

X-612-64-323

NASA TMX-55144

THE MAGNETOHYDRODYNAMIC WAKE OF THE MOON

GPO PRICE \$
OTS PRICE(S) \$
Hard copy (HC) \$3.00
Microfiche (MF) \$0.15

BY
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N65-19718

(ACCESSION NUMBER)	(THRU)
61	1
(PAGES)	(CODE)
TMX-55144	29
(NASA CR OR TMX OR AD NUMBER)	(CATEGORY)

FACILITY FORM 602

OCTOBER 1964



GODDARD SPACE FLIGHT CENTER
GREENBELT, MD.

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To be submitted to

October 1964

Journal of Geophysical Research

Abstract

19718

The possible detection of the lee wake of the magneto-hydrodynamic interaction of the solar wind with the Moon as observed by the IMP-1 satellite is discussed. The interplanetary magnetic field was found to fluctuate very rapidly and reach anomalously large values when the satellite was approximately eclipsed by the Moon in December 1963. Later data on the interplanetary field in February 1964 suggest that a detached lunar shock wave analogous to that observed by IMP-1 associated with the Earth may not be a permanent feature of the lunar environment. The approximate length of the wake region behind the Moon is 150 lunar radii at which distance the diameter of the region is about 70 lunar radii. A review of related studies on 29.5 day periodicities of K_p is presented. The solar wind interaction with the geomagnetic field extends the magnetosphere far behind the Earth. Hence, lunar synodic periodicities in K_p may reflect the interaction of the Moon with the Earth's magnetic tail rather than the moon's wake with the Earth.

Author

Table of Contents

	<u>Page</u>
1.0 Introduction.....	1
2.0 Magnetic field of the Moon.	3
3.0 Lunar Shock Wave.	6
4.0 Observations of the Lunar Magnetohydrodynamic Wake. . . .	10
5.0 Fluid Dynamic Considerations.	18
6.0 K_p and Related Studies	24
7.0 Summary and Conclusions	27
Acknowledgements.	29
References	
List of Figures	
Figures 1-17	

The Magneto-hydrodynamic Wake of the Moon

Norman F. Ness

1.0 Introduction

Lunar associated terrestrial phenomena have been studied extensively for many years in a wide range of scientific disciplines including geomagnetism (Chapman and Bartels, 1940). The principal geophysical effects which have been observed are due primarily to the direct or indirect influence of the Moon's gravitational field. The rotation of the Earth coupled with the elliptic orbit of the Moon introduces characteristic time modulations and fluctuations of geophysical phenomena with frequencies which can be accurately ascribed to a lunar gravitational influence. The various "tidal" phenomena with semi-diurnal to monthly periods occurring in both the solid and fluid Earth contain important lunar constituents (Melchior, 1957; Doodson, 1958, Siebert, 1960). Recently attention has been directed to a study of the expansion of the solar corona into interplanetary space. This can lead to a somewhat different and more complex lunar as well as solar influence on the immediate terrestrial environment. Fejer (1964) has suggested that at least a portion of the classical "tidal" variations in geomagnetism may be directly related to this phenomenon.

Subsequent to the early suggestion by Biermann (1951) that an adequate explanation of cometary tail structures required a substantial and continuous solar corpuscular flux, Parker (1958,1960) developed the hydrodynamic theory of the coronal expansion, referring to this plasma flow as the "solar wind". Direct measurements by satellite and space probes since 1959 have confirmed experimentally the existence of a solar plasma flowing approximately radially from the Sun with a positive ion flux between 10^7 to 10^9 particles/cm²/sec and energies between 200ev to 10 Kev (Gringauz, 1961; Bonetti et al, 1963; Snyder and Neugebauer, 1964; Bridge et al, 1964). A direct consequence of the radial solar wind velocity, the highly ionized coronal gases, and the rotation of the Sun is that the photospheric magnetic fields are extended in the plane of the ecliptic and twisted into the form of an Archimedes spiral (Parker, 1963). Accurate measurements of the interplanetary magnetic field have recently been made on the IMP-1 satellite (Ness et al, 1964) confirming certain of the theoretical predictions on the direction of the field and determining the average magnitude to be close to 5 gammas (Ness and Wilcox, 1964).

The interaction of the solar wind with planetary objects is an important factor in determining their space environment. The principal result of the solar wind impacting a planetary magnetic field is to confine the field to a region of space surrounding the planet. The existence of a quasi-static Chapman-Ferraro cavity (reviewed by Chapman (1963)) which excludes the direct

penetration of solar plasma into the geomagnetic field has been demonstrated by the recent satellite experiments of Bonetti et al (1963), Heppner et al (1963), Cahill and Amazeen (1963), Freeman et al (1963), Ness et al (1964), Anderson et al (1964), Bridge et al (1964), and Freeman (1964). An important feature of the interplanetary medium, with respect to its interaction with planetary objects, is that it is a magnetized plasma and thus supports magnetohydrodynamic wave propagation. In this sense the plasma flow is super-Alfvénic since the velocity of magnetohydrodynamic wave propagation is less than 90 km/sec while the solar plasma velocity is between 300-900 km/sec. This leads to Alfvén Mach numbers usually greater than 4.

This paper is concerned with an expanded discussion of possible direct experimental evidence of the magnetohydrodynamic interaction of the solar wind with the Moon as obtained by the IMP-1 magnetic field experiment (Ness et al, 1964). During the month of December 1963 the IMP-1 satellite appears to have been located within the downstream wake region of the Moon as it interacts with the solar wind. This interpretation of the data as well as the data itself will be discussed in the following sections.

2.0 Magnetic Field of the Moon

The existence or absence of an intrinsic lunar magnetic field is important in the development of adequate theories to explain planetary magnetism and the origin of the solar system. The presently accepted theory for the origin of the geomagnetic

field is based upon a fluid core sustaining a regenerative dynamo system of electrical currents (Elsasser, 1950; Inglis, 1955). The possibility of a lunar magnetic field maintained by such fluid motion has been theoretically investigated by Zharkov and Ulinich (1960) concluding that surface fields of 0.1 to 1.0 gauss are possible. The internal constitution of the Moon is not well known (MacDonald, 1961) but the possibility of a dense fluid core analogous to the Earth's seems highly unlikely. Another possibility is that sometime in the ancient past the Moon cooled down through its Curie point while in the presence of an external magnetic field thus acquiring thermo-remanent magnetization. This latter suggestion requires that the Moon was at one time nearly entirely molten whether it accreted from a large number of smaller masses or was formed from one large mass. At the present time this hypothesis cannot be conclusively argued (Levin (1960), MacDonald (1963)).

The only direct evidence of the state of a lunar magnetic field has been provided by the Soviet space probe Lunik II (Dolginov et al, 1961). Measurements with a sensitivity of about 30 gammas were performed along an impact trajectory to within a distance of 55 km from the lunar surface. No lunar magnetic field larger than the noise level was detected. The conclusion reached by these authors on the basis of a simple dipole model of the lunar magnetic field was that the effective lunar magnetic moment must be less than 10^{-4} that of the Earth's. As pointed out by Vestine (1957) and Neugebauer (1960) however,

the solar wind is sufficiently strong to confine the magnetic field of the Moon to a region very close to or even below its surface. In the latter case the solar wind directly impacts the lunar surface. On the assumption that

- (1) the Moon possesses a dipolar magnetic field with equatorial field strength = B_0 ,
- (2) the dipole axis is perpendicular to the solar wind velocity and
- (3) the solar plasma flows on around to the back side of the Moon rather than to be specularly reflected

then the radius of the lunar magnetic cavity boundary at the subsolar or stagnation point is given by :

$$R_c = R_m \left[\frac{B_0^2}{2\pi mnV_s^2} \right]^{1/6} \quad (2.1)$$

where V_s = velocity of solar wind (Km/sec)
 n = proton density (p/cm^3)
 m = proton mass (gms)

This is illustrated in Figure 1 and clearly shows that for the observed values of the solar wind any such lunar magnetic field will be compressed rather close to the surface of the Moon.

Gold (1964) has suggested an origin of a lunar field which incorporates the interaction of the magnetized solar plasma with the lunar body. The finite electrical conductivity of the Moon provides a mechanism for the trapping of the interplanetary

magnetic field. The model proposed has not been quantitatively developed. It depends critically upon the magnetic Reynolds number of the Moon, requiring that the interplanetary field be obstructed in its motion through the lunar body so that lines of force are accumulated and compressed on the sunlight hemisphere. This must occur for a time interval sufficiently long that a quasi-static field configuration can develop in spite of the rotation of the Moon and the observed variability of the direction of the interplanetary magnetic field.

3.0 Lunar Shock Wave

The presence or absence of a lunar magnetic field is important in determining the detailed characteristics of the solar wind interaction with the Moon. Far downstream it is not as clear how important any lunar field may be in determining the characteristics of the resultant interactions in the solar wind as it resumes a free stream flow. The overall situation may well resemble more closely the interaction of the solar wind with comets (Marochnik, 1963) rather than its interaction with the geomagnetic field. For the present study, the most pertinent feature of the solar wind interaction is the distance behind the Moon to which observable effects of such magnetohydrodynamic phenomena would persist. Various authors (Beard, 1960; Johnson, 1960; Piddington, 1960; Harrison, 1963; Lees, 1964; Axford et al, 1964 and Dessler, 1964) have presented qualitative arguments on the length of the geomagnetic "tail" behind the Earth. This region of the magnetosphere has yet to be experimentally probed and existing theoretical treatments are limited in their scope.

The best efforts thus far have utilized the analogy with supersonic gas dynamics representing the solar wind as a viscous fluid and translating the particle characteristics of the plasma to a continuum property of the fluid.

The suggestion that a detached collisionless magnetohydrodynamic shock wave encloses the Earth's magnetosphere has been presented by Axford (1962) and Kellogg (1962) among others. Spreiter and Jones (1963) have applied classical supersonic flow theory to determine the location and geometry of the shock wave surface. The agreement between theory and observation is very good, requiring only a minor modification in the choice of equivalent specific heat ratio used in the fluid dynamic analogy to yield improved comparisons with the observations. The most critical point in these studies being the ratio at the stagnation point of the shock wave radius to the geomagnetic cavity radius. The success of this similitude argument has been verified experimentally only near the stagnation point of the solar wind interaction with the Earth's magnetic field. However this suggests its consideration for conditions far from the stagnation point, i.e. the tail region of the solar wind interaction with the geomagnetic field. This has been done by Lees (1964) who showed that a secondary shock or tail shock would develop in the wake of the plasma flow around the earth. Data obtained by the IMP-1 satellite which have yet to be analyzed will partially answer these important questions about the magnetic field topology within the geomagnetic tail.

In the absence of more definite knowledge about a lunar magnetic field the argument for a lunar shock wave is not on as firm a basis as in the case of the Earth. In the relatively weak interplanetary magnetic field the radius of gyration of a solar wind proton is comparable to the lunar radius. Table I presents representative values for the proton Larmor radius as a function of field strength and plasma energy (or velocity).

Magnetic Field Strength (γ)		10	5	2
Proton Energy	Velocity			
4 Kev	876 Km/sec	914	1828	4572
2 Kev	619 Km/sec	646	1292	3232
1 Kev	438 Km/sec	457	914	2286
500 ev	310 Km/sec	323	646	1616
250 ev	219 Km/sec	229	457	1143

TABLE I

Proton Larmor radius (in Kilometers) as function of particle Energy (or velocity) and magnetic field strength (gammas).

The Larmor radius is equal to or greater than the stand off distance of 550 km. of the shock wave at the stagnation point that is obtained using the value of $R_S/R_C \doteq 1.31$ as measured in the case of the Earth (Ness et al, 1964). For the case of a sphere Kellogg (1962) using Hida's (1953) analysis of a shock surrounding a spherical object determined the stand off ratio

to be approximately 1.25 for Mach values greater than 4. It may well be that in the case of the moon a collisionless shock wave analogous to the Earth's may not develop at all times, if indeed at all. Whether or not such a shock develops depends very critically upon the physical parameters in the interplanetary medium and the state of the lunar magnetic field. This point has also been discussed by Gold (1964) with regard to the direct penetration of the solar plasma into the lunar body.

The detailed characteristic of the lunar surface and atmosphere are strongly dependent upon whether or not the surface is shielded from direct impact of the solar wind by either a lunar field or a shock wave. Studies on these and related lunar surface characteristics have been performed by Bernstein et al (1963), Wehner et al (1963), Hapke (1964), Hinton and Taeusch (1964) and Kopal and Rackham (1964).

