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THE MAGNETOSPHERE AND ITS BOUNDARY LAYER

BY

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The Magnetosphere and Its Boundary Layer

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The sun is an ubiquitous source of the Earth's energy input. More than 30 years ago in an attempt to explain the characteristic storm-time fluctuations of the geomagnetic field, a solar origin was postulated by Chapman and Ferraro (1933). It was suggested that the sun, at times of solar disturbances such as flares, emitted a neutral but ionized gas referred to as a plasma. When this plasma reached the earth it compressed the earth's magnetic field and contained it in a region of space surrounding the earth. The cavity in the solar plasma thus formed has been termed Chapman Ferraro cavity and the mechanism of its formation has been reasonably successful in explaining the temporal characteristics of various geomagnetic sudden commencement and other storm phenomenon. A naive representation of the interaction of the solar plasma with the earth's magnetic field is shown in Figure 1. Here the individual particles are assumed to be specularly reflected at the boundary of the earth's magnetic field. The region within the boundary the geomagnetic cavity has been referred to as the magnetosphere since the dominant factor influencing charged particle motion within this region of space is the earth's magnetic field. In the remainder of this paper the terminology will utilize magnetosphere rather than the Chapman-Ferraro cavity.

In an attempt to explain the fluctuations and characteristics of type I cometary tails, Biermann (1951) early in the 1950's suggested that a continual flux of solar plasma was required. This was similar to that postulated by Chapman and Ferraro (19 33) in their theoretical studies. Subsequent to this, Parker (1958) developed his hydrodynamic theory of the expansion of the solar corona referring to the phenomena as the "solar wind". This was predicted to consist of ionized gas with the principal constituent being hydrogen and flowing radially from the sun with flux values of 10^7 to 10^{10} particles/cm^2/sec. The energy of the particles was assumed to be approximately 1 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) and by the USSR (Gringauz, 1962). As a part of the overall NASA program investigating the characteristics of the interplanetary medium on a continuing basis, a series of interplanetary Explorer satellites has been developed. Figure 2 presents a photograph of the IMP-1 satellite, the first Interplanetary Monitoring Platform in this series which was successfully launched Novemger 27, 1963. It transmitted information on the characteristics of magnetic fields, plasmas and energetic particles in the region surrounding the earth for a period of more than six months. The apogee of the satellite was 31.7 R_e (earth radii) or 197,616 km with an orbital period of 93 hours. The interaction of the solar wind with the earth's magnetic field leads to a distortion of the earth's magnetic field as well as creating a disturbance in the flow field of the solar wind. This paper is concerned principally with the distortion of the earth's magnetic field and the resultant boundary layer region between the magnetosphere and the undisturbed interplanetary medium as measured by the IMP-1 satellite.

A broad compliment of experiments in the measurement of energetic particles, low energy plasmas and magnetic fields was instrumented for flight on the IMP-1 satellite. Figure 3 presents a summary of the various instruments, their measurement range and energy characteristics. Figure 4 presents the solar-ecliptic coordinate system appropriate for studying the interaction of the solar wind with the earth's magnetic field. In this coordinate system the X-axis is directed at all times from the earth's center to the sun, the Z -axis is chosen to be perpendicular to the ecliptic plane and the Y-axis forms a right handed coordinate system. In addition two angles are defined to represent a vector field: θ being the latitude, positive about the plane of the ecliptic and negative below and Φ the longitude, being 0^{o} directed to the sun and 180^{o} when pointed away from the sun. The characteristics of the highly eccentric IMP-I orbit are shown in Figure 5 as projected on the ecliptic plane. The first four orbits are shown with the figures adjacent to the trajectory indicating the time at which the satellite was at a particular position in space. Upon inspection of this figure it is noted that for approximately 60% of each orbit the satellite is well beyond 20 R_e distance from the center of the earth. A corresponding view of the orbit projected on a plane perpendicular to the ecliptic plane is shown in Figure 6. It is seen from these two figures that the orbit of IMP-1 is a very elongated ellipse. This paper shall utilize the experimental results obtained from the magnetometers (Ness et al, 1964) and the plasma probe (Bridge et al, 1964) to illustrate the characteristics of the magnetosphere and its boundary region.

The results of the magnetic field measurements on the inbound portion of orbit 1 are shown in Figure 7. The experimental data is presented as a magnitude $\bar{F}$ and two angles θ and Φ. Each data point represents the average of the vector magnetic field over a time interval of 5.46 minutes. The satellite is moving approximately 2 km/sec in this region of space so that over this time scale the satellite traverses a radial distance of approximately 660 kilometers. The measurements at geocentric distances beyond 10.7 R_e are seen to be highly variable in both magnitude and direction of the magnetic field. However, at a distance of 10.7 R_e the magnetic field abruptly increases in magnitude to a value of 60 gammas and assumes a stable configuration. The theoretical magnetic field to be measured in space, extrapolated by spherical harmonic analysis from surface measurements, is shown as dashed lines in this figure. The abruptness in both magnitude and direction as well as the temporal characteristics of the magnetic field at and beyond 10.7 R_e are identified as the boundary of the magnetosphere. It is seen that the observed magnitude is approximately twice that which would be theoretically predicted by considering the magnetic field in space to be only that due to the earth's magnetic field.

The containment of the earth's field by the solar plasma essentially doubles the magnetic field strength at the boundary surface. This can be understood simply by viewing the plasma impacting the geomagnetic field as being represented by a plane boundary across which the normal component of magnetic field must be zero. This is related to the phenomenon that in a highly conducting plasma, such as the solar wind, the magnetic field is "frozen into" the plasma motion. Hence as a plasma stream interacts with a magnetic field it does so by compressing the lines of force ahead of it. Mathematically this can be represented by placing an image dipole on the sunward side of the earth at an equal distance from the boundary and thus the normal component of the field is zero. This can explain both the magnitude increase of the observed magnetic field as well as the preservation of its direction. This simplified viewpoint is not completely correct but is substanially valid as long as the discussion refers only to the boundary near the subsolar or stagnation point.

Utilizing this simplified theoretical model of the solar plasma directly impacting the earth's magnetic field permits an interpretation of the solar stream properties on the basis of the size of the earth's magnetosphere. On the assumption that the subsolar radial distance to the magnetosphere boundary is 10.7 R_e it is seen in Figure 8 the plasma density ranges from 1 to 10 protons per cubic centimeter for velocities between 200 and 600 km/sec. These plasma values are representative of those which have been measured on previous satellites and space probes. Thus, it would appear that the general characteristics of the bounding of the earth's magnetic field by the solar plasma and the distance at which it occurs can be reasonably well understood on the elementary individual particle basis.

However, this is not the complete story on the characteristics of the magnetosphere and its boundary region. A correlated set of data from the MIT plasma probe and the GSFC magnetic field experiment is shown in Figure 9. This included the same interval shown in greater detail in Figure 7. The important feature of the MIT plasma detector, a Faraday cup, is that it is directionally sensitive to the flow of plasma. As the satellite rotates, the acceptance aperture of the detector scans the celestral sphere and includes orientations directly toward and away from the sun. Shown on this figure are the plasma flux values when the detector is pointed almost directly toward the sun and directly away from the sun. The difference between these two measurements is a measure of the anisotropy of the plasma flow. It is seen that at very large distances from the earth, greater than 16 R_e, the plasma flow is principally from the sun. However, at a distance of 13.6 R_e the flow of plasma suddenly comes apparently from all directions i.e. the flux is isotropic. It is also at this point that the fluctuations in the magnetic field increase appreciably. This is measured by the root-mean-squared deviations shown in the top most three curves illustrating the Z, Y, Z, components of the deviation of the magnetic field over the 5.46 minute time intervals. The fluctuating magnetic field and the isotropic plasma are observed until the distance at which the magnetic field abruptly increases to a very large value. This region of space surrounding the earth's magnetosphere in which a thermalized or isotropic plasma flux is observed to be correlated with fluctuating magnetic fields is termed the transition region of the magnetosphere boundary layer. It is this boundary layer which this paper studies, discusses its characteristics and attempts to present the current concepts related to its formation.

