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Time delays in the solar wind flow past Venus: Galileo-Pioneer Venus correlations

D. E. Huddleston, C. T. Russell[1], and M. G. Kivelson[1]

Institute of Geophysics and Planetary Physics, University of California, Los Angeles

J. G. Luhmann

Space Sciences Laboratory, University of California, Berkeley

Abstract. The Galileo and Pioneer Venus Orbiter (PVO) spacecraft obtained simultaneous measurements at Venus during the Galileo flyby on February 9 and 10, 1990. The magnetic field data sets from the two spacecraft show corresponding convected features, even when Pioneer Venus is near periapsis on the nightside of the planet. Comparison of the observation times of these corresponding features reveals substantial delays at PVO associated with the deceleration of the flow carrying the draped magnetic field past Venus. Convection lags of up to 10 min are identified near PVO periapsis at an altitude of 1/4 Venus radii (1500 km) above the planet surface. A three-dimensional convected field gas dynamic model is used to calculate expected lag times by tracing field lines from PVO to the open solar wind. Expected lags from the model are relatively insensitive to changes in field orientation and Mach number. This simple gas dynamic model with the standard ionopause obstacle size gives convection lags too small to explain the Galileo-PVO observations. A likely explanation is that mass loading of the solar wind by the Venus atmosphere contributes to the deceleration of the flow near the planet. The observation of similar magnetic structures in the solar wind and deep in the Venus nightside ionosphere suggests that the impenetrable obstacle model is inappropriate in this region and the solar wind magnetic field is convected into the nightside ionosphere on timescales of 10 min or more.

Introduction

On February 10, 1990, the Galileo spacecraft flew by Venus while the Pioneer Venus Orbiter (PVO) was still operational. Two special Galileo data-taking sessions were scheduled during the flyby while PVO was at periapsis on both February 9 and 10, the day before and the day of Galileo's closest approach. The purpose of these simultaneous observations was, in part, to assess the time lags in the flow of the plasma as it passed Venus. We identify delays by timing the observed discontinuities in the magnetic field, **B**, as they passed the two spacecraft. In December 1990, the PVO magnetometer [*Russell et al.*, 1980] was returning only one component of the magnetic field, that perpendicular to the Venus orbital plane, which we compare with the corresponding component of the magnetic field measured by the Galileo magnetometer [*Kivelson et al.*, 1992].

In the open solar wind, the time delay between observation of the same identified feature passing each spacecraft depends on the spacecraft spatial separation, the solar wind flow velocity, and the orientation of the discontinuity. Additionally, when PVO descends in altitude into the magnetosheath and the night ionosphere of Venus, the slowing down of the flow due to the shock and mass loading modifies the observed lag times. Since Galileo is in the solar wind downstream of PVO during the time period of interest, delays due to the Venus obstacle reduce the total PVO-to-Galileo lag time when PVO is within the bow shock. Figure 1 shows the trajectories of the Galileo and PVO spacecraft drawn in units of Venus radii, R_v = 6052 km. In this paper, the Venus solar orbital (VSO) coordinate system is used throughout, where X_{vso} is toward the Sun, Y_{vso} is along the direction opposite to the planet's orbital motion, and Z_{vso} is directed out of the Venus orbital plane along the pole axis completing a right-handed set. For illustrative purposes, a model bow shock is included in Figure 1, with standoff given by $R = \kappa/(1+ \varepsilon \cos \theta)$ at angle θ from the planet-Sun line [e.g., *Tatrallyay et al.*, 1983] for parameters κ = 2.42 and ε = 1.0167. This curve underestimates the standoff distance at the nose of the shock, but is quite appropriate for the flanks. The Galileo spacecraft approached Venus from downstream and observed the flank bow shock several times [*Kivelson et al.*, 1991; *Khurana and Kivelson,* 1994], probably as a result of shock motion in response to changing solar wind conditions [see also *Russell et al.*, 1988; *Hospodarsky et al.*, 1994]. Galileo remained downstream of PVO throughout our period of interest, and thus in general, features were observed first by PVO and then by Galileo.

The Venus neutral exosphere is gravitationally constrained by the planet. The most energetic excited oxygen atoms (~7 eV) are expected to reach altitudes up to ~4000 km or so [*Nagy and Cravens,* 1988], which is some distance outside of the subsolar bow shock standoff at ~2000 km altitude [e.g., *Russell et al.,*

[1]Also at Department of Earth and Space Sciences, University of California, Los Angeles.

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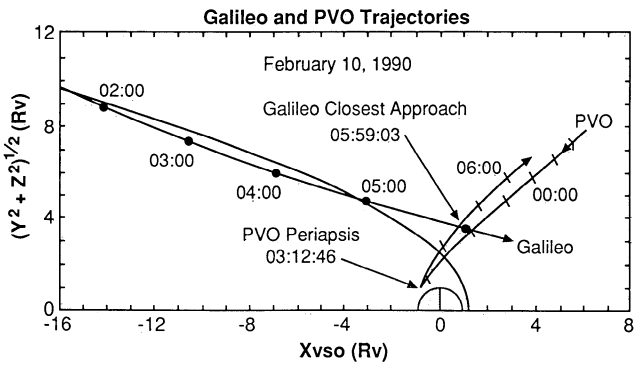

Figure 1. Trajectories of the Galileo and PVO spacecraft during the Galileo Venus flyby on February 10, 1990, are shown in a cylindrically collapsed system with X_{vso} toward the Sun, and the perpendicular distance from the planet projected onto the vertical axis. Plot axes are drawn in units of Venus radii, R_v = 6052 km. The trajectories are annotated with time (UT). The curve shown to represent the bow shock is described in the text.

