Average and Unusual Locations of the Earth's Magnetopause and Bow Shock

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A best-fit ellipse and hyperbola have been calculated to represent several hundred magnetopause and bow-shock positions observed by six Imp spacecraft. Average geocentric distances to the magnetopause and bow shock near the ecliptic plane are 11.0 and 14.6 R_E in the sunward direction, 15.1 and 22.8 R_E in the dawn meridian, and 15.8 and 27.6 R_E in the dusk meridian. The bow-shock hyperbola is oriented in a direction consistent with that expected when the aberration of a radial solar wind is considered. Observed magnetopause crossings agree well with theoretical predictions in the noon meridian plane but fall outside the theoretical boundaries in the dawn-dusk meridian planes. Imp 4 plasma data are used to demonstrate that the solar-wind momentum flux is the prime factor controlling the orbit-to-orbit changes in the boundary positions. Data suggest that the interplanetary-field orientation also affects the distance to the magnetopause boundary, more earthward crossings corresponding to southward fields. Six unusual bow-shock locations up to 22 R_E beyond the average position are found to be due to an enhanced standoff distance associated with a low Alfvén Mach number. The possibility that the solar wind may have become sub-Alfvénic on July 31, 1967, is suggested.

The earth's magnetopause and bow shock have been detected by numerous types of experiments on virtually every scientific spacecraft traversing the appropriate regions of space. Pioneer 1 [*Sonett et al.*, 1960], Pioneer 5 [*Coleman*, 1964], Explorer 10 [*Heppner et al.*, 1963; *Bonetti et al.*, 1963], and early Soviet probes [*Gringauz et al.*, 1961; *Shklovskii et al.*, 1960] provided the early measurements in the boundary regions, but the exploratory nature of the experiments and the limited quantities of data prevented a clear understanding of the underlying physics of the interaction of the solar wind and the earth. The first definitive studies, which included mapping of the positions of the boundaries, were made with data from Explorer 12 [*Cahill and Amazeen*, 1963; *Freeman*, 1964; *Cahill and Patel*, 1967] (magnetopause only) and Imp 1 [*Ness et al.*, 1964; *Bridge et al.*, 1965; *Wolfe et al.*, 1966] (magnetopause and shock). Subsequently, observation from Explorer 14 [*Frank and Van Allen*, 1964], Imp 2 [*Fairfield and Ness*, 1967; *Binsack*, 1968], Imp 3 [*Ness*, 1967], Ogo 1 [*Heppner et al.*, 1967; *Holzer et al.*, 1966], Vela 2A and 2B [*Gosling et al.*, 1967], and Ogo 3 [*Russell et al.*, 1968] further refined the measurements within 35 R_E, and observations from Explorer 33 and 35 [*Behannon*, 1968, 1970; *Mihalov et al.*, 1970; *Howe*, 1970] extended the observations to greater distances behind the earth.

The general picture revealed by all the measurements is one of time-dependent magnetopause and shock positions whose distances from the center of the earth are scattered about average values near 11 and 14 R_E, respectively, in the solar direction and 15 and 25 R_E in the meridian planes. To a first approximation, the boundaries are symmetrical about the earth-sun line, but, owing to the earth's motion about the sun, a 3°–5° deviation from symmetry is expected. *Walters* [1964] predicted an additional asymmetry due to the interplanetary field, which on the average should increase the asymmetry due to the orbital motion. The spacecraft making both dawn and dusk hemisphere measurements [*Heppner et al.*, 1967; *Ness*, 1967; *Gosling et al.*, 1967; *Behannon*, 1968; *Mihalov et al.*, 1970] confirm an asymmetry, but it is not necessarily larger than that expected for aberration. A larger 8° skewing suggested by *Hundhausen et al.* [1969] on the basis of observed flow directions in the magnetosheath has not been confirmed by boundary position measurements.

The magnetopause crossing nearest the earth is the crossing detected by ATS 1 at 6.6 R_E [*Opp*, 1968, and companion papers], which was accompanied by an abnormally close-in bow shock at 13.4 R_E near the dawn meridian [*Russell et al.*, 1968]. An abnormally distant bow-shock location [*Heppner et al.*, 1967] occurred approximately 4 R_E beyond the average position and was explained by magnetosphere inflation plus an unusually low Alfvén Mach number, which in accord with predictions of *Spreiter and Jones* [1963] should enhance the standoff distance of the bow shock. *Gosling et al.* [1967] presented several instances when observed plasma parameters changed in a manner consistent with boundary motion and worldwide geomagnetic-field compression events. *Binsack and Vasyliunas* [1968] were quite successful in predicting the observed position of the boundaries with solar-wind data obtained at the time of a boundary crossing. This prediction suggests that boundary positions are controlled primarily by the solar-wind momentum flux, which compresses the magnetosphere to a greater or lesser extent at different times.

Further studies of solar-wind control of boundary position have generally utilized the reported positive correlation of solar-wind velocity and geomagnetic-activity index *Kp* [*Snyder et al.*, 1963]. Since the solar-wind velocity tends to be high when *Kp* is high, several workers [*Patel and Dessler*, 1966; *Cahill and Patel*, 1967; *Holzer et al.*, 1966; *Heppner et al.*, 1967; *Gosling et al.*, 1967] have searched for a correlation between boundary position and *Kp*. The net result of these studies is that there is a weak correlation between boundary position and *Kp* with a tendency for more earthward positions to correspond to high *Kp*. Lack of a better correlation is probably due to the fact that there is an inverse relationship between solar-wind density and velocity [*Neugebauer and Snyder*, 1966; *Hundhausen et al.*, 1970; *Burlaga and Ogilvie*, 1970*a*], which tends to keep the flux constant even though the velocity changes. *Snyder et al.* [1963] and *Neugebauer and Snyder* [1966], in fact, report that momentum flux does not correlate with *Kp* so well as velocity does. Recently *Meng* [1970] has demonstrated that distant magnetopause crossings invariably correspond to quiet conditions (low *AE* index), whereas crossings nearer the earth may correspond to either quiet or disturbed conditions. *Aubry et al.* [1970] report a situation where the solar-wind flux remains constant but the magnetopause moves inward as the interplanetary field becomes southward. Their suggestion is that the interplanetary-field direction exerts some control on the boundary position by eroding magnetic flux from the subsolar magnetosphere.

ANALYSIS

The present study was undertaken to establish an accurate two-dimensional representation of the average position and shape of the magnetopause and bow shock and to investigate the magnitude and the causes of the variations from the average. Therefore, plots of magnetic-field direction and magnitude versus time from six spacecraft, Imp 1–4 and Explorer 33 and 35, were scanned, and the magnetopause and bow-shock positions were tabulated for each pass. The distribution of 389 shock and 474 magnetopause crossings is given in Table 1. The positions determined in instances of multiple boundary crossings were average positions in the sense that the interval of magnetosheath (magnetosphere) data on the sunside of the selected bow-shock (magnetopause) location was chosen to be equal to the interval of interplanetary (magnetosheath) data inside the selected bow-shock (magnetopause) location. Boundary positions were listed in the solar ecliptic coordinate system (X_{SE} along the earth-sun line and positive in the sunward direction, Z_{SE} perpendicular to the ecliptic plane and positive in the northward direction, and Y_{SE} completing the right-handed orthogonal system). The solar ecliptic coordinates were found to be approximately as good as solar magnetospheric coordinates and better than solar magnetic coordinates in ordering Vela data [*Gosling et al.*, 1967]. Solar ecliptic and solar magnetospheric coordinates differ by a rotation about the X axis, and, to the extent that there is cylindrical symmetry about this axis, the two coordinate systems should yield equivalent results.

