections, and (d) technology transfer that is oriented to the national goal of achieving long range predictions of geomagnetic storms.

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## FIGURE CAPTIONS

- Figure 1 Two-fluid, steady-state, solar wind solution with full equations (rather than Fourier heat flux expressions) for electron and proton thermal conductivities using higher order, closed system of equations starting from the Boltzmann equations. The streaming velocity, density (assumed:  $n = n_p = n_e$ ), temperature, and electron heat flux distributions are shown above as a function of heliocentric distance in solar radii. The lower plot shows the various contributions to the total energy flux. (Cuperman, Tzur, and Dryer, 1984).
- Figure 2 Typical homogeneous solar wind velocity profile (i.e., independent of heliolongitude) in the ecliptic plane. It is essential in MHD simulations research that the pre-disturbed condition (represented by velocity maps such as this one) be recovered after the effects of simulated disturbances move to distances beyond 1 AU. (Dryer et al., 1984)
- Figure 3 Temporal and spatial solar wind velocity dispersion produced by a strong solar flare-generated shock wave as viewed in the ecliptic plane. Figure 3(a) - 3(d) show the vector change, with maximum increases as indicated, as time increases from  $t = 20.2$  hr to  $t = 80.2$  hr. Note that the  $\Delta V$  decreases with time as the disturbance propagates beyond 1 AU.
- Figure 4 Fractional density changes in the ecliptic plane for the same case shown in Figure 3. The maximum initial shock velocity in the simulation is taken to be  $V_s = 3000$  km sec<sup>-1</sup> along the central (vertical) axis with a sinusoidal decrease to zero at  $\pm 12^\circ$  of this axis. This approximation to a non-spherical shock is applied near the sun (18 solar radii) for a period of 5400 sec to simulate a finite duration of flare energy output rate. The half-tone presentation demonstrates both compression and rarefaction, followed by a numerically-acceptable return to ambient conditions after the shocked disturbances passes out of the 1.2 AU circular computational domain.
- Figure 5 Representative solar wind response to a series of simulated coronal hole streams followed by an eruptive prominence during STIP Interval VII (August 1979). As in Figure 2, the vertical dimension represents the total solar wind velocity within a  $150^\circ$  range of ecliptic heliolongitudes. The time shown ( $T = 140.1$  hr) is elapsed time since  $T = 0$  hr as simulated in this 2-1/2D MHD model since 0 hr on 8 August 1979. (Dryer et al, 1986).
- Figure 6 Simulated unit vectors of the interplanetary magnetic field (IMF) at  $T = 160$  hr during the simulation of the compounded, multiple events in August 1979. (Dryer et al., 1986).

- Figure 7 Simulated solar wind velocity (center panel) at Earth's location for the multiple events in August 1979. The lowest panel shows the simulation for a nine-day period under the assumptions that there were no solar disturbances other than a series of the three corotating solar wind streams, two moderately-high ones that led and followed a lower speed stream. The upper panel shows the ISEE-3 observations.
- Figure 8 Simulated IMF magnitude (center panel) at Earth's location for the multiple events in August 1979 (see, also, Figure 7). The ISEE-3 observations, when compared to the simulated ones demonstrate the need for improved observational requirements for driving the model close to the sun as well as improvements to the physics and numerical procedures (grid size, for example) for the model.
- Figure 9 Illustration of the temporal series of several proposed indices ( $\epsilon$  and  $VB_z$  [or  $VB_z$ ]) at 1 AU. Three possible locations of Earth relative to a representative, single, solar-flare-generated shock disturbance are shown in this example.
- Figure 10 Total pressure contours (logarithm of the thermal plus magnetic pressures) in the ecliptic plane following a series of three separate assumed solar disturbances. The responses detected by hypothetical observers along the heliocentric ray paths labeled 1-5 are all different. They depend upon the spatial locations and strengths of each individual solar pulse. Strong attenuation can occur; for example, at  $15 < T < 30$  hr, the interplanetary MHD shock wave from the second pulse is nearly completely dissipated by its interactions with the reverse MHD shock from the first pulse. (Z. Smith, Dryer, and Han, 1985b)
- Figure 11 Three-dimensional deformation of the interplanetary magnetic field (IMF) caused by a single solar flare-generated shock wave. Left side of the figure shows the ecliptic plane projections of the IMF; the MHD shock at times of 5 and 10 hr can be discerned where the Archimedian spiral is initially distorted. The leading shock has moved outside of the outer limit, 76 solar radii, of this display at 20 hr and has nearly returned to its original spiral at 30 hr. Right side of the figure shows a meridional "cut" at latitudes from  $\pm 45$  through the center of the left-side display. The outward, bubble-like deformations of the IMF is caused by a large amplitude nonlinear Alfvén wave behind the leading fast mode MHD shock. (Han et al., 1984a; Dryer, Wu, and Han, 1986)
- Figure 12 Three-dimensional model simulation of changes in the solar wind at 32 solar radii following a solar-flare shock wave that was generated 5 hrs. earlier. The top two panels show the near-doubling of the radial solar wind velocity within a  $90^\circ$  longitudinal sector. The center panels show the transverse components of the disturbed solar wind velocity. The lower panels show the magnitudes of the IMF. (Han et al., 1984a; Dryer, Wu, and Han, 1986).

Figure 13 Three-dimensional model simulation of the plasma density changes at several heliocentric radial locations and at several times following the outward progression of a single solar flare-generated shock wave. Development of a secondary, annular density maximum (the first being at the MHD forward shock itself) is clearly seen. It is believed that this internal maximum represents development of a MHD reverse shock. (Han et al., 1984a; Dryer, Wu, and Han, 1986).

Figure 14 Empirically-derived average characteristic velocity profile of flare-generated interplanetary shock waves as based on a sample of 39 cases. This presentation, based on a model developed at the Air Force Geophysics Laboratory, approximates an initially constant velocity piston-driven shock, followed by a decelerating "blast" shock that is convected by the background solar wind plasma. In the average case, a shock is driven at its Type II-determined velocity of  $1560 \text{ km sec}^{-1}$  to a distance of 0.12 AU during a time suggested by the duration of the soft X-ray or Type IV event. Following this "flare duration" or "piston driving time", the shock decelerates to  $540 \text{ km sec}^{-1}$  (at 0.837 AU) convected by an average background solar wind velocity of  $300 \text{ km sec}^{-1}$ . The blast wave's average velocity, then, is  $890 \text{ km sec}^{-1}$  from the end of its driven phase. This average characteristic is based on the 39 cases that had a wide range of shock shapes and flare locations relative to Earth. (Pinter and Dryer, 1985b).

Figure 15 Block diagram illustrating a physically-based strategy for the predictions of geomagnetic storms: whether and when it will occur, how long it will last, and how severe it will be. The upper half of the figure is limited to the solar and interplanetary portion of the physical linkage: real time observations from the SOON/RSTN sites plus satellites (GOES-NEXT, SAMSAT) would provide input parameters that will drive MHD models of the photospheric, chromospheric, and coronal dynamics under both quiet and active conditions. The outputs of these models then feed into MHD solar wind codes that output basic geoeffective physical parameters such as dynamic pressure, Poynting power flux, and cross tail electric field from the solar wind velocity, density, and IMF parameters. The lower half of the figure indicates the need for "ISEE-3 type" of upwind real-time monitoring by a Synoptic Interplanetary Monitoring Platform (SIMPL) which would be required for updating the MHD solar wind "interplanetary global circulations model." The solar wind parameters, thus determined, are used via statistical studies incorporated into a kinematic code to determine predictions of the polar cap and auroral zone boundaries and, if desired, the geomagnetic and auroral electrojet indices as well as the ionospheric current and electrical conductivity distributions. Meanwhile, real-time ground-based magnetometer variations, ionospheric observations, AF/DMSP and NOAA/TIROS data are used as inputs for additional models of magnetosphere-ionosphere coupling processes (KRM, "Polar") to determine Joule heat, electron density profiles, and probable locations for satellite drag increases. (Dryer, et al., 1985).