1985]. These exospheric atoms, as well as any in the upper thermosphere that are present above the ionopause, can be ionized and picked up into the solar wind flow. If sufficient pickup ions are produced, the resulting mass addition will slow the solar wind, which is the process of "mass loading." However, the effect of this process outside of the Venus bow shock is likely to be less important than at Mars, due to greater gravitational force at Venus and the consequent smaller scale height of both the thermosphere and the hot oxygen exosphere. Heavy energetic planetary ions at Venus have been observed close to the planet and downstream in the tail [e.g., *Brace and Kliore*, 1991, and references therein]. While inferred ion densities indicate upstream mass loading at Mars [e.g., *Dubinin et al.,* 1994], to date, pickup ions have not been conclusively detected upstream of the shock at Venus. Recent simulations by *Murawski and Steinolfson* [1995], however, predict that upstream mass loading slows the solar wind flow, causing the shock to stand off further from the planet, and leading to modification of the magnetic barrier and magnetotail. Their simulations were performed with exospheric oxygen ion production rates based on PVO observations for solar maximum, for which a boundary layer develops along the dayside ionopause as in the model of *McGary and Pontius* [1994].

The processes of mass loading by pickup of photoionized or impact ionized (by solar wind electrons) planetary particles and by charge exchange of solar wind protons with "hot" planetary neutrals, the erosion of the ionosphere, and the incorporation of any ionized sputtering products into the magnetosheath flow may significantly affect the solar wind flow around the planet. By the addition of mass, these processes slow the plasma in the magnetosheath (according to conservation of momentum) beyond the amount of expected deceleration that is necessary for simple diversion of shocked flow around the ionospheric "obstacle." The effect of mass loading is expected to vary with the solar cycle, since the solar radiation and particle flux will determine the ionization rate in the Venus atmosphere. We note that the observations presented here were obtained near solar maximum. The combination of the Galileo and PVO data allows us to look for additional lags and determine their magnitude.

Our interest in this problem is twofold. First, we are concerned with whether magnetic features convected by the solar wind are transported into the ionosphere, or whether such features become unrecognizable there. Second, if such corresponding features are seen, how long do they take to convect into the nightside ionosphere? To provide a yardstick against which to measure these delays and discuss the observations, we compare with the time delays expected from the convected magnetic field gas dynamic model of *Spreiter and Stahara* [1980]. Our results can be used to test the accuracy of mass-loaded models of the Venus-solar wind interaction (e.g., models by *Spreiter and Stahara* [1992] and *McGary and Pontius* [1994]).

Observations

Figures 2 and 3 present the simultaneous magnetic field B_z observations taken by PVO and Galileo on February 10 and 9, 1990, the day of and the day before Galileo's closest approach to Venus, respectively. The PVO orbit provided measurements down to a distance of just 1/4 R_v above the planet surface at periapsis. February 10 was the day of Galileo closest approach to Venus (and to PVO), and thus there is generally little significant evolution of solar wind magnetic features over the convected distances between the two spacecraft. The data sets are well correlated (with the appropriate lags) even though the spacecraft made several crossings in and out of the magnetosheath (marked in Figure 2). Lag times for this period are calculated by performing cross-correlation analysis on the simultaneously obtained PVO and Galileo data sets. A time-dependent, or equivalently spacecraft-separation-dependent, profile of lags is obtained by considering several small sections of the available data. These observed lags are displayed in Figure 4. Lags are positive when the feature is observed by PVO before Galileo, and the values are plotted against the component of spacecraft separation along the solar wind flow direction. Note that when PVO was close to periapsis, the apparent lag was temporarily reversed, so that Galileo observed a feature at ~0321 UT before PVO did at ~0326 UT. Identification of corresponding features, however, is a little uncertain here.

A brief period of data-taking by Galileo on February 9, the day before the encounter, allows comparison with PVO data near periapsis on its previous orbit. Observed features at PVO are still recognizable convected over 90 R_v to Galileo. Lags for this period may be estimated "by eye," as illustrated in Figure 3, by the identification of the more distinct corresponding B field signatures. The time axes along the top and bottom of each plot, belonging to the PVO and Galileo data sets, respectively, have been shifted with respect to one another to match up the observed features. Note that using the entire section of Galileo data, the peak cross-correlation coefficient is found for a lag of ~20 min PVO → Galileo. The upper panel aligns the data with 20 min lag, which appears most appropriate for the earlier part of the Galileo data, while in the lower panel the delay time is nearer 16 min for solar wind features that approximately match those near PVO periapsis. We note, however, that since significant evolution of solar wind structures is apparent, our identifications cannot be regarded as unambiguous and should be taken with some caution. Nevertheless, it is interesting that the delay appears to be significantly less than the ~26 min expected for convection from PVO → Galileo at the ambient V_{sw} = 350 km/s on February 9, demonstrating again that the Venus magnetosphere slows the flow of plasma near PVO periapsis. In other words, we see evidence for considerable delays in the magnetosheath at PVO in terms of a reduction in the total lag observed over the convection distance to Galileo at ~90 R_v downstream.

