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SIMULATION OF JANUARY 1-7, 1978 EVENTS

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ABSTRACT

The solar wind disturbances during January 1-7, 1978 is reconstructed by a modeling method. First of all, the interplanetary IMF background pattern, including a co-rotating shock, is reproduced using the Stanford source surface map. Then, two solar flares with their onset times on January 1, 0717 at S17°E10° and 2147 UT S17°E32°, respectively, are selected to generate two interplanetary transient shocks. It is shown that these two shocks interacted with the corotating shock, resulting in a series of interplanetary events observed by four spacecraft, Helios 1 and 2, IMP-8, and Voyager 2. In particular, our simulation results show that these three shock waves interact and coalesce in interplanetary space such that Helios 2 and Voyager 2 observed only one shock and Helios 1 and IMP-8 observed two shocks. All shocks observed by the four spacecraft, except the corotating shock at Helios 1, are either a transient shock or a shock which is formed from coalescing of the transient shocks with the corotating shock. Our method is useful in reconstructing a very complicated chain of interplanetary events observed by a number of spacecraft.

(NASA-CR-181069) SIMULATION OF JANUARY 1-7, 1978 EVENTS (National Central Univ.) 21 p
Avail: NTIS HC A02/MF A01 CSCL 03B

N87-25261

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I. INTRODUCTION

The shape and nature of interplanetary shocks are usually studied using multiple spacecraft observations in order to understand their propagation and origin. During a particular time interval, there may be more than one shock event in interplanetary space. Therefore, it is not a trival matter to identify a given shock event in the data from several spacecraft. In addition to this difficult task, it has been observed that one shock event observed at one spacecraft is not necessarily observed by another spacecraft at a nearby location in interplanetary space. This makes the identification of shock events even more difficult.

Since the multiple spacecraft observations can only determine the macroscopic configuration of the shock event, a detailed description of the propagation of the interplanetary shock wave has to rely on a numerical simulation method. A solar flare and/or a coronal mass ejection (CME) can generate interplanetary transient shocks (Sheeley et al., 1983), while high speed streams from coronal holes can generate corotating shocks (Smith and Wolfe, 1976). Thus, we must examine carefully how effects of a series of solar events for a given period are propagated into interplanetary space by adopting a numerical method.

Simulations from the simple one-dimensional gas dynamics to the sophisticated three-dimensional MHD have been used to simulate the interplanetary shocks (Hundhausen and Gentry, 1969; Dryer, 1975; Hakamada and Akasofu, 1982; Wu et al., 1983). The prediction of such simulations for the configuration and propagation of interplanetary disturbances show reasonable agreement with observations. However, so far even the most sophisticated three-dimensional MHD simulation models have not taken into account all available nonuniform properties of the solar wind. Thus, there are some important observational facts which cannot be predicted from the numerical studies at the present time. Thus, in adopting the numerical methods, we must be cautious about this limitation.

In this study, interplanetary disturbances and shock waves during the period of January 1-7, 1978 will be analyzed using the solar observations, the arrival time of the shocks at each spacecraft, the plasma and magnetic field data observed by Helios 1 and 2, IMP-8 and Voyager 2, as well as a numerical simulation method developed by Hakamada and Akasofu (1981, 1982). Their method has recently been improved by incorporating MHD solutions (Sun et al., 1985; Olmsted and Akasofu, 1983). In this paper, we utilize the improved method.

Burlaga et al. (1981) have already analyzed the magnetic field and plasma data from 5 spacecraft (Helios 1 and 2, IMP-8 and Voyager 1 and 2) for the period of January 1-7, 1978 and concluded that only one interplanetary shock event followed by a magnetic cloud is observed by all 5 spacecraft. As we describe in detail in the following, a close examination of the solar wind data has led us to a different conclusion. Thus, in order to confirm our conclusion, we reconstruct the chain of events using our numerical simulation method. Indeed, our results show that there were three interplanetary events: two flare- (or solar activity) associated shocks and one corotating shock. They interact with each other during this period, resulting in a sequence of interplanetary events observed by Helios 1 and 2, IMP-8 and Voyager 2.

II. OBSERVATIONS AND INTERPRETATIONS OF THE JANUARY 1-7, 1978 EVENTS

1. The positions of the spacecraft are shown in Figure 1. Helios 1 was near the Voyager-Sun line at 0.9 AU; Helios 2 and IMP-8 were close to one another near 1 AU; and Voyager 2 was at 2 AU and was 30° east of the earth.

The arrival time of the shocks and the locations of the spacecraft are listed in Table I.

Table I.

Shock Events Observed by Five Spacecraft

S/C	Shock Date	Time	Distance	SSE* (Deg)
Helios 1	1978, Jan. 2	01:00	0.94	-39.2
**Helios 1	1978, Jan. 3	08:38	0.95	-39.6
Helios 2	1978, Jan. 3	14:50	0.94	- 5.3
IMP-8	1978, Jan. 3	20:41	1.00	0.0
**IMP-8	1978, Jan. 5	16:00	1.00	0.0
Voyager 2	1978, Jan. 6	01:34	2.00	-30.0

* SSE - Spacecraft-Sun-Earth Angle

**Transient Shock

These shocks were selected by Burlaga et al. (1981) from the high resolution plasma and magnetic field data given in Burlaga et al. (1981) except the transient shock of IMP-8 in Table I was selected by Borrini et al. (1982) also using the high resolution plasma and magnetic field data and have been shown to satisfy the Rankine-Hugoniot jump relations. In Figure 2, the hourly averages of the plasma data are shown. The stream structures of the solar wind can easily be seen from the solar wind speed V_P. All five spacecraft have observed a stream behind an interplanetary shock. The shocks are marked with an arrow denoted by a S. The plasma parameters V_P, N_P and T_P of each of these shocks show a signature which is consistent with a shock. This figure shows that all spacecraft observed only one shock except Helios 1 and IMP-8 which observed two interplanetary shocks.