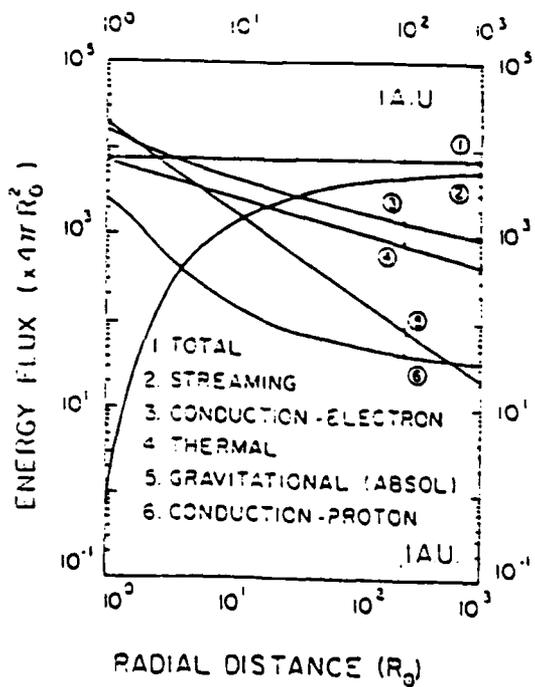
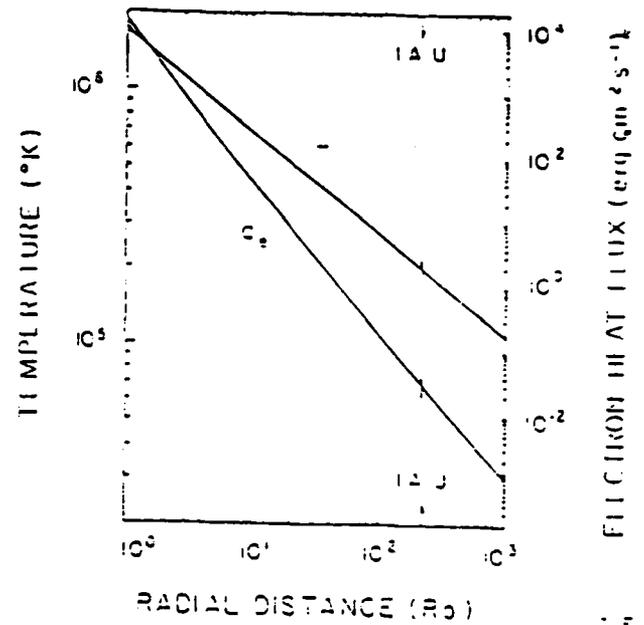
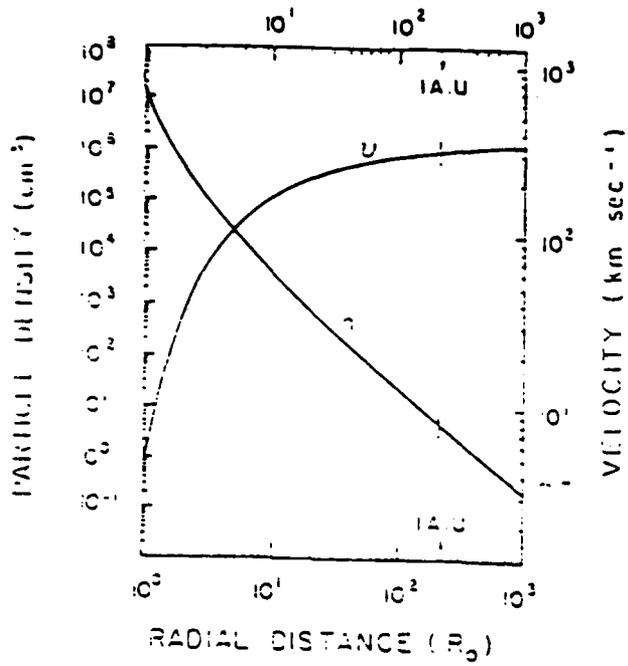


Figure 1.

T=0.0 HOURS  
VELOCITY SURFACE

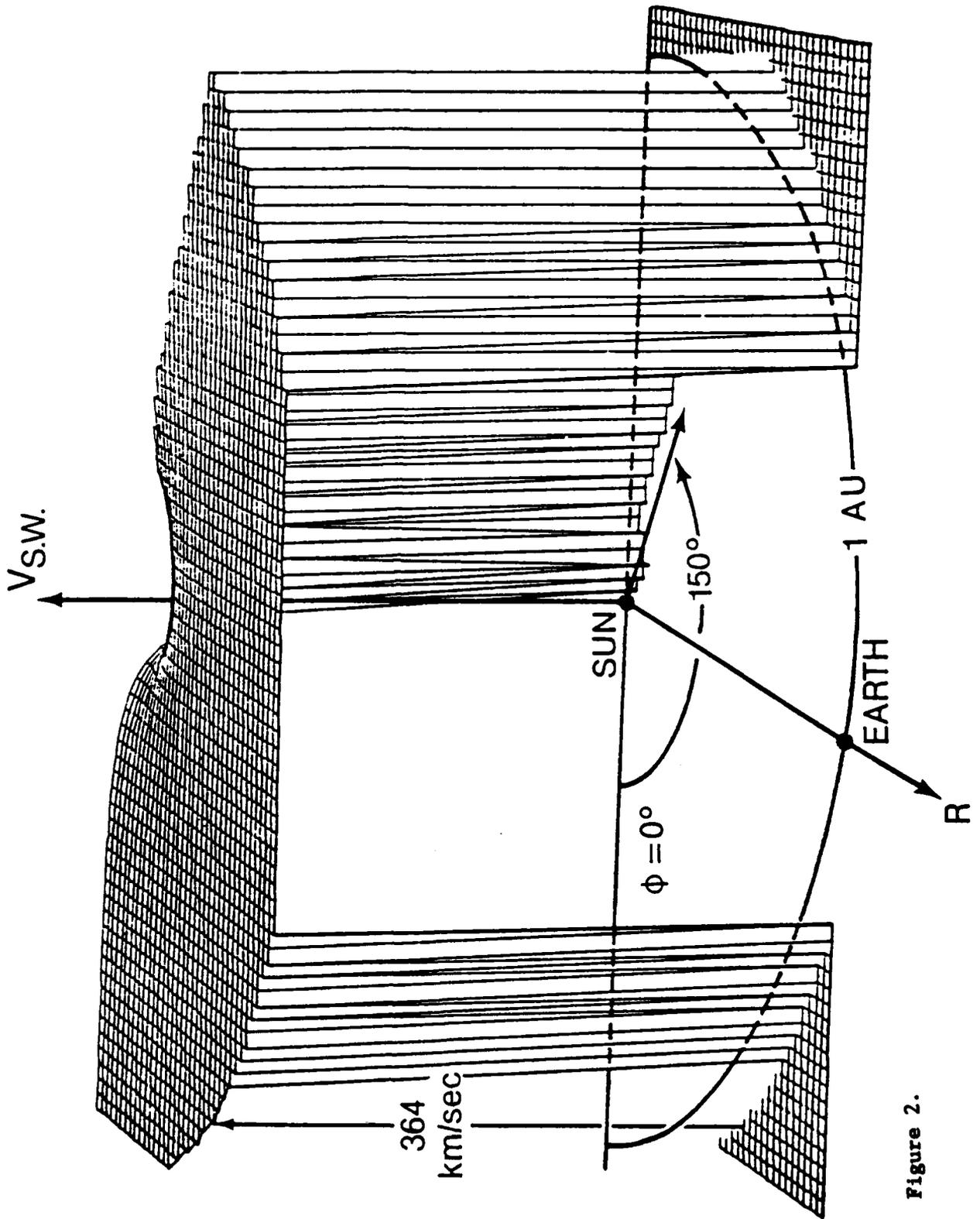


Figure 2.