The first measurements clearly suggesting a continual containment of the earth's magnetic field were provided on the leeward side of the solar wind plasma flow by the Explorer X satellite in March, 1961 (Heppner et al, 1963). Over an interval of 48 hours the magnetic field and plasma was observed in a characteristic pattern in which strong fields directed radially from the earth were exchanged with periods during which radial plasma flow from the sun and fluctuating magnetic fields were observed. Conclusive experimental evidence for the bounding of the geomagnetic field by the solar wind was provided by the Explorer XII satellite measurements of the magnetic field and trapped particle fluxes as reported by Cahill and Amazeen (1963) and Freeman, Van Allen and Cahill (1963). Subsequent to the Explorer XII, the Explorer XIV satellite provided additional information on these characteristics. Thus far only limited summaries of the magnetic field in these regions have appeared although detailed discussions of the particle flux measurements have been presented in numerous articles. The plasma probes on board the Explorer XII and XIV did not reveal the isotropic fluxes observed on IMP-1.

Although the purpose of the IMP-1 satellite was primariàlly to investigate the characteristics of the interplanetary medium, the fact that the satellite is gravitationally anchored to the earth implies a traversal of the magnetosphere boundary region twice each orbit. The results of the IMP-1 satellite obtained in these traversals have substantially confirmed and extended our knowledge of the magnetosphere boundary layer. Our overall interpretation of the results is based upon an analogy with high speed aerodynamic flow. It is assumed that the magnetosphere acts as a blunt body which deflects the flow of the solar plasma. An important aspect of the rarefied solar plasma flow is that it contains a magnetic field. The average interplanetary magnetic field value has been accurately established by the IMP-I satellite (Ness and Wilcox, 1964). For the average solar proton of 1 Kev energy this leads to a Larmor radius of approximately 500 kilometers. This small characteristic length permits the use of a fluid continuum approximation. This is also about the spatial resolution with which the boundaries of both the magnetosphere and the transition region are sampled. In this magnetized plasma the propagation of disturbances is by magnetohydrodynamic waves as contrasted to the supersonic gas dynamic case when propagation is by acoustic waves. The appropriate propagation velocity, the Alfvén mode is presented in figure 10 as a function of plasma density and magnetic field strength. The important feature of this diagram is that it shows that for the interplanetary medium the Alfven velocity is characteristically less than 100 Km/sec. The estimated velocity of the solar plasma is 385 km/sec from the interpertations of solar magnetic fields and the interplanetary magnetic field (Ness and Wilcox, 1964). Thus, the flow of the solar wind is supersonic in the magnetohydrodynamic sense. Actually the flow is hypersonic since the equivalent Mach number or more appropriately the Alfvén number is greater than 4. Under such conditions the well known phenomenon of a detached shock wave develops in the gas dynamic case which encloses the disturbing body in a region of space with a boundary across which discontinuous changes in parameter values occur. At the present time the detailed quantitative study of the physical properties of the boundaries as observed by the IMP-1 satellite have yet to be completed. A particular limitation to their detailed study will be the spatial and time resolution limitations inherent in the spacecraft orbit and telemetry system. The detached shock wave which is observed in gas dynamics has characteristics which closely resemble that of the earth's magnetic field interacting with the flow of the solar wind. The termination of the turbulent transition region observed as the satellite moves radially away from the earth is interpreted to be the collisionless magnetohydodynamic shock wave associated with the interaction of the solar wind with the geomagnetic field. The IMP-1 data has provided the first accurate measurements of this phenomenon and indeed have mapped in detail its position relative to the earth sun line. This is a most important feature of the boundary of the magnetosphere since it may provide mechanisms for acceleration of charged particles.

Within and adjacent to the transition region, satellite detectors have shown transient fluxes of energetic electrons having energies greater than 45 Kev and total fluxes of $10^6/cm^2/sec$ an order of magnitude greater than background (Anderson et al, 1964; Fan et al, 1964). The IMP results suggest these observations are related to the formation of the magnetosphere and the shock wave boundary. The experimental evidence is very recent and the full theoretical significance of these data has yet to be completely evaluated. The particle fluxes which are observed are substantially less then those observed within the trapped particle belts within the earth's magnetic field. Hence it is not possible to consider these as hazards to manned space flight travel or to satellite hardware systems when one considers the more important contributions due to the Van Allen Radiation Belts.

A summary of the observed positions of the shock wave boundary and the magnetosphere boundary is shown in Figure 11. In this presentation the boundaries of the magnetosphere and transition region as detected by the magnetic field experiment are illustrated. It is seen that the geocentric distance to the shock wave at the stagnation point is approximately 13.4 R_e. but this distance increases away from the subsolar or stagnation point. This indicates an increase in the thickness of the transition region. The data also indicates that the magnetosphere is not closed, at least to the distance of 10 to 20 R_e behind the earth. The data are suggestive that the magnetosphere trails out far behind the earth in the fashion analogous to cometary tails. On this basis it is reasonable to expect the moon to intersect the earth's magnetosphere once each month (Ness, 1964).

A comparison of the theoretical shape and position of the shock wave boundary and magnetosphere boundary with observations is shown in Figure 12. Using a gas dynamic ratio of less than 2 but more than 5/3 permits exact comparison of the data. The small scatter in the position of the boundary crossings is related to the variability of the solar plasma flow. The comparison with theory (Spreiter and Jones, 1963). is very good and indicates a fundamental characteristic of the interplanetary plasma near the stagnation point and on the scale on which the observations are made. The standoff ratio between the shock wave distance and the magnetosphere boundary is shown in Figure 13 as a function of Mach number for two models of the shape of this magnetosphere. One is that of a sphere utilizing the theoretical results by Hida (1953) and the other utilizes the various madels in generally good agreement as represented by Beard (1960) and Spreiter and Jones (1963). The observed value of 1.31 $\pm$ 1% is seen to be between the two limits. For the observed Mach numbers the standoff ratio is reasonably insensitive to the exact value of Mach number. Hence time variations in the characteristics of the solar plasma do not affect to first order the standoff ratio, as do the magnetosphere shape and specific heat ratio used in the gas dynamic analogy.

A summary of the description of the magnetosphere and its boundary layer as projected on the plane of the ecliptic is shown in Figure 14. In this figure the interplanetary magnetic field is shown at an angle of 135 degrees to the

Earth Sun line and in a sense which is positive with respect to flux lines extending from the sun into interplanetary space. The projected positions of the IMP satellite are shown for the first 19 orbits and the positions of the magnetosphere boundary and shock wave are shown as average positions. Within the transition region is a turbulent plasma flow of very high temperatures with fluctuating magnetic fields. Within the magnetosphere a distorted geomagnetic field is observed, dependent upon the strength of the earth's magnetic field and the strength of the solar wind containing it. Present measurements do not indicate a termination of the magnetosphere on the leeward side of the solar wind flow. It is very possible that the earth's magnetic field trails out 100 R_e or more behind it, intersecting the orbit of the Moon (Ness, 1964).

ACKNOWLEDGEMENTS

I acknowledge the contribution of the other experimenters on the IMP-1 satellite, in addition to my own co-experimenters, Mr. C. S. Scearce and Mr. J. B. Seek.

