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CONCERNING A NEW THEORY OF TYPE I COMET TAILS

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BY

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GREENBELT, MARYLAND

Presented at the 13th Int. Astrophysical Symposium July 5-7, 1965

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Concerning a New Theory of Type I Comet Tails

Introduction

The Type I tails of comets have been observed and studied for many years but these visual phenomena have largely remained an enigma since an adequate theory of their formation and dynamics has yet to be presented. As a direct result of recent measurements performed by instruments carried into interplanetary space by satellites and space probes, our quantitative knowledge of the interplanetary medium has increased significantly. In addition, detailed measurements of the earth's immediate environment in interplanetary space suggest that a close analogy may be drawn between comets and planets with magnetic fields. The basic mechanism relating these two celestial objects is their interaction with the flux of ionized gas or plasma from the sun referred to as the solar wind by Parker (1958, 1963). The interaction of the magnetized plasma with a comet or the geomagnetic field apparently leads to the development of similar features, namely: an approximately antisolar extended magnetic tail of gaseous material or geomagnetic field lines.

The Interplanetary Medium

Chapman and Ferraro (1933) postulated the transient existence of an appreciable flux of plasma following solar disturbances. Biermann (1951) suggested that the physical characteristics of Type I comet tails could be explained on the basis of the interaction with a continuous flux of solar plasma. This directed the attention of subsequent investigators to consider the expansion of the solar corona into interplanetary space. In a series of papers beginning in the late 1950's Parker developed the theory of the hydrodynamic expansion of the solar corona, referred to as a solar wind. It was predicted that this would consist principally of hydrogen flowing radially from the sun with flux values between 10^7 to 10^{10} particles/cm^2/sec and an energy of the individual particles of approximately one Kev.

Direct measurements of this solar wind or plasma have recently been performed by means of satellite measurements conducted both by this country (Bonetti et. al, 1963; Snyder and Neugebauer, 1963; Bridge et. al, 1965) and by the USSR (Gringauz, 1960,1961). These measurements, with average fluxes near 3×10^8/cm^2/sec of 1 Kev protons, confirm the theory of the solar wind as predicted by Parker and show that the original estimates by Biermann of substantially higher fluxes are not observed. A summary of the direct measurements of the interplanetary plasma characteristics is shown in Table I.

Table I

Summary of Direct Measurements
of the Interplanetary Plasma

Spacecraft	Time	Ion Flux (per cm^2-sec)	Range of Equivalent Energy (ev)	Average Velocity (Km/sec)	Average Density
Lunik I	Jan 1959	$\sim 2 \times 10^8$	> 15	> 60	> 30
Lunik II	Sept 1959	$\sim 4 \times 10^8$	> 15	> 60	> 30
Explorer X	March 1961	3×10^8	300-800	300	10
Mariner II	Aug-Dec 1962		800-2400	505	2
IMP-I	Nov 1963-Jan 1964	3×10^8	300-1000	319	2-10

The most important conclusion reached from these recent measurements is that the flux of solar plasma is a continuous phenomena, with important solar related time variations. The composition of the solar wind, not accurately measured, appears at the present time to consist principally of hydrogen with approximately 5% helium. The velocity corresponding to 1 Kev hydrogen ions is about 400 Km/sec.

Magnetic lines of force originating in the photosphere are dragged into interplanetary space and form the interplanetary field (Ness and Wilcox, 1964) with an average magnitude of 5 gammas at 1 A.U. During times of quiet intervals in the solar cycle, IMP-I measurements have established that an Archimedean spiral structure, derivable from the basic model of uniform coronal expansion as proposed by Parker, is well approximated by these measurements (Ness and Wilcox, 1965). At 1 A.U. the angle between the field line and a radius vector from the sun is about 45°.

Interaction of Solar Plasma with the Geomagnetic Field

The presence of the magnetic field in the solar plasma is particularly important in its interaction with the geomagnetic field. The rarefied density of approximately a few particles/cm^3 and the temperature of the plasma 10^4 - 10^5 $^{\circ}K$ are such that the mean free path for collisions would be on the order of fractions of an astronomical unit. Thus, the interaction of the "collisionless" plasma with the geomagnetic field might be approximated as individual particle specular reflection from the geomagnetic boundary. Direct measurements the satellites Explorers 12, 14 and IMP-I have provided conclusive evidence for a containment of the geomagnetic field at the subsolar point at a geocentric distance of approximately 10 R_e. Figure 1 summarizes the detailed positions of the boundary of the geomagnetic field as observed by the IMP-I satellite, projected on the plane of the ecliptic, from the subsolar point to the sunrise terminator.

The highly eccentric orbit of IMP-I, with an apogee of 31.7 R_e, permits a detailed mapping not only of the boundary of the geomagnetic field but also the transition region between the magnetosphere and the interplanetary medium. A significant result of experimental measurements by both the magnetic field (Ness et.al., 1965) and the plasma experiment (Bridge et.al., 1965) is the observation of a detached bow shock wave standing off from the magnetosphere by 3-4 R_e. The presence of the shock wave has been predicted (Axford, 1962; Kellogg, 1962) on the basis of an analogy between supersonic gas dynamics and limiting conditions approximating the interplanetary medium as a continuous fluid. The interplanetary magnetic field permits the reduction of characteristic scale lengths to an electrodynamic scale of proton Larmor radii, approximately 10^3 Km.

The MHD wave phase velocity or Alfven speed is 50-100 Km/sec so that the solar wind is supersonic at a Mach number of 5-10. Although the details related to the formation of the collisionless shock wave have yet to be theoretically developed in detail (Cordey, 1965), the results of the IMP-I satellite have indicated that the existence of a shock wave surrounding celestial objects in the flow of the solar wind is an important aspect of their space environment. It is important to note in this context that the size of the magnetosphere, 20 $R_e = 10^5$ Km, is approximately equal to that of a comet coma and hence the existence of a similarly detached shock wave enveloping a comet may be reasonably anticipated (Axford, 1964). Related to the bow shock wave is the existence of energetic particle fluxes beyond the magnetosphere and presumable generated either directly or indirectly by the shock wave mechanism. Measurements of energetic particle fluxes with energy 40 Kev in the vicinity of the bow shock wave have been performed by the Explorer 12 (Freeman, 1964) and IMP-I satellites (Anderson et. al., 1965; Fan et.al., 1964).