The shocks associated with the high speed stream can be identified in all five spacecraft observations. However, the second shock found in the data of Helios 1 and IMP-8 should be classified as a transient shock. This shock was not observed at spacecraft Helios 2, and Voyager 2. Five possible flares that could generate this shock are listed in Table II.

Table II.

Probable Flares (1978)

Flare Date	Time (UT)	Location	Importance
Jan. 1	0554	S20° E34°	1N
Jan. 1	0727	S17° E10°	1N
Jan. 1	0920	S17° E37°	1N
Jan. 1	2145	S21° E06°	2N
Jan. 1	2147	S19° E28°	SN

On January 1, 1978, the sun was very active. In addition to these five solar flares, solar radio bursts of Type II and IV were observed in the period 21:52 - 22:11 UT. There were also simultaneous flares at the adjacent region to the site of the 21:47 UT flare.

The first shock event can be identified as a corotating shock because it was associated with a corotating stream. Indeed, this corotating stream is also observed by Helios 2 in the previous and the following solar rotations as shown in Figure 3. Thus, the shock associated with this stream is a corotating shock. The travel time τ_{AB} between spacecraft A and B of a corotating shock can be estimated as:

$$\tau_{AB} = \frac{\Delta\phi}{13.3} + \left(\frac{r_B}{V_{SB}} - \frac{r_A}{V_{SA}}\right) \qquad (1)$$

where $\Delta\phi$ is the angular separation of the two spacecraft; r_B and r_A are the heliocentric distances of B and A respectively; and V_{SB} and V_{SA} are the radial speeds of the stream behind the corotating shock at longitudes of B and A, respectively. The estimated and observed travel times between each spacecraft are shown in Table III.

Table III.

Travel Time of the Corotating Shock

		Travel Time (Day)	
From	To	Observed	Estimated
Helios 1	Helios 2	1.6	2.5
Helios 2	IMP-8	0.3	0.5
Helios 1	Voyager 2	4.0	4.3

The observed and estimated travel times of the corotating shock do not agree with each other as can be seen in Table III. The observed travel time is less than the estimated time. A possible explanation of the discrepancies is given as follows. The January 1st flare disturbance starting at 0727 UT (originating from the east side of IMP-8 and Helios 2 in heliocentric longitude) can push the corotating stream in such a manner that the flare shock coalesces with the corotating shock and the configuration of the corotating shock front resembles that of a transient shock. Thus, this distorted corotating shock front will reach Helios 2 and IMP-8 at an earlier time than that estimated from a corotating shock which is not influenced by the flare shock. The observed travel time can thus be shortened.

The transient shocks observed at Helios 1 on Jan. 3, 0838 UT and at IMP-8 on Jan. 5, 1600 UT can be assumed to be caused by a solar event associated with a flare and solar radio bursts of Type II and IV starting at 2147 UT. The solar observations strongly suggest that a transient shock has already developed near the sun. In order for the shock to arrive at Helios 1 and IMP-8 at the observed times, the shock configuration has to have an elongated shape. From the description given above, we conclude that there were at least two transient shocks and one corotation shock to generate a sequence of interplanetary events which arrived at each spacecraft in agreement with observations. An improved numerical simulation method of Hakamada and Akasofu (1981, 1982) by Olmsted and Akasofu (1983) will be used to demonstrate that our description of this solar and interplanetary event is self-consistent.

III. SIMULATION OF THE JANUARY 1-7, 1978 EVENT

A series of events during the period between 2 and 7 January 1978 has been recorded by a set of spacecraft, Helios 1 and 2, IMP-8 and Voyager 2. The solar origin of these events has been identified. The background flow pattern including the corotating shock will be simulated first using the observations of the large-scale solar magnetic fields (Hoeksema, 1984) as the simulation input. The heliospheric current sheet computed on a source surface at 3.5 solar radii for the Carrington Rotation 1663 is shown in Figure 4; the map was provided by Hoeksema (1984). It is assumed that the initial solar wind speed from the neutral line is minimum (300 km/sec) and that it increases towards higher latitudes with a given gradient for a given epoch of a sunspot cycle; for details see Akasofu and Fry (1986). This source surface generates the basic IMF pattern as can be seen in Figure 5. The resulting IMP pattern is characterized by only a one-spiral arm structure during this particular

Carrington Rotation. The magnetic field is considerably compressed in the vicinity of the corotating shock. The calculated arrival time of the corotating shock at Helios 1 agrees with observations shown in Table I. Thus, we conclude that the observed IMF structures associated with high speed streams can be reproduced by our simulation method on the basis of the Stanford source surface data.

Assuming this shock is a stationary structure corotating with the sun, then the estimated arrival time at Helios 1 and IMP-8 do not agree with observations as shown in Table III. The simulation result suggests that this difficulty can be removed by noting that at least two solar flares occurred during this period, generating a series of interplanetary events. Here, we reconstruct the event quantitatively by our simulation method. The starting time of the flares, and the basic values for the flare parameters used for the simulation are given in Table IV.