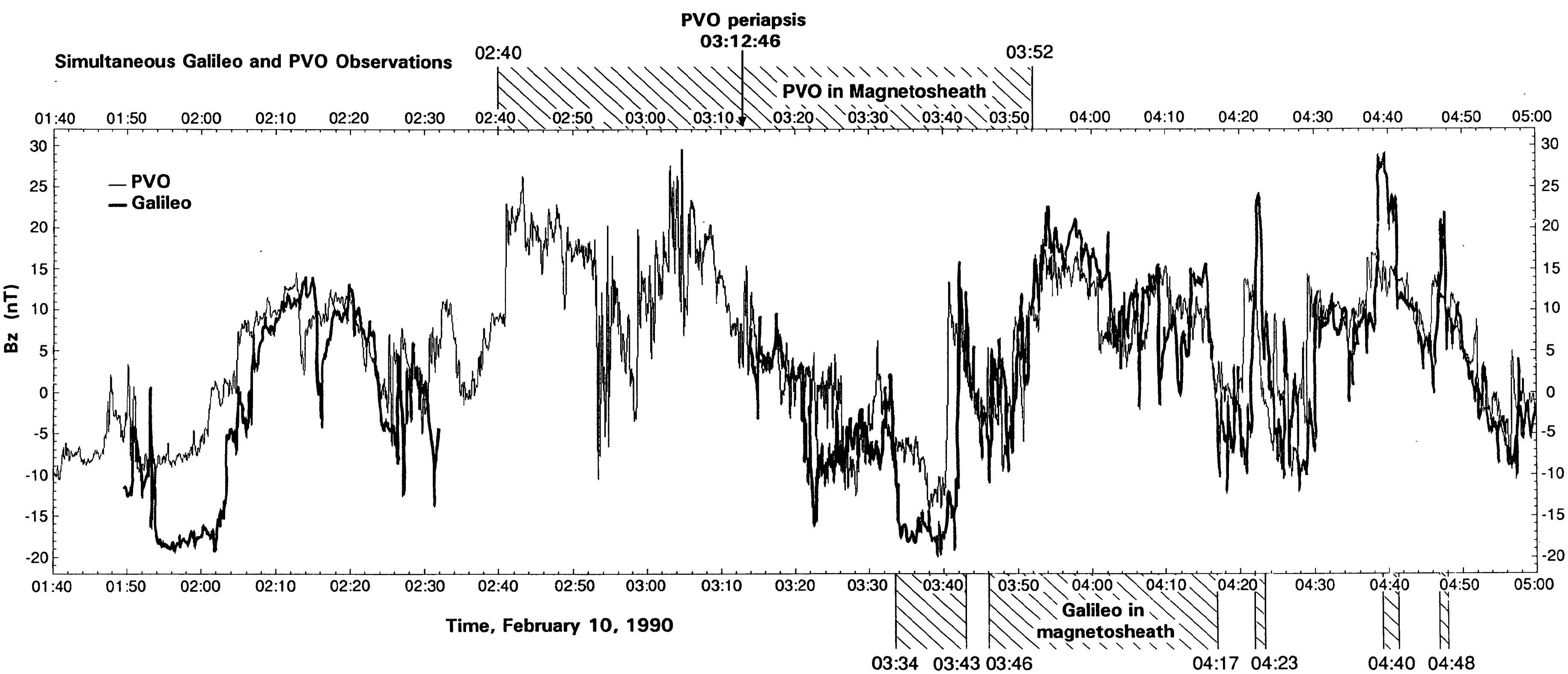

Figure 2. Comparison of Galileo and PVO observations on February 10. Shaded areas along the top and bottom of the plot indicate when the PVO and Galileo spacecraft were inside the magnetosheath. The orbit of PVO passes within the magnetosheath between 0240 and 0352 UT, while Galileo skips along the bow shock making several excursions into the magnetosheath between 0334 and 0448 UT (see Figure 1). At Galileo, there are possibly additional partial excursions across the shock between 0406 and 0416 UT. As the shocks on the flanks are relatively weak, they modify the field at Galileo only slightly. The correlation between the two data sets (with appropriate lag) is excellent. Within the time period shown, lag times vary with the changing spacecraft positions.

