



THE LOCATION OF THE JOVIAN BOW SHOCK AND MAGNETOPAUSE: GALILEO INITIAL RESULTS

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ABSTRACT

The Galileo spacecraft observed multiple bow shock crossings and a single magnetopause crossing on its inbound approach to Jupiter in November 1995. We compare these observations to those obtained on previous missions, taking account of variable solar wind pressure and the disk-like shape of the magnetosphere. We find that the subsolar magnetopause location varies with solar wind dynamic pressure to the -0.22 power in contrast to the terrestrial -0.167 power. This difference is well known, and has been attributed to the presence of hot plasma and centrifugal stretching in the Jovian magnetodisk that lessens the pressure gradients in the outer magnetosphere. Our analysis also reveals for the first time that the magnetopause boundary of magnetosphere exhibits polar flattening, as has been previously inferred from the stretched magnetic field lines seen within the magnetosphere. The bow shock is not so asymmetric in shape. Finally, we find that Galileo observed expanded boundaries early on its inbound pass, perhaps in part due to hotspot activity at Io in the fall of 1995 prior to the Galileo encounter. Observations within the magnetosphere are consistent with externally driven motion of the boundaries.

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INTRODUCTION

The shape of the Jovian magnetosphere is significantly different than the other magnetospheres in the solar system. Rapid rotation together with interior mass loading by Io stretches the magnetosphere into a disk-like shape so that its equatorial cross-section is quite different than its cross-section in the noon-midnight meridian. Furthermore, this streamlined shape (at least in the north-south direction) allows the bow shock to approach more closely to the magnetopause than at blunter obstacles such as that of the Earth. Finally, the activity of the volcanoes of Io is episodic, possibly leading to variable mass loading of the Jovian magnetosphere thereby possibly adding another source of variability to its size. In this paper we examine the recent Galileo observations of the locations of the magnetopause and bow shock of Jupiter in the context of previous observations to address these issues. We explore the dependence of the magnetopause position on the solar wind dynamic pressure, the location and shape of the low latitude magnetosphere and bow shock boundaries, and the possibility of a distended magnetosphere during the Galileo encounter.

OBSERVATIONS AND METHOD OF ANALYSIS

In November 1995, the Galileo spacecraft recorded multiple bow shock encounters between 215 and 130 R_J on its approach to Jupiter. (R_J = Jovian radius). Shown in Figure 1 are the magnetometer data from the inbound approach, including the 7 shock crossings, traversal through the sheath, and a single magnetopause crossing at 118 R_J . A period of possible "close encounters" with the magnetopause subsequently occurred as Galileo passed through 90 to 60 R_J in the "outer magnetosphere" characterized by generally southward field orientation and large fluctuations (Kivelson *et al.*, 1997).

Observed boundary crossings from Galileo, Ulysses, Voyagers 1 & 2, and Pioneers 10 & 11 provide considerable longitudinal information (X,Y plane) about these boundary surfaces, as seen in Figure 2a. In the third dimension, at high ecliptic latitudes there is limited coverage (notably Ulysses and Pioneer 11). However, the 9.6° tilt of the magnetic dipole axis from the spin axis provides additional $\sim 19^\circ$ changes in magnetic latitude on ~ 10 hr timescales along the spacecraft paths. We therefore rotate all the observed crossing positions into Jupiter-centered magnetic

(JSM) coordinates, where X_{JSM} points to the Sun, Z_{JSM} is along the projection of the Jovian dipole axis in the plane perpendicular to X , and Y_{JSM} is aligned with the magnetic equator (Figure 2b). A magnetic coordinate system is appropriate for this analysis because we expect the boundary shapes, particularly the magnetopause, to be influenced by the orientation and shape of the Jovian magnetodisk. (The latitudinal information is neglected by those modelers who assume cylindrical symmetry when fitting the boundary profiles.)