Shock crossings are characterized by an increase in the field magnitude when moving from the interplanetary medium to the magneto-

TABLE 1. Distribution of Shock and Magnetopause Crossings

Satellite	Dates	Apogee, R_E	Number of Crossings: Magnetopause	Shock	Measurements, min^{-1}: Sampled	Plotted
Imp 1	Nov. 1963–Feb. 1964	31.7	36	30	2.2	2.2
Imp 2	Oct. 1964–Dec. 1964	15.9	70	0	2.2	2.2
Imp 3	May 1965–Feb. 1966 June 1966–Feb. 1967	41.9	158	126	1.1	1.1
Imp 4	May 1967–Dec. 1967 June 1968–Dec. 1968	34.1	178	164	23.5	2.9
Explorer 33	Nov. 1966–May 1968	~80	32	48	11.7	0.75
Explorer 35	July 1967–Sept. 1968	~60	0	21	11.7	0.75

Total crossings of the magnetopause, 474; of shock, 389.

sheath. The increase is typically a factor of 2 to 4 and occurs over a time interval that is usually small as compared with adjacent plotted points. (See Table 1 for the number of points measured and plotted each minute.) The bow shock was observed on every pass when data were available in the appropriate region, although occasionally the exact position was uncertain by a few tens of minutes (a few tenths of an earth radius) owing to rapid multiple crossings, upstream waves, or unusual shock thicknesses [*Greenstadt et al.*, 1970]. Orbits where the apogee was not well beyond the shock position were omitted (all of Imp 2) to avoid biasing the sample toward the more earthward crossings. Intervals during which the unique Explorer 33 trajectory ran approximately parallel to a boundary were also omitted.

Magnetopause crossings are characterized by discontinuities in field direction and magnitude [e.g., *Hyde*, 1967] and by a change in the field fluctuation level. Boundary identification occasionally becomes difficult when the magnetosphere and magnetosheath fields happen to align, and on approximately 5% of the passes a boundary could not be chosen with reasonable confidence. This problem was somewhat more prevalent on the earlier spacecraft with lower sampling rates. Explorer 35 crossings of the magnetic-tail boundary were reported by *Mihalov et al.* [1970] and were not reinvestigated.

To obtain an accurate analytical representation for the bow shock and magnetopause, a computer program was written to obtain the best-fit conic to the two-dimensional representation of the magnetopause or shock data in the solar ecliptic plane. This program in effect translates, rotates, and changes the shape of a conic to minimize the sum of the differences between the data points and the curve. Only the type of conic was specified for a given run (an ellipse for the magnetopause and a hyperbola for the bow shock) along with reasonable starting values, which were found not to affect the final solution. For computational ease, a convex-body norm [*Householder*, 1958] was used with which the distance between data points and fitted curve was calculated along the line between the data point and the points (−5, 0) and (−30, 0) for the ellipse and hyperbola, respectively. Since no constraints were imposed on the center or orientation of the conic, it was hoped that an east-west asymmetry could be detected. Although there is no guarantee of a unique solution to such a curve-fitting problem, the data were ordered well enough that the program invariably approached a solution that was reasonable and also was the best fit for a limited region of parameter space.

RESULTS

Average boundary positions. The crosses in Figure 1 represent the average position of the bow shock on 188 passes with position $|Z_{SE}| < 7\ R_E$. Figure 2 shows similar data for 255 passes through the magnetopause region. The actual three-dimensional locations have been converted to two dimensions by rotating the points into the solar ecliptic plane. The rotation is about the X_{SE} axis for $X_{SE} < 0$ and in a meridian plane for $X_{SE} > 0$. These rotations mean that the two-dimensional representation is valid only to the extent that the boundaries exhibit spherical and cylindrical symmetry in the subsolar and antisolar hemispheres, respectively. Each point in the ecliptic plane is then converted to the

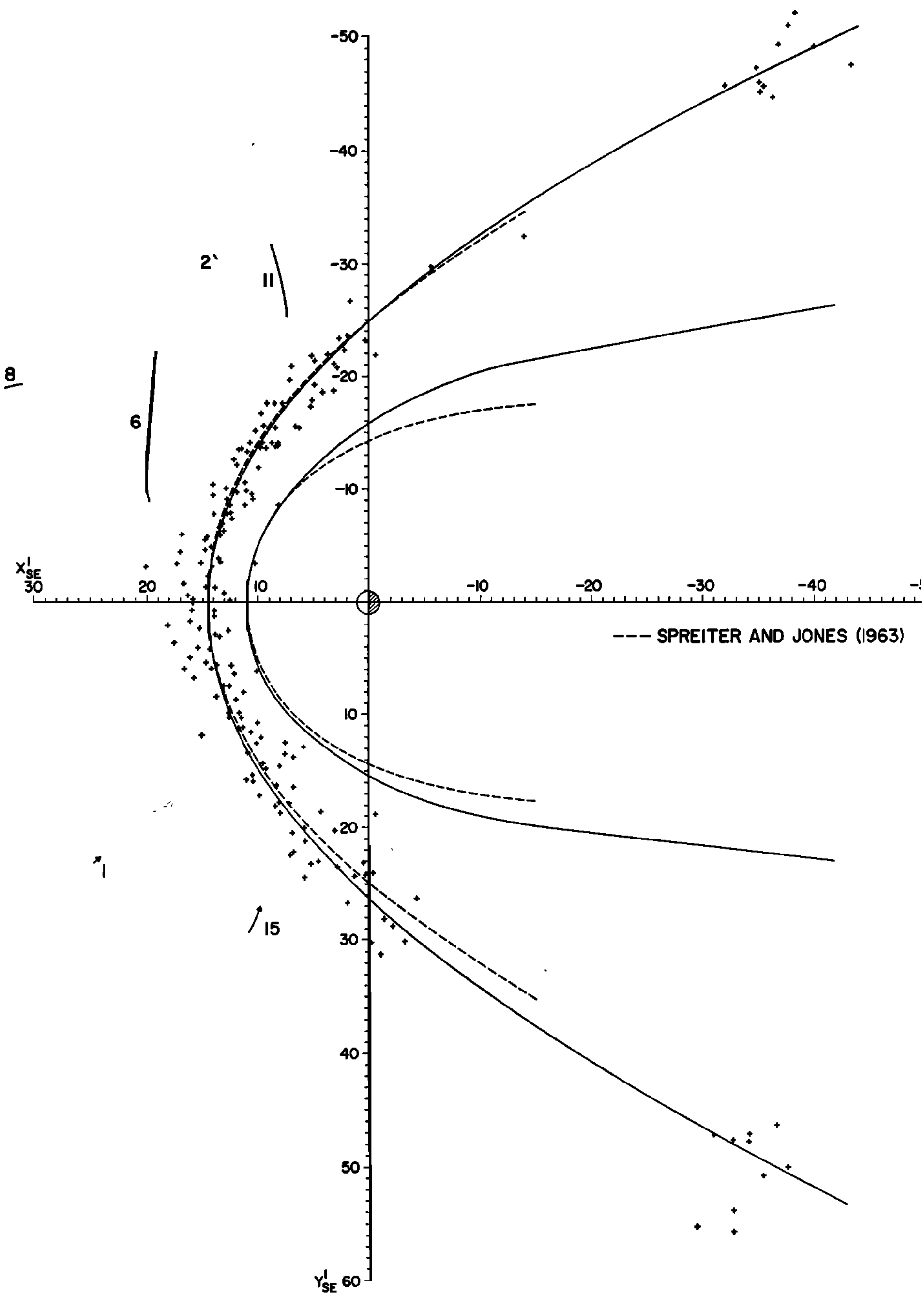

Fig. 1. Position of the bow shock in the solar ecliptic plane as determined by measurements on five Imp spacecraft, 1963–1968. Crosses represent the average location on individual passes, and the solid line hyperbola represents the best-fit curve to the points. $|Z_{SE}| < 7\ R_E$. Points have been rotated by 4° to remove the effects of aberration due to the earth's motion about the sun. The line segments beyond the average shock position represent the positions of unusually distant bow-shock locations.