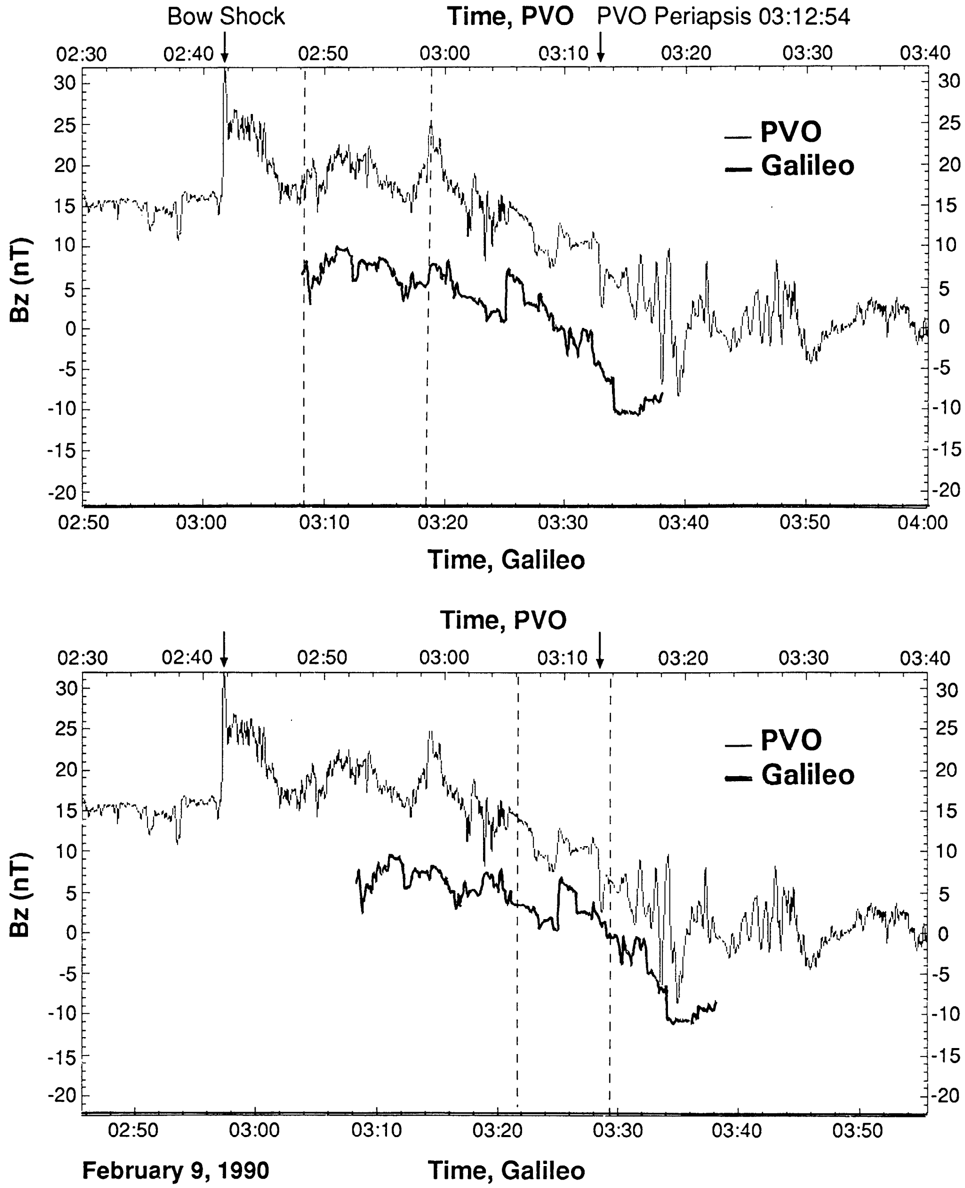

Figure 3. Comparison of Galileo and PVO observations on February 9. The Galileo and PVO data sets are plotted against axes shifted with respect to one another to show the lag times found by aligning corresponding features in the regions indicated between the dashed vertical lines (see text). At this time, Galileo is approximately 90 R_v downstream from Venus. PVO crosses the bow shock and enters the sheath at approximately 0242 UT. If PVO were not inside the magnetosheath, the expected lag time for solar wind features to convect to Galileo would be approximately 26 min for V_{sw} = 350 km/s.

If the observed features are aligned perpendicular to the solar wind flow and convect parallel to the X axis at the solar wind speed V_{sw}, then in the absence of a planetary obstacle, the expected lag times due to convection at the ambient solar wind speed may be calculated simply from the spacecraft X separation. For February 10, the dashed line in Figure 4 shows this calculation for an average ambient upstream solar wind speed of V_{sw} = 450 km/s obtained from PVO plasma observations outside the bow shock on that day. Observed lags are thus assumed to be a combination of the slowing and draping effects due to the Venus obstacle, modifying the "undisturbed" solar wind convection time between the positions of the two spacecraft. To investigate the delays in the flow due to the Venus obstacle, the observed lags may be "normalized" to a zero spacecraft separation. We first calculate the lag expected for simple solar wind convection at the unaffected upstream V_{sw} (e.g., dashed line in Figure 4), and then subtract this from the observed lag to give the delays that must be attributed to PVO's position within the magnetosphere of Venus. Note that PVO 10-min solar wind velocity data on February 10 show a predominantly antisunward flow (along -X) with variations in speed of up to ±40 km/s, indicating possible errors in calculated convection lags of up to ~10% due to flow speed changes.

The convection lags are sensitive to the actual alignment of the features with respect to the flow direction. If the surfaces of constant field orientation are perpendicular to the solar wind flow,

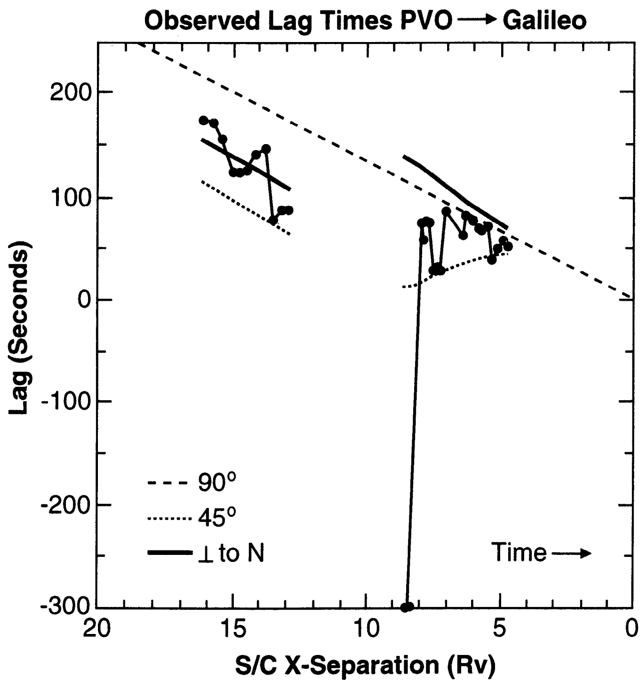

Figure 4. Observed lags from PVO to Galileo, for the data sets obtained on February 10, plotted against the spacecraft separation in X parallel to the solar wind flow. The dashed line represents calculated lags for simple convection of perpendicularly aligned features at the observed V_{sw} = 450 km/s on that day, if the Venus obstacle were not present. The dotted lines assume features are aligned at the 45° spiral angle, and the thick solid lines use the average alignment of planes given by a minimum variance analysis (see text).

or if the two spacecraft are aligned along the flow vector, the simple X convection time is an accurate measure of the expected lags due to undisturbed convection. On the other hand, if the surfaces are not perpendicular to V_{sw}, the expected undisturbed convection lags now not only depend on the spacecraft X separation, but on the exact spacecraft relative positions in three-dimensional space including Y,Z separation. The normal component of the field across solar wind magnetic discontinuities is generally small, i.e., the planes of constant field orientation are expected to parallel any discontinuity surfaces present. To determine the average orientation of these planes, we calculate the minimum variance directions over each of the time periods 0150-0230 UT and 0450-0640 UT at Galileo in the ambient solar wind on February 10. The average minimum variance directions were N_1=(0.75,0.46,0.47), and N_2=(0.97,-0.22,-0.02), respectively, in VSO coordinates. In Figure 4 the heavy solid lines are the calculated undisturbed convection lags for planes perpendicular to these average observed normal directions, where the times of N_1 and N_2 correspond to PVO preperiapsis and postperiapsis, respectively. Also for comparison, the dotted lines show the expected undisturbed convection lags for features aligned at 45° to V_{sw}, the nominal Parker spiral B field geometry in the X,Y plane.