The Earth's Magnetic Tail

The most pertinent feature to comet tail studies of the interaction of the solar wind with the geomagnetic field has been the detailed mapping of an extended magnetic tail of the earth by the IMP-I satellite (Ness, 1965). On the antisolar side of the earth the magnetic field is observed to be strongly distorted in both direction and magnitude. At distances greater than 8 R_e the field approaches a direction approximately parallel to the Earth-Sun line. In the southern hemisphere region the magnetic field is observed to be directed away from the sun while in the northern hemisphere the field is observed to be directed back towards the sun as shown in Figure 2. Separating these two regions of space a magnetically neutral sheet-like region of space has been experimentally discovered.

Theoretical estimates of the presence of a neutral sheet in the earth's magnetic tail have been recently suggested, principally by Axford, Petschek and Siscoe (1965) but also discussed in a related sense by Dessler, (1964), Dessler and Juday (1965) and Piddington (1960). The magnetic field strengths observed in the earth's magnetic tail are approximately 10 to 30 gammas. Dynamic changes of the tail can be correlated with solar activity, terrestrial magnetic disturbances and variations in the characteristics of the earth's radiation belt (Ness and Williams, 1965).

The presence of the neutral sheet embedded within the earth's tail is most important in the study of Type I comet tails. As pointed out by Axford et.al. (1965), the existence of a stable or quasi-stable sheet requires the presence of an enhanced plasma flux to balance the magnetic pressures on opposite sides of the neutral surface. Particle measurements on the night-side of the earth by satellites have revealed the existence of an electron tail (Frank, 1965) and it is suggested that this electron tail provides the experimental evidence confirming the general characteristics of the earth's neutral sheet.

The confinement of a plasma in the neutral sheet offers an opportunity for a direct comparison with Type I comet tails. However, the extension of the geomagnetic field to form a magnetic tail of the earth does not imply that the comets with Type I tails require an inherent large magnetic field. As discussed by Alfven (1957) it is likely that the coma will entrap the interplanetary magnetic field, which will be dragged out behind the coma to form a tail like appendage of interplanetary field lines which were originally being swept past the comet by the solar wind.

On the basis of the measurements performed by IMP-I in the interplanetary medium, it has been found that the direction of the magnetic field periodically reverses itself. Between the oppositely directed fields are neutral surfaces being convectively transported into interplanetary space. Thus a capture of the interplanetary magnetic field, as suggested by Alfven, also implies the capture of neutral sheets or surfaces by comets as illustrated in Figure 3. The scale of the neutral sheet, as measured in the earth's tail, indicates a thickness on the order of a few thousand kilometers. The diameter of the earth's magnetic tail, 44 $R_e \approx 3 \times 10^5$ Km, is approximatly a comet tail diameter, as estimated from the outermost rays of a Type I tail. Suggestions related to the spatial extent of the earth's magnetic tail have been made by Dessler (1964) and Dungey (1965). The extended geomagnetic tail was not observed by the Mariner IV space probe at a distance of 3020 $R_e = 1.9 \times 10^8$ Km (Van Allen, private communication). The data from this unique opportunity have yet to be adequately reviewed so that firm negative conclusions from other experiments are not available at the present time concerning the length of the earth's tail.

Because of the apparently similar relation of the interaction of the solar wind with either the geomagnetic field or the entrapped magnetic field of comets, we suggest in this paper that Type I comet tail rays represent enhanced densities of plasma confined to neutral tubes or surfaces within the tails of comets. The remainder of the paper is devoted to a discussion of the physical characteristics of Type I tail rays on the basis of of this hypothesis.

Formation of Tail Rays

Alfven's original suggestion for trapping of the interplanetary magnetic field by an ionized coma can be adapted with little modification. The quasi-periodic reversal of the interplanetary field at intervals of 4-7 days, as observed by IMP-I, will produce a symmetric pair of neutral tubes corresponding to each field reversal. We propose that these neutral tubes are the locus of tail rays as shown in Figure 3. It is also possible that a single interplanetary neutral sheet or field reversal will form multiple neutral tubes which may be aided by inhomogenities of the solar wind.

Relatively strong field gradients will be present at the boundary of neutral regions which will tend to concentrate ions in the neutral zones. The existence of such regions balances the magnetic pressures and prevents field lines of opposite sense from collapsing together and annihilating themselves. Details of such magnetically neutral regions need to be worked out in the case of comet tail rays. They represent a more satisfactory basis for the existence of well defined tail rays than do ion clouds trapped on lines of force with the motion of ions restricted to field lines in a very limited region of the comet tail.

Characteristics of Tail Rays

Observations of comet tails have revealed several general features of the rays (Wurm, 1963). The most important characteristics, with respect to this paper, are:

1. The occurrence of long, narrow rays with widths less than the resolution of the plates, $\sim$ 2000 Km, and lengths extending to 10^7 or 10^8 Km,
2. Tail rays display a symmetry with respect to the tail axis or approximately antisolar direction, and
3. Tail rays first appear at large angles to the axis, 60° or more, and grow longer as they approach the tail axis. These physical details have been described as the "folding umbrella" geometry by Marochnik (1964).

These characteristics are seen to follow from the model of Figure 3 and the properties of the earth's neutral sheet. No specific requirements for ejection velocity or angle are required. Initial velocities greater than 10 Km/sec (Wurm, 1953; Eddington, 1910) are not required. The envelope of Comet Morehouse (Eddington, 1910) also appears to be plausibly explained with the present hypothesis. In this case we are dealing with the interaction of the magnetized plasma cloud with the coma in front of the comet. A detailed study of this phenomenon may furnish insight into the manner in which the magnetized solar plasma and the coma first interact.