VELOCITY DISPERSION

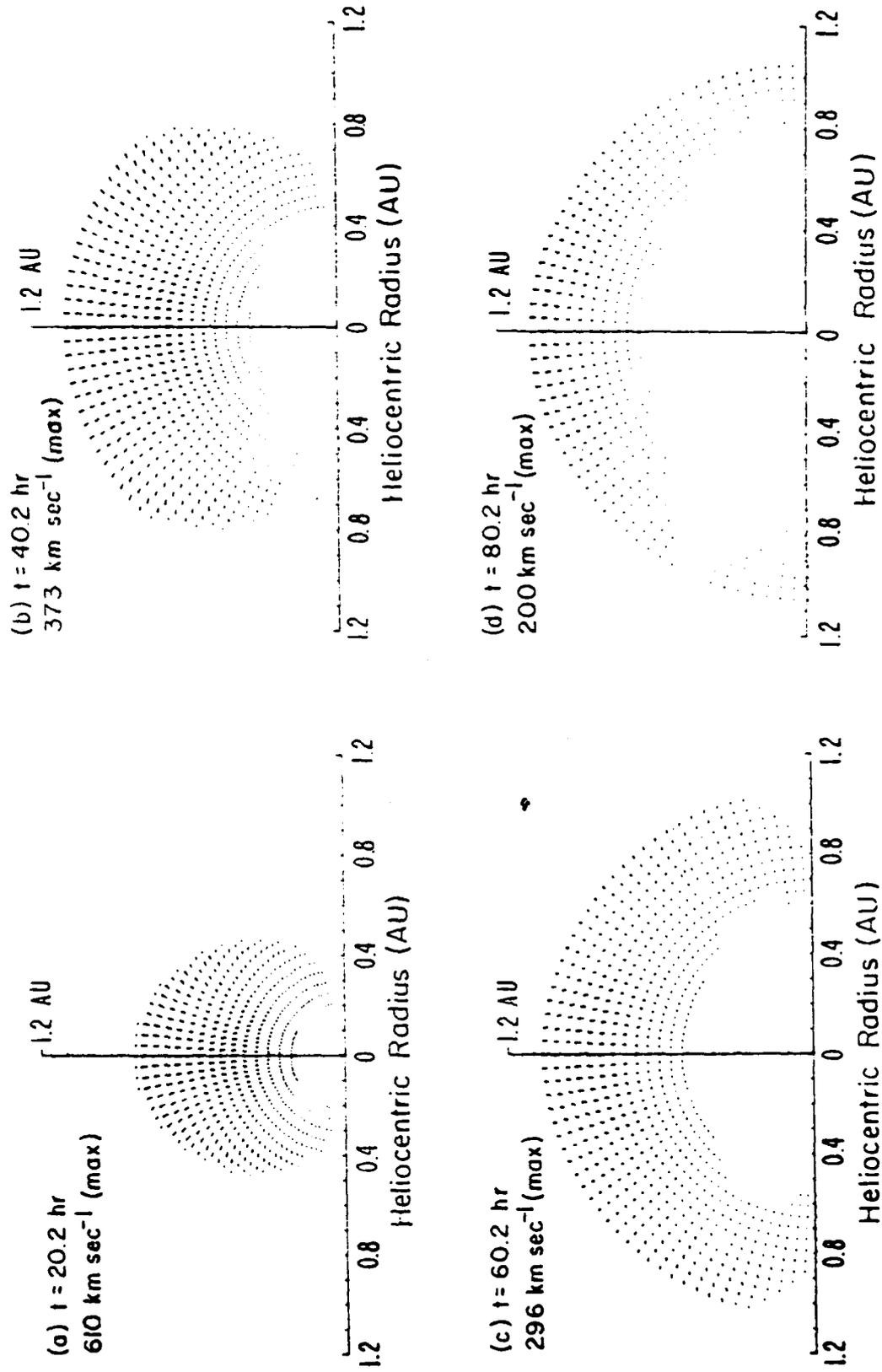


Figure 3.

FRACTIONAL DENSITY CHANGE  $\left( \frac{n - n_0}{n_0} \right)$

$V_S = 3000 \text{ km sec}^{-1}$ ,  $\Delta t = 5400 \text{ sec}$

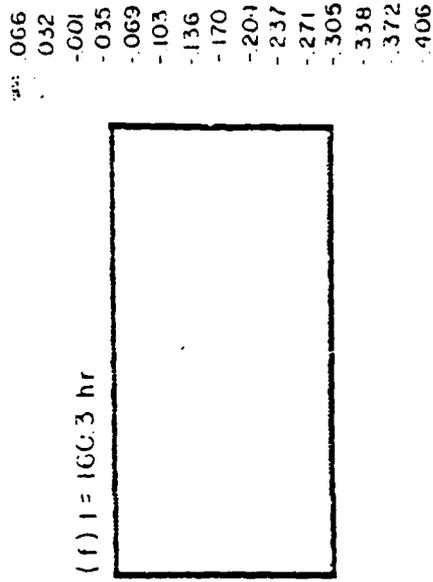
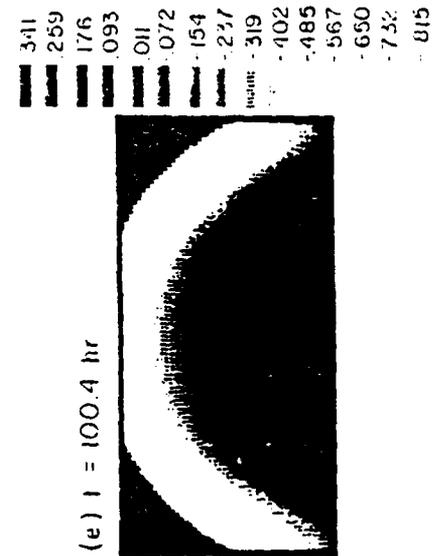
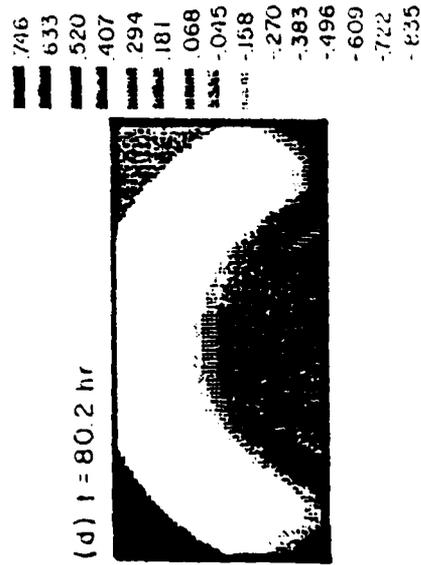
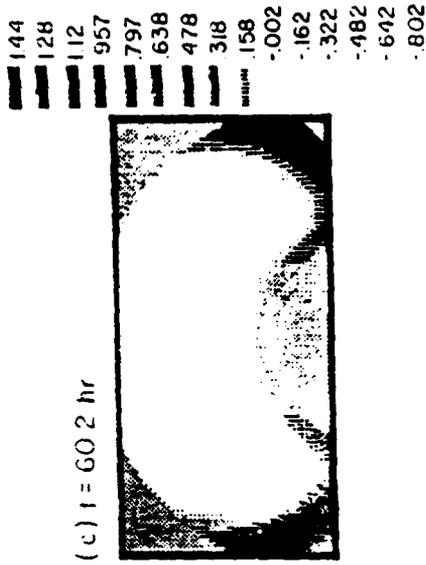
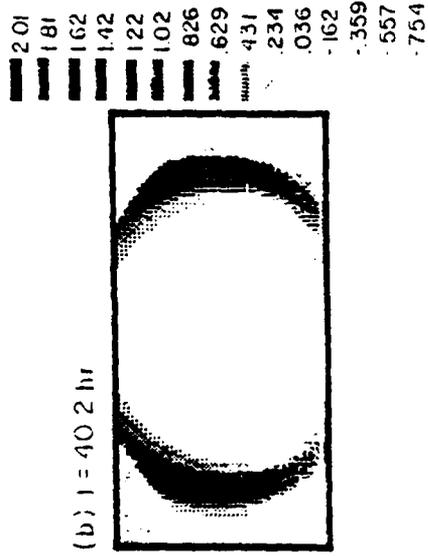
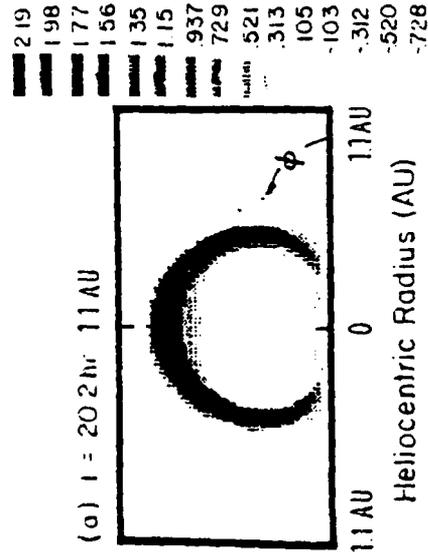


Figure 4.

# T=140.1 HOURS VELOCITY SURFACE

Attenuation of MHD fast  
reverse wave caused by  
eruptive prominence on  
10 August 1979.

Attenuation of MHD fast forward  
wave produced by eruptive  
prominence on 10 August 1979.