4.0 Observations of a Lunar Magnetohydrodynamic Wake

The IMP-1 magnetic field experiment has been described in an earlier publication (Ness et al, 1964) which should be consulted for a detailed description of the satellite, its orbit, the instrumentation and telemetry system and the general characteristics of the interplanetary magnetic field. In addition the interaction of the solar wind with the geomagnetic field is discussed. In the following presentation the positions of the satellite, earth and moon are initially presented in the solar ecliptic coordinate system defined as : X_{se} is the axis from the Earth to the Sun, Z_{se} is the axis normal to the ecliptic

plane and in the same sense as the Earth's angular momentum and Y_{se} which forms a right handed coordinate system. All distances are given in units of an Earth radius ($R_e = 6378.4$ Km) although in the final interpretation of the data a translation will be made to a lunar associated coordinate system using a scale in Moon radii ($R_m = 1738$ Km) .

The positions of the Moon and IMP-1 during December 1963 are shown in Figure 2 as projected on the plane of the ecliptic. The solar wind direction has been adjusted to appear to come from 5° west of the Sun in order to represent the aberration effect due to the heliocentric motion of the Earth. The orbital velocity of the Earth is 30 Km/sec and for a solar wind velocity of approximately 330 Km/sec the angular displacement is 5° . Ness and Wilcox (1964) have determined from a correlation of the solar photospheric magnetic field and the interplanetary field as measured on IMP-1 that the average solar wind velocity was approximately 385 Km/sec during the time interval November 27, 1963 to February 19, 1964. Thus the correction for a 5° aberration is slightly larger than would be justified on the basis of experimental data. The projected traces of the average position of the magnetopause and shock wave boundaries are also included in the figure in order to show when the satellite was outside of these boundaries and within the relatively undisturbed interplanetary medium. It is seen that on December 14 the satellite was close to apogee and approximately in line with the Moon with respect to the propagation of the solar wind.

This is a measure only in the XY plane however, and does not include the distance of the satellite either above or below the Sun-Moon line.

In Figure 3 the positions of the satellite and the Moon during the same time interval are shown projected onto the plane perpendicular to the X_{se} axis. The satellite was several Earth radii below the Moon during the entire period of interest, December 14-15. The location of the satellite with respect to the Moon as a function of time is summarized in Figure 4. The two angles λ_{xy} and λ_{yz} are introduced as a measure of the apparent angular displacement of the Moon with respect to the satellite as projected onto the XY and YZ planes respectively. The quantity D_{yz} measures the projected distance in the YZ plane, D_{sm} measures the distance from the satellite to the Moon and $D_y ' z$ measures the distance projected onto a YZ plane which has been rotated by 5° West so as to be perpendicular to the aberrated solar wind. These parameters show that on December 14 at approximately 0915 the satellite was close to being immediately behind the Moon. At this time the satellite was $37.8 R_e$ from the Moon and $8.7 R_e$ below the Sun-Moon line. The aberration of the solar wind by 5° leads to a change in the alignment of the satellite with regard to the Moon and solar wind as shown by the dashed curve in Figure 4. The time at which the satellite is closest to being aligned with the Moon-Sun direction occurs several hours in advance of the non-aberrated case although the distance is approximately the same. On the basis of these data the most probable time for the observation of solar wind interactions with the lunar body would be centered around 0900

December 14, on the assumption that the lunar wake extended in the general flow direction behind the Moon.

The 5.46 minute averages of the magnetic field obtained by this experiment for the time interval 1600 December 13 to 1600 December 15 are shown in Figures 5 and 6. The format for the presentation is identical to that used by Ness et al (1964). The two angles θ and ϕ measured the latitude and longitude respectively of the magnetic field vector in the solar ecliptic coordinate system. In figure 5 the first 9 hours of data show the characteristic behavior of the interplanetary magnetic field with a stable orientation and magnitude. At this time the magnetic field was directed approximately in the plane of the ecliptic ($\theta = 0 \pm 30^\circ$) and pointed back toward the Sun along the Archimedian spiral angle predicted for the interplanetary field ($\phi = 315^\circ \pm 20^\circ$). During this time the satellite is close to apogee, (geocentric distance = $31.7 R_e$) and far removed from any direct effects of the solar wind interaction with the Earth. As time progresses the field becomes variable in both magnitude and direction. The onset of this turbulence occurs at approximately 0130 December 14, and persists until 0900 December 15. Midway in this time interval the field magnitude reaches the anomalously large value of about 15 gammas for more than 3 hours, from 1800-2100 December 14, while the turbulent characteristics of the field as measured by the angle ϕ noticeably decreases. Following 0900 December 15 the magnetic field again resumes its characteristic stable configuration although it is not as stable as it was prior to these events.

Superimposed on the time plots are specific values of parameters related to the position of the satellite with respect to the Moon. It should be noted that when the satellite is closest to being in line ($\lambda_{xy} = 0$) the distance D_{yz} is not necessarily at a minimum. Indeed the minimum value of D_{yz} occurs at 1830 December 14 and is approximately the same time as the midpoint of the time interval during which the turbulent magnetic field observations were made. The closest aberrated distance, $D_{y'z} = 9.3 R_e$, occurs at 0840. The characteristics of the magnetic field during this time interval are unlike those during other occasions on which the satellite was in the interplanetary medium. The turbulence and large field values, as well as the orientation during the time of large field magnitudes suggest that the IMP-1 satellite passed through the turbulent lee wake of the Moon in the solar wind. The strong fields observed correspond to the magnetosphere of the Moon and the turbulent fields to the transition region between the lunar magnetosphere and the undisturbed interplanetary medium.

In Figure 7 the positions of IMP-1 and the Moon during January 1964 are shown as projected onto the ecliptic plane. This presentation is identical to that for December as shown in Figure 2. Here, however, the relative positions of the satellite and the Moon are seen to be quite different. The time at which IMP-1 is roughly aligned with the Moon occurs at 0730 January 13 but at this time the satellite is enclosed within the Earth's shock wave. Figure 8 presents the relative positions of IMP-1 and the Moon as projected onto the YZ plane. The

satellite is about in the same position relative to the plane of the ecliptic as in December but the Moon is considerably lower. A summary of the relevant position parameters related to the relative positions of IMP-1 and the Moon is given in Figure 9. The format is identical to that of Figure 4 and illustrates that during the 13th orbit when the satellite was in the lee of the Moon it was also within the region of space surrounding the Earth enclosed by the shock wave surface. The time at which the Earth's shock wave was traversed by the satellite is indicated by the solid vertical line. It occurred several hours after the satellite was aligned with the Moon and the Sun. The situation with respect to the aberrated solar wind direction does not favor the observation of a lunar wake since the satellite is seen to spend a longer time within the region of space associated with the solar wind interaction with the geomagnetic field. Thus the satellite motion in the month of January 1964, was such as to preclude being in a favorable position with respect to observation of the lunar wake. In spite of this the interplanetary magnetic field data for January 13 and 14 has been inspected in detail since the December observation extended over a time period of more than one day. It has not disclosed any characteristics which are suggestive of a lunar wake, either in turbulence or field magnitude.

The last opportunity for observation of the lunar wake with IMP-1 occurred in February 1964 during orbit 20. On the succeeding opportunities for wake observations during the next six months,

the IMP-1 satellite was enclosed completely within the interaction region of the solar wind with the geomagnetic field. The steady precessional motion of the IMP-1 orbit in the solar ecliptic coordinate system is evident by comparing Figure 10 for February 1964 with that of Figure 2 for December 1963. The relative positions of IMP-1 and the Moon in February are such that they are approximately aligned at 0020 February 11. The position of these two objects in February projected onto the YZ plane is shown in Figure 11. Both the elongation of the IMP-1 orbit relative to Figures 3 and 8 and the location of the Moon below the ecliptic plane are a result of the heliocentric motion of the Earth about the Sun. It can be seen from this figure, however, that the two objects are very close to being in precise alignment. Figure 12 summarizes the relative positions of IMP-1 and the Moon as a function of time in a format identical to that used for Figures 4 and 9. The distance from the satellite to the Moon is seen to have increased now to $57.9 R_e$ while the minimum value for the distance in the YZ plane is $1.7 R_e$. For the aberrated solar wind the closest distance $D_{y,z}$ of $3.7 R_e$ occurs at 1640 February 10.

The magnetic field data for the time interval 0430 February 10 to 0430 February 12 is shown in Figure 13 and 14. The data in Figure 13 illustrates the outbound traversal of the shock wave associated with the Earth's magnetosphere at a distance of $30.3 R_e$ at 0958 February 10. The characteristic of large turbulent fields in the transition region is clearly evidenced. Also

shown and to be discussed in a future separate publication on the magnetic field characteristics in the transition region is the compressed and reasonably well aligned magnetic field such as were first observed by Explorer X (Heppner et al, 1963). The abruptness of the shock boundary, as shown by the variance plot, is a persistent feature of the shock phenomena in which the thickness is small and comparable with the ion gyro-radius. Subsequent to the outbound shock wave traversal the magnetic field in interplanetary space is somewhat variable in direction as measured by θ and ϕ but is not turbulent in the same sense as in the transition region as measured by the variance characteristics. However, during the time interval 0400 to 1200 February 11 there is a small increase above the noise level in the turbulence as measured by the variance. At the same time the variability between successive values of θ and ϕ is increased. However, during the time interval while the variance is higher than the noise level, the field is at its lowest value, less than 3 gammas, during this sample of the interplanetary medium on orbit No. 20.

Figure 14 contains the remainder of the interplanetary magnetic field data observed on orbit 20 and also illustrates the inbound traversal of the Earth's shock wave by the IMP-1 satellite. Again the characteristics of the transition region on the inbound pass are quite similar to those observed on the outbound traversal although they occur at a different geocentric distance, $23.6 R_e$, with a suggestion of a "precursor" at $24.3 R_e$.

The nonspherical symmetry of the shock wave surface enclosing the Earth coupled with the fact that the satellite traverses these boundaries at considerably different satellite-earth-sun angles on successive transits leads to these differences. Throughout the time interval during which the interplanetary medium was sampled, features similar to the December 1963 observation can not be seen. At this time it is suggested that the February 1964 data show characteristics which are similar in some respects but are not as conclusive an evidence of a lunar wake as observed in December 1963.

5.0 Fluid Dynamic Considerations

The classical magnetohydrodynamic problem of the interaction of a spherical object with a conducting fluid in the presence of a magnetic field has been treated by Stewartson (1956), Imai (1960) and Ludford and Murray (1960) among others. For the case of either compressible or incompressible fluid flow a downstream wake always develops for large or small magnetic Reynolds numbers as long as the magnetic field strength is small (Sears (1960)). This is measured by the ratio of free stream velocity (V_s) to the pure Alfvén velocity (V_a) or the geometric mean (V_a^*) of the Alfvén and sound velocities. This ratio, V_s/V_a or V_s/V_a^* , must be greater than unity in order that a lee wake develop and effectively determines whether or not the presence of the body in the flow field can be communicated upstream by magnetohydrodynamic wave propagation. A major limitation in the quantitative use of the presently available analytical treatments

is that they employ restrictive assumptions which are not justified in the case of the interaction of the solar wind with the Moon. In general these include one or all of the following: infinitely conducting fluid, magnetic fields aligned with the flow velocity, nonconducting or infinitely conducting body, and collision mean free paths much smaller than other lengths characteristic of the flow. The case of the Moon in the solar wind satisfies few of these assumptions and thus direct comparisons are not possible. Further development of analytical studies on collisionless magnetohydrodynamic shocks (see review by Kantrowitz and Petschek (1964)) is required for application to the present problem.

In the case of the interaction of the solar wind with the geomagnetic field rather successful results, at least near the stagnation point, have been obtained through use of a pure fluid dynamic analogy. A general review of the use of the aerodynamic similitude and its application to the solar wind interaction with the Earth's magnetic field has been given by Levy et al (1964) and Lees (1964). On this basis an important aspect of the interpretation of the magnetic field data on IMP-1 is that the free stream Mach number can provide a measure of the angular width of the shock surface associated with the interaction. (Michel (1964) has treated this problem assuming complete magnetohydrodynamic flow of the solar wind.)