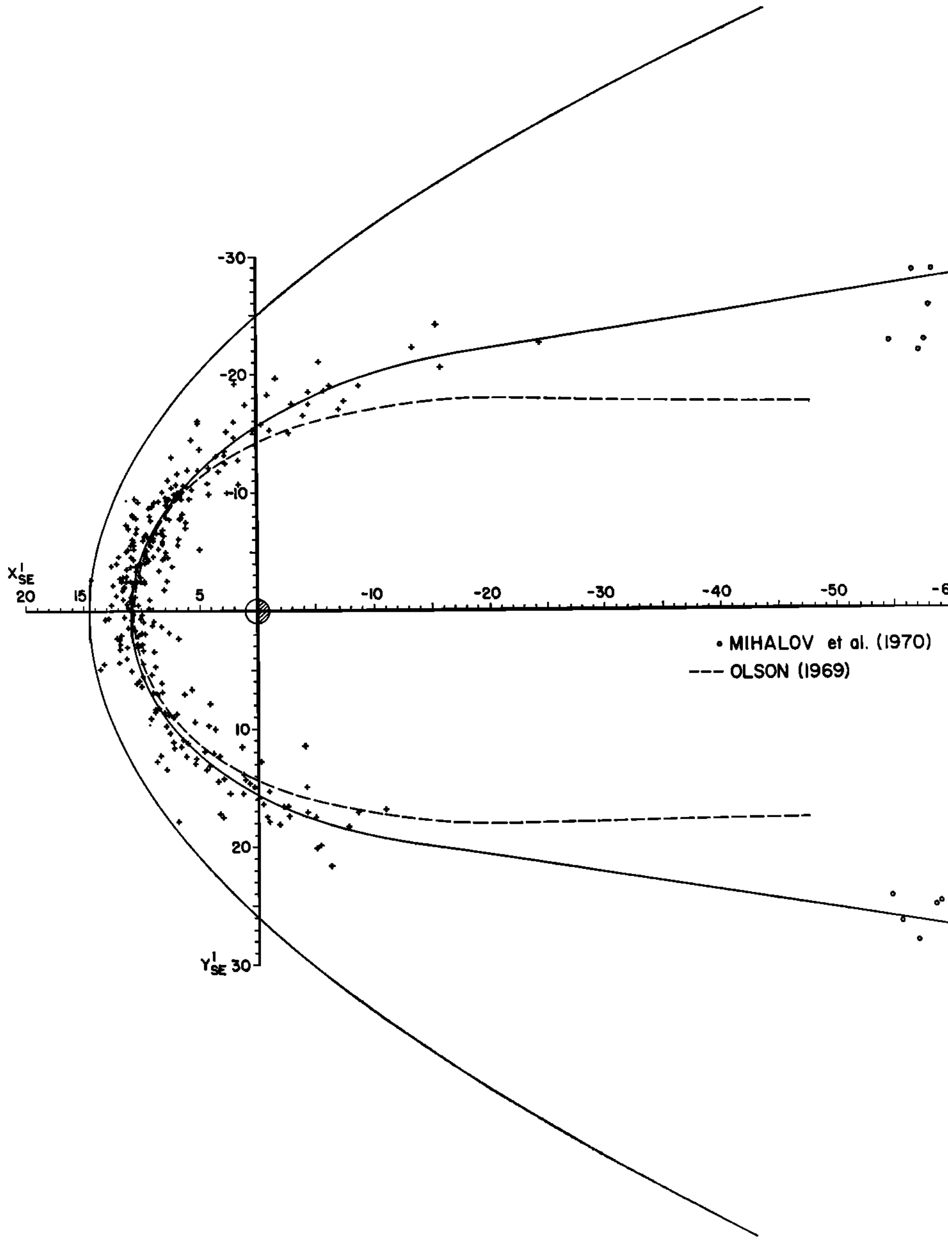

Fig. 2. Position of the magnetopause in the solar ecliptic plane as determined by measurements on six Imp spacecraft, 1963–1968. Crosses represent the average location on individual passes, and the solid line ellipse represents the best-fit curve to the points. $|Z_{SE}| < 7\ R_E$. Points have been rotated by 4° to remove the effects of aberration due to the earth's motion about the sun. A solid line has been joined to the ellipse at $X = -15$ to represent the boundary of the tail.

prime coordinate system by a rotation of 4° to eliminate the expected aberration due to the earth's motion in the presence of an average 420-km/sec solar wind.

The best-fit conics (see previous section) are illustrated by the solid curves in the figures and can be expressed by the equation

$$y^2 + Axy + Bx^2 + Cy + Dx + E = 0 \quad (1)$$

with the constants given in columns 1 and 4 of Table 2. The tail boundary crossings of *Mihalov et al.* [1970] were rotated by 4° and plotted in Figure 2 but were not used in the curve fitting. Straight lines have been joined to the ellipse at $X = -15\ R_E$ to represent the extended tail. The dashed shock curve in Figure 1 is the theoretical curve that *Spreiter and Jones* [1963] obtained by using the dashed theoretical magnetopause of *Beard* [1960]. The dashed magnetopause in Figure 2 represents the more recent work of *Olson* [1969]. The geocentric distances to the experimental curves at the subsolar point are 10.9 and 14.5 for the magnetopause and the shock, respectively. The magnetopause (shock) intersections with the dawn and dusk meridian planes are −15.7 (−24.9) and 15.3 (26.2), respectively. Agreement between experiment and theory is quite good, the primary discrepancy being the increased dimension of the experimental magnetosphere in the dawn-dusk plane. *Spreiter and Alksne* [1969] demonstrated that theoretical consideration of tail neutral-sheet currents leads to an increased tail diameter, in better agreement with the experimental results. The experimental deviation from symmetry after the 4° rotation is apparent from the difference between the solid curve and the symmetrical theoretical dashed curve.