Table IV.

Parameters Used for the Simulation

	START TIME UT	LONG.	LAT.	V_F (km/sec)	τ (HRS)	σ (°)	REMARKS
Flare I	Jan. 1 0727	E10°	S17°	1000	4.0	20	Type II & IV
Flare II	Jan. 1 2147	E32°	S19°	3300	7.5	20	Radio Bursts

These two flares are selected from the book "Experimental Comprehensive Solar Flare Indices for "Major" and Certain Lesser Flares 1975-1979" compiled by Dodson and Hedeman (1981). The detailed description of the flare parameters is given by Akasofu et al. (1983).

Figure 5 shows our simulation results. With the assumed sets of the parameters, the computed arrival times of the shock waves agree well with the observed ones (see Table 1). According to our simulation study, the interaction of the flare shock I with the corotating shock on Jan. 1, 1200 UT (see Figure 5) causes the corotating shock changing in shape. The flare I shock has coalesced with the corotating shock before reaching Helios 2. Therefore, the observations at Helios 2 and IMP-8 did not find the flare I shock. In fact, Helios 2 and IMP-8 have observed a coalesced shock with a shock surface which is pushed to resemble more like a transient shock. This is the reason why the estimated arrival times of the corotating shock at Helios 2 and IMP-8 from Eq. (1) did not agree with the observed ones shown in Table 1. The flare II shock was launched 15 hours later with a faster speed reaching Helios 1 at approximately the same time as the flare I shock arrives at Helios 2. The flare II shock had a shape which is so elogated that at Helios 1, a moderate strength shock followed by a high speed stream has been observed. Away from the central meridian of flare II, the strength of the flare II shock becomes so weak that the shock may not be well-developed near the skirt by Helios 2 and IMP-8. In fact, the observations show that the flare II shock at IMP-8 is a very weak shock with a broad transition region in all the plasma and magnetic field data. It should be called a non-linear compressional wave. At Helios 2, this shock has not been observed at all.

Beyond 1 AU, the flare II shock also coalesced with the corotating and flare I shock such that all three shocks coalesced into one shock in a region in IP space between the heliocentric longitudes of Helios 1 and 2. This coalesced shock reaches Voyager 2 on Jan. 6, 0100 UT which agrees with the observed time.

In Figure 6, we show both the time profiles of the solar wind velocity, density and the IMF magnitude observed by the IMP 8 satellites and the simulated time profiles. Although details are significantly different, the simulated profiles reproduce fairly well the observed ones.

IV. DISCUSSION

The disappearance of the transient shock at Helios 2 is still an unresolved question in this study; even the transient shock at IMP-8 is not a well developed shock and should be called a nonlinear compressional wave. One possible suggestion is that the transient shock propagated into the downstream region of the corotating shock and parts of the shock front may have degenerated into nonlinear disturbances or disappeared. The flare sends a very narrow ejecta into interplanetary space such that a well developed shock, and its associated flow, can be observed only at Helios 1's longitude. On the other hand, the nonlinear disturbance generated by the flare will cover a greater range in heliocentric longitude so that a nonlinear shock-like disturbance was observed at IMP-8.

Burlaga et al. (1981) suggested that one transient interplanetary shock with a magnetic cloud was observed by 5 spacecraft (Helios 1 and 2, IMP-8 and Voyager 1 and 2). Although our interpretation of the interaction of shock events is different from theirs, we also conclude that those shocks identified by Burlaga et al. (1981) are flare-associated. Those flare-associated shocks, except the one observed by Helios 1, have a characteristic of a corotating shock because they are associated with a corotating stream. It is not possible for us to state whether or not the magnetic cloud following the shocks is a characteristic of a transient or a corotating shock.

In conclusion, we have used a numerical simulation method of Hakamada and Akasofu (1981, 1982), and Olmsted and Akasofu (1983) to demonstrate that a sequence of interplanetary shock events are caused by the two flare-associated shocks and one corotating shock as a result that the arrival times at each spacecraft are in agreement with the observations.

Acknowledgments. The work reported here was supported in part by a grant from the National Science Foundation (ATM-85-18512), a grant from National Aeronautics and Space Administration (NAG5-571), and by a contract from the United States Air Force (F19628-86-K-0030).

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FIGURE CAPTIONS

Fig. 1. Positions of Helios 1 and 2, IMP-8 and Voyager 1 and 2 in the period from January 1-7, 1978.

(a) Solar equatorial plane view.

(b) Solar meridinal plane view.

Fig. 2. Hourly averages of the plasma data from Helios 1 and 2, and IMP-8 for one solar rotation period including the January 1-7, 1978 event.