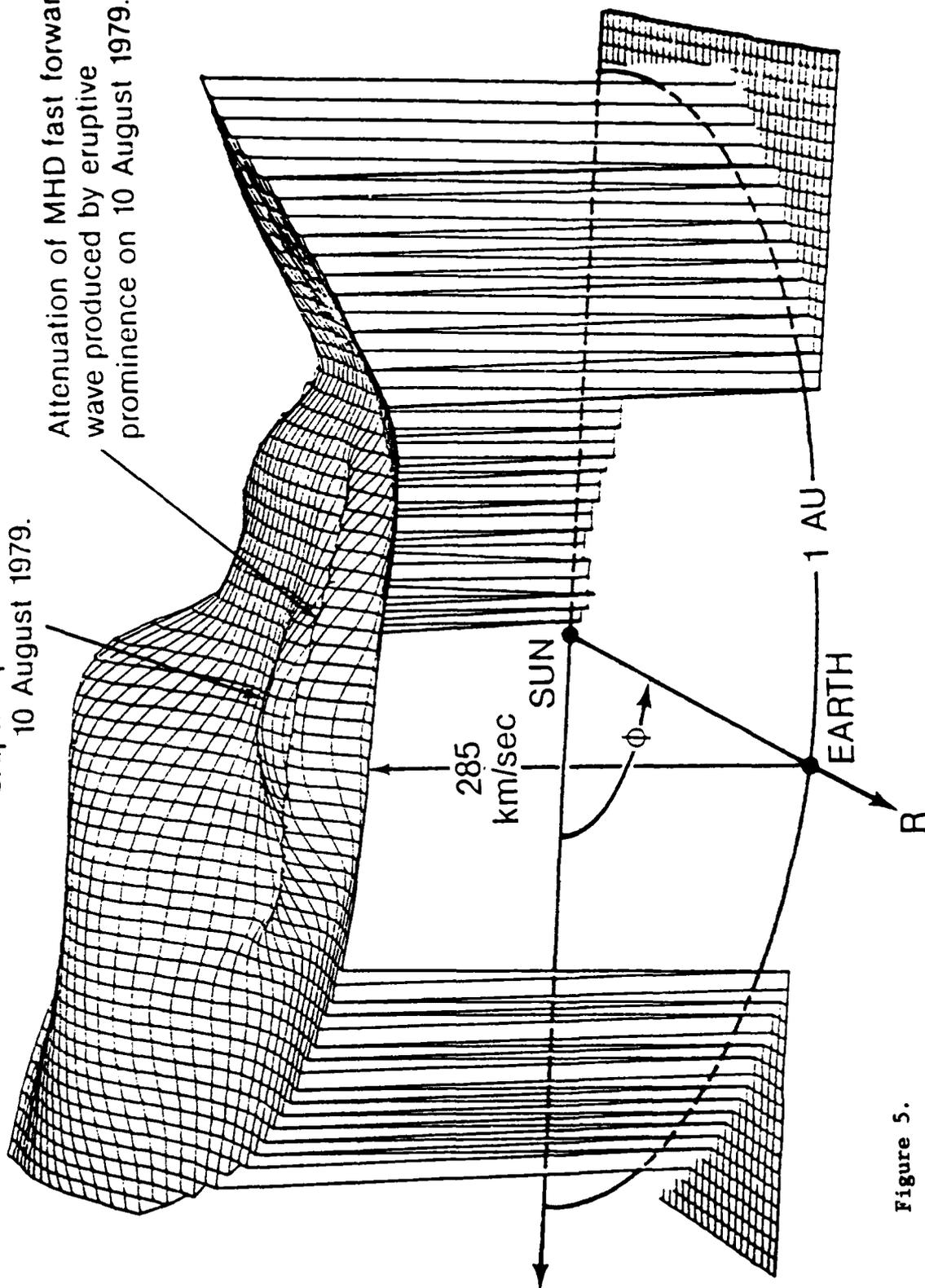


Figure 5.

IMF Unit Vectors  
 $t=160$  HR

Moderate compression  
caused by eruptive  
prominence of 10 August  
1979... followed by  
rarefaction and  
IMF rotation

Sector Boundary

1.2 AU

1.0

1.0 AU

SUN

0.2

0.4

0.6

0.8

1.0

AU

Shock from 14 August 1979  
solar flare and coronal  
mass ejection

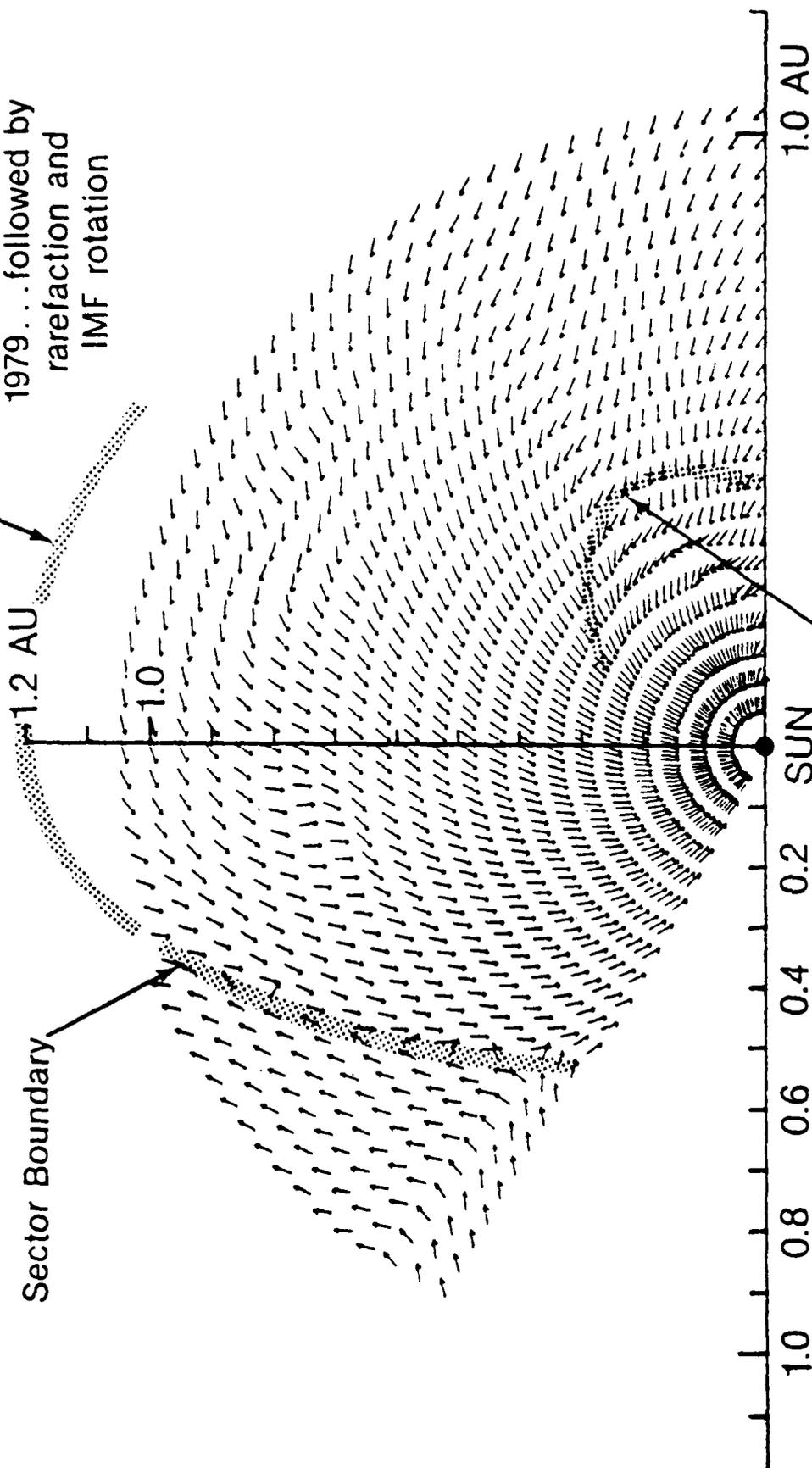


Figure 6.