On each pass, multiple crossings separated by <1 hr are averaged to reduce weighting of the statistics toward times of boundary disturbance or instability. Scatter in the positions of the multiple boundary crossings is expected in response to solar wind dynamic pressure variations. We use the empirical relationship obtained by Slavin *et al.* (1985) for the subsolar ("nose") standoff R_N to scale boundary crossing positions by $R_{N,obs} \times (P_{sw}/P_{AV})^{1/4}$ to the average solar wind dynamic pressure P_{AV} (approx 0.1 nPa). Simultaneous observations by Voyagers 1 and 2 (0.5 AU apart) and Pioneers 10 and 11 (1.5 to 2 AU apart) allow solar wind pressure P_{sw} at Jupiter to be inferred with reasonable or high confidence for periods while one of each spacecraft pair traversed the magnetosphere. Density estimates are projected assuming $1/r^2$ fall-off with distance from the Sun, while solar wind speed is assumed to remain constant. For Ulysses and Galileo (with no nearby spacecraft), we estimate solar wind conditions based on near-Earth observations. Time of

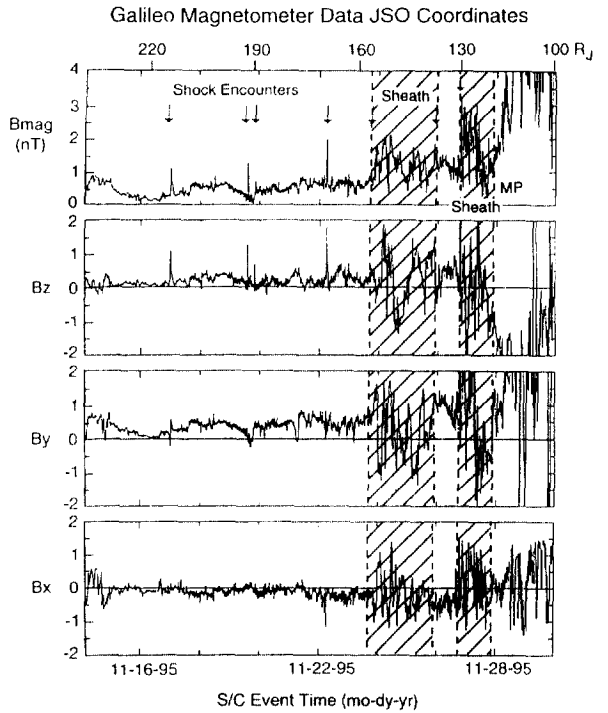


Fig. 1. Galileo magnetometer data on approach to Jupiter. The bow shock crossings and magnetopause are shown.

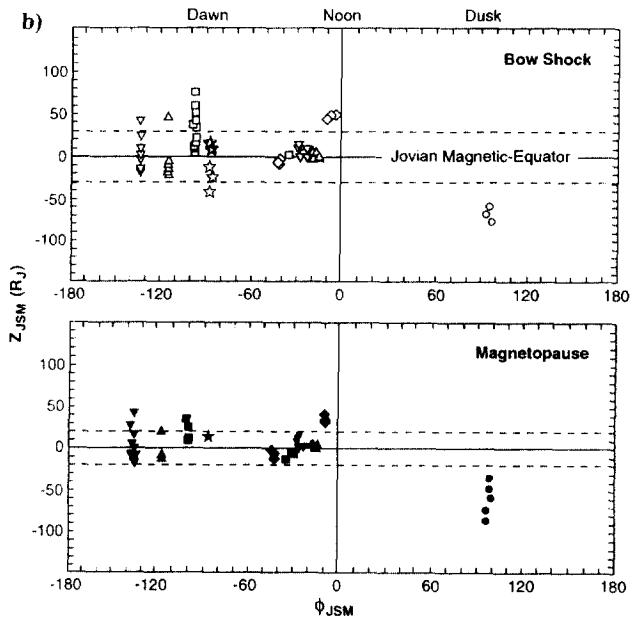
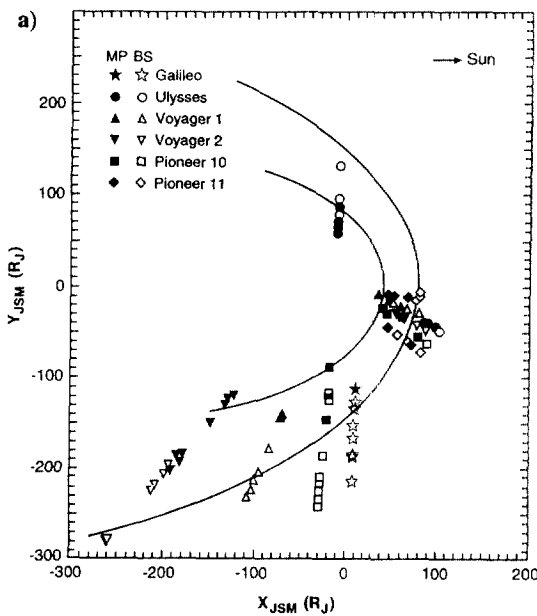