The time history of a ray and the angle between it and the tail axis can be calculated from our model. If the ions are trapped in the neutral sheet they are carried back with it by the motion of the field lines and no large velocity component along the ray is necessary. The two parameters needed are the velocity of the solar wind and the diameter of the region which interacts with the solar plasma and retards its motion.

In Figure 4 this geometry is illustrated where θ denotes the angle between a ray and the tail axis, L the projection of a ray on the axis and D the effective radius of the region for interaction with and subsequent slowing of the solar plasma cloud. The uninterrupted velocity of the plasma is the velocity of the solar wind, indicated by V_s, which at a later time drags the ray to the position indicated by the dashed line.

The angle θ is derived from D and L as,

$$\tan \theta = \frac{D}{L} \qquad (1)$$

so that the angular rate at which rays approach the axis is given by:

$$\frac{d\theta}{dt} = -\sin^2 \theta \, \frac{V_s}{D} \qquad (2)$$

Representative values of D, V_s and θ are chosen in the curves of Figure 4 illustrating the angular rate of ray closure.

The time for a ray to reach an inclination θ is given by the integral of equation (2) assuming D to be constant:

$$t = \frac{D}{V_s} \left(\operatorname{ctn} \theta - \operatorname{ctn} \theta_i \right) \qquad (3)$$

Figure ~~5~~ 6 presents the time history of tail ray formation for the same values of the critical parameters as used previously. As known from previous observations, the rate of ray closure decreases rapidly with θ. For most of the time in the history of a ray, it is predicted to be observed at a small angle to the tail axis. Shown in Figure ~~6~~ 5 are data points for $\frac{d\theta}{dt}$ obtained from the measurements of Wurm and Mammano (1964) for Comet Morehouse. These points as published, must be corrected for true angle and angular velocities in the plane of the tail. It is seen in this figure that the apparent value of D which best fits the data is 5 x 10^6 Km. The trend of the successive points for each separate ray is in agreement with that which would be predicted by this theory.

Certain additional geometrical features of the tail also follow from the present model. The tail axis is now clearly the symmetry axis toward which rays converge. As proposed the tail direction is determined by the local solar wind velocity, and will lag behind the radius vector by an angle θ given by:

$$\tan \theta = \frac{V\theta}{Vs} .$$

where V_θ is the comet velocity perpendicular to the radius vector from the sun. For V_θ of about 30 Km/sec and V_s of 400 Km/sec, θ will be 4.5^o. This aberration effect of the tail axis, coupled with distortion of the angle between the axis and the ray due to viewing geometry may significantly affect the interpretation of observations.

As pointed out by Wurm, care must be taken in establishing the tail direction since with an asymmetrical geometry, the apparent direction may deviate from the real direction. Malaise (1953) assumed that the tail axis direction is given by the direction of the longest ray. The reproduced photographs indicate that Comet Burnham possessed multiple ray structures. These rays should first appear at large angles and gradually approach the axis with a lifetime of a day or at most a few days (Wurm, 1963).

We would also expect that a series of observations at intervals of one half to one day might give the impression of a "wagging" tail. This is shown in Figure 7, which reproduces the observations of Malaise. We feel it is doubtful that the same ray was continuously observed and in our interpretation about 5 distinct rays were observed. The satisfactory resolution of this problem requires continuous observations, at short intervals, for several days at about an hour apart.

Another property of the tail geometry is the orientation of the tail. The axis must be in the orbital plane as it is a radius vector which has been subjected to aberration. However, the ray structure, in the ideal case of the present hypothesis, would be in a plane containing the captured magnetic field lines and the radius vector, as seen from Figure 3. This is the plane tangent to the Archemedian helix passing through the comet and including the radius vector to the comet. Although the orbital plane and the tangent plane intersect along the radius vector any angle between the two may occur.

The apparent angle between ray and axis will be 0^{o} when the earth lies in the tangent plane and thus the tail would appear as a narrow spike with a thickness equal to that of the neutral tubes. A study of the relation between Type I tail forms will serve as a critical test of this tail hypothesis.

A major problem exists with respect to the origin of the ions within the neutral tubes. Possibly they develop from neutral molecules which become ionized by energetic particles in the neutral regions. The luminosity of the tail rays depends on the contained ion concentration. This depends upon the CO concentration at the point where ionization and trapping first occurs. Structural features of neutral regions which affect ionization determine the distribution of ions into one of the pair of rays formed by the interplanetary neutral sheets.

The well known variations of luminosity and internal structure within rays can be accounted for by instabilities and MHD waves in neutral tubes. Stability problems depend upon the magnetic field strength and plasma densities. According to Wurm (1961) CO^+ densities in comet tail rays are about $10^3/cm^3$. To this must be added the other visible ions, which are probably a small correction, unobservable ions, which may be considerably greater by perhaps a factor of 100, and finally energetic protons and electons trapped or produced in the neutral regions. The presence of energetic electrons in the comet tail neutral region, analogous to the case of the high flux of electrons with energy >40 Kev observed in the earth's tail, may be the dominant factor in producing CO^+ in the tail or perhaps removing it by further ionization and dissociation. In either case the CO^+ concentration will depend upon the concentration of energetic electrons.

Wurm (1963) has critized the solar corpuscular hypothesis of tail formation because considerable activity may occur in some rays without any effect in others. Instabilities in the neutral regions depend upon characteristics of individual regions. Density fluctuations, even of an extreme nature, may vary widely from ray to ray. A violent, large scale disturbance in the interplanetary plasma could affect the entire tail as in the case of comet Humason (Roemer, 1961)

We can also calculate the velocity of Alfven waves in the tail and compare these velocities with observed "cloud" velocities of 20-100 Km/sec. Assuming field strengths of 20 gammas and CO^+ densities of 10^3 then the Alfven speed $V_a = \frac{B}{4\pi}$ is approximately 5 Km/sec. Stronger fields of 30 or 40 gammas may be required and appear plausible at this time. Increased densities of ions reduce the velocities but even an order of magnitude error in these estimates will only reduce the speed by a factor of 3.