However, the detailed characteristics within the interaction region and more importantly the wake region may not be completely specified. The Mach number in the case of the solar wind is

measured by the ratio of the plasma bulk velocity (V_s) to the magnetohydrodynamic wave phase velocity (V_a). In the interplanetary medium the velocity V_a is approximately given by the Alfvén velocity so that the Mach number is given by

$$M_a = \frac{V_s}{V_a} = \frac{V_s \sqrt{4\pi mn}}{B} \quad (5.1)$$

where B is the strength of the interplanetary field.

A plot of the Alfvén velocity as a function of the plasma density and magnetic field strength is shown in Figure 15. From classical supersonic flow (Hayes and Probstein, (1959)) the Mach angle β associated with a specific Mach number is given by

$$\beta = \sin^{-1}\left(\frac{1}{M_a}\right) \quad (5.2)$$

and represents the asymptotic direction of the shock surfaces far downstream from the obstruction. The Mach angle is plotted in Figure 16 as a function of the Mach number.

The average magnetic field in the interplanetary medium has been determined by the IMP-1 measurements to be 5.0 gammas. The average solar wind velocity has been estimated to be approximately 385 Km. Using these average values for the magnetic field and solar wind velocity and assuming a plasma density between 1.5 to 35 p/cm³ yields a Mach number between 4 and 20.

For these two values of Mach number the limits on the Mach angle are 14.5° and 2.8° respectively.

Obayashi (1964), in a review of previous satellite measurements related to the solar wind interaction, has adapted classical hydrodynamic equations for approximating the geometry of the shock surface surrounding a spherical object.

Defining:

R_s = the radial distance to the shock from the center
of the sphere at the stagnation point

R = the radial distance to the shock surface

ϕ = the angle between R and R_s , then he deduces that :

$$R = R_s \left[\frac{1 + \sec \beta}{1 + \sec \beta \cos \phi} \right] \quad (5.3)$$

A translation of the position of the IMP-1 satellite to a lunar set of coordinates has been made for the pertinent time periods in December 1963 and February 1964. The position of the satellite in these lunar associated coordinates is shown in Figure 17 with the abscissa being given by D_{xy} or D_{xy}' where

$$D_{xy} = \sqrt{(D_{sm})^2 - (D_{yz})^2} \quad (5.4)$$

$$D_{xy}' = \sqrt{(D_{sm})^2 - (D_{y'z})^2}$$

and the ordinate by D_{yz} or $D_{y'z}$. This presentation essentially assumes that far down stream from the Moon the lunar wake region is cylindrically symmetrical about the solar wind flow direction. Superimposed on these trajectory positions are the two shock surfaces corresponding to Mach numbers 4 and 20. These surfaces assume that the lunar magnetic field strength is inherently less than a few hundred gammas and that the shock stand off ratio $R_s/R_m = 1.25$. It is seen that if the flow is such that the Mach number is less than about 10 then the position of the satellite in December 1963 is well within the shock region of the lunar wake. If the Mach number of the flow is less than about 40 then the satellite is within the shock for February 1964.

The detection of a lunar wake is definitely consistent with supersonic flow theory for the orbit No. 5 observation and with the orbit 20 observation. However, even though the wake was possibly observed in December 1963, the interaction of the solar wind with the Moon is probably so variable that appropriate interplanetary conditions in the vicinity of the Moon are required in order to initiate the formation of a collisionless magnetohydrodynamic shock. Indeed using the average velocity of 385 km/sec and the average field strength of 5 gammas leads to a proton Larmor radius of 830 Km. This implies that on average the shock wave radius assumed for the Moon, 2173 Km, is only 2.6 times this critical value. The stand off distance is about 430 Km so that as previously noted it is somewhat questionable whether a lunar shock can develop that is

similar to the case of the Earth. In the case of the Earth the values of the parameters are such that the radius of the shock surface at the stagnation point is more than 100 times the proton Larmor radius. If one considers the field internal to the magnetosphere the radius of the magnetosphere is some 500 times the proton gyro radius since the magnetic field is 50 gammas or greater at the magnetopause boundary.

6.0 K_p and Related Studies

During the three month interval, December 1963 to February 1964, solar conditions were reasonably undisturbed. A geomagnetic storm observed on December 2, 1963, at 2117 UT was also measured in interplanetary space by the magnetic field experiment (Ness et al, 1964). During the remainder of the interval however, terrestrial magnetic activity as measured by the planetary index K_p was generally low. Because the solar-terrestrial conditions were relatively quiescent those disturbances which were observed and identified as the lunar wake have not been associated with any solar origin that might cause these variable properties of the interplanetary medium.

Recent studies (Bell and Defouw, 1964; Davidson and Martyn, 1964; Michel et al, 1964; Stolov and Cameron, 1964) on K_p have been directed to a resolution of the important question raised by the work of Bigg (1963a, b; 1964) on lunar influences on geomagnetic activity with a synodic period of 29.53 days. The original work was based on the physical supposition that any lunar magnetic field would shield the Earth from propagation of solar particles and thereby affect the level of terrestrial

magnetic activity. The specific result of this paper is that a turbulent lunar wake associated with a magnetohydrodynamic interaction of the solar wind with the Moon does exist. If such turbulence in the magnetic field implies equivalent turbulence in the interplanetary plasma it suggests further that fluctuations of magnetic activity could possibly be enhanced at about the time of new Moon.

The statistical significance of the early work has come under severe criticism, although the use of K_p as a quantity obeying the normal laws of algebra is inherently presumed by all participants in these discussions. In spite of this, separate but very similar correlative studies by two groups using identical data have been interpreted quite differently. Stolov and Cameron (1964) have concluded that a lunar effect exists but with the interesting result that the phase corresponds to a full Moon disturbance Michel et al. (1964) on the contrary state that their results are not statistically significant. Bell and Defouw (1964) using a superposed epoch method however concluded a lunar effect at full moon does exist statistically.

Davidson and Martyn (1964) using a superposed epoch and harmonic dial analyses on A_p conclude that no statistically significant effect exists. These authors conducted "a simple statistical experiment" to illustrate their case. A major problem in the analysis of a dimensionless index such as K_p or A_p is whether or not the statistical significance tests are based on valid statistical properties of the variable being investigated. In the case of these indices it is by no means clear that definitive answers can be obtained. Davidson and

Martyn (1964) also state that smoothing the data such as done by Bigg can introduce spurious, periodicities. This is not true for the weighting function used by Bigg (running average by three's) and is in general not true for most classical numerical filtering procedures. The general situation with regard to statistical studies on K_p or A_p is definitely not yet resolved concerning lunar periodicities. Finally a very recent study by Dodson and Hedeman (1964) indicated an anomalous periodicity of 29.5 days in solar cosmic ray data. This latest result is certain to contribute to our apparent lack of understanding of possible lunar related phenomena.

If the geomagnetic tail extends far behind the Earth to the distance of or beyond the Moon, that is at least $60 R_E$, then the Moon will interact with the tail and this may lead to temporal variations in the characteristics of the magnetospheric fields and particle populations independent of solar activity. Indeed such an extended magnetospheric tail has recently been proposed by Dessler (1964). A more pertinent discussion with respect to the magnetic field topology interior to the tail has been given by Axford et al (1964). Detailed studies on the IMP-1 data obtained while in the geomagnetic tail region are presently being conducted to determine the possible lunar effects during March, April and May of 1964, as well as the detailed topological characteristics of the field. On the basis of these IMP-1 results and others obtained on the Explorer X satellite (Heppner et al (1963)) and Explorer XIV (Cahill (1964)) it appears certain that the geomagnetic field and its tail extend far away from the Earth

in an anti-solar direction. Thus, interaction of the Moon with the Earth's magnetic tail can be reasonably anticipated. The studies of Stolov and Cameron (1964) and Bell and Defouw (1964) lend support to such a conclusion.

Howard et al (1964) have suggested that variations in the electron density in the cislunar medium during a solar eclipse are related to a shadowing effect in the lee of the Moon as it interacts with the solar wind. Although the maximum change in solar wind density required to explain the observations is rather high, 100 p/cm^3 , there is considerable difficulty in accurately removing changes caused by the ionosphere and magnetosphere. This propagation experiment on lunar associated changes in the cislunar medium may indicate a separate technique for the investigation of the magnetohydrodynamic wake of the moon during the time of new moon.

Summary and Conclusions

During the period in which the IMP-1 satellite was located in interplanetary space beyond the direct effects of the solar wind interaction with the geomagnetic field a unique disturbance was observed. This was characteristic of the transition region and magnetosphere tail associated with the solar wind interaction with the geomagnetic field. This temporal disturbance showed turbulent magnetic fields and enhanced magnetic flux values well above the normal interplanetary condition. This event is identified as the magnetohydrodynamic wake of the Moon's interaction with the solar wind. The use of an aerodynamic analogy, which has proven so successful in studying the Earth's interaction with the solar wind, shows that the satellite was within the primary shock region associated with a super Alfvénic solar wind flow. A second opportunity to investigate the lunar wake in January 1964 was obscured by the location of the satellite within the shock region of the solar wind interaction with the geomagnetic field. A third opportunity in February 1964, possibly detected a wake but it did not demonstrate the same characteristic features. At this time the satellite was some 200 lunar radii from the Moon.

The great distance at which the lunar wake is observed and the lack of quantitative descriptions regarding the Earth's magnetic tail preclude an estimate of the strength of any lunar magnetic field. However, the fact that a lunar wake was observed during December 1963 is suggestive of a lunar magnetic

field at the equatorial surface of several hundred gammas or more.

A major question raised by this paper is whether or not a shock wave due to the moon is expected to develop at all times in the interplanetary medium unless an intrinsic lunar magnetic field is present. It would appear that the absence of a strong field, and the small size of the Moon preclude a condition analogous to that in the case of the Earth in which a shock wave is usually expected to occur. The Larmor radius of the average solar wind proton is of the same order of magnitude as the lunar radius and thus the analogy with fluid dynamics is probably not justified.

The Russian measurements on the Lunik II spacecraft impacting the lunar surface indicate that the magnetic field of the Moon is not sufficiently strong to produce field strengths larger than 100 gammas at a distance of 55 Km. This can be understood on the basis of a compression of a lunar magnetic field by the solar wind. However, at the same time that this data was obtained scintillation counter data (Vernon et al, 1960) obtained at a distance of less than 1000 Km from the lunar surface indicated energetic particle flux values 100 times those found typically in interplanetary space. This value of 1000 Km is tantalizingly close to the lunar shock wave stand off distance. Indeed the magnetic field data for distances less than 1000 km are also larger and more variable also. This may indicate that shock region characteristics similar to that observed surrounding

the Earth may have been present surrounding the Moon at that time.

The fact that the Earth's magnetospheric tail does extend far behind the Earth may well lead to lunar associated variations of K_p or A_p at full moon as the Moon sweeps through the Earth's tail.

Acknowledgements

I am indebted to C. S. Searce and J. B. Seek for their important participation in the IMP-1 magnetic field experiment. Stimulating discussions of the lunar wake with Drs. E. K. Bigg, A. G. W. Cameron and T. Obayashi are hereby acknowledged. The comments of Dr. J. M. Wilcox are particularly appreciated.