Comparison With a Gas Dynamic Model

In order to better understand the magnetosheath processes that lead to the observed changing time lags, the observed lags are normalized for spacecraft position according to undisturbed convection of features aligned in planes perpendicular to the observed N_1 and N_2 vectors, to give lags caused only by the presence of the Venus obstacle. For comparison, the *Spreiter and Stahara* [1980] three-dimensional gas dynamic model is employed to trace magnetic field lines in the magnetosheath for positions along the PVO orbit [see also *Luhmann et al.*, 1986; *Ong et al.*, 1991]. In this model the convected plasma flow field is obtained by neglecting the effects of the magnetic field on the flow, using γ = 5/3, and with no mass loading. The draped field lines are then calculated assuming that **B** is "frozen-in" with the plasma as it slows. At the obstacle boundary therefore the calculated field piles up where the flow stagnates, and model results become unrealistic at the boundary, since the effect of the field back on the plasma has been neglected. Our standard obstacle is the Venus ionopause, standing approximately 300 km above the planet surface at the "nose," and cylindrically symmetric about X (the planet-Sun line). Its chosen tail shape, which flares like a magnetopause, has been previously found to give good bow shock profile fits. At the outer magnetosheath boundary, the bow shock standoff is determined by the Mach number of the flow, which is a parameter in the model, lower Mach number giving larger standoff.

Figures 5 and 6 show the calculated field line geometries for two examples of interplanetary magnetic field (IMF) B orientation; at 90° and at 45° (nominal Parker spiral) to the upstream solar wind velocity or X axis in our simplification. During the Galileo flyby, the field direction was variable [*Kivelson et al.*, 1991] but on occasion was nearly 45° to X, and sometimes the X component of B was small so that a 90° orientation was a good approximation. In each figure, a pair of plots shows the projections in the Y,Z (top panel) and X,Y planes. Venus and the PVO trajectory are also shown. Example Mach numbers of 2.5 in Figure 5 and 4.5 in Figure 6 determine the bow shock standoff, which can be seen outlined by the points of discontinuous deflection of the B lines. For the analysis that follows, Mach 4.5 is used as appropriate for Venus. However, we note that changing the input Mach number (e.g., 2.5, 4.5, or 8) produces little change in terms of the flow deceleration inside the magnetosheath. Similarly, changing the IMF orientation has no significant effect on predicted normalized lags because the flow stagnation in the gas dynamic model is calculated independent of the effects of B draping and pileup. The draped field lines traced from PVO to the open solar wind allow calculation of the projected position directly antisunward of the spacecraft that the observed field line would have reached if the obstacle had not been present. The difference between this and the PVO spacecraft position is used to calculate the model lag time due to the magnetosheath, using observed V_{sw} values outside the bow shock (350 km/s on February 9, 450 km/s on February 10).

Figure 7 shows the comparison of the normalized observed lags with the expected magnetosheath delays predicted by the model. The data also include our February 9 values. The plot is against PVO altitude from the center of the planet (in R_v) where altitude of the inbound path is designated negative and the outbound positive for clarity. If the February 9 values are valid, delays of up to 10 min are identified due to Venus near PVO periapsis, which is comparable to the 10-20 min and ≤30 min lags quoted by *Yeroshenko* [1979] based on Venera magnetic tail observations.

The results of three model runs are overlaid for the standard ionopause obstacle (solid line), and for the obstacle size increased by factors of 1.5 (dotted) and 2.0 (dashed line). A Mach number