Conclusions

The experimental observation of continuous flux of plasma from the sun with quantitative measurements of its characteristics forms the basis of a new theory concerning the formation of Type I comet tail rays. The interaction of this solar wind with the geomagnetic field leads to the development of an extended magnetic tail with an embedded magnetically neutral sheet contained within it. The magnetically neutral region represents an effect of confinement of plasma of enhanced density which may have a parallel in the rays of Type-I comet tails.

Because the solar plasma is magnetized and convectively transports solar field lines into interplanetary space it is not necessary that comets possess inherent magnetic field. Following the original suggestion of Alfven for capture of the interplanetary magnetic field we suggest that the observed reversals of direction in the interplanetary medium are reflected into the tails of comets by the formation of neutral tubes. These neutral tubes form the trapping regions for plasmas which are observed visually.

Characteristics of tails rays formed in this manner explain observed features of the time history of tail rays. A direct result of this model is the suggestion for continuous monitoring of comet tails of Type-I over intervals of 3 or

4 days with observations at intervals of 1 to 2 hours. An additional new feature is the prediction that these tails lie nearly in the plane containing the radius vector from the sun and the magnetic field lines. Time lapse photography of the dynamics of tail rays and investigations of perspective effects on tail structure will provide critical tests of this hypothesis and also lead to new insight into the nature of comet tails.

Finally, further study of the geomagnetic tail particularly with regard to plasma densities and instabilities will provide a valuable method for understanding comet tail phenomena.

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1. Summary of the magnetopause and shock wave boundary positions as observed by the IMP-I satellite. Individual observations have been rotated in a solar ecliptic meridian plane into the ecliptic plane. Successive traversals of the boundary are connected by straight lines if no gap exists in the data. Three regions of space are distinguished by these two boundaries: the interplanetary medium, the turbulent transition region and the magnetosphere or distorted geomagnetic field.

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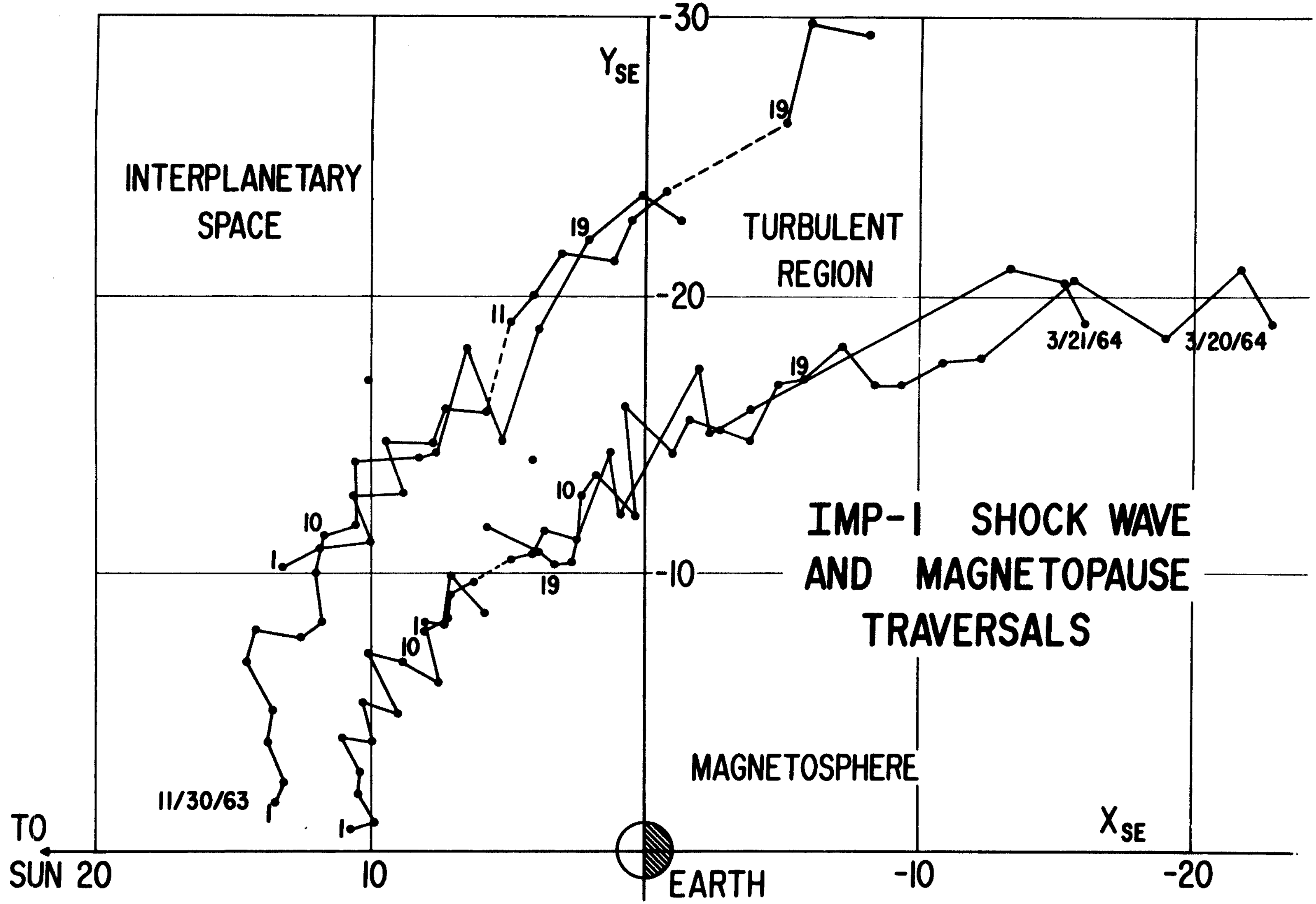

IMP-I SHOCK WAVE
AND MAGNETOPAUSE
TRAVERSALS
INTERPLANETARY
SPACE
TURBULENT
REGION
MAGNETOSPHERE
Y_{SE}
X_{SE}
TO
SUN 20
10
EARTH
-10
-20
-30
-20
-10
11/30/63
3/21/64
3/20/64
1
10
11
19
1
10
19