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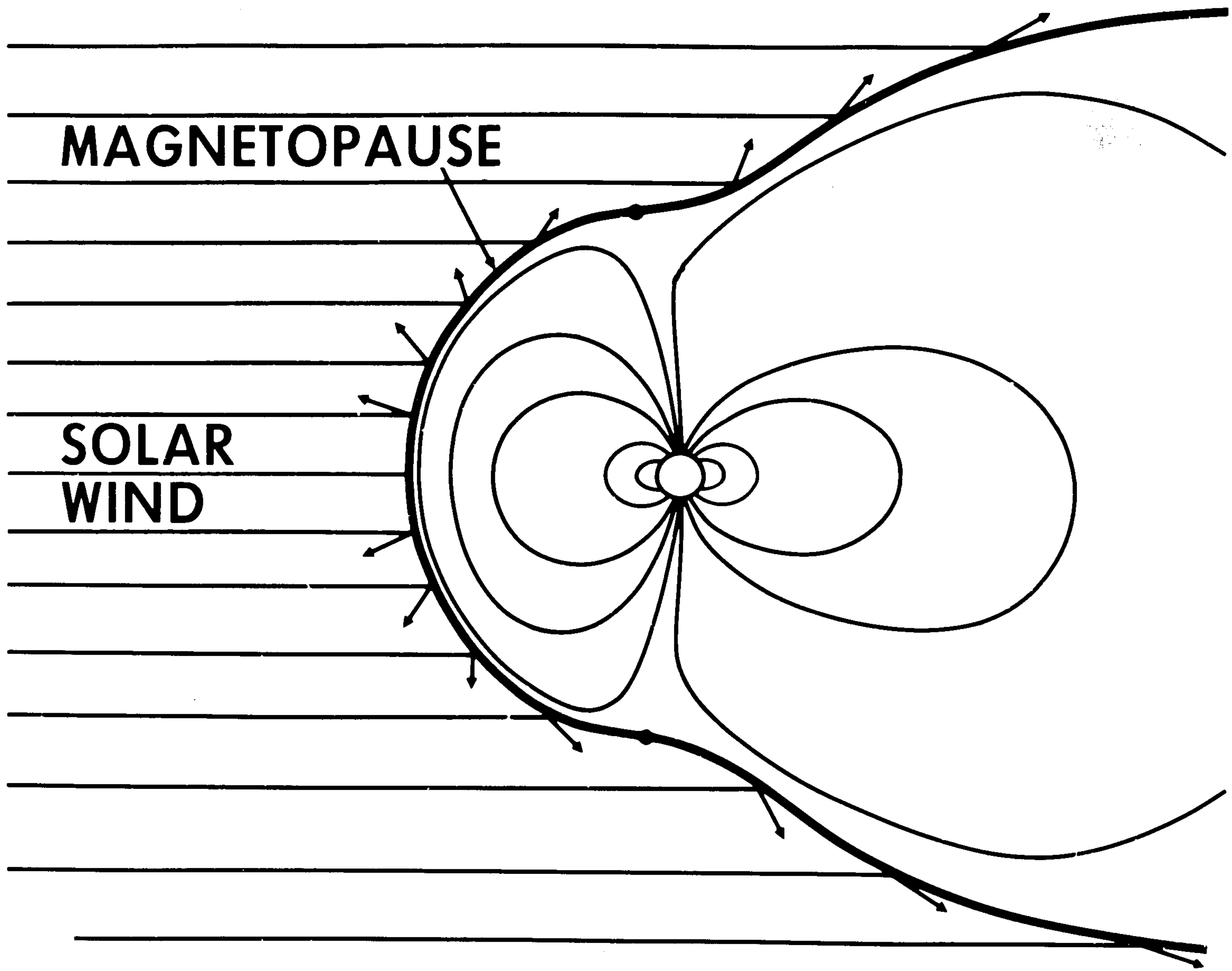
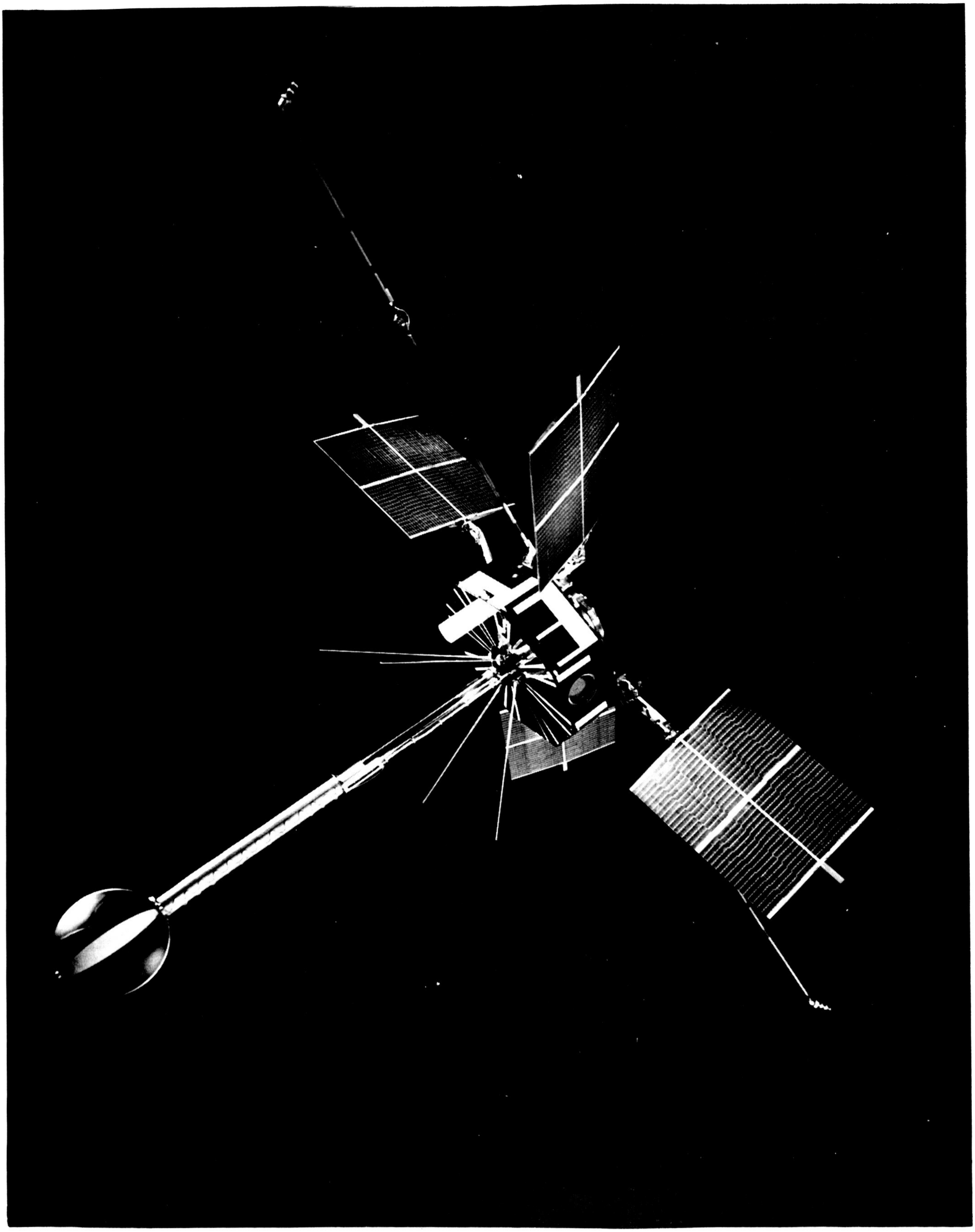
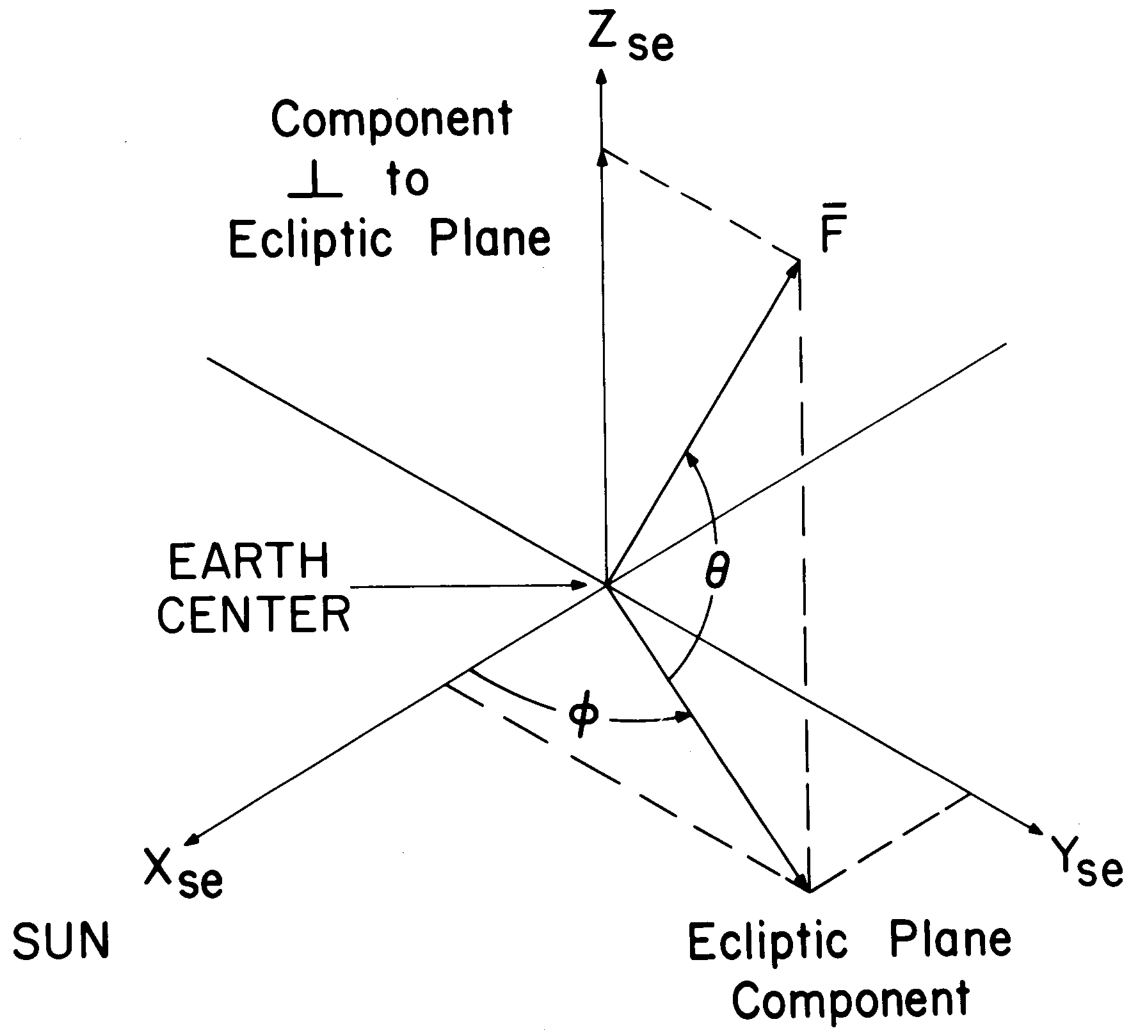

