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First evidence of IMF control of Jovian magnetospheric boundary locations: Cassini and Galileo magnetic field measurements compared

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Abstract

The Cassini spacecraft, en route to Saturn, passed close to Jupiter while the Galileo spacecraft was completing its 28th and 29th orbits of Jupiter, thus offering a unique opportunity for direct study of the solar wind–Jovian interaction. Here evidence is given of response of the Jovian magnetopause and bow shock positions to changes of the north–south component of the solar wind magnetic field, a phenomenon long known to occur in equivalent circumstances at Earth. The period analyzed starts with the passage over Cassini of an interplanetary shock far upstream of Jupiter. The shock's arrival at Galileo on the dusk-flank of the magnetosphere caused Galileo to exit into the solar wind. Using inter-spacecraft timing based on the time delay established from the shock arrival at each spacecraft, we point out that Galileo's position with respect to the Jovian bow shock appears to correlate with changes in the disturbed north–south reversing field seen behind the shock. We specifically rule out the alternative of changes in the shape of the bow shock with rotations of the interplanetary magnetic field as the cause.

Keywords: Magnetospheric configuration and dynamics; Magnetospheric transport; Jovian magnetospheric structure

1. Introduction

The position of a planetary magnetopause is determined first and foremost by the requirement that the normal component of the dynamic pressure of the solar wind must balance the internal pressure of the magnetosphere across the surface (Walker and Russell, 1995). Nevertheless, a secondary control of the position of the boundary is provided by the sense of the interplanetary magnetic field. Aubry et al. (1970) put forward the first direct evidence that the low latitude dayside terrestrial magnetopause moves inwards at a time of constant solar wind dynamic pressure in response to changes in the orientation of the north–south (NS) component of the interplanetary magnetic field (IMF). Subsequently studies by Fairfield (1991) and others (Russell, 1979; Sibeck et al., 1991; Petrinec and Russell, 1993a, b; Roelof and Sibeck, 1993, 1994) extended the investigation, showing that, beyond the dawn-dusk meridian, southward IMF increases the flaring. Here we present evidence from joint Galileo and Cassini magnetometer measurements that the low latitude magnetopause at Jupiter also appears to move in conjunction with a component of the external magnetic field. We believe that the process is analogous to that found at Earth but, because Jupiter's planetary dipole moment is roughly antiparallel to that of Earth, the effects of northward and southward interplanetary magnetic field are reversed.

2. Observations

In the months from October 2000 to March 2001, the Cassini spacecraft acquired data near the orbit of Jupiter en route to its encounter with Saturn. Galileo, in orbit around Jupiter, provided simultaneous measurements within Jupiter's magnetosphere and in the solar wind near Jupiter. The two data sets provide the basis for the first investigations of the way in which changes of solar wind properties affect aspects of Jupiter's magnetospheric response. Here we examine in detail the data from a few days during which Galileo was near the dusk flank of the Jovian

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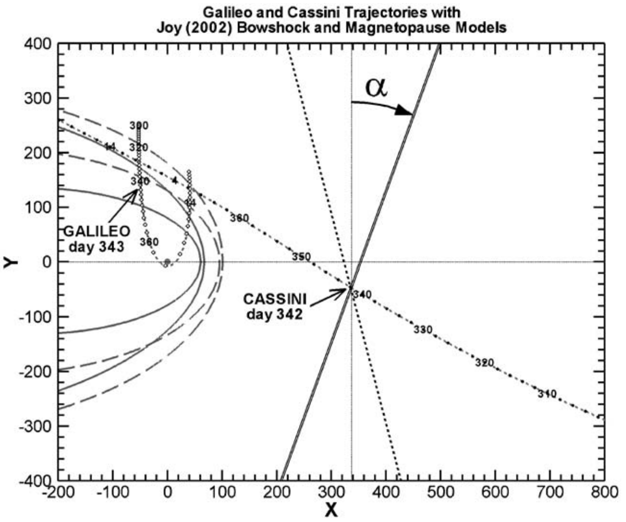

Fig. 1. Trajectories of Galileo and Cassini in December 2000 and January 2001 during the Cassini flyby of Jupiter. Labels on the trajectories provide the day of year in 2000 (numbers in the 300s) or 2001 (numbers less than 100). On the Cassini (Galileo) trajectory, black dots (open circles) are separated by 2 days. The approximate positions of Galileo and Cassini during the interval discussed in this paper are indicated. Because the boundaries move in response to solar wind dynamic pressure changes, the positions of the bow shock (dashed curves) and magnetopause (solid curves) are plotted for both the compressed and the expanded magnetosphere using Joy's (2002) statistically determined locations.

magnetosphere and Cassini was monitoring the solar wind as illustrated in Fig. 1.