Best-fit curves to the data analyzed in a different manner are described by the constants listed in columns 2, 3, 5, and 6 of Table 2. Columns 2 and 5 describe curves fit to data that were rotated to the meridian plane as explained above but that were not rotated 4° to correct for the aberration. Columns 3 and 6 represent curves fit to data that have been rotated into the ecliptic plane about the X axis and for which no 4° rotation has been performed. The fourth row of the table lists the angle between the X axis and the axis of the conic. The angle is defined as positive in the direction of an increasing aberration effect. Columns 2 and 3 show the expected 4° difference from column 1, and the absolute values suggest an angle approximately 1° larger than expected from aberration. The orientation of the magnetopause fails to show any rotation in the direction expected owing to the earth's motion about the sun. The net effect is that in the system corrected for the 4° aberration the magnetosheath in the dawn-dusk meridian plane is more than 1.5 R_E or 20% wider in the dusk quadrant than it is in the dawn quadrant. In an uncorrected coordinate system, where the dawn-dusk meridian plane cuts asymmetrically through the boundaries, this difference is about 4 R_E or almost 50% wider in the dusk meridian than in the dawn meridian. Since downstream boundary measurements at the moon's orbit [*Mihalov et al.*, 1970] and measurements within the magnetotail [*Behannon,* 1970] clearly revealed the aberration effect, either the magnetopause meas-

TABLE 2. Results

	Bow Shock			Magnetopause		
	Meridian 4°	Meridian No 4°	X Rotation No 4°	Meridian 4°	Meridian No 4°	X Rotation No 4°
X	14.5	14.6	14.3	10.9	11.0	10.8
Y dawn	−24.9	−22.8	−22.9	−15.7	−15.1	−15.0
Y dusk	26.2	27.6	27.2	15.3	15.8	15.6
θ	1.1°	5.2°	5.6°	−4.3°	−1.5°	−1.2°
A	0.0296	0.2012	0.2164	−0.0942	−0.0330	0.0278
B	−0.0381	−0.1023	−0.0986	0.3818	0.3539	0.3531
C	−1.280	−4.76	−4.26	0.498	−0.676	−0.586
D	45.644	44.466	44.916	17.992	17.808	17.866
E	−652.10	−629.03	−623.77	−240.12	−238.22	−233.67

urements nearer the subsolar hemisphere are not sensitive enough to reveal aberration, or asymmetries within the magnetosphere are contributing an effect. *Heppner et al.* [1967] made the latter suggestion in proposing that 'bumps' may form on the magnetopause in response to variations of the magnetosphere plasma pressure with latitude and longitude.

Another fact to be deduced from Figures 1 and 2 concerns the effective ratio of specific heats γ. *Spreiter et al.* [1966] have noted that the ratio of the shock standoff distance (subsolar shock distance minus subsolar magnetopause distance) to the subsolar magnetopause distance is essentially independent of Mach number for large Mach numbers and dependent only on γ. Consequently, if the solar wind fulfills the large Mach number criterion, the experimental value of the standoff distance can be used as an indicator of the appropriate γ.

The frequency distribution of Mach numbers is presented in Figure 3, which was prepared by using the Imp 4 plasma data of *Ogilvie and Burlaga* [1970] along with magnetic-field data. All available hourly averages of plasma density, velocity, proton temperature, and field strength have been used to calculate both Alfvén Mach number M_A which equals V/V_A, where V is the solar-wind velocity and V_A is the Alfvén velocity $(H^2/4\pi\rho)^{1/2}$, where H is the measured magnetic-field strength and ρ is the mass density computed from the observed density of protons. The gas dynamic Mach number M is equal to V/a, where

$$a = \left(\frac{\gamma(p_e + p_p)}{\rho}\right)^{1/2} \approx \left(\frac{\gamma k(T_e + T_p)}{m_p}\right)^{1/2}$$

and p_e and p_p represent the electron and proton pressures, ρ is the mass density, k is the Boltzmann constant, m_p is the proton mass, and T_p is the proton temperature. The electron temperature T_e is not measured on Imp 4, but it has been shown [*Montgomery et al.*, 1968; *Burlaga and Ogilvie*, 1970*b*] to be approximately independent of solar-wind conditions at a value of 1.5×10^5 °K, which is the value used here. The appropriate Mach number is not completely evident, but *Spreiter et al.* [1966] suggest that M is appropriate when the magnetic-field alignment is arbitrary and the field magnitude is small enough that $M_A \gg 1$. Figure 3 indicates that both M and M_A are usually large enough that the average experimental value for the standoff distance should be independent of Mach number to the extent that it can be used as an indicator of the appropriate γ.

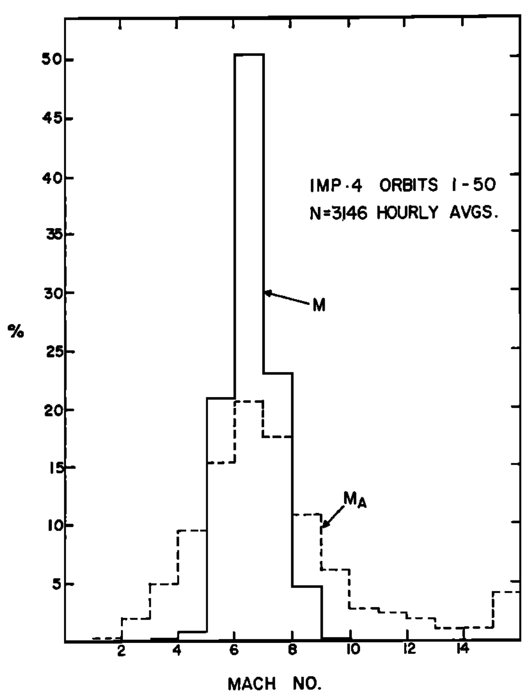

Fig. 3. Relative frequency of occurrence of solar-wind Alfvén Mach number M_A and gas dynamic Mach number M as calculated from the Imp 4 interplanetary magnetic field and plasma measurements.

Table 2 indicates that the ratio of standoff distance to magnetopause distance has a value of 0.33. According to Figure 16 of *Spreiter et al.* [1966], this value falls between the values expected for $\gamma = 5/3$ and $\gamma = 2$, although it is slightly nearer to the $\gamma = 2$ value. It should be remembered, however, that, if occasional shocks of low Mach number could be eliminated from the experimental data, the standoff distance would be reduced and a slightly smaller γ would be selected. Also, if Spreiter et al. had used a wider magnetopause, as now appears appropriate, the standoff distances would be slightly increased, their curve would be raised, and a smaller γ would be indicated. In spite of these restrictions, a γ of less than 5/3 appears to be inappropriate for use in solar-wind studies.

Magnetopause crossings within 15° of the noon-midnight meridian plane and the dawn-dusk meridian plane are shown in Figures 4 and 5, respectively. Solid lines represent theoretical boundaries [*Olson*, 1969] for three different values of μ, the geomagnetic latitude of the subsolar point. Olson's boundary was computed for a subsolar distance of 10.7 R_E, which is near the experimental value obtained in this paper. Although Olson's model is computed in solar magnetospheric coordinates and the data points are in solar ecliptic coordinates, this discrepancy should not produce significant differences. The agreement with theory is quite adequate in the noon-midnight meridian plane if the wide range of solar-wind conditions and dipole orientations occurring for the measured points is considered. The positions within 15° of the dawn and dusk meridian plane have been superposed in Figure 5. In this plane it is clear that the great majority of the experimental points are located outside the theoretical boundary. This discrepancy is probably due to the presence of plasma in the magnetosphere [*Heppner et al.*, 1967; *Vasyliunas*, 1968], the neglect of tail neutral-sheet currents [*Spreiter and Alksne*, 1969], and the presence of the bow shock, all of which are completely neglected in the theory.