Fig. 2. Jovian bow shock (open symbols) and magnetopause (solid symbols) crossings observed by: Galileo (Kivelson *et al.*, 1997); Ulysses (Bame *et al.*, 1992); Voyager 1 and 2 (Lepping *et al.*, 1981); and Pioneers 10 and 11 (Intriligator and Wolfe, 1976). These are shown in Jupiter-centered magnetic coordinates (JSM) in both (a) X_{JSM} , Y_{JSM} plane projection, and (b) the Z_{JSM} , magnetic-longitude view.

arrival is predicted based on solar wind speed and the angular separation of Earth and Jupiter in their orbits about the Sun assuming a source region on the Sun emits similar plasma for at least a partial solar rotation. These are low-confidence estimates; only large-scale variations survive. For Galileo and Ulysses, the average of the projected pressure estimates for the encounter period is ~ 0.1 nPa in both cases and we need not normalize these crossings.

We then fit an ellipse profile for boundary standoff, $R = L/(1 + \epsilon \cos \vartheta)$, to observations in two different latitudinal slices: (1) near the magnetic equator, $|Z_{JSM}| < 30 R_J$ for the bow shock, $< 20 R_J$ for the magnetopause; (2) at "high" latitudes, $|Z_{JSM}| > 30 R_J$ for the bow shock, $> 20 R_J$ for the magnetopause. Our ultimate aim is to explore the 3-D shape of the magnetopause and bow shock boundaries at Jupiter. Here, we present some preliminary results.

RESULTS AND DISCUSSION

Dependence on Solar Wind Dynamic Pressure. The dependence of subsolar standoff (R_N) on solar wind dynamic pressure is in general agreement with that found by Slavin *et al.* (1985) who used solar wind pressure estimates from outside the bow shock and magnetic pressure estimates just within the magnetopause. In Figure 3 we present the relationship obtained from the magnetopause crossings of Voyagers 1 and 2 (for which we have high confidence in the pressure estimates), and we have included only those crossings at low magnetic latitudes ($Z_{JSM} < 20 R_J$) to exclude the effect of magnetodisk wobble. The magnetopause R_N depends on P_{sw} to the power -0.22. There are other factors which affect the observed boundary locations, particularly for the bow shock (for which there is large scatter). These include the amount of internal plasma in the magnetosphere, and whether or not the boundary was at an equilibrium position or whether it was moving when observed.

Galileo Inbound Pass. The magnetic field strength $|B| \sim 2$ nT just within the magnetopause corresponds to a magnetic pressure of ~ 0.002 nPa. The solar wind dynamic pressure inferred from projection of the near-Earth observations is around 0.1 nPa. At this location on the flank of the magnetopause, the angle ϑ_N between the boundary normal and the solar wind flow is $\sim 50^\circ$ so that the ram pressure is ~ 0.04 nPa. This is not in balance with the internal magnetic pressure alone (as expected); clearly, the internal plasma pressure is extremely significant. But is the Galileo case unusual? Figure 4 shows that all but 2 of the 7 Galileo inbound shock crossings were observed farther from Jupiter than the average (fitted) bow shock location, suggesting an expanded magnetosphere during the early portion of the Galileo approach. However, our survey of the Earth-based solar wind data does not find an unusual solar wind at this time. Jupiter's satellite Io is the major source of plasma for the Io torus and Jovian magnetosphere as a whole. A brightening of the major volcanic hot-spot, "Loki", persisted during most of fall 1995, and may have continued through the Galileo flyby (J. Spencer, private communication 1996). A state-of-the-art magnetosphere model (O6 internal field with hinged and warped magnetodisk current system (Khurana, 1997)) compared to the Galileo observations suggests that the current density J on initial entry to the magnetosphere is approximately consistent with that seen during the Pioneer 10 encounter, but becomes higher at later times (Khurana, 1996; Kivelson *et al.*, 1997). Galileo's second encounter with the outer magnetosphere and the inferred inward motion of the magnetopause boundary are best explained by a change in external solar wind conditions (Kivelson *et al.*, 1997).