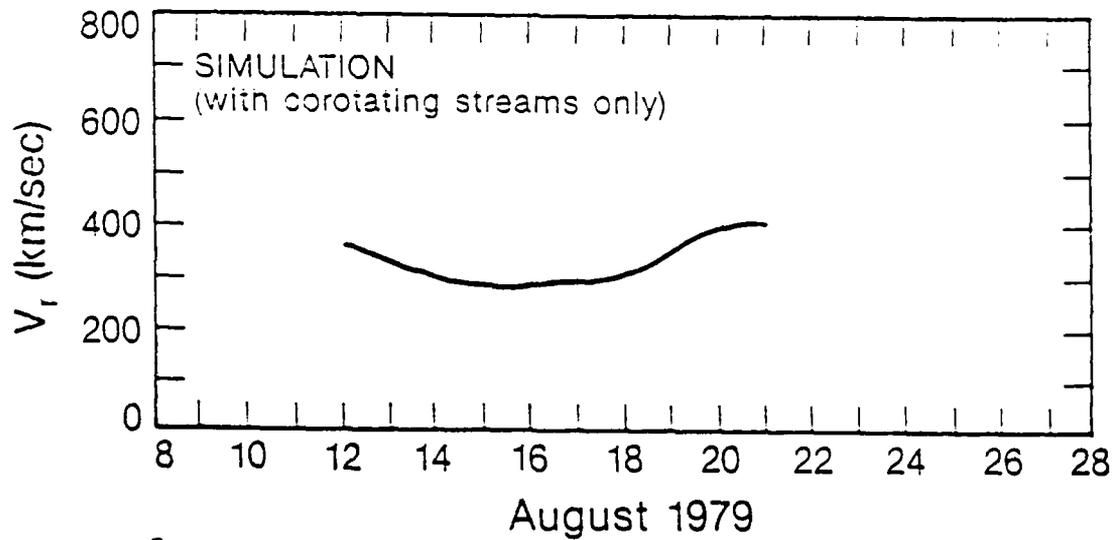
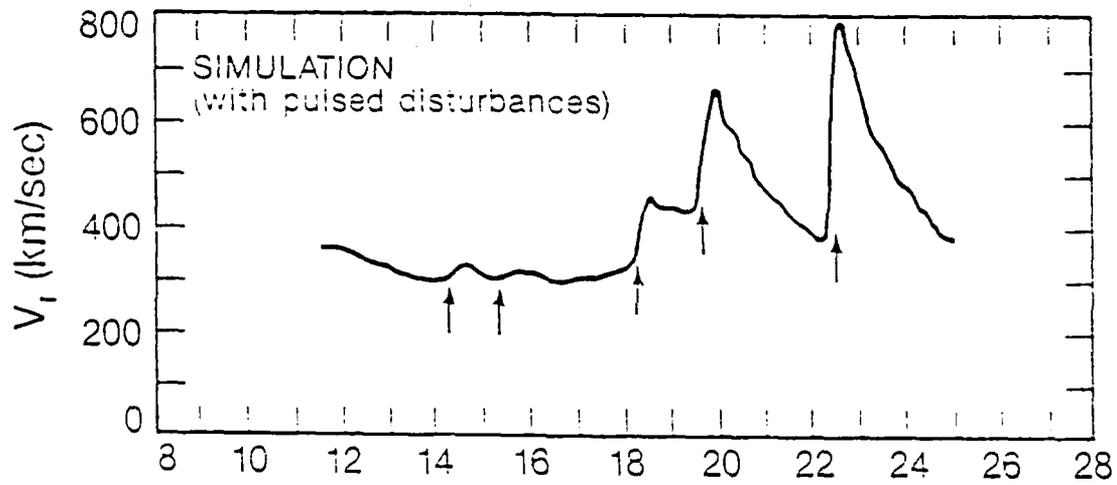
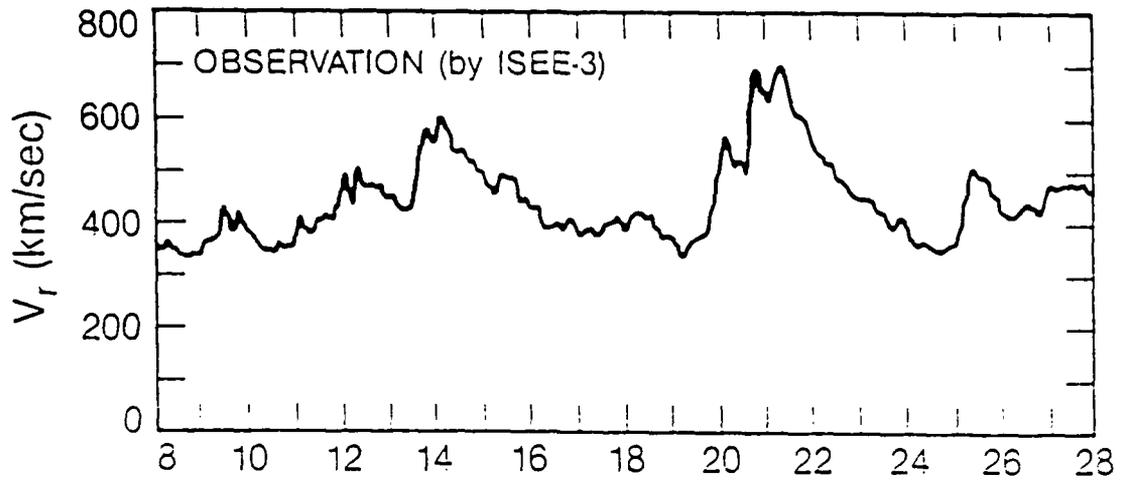


Figure 7.

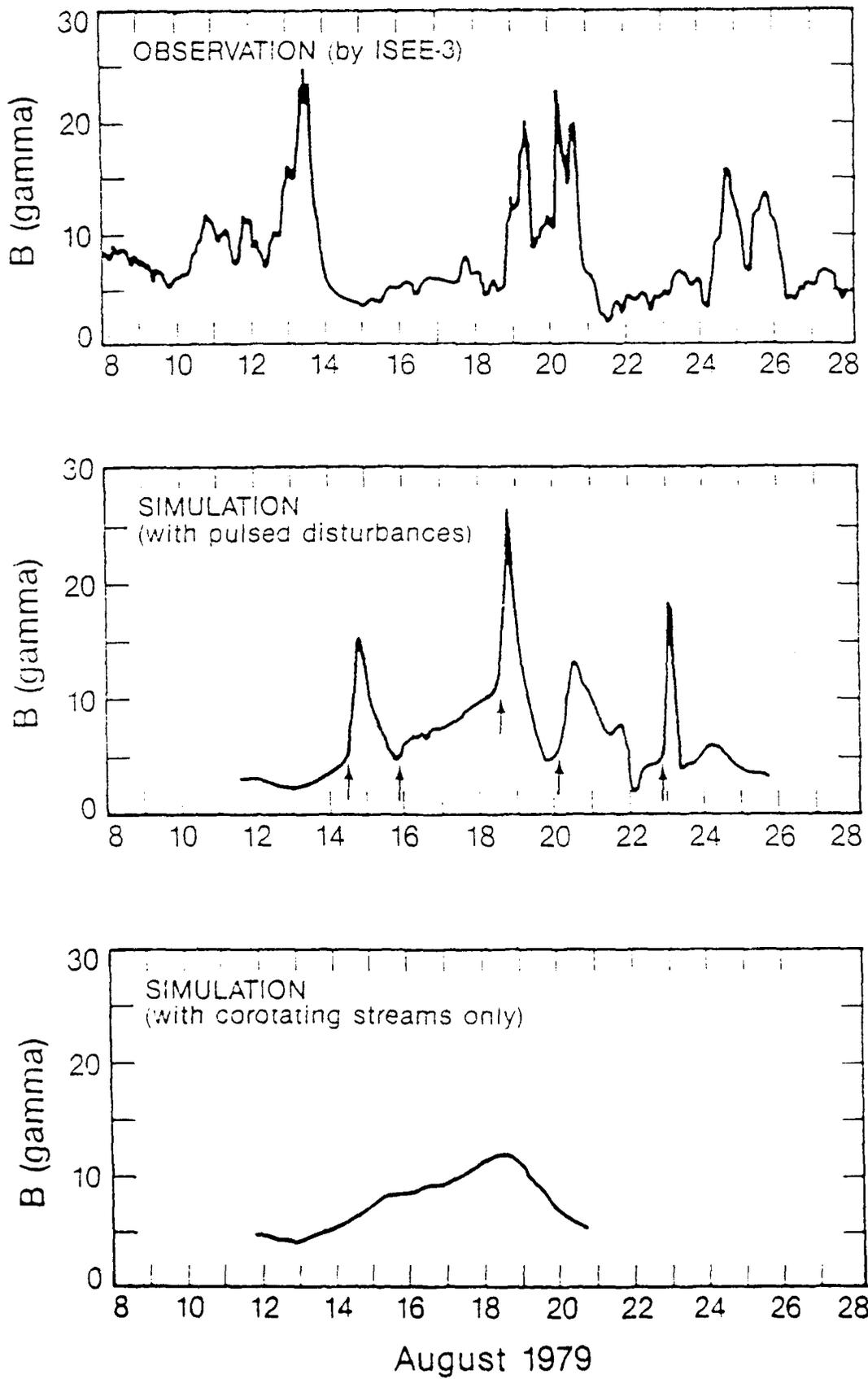


Figure 8.

# GEOEFFECTIVE SOLAR WIND PARAMETERS AT 1.0 AU

- Central Meridian Direction
- - - 30° W of C.M.
- · - 75° W of C.M.