At 23:12 UT on December 7, day 342, the solar wind magnetic field at the Cassini spacecraft, upstream of Jupiter at (323, −38, 20) in Jovian solar ecliptic coordinates with distances in R_J, increased from 0.5 to 1.7 nT. We attribute this increase to the passage of an interplanetary shock. On December 8, approximately at ~ 11:43 UT, the field magnitude at the Galileo spacecraft, within the dusk flank of Jupiter's outer magnetosphere at (−49, 136, −2), began to increase from < 2.8 nT to 3.6 nT. We interpret the increase of field magnitude as a compression of the magnetosphere resulting from the propagation of the effects of the shock to Galileo's position. The compression caused the magnetopause to move inward so that 1 h later Galileo encountered the magnetosheath and within 3 h found itself back in the solar wind. In estimating the time delay for the shock to move from Cassini to Galileo, we argue that the beginning of the field increase at Galileo, 12.5 h after the shock passed Cassini, corresponds approximately to the time needed for the shock to propagate within the solar wind. However, the compressional signature may have traveled from the nose of the magnetosphere to Galileo partly through signals propagating within the magnetosphere at speeds higher than the solar wind speed. For this reason, we estimate the solar wind transport time more closely by shifting the Cassini data so that the two data sets track each other closely when both are within the solar wind. Fig. 2, in which the Cassini data have been shifted by 13 h, shows excellent correspondence between 15:50 and 19:15 UT when both data sets describe the solar wind. The 13 h shift would require a travel speed of ~ 568 km/s if the front were oriented radially. The inferred speed is nominal for the solar wind behind a shock.

Direct comparison of the shock propagation speed with inferences from the solar wind ions measured by Cassini is not possible because there is a gap in the data from the Cassini CAPS instrument (Young et al submitted) from December 4, day 339, at 22:10 UT to December 8, 2000, day 343, at 22:22 UT, just over 23 h after the shock passage. Prior to the gap, the ion density fluctuated between 0.3 and 0.6 cm^{-3} and the flow speed remained near 415 km/s. One day after the shock, when CAPS data again became available, the density was 1.5 cm^{-3} and the flow speed had changed to ~ 490 km/s where it remained for the entire day (D. Young and F. Crary, 2002, personal communication). The ion thermal speed three days before the shock passage is estimated by Young and Crary as of order 10 km/s while on days 343-4 their estimates lie between 20 and 50 km/s. [The electron data showed a similar picture of the density evolution (A. Coates, personal communication).] Perhaps the best check of the veracity of our estimate of the speed of travel of the shock front is that during later periods where we have the ion speed estimates, the corresponding delays that they would indicate for transmission from Cassini to Galileo (of order 15 h) also fit well with the intercomparison of data from the two magnetometers at that time. One should also note that a shock or indeed waves in the solar wind do not travel at the solar wind speed but may travel slightly in excess of it.

Delay times between observations at the two spacecraft can also depend on the orientation of the shock surface relative to the radial direction from the Sun. The dotted and double lines in Fig. 1 show two possible orientations. Using minimum variance analysis, we have estimated the direction of the shock normal as the structure passed Cassini and find it to be consistent with a rotation through an angle α of about 20° in the clockwise sense as shown in Fig. 1. We can only conclude that a rotation consistent with our normal estimate requires there to be an even higher radial transmission speed to bring the shock to Galileo's position in 13 h. Nevertheless, the arrival of the compressional signal at Galileo in 12.5 h followed by the close resemblance of the Galileo signatures with those of Cassini shifted by 13 h at times when both are in the solar wind seems to pin down the delay time fairly closely. We propose that either the solar wind speed was higher for part of the time during which there were no plasma measurements or that at the time Cassini encountered the shock, there were waves on the shock surface that caused the local orientation to differ from the mean surface orientation.

The analysis that follows takes the 13 h delay as a basis for mapping the IMF from Cassini to the near vicinity of