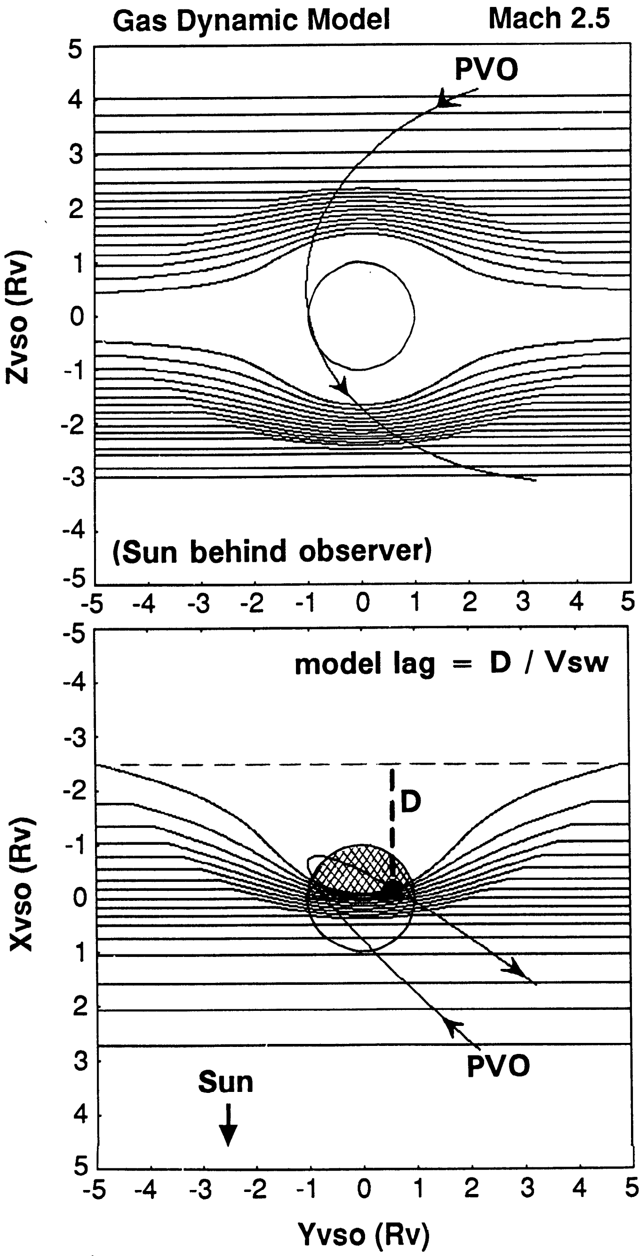

Figure 5. Field lines traced using the Spreiter gas dynamic model [*Spreiter and Stahara*, 1980]. Note that in the upper panel, the shock appears squashed in the Z_{vso} direction (or elongated in Y_{vso}) because the spacecraft orbit (positions from which the field lines are traced) has an X_{vso} variation and thus the projection shown is not a simple constant-X_{vso} plane cross section. The *B* lines are traced from several positions along the PVO orbit, and the expected lag due to the model magnetosheath at PVO is calculated from the corresponding "undisturbed" *X* position of the field line as shown in the lower panel.

of 4.5 was used in each case, which is appropriate for Venus. It is clear from Figure 7 that the present model with the standard obstacle does not give sufficient lags to explain the observations inside of the shock in the magnetosheath, particularly for the postperiapsis observations. The obstacle size must be increased by a factor of around 1.5 to fit these outbound data. (The magnetospheric obstacle shape used is blunter than an ionopause, which may affect results at low altitudes, but has previously been found to give good shock profile fits.) A very large effective obstacle size cannot be the answer because the location of the bow shock is inconsistent with a large obstacle [*Russell et al.*, 1985; *Zhang et al.*, 1990]. The more likely explanation is that the flow is slowed in the Venus magnetosheath more than expected from the gas dynamic model. This may be partially the result of the solar wind interaction with the ionized fraction of the planetary neutrals above the ionopause and the associated mass loading.

While at magnetized planets the intrinsic field provides the obstacle, weakly or nonmagnetized planets have characteristics in common with comets. The effect of mass loading at a planet is generally weaker than that at comets, particularly outside the bow shock, in the following regard. The comet obstacle in the solar wind is provided only by the gas emitted from the nucleus, which becomes ionized and then picked up to mass load the solar wind.

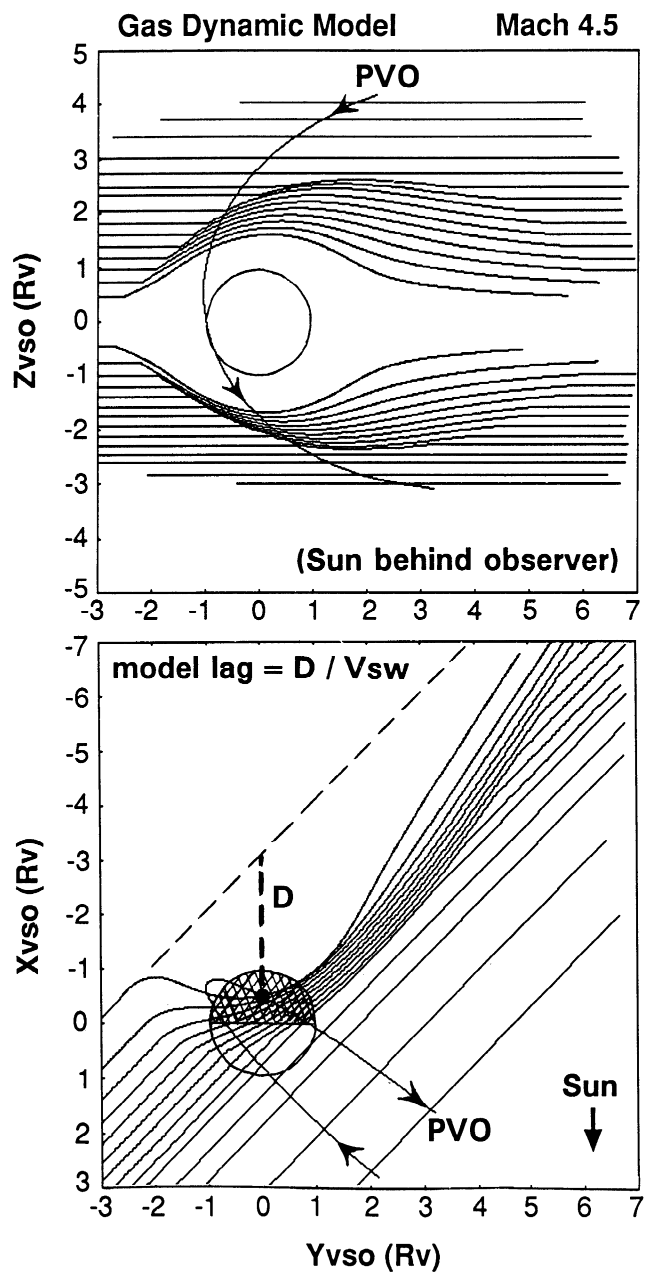

Figure 6. Similar to Figure 5, for an IMF at 45° to the V_{sw} flow direction.