Shape of Average Boundary Cross-Sections. From Figure 4a, the subsolar shock-to-magnetopause standoff ratio is approximately 1.12; we find the bow shock forms closer to the magnetopause than in Earth's case (ratio ~ 1.33), in

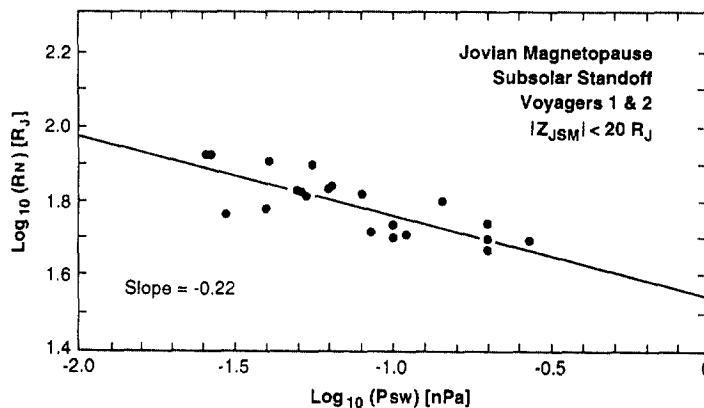


Fig. 3. The extrapolated subsolar standoff distance of the Jovian magnetopause versus solar wind dynamic pressure for Voyagers 1 and 2 for low magnetic latitudes.

agreement with previous works. In Figure 5 we present the average low and high magnetic latitude cross-sections. The "high" latitude fit includes boundary crossings $20 < Z_{JSM} < 90$ (average $Z_{AVG} = 45 R_J$) for the magnetopause and $30 < Z_{JSM} < 80$ ($Z_{AVG} = 53 R_J$) for the bow shock. The magnetopause comparisons show a closer boundary standoff at height Z_{AVG} above the subsolar "nose" than at the same Y_{JSM} east or westward around from the nose (dashed lines in plot). This "squashing" about the magnetic equator is indicative of the influence of the Jovian magnetodisk on the boundary shape. Our results show that the effect is greater for the magnetopause than for the bow shock, as might be expected for an internal cause rather than the result of draped B_{IMF} direction. A 3-D MHD simulation by Ogino *et al.* (1997), which models a strongly corotating Jovian magnetosphere, shows a similar effect on the bow shock surface shape, and additionally an east-west asymmetry due to corotation, with dawn side standoff greater than dusk side standoff.

SUMMARY

Galileo observed an expanded magnetosphere during the early portion of its inbound pass. The projected average solar wind conditions suggest at least partly an internal cause, consistent with Io hotspot brightening observations in fall 1995 prior to the Galileo encounter (J. Spencer, private communication 1996). This may have relevance to the "average" boundary locations during this encounter. However, observations within the magnetosphere are consistent with externally driven motion of the boundaries (Kivelson *et al.*, 1997).