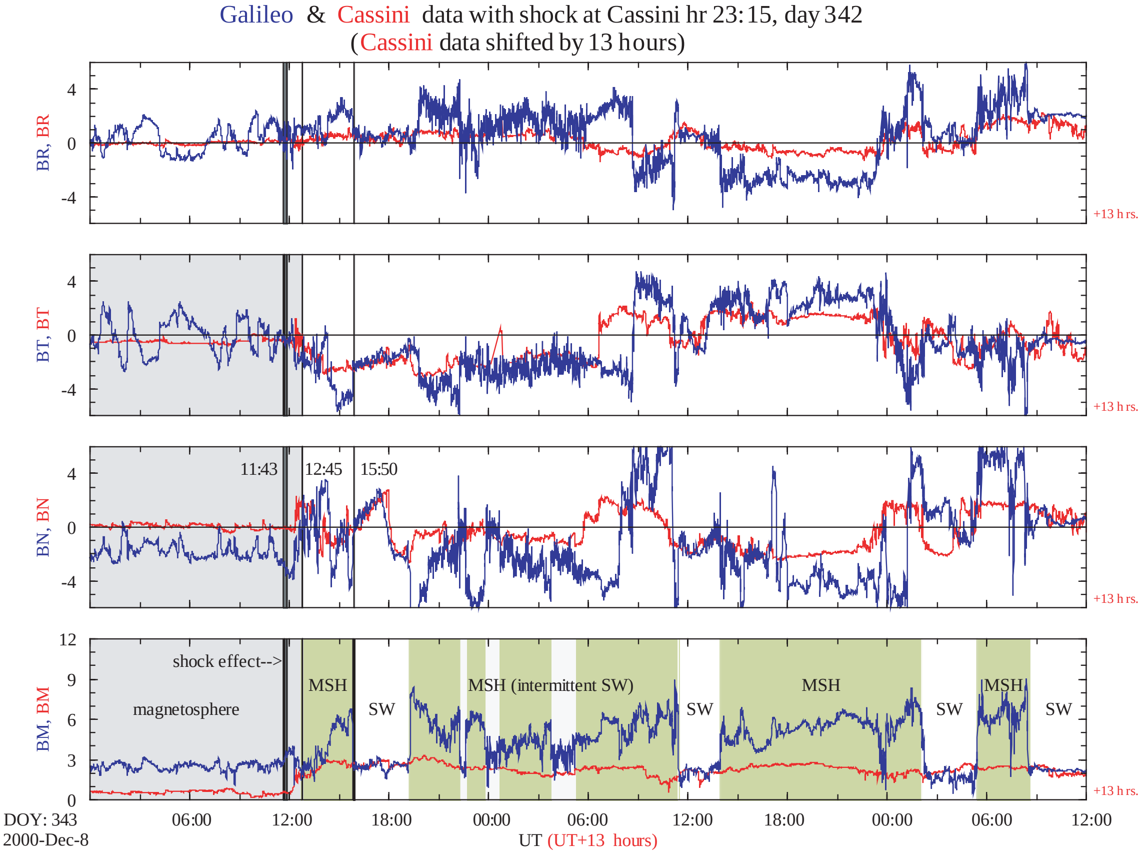

Fig. 2. Cassini (red) and Galileo (blue) magnetic field magnitude and components from December 8–10 in the RTN heliocentric coordinate system with R radial from the sun, N normal to the ecliptic plane, and T completing an orthogonal coordinate system. A heavy black line shows the time when an interplanetary shock observed 13 h earlier at Cassini reached Galileo's position. Intervals when Galileo was not in the solar wind are shaded. Galileo was within the magnetosphere in the interval shaded gray. In the lower panel, olive denotes magnetosheath and lack of color denotes solar wind. Cassini data have been shifted ahead by 13 h.

Galileo in the interval that follows its arrival. The critical observations were made on days 343–346, 2000 (December 8–December 11) when Cassini was close to the Sun–Jupiter line and Galileo was inbound through the duskside magnetosphere. The magnetic field components and magnitudes are plotted in Fig. 2, with Galileo data (Kivelson et al., 1992) in blue and Cassini data (Kellock et al., 1996; Dougherty et al., 2003 in press) in red. The plot uses a heliocentric RTN coordinate system, with R radial from the sun, N normal to the ecliptic plane, and T, positive in the sense of planetary orbital motion, completing the orthogonal system.

In Fig. 2, the effects of the interplanetary shock appear as a clear increase in the field magnitude at Galileo, starting at 11:43 UT. In the discussion to follow, the Cassini field properties are discussed in terms of the times shifted by 13 h unless specifically indicated otherwise. In Fig. 2, on day 343 at the start of the interval (and until day 343 at 11:43 UT), the field mapped from Cassini is small (< 0.7 nT) and quiescent. In this time interval, Galileo is seen to be within the Jovian magnetosphere as evident from the stably southward field orientation with a quasi-periodic variation of the radial and azimuthal components of the field (see, for example, Fig. 3 of Kivelson et al. (2002) which shows data from a different interval in the outer duskside magnetosphere).

The shock in the Galileo data is followed directly by Galileo's rapid ($\sim$ 1 h) transition from the magnetosphere to the magnetosheath and then into the solar wind where, after $\sim$ 15:50 UT, the field magnitudes in the two data sets are approximately the same. Between 12:45 and 15:50 UT, the entire magnetosheath moves across Galileo. It is clearly in the magnetosphere prior to 11:43 UT. From 15:50 to 19:15 UT, it is in a regime where the field magnitude and components are very close to those recorded earlier by Cassini. We conclude that the two spacecraft are both in the solar wind.

Olive shading in Fig. 2 indicates additional intervals during which Galileo was either within the magnetosheath or made only very brief entries into the solar wind (uncoloured). Within the uncoloured intervals, the field magnitudes measured at the two spacecraft were approximately the same.