MAGNETOPAUSE
SOLAR
WIND

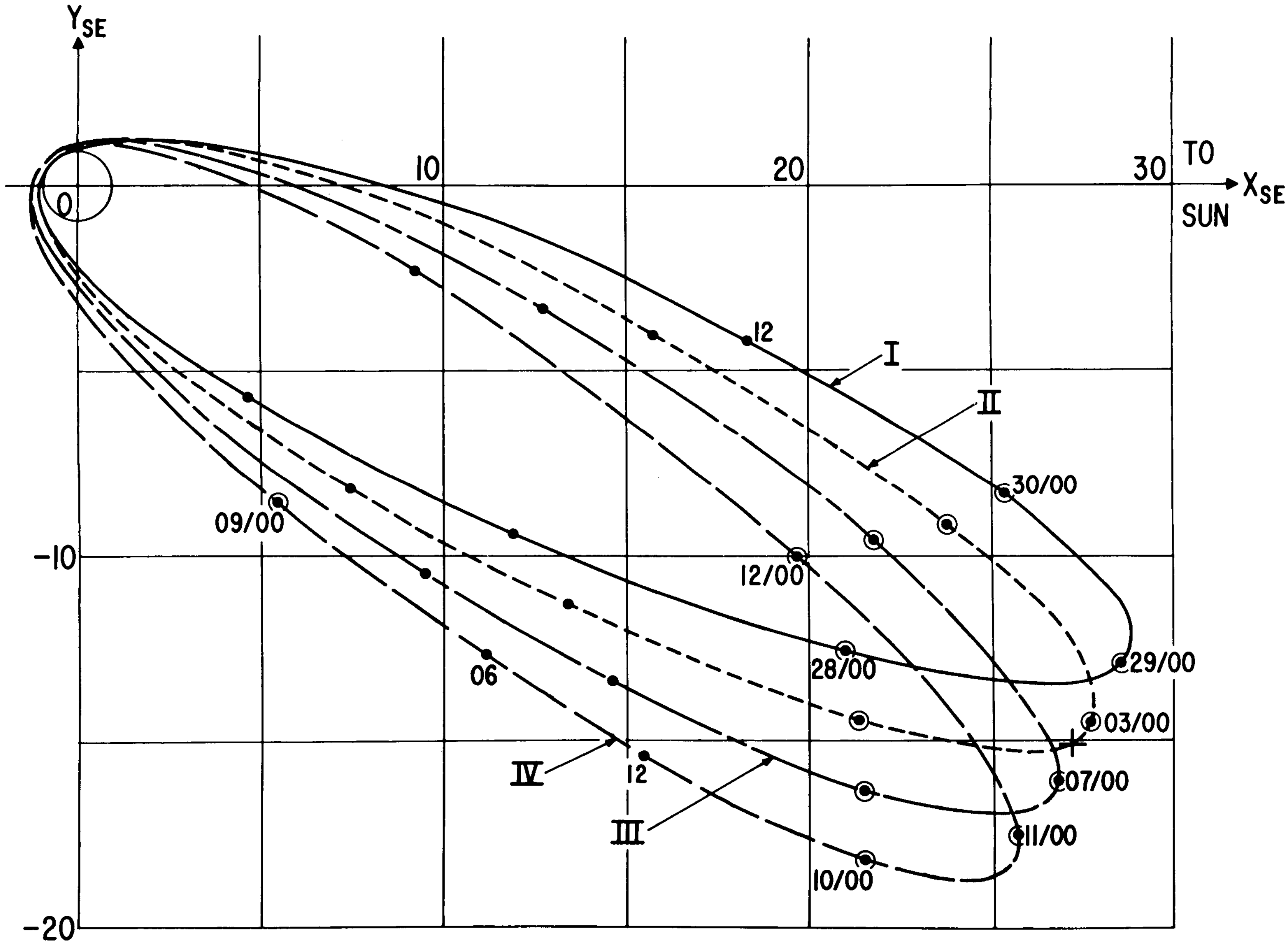


IMP EXPERIMENT REPERTOIRE

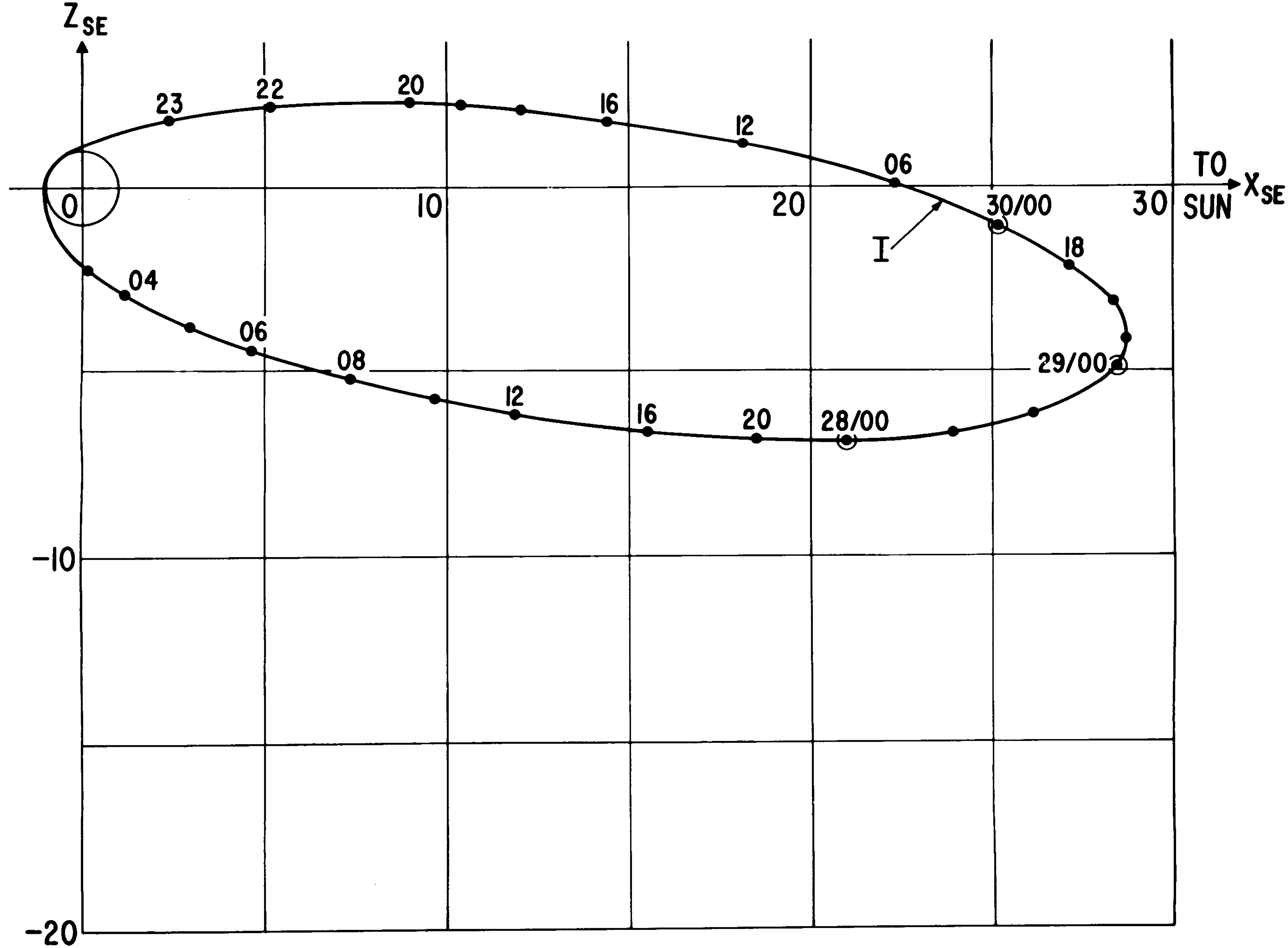
#	Study	Experiment	Characteristics
1.	Cosmic Rays	Range / Energy Loss	100 kev $< P <$ 200 mev
2.	Cosmic Rays	Total Energy / Energy Loss	Energy, Charge Spectra
3.	Cosmic Rays	Neher Ionization Chamber	Total Ionization
4.	Cosmic Rays	Orthognal Geiger — Counter Telescope	Spatial Isotropy CR Events
5.	Magnetic Fields	Rubidium Vapor Scaler Mag.	$\lvert\vec{B}\rvert <$ 2000 Gammas
6.	Magnetic Fields	Fluxgate Vector Sensor Mag.	$\vec{B} <$ 40 Gammas
7.	Solar Wind	Proton Flux — Electrostatic	200 ev $< P <$ 20 kev
8.	Solar Wind	Proton Flux — Faraday Cup	10 k/s $< V_p <$ 1000 k/s
9.	Solar Wind	Thermal Ion — Electrons (Charged — Particle Trap)	few ev $<$ electrons, ions



