

ON THE SPATIAL RANGE OF VALIDITY OF THE GAS DYNAMIC MODEL
IN THE MAGNETOSHEATH OF VENUST. L. Zhang¹, C. T. Russell², J. G. Luhmann², J. R. Spreiter³, and S. S. Stahara⁴¹Space Research Institute, Austrian Academy of Sciences, Graz, Austria²Institute of Geophysics and Planetary, University of California, Los Angeles³Stanford University, Stanford⁴RMA Aerospace Inc., Mountain View

Abstract. In the past the global solar wind interaction with Venus has been treated principally with gas dynamic models. While this gas dynamic treatment has proven successful in modeling some of the global characteristics of the interaction, this model does not include the magnetic barrier in a self-consistent manner. This magnetic barrier is formed in the inner magnetosheath where it transfers solar wind momentum flux to the obstacle via magnetic pressure. In this study we examine the extent to which the gas dynamic fluid approximation describes the magnetic field in the dayside Venus magnetosheath by comparing with two gas dynamic models, one which matches the observed ionopause location and one which matches the bow shock location. We find that each model predicts the field profile reasonably well in the vicinity of the matched bow shock or ionopause but neither model provides an adequate model over the entire range from the ionopause to the bow shock.

Introduction

The global solar wind interaction with Venus has generally been treated with fluid models, such as that of a compressible gas dynamic flow around an impenetrable blunt obstacle [cf., Spreiter and Stahara, 1980]. This fluid approximation neglects the individual particle behavior and the effects of the magnetic field on the plasma dynamics. Gas dynamic models have been compared to observations of the Venus magnetosheath and shock [Slavin and Holzer, 1983; Tatrallyay, 1984; Spreiter and Stahara, 1980; Mihalov et al., 1982; Luhmann et al., 1986] and are used to study pickup ion effects [Luhmann et al., 1985; Phillips et al., 1988; Moore, 1990; Moore et al., 1991; Zhang et al., 1991]. It has been found that the gas dynamic model provides a generally good first order approximation of the observations. However, we expect to find some differences because of the limitations of the model.

First, the non-self-consistent calculation of the magnetic field neglects the contributions of this field to the momentum and energy equations. The Venus ionosphere is an excellent electrical conductor and the time scale for the

diffusion of the magnetic field into the ionosphere is long. Thus the ionosphere deflects the oncoming supersonic solar wind around the planet so that a bow shock is formed. The inner edge of the post-shock magnetosheath flow is called the ionopause. Here the magnetic field and ionospheric plasma provide most of the pressure in the plasma. The field decreases rapidly as the ionosphere is entered and the plasma pressure rises rapidly. While in the outer magnetosheath the field is sufficiently weak that its effect on the flow may be assumed to be negligible, the magnetic field's effects may not be negligible in the inner magnetosheath where there is a more draped and stronger magnetic field and apparently little magnetosheath plasma.

Secondly, the basic gas dynamic treatment does not consider the exospheric ion pickup process by the $-\mathbf{v} \times \mathbf{B}$ electric field. The hot oxygen exosphere extends well into the magnetosheath. Newly created photo ions will add mass to the flow, slowing it and leading to additional draping and magnetic flux buildup. Moore et al. [1991] used a mass source term to represent these newly added ions and showed that the location of the bow shock was relatively insensitive to the mass addition, for rates we expect at Venus. Nevertheless, even small mass addition rates could affect the magnetic field strength and draping effects.

In spite of these limitations of the gas dynamic approximation, it appears to be justified when the Mach number, the ratio of the flow speed to the characteristic speed of propagation of a compressional disturbance, is high. The fast magnetosonic Mach number of the solar wind flow relative to Venus is about 4.5. If the Mach number was this high throughout the magnetosheath, the gas dynamic approximation would be good everywhere. However, in the inner magnetosheath the Mach number of the flow is much lower and the magnetic barrier and pickup effects could dominate the physics. Therefore, it is important to determine observationally where in the magnetosheath the gas dynamic model becomes inadequate.

Comparison of Observations with
the Gas Dynamic Model

In our earlier study, altitude profiles of the Venus magnetic barrier were derived from a statistical analysis of the PVO magnetometer data [Zhang et al., 1991]. The data used for both that study and the present investigation are

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Paper number 93GL00484
0094-8534/93/93GL-00484\$03.00

the Pioneer Venus Orbiter (PVO) measurements in the Unified Abstract Data System (UADS) file available from the National Space Science Data Center. These data consist of 12-s averaged magnetic field component measurements for the period within ± 30 minutes of periapsis together with the spacecraft position vectors. For this study, we used the first three seasons (defined as complete circuits of the planet by the PVO periapsis, or equivalently, as Venus years). After that time the spacecraft periapsis was above the ionopause. Only dayside periapsis orbits were used, or more precisely, orbits 134-234 in season 1, orbits 361-460 in season 2 and orbits 585-685 in season 3. In this study, magnetic pressure data along each pass were normalized by the upstream solar wind dynamic pressure. The solar wind data were obtained with the Ames plasma analyzer (provided to us courtesy of A. Barnes, J. D. Mihalov, and P. Gazis). We selected periods when the solar wind data on either inbound or outbound legs just outside of the bow shock were relatively steady. Only a few orbits were not used in this study because of missing or uncertain solar wind data. Figure 1 shows normalized altitude profiles of median normalized magnetosheath magnetic pressure from the first three PVO seasons, from data divided into three solar zenith angle (SZA) bins.