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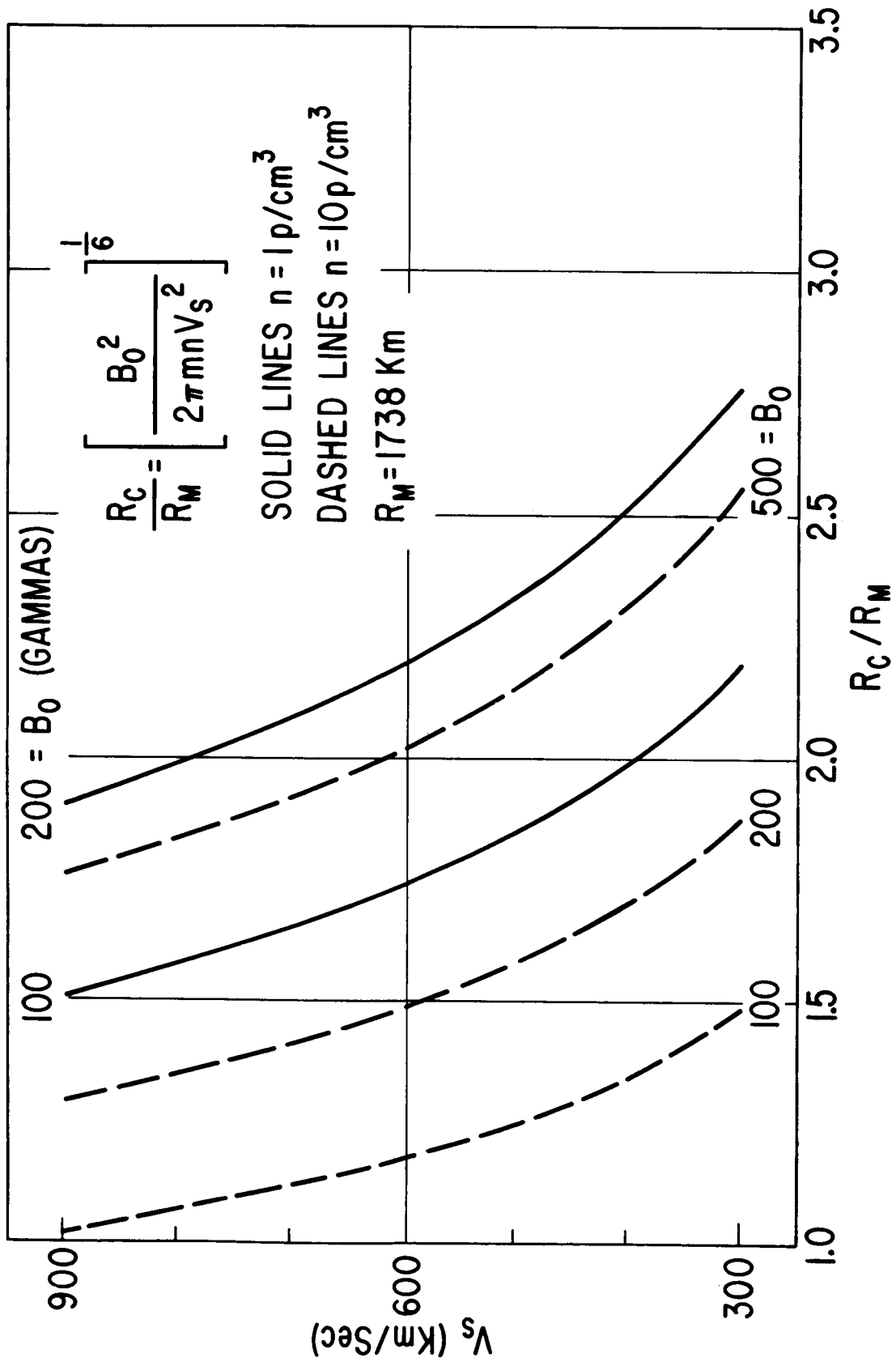
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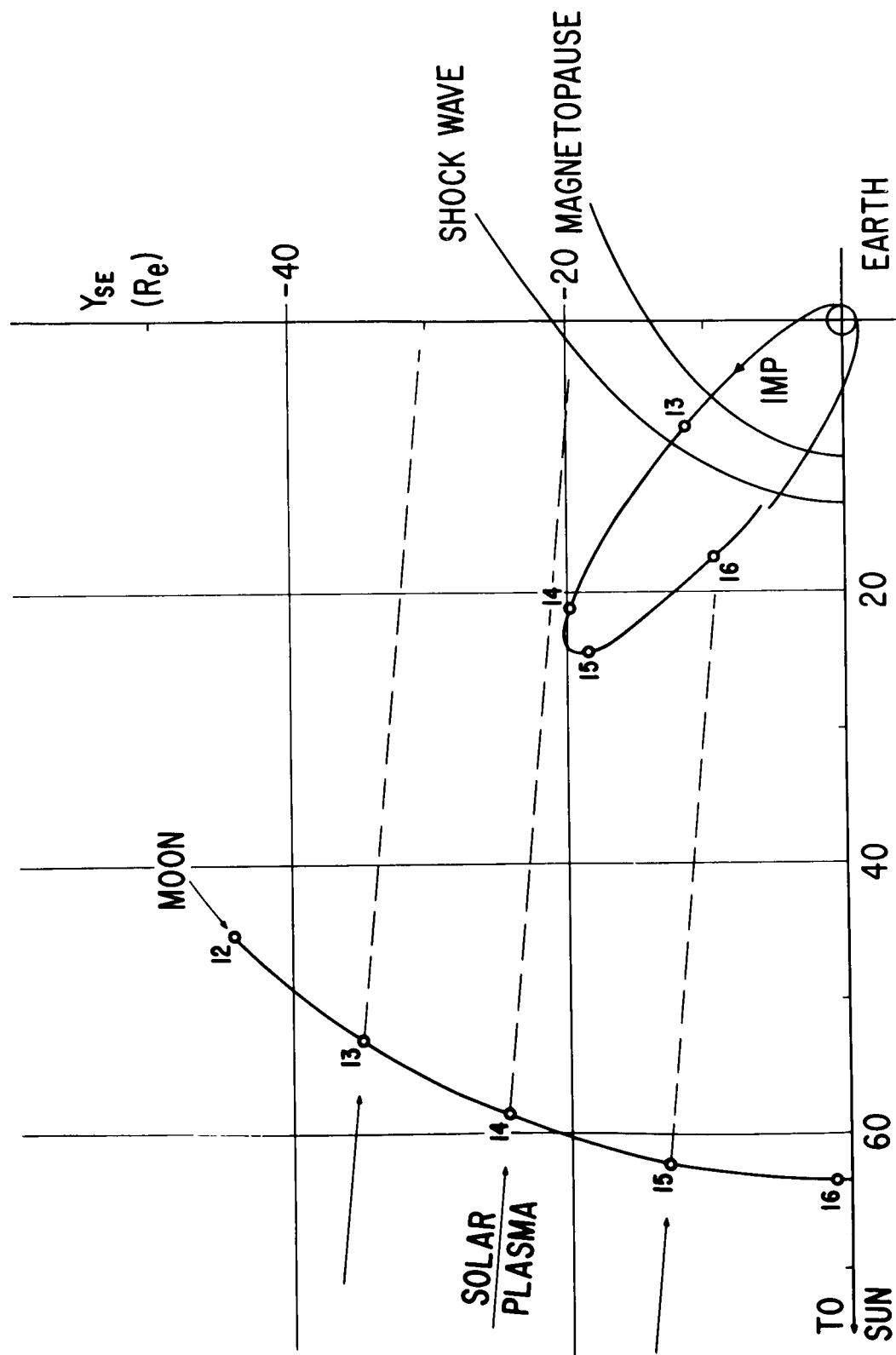
1. Lunar magnetic cavity radius of curvature (R_c) in units of lunar radius (R_m) as a function of the solar wind flux and equatorial field strength (B_0) of assumed lunar dipole.
2. Relative positions of IMP-1 satellite, earth and moon projected on ecliptic plane during period December 12-16, 1963 when the wake of the moon was detected in interplanetary space.
3. Relative positions of IMP-1 satellite, earth and moon projected on solar ecliptic Y-Z plane during period December 12-16, 1963 when the wake of the moon was detected in interplanetary space.
4. Variation of relevant earth, moon and IMP-1 satellite position parameters during period December 12-16, 1963. The wake of the moon was detected between 0130 December 14 to 0900 December 15. The time intervals of turbulence and of unusually strong fields are indicated.
5. Magnetic field data from orbit No. 5 December 14, 1963 illustrating IMP-1 entry into lunar magnetohydrodynamic wake from relatively undisturbed interplanetary space at 0130.
6. Magnetic field data from orbit No. 5 December 15, 1963 illustrating IMP-1 exit from lunar magnetohydrodynamic wake into relatively undisturbed interplanetary space at 0900 with large field magnitudes observed between 1800 to 2100 December 14.
7. Relative positions of IMP-1 satellite, earth and moon projected on ecliptic plane during period January 11-15, 1964.

8. Relative positions of IMP-1 satellite, earth and moon projected on solar ecliptic Y-Z plane during period January 12-16, 1964.
9. Variation of relevant earth, moon and IMP-1 satellite position parameters during period January 12-16, 1964.
10. Relative positions of IMP-1 satellite, earth and moon projected on ecliptic plane during period February 9-14, 1964 when a weak wake of the moon was possibly observed.
11. Relative positions of IMP-1 satellite, earth and moon projected on solar ecliptic Y-Z plane during period February 9-14, 1964 when a weak wake of the moon was possibly observed.
12. Variation of relevant earth, moon and IMP-1 satellite position parameters during period February 10-15 when a weak wake of the moon was possibly observed between 0400 to 1200 February 10.
13. Magnetic field data from orbit No. 20, February 10, 1964 , illustrating IMP-1 sampling of the interplanetary magnetic field and possible lunar magnetohydrodynamic wake after exit from transition region of the solar wind interaction with the geomagnetic field. The Earth's shock wave was traversed at a geocentric distance of $30.3 R_e$.
14. Magnetic field data from orbit No. 20, February 11, 1964, illustrating IMP-1 sampling of the interplanetary magnetic field and possible lunar magnetohydrodynamic wake before entry into transition region of solar wind interaction with geomagnetic field. The earth's shock was traversed at a

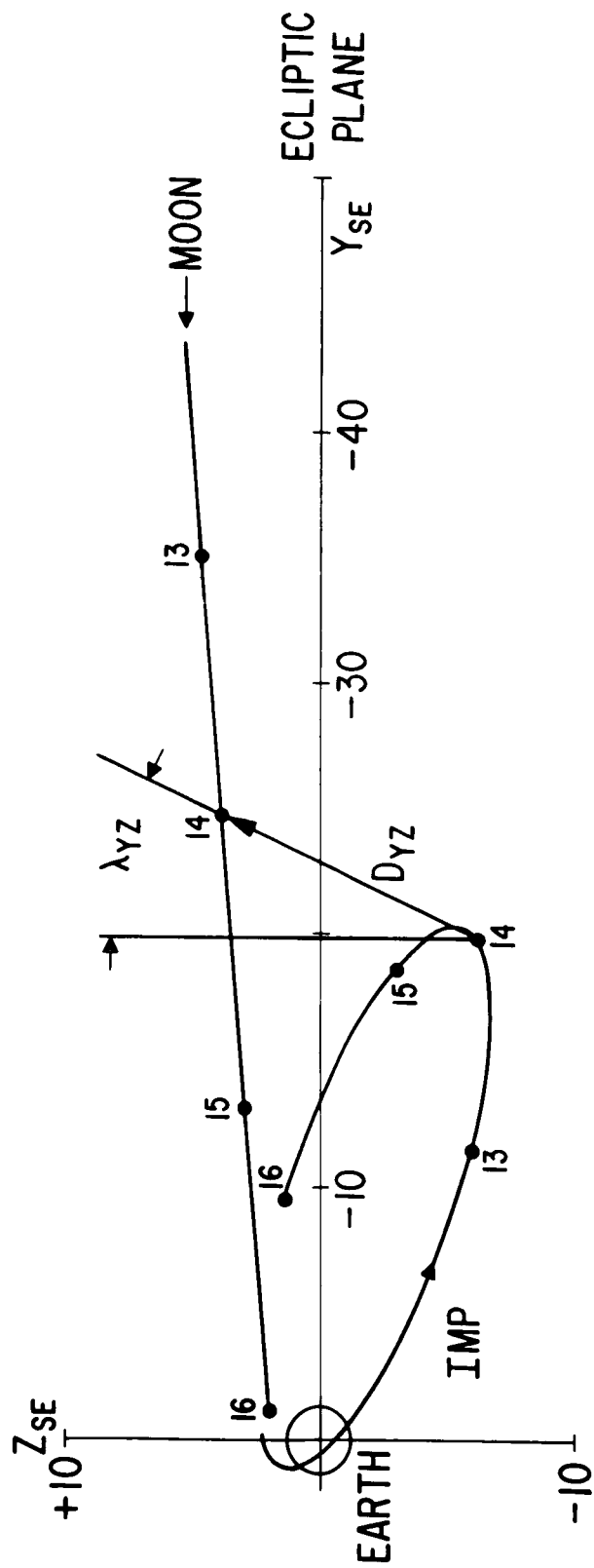
geocentric distance of $23.6 R_e$ with a possible "precursor" detected at $24.2 R_e$.