SOLAR ECLIPTIC COORDINATES



Y_{SE}
X_{SE}
TO SUN
0
10
20
30
-10
-20
I
II
III
IV
12
30/00
29/00
28/00
12/00
03/00
07/00
11/00
10/00
09/00
06
12



Z_{SE}
X_{SE}
TO SUN
0
10
20
30
-10
-20
I
23
22
20
16
12
06
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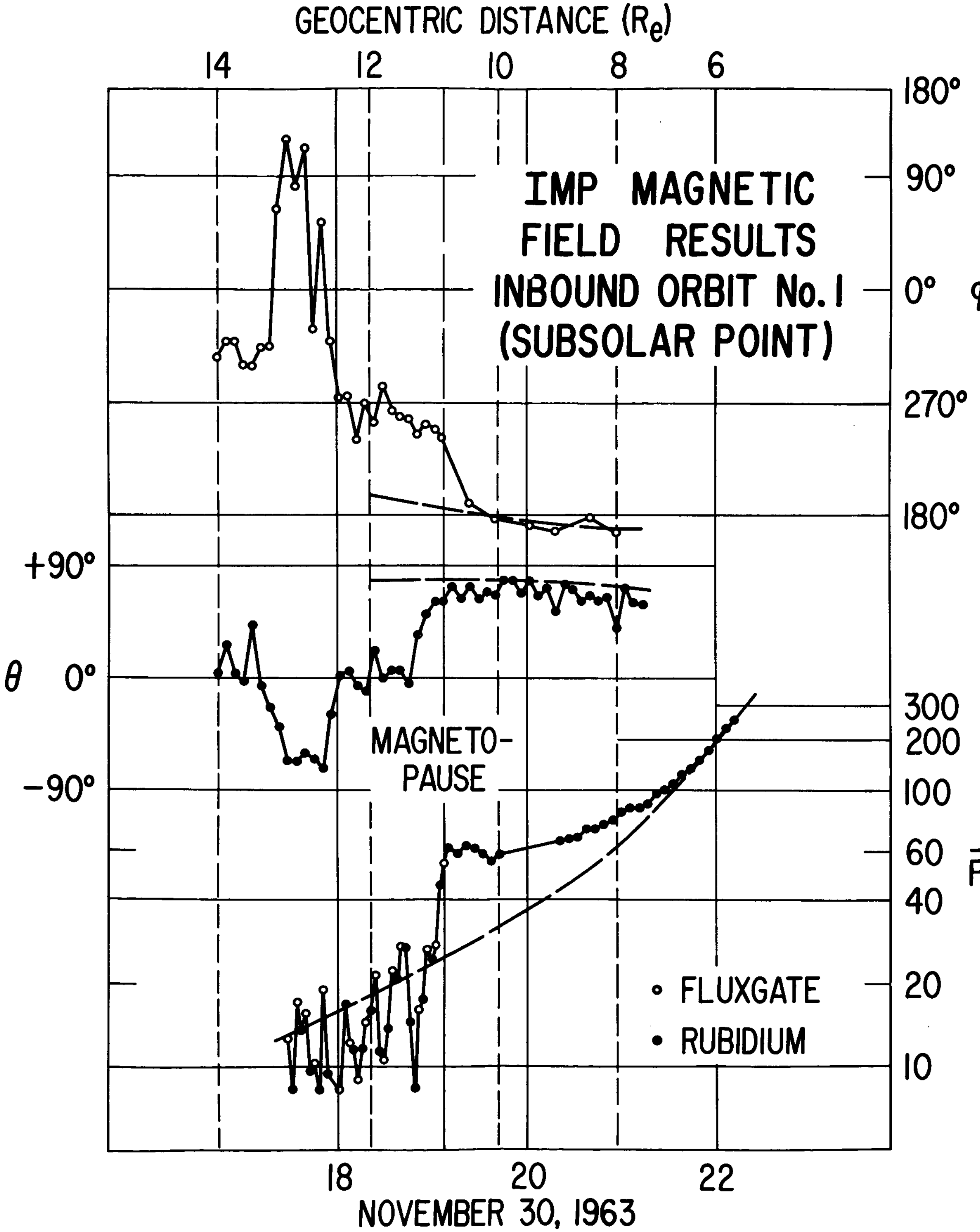
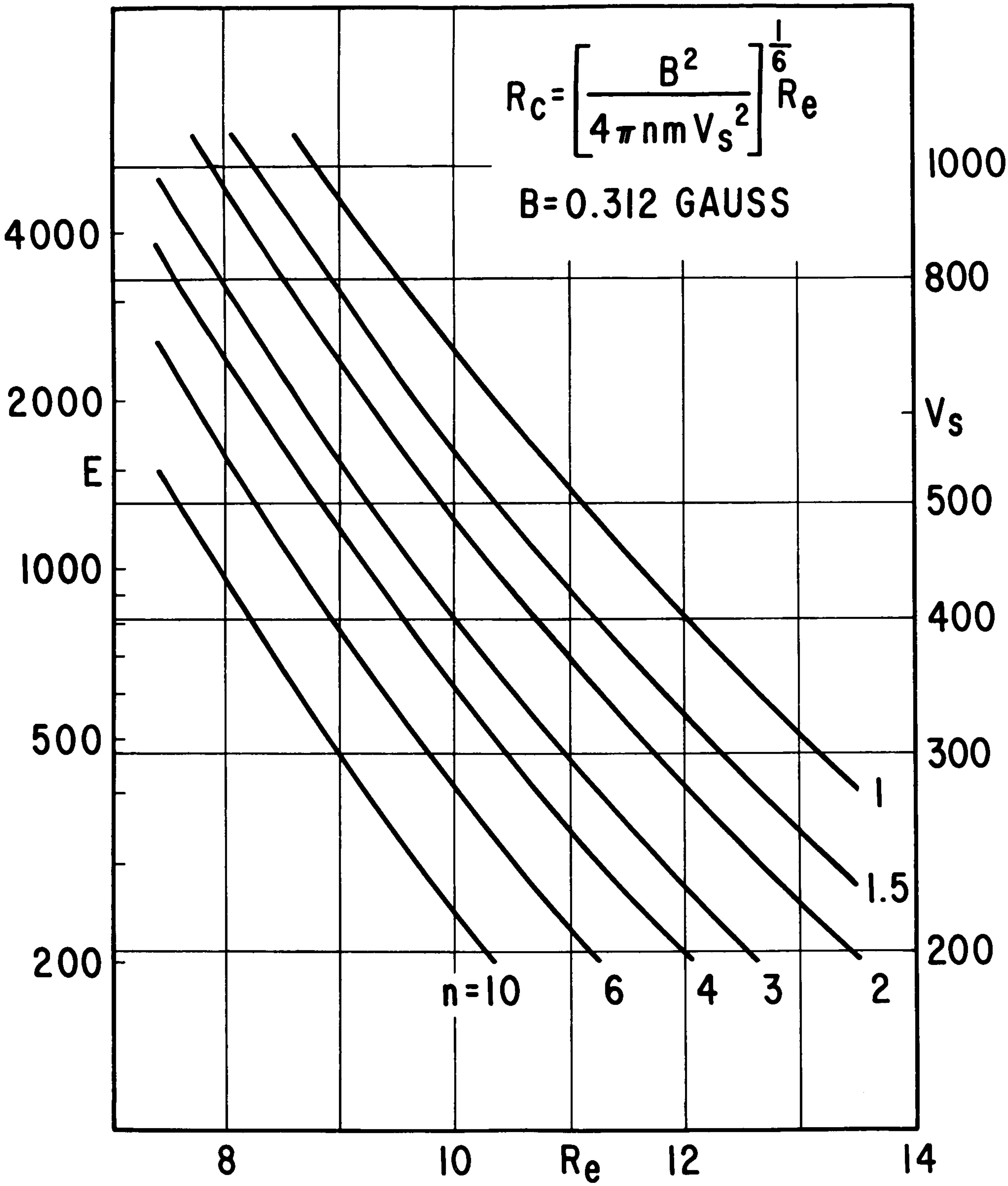
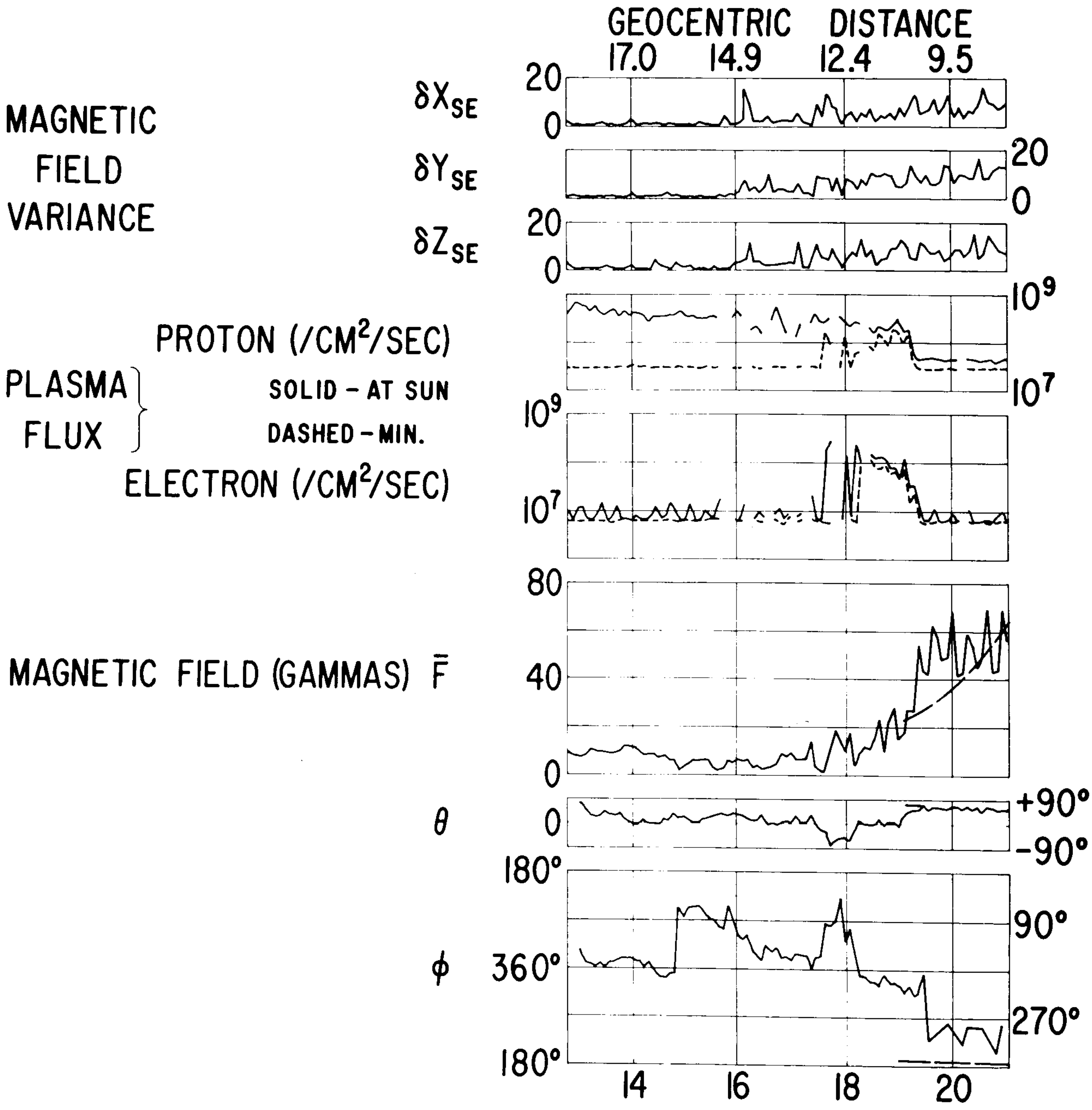
06
08
12
16
20