Figure 1

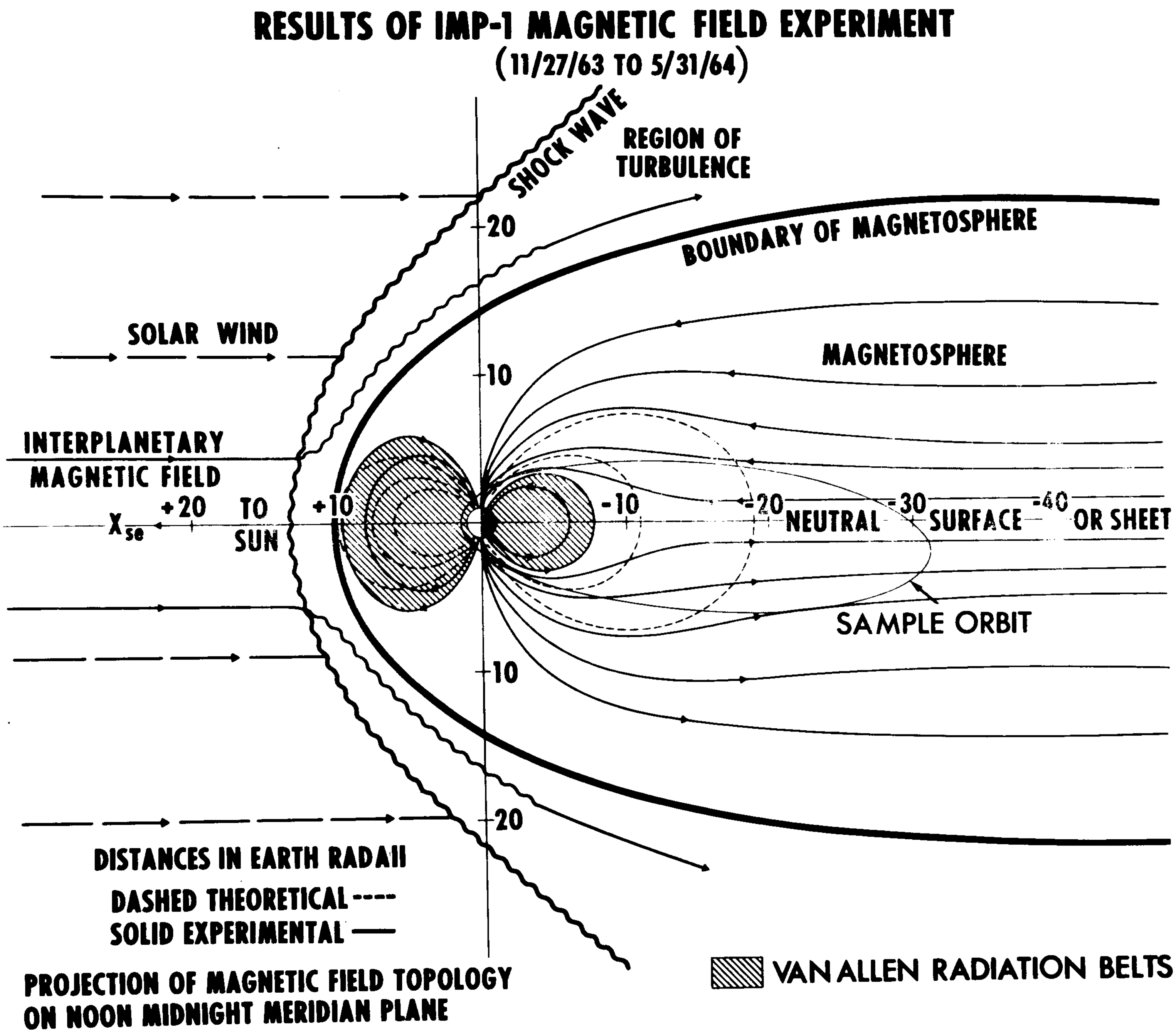