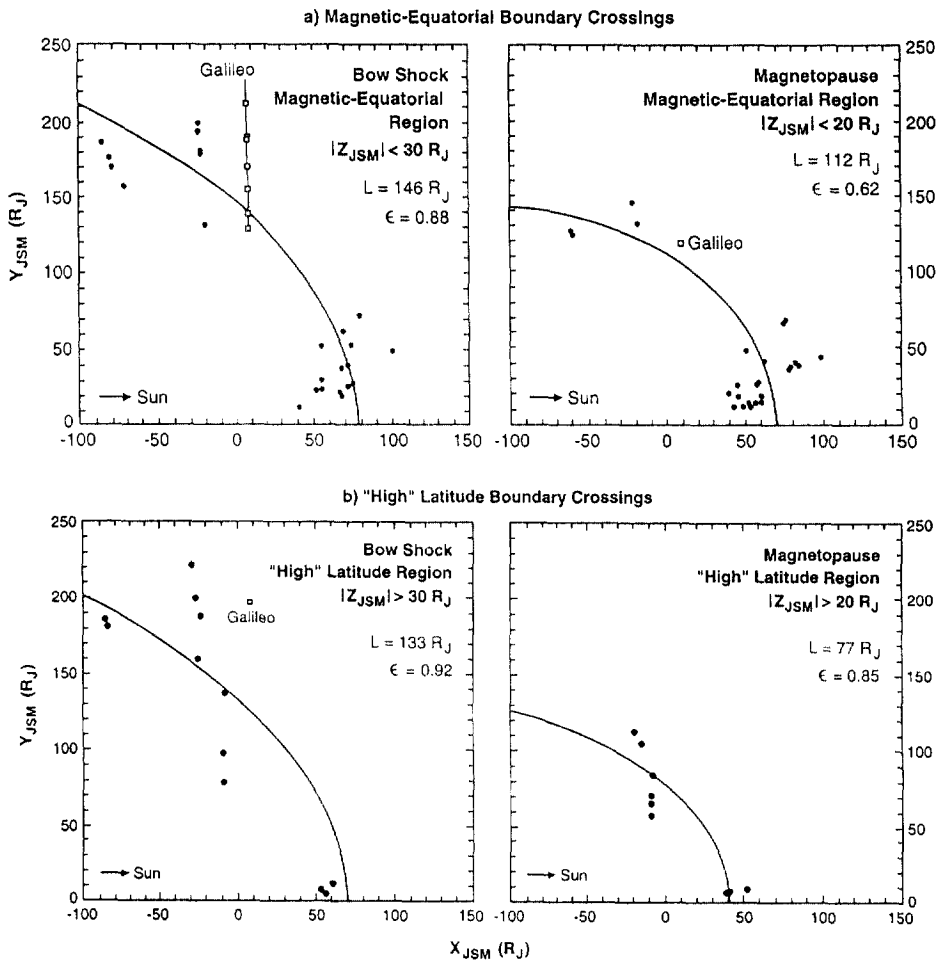


Fig. 4. Cross-sectional fits to the Jovian bow shock and magnetopause crossings (normalized to average P_{sw}) using data from all spacecraft for (a) low, and (b) "high" magnetic latitude regions separately. The Galileo crossings are highlighted as open squares.

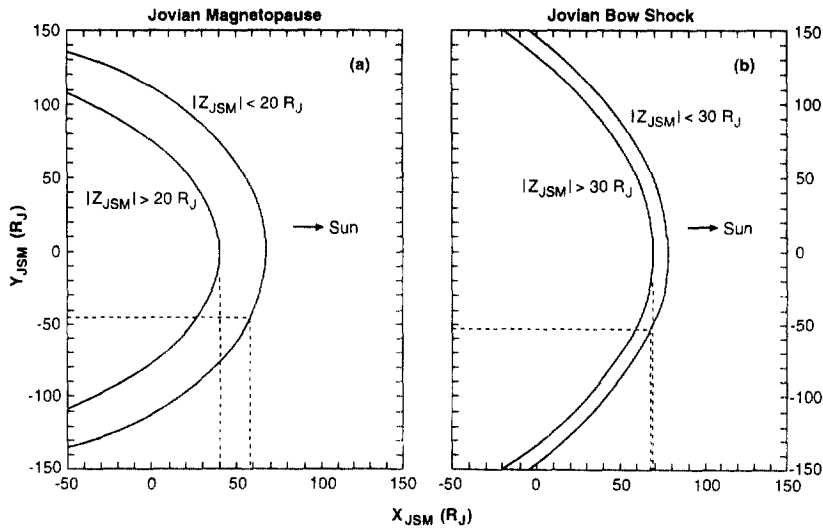


Fig. 5. Comparison of low-latitude and high-latitude cross-sections for (a) the magnetopause and (b) the bow shock.

From Figure 4 it is seen that the bow shock is more flared than the magnetopause, as expected, and the subsolar shock-to-magnetopause standoff ratio is ~ 1.12 . There is a large scatter in the observed crossing positions. The location and shape (and the number of crossings) of the bow shock and magnetopause boundaries observed by the spacecraft depend upon: the internal magnetospheric plasma content (Io activity); the magnetodisk wobble with Jovian rotation (period ~ 10 hrs); and solar wind control by dynamic pressure variations, solar wind direction changes and transients (which may result in magnetotail "flapping").

Figure 5 suggests a magnetopause surface which is flattened in the Z_{JSM} direction, i.e. "squashed" on either side of the magnetic equator. This is in agreement with 3-D MHD model results of Ogino *et al.* (1997). The conclusion for the bow shock is uncertain from our analysis because the large scatter in the observations leaves some uncertainty in the shape of the fits. Nevertheless, the effect is clearly larger for the magnetopause, demonstrating that internal influence of the magnetodisk is more important than the effects of the solar wind B field direction in determining asymmetries of Jovian boundary shape.

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