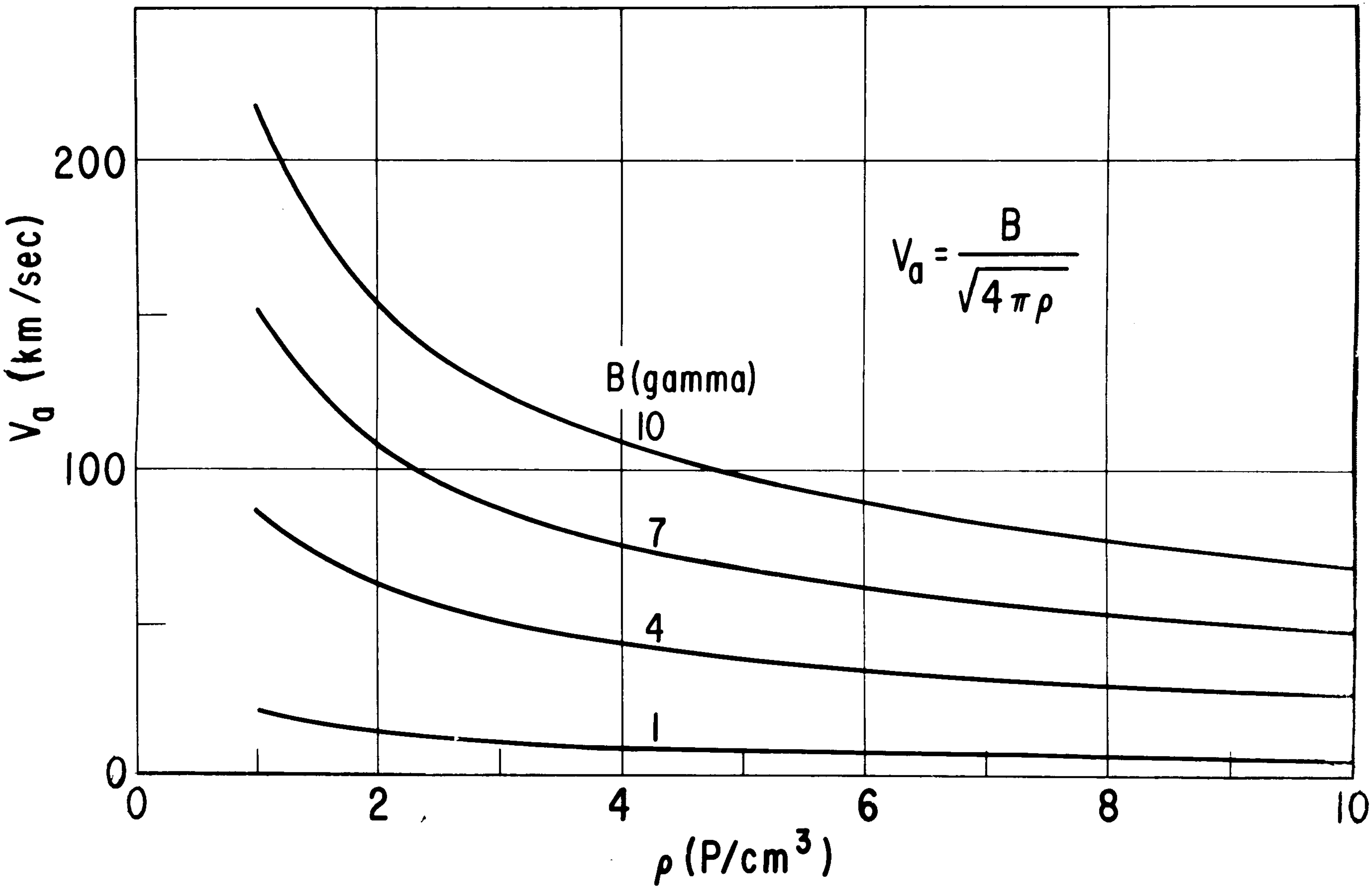

GEOCENTRIC DISTANCE (R_e)
14
12
10
8
6
IMP MAGNETIC FIELD RESULTS INBOUND ORBIT No. 1 (SUBSOLAR POINT)
180°
90°
0°
ϕ
270°
180°
+90°
θ
0°
-90°
MAGNETO-PAUSE
300
200
100
60
40
20
10
$\bar{F}$
FLUXGATE
RUBIDIUM
18
20
22
NOVEMBER 30, 1963



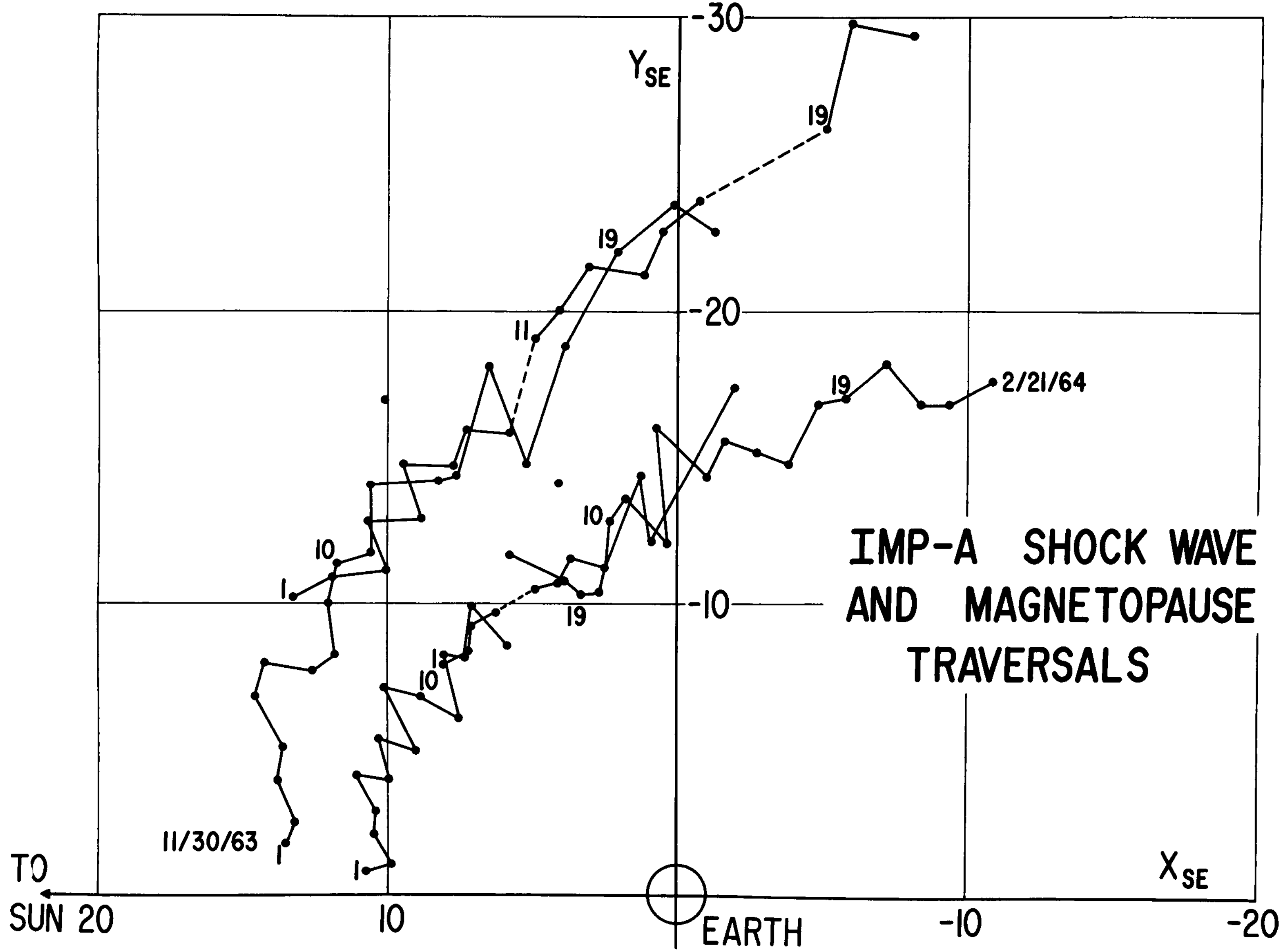
$R_c = \left[\frac{B^2}{4\pi n m V_s^2}\right]^{\frac{1}{6}} R_e$
B=0.312 GAUSS
4000
2000
E
1000
500
200
1000
800
V_s
500
400
300
200
1
1.5
n=10
6
4
3
2
8
10
R_e
12
14