15. The Alfvén velocity as a function of the interplanetary magnetic field strength and solar plasma flux parameters. The average magnetic field in interplanetary space was 5 gammas with limits of 1 to 10 γ .
16. Mach angle as function of the corresponding Alfvén mach number.
17. Relative position of IMP-1 satellite and moon in lunar associated coordinates illustrating envelopment within lunar shock wave assuming aerodynamic similitude during December 1963 and February 1964.

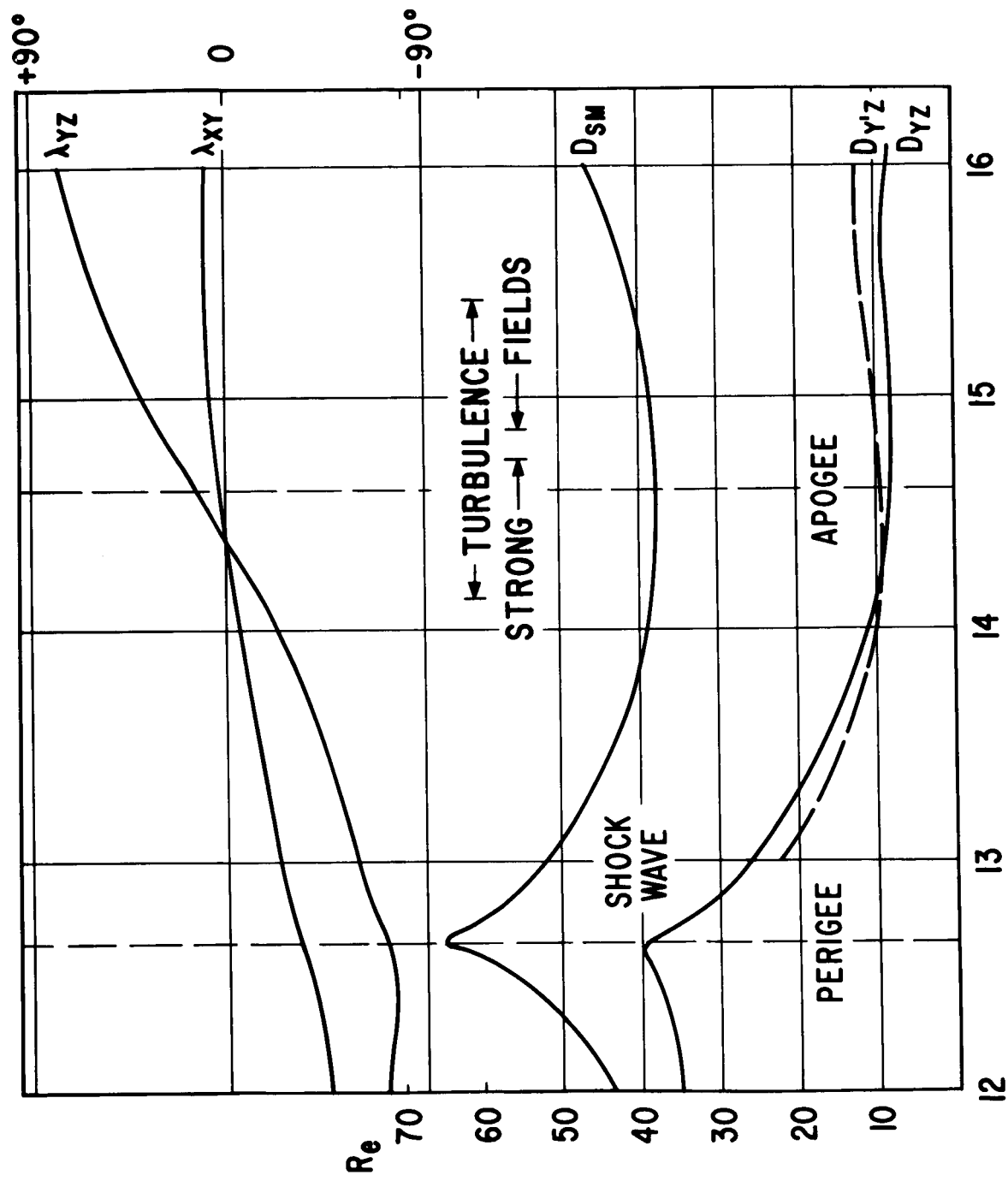




MOON AND IMP (ORBIT 5) POSITIONS, DECEMBER 1963

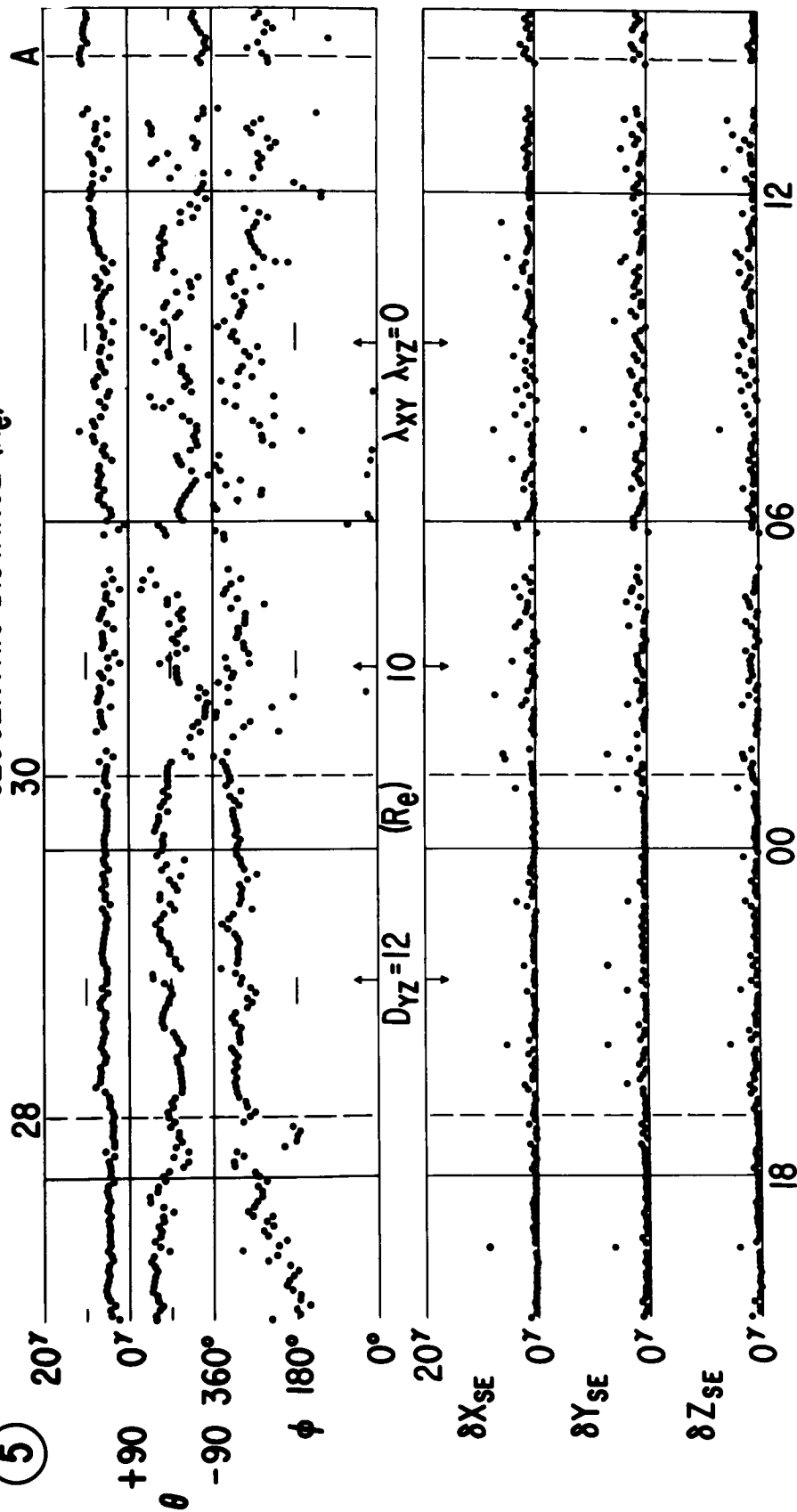


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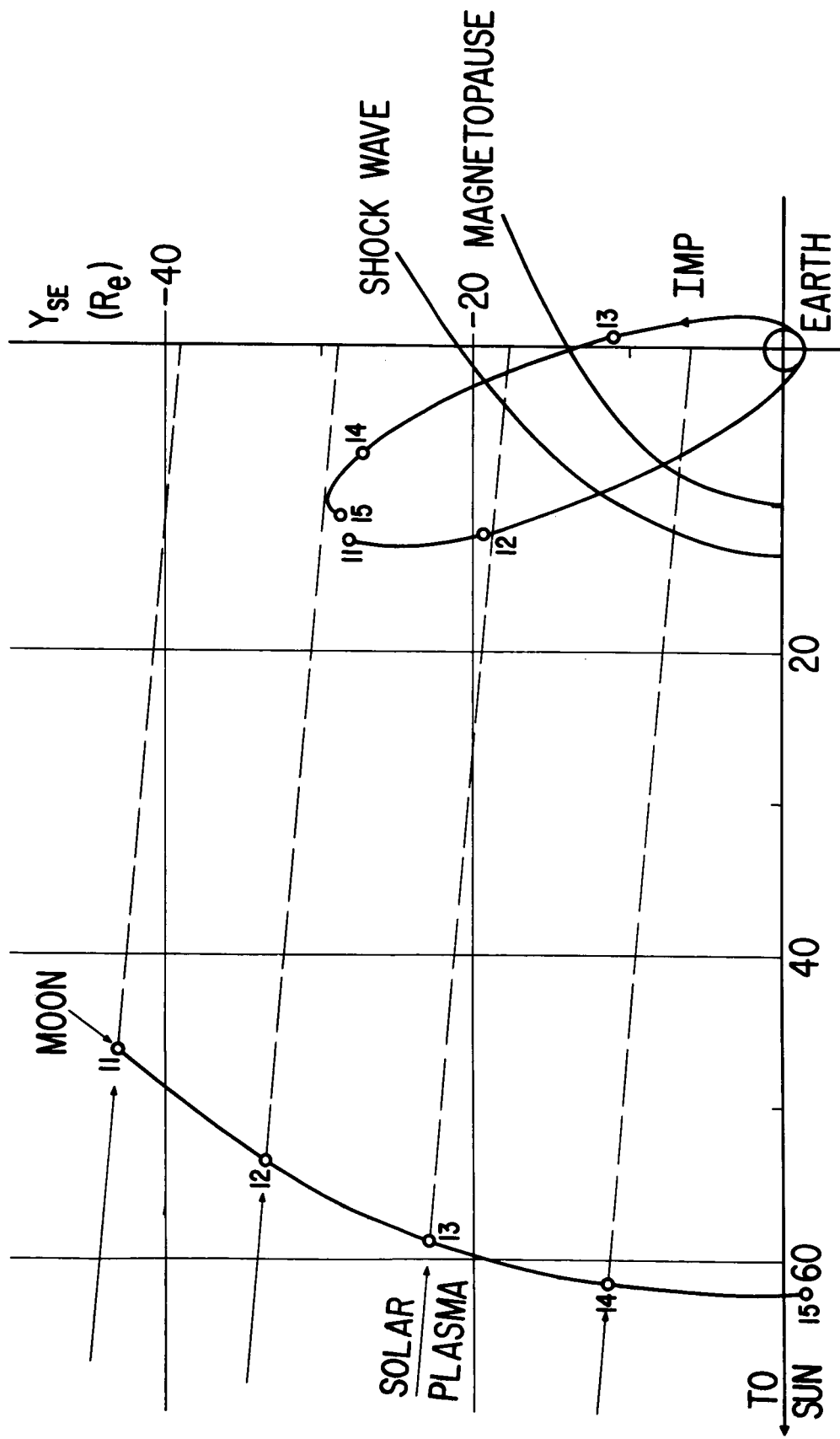