Normal boundary variations. To test the hypothesis that a variable solar wind is responsible for the differences in boundary position, the Imp 4 interplanetary plasma measurements were analyzed in conjunction with the observed boundary crossing. Theory predicts that the subsolar magnetopause distance is given by

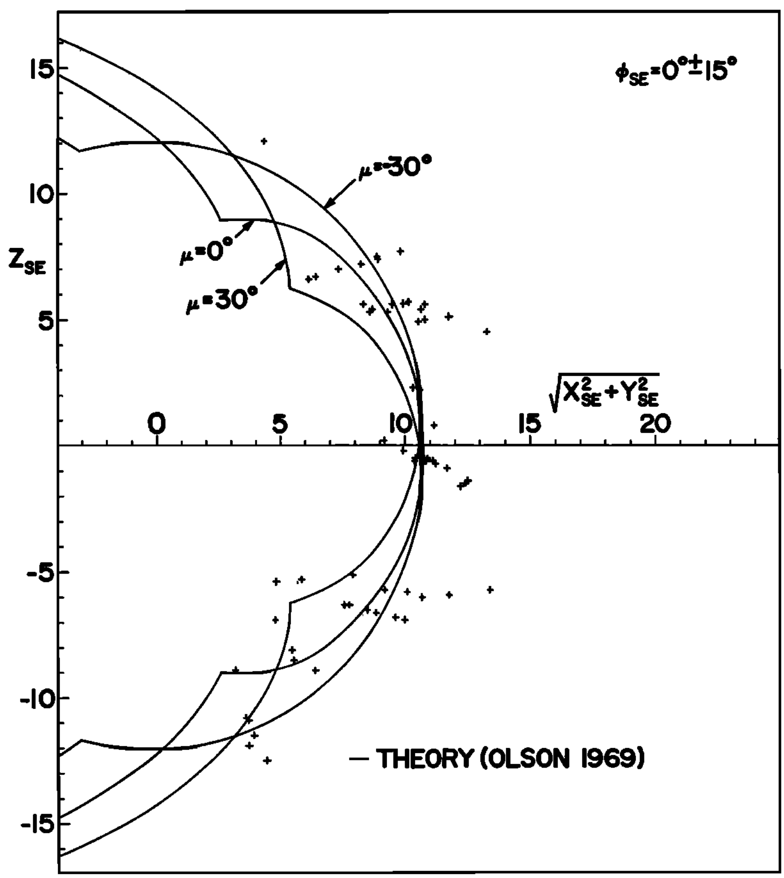

Fig. 4. Position of the magnetopause in the noon meridian plane. Crosses represent the observed locations within 15° of the noon meridian, and curves represent the theoretical predictions of *Olson* [1969].

$$D = (f^2 H_0^{\ 2}/2\pi K \rho V^2)^{1/6} \tag{2}$$

[e.g., *Spreiter et al.*, 1968], where H_0, the geomagnetic-field strength at the earth's surface on the equator, is 0.312 gauss and ρ, the mass density, is here taken as plasma density n times proton mass m_p. The factor f^2/K is determined by the physics of the interaction [*Spreiter et al.*, 1966; *Schield*, 1969]. The factor K in the denominator is a measure of how efficiently solar-wind particles transfer their momentum to the magnetosphere. ($K = 1$ for inelastic collisions, $K = 2$ for elastic collisions, $K \approx 0.8$ in gas dynamic theory.) The factor f relates the geomagnetic field just inside the magnetopause to the undistorted dipole field at that point. The quantity f probably assumes a value between 1 (image dipole model) and 1.54 (in a model with a ring current [*Schield*, 1969]). The factor f^2/K is taken to be unity in the present calculation.

With the use of the Imp 4 interplanetary plasma data and equation 2, a subsolar magnetopause distance was obtained for each hour the spacecraft was in the interplanetary medium. In addition, a prediction of the shock position was obtained by using the work of *Spreiter and Jones* [1963]. Figure 1 in their paper predicts that the shock standoff distance should be approximately 1.37 D for solar-wind Mach numbers greater than 10 and successively

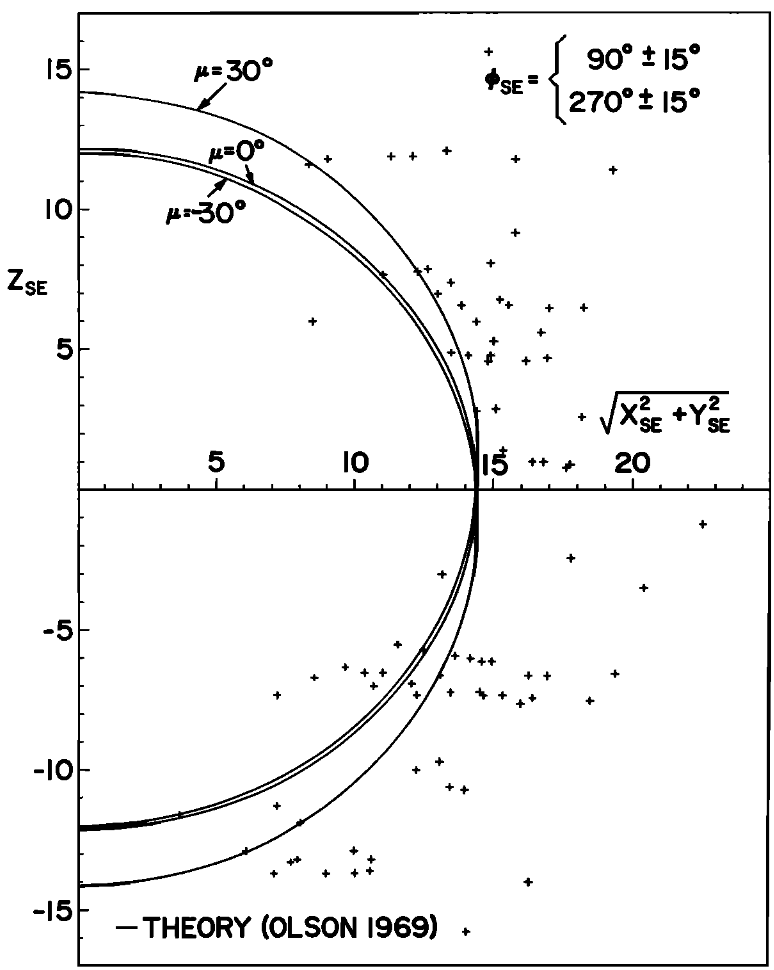

Fig. 5. Position of the magnetopause in the dawn and dusk meridian planes. Crosses represent the observed locations obtained within 15° of the dawn and dusk meridian planes, and curves represent the theoretical predictions of *Olson* [1969].

higher for decreasing Mach numbers. The gas dynamic Mach number M, rather than the Alfvén Mach number M_A, has been used in the present work in accord with a later suggestion [*Spreiter et al.*, 1966].