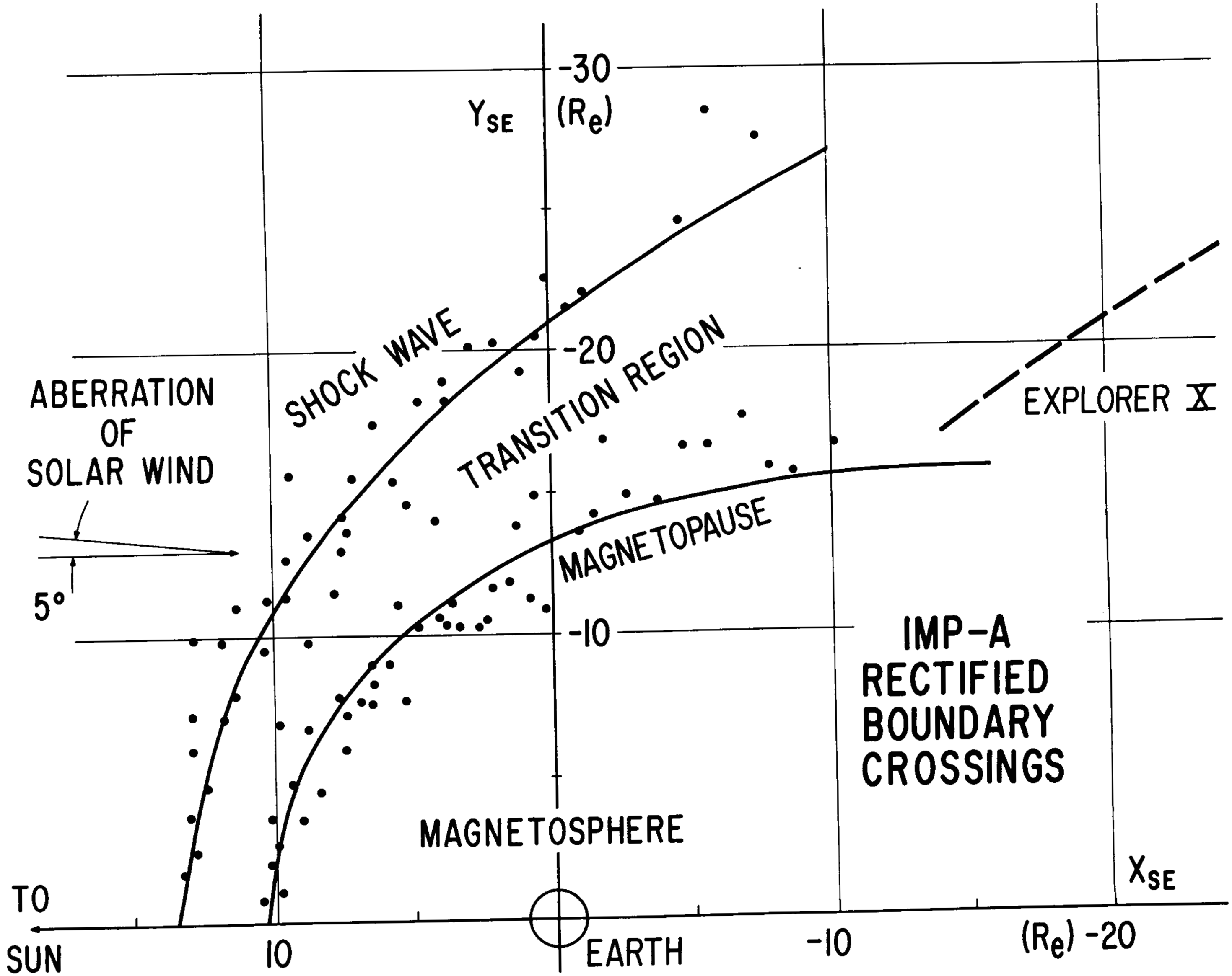
IMP PLASMA, MAGNETIC FIELD DATA - NOVEMBER 30, 1963

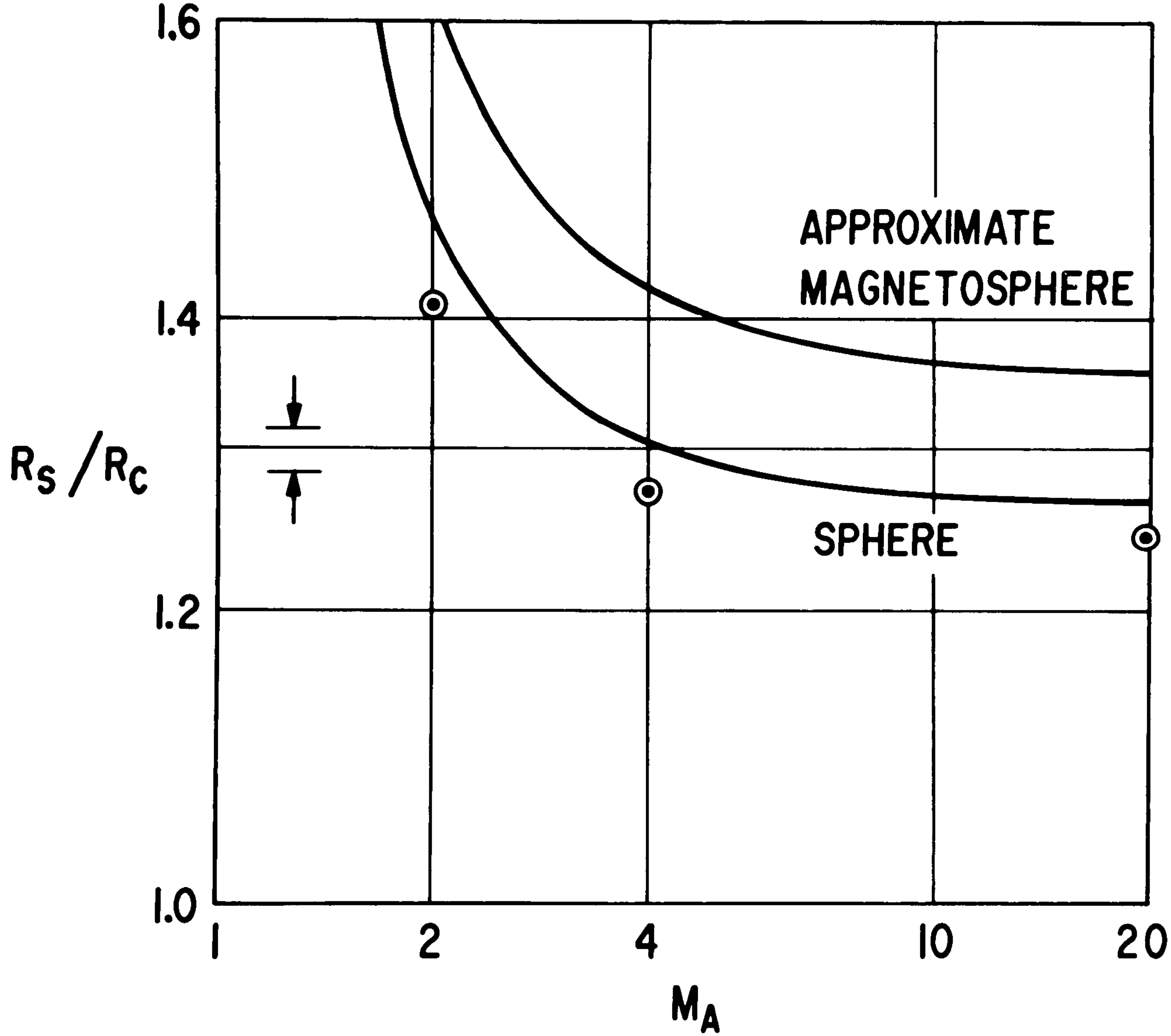


$V_a = \frac{B}{\sqrt{4\pi\rho}}$
B(gamma)
10
7
4
1
200
100
0
V_a (km/sec)
0
2
4
6
8
10
ρ (P/cm^3)



IMP-A SHOCK WAVE
AND MAGNETOPAUSE
TRAVERSALS
Y_{SE}
-30
-20
-10
X_{SE}
TO
SUN 20
10
EARTH
-10
-20
11/30/63
2/21/64
1
10
11
19


-30
Y_{SE} (R_e)
-20
-10
SHOCK WAVE
TRANSITION REGION
MAGNETOPAUSE
MAGNETOSPHERE
ABERRATION
OF
SOLAR WIND
5°
EXPLORER X
IMP-A
RECTIFIED
BOUNDARY
CROSSINGS
TO
SUN
10
EARTH
-10
(R_e) -20
X_{SE}



THEORETICAL POSITION OF SHOCK WAVE

MAGNETIC FIELD EXPERIMENT (IMP I)

GODDARD SPACE FLIGHT CENTER