RELATIVE LOCATION OF IMP AND MOON DECEMBER 1963

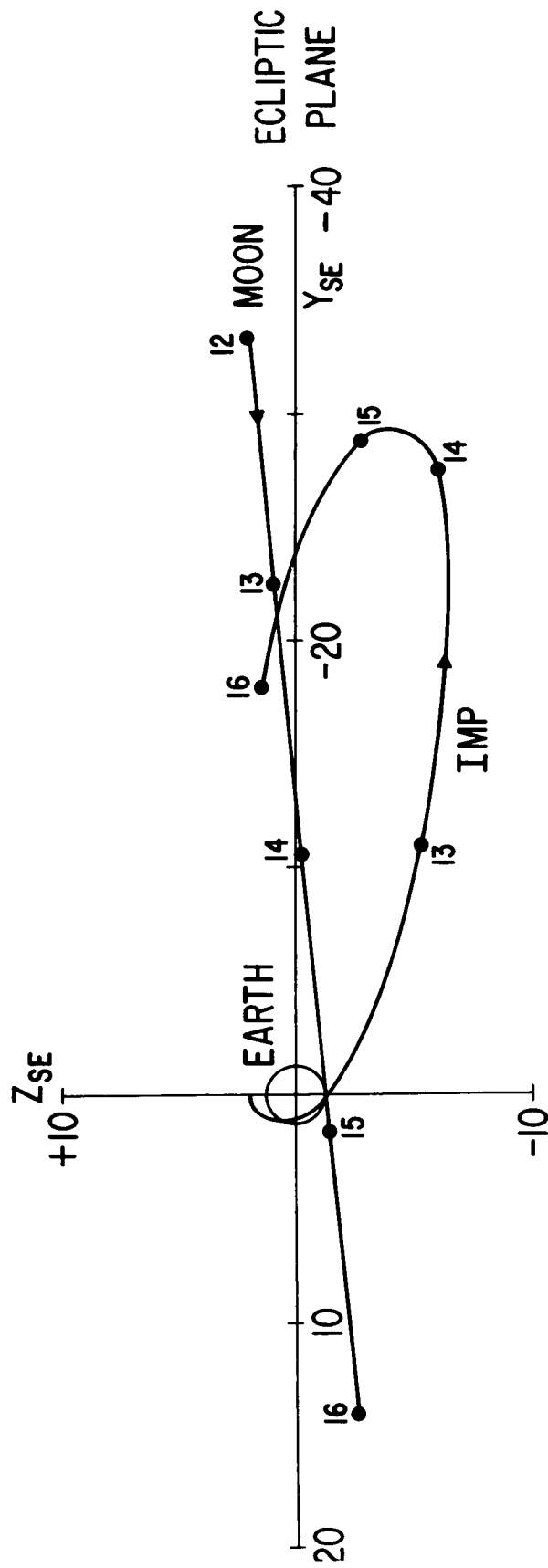
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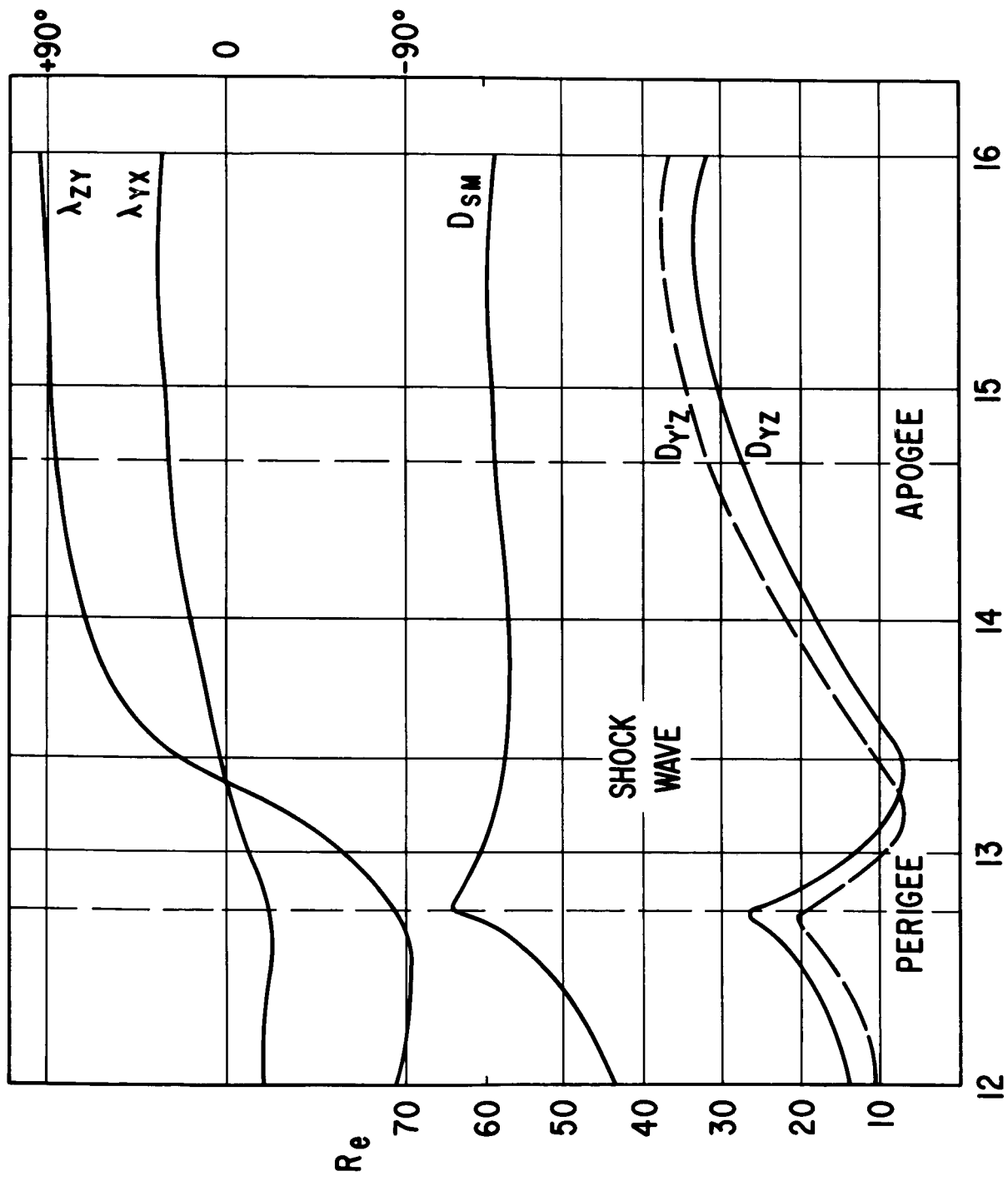
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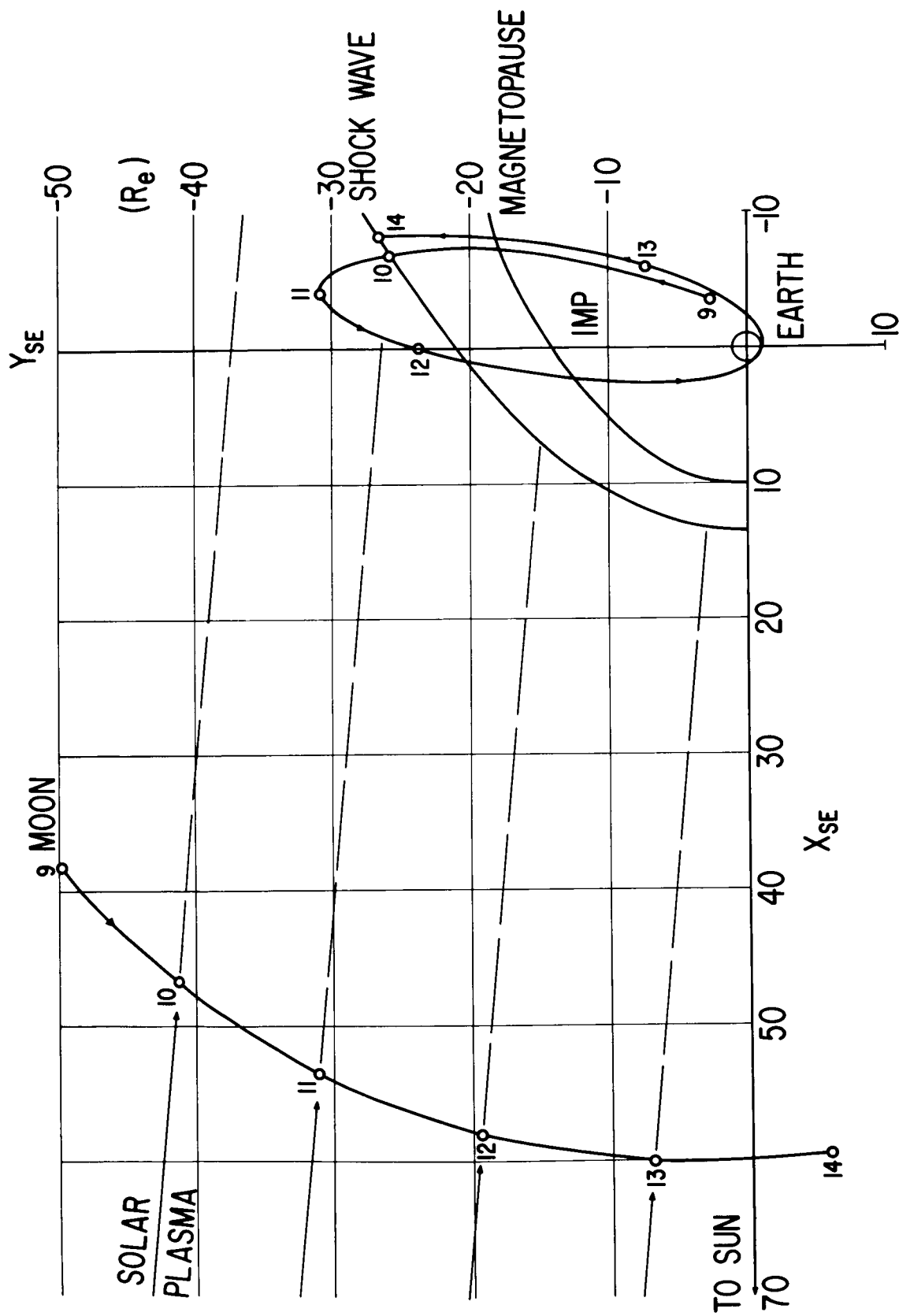
MOON AND IMP (ORBIT 13) POSITIONS, JANUARY 1964