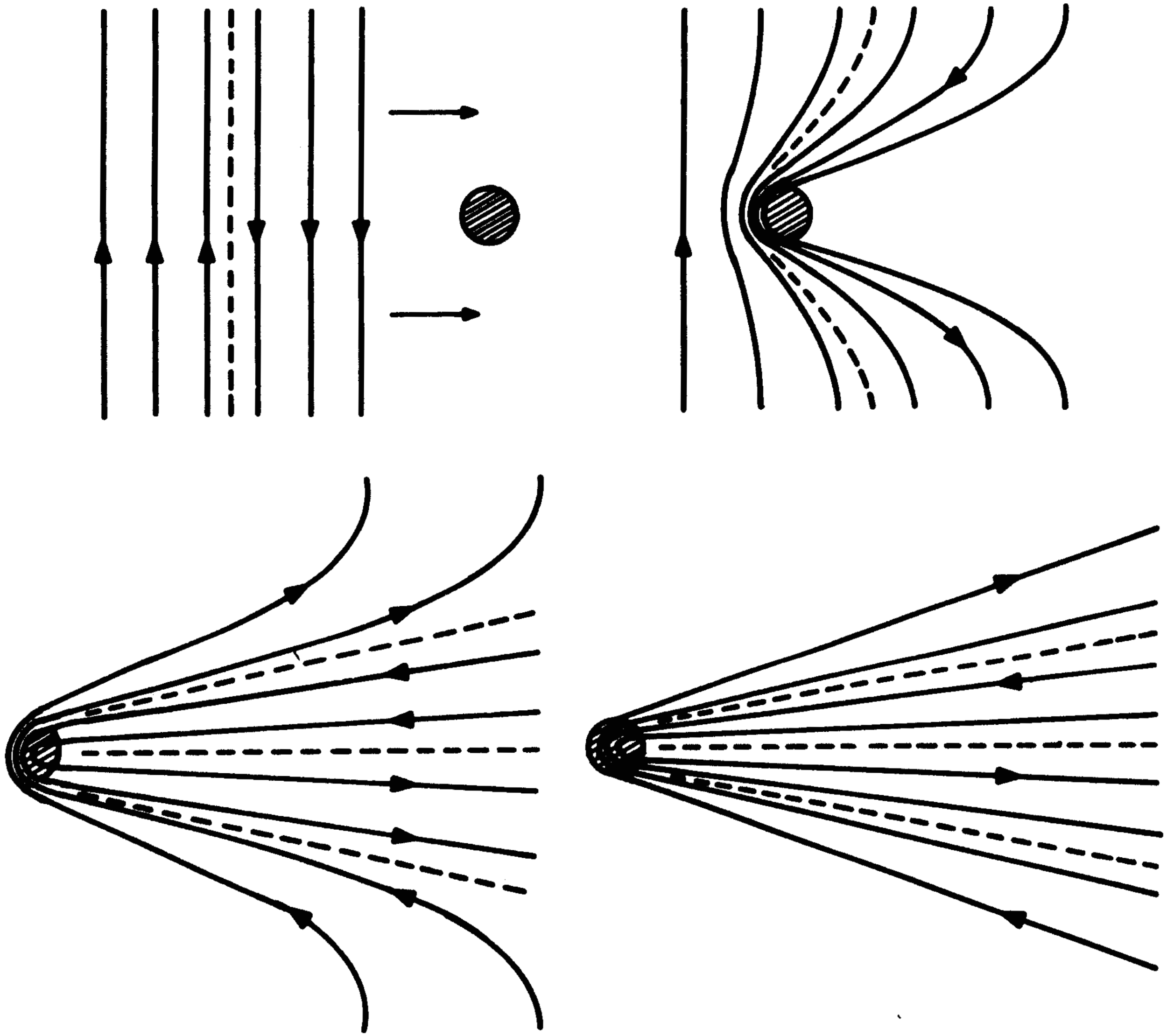
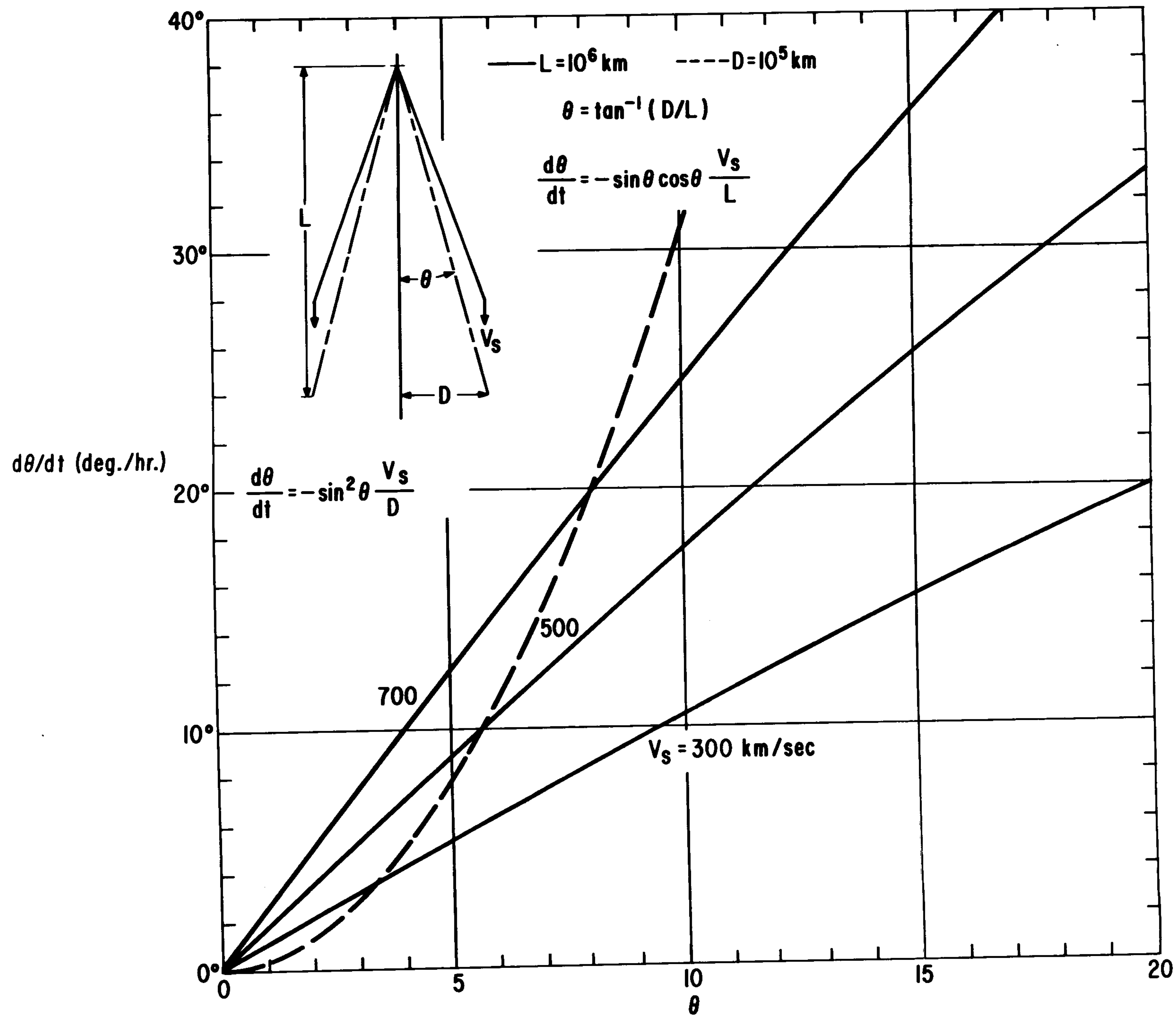