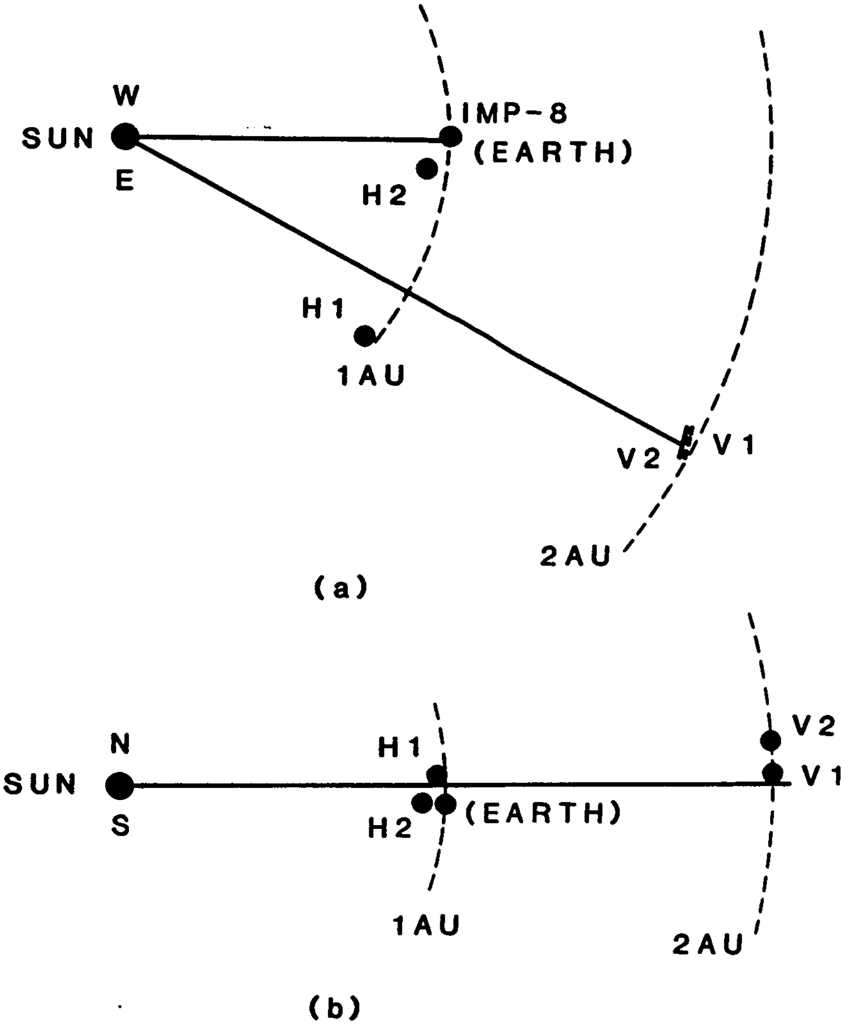
Fig. 3. Three consecutive solar rotations of plasma data of Helios 2 spacecraft.

Fig. 4 The Stanford magnetic field map on the source surface. The neutral line is indicated by -0.0- (courtesy of J. T. Hoeksema, 1986). The locations of Flare I and Flare II are indicated by dots, and the projection of the earth to the south surface is indicated by a star.

Fig. 5. Successive IMP patterns for the January 1-7, 1978 event.

Fig. 6. Comparison of the observed time profiles of the solar wind speed, density and the IMF magnitude and the corresponding simulated profiles.