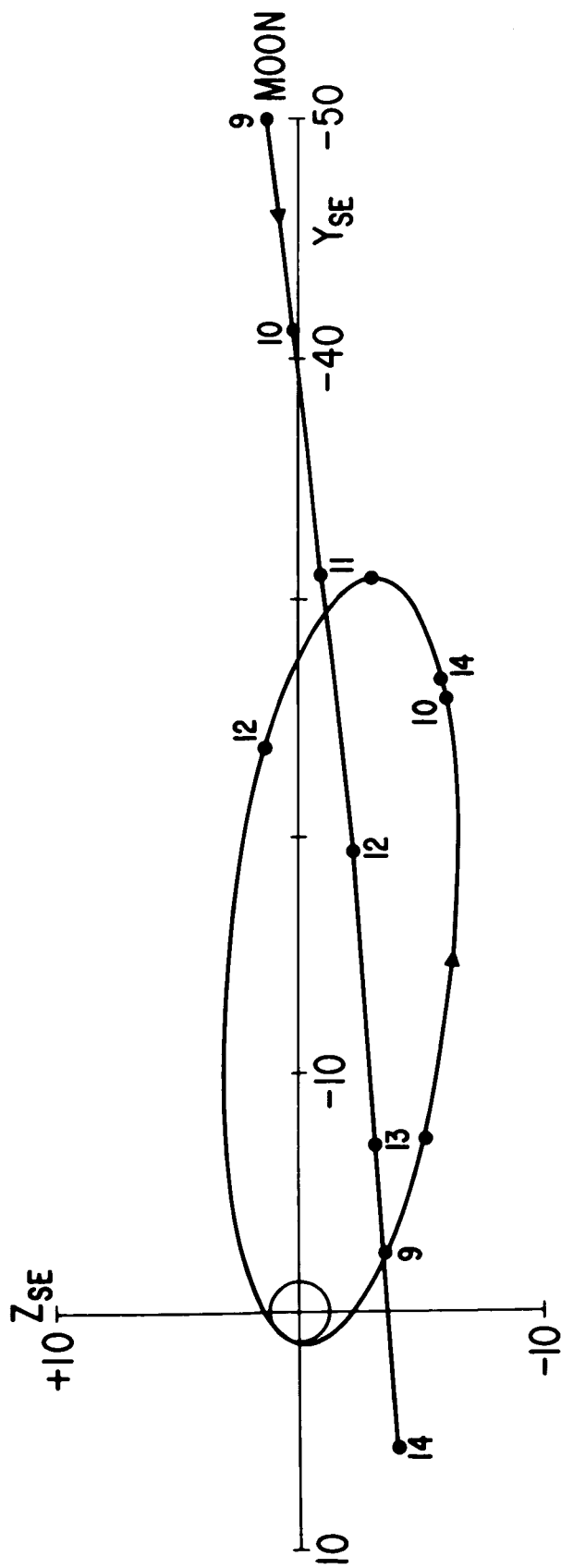
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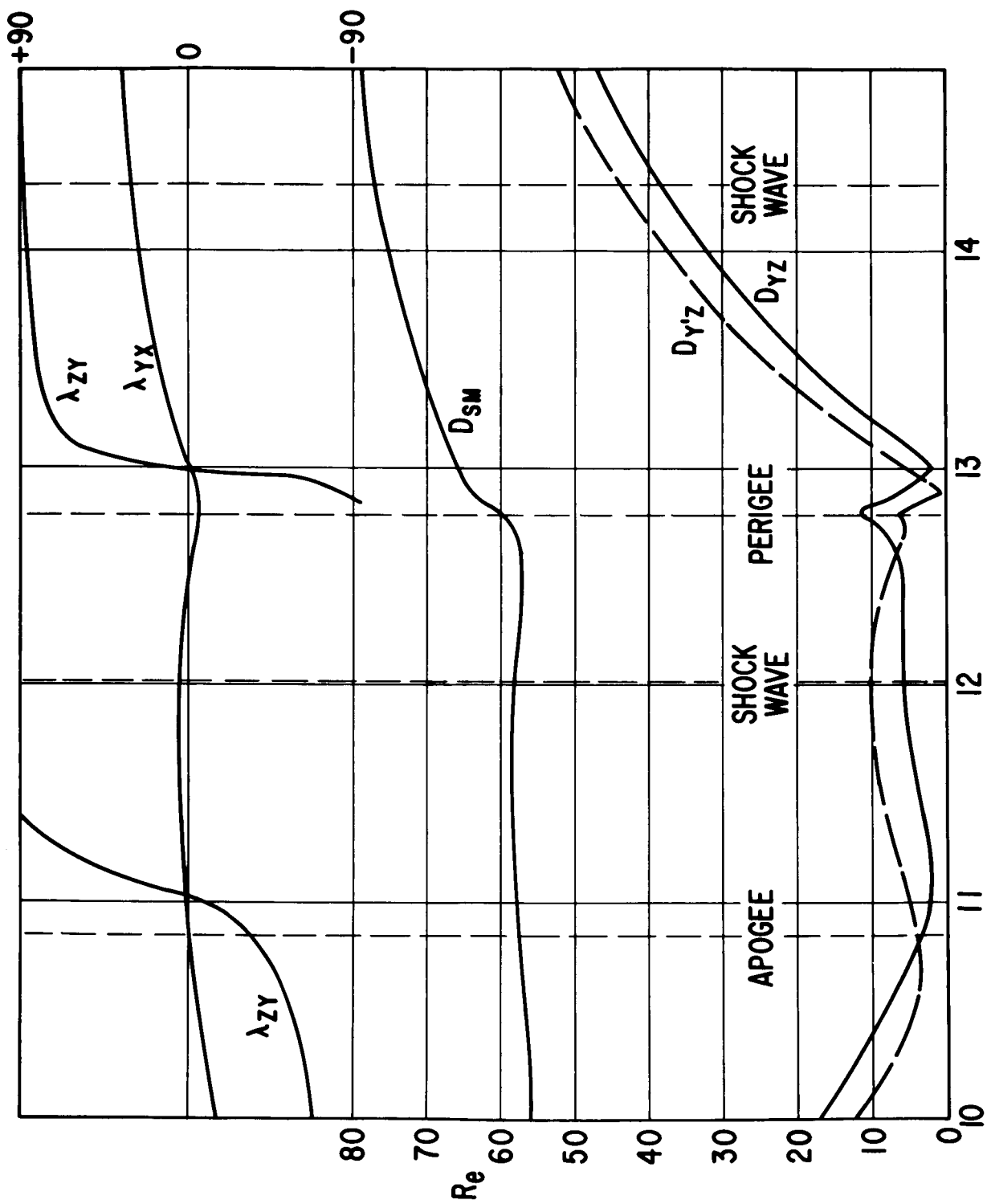
RELATIVE LOCATION OF IMP AND MOON JANUARY 1964



MOON AND IMP (ORBIT 20+) POSITIONS, FEBRUARY 1964



MOON AND IMP (ORBIT 20+) POSITIONS—FEBRUARY 1964

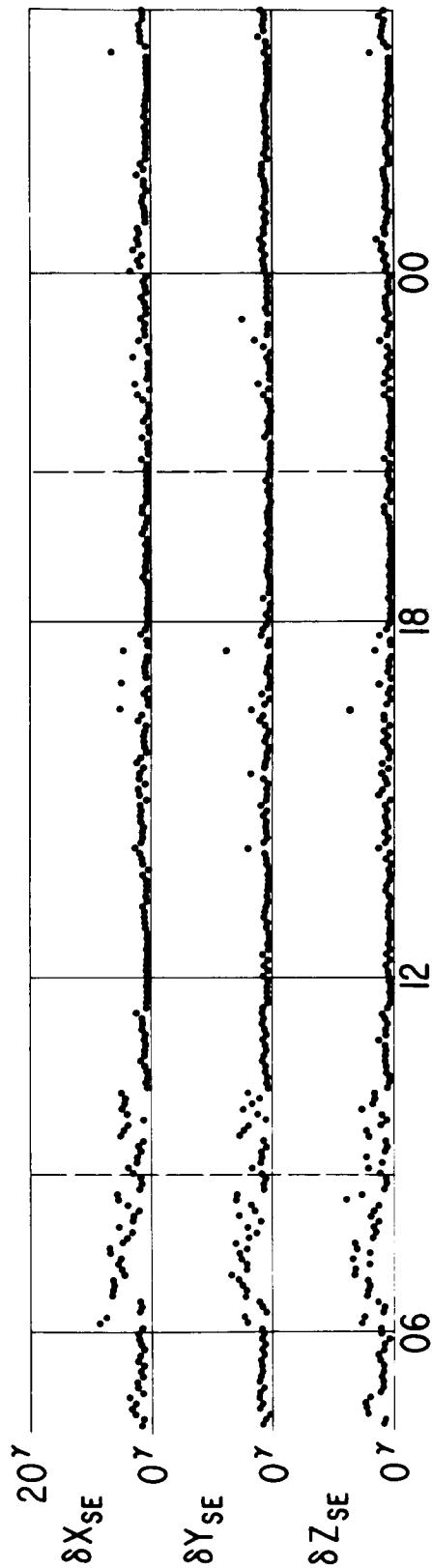
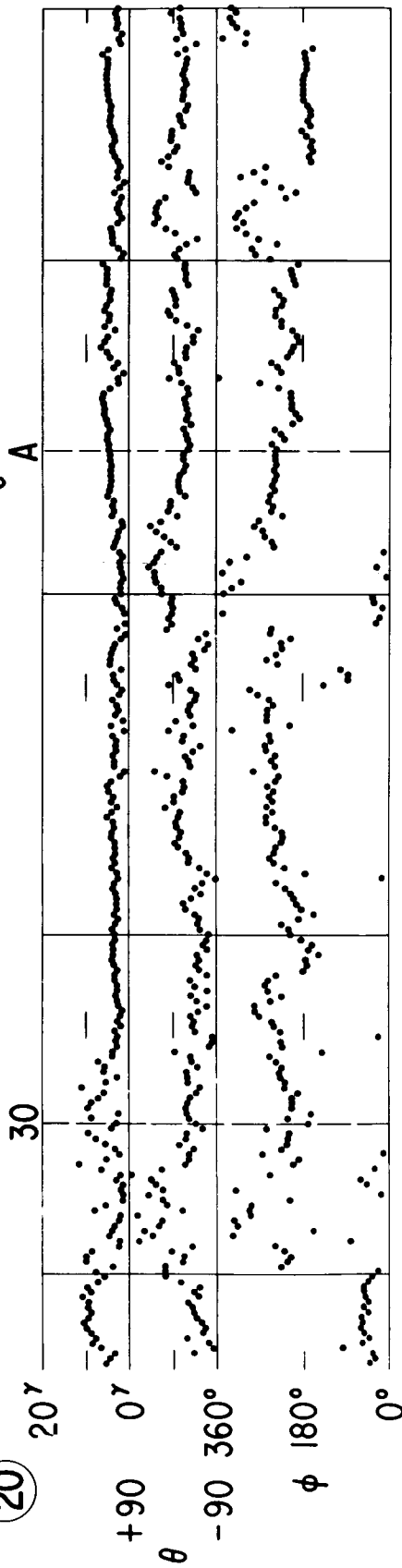