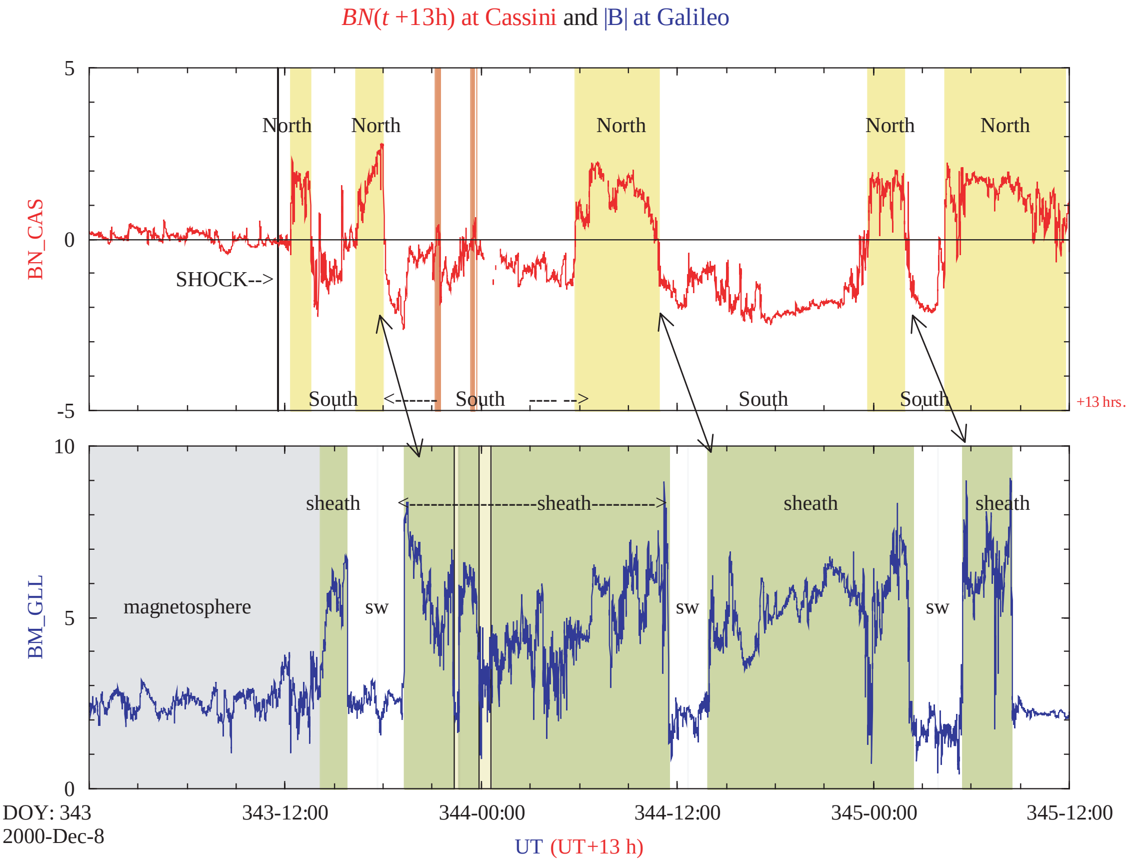

Fig. 3. Bottom panel, field magnitude at Galileo from December 8, 2000 at 00:00 UT to December 10, 2000 at 12:00 UT. Intervals when Galileo was in the magnetosheath are shaded olive. Upper panel, the north–south component of the magnetic field at Cassini (in the solar wind) 13 h earlier, with yellow shading showing intervals during which the field at Cassini was northward oriented. Arrows link southward turning at Cassini with a return from the solar wind to the magnetosheath at Galileo.

3. Discussion

As described above, our deduction is that the effects of an interplanetary shock that compressed the magnetosphere were detected by Galileo starting at 11:43 UT. Very shortly afterwards, Galileo crossed the magnetopause and entered the magnetosheath. Following an interval during which the fields at Galileo and Cassini were consistent with Galileo's being in the sheath, Galileo entered a new magnetic regime that, by comparison with Cassini, we identify as the solar wind. If this interpretation is correct, one can note that the bow shock on the flanks probably moved in the boundary normal direction at a speed of order 50 $R_J/4$ h or about 250 km/s, where the distances are consistent with shock models (Joy et al., 2002) that appear in Fig. 1.

Galileo's first encounter with the solar wind was relatively short-lived and it returned to the sheath at 19:15 UT. Two subsequent persistent encounters with the solar wind occur shortly after 11:27 UT on December 9 and 02:12 UT on December 10, and in these lengthier encounters, the magnitudes are well correlated between the two spacecraft. The correlation of the components of the field improves if the delay time between the spacecraft is increased to 15 h corresponding to a slightly decreased solar wind speed of 492 km/s. This speed is consistent with the measured values from CAPS at the appropriately time shifted observing time.

It is easy to argue that the first magnetopause and outbound shock crossings resulted from compression of the Jovian magnetosphere following the arrival of the interplanetary shock. It is less clear how to account for the subsequent multiple shock crossings, particularly because following the shock the field magnitude at Cassini is remarkably steady and one would expect little additional change in the ambient solar wind dynamic pressure. Although we are not able to verify this hypothesis directly, we can argue that the good correlation between the Cassini magnetic field vectors shifted by 13–15 h and those measured when Galileo was in the solar wind after 12:00 UT on December 8 indicates that the solar wind slowed only slightly in the day following the passage of the shock.