RESULTS OF IMP-1 MAGNETIC FIELD EXPERIMENT
(11/27/63 TO 5/31/64)
SHOCK WAVE
REGION OF TURBULENCE
BOUNDARY OF MAGNETOSPHERE
SOLAR WIND
MAGNETOSPHERE
INTERPLANETARY MAGNETIC FIELD
X
se
+20
TO SUN
+10
-10
-20
NEUTRAL
-30
SURFACE
-40
OR SHEET
SAMPLE ORBIT
20
10
10
20
DISTANCES IN EARTH RADAII
DASHED THEORETICAL ----
SOLID EXPERIMENTAL ——
PROJECTION OF MAGNETIC FIELD TOPOLOGY ON NOON MIDNIGHT MERIDIAN PLANE
VAN ALLEN RADIATION BELTS

Figure 2



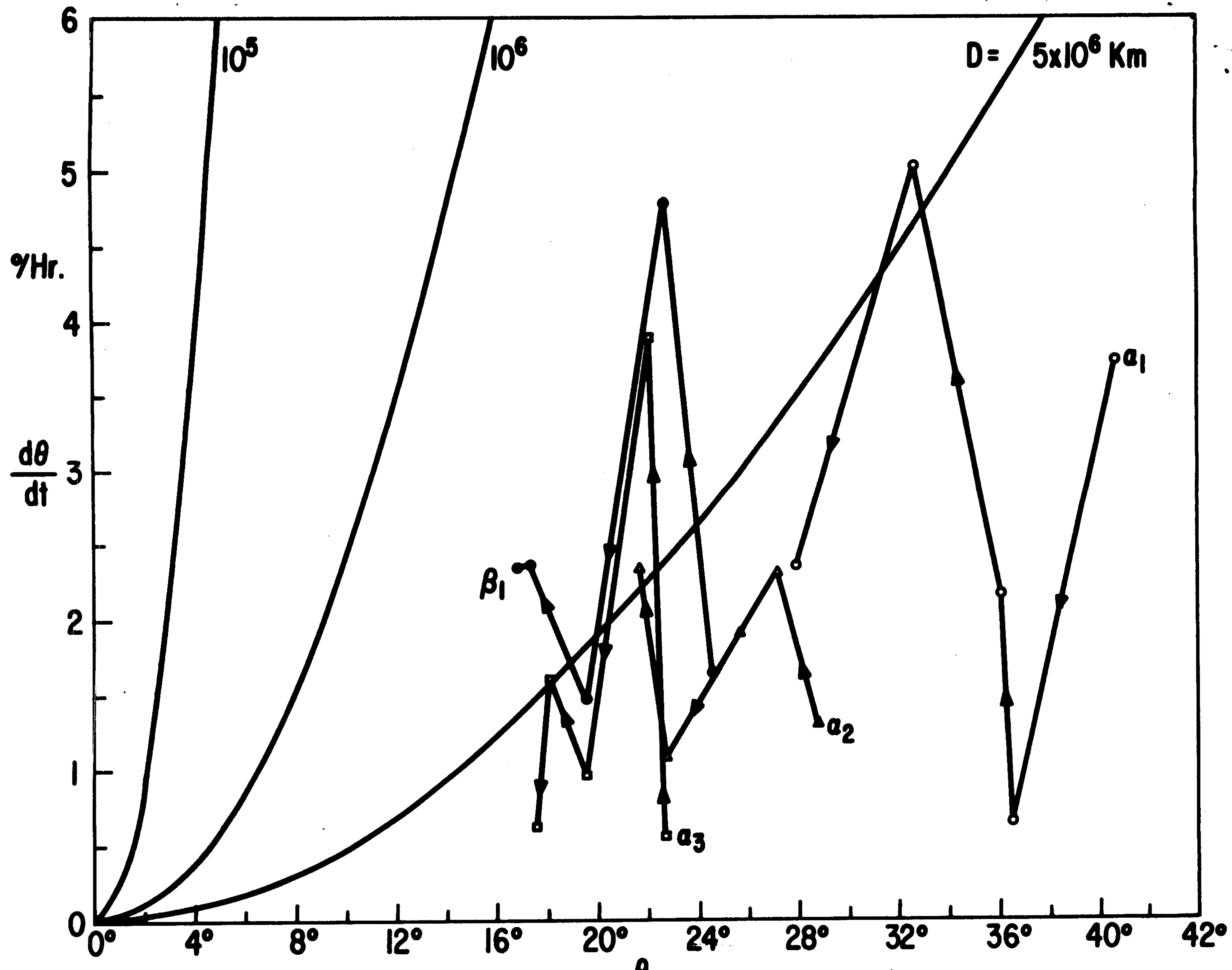