The magnetopause position predictions are illustrated by the lower trace on each grid in Figure 6. Shown above the magnetopause prediction is the shock prediction given by 1.37 D. Nearly coincident with but just above this trace is the more refined prediction dependent on Mach number. The close proximity of these upper two traces reflects the fact that M is generally larger than 5 (see Figure 3). Also shown in Figure 6 are the experimentally observed positions of the bow shock (circles) and magnetopause (crosses). To normalize the observed position data and eliminate the effect of the flaring out of the boundaries with longitude, differences between the observed boundary positions and the average fitted curves are plotted relative to the horizontal lines representing the average subsolar distances. The data shown are from within approximately 50° of the earth-sun line. Geomagnetic conditions were relatively quiet during this interval with four small sudden commencement storms occurring (marked by triangles in Figure 6) of which only one (September 19–21) had a significant *Dst* not larger than 80 γ [*Sugiura and Cain*, 1970]. It is apparent in Figure 6 that the bow-shock observations agree quite well with the predictions, but the magnetopause observations are frequently substantially different from the predictions. Since the shock predictions are highly dependent on the magnetopause prediction, it can be concluded that the solar-wind data accurately predict the position of the average magnetopause. The greater variation in observed and predicted magnetopause positions relative to the observed and predicted shock positions may be due to (*a*) the fact that the solar wind may change in the several hours between the last interplanetary measurement and the observation of the magnetopause, (*b*) irregularities on the surface of the magnetopause producing variations in the locally observed boundary position that do not substantially affect the shock location, and/or (*c*) the fact that the observed magnetopause position is more likely to be inaccurately identified, since the magnetopause is more difficult to determine than the bow shock. Because possibilities *a* and *c* could be eliminated with simultaneous interplanetary and boundary data and multiexperiment detection of the magnetopause, the technique shown in Figure 6 offers a possible means of detecting the presence of local irregularities on the magnetopause in future work. From Figure 6 it can be concluded that the position of the bow shock can be predicted to better than 1 R_E 80% of the time and to better than 0.5 R_E 50% of the time.

Variations in the positions of the magnetopause observed by all the spacecraft are compared with the variations predicted from the interplanetary plasma data in Figure 7. The distribution of variations of 137 observed magnetopause positions from the fitted curve is represented by the dashed line, and the predictions of the Imp 4 plasma data are represented by the solid line. Zero variation from the fitted curve has been made equivalent to 10.9 R_E on the scale in Figure 7. The plasma predictions have been centered on this value, even though the average distance predicted by the plasma data with $f^2/K = 1$ was 10.3 R_E. The difference could be due either to the improper f^2/K or to a systematic error in the density, which could be as large as ±30% [*Ogilvie et al.*, 1967]. To bring the predicted values into agreement with the observations, a 30% decrease in density is needed; however, there are other indications that the Imp 4 densities should not be reduced [*Burlaga and Ogilvie*, 1970*b*]. Therefore, it appears that the likely source of the discrepancy is in the value f^2/K. Accepting the measured average values of n and v requires an f^2/K of 1.4 to bring the predictions into line with the observations. The somewhat broader width of the observed distribution in Figure 7 again suggests that effects other than a uniform pressure balance may control the position of the magnetopause. It is also possible that there might be a solar-cycle variation in the solar-wind momentum flux that would broaden the distribution of experimental points. It is very difficult to test for such a variation because the measurements from each spacecraft (each year) are made at characteristic latitudes and with certain dipole inclinations at certain longitudes. The result is a complex combination of several small effects that may influence boundary position.

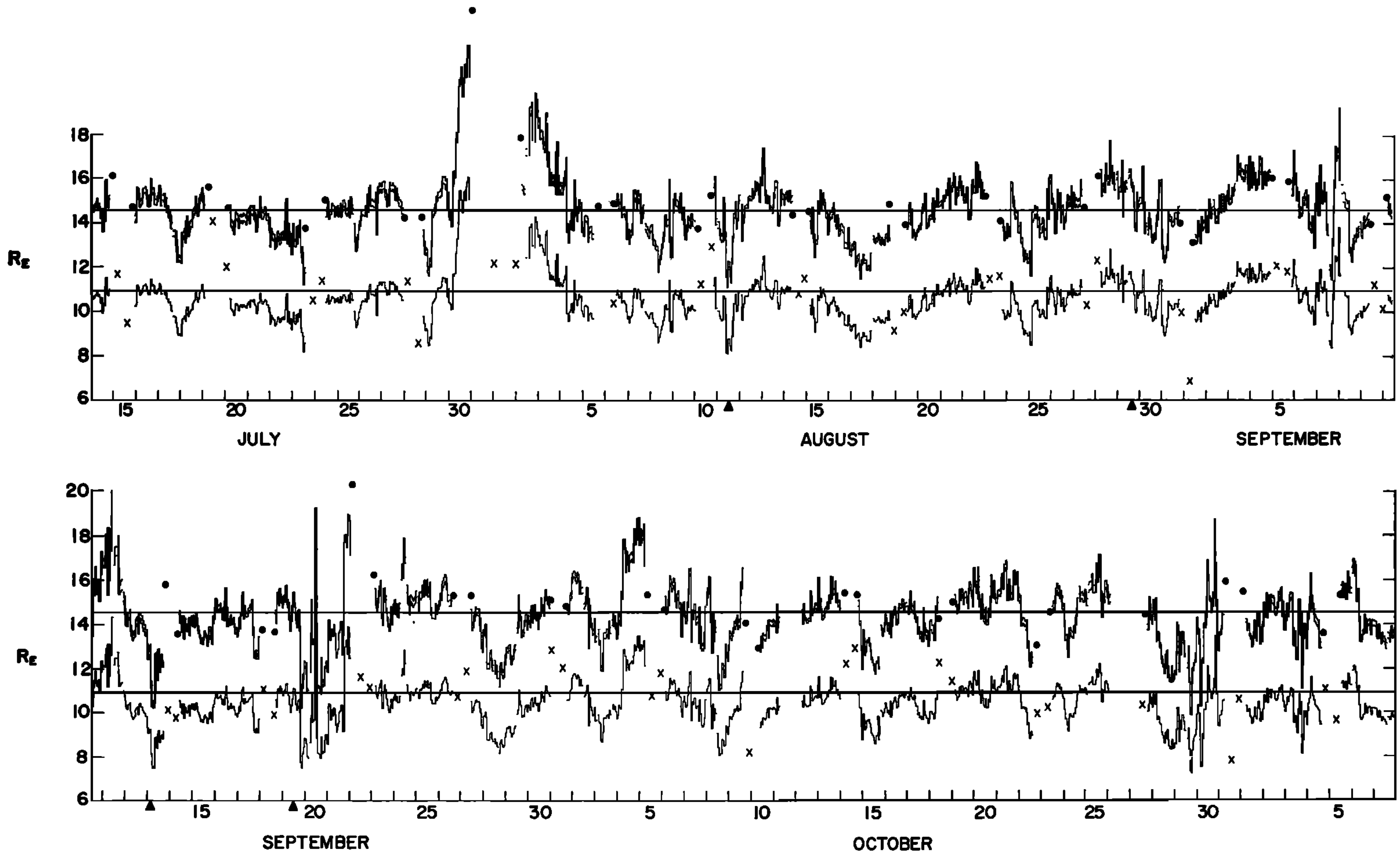

Fig. 6. Subsolar magnetopause and bow-shock positions during 1967. The histogram trace represents the positions predicted from the interplanetary hourly average measurements, and the crosses and dots represent the observed average positions on each orbit. Observed positions have been normalized to the subsolar point by taking variations from the average curve and plotting them relative to the average subsolar points represented by the horizontal lines.