Assuming that the Mach number of the IMF changed relatively little during the interval following the shock, causes of the bow shock displacement across Galileo's position other than changes of solar wind dynamic pressure must be considered. Plausible mechanisms causing displacement are suggested from our knowledge of processes controlling the boundaries of Earth's magnetosphere, where not only solar wind dynamic pressure but also the interplanetary magnetic field direction can be influential in moving both the bow shock (Greenstadt, 1984; Khurana and Kivelson, 1994; Bennett et al., 1997) and the magnetopause (Russell, 1979; Fairfield, 1991; Sibeck et al., 1991; Petrinec and Russell, 1993a, b; Roelof and Sibeck, 1993, 1994) inwards or outwards. Motions of the magnetopause naturally require the bow shock to move in or out.

Support for the proposal that the orientation of the IMF controlled the motion of the bow shock in the present case is given in Fig. 3 where we plot the north–south component of the IMF measured at Cassini, time-shifted to the inferred arrival at Galileo's position. Shading in the top panel indicates times when the IMF was northward oriented. The bottom panel of the figure shows the field magnitude at Galileo. Shading in the lower panel indicates times when the bow shock had swept outward beyond Galileo's position, leaving Galileo in the magnetosheath. There is a striking correlation between the regions shaded in the two panels, with each IMF rotation from north to south followed in short order by an outward shock motion as shown by arrows. The times of Galileo's entries and exits from the sheath follow the IMF rotations with delays resulting from the finite response time required for the boundaries to move between initial and final equilibrium positions and the unknown distances between the initial boundary positions and Galileo's location. However, the delays are in every case positive.

We first consider the possibility that the shock displacements relate directly to the changing properties of the bow shock for different orientations of the IMF, $\mathbf{B}_{\mathrm{sw}}$. For example, it is known that the properties of the terrestrial bow shock change markedly when the IMF cone angle ($\tan\theta_{\mathrm{Bn}} = \pm(B_{\mathrm{T}}^2 + B_{\mathrm{N}}^2)^{1/2}/|B_{\mathrm{R}}|$) changes from being larger than $\sim 45^\circ$ (quasi-perpendicular shock) to being smaller than $\sim 45^\circ$ (quasi-parallel shock). If the Jovian bow shock changed from quasi-perpendicular to quasi-parallel (Greenstadt, 1984) in conjunction with the N–S and S–N rotations of the interplanetary magnetic field, one might expect surface waves to distort the bow shock and possibly cause outward displacement.

Another way in which the orientation of $\mathbf{B}_{\mathrm{sw}}$ can control the location of the bow shock relates to the anisotropic propagation speed of the fast magnetosonic mode from which the shock forms. The fast magnetosonic group velocity is smaller in the direction along $\mathbf{B}$ than in the direction transverse to $\mathbf{B}$. The asymmetry of the bow shock relates to the angle α_{c}, the clock angle of the field about the Sun–Jupiter direction. Khurana et al. (1994) and Bennett et al. (1997) have established that the equatorial cylindrical radius of a planetary bow shock is greatest for otherwise fixed solar wind conditions when α_{c} is near $\pm 90^\circ$ and that the radius becomes monotonically smaller as α_{c} rotates towards 0° or 180°. Here α_{c} is measured from the downward direction, and is defined as $\alpha_{\mathrm{c}} = \tan^{-1}(B_{\mathrm{N}}/B_{\mathrm{T}})$ in the RTN coordinate system of the plots.

By determining whether Galileo's entries from the solar wind into the magnetosheath and exits therefrom are systematically correlated with changes of θ_{Bn} and α_{c} we test whether the form of the bow shock itself controls the transitions. In Table 1, we list the intervals during which Galileo was in the magnetosheath. The rotations of the solar wind whose influence we wish to examine occur at times that precede the entries and exits as illustrated in Fig. 3. In Fig. 4 the Cassini data for the period of multiple rotations is plotted with key times labeled. The angles θ_{Bn} and α_{c} measured before and after each rotation of $\mathbf{B}_{\mathrm{sw}}$ are listed (in Galileo time) in Table 1. Although there are small changes of the θ_{Bn}, the bow shock conditions remain quasi-perpendicular. This allows us to rule out the possibility that a change of the nature of the shock from quasi-perpendicular to quasi-parallel produced the inward and outward displacements of the shock.

If shock asymmetry controls entries and exits from the magnetosheath, entries should correlate with increases of α_{c} and exits should correlate with decreases of α_{c}. The right hand column of the table shows that 6 of the 8 crossings occur in conjunction with changes of α_{c} inconsistent with the shock asymmetry model. Two of the crossings are listed as consistent with linking the crossing to shock asymmetry, but in one of those cases the angular change is small enough to be considered as a fluctuation of no importance. With at least 6 of 8 encounters not satisfying the hypothesis, we may reject the possibility that bow shock anisotropy controlled the entries and exits.