JAN 1 - 7, 1978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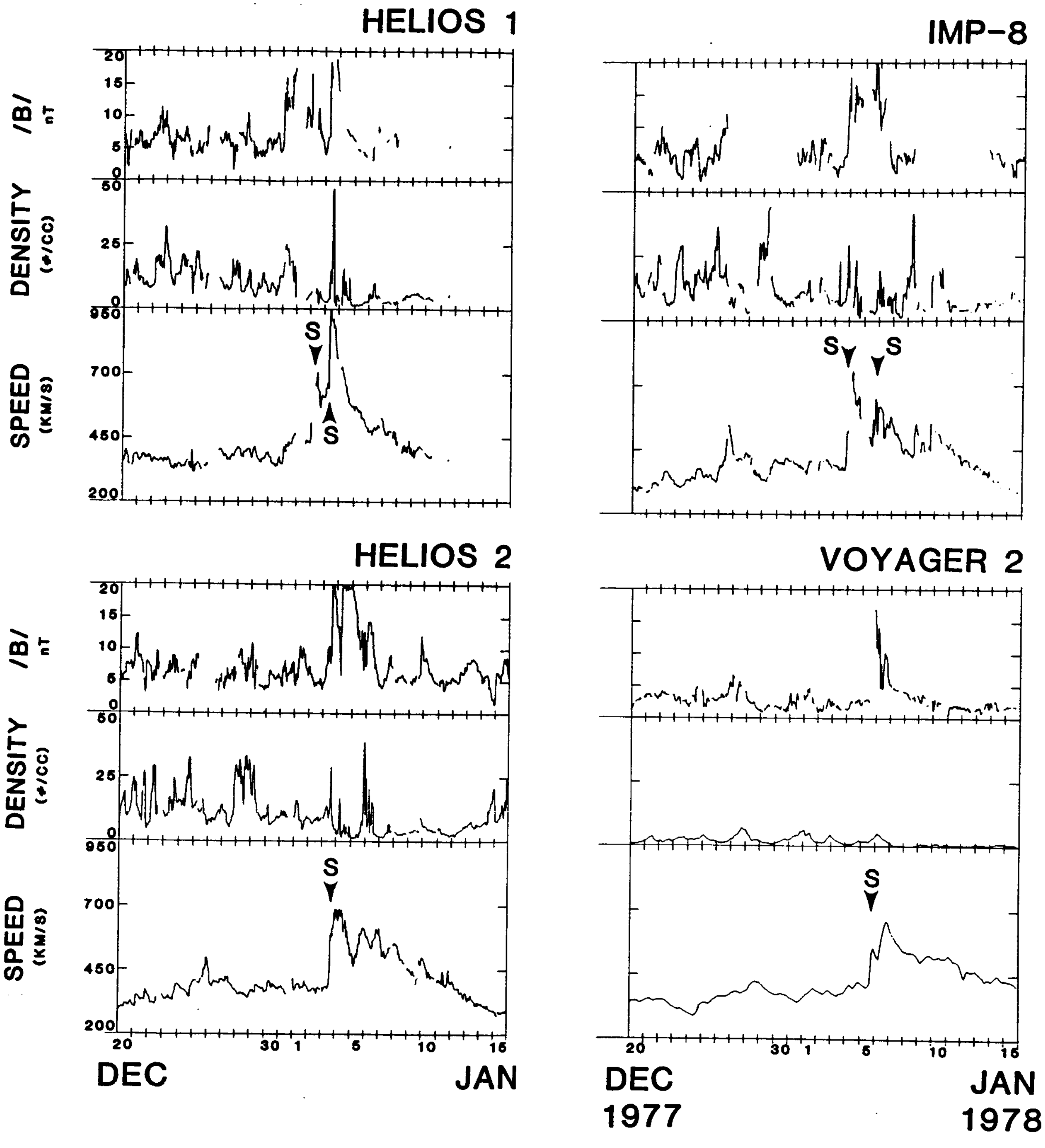
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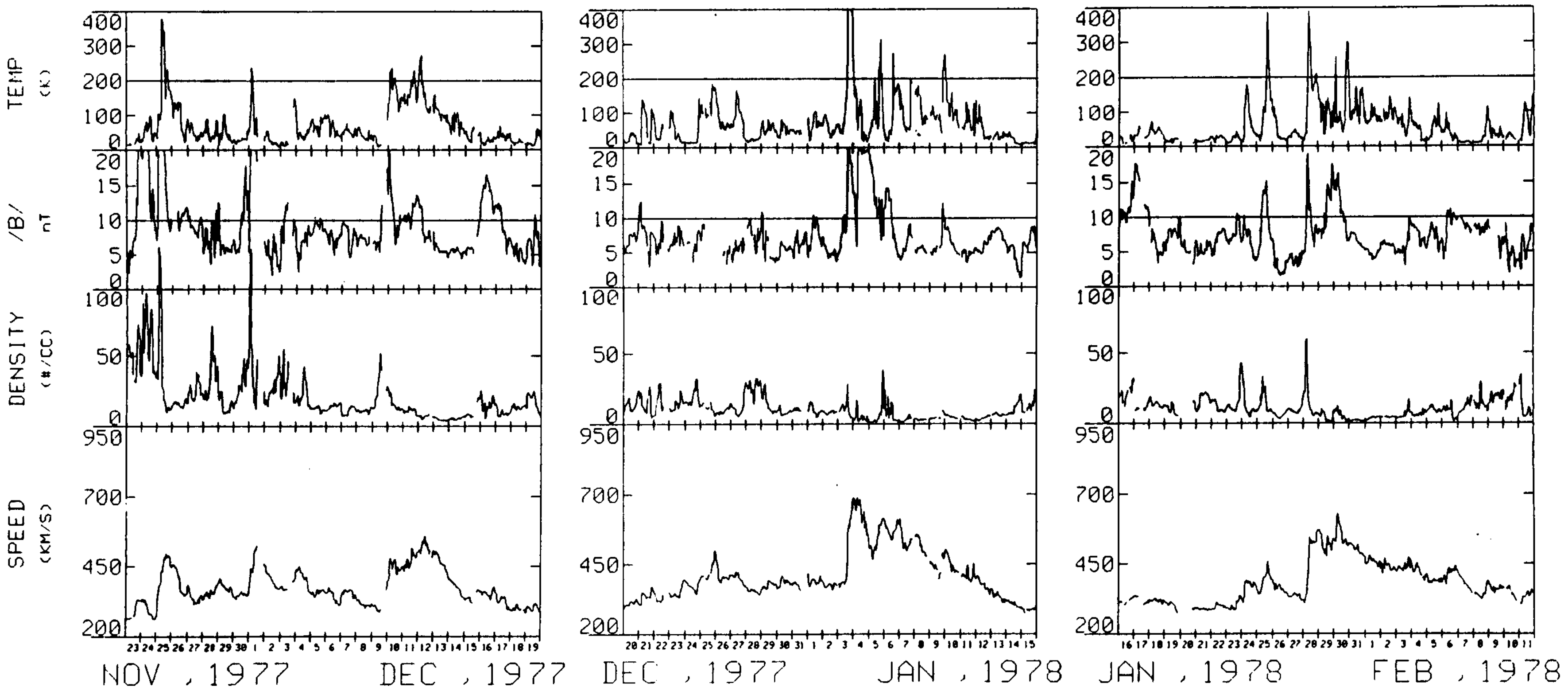
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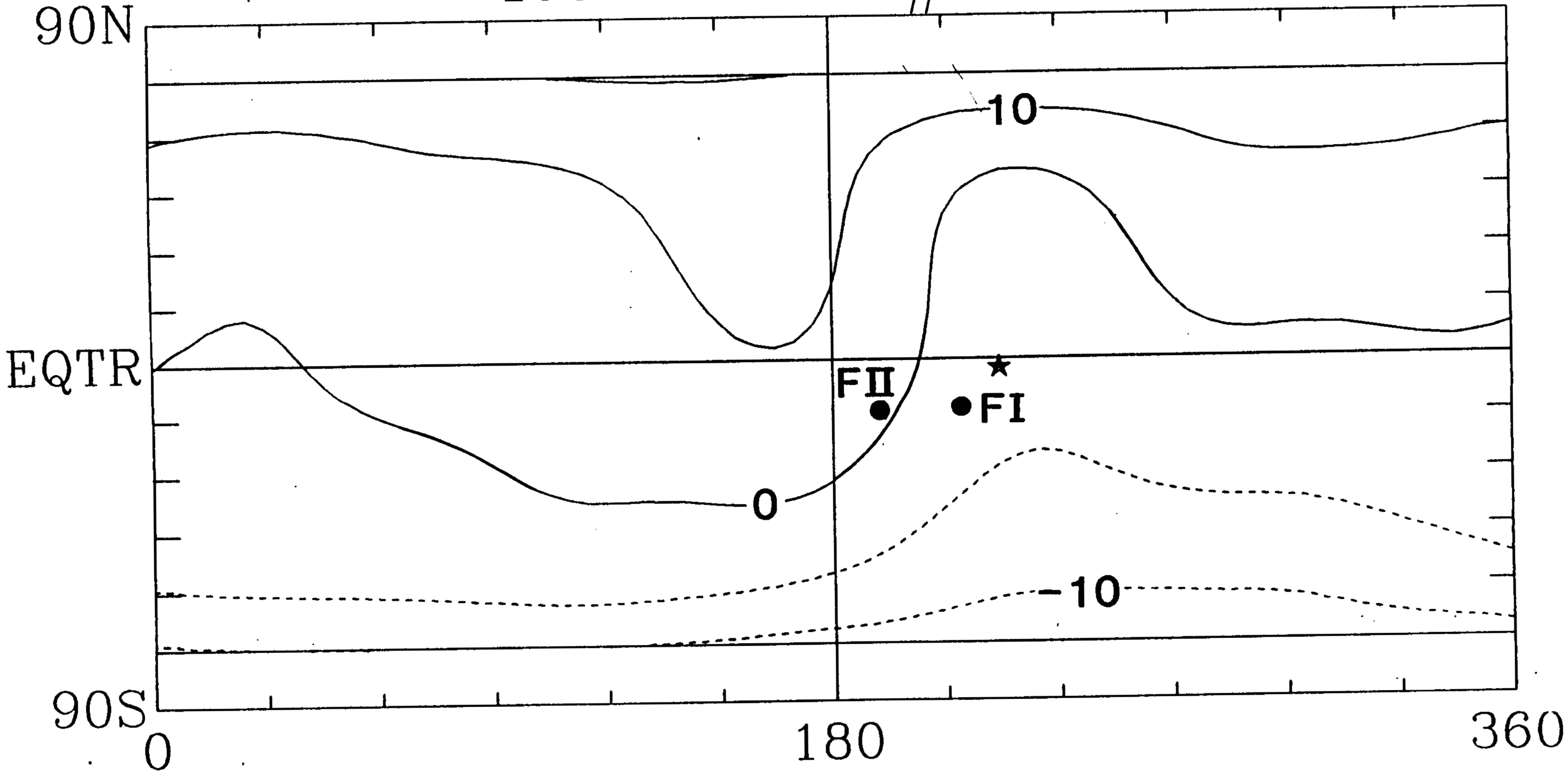