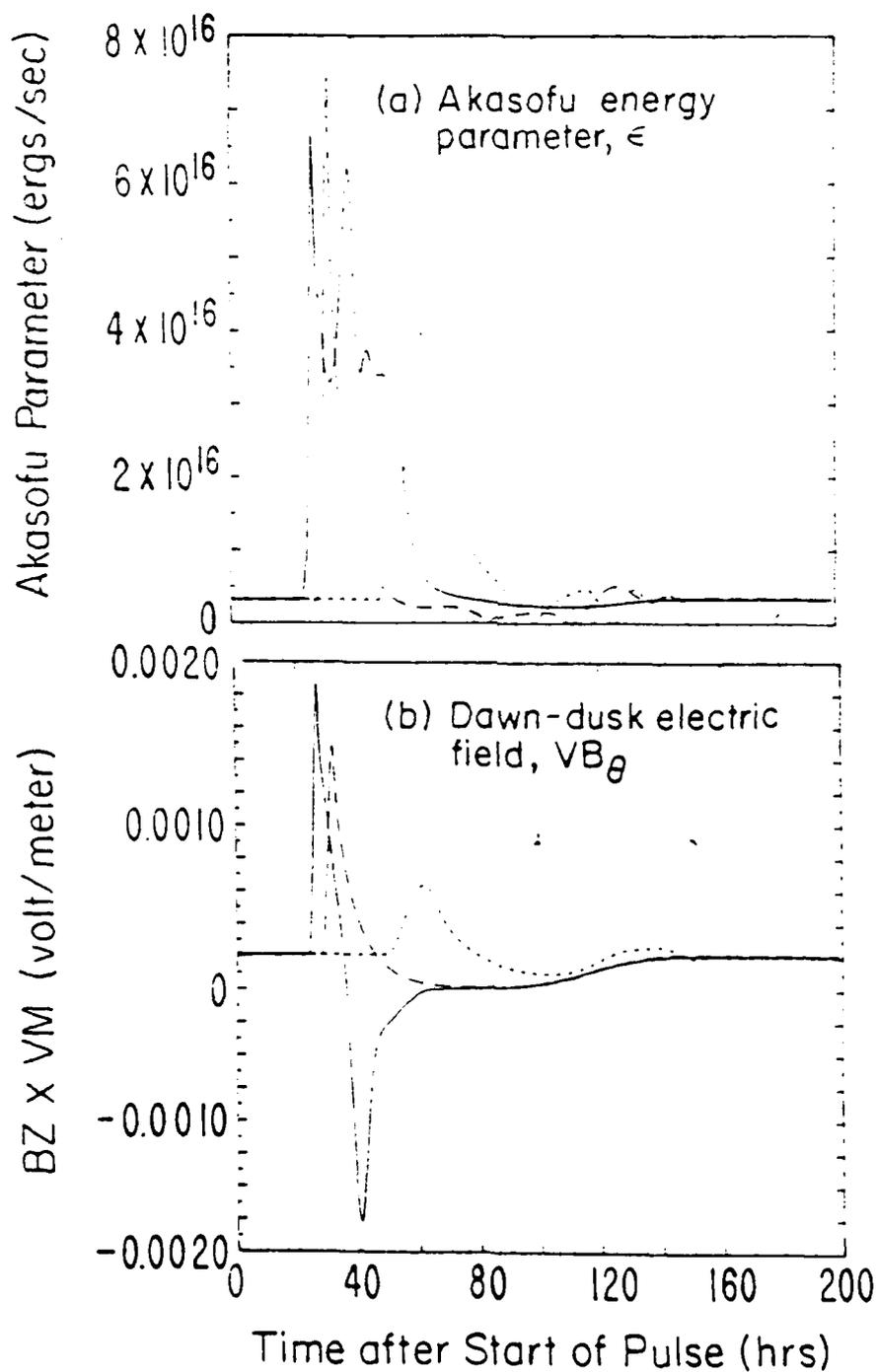


Figure 9.

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permit fully legible reproduction

### PRESSURE CONTOURS

Showing evolution of the three pulses initiated at  $T=0$ , 10 and 25 hours

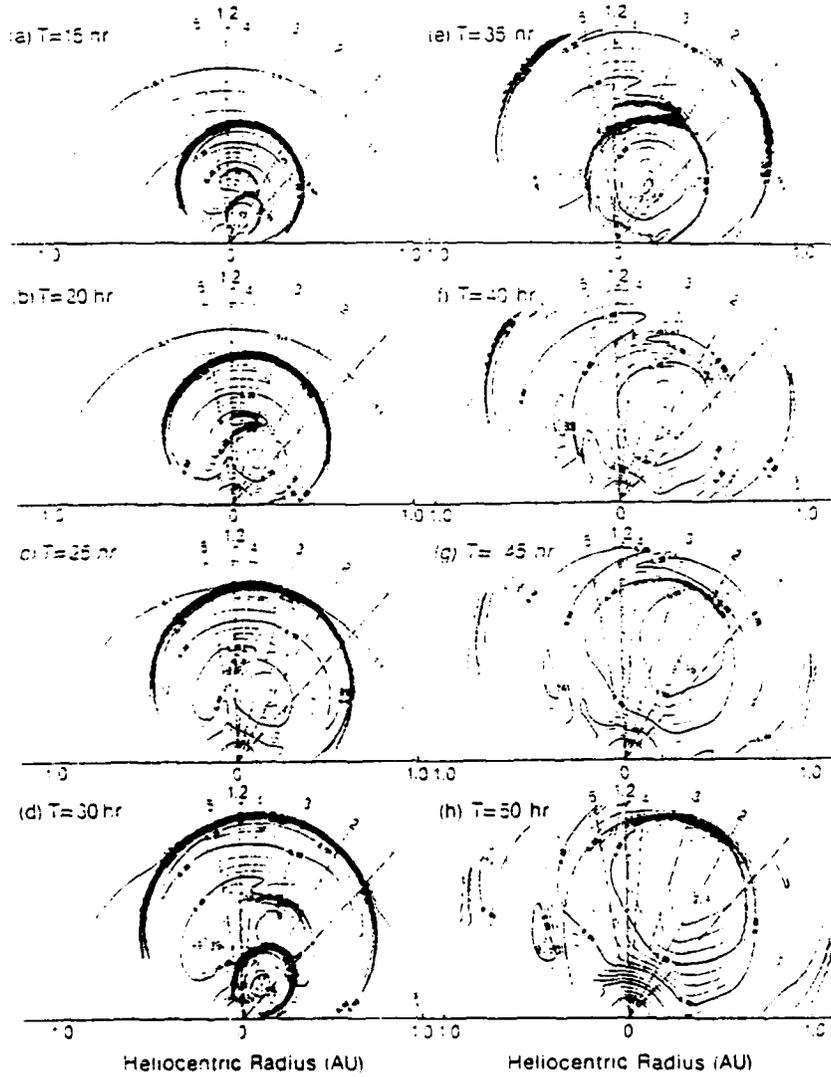


Figure 10.

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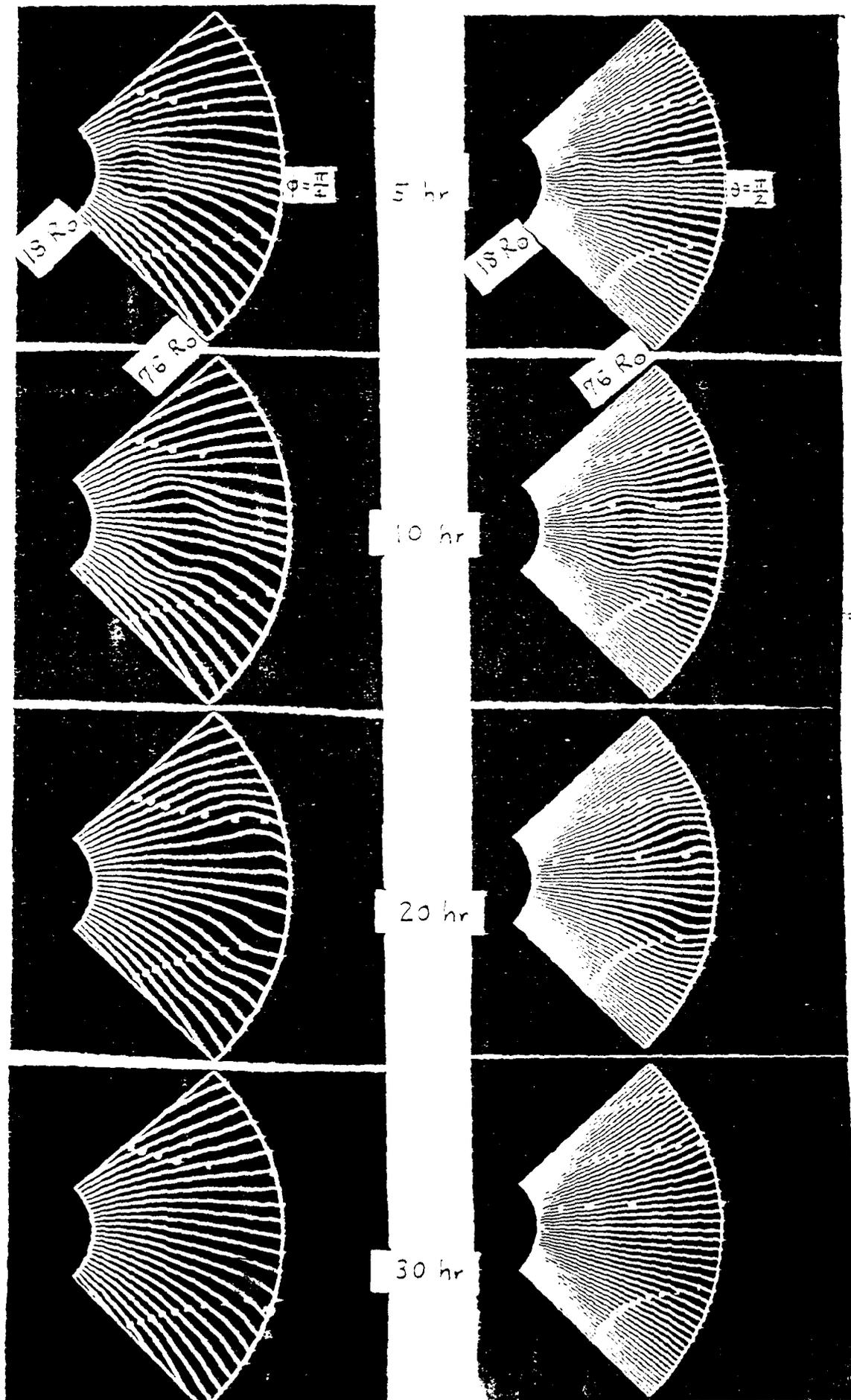
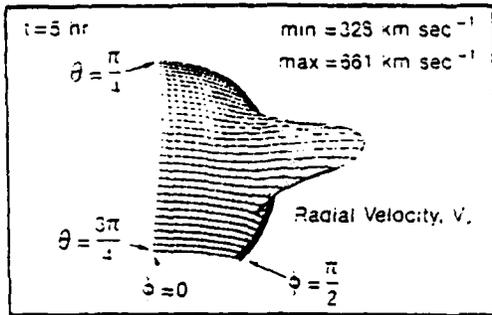