COMETARY CAPTURE OF INTERPLANETARY MAGNETIC FIELD

Figure 3



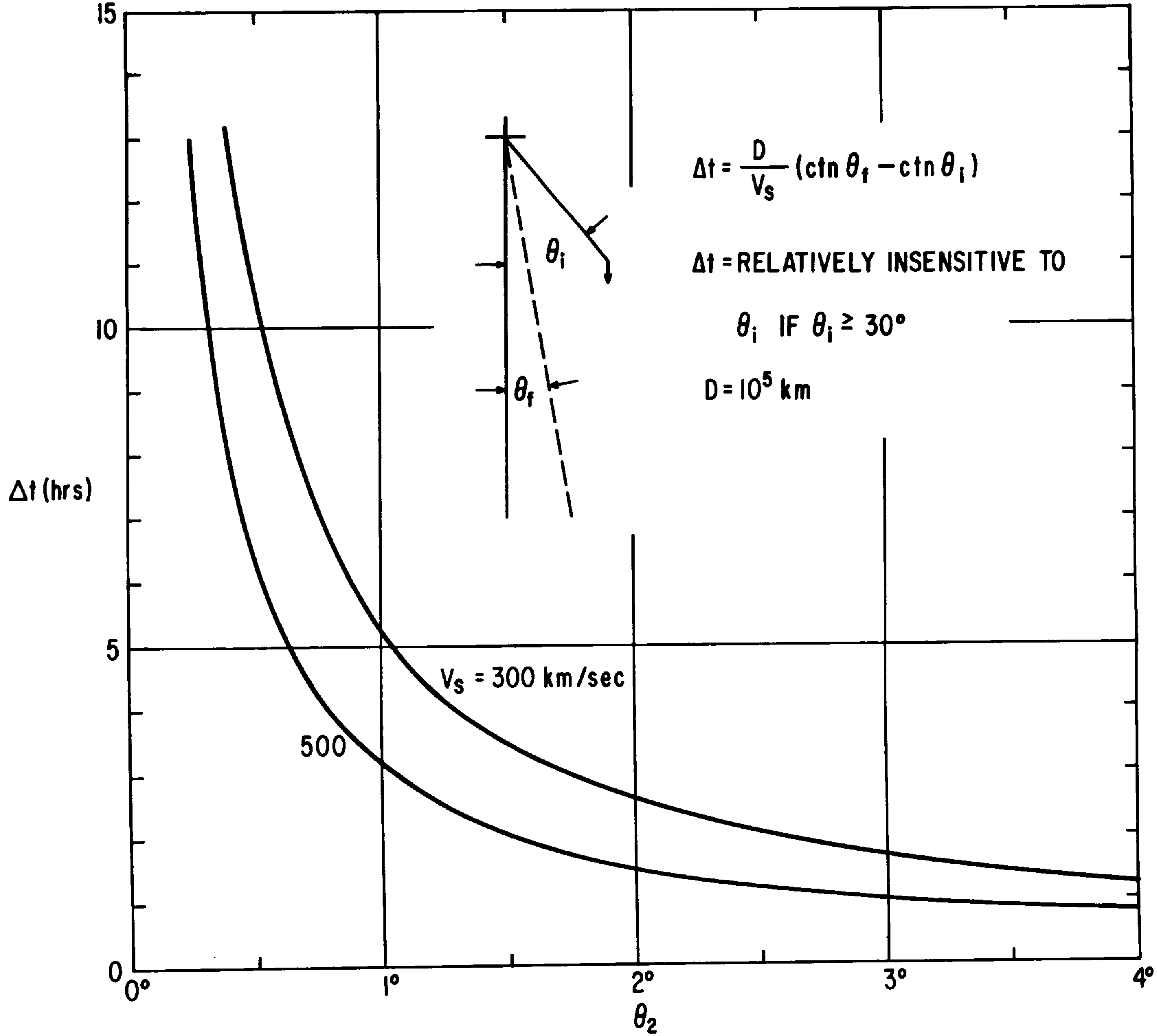
—L = 10⁶ km ----D = 10⁵ km
θ = tan⁻¹ (D/L)
dθ/dt = −sinθ cosθ Vs/L
dθ/dt = −sin²θ Vs/D
L
θ
D
Vs
700
500
Vs = 300 km/sec
dθ/dt (deg./hr.)
40°
30°
20°
10°
0°
0
5
10
15
20
θ

Figure 4



6
5
4
3
2
1
0
%Hr.
dθ/dt
10^5
10^6
D = 5×10^6 Km
a_1
a_2
a_3
β_1
0°
4°
8°
12°
16°
20°
24°
28°
32°
36°
40°
42°
θ

Figure 5



TOTAL TIME FOR RAY CLOSURE TO AXIS

Figure 6

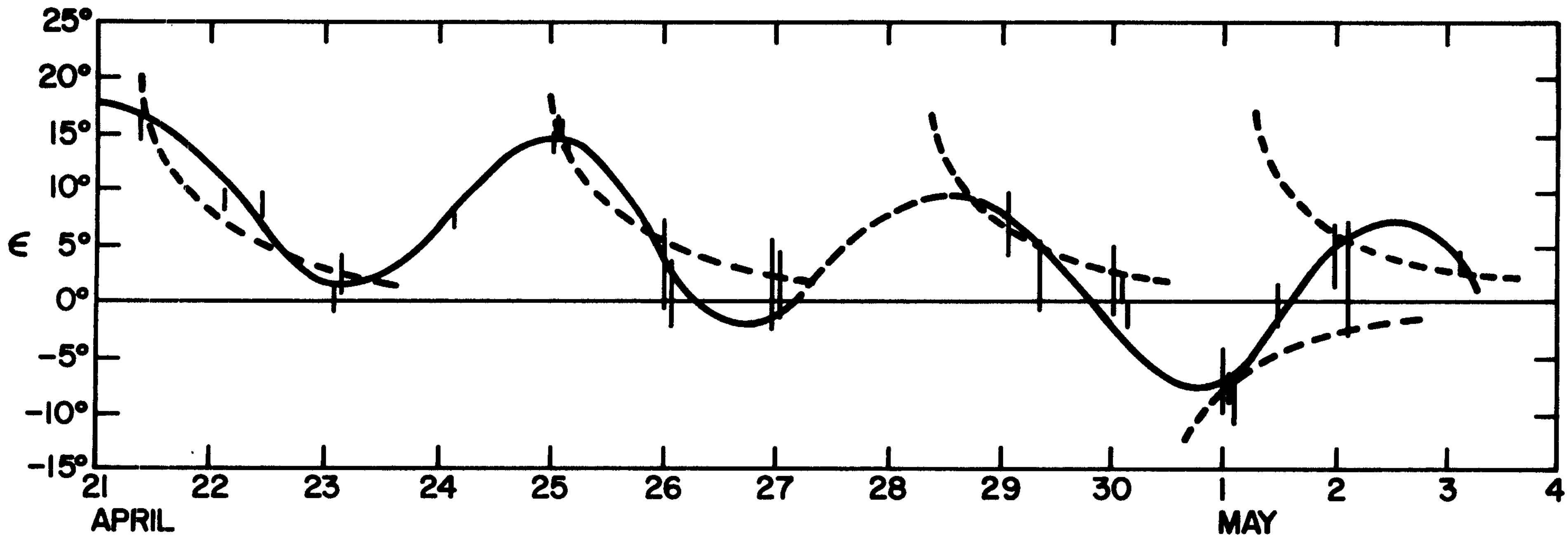


Figure 7