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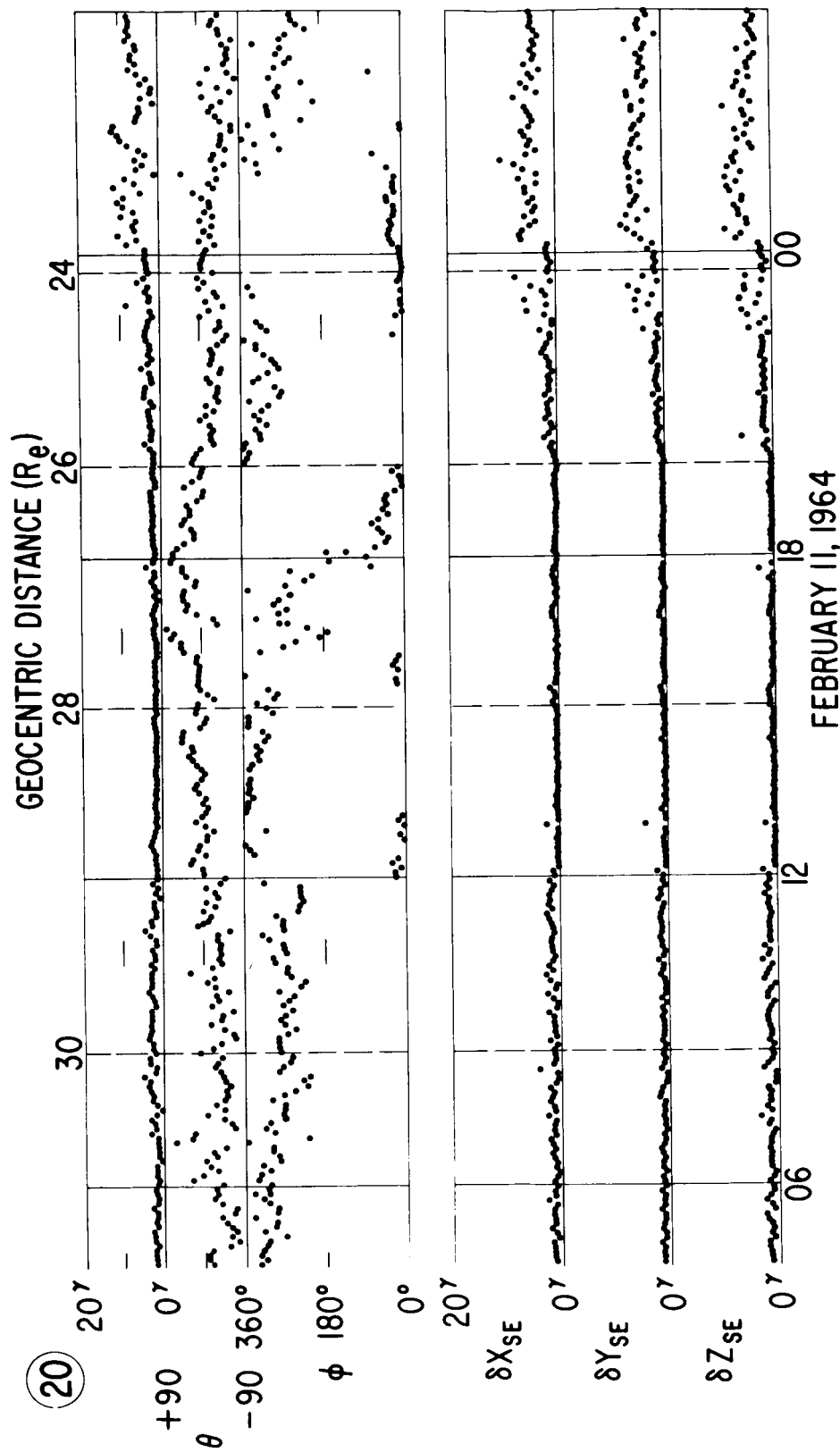
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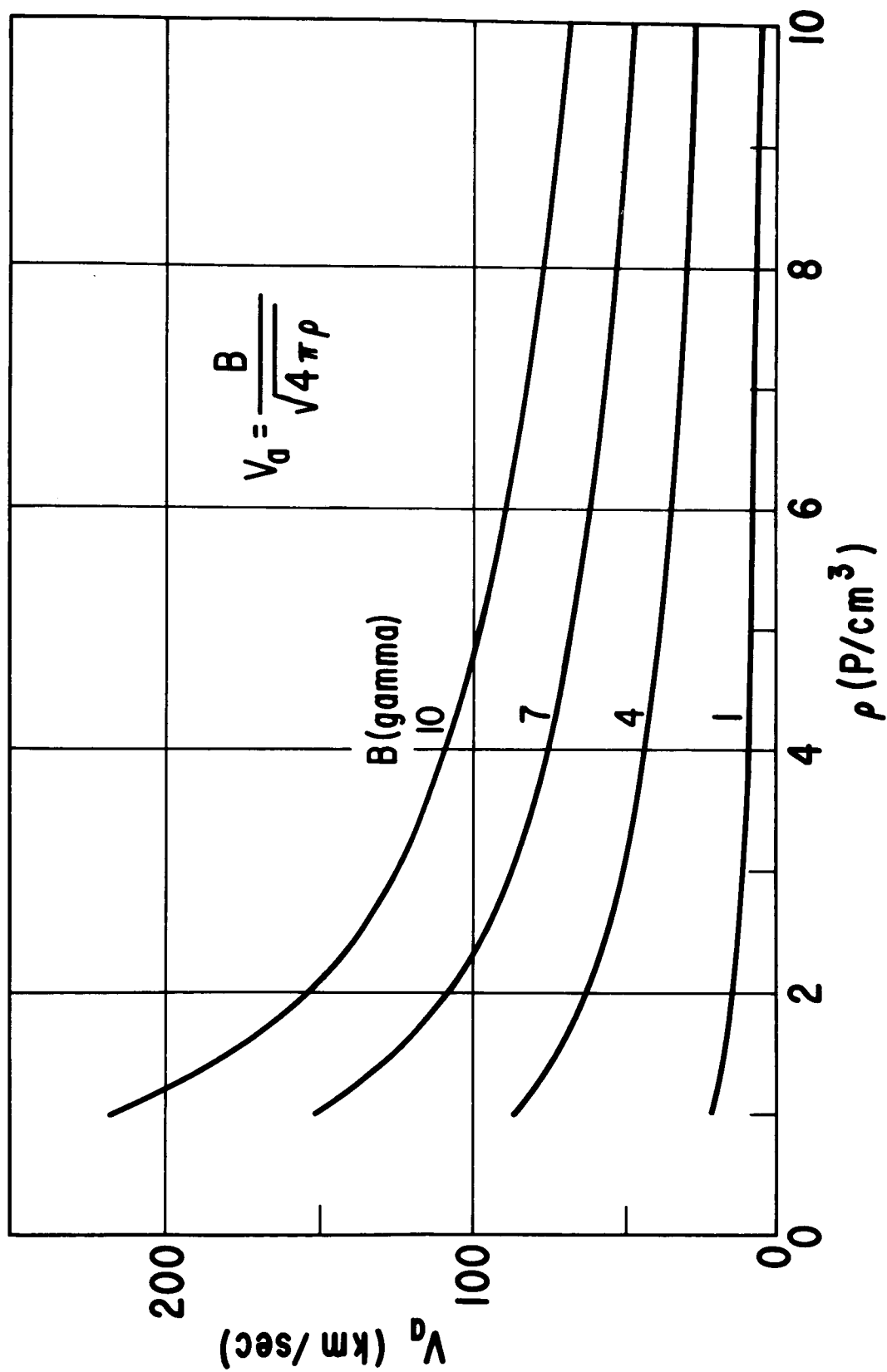
GEOCENTRIC DISTANCE (R_e)

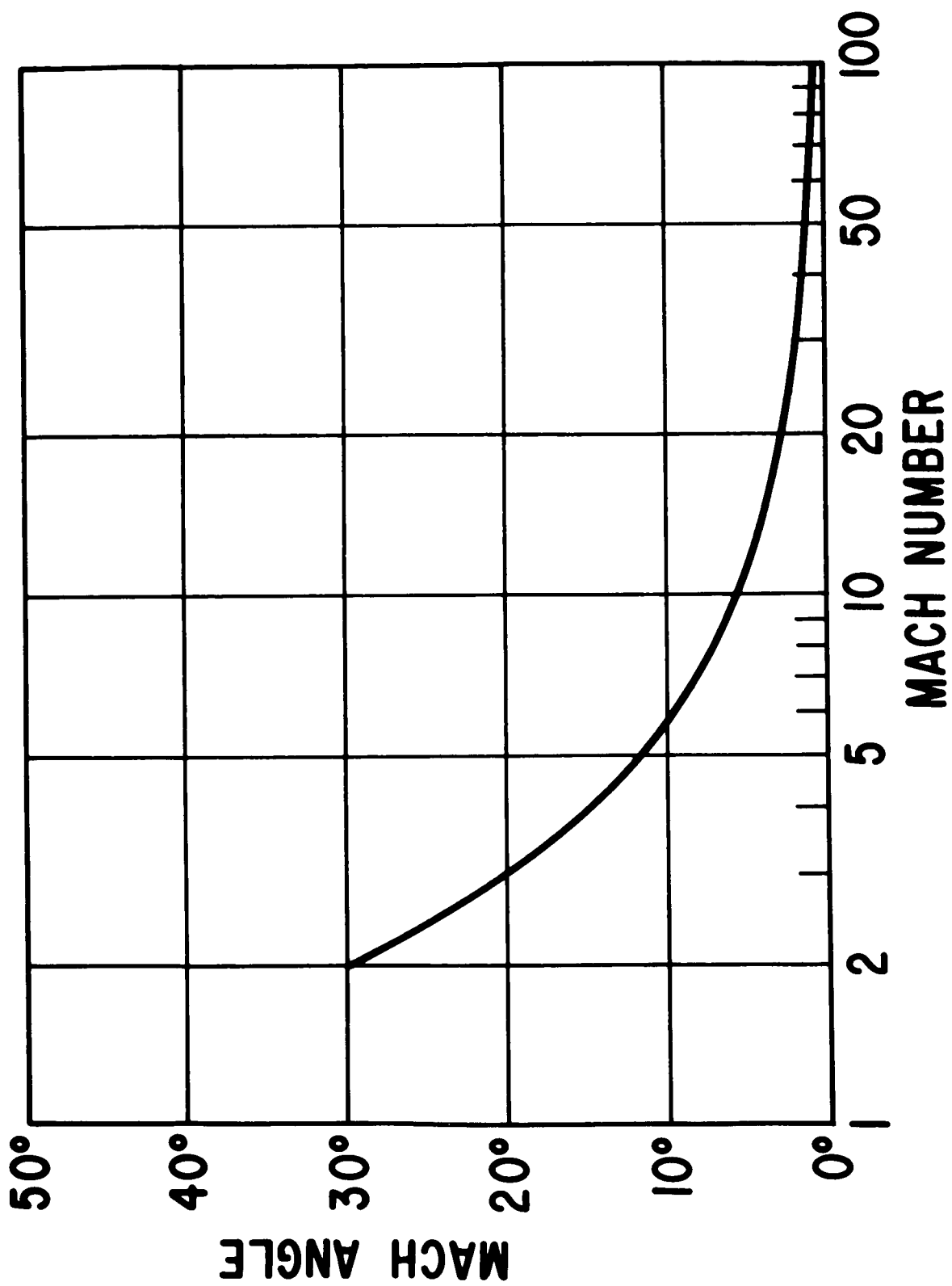
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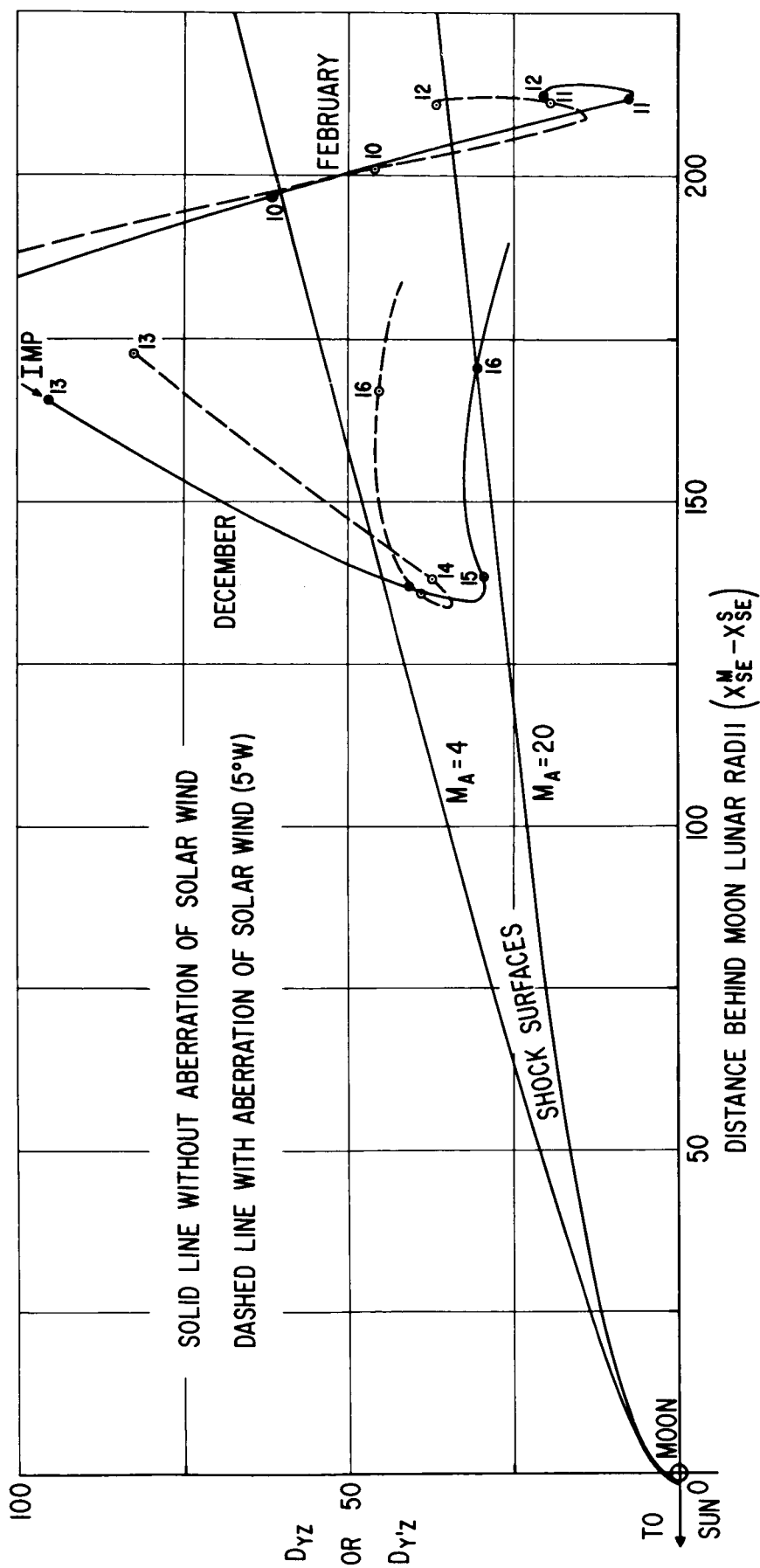


FEBRUARY 10, 1964









POSITION OF IMP-1 SATELLITE RELATIVE TO SUGGESTED WAKE OF MOON