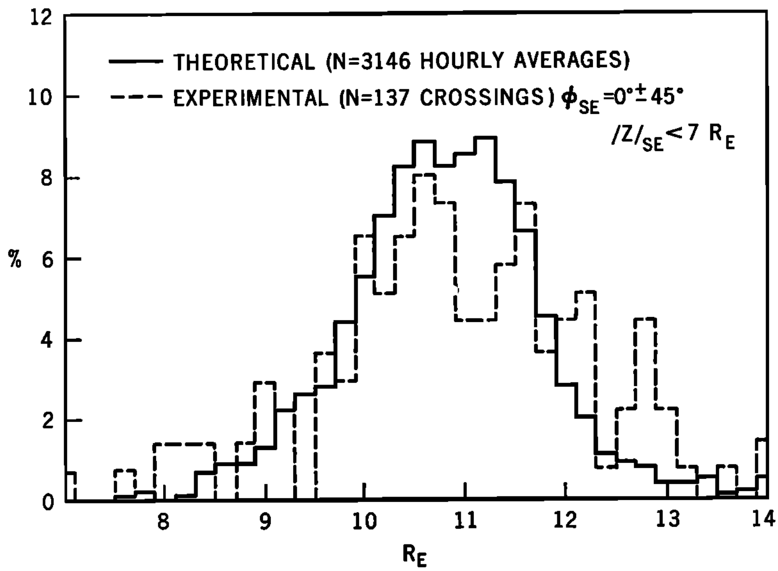

Fig. 7. Distribution of observed and predicted subsolar magnetopause positions. Predicted positions have been adjusted so that they are centered on the observed average position at 10.9 R_E.

To pursue the relation between boundary position and magnetic activity, the analysis of *Meng* [1970] was repeated, and more than 3 times as many data than were previously available were used. A plot of the geomagnetic *AE* index [*Davis and Sugiura,* 1966] versus the magnetopause position relative to its average location confirmed the result of Meng that an abnormally earthward magnetopause can correspond to either quiet or disturbed geomagnetic conditions but a distant magnetopause invariably corresponds to quiet periods. Because of their great similarity to Meng's Figure 1, these data are not presented here.

To pursue the suggestion of *Aubry et al.* [1970] that interplanetary-field orientation affects magnetopause location, the 178 available Imp 4 magnetopause crossings were utilized in a study of boundary position as a function of field orientation outside the boundary. For 65% of the crossings, it was judged that the magnetosheath field during the approximately 2-hour period the spacecraft was nearest the magnetopause was fairly steady and could be characterized as being predominantly northward or southward. Two groups of northward (62) and southward (54) crossings were thus determined, and ellipses were fit to these two groups. The subsolar distances were 10.5 ± 1.3 and 11.6 ± 2.0 for the south and north groups, respectively, where the plus or minus value represents the standard deviation of the points from the fitted curve. Since the variability is due largely to solar-wind pressure changes, this 1.1-R_E difference in the average position would seem quite significant. When the analysis was repeated with Imp 1, 2, and 3 data, a similar result was obtained, although the difference between the subsolar points was only 0.3 R_E. This relation between field direction and boundary position supports the suggestion of *Aubry et al.* [1970] that the magnetopause moves inward when the interplanetary field is southward.

It is well known that geomagnetic disturbance is associated with a southward-directed interplanetary magnetic field [e.g., *Hirshberg and Colburn,* 1969] as well as with a high solar-wind velocity. Apparently the weak tendency for earthward boundary crossings to be associated with high *Kp* is due not only to enhanced momentum caused by higher velocities but also to a southward field.

Distant bow-shock observations. In the course of determining bow-shock locations, six passes were discovered where the bow shock was found to be at least 10 R_E beyond the average location. These locations are designated by line segments in the upstream region in Figure 1, and they are labeled with the number of crossings that occurred during the interval. These events are listed in Table 3, which includes the observing spacecraft, date and time of the first crossing, duration of the interval of crossings, number of crossings, average solar ecliptic position, average Kp and Dst values for the interval, and average of the interplanetary-field magnitude observed outside the various shock crossings. Clearly, Kp and Dst bear no important relation to the abnormal locations. In the magnetosheath adjacent to these crossings, the field tended to be very quiet [*Fairfield and Ness*, 1970].

In the first three of the Imp 4 distant shock events listed in Table 3, Imp 4 plasma data are available in the upstream region adjacent to the shocks, and they may be used in trying to explain their distant locations. For two of these passes, MIT Explorer 35 interplanetary plasma data were generously supplied by J. Binsack and H. Howe for the entire interval of the pass.

During the July 5 event, the Imp 4 plasma experiment measured plasma densities between 1.0 and 1.5 particles/cm^3 and solar-wind velocities between 420 and 440 km/sec in the interplanetary region adjacent to the distant shock crossings. These parameters predict a subsolar magnetopause distance near 12.5 R_E (equation 2) and subsolar shock distance (1.37 D) of approximately 17 R_E if the Mach number is high. The corresponding distance to the shock at the subsatellite point is 25 R_E, which is 6–7 R_E inside the observed position of the shock. The Alfvén Mach number at the time of the distant shock crossings is between 1.2 and 1.6. Under these conditions, undoubtedly $M > M_A$, and therefore M_A is the relevant Mach number [*Dryer and Heckman*, 1967]. In accord with the work of *Spreiter and Jones* [1963], such low Mach numbers would account for the observed increase. A small ring current ($Dst = -10\ \gamma$) would also tend to increase the boundary distances by a small factor.

On July 30 at 2320 UT, the Imp 4 spacecraft observed the bow shock at a position 17 R_E beyond the average position of the shock. Both Imp 4 and Explorer 35 plasma experiments measure a solar wind with a velocity of 325 km/sec and a density of 0.5 particles/cm^3 at the time of the shock crossing. These values predict a subsolar magnetopause distance of 16.1 R_E and a subsolar shock (1.37 D) distance of 22 R_E. This subsolar distance corresponds to a subsatellite distance of 23 R_E, which is at least 10 R_E inside the observed location. With the plasma density of 0.5 and the observed interplanetary-field magnitude of 7.5 γ, the Alfvén Mach number is 1.4, which again is unusually low and can easily explain the large distance of the observation.

During the 24 hours following this shock crossing, the inbound Imp 4 spacecraft observes a magnetic field that remains enhanced relative to the interplanetary field measured further upstream ($X_{SE} = 23$, $Y_{SE} = -51$, $Z_{SE} = 3$) by Explorer 35 by a factor 1.4 to 1.7. In the interval between 0100 and 2300 UT on July 31, the plasma flux at Explorer 35 reached an even lower level, which, in fact, was below the detectability level of the experiment. It is interesting to note that, if this decrease to an unobservable

TABLE 3. Distant Bow Shock Observations

Date	First Crossing	Duration, hours	Number of Crossings	Average Position, R_E X_{SE}	Y_{SE}	Z_{SE}	Satellite	Kp	F	Dst
Nov. 4, 1965	1820	5.5	8	28	−19	−16	Imp 3	0+	15.8	17
May 3, 1967	0420	11.8	6	16	−15	12	Explorer 33	7−	15.5	−80
July 5, 1967	0920	7.8	15	12	26	2	Imp 4	3+	6.7	−10
July 30, 1967	2320	*	1	26	21	−1	Imp 4	0+	7.5	−20
Nov. 27, 1967	1605	19.9	11	6	29	−5	Imp 4	3−	8.5	−9
Nov. 17, 1968	1730	0.3	2	11	31	4	Imp 4	4	10.6	−11

* The inbound spacecraft is never in the interplanetary medium again on this orbit. The spacecraft is more than 5 R_E beyond the average shock until August 1, 0400.

level was caused by a density decrease of a factor of 2 from the density value of 0.5 or by a 30% decrease in velocity, the solar wind becomes sub-Alfvénic. Throughout this interval of possible sub-Alfvénic solar wind, the Imp 4 magnetic field strength remained very quiet and greater by a factor of 1.4 to 1.7 than that measured further upstream by Explorer 35. The enhanced magnitude at Imp 4 could indicate the continued presence of an upstream shock, but it could also be the normal increase associated with a new shockless mode of interaction between the geomagnetic field and a sub-Alfvénic solar wind.