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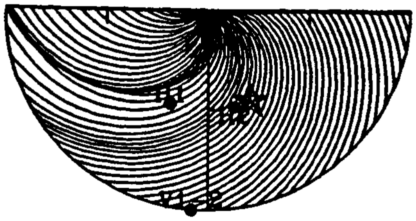

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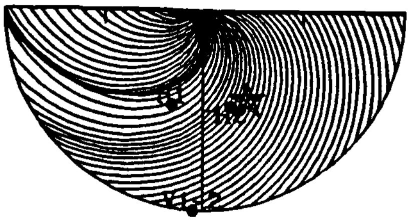

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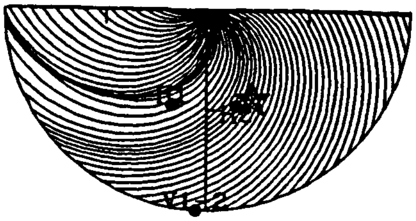

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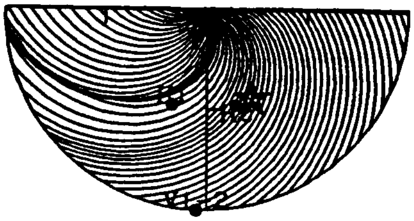

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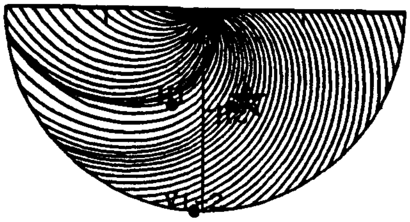

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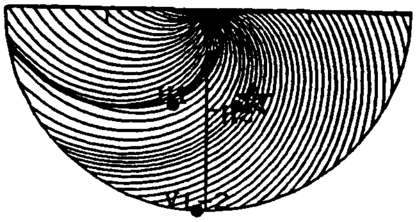

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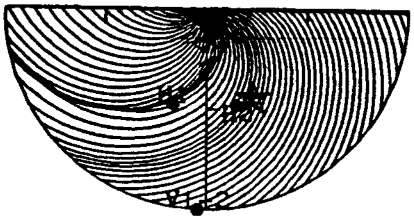

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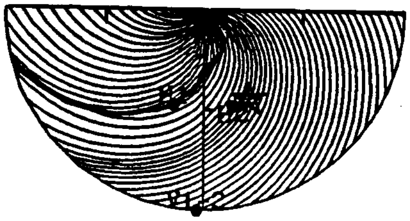