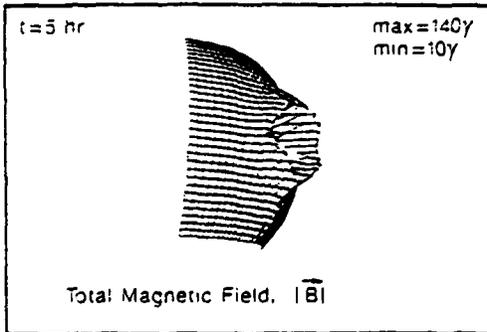
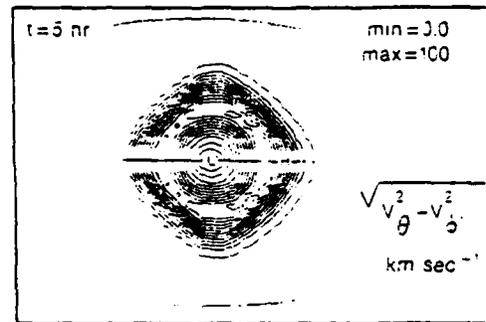
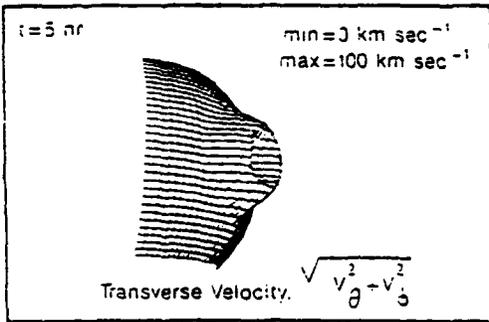
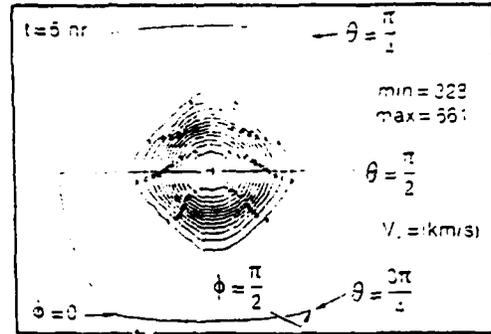
Figure 11.

Velocity and IMF at  $32R_{\odot}$ ,  $t=5$  hr.



A = 328 km sec<sup>-1</sup>  
 D = 399  
 G = 470  
 J = 542  
 M = 613  
 O = 661

Contours of Velocity and IMF at  $32R_{\odot}$ ,  $t=5$  hr.



A = 10 $\gamma$   
 C = 30 $\gamma$   
 K = 110 $\gamma$   
 L = 120 $\gamma$   
 N = 140 $\gamma$

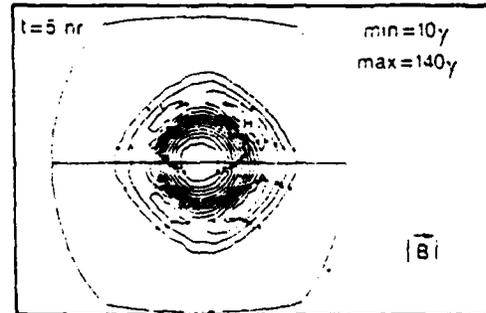


Figure 12.

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Density Contours on  $\phi - \theta$  Surfaces at Several Radial Locations and Times  
 $V_S = 1000 \text{ km sec}^{-1}$

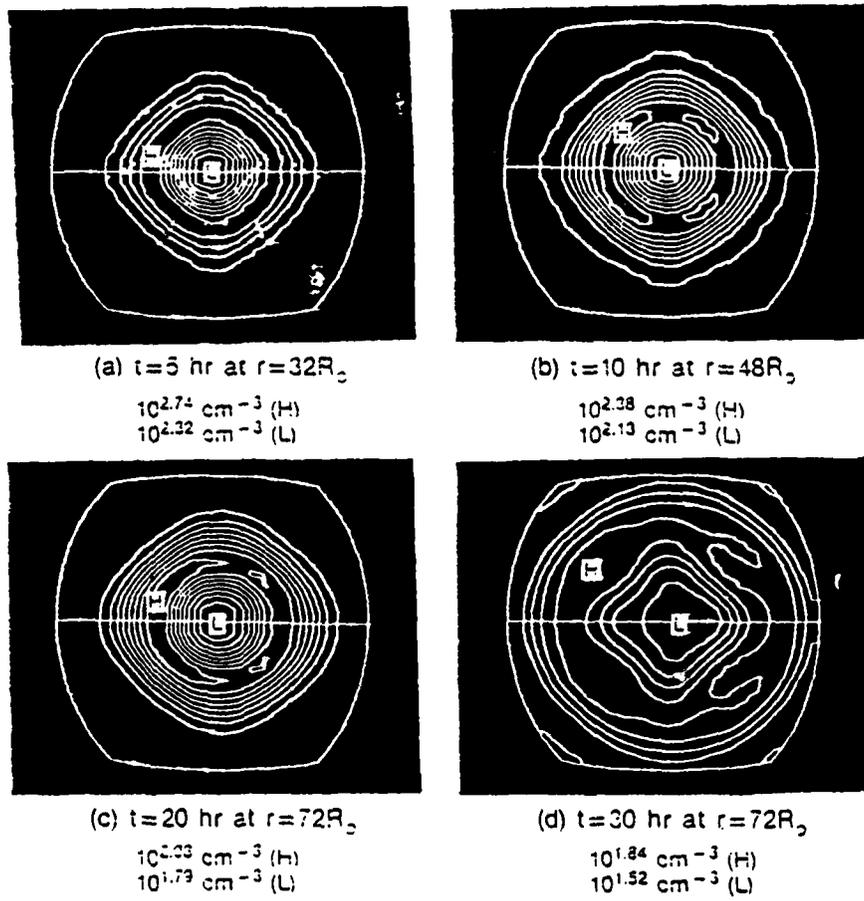


Figure 13.