The abnormal shock locations on November 27 are somewhat more difficult to explain. Plasma parameters measured by Explorer 35 and Imp 4 at the time of the initial and innermost shock crossing indicate that shock location should be very near the average position if the Mach number is high. The Alfvén Mach number is, in fact, 3, which, although unusually low, should increase its distance by only about 1 R_E. The observed position remains about 5 R_E beyond this predicted location. The solar wind is measured by Explorer 35 as coming from 10° north of the ecliptic plane at this time, which should rotate the shock outward at the position of the spacecraft, which is 6.5 R_E below the ecliptic plane. A small ring current would also tend to increase the observed location. On subsequent crossings during this pass at greater distances, the density observed at Imp 4 decreases as low as 1.5 particles/cm^3 so that the predicted shock moves outward about 3 R_E. The magnetic field decreases to about 6 γ, however, so the Alfvén Mach number remains at a value near 3. The discrepancy between prediction and observation remains as large as 8 R_E unless the secondary effects are considered.

Although no plasma data are available for the remaining three events in Table 3, it should be noted that each of these events has an unusually strong interplanetary-field strength associated with it. Since the Alfvén Mach number is inversely proportional to the field strength, these events are consistent with the suggestion that an abnormally low Alfvén Mach number is responsible for an increased standoff distance and the unusually distant location of the bow shock.

The frequency distribution of Alfvén Mach numbers shown in Figure 3 illustrates how unusual low Mach numbers are. It can be seen that Alfvén Mach numbers less than 3 constitute less than 2.2% of the total and those less than 2 (the distant shock events of July 5 and 30) are hardly ever seen by spacecraft orbiting the earth. Field strengths greater than 10 γ (the three events without plasma data) are observed less than 10% of the time, and those greater than 15 γ (November 4 and May 3 events) are observed less than 2% of the time (N. F. Ness, unpublished manuscript, 1969).

To obtain evidence that shocks located at greater distances from the earth are unusually weak shocks associated with lower Mach numbers, the increase in field strength across the shock was investigated. From the MHD shock equations, it can be shown (Y. C. Whang, private communication, 1970) that the ratio of the jump in tangential field components across a perpendicular shock is given by the expression

$$\frac{H_1}{H_2} = \frac{(2M_A^2 + 5\beta + 5) + [(2M_A^2 + 5\beta + 5)^2 + 32M_A^2]^{1/2}}{16M_A^2} \quad (3)$$

where H_1 and H_2 are the upstream and downstream tangential field components, respectively, and β is the ratio of $p_e + p_p$ to field energy $H^2/8\pi$. This ratio is relatively insensitive to β and is a decreasing function of M_A with the limit $H_1/H_2 \rightarrow 1/4$ as $M_A \rightarrow \infty$. Although the actual shocks are not necessarily the perpendicular shocks to which the equations refer, this decreasing tendency should also apply to the more general case. To compare the data with the predictions of this equation, a simple hyperboloid of revolution was used to locate the approximate plane of the shock, and the measured field components parallel to this plane were determined. For the distant shock crossings, the tangential field component increases were found to range from 1.4 to 2.5. These numbers correspond to Mach numbers below 3.3 as indicated by equation 3. For 77 shocks at more normal positions throughout the subsolar hemisphere, the corresponding field component increased by a factor of 3.2, which corresponds to a Mach number of 5. This result supports the conclusion that the distant shocks are weak and associated with low Mach numbers.

SUMMARY AND CONCLUSIONS

Magnetopause and bow-shock locations measured by six Imp spacecraft have been analyzed to determine the average boundary positions and the causes for their variations with time. Best-fit curves obtained to represent the average boundaries in the solar ecliptic plane are characterized by geocentric distances to the magnetopause and bow shock of 11.0 and 14.6 R_E, respectively, near the subsolar point. The average bow-shock orientation is symmetrical about the expected incident direction of the solar wind to better than 2°. The average magnetopause orientation deduced from subsolar hemisphere measurements, on the other hand, fails to reveal a corresponding aberration effect, although such an effect is clear from tail measurements in the downstream region. The width of the average magnetosheath in the solar ecliptic dawn-dusk plane is almost 50% greater in the dusk hemisphere than in the dawn hemisphere because of asymmetry of the shock. The usual theoretical methods of calculating the shape of the magnetopause appear to be adequate in the noon-meridian plane but predict a magnetopause that is too close to the earth in the dawn-dusk meridian plane. This discrepancy is probably due to the theoretical assumption that there is no bow shock and no plasma in the magnetosphere. It is suggested that the experimentally determined value of 0.33 for the ratio of the shock standoff distance to the geocentric subsolar magnetopause distance and relatively high values of the gas dynamic Mach number imply that an effective value of γ between 5/3 and 2 is appropriate for the interaction of the solar wind and the earth.

Analysis of Imp 4 plasma data in conjunction with the boundary positions shows that solar-wind flux appears to be the primary factor controlling the average position of the magnetopause and the bow shock observed on any given spacecraft pass. Knowledge of solar-wind density and velocity is found to be adequate to predict the average position of the bow shock to better than 1 R_E 80% of the time and to better than 0.5 R_E 50% of the time when the geomagnetic ring current is not unusually large. Evidence is presented suggesting that the factor f^2/K used in predicting the magnetopause position assumes a value greater than unity. Prediction of the exact magnetopause position may be more difficult than prediction of the shock position if local variations of the boundary are important. Analysis confirms *Meng*'s [1970] finding that distant magnetopause positions correspond to quiet conditions, whereas earthward positions are observed during either disturbed or quiet times. The direction of the interplanetary magnetic field is found to be a secondary factor influencing the boundary positions, a southward field producing a more earthward magnetopause. This finding supports the suggestion of *Aubry et al.* [1970] that in the presence of a southward interplanetary field, magnetic flux is eroded from the subsolar magnetosphere and added to the tail.

On rare occasions, the bow shock is observed at exceptionally distant locations, as much as 22 R_E beyond the average position. These locations cannot be explained by a comparably distant magnetopause whose position varies only as the one-sixth power of the momentum flux, but they must rather be due to an enhanced standoff distance for the bow shock. These distant shocks are found to be weaker than average bow shocks on the basis of a decreased jump in the tangential field strength across the shock. An unusually low Alfvén Mach number is often observed at these times and is consistent with an enhanced standoff distance, proposed by *Spreiter and Jones* [1963]. The result agrees with the conclusions of *Heppner et al.* [1967], but the observations extend the position of distant shocks to far greater distances.

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Boundary positions used in this study may be

obtained from the National Space Science Data Center, Code 601.4, Goddard Space Flight Center, Greenbelt, Maryland 20771.

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