We are therefore led to the conjecture that Galileo's multiple encounters with the magnetosheath resulted from systematic displacements of the magnetopause. In response to northward turnings of the IMF, the magnetopause moves inwards and the bow shock responds by moving inwards. Our observations imply that the magnetopause moves back out following southward turnings of the IMF and the outward displacement of the bow shock follows naturally. There are two cases in the data shown in Fig. 3 where short excursions from southward to northward orientation appear to lead to inward displacement of the shock. In the figure the short northward intervals in the Cassini data on Dec. 8 from 21:12–21:30 and from 23:24–23:42 UT are marked in orange. In both cases, Galileo briefly returned to the solar wind within the following hour, consistent with expectations from the model of magnetopause displacement.

The proposed inward and outward motions are consistent with displacements of the magnetopause controlled by dayside reconnection. If at Jupiter reconnection has an effect analogous to that now generally accepted at Earth, northward turnings will switch on reconnection between the IMF and the Jovian field, while southward turnings will switch off reconnection. At Earth, the onset of enhanced reconnection causes the dayside magnetopause to move inward as described by Aubry et al. (1970). In view of the different orientations of Jupiter's and Earth's dipole moments, one

Table 1

Solar wind cone (θ_{Bn}) and clock (α) angles upstream of Jupiter's bow shock from Cassini magnetometer data[a] as a test of the hypothesis that shock asymmetry[b] or change from quasi-perpendicular ($\theta_{Bn} > 45°$) to quasi-parallel ($\theta_{Bn} < 45°$) character accounts for the multiple entries into the magnetosheath

Sheath interval UT at Galileo	Related Cassini rotation (shifted times) (Figs. 3 and 4)	B_{Ro} (nT)	B_{Rf} (nT)	B_{To} (nT)	B_{Tf} (nT)	B_{No} (nT)	B_{Nf} (nT)	α_{co} (deg)	α_{cf} (deg)	θ_{Bno} (deg)	θ_{Bnf} (deg)	Consistent with hypothesis of shock asymm.?
Dec. 8, 14:10-	N → S: 13:19-13:56	0.3	0.1	−1.1	−1.6	1.9	−2.1	−60	53	82	88	No
Dec. 8 15:45	S → N: 15:12-17:12	0.5	0.4	−2.6	−2.4	−1.1	1.4	23	−30	80	82	No
Dec. 8 19:18-	N → S: 17:34-18:45	0.6	0.0	−1.9	−1.7	2.2	−2.1	−50	51	78	90	Yes, ∼ constant
Dec. 8 22:20	S → N: 05:34-06:49	0.2	−0.9	−1.8	0.5	−1.3	2.2	36	77	68	68	No
Dec. 8 22:38-	N → S: 10:27-11:23	−0.3	0.6	0.9	−0.6	0.6	−1.3	34	65	74	67	Yes
Dec. 9 11:30	S → N: 21:53-00:10	−0.7	0.3	1.2	0.1	−1.9	1.7	−58	87	73	80	No
Dec. 9 13:53 -	N → S: 01:44-02:25	1.1	−0.3	−1.2	1.2	1.2	−1.1	−45	43	57	80	No, ∼ constant
Dec. 10 02:28	S → N: 03:45-06:00	−0.6	1.3	−0.7	−0.7	−2.1	1.7	72	−68	75	55	Yes, ∼ constant

[a] Times in the table for Galileo are times of observations and times at Cassini are given as time of arrival of the solar wind feature in the vicinity of Galileo and are shifted forward by 13 h from the times at which Cassini measured the field.

[b] Sheath entry correlates with southward turnings of the IMF and sheath exits correlate with northward turnings of the IMF. The subscript "o" ("f") indicates values at the start (end) time of the rotation interval indicated in column 2. If the bow shock asymmetry about the sun–Jupiter direction is the cause of Galileo's entry into the sheath, the magnitude of the angle α_c should increase across a southward turning. Sheath exit corresponds to northward turning. If asymmetry is the cause of Galileo's exit from the sheath, the magnitude of the angle α_c should decrease across a northward turning. The last column indicates whether the data are consistent with this hypothesis. Marginal change of angle is regarded as inconsistent with the hypothesis. The cone angle is seen to change very little for most of the rotations.