# Average Characteristic of Flare-generated Interplanetary Shock Waves

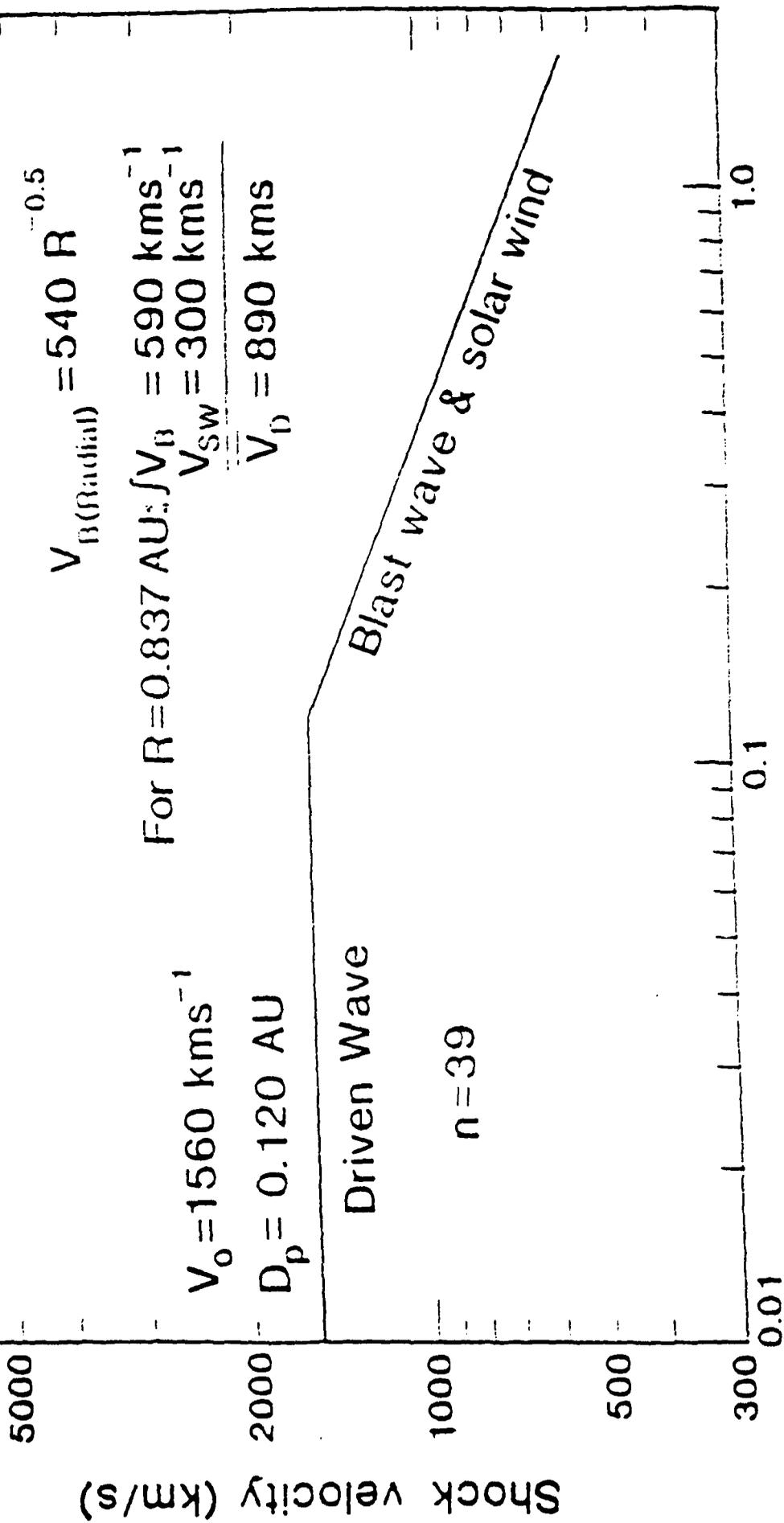
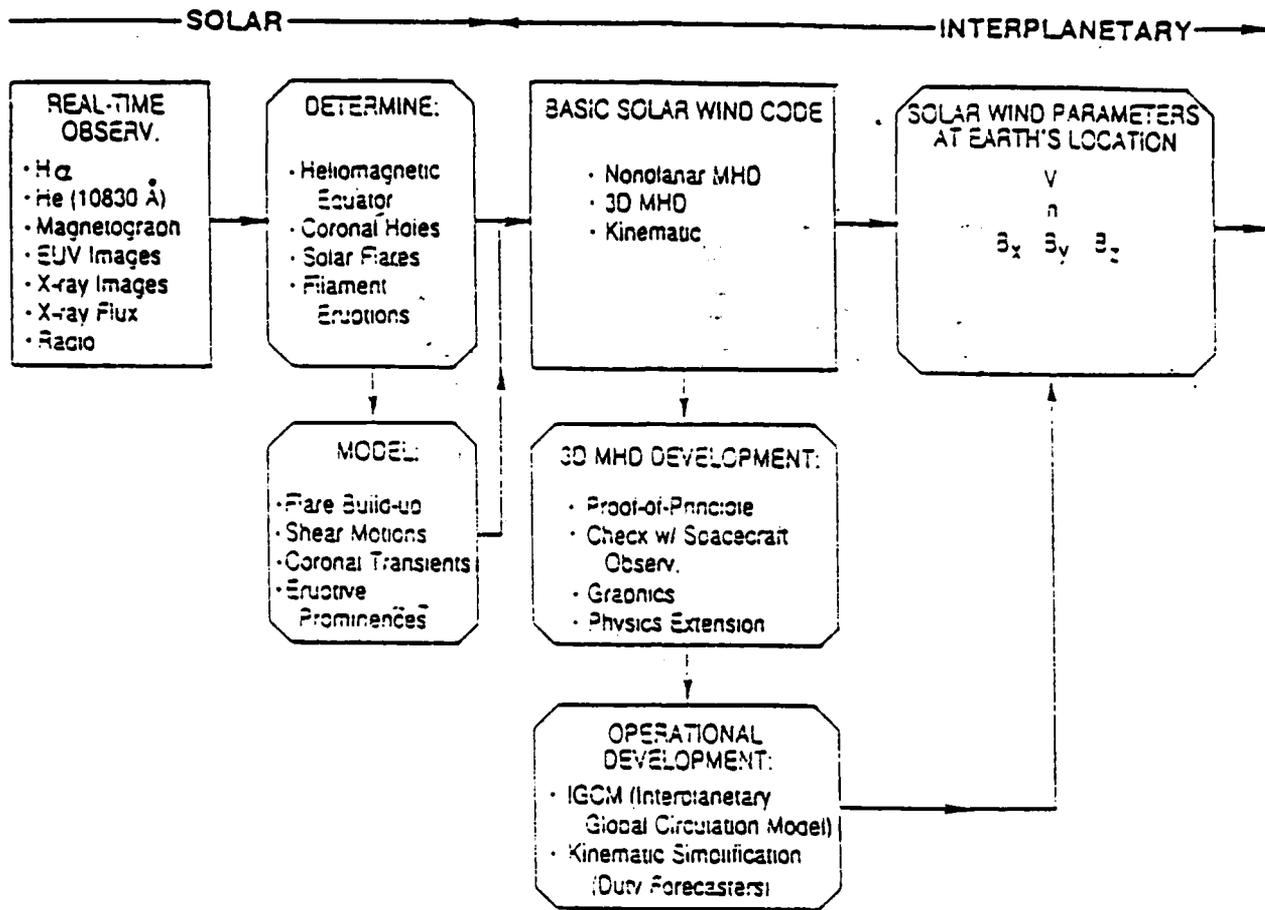


Figure 14.

# STRATEGY FOR GEOMAGNETIC STORM PREDICTION — I



# STRATEGY FOR GEOMAGNETIC STORM PREDICTION—II

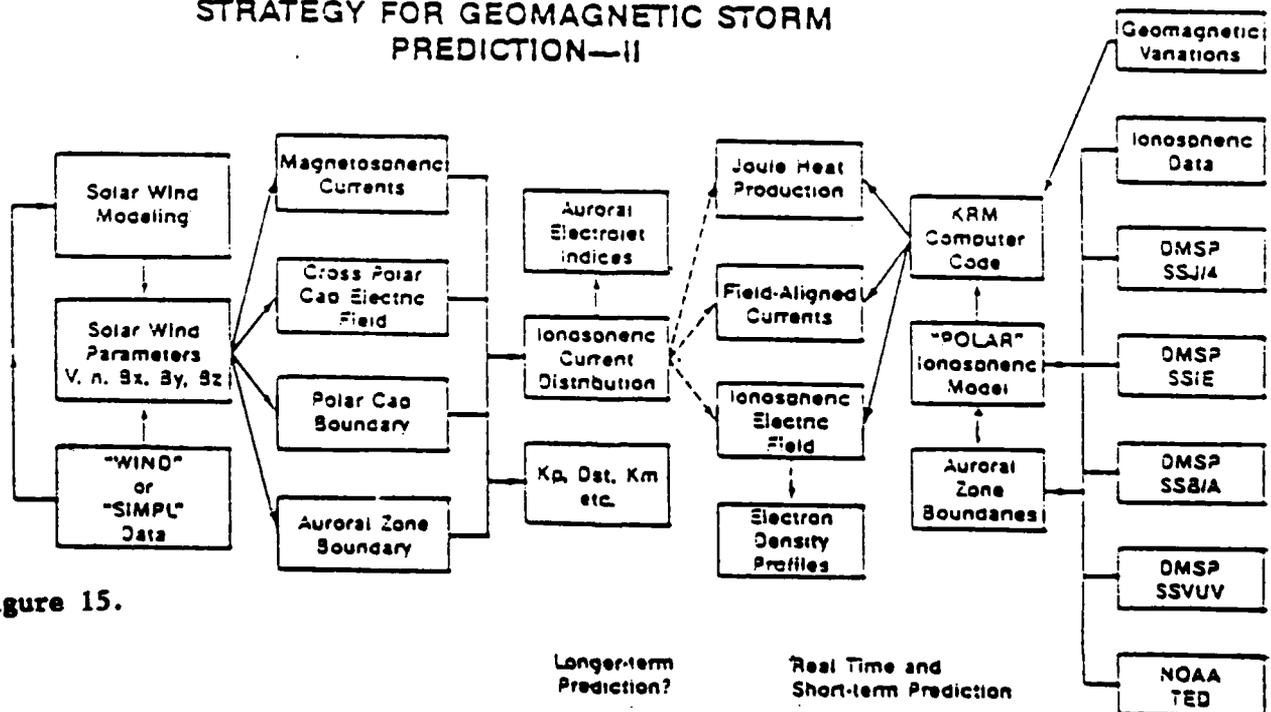


Figure 15.

END

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