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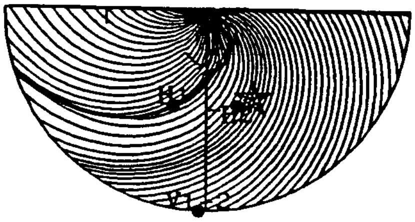

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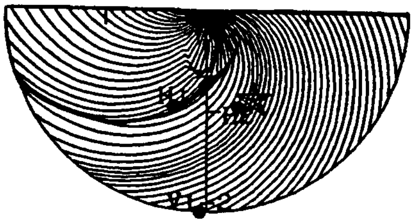

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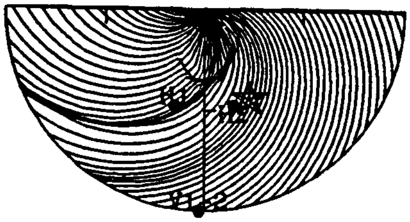

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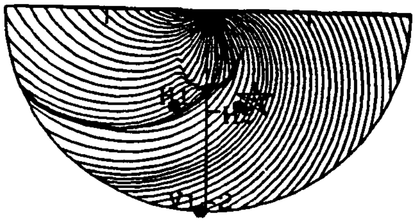

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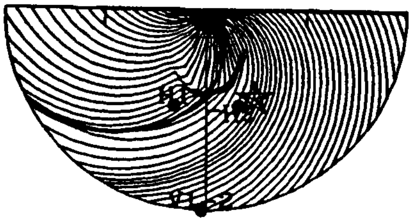

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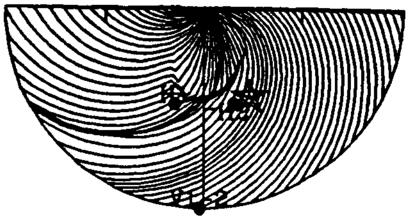

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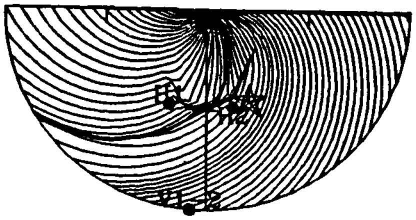

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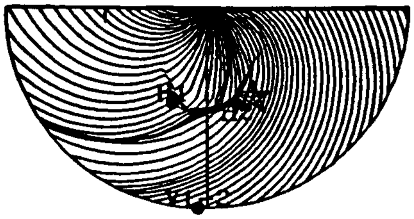

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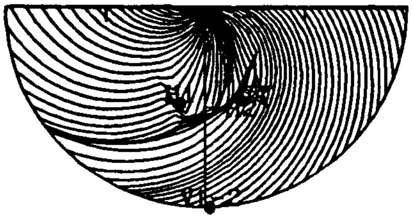

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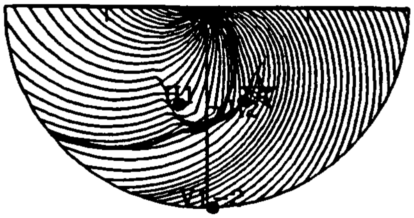

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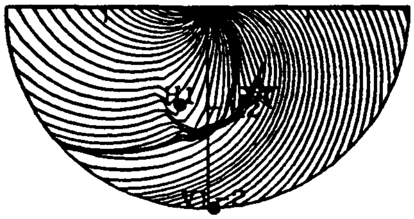

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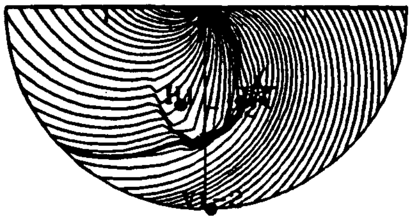

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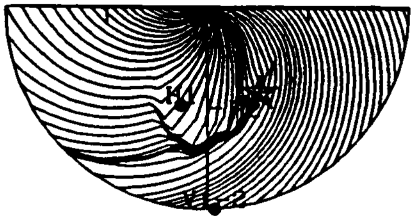

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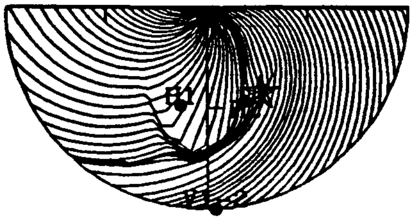

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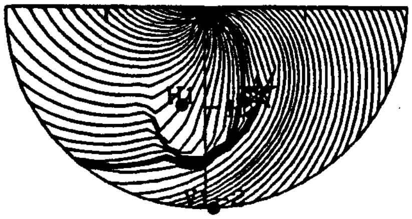

JAN. 5,1978
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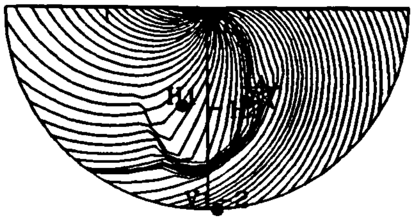

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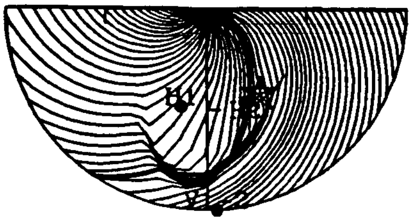