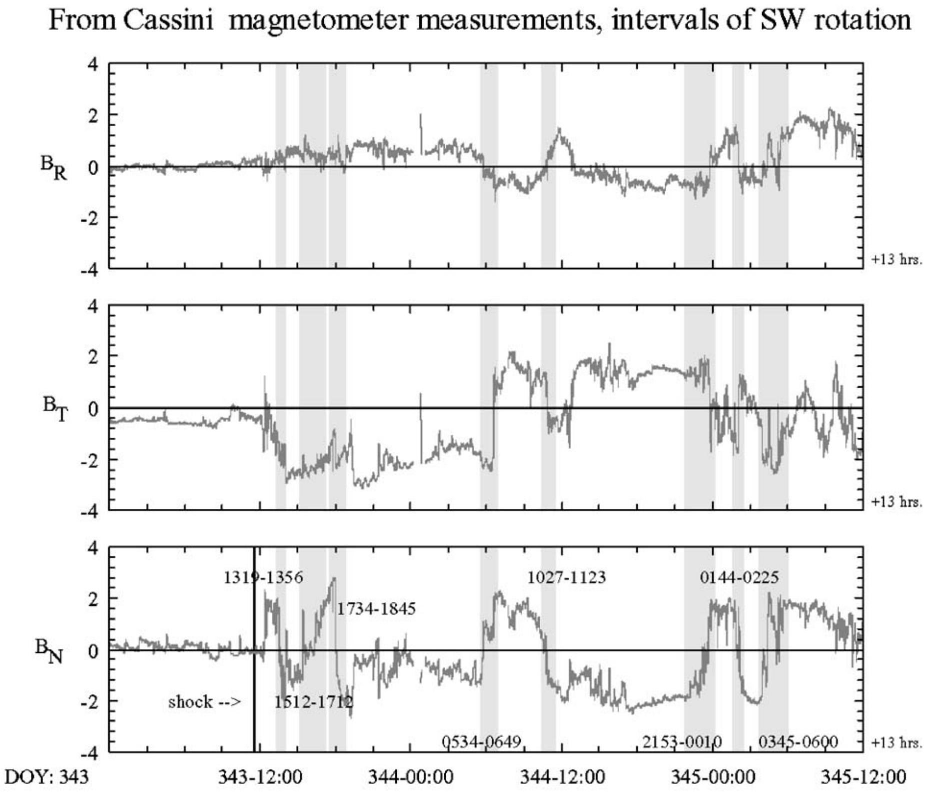

Fig. 4. Three components of the Cassini magnetic field versus UT + 13 h from day 343 00:00 to 345 18:00. Shading identifies intervals during which NS or SN rotations occur and the time intervals are labeled in the lower panel. These are the intervals used for the values entered in Table 1.

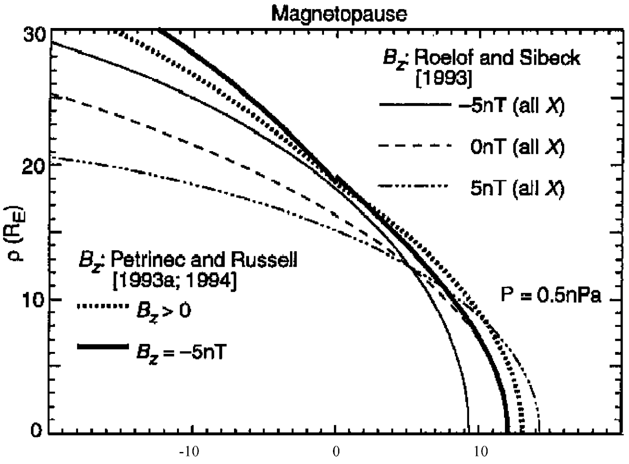

Fig. 5. From Fig. 1 of Roelof and Sibeck (1994) showing outward displacement of the nose of the magnetosphere in the presence of northward IMF at constant pressure for both models.

supposes that in the presence of northward IMF, Jupiter's dayside magnetopause will move inward. If the switch off of reconnection also results in an outward displacement of the magnetopause, then we have a potential explanation of what is reported here. At Earth, the statistical difference between the location of the Earth's dayside magnetopause for southward and northward IMF would suggest that such a relaxation occurs (Russell, 1979; Fairfield, 1991; Sibeck et al., 1991; Petrinec and Russell, 1993a, b; Roelof and Sibeck, 1993, 1994).

Fig. 5 shows the average location of the terrestrial magnetopause for different orientations of the NS component of the IMF. The boundaries were obtained in two studies compared by Roelof and Sibeck (1994). In both cases, the radial distance to the flank magnetopause changes in the sense opposite to that of the dayside magnetopause, with a cross-over somewhere beyond the dawn-dusk meridian. This requires us to question whether motions of the bow shock in the region near dusk are more closely controlled by the distance to the subsolar magnetopause or are affected by the magnetopause flaring at the flanks. It is clear that the hypothesis given in this paper would lead one to conclude that the effect of an externally applied field component anti-parallel to the planetary field is to displace the boundary inwards at least somewhat tailward of the dawn-dusk meridian at Jupiter. There are fundamental reasons why the crossover in the displacement of the boundary at Jupiter might lie tailward of its location relative to local time at Earth. At Earth the solar wind and reconnection are fundamental in tail formation and organization of the tail. At Jupiter the morphology of the tail could well be organized largely by the outflow of plasma from internal sources and only secondarily by solar wind effects, and the flare of the tail may be less sensitive to solar wind effects than at earth.

Several points remain to be considered. The observations do not place limits on the distances over which the magnetopause and bow shock move during the inward and outward displacements. In order to account for the observations, the bow shock need only move inside or outside of Galileo's position. Our observations refer to a time period when Galileo was near the nominal position of the bow shock, so large boundary displacements, while not ruled out, are not required to cause its shift from one magnetic/plasma regime to another. In the Aubry et al. case, the motion was inferred to be on scale lengths of order 1 R_E, or 10% of the distance to the magnetopause. If a similar scale size is inferred for the case that we consider, the bow shock motion would be over distances of order 20 R_J in and out during the multiple crossings.