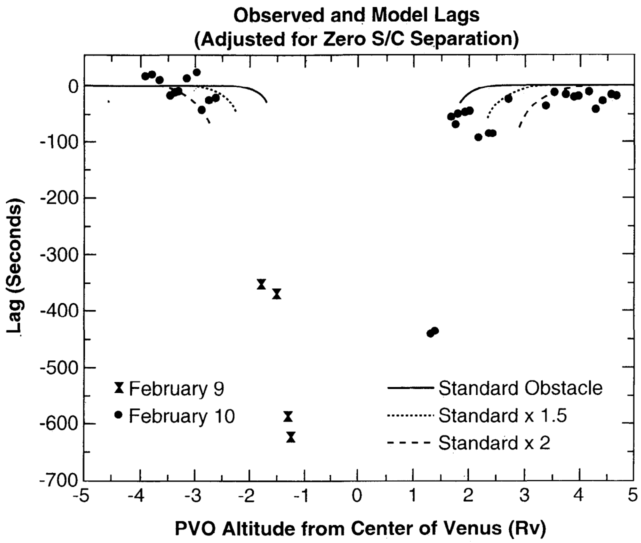

Figure 7. Comparison of observed lags (PVO to Galileo) with those predicted by the gas dynamic model. Observed lags are "normalized" to a zero spacecraft separation, for both February 9 and February 10. Overlays are the model profiles for the delays due to the magnetosheath for three example obstacle sizes. The "standard" ionopause obstacle used for Venus is 300 km above the planet surface at the "nose" (on the planet-Sun line). Note that field lines cannot be traced through the obstacle.

Thus the cometary bow shock forms as a direct result of this mass loading, when a critical ratio of pickup ion mass flux to incident solar wind mass flux is achieved [*Schmidt and Wegmann*, 1982]. This necessarily means that a substantial effect on the solar wind due to mass loading is always observed outside of the bow shock in the case of the active comets at which such a shock forms. At highly active outgassing comets, a very large interaction region forms, and the solar wind convection through the region can be greatly slowed. At comet Halley, for example, a comparison of the Vega observations with simulations [*Schwingenschuh et al.*, 1987] has found convection times of up to ~5 hours from the upstream solar wind (outside the shock) to the spacecraft at closest approach (8890 km from the nucleus on the Sun side), while the undisturbed solar wind would take 1.2 hours to travel the same distance. At Venus, the neutral exosphere is not expected to extend much beyond the bow shock due to gravitational constraint; thus only relatively small mass loading effects outside of the shock are expected.

With regard to the asymmetry of the observed lag times about PVO periapsis in Figure 7, we note that to a lesser extent an asymmetry also exists in the modeled profiles, due to the tilt of the PVO orbit (see Figure 1). In the observations, additional effects may exist for the Parker spiral angle B orientation, such as a dawn/dusk asymmetric bow shock profile and thickness, or effects due to the Venus atmosphere and mass loading of the flow. The magnitude of mass loading can be asymmetric around the planet for B angles oblique to V_{sw} [e.g., *Cloutier et al.*, 1987; *Phillips et al.*, 1987]. Recently, *Dubinin et al.* [1994] have modeled the effect of reflection of pickup ions at the bow shock on the upstream ion densities at Mars. The angle of B to the solar wind flow determines the cycloidal trajectories of the pickup ions and hence their incidence angle at the shock and their subsequent reflection geometry. Dubinin et al. used the resulting modeled asymmetric spatial distribution to explain the observed ion density asymmetries inbound and outbound in the Phobos 2 data. It is possible but unlikely that this shock-reflection mechanism could be relevant to Venus, since the mass loading process is expected to be considerably less of a factor outside the Venus bow shock (as discussed previously above). However, since the PVO outbound path is slightly tailward of the inbound path, there exists the possibility of a slightly greater accumulation of pickup ions downstream in the region encountered postperiapsis.

Conclusions

A comparison of simultaneously acquired magnetic field data sets from the PVO and Galileo spacecraft at the time of the Galileo Venus flyby has enabled the identification of significant convection lags resulting from the Venus obstacle in the solar wind flow. The features in the night ionosphere were not greatly distorted by the interaction. This suggests that the mass loaded solar wind magnetic field is convected into the upper nightside ionosphere. This can be understood in terms of the recent simulations by *McGary and Pontius* [1994], in which mass loading leads to the formation of a boundary layer along the dayside ionopause, if that boundary layer extends to the nightside of the planet to form the upper ionosphere. The observed lags normalized to a zero spacecraft separation allow convenient comparisons of the magnetosheath and ionosphere effects alone. Delays of up to 10 min were seen in the Venus magnetosheath and nightside ionosphere down to an altitude of 1/4 R_v (1500 km) above the planet surface.

The variability and apparent asymmetry of the lag measurements about PVO periapsis could be due to a number of contributing factors, including (1) differing alignments of the individual discontinuities and other magnetic features relative to the flow, (2) variation of V_{sw} on long timescales ≥ the lag times, (3) N/S pole or dawn/dusk asymmetries in the Venus magnetosheath not accounted for in a cylindrically symmetric model, (4) ambiguities in the identification of corresponding features, (5) propagation of features in the V_{sw} plasma frame, and (6) possibly some effect due to interaction with planetary pickup ions or shock-reflected ions. Figure 4 shows that factor 1 is certainly an important consideration in general, and is likely to be a source of scatter in the observed lag values because we have used average directions of the minimum variance to define the normals to the features.

The three-dimensional gas dynamic model developed by *Spreiter and Stahara* [1980] and coworkers was used to trace field lines from positions along the PVO orbit, to enable calculation of expected delays due to Venus according to this model. Changes in field orientation and Mach number of the shock produce little change in the lag profiles obtained from the present model for positions within the magnetosheath. The simple gas dynamic model does not predict sufficient lags (i.e., flow deceleration) at PVO to explain the observations for the standard ionopause obstacle.