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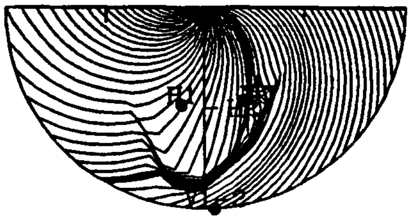

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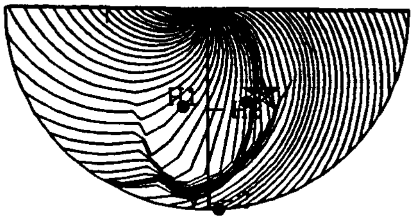

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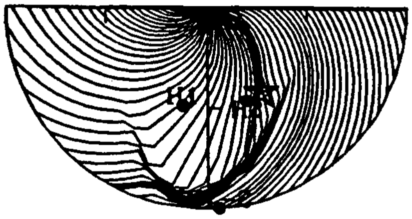

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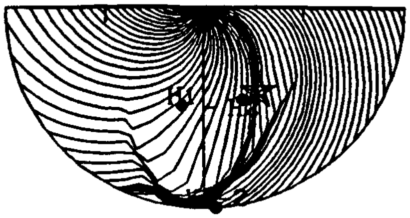

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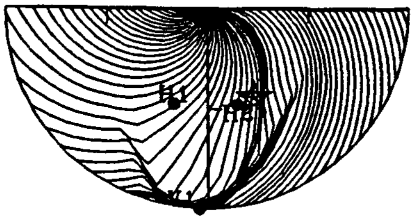

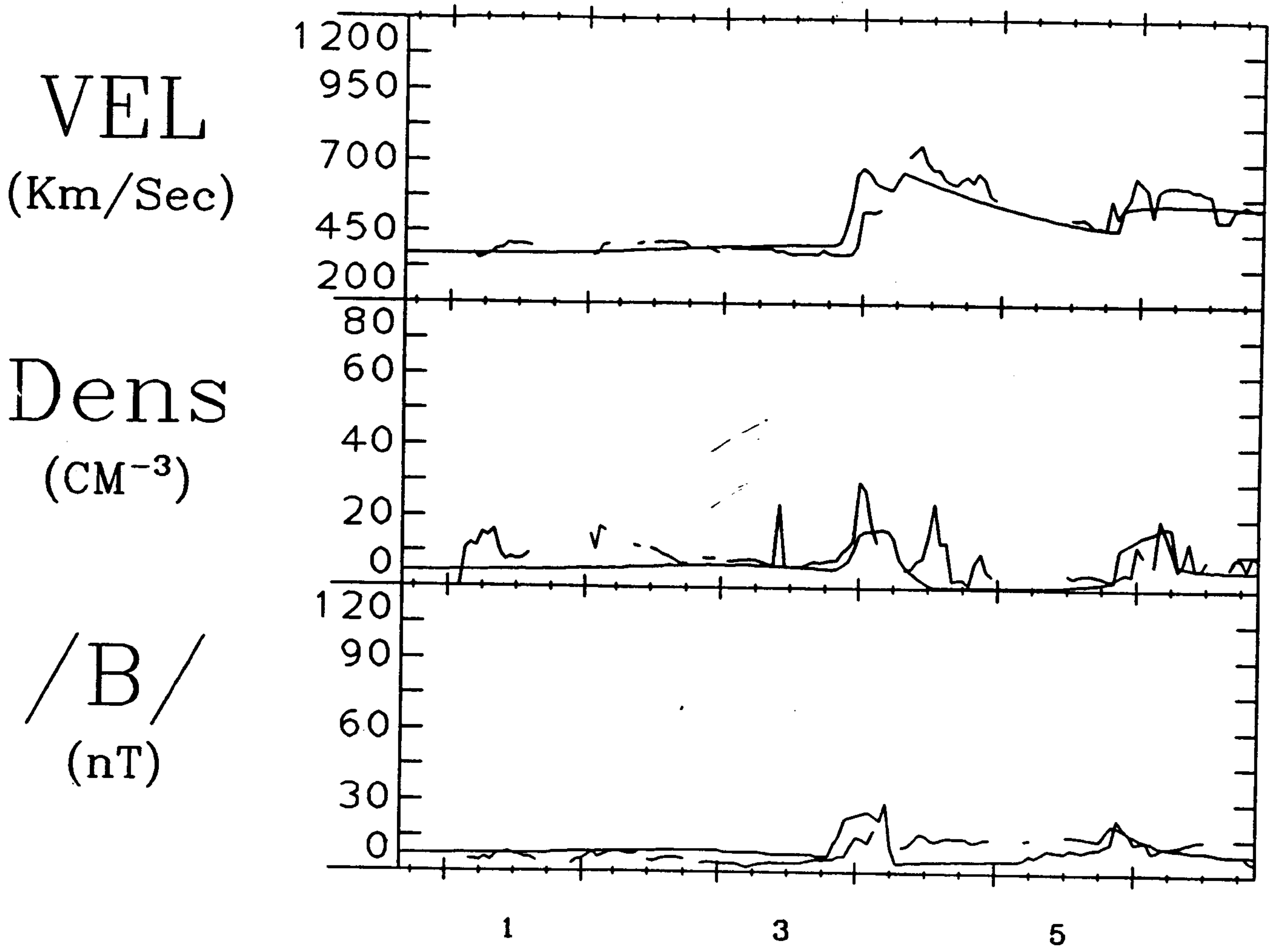

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IMP−8