The close correlation between field rotations at Cassini and crossings of the bow shock begins to break down after day 346 during an interval of persistent northward IMF. A possible explanation is that, following a prolonged interval of reconnection, the magnetopause moved significantly inward, reducing the distance between the bow shock and Galileo and increasing the likelihood that another boundary crossing would occur. At the same time, Galileo's inward motion increased its distance from the bow shock, reducing the probability of a return to the solar wind. With two opposing effects acting, one can only speculate on which will dominate.

The suggestion of direct control of the magnetopause location by the north–south component of the IMF shows that IMF control of magnetospheric processes cannot be ignored, but small motions of the boundary need not greatly affect the global dynamics of the system because the outer magnetosphere contains only a small portion of the energy density of the Jovian system. The conjectured role of reconnection that we put forward here casts no light on the overall importance in the dynamics of the system. Southwood and Kivelson (2001) have argued that reconnection is a secondary process in the control of energy input into the magnetosphere, but their conclusions are disputed by others (Walker et al., 2001; Khurana, 2001).

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References

Aubry, M.P., Russell, C.T., Kivelson, M.G., 1970. On inward motion of the magnetopause preceding a substorm. J. Geophys. Res. 75, 7018.

Bennett, L., Kivelson, M.G., Khurana, K.K., Frank, L.A., Paterson, W., 1997. A model of the earth's distant bow shock. J. Geophys. Res. 102, 26,927.

Dougherty, M.K. et al, 2003. The Cassini magnetic field investigation. Space Sci. Rev., in press.

Fairfield, D.H., 1991. Solar wind control of the size and shape of the magnetosphere. J. Geomag. Geoelectr. 43, 117.

Greenstadt, E.W., 1984. Oblique, parallel, and quasi-parallel morphology of collisionless shocks. J. Geophys. Res. 89, 2151.

Joy, S.P. et al, 2002. Probabilistic models of the Jovian magnetopause and bow shock locations. J. Geophys. Res: 2001JA009146. 107, 1309, doi:10.109/2001JA009146.

Kellock, S. et al, 1996. Cassini Dual Technique Magnetometer instrument (MAG), in Cassini-Huygens: A mission to the Saturnian systems, Proceedings of the Society of Photo-Optical Engineering, SPIE, Vol. 2803, p. 141.

Khurana, K.K., 2001. The influence of solar wind on Jupiter's magnetosphere deduced from currents in the equatorial plane. J. Geophys. Res. 106, 25,999.

Khurana, K.K., Kivelson, M.G., 1994. A variable cross-section model of the bow shock of Venus. J. Geophys. Res. 99, 8505.

Kivelson, M.G., Khurana, K.K., Means, J.D., Russell, C.T., Snare, R.C., 1992. The Galileo magnetic field investigation. Space Sci. Rev. 60, 357.

Kivelson, M.G., Khurana, K.K., Walker, R.J., 2002. Sheared magnetic field structure in Jupiter's dusk magnetosphere: Implications for return currents. J. Geophys. Res, (107(A7),): 10.1029/2001JA000251.

Petrinec, S., Russell, C.T., 1993a. An empirical model of the size and shape of the near-Earth magnetotail. Geophys. Res. Lett. 20, 2695.

Petrinec, S., Russell, C.T., 1993b. External and internal influences on the size of the dayside terrestrial magnetosphere. Geophys. Res. Lett. 20, 339.

Roelof, E.C., Sibeck, D.G., 1993. Magnetopause shape as a bivariate function of interplanetary magnetic field B_z and solar wind dynamic pressure. J. Geophys. Res. 98, 2142.

Roelof, E.C., Sibeck, D.G., 1994. Correction to "Magnetopause shape as a bivariate function of interplanetary magnetic field B_z and solar wind dynamic pressure". J. Geophys. Res. 99, 8787.

Russell, C.T., 1979. The control of the magnetopause by the interplanetary magnetic field, Dynamics of Magnetosphere, pp. 3–21.

Sibeck, D.G., Lopez, R.E., Roelof, E.C., 1991. Solar wind control of the magnetopause shape, location, and motion. J. Geophys. Res. 96, 5489.

Southwood, D.J., Kivelson, M.G., 2001. A new perspective concerning the influence of the solar wind on the Jovian magnetosphere. J. Geophys. Res. 106, 6123.

Walker, R.J., Russell, C.T., 1995. Solar-wind interactions with magnetized planets. In: Kivelson, M.G., Russell, C.T. (Eds.), Introduction to Space Physics. Cambridge U. Press, New York.

Walker, R.J., Ogino, T., Kivelson, M.G., 2001. Magnetohydrodynamic simulations of the effects of the solar wind on the Jovian magnetosphere. Planet. Space Sci. 49, 237.

Young, D.T. et al submitted. Cassini plasma spectrometer investigation. Space Sci. Rev, in press.