The results presented here are consistent with the expectation that mass loading of the solar wind by ionized planetary neutrals and sputtering products, and erosion of the ionosphere, may contribute to the dynamics of the plasma flow near Venus. That is, the simple diversion and deceleration of the solar wind to accommodate an impenetrable obstacle in the flow, as described by the (non-mass-loaded) gas dynamic model considered here, does not give the complete picture. For the future, detailed analysis of mass-loaded magnetohydrodynamic models [e.g., *Spreiter and Stahara,* 1992; *McGary and Pontius*, 1994] can be carried out to determine if they predict lags of the order of those observed between PVO and Galileo.

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References

Brace, L. H., and A. J. Kliore, The structure of the Venus ionosphere, in *Venus Aeronomy*, edited by C. T. Russell, Kluwer Acad., Norwell, Mass., 1991. (Reprinted from *Space Sci. Reviews, 55*, 81.)

Cloutier, P. A., H. A. Taylor Jr., and J. E. McGary, Steady state flow/field model of solar wind interaction with Venus: Global implication of local effects, *Planet. Space Sci., 22*, 967, 1987.

Dubinin, E., D. Obod, A. Pedersen, and R. Grard, Mass-loading asymmetry in upstream region near Mars, *Geophys. Res. Lett., 21*, 2769, 1994.

Hospodarsky, G. B., D. A. Gurnett, W. S. Kurth, M. G. Kivelson, R. J. Strangeway, and S. J. Bolton, Fine structure of Langmuir waves observed upstream of the bow shock at Venus, *J. Geophys. Res., 99*, 13,363, 1994.

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

Kivelson, M. G., C. F. Kennel, R. L. McPherron, C. T. Russell, D. J. Southwood, R. J. Walker, C. M. Hammond, K. K. Khurana, R. J. Strangeway, and P. J. Coleman, Magnetic field studies of the solar wind interaction with Venus from the Galileo flyby, *Science, 253*, 1518, 1991.

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

Luhmann, J. G., R. J. Warniers, C. T. Russell, J. R. Spreiter, and S. S. Stahara, A gas dynamic magnetosheath field model for unsteady interplanetary fields: Application to the solar wind interaction with Venus, *J. Geophys. Res., 91*, 3001, 1986.

McGary, J. E., and D. H. Pontius Jr., MHD simulations of boundary layer formation along the dayside Venus ionopause due to mass loading, *J. Geophys. Res., 99,* 2289, 1994.

Murawski, K., and R. S. Steinolfson, Numerical simulations of mass loading in the solar wind interaction with Venus, *J. Geophys. Res.*, in press, 1995.

Nagy, A. F., and T. E. Cravens, Hot oxygen atoms in the upper atmosphere of Venus and Mars, *Geophys. Res. Lett., 15*, 433, 1988.

Ong, M., J. G. Luhmann, C. T. Russell, R. J. Strangeway, and L. H. Brace, Venus ionospheric "clouds": Relationshop to the magnetosheath field geometry, *J. Geophys. Res., 96*, 11,133, 1991.

Phillips, J. L., J. G. Luhmann, C. T. Russell, and K. R. Moore, Finite Larmor radius effect on ion pickup at Venus, *J. Geophys. Res., 92*, 9920, 1987.

Russell, C. T., R. C. Snare, J. D. Means, and R. C. Elphic, Pioneer Venus fluxgate magnetometer, *IEEE Trans. Geosci. Remote Sens., GE-18*, 32, 1980.

Russell, C. T., J. G. Luhmann, and J. L. Phillips, The location of the subsolar bow shock of Venus: Implications for the obstacle shape, *Geophys. Res. Lett., 12*, 627, 1985.

Russell, C. T., E. Chou, J. G. Luhmann, P. Gazis, L. H. Brace, and W. R. Hoegy, Solar and interplanetary control of the location of the Venus bow shock, *J. Geophys. Res., 93*, 5461, 1988.

Schmidt, H.U., and R. Wegmann, Plasma flow and magnetic fields in comets, in *Comets*, edited by L. L. Wilkening, p. 538, Univ. of Arizona Press, Tuscon, 1982.

Schwingenschuh, K., W. Riedler, Ye. Yeroshenko, J. L. Phillips, C. T. Russell, J. G. Luhmann, and J. A. Fedder, Magnetic field draping in the comet Halley coma: Comparison of Vega observations with computer simulations, *Geophys. Res. Lett., 14*, 640, 1987.

Spreiter, J. R., and S. S. Stahara, A new predictive model for determining solar wind-terrestrial planet interactions, *J. Geophys. Res., 85*, 6769, 1980.

Spreiter, J. R., and S. S. Stahara, Computer modeling of solar wind interaction with Venus and Mars, in *Venus and Mars: Atmospheres, Ionospheres, and Solar Wind Interactions, Geophys. Monogr.*, vol. 66, edited by J. G. Luhmann et al., pp. 345-383, AGU, Washington, D. C., 1992.

Tatrallyay, M., C. T. Russell, J. D. Mihalov, and A. Barnes, Factors controlling the location of the Venus bow shock, *J. Geophys. Res., 88*, 5613, 1983.

Yeroshenko, E. G., Unipolar induction effects in the magnetic tail of Venus, *Kosm. Issled., Engl. transl., 17*(1), 93, 1979.

Zhang, T. L., J. G. Luhmann, and C. T. Russell, The solar cycle dependence of the location and shape of the Venus bow shock, *J. Geophys. Res., 95*, 14,961, 1990.

D. E. Huddleston, M. G. Kivelson, and C. T. Russell, Institute of Geophysics and Planetary Physics, University of California, 405 Hilgard Avenue, Los Angeles, CA 90095. (email: dhuddleston@igpp.ucla.edu; mkivelson@igpp.ucla.edu; ctrussel@igpp.ucla.edu)

J. G. Luhmann, Space Sciences Laboratory, University of California, Berkeley, CA 94720. (email: jgluhman@sunspot.ssl.berkeley.edu)

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