The gas dynamic simulation code used here has been described in *Spreiter and Stahara* [1980]. In this model, the obstacle, or ionopause, is a tangential discontinuity separating the planetary plasma and the post-shock solar wind or magnetosheath. The obstacle shape can be defined as the locus of altitudes at which the ionospheric pressure is sufficient to withstand the normal incident component of solar wind pressure. The magnetosheath derived from the gas dynamic model is cylindrically symmetric about the axis defined by the upstream flow. The model calculates

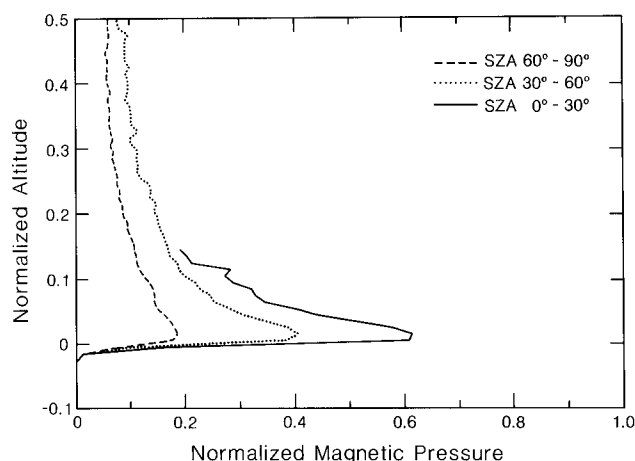


Fig. 1. Normalized altitude profiles of normalized magnetic pressure from the first three PVO seasons. The altitude is normalized by ionopause altitude. The magnetic pressure is normalized by upstream solar wind dynamic pressure. The upstream solar wind dynamic pressure has been corrected by two factors: the consideration of 4 to 5 percent Helium and the consideration of a solar wind pressure coefficient K which is about 0.844 to 0.881.

the location of the bow shock, and the velocity, density, and temperature in the magnetosheath for a specified ionopause shape. The imbedded magnetic field is then calculated based on the gas dynamic distortion of the fluid elements without actually considering electromagnetic effects, i.e., from $\mathbf{J} \times \mathbf{B}$, on the flow.

To determine where the gas dynamic model is valid in the Venus magnetosheath, we compare the results from the model with the observations described above. We calculate the model magnetic field strength in the magnetosheath in SZA bins using the gas dynamic values along each spacecraft trajectory, and compare the resulting model field statistics with the observational statistics of the field magnitude. As in the observational study, the position data are from the UADS files for orbits 134-234, 361-461 and 585-685. All together, 231 orbits of UADS position data were used, giving 69300 vectors in the dayside magnetosheath. The required input of interplanetary magnetic field (IMF) for the gas dynamic model is specified for each orbit according to the measured IMF. The calculated magnetic pressures along the trajectory are normalized by the measured upstream solar wind dynamic pressure pertinent to each individual orbit.

Two gas dynamic magnetosheath model flow fields are used. Both have upstream Mach number 4.5, and $\gamma = 5/3$. Their obstacle shapes are described by the scale height factors, $H/R_0 = 0.11$ and 0.03. The scale height H/R_0 is the ratio of the ionospheric scale height to the radius of the obstacle to the flow at the subflow point. For purposes of using the gas dynamic model, it is an input parameter that specifies the shape of the ionopause [see *Spreiter and Stahara*, 1980]. The Mach number, 4.5, is the average magnetosonic Mach number of the solar wind during the first three seasons. The scale height, $H/R_0 = 0.11$, is derived from the observed bow shock shape, while the scale height, $H/R_0 = 0.03$ approximates the observed ionopause shape. The results for the $H/R_0 = 0.11$ case are scaled to place the predicted shock on the observed shock. At the terminator this distance is $2.38 R_v$. When this is done gas dynamic obstacle position is at a higher altitude than the observed ionopause position. The case with $H/R_0 = 0.03$ more closely fits the obstacle boundary location, but underestimates the shock distance. These two cases represent the two extrema in attempting to fit the model to the observations.

Figure 2 compares the observed and calculated results for the normalized magnetic pressure in the subsolar magnetosheath. The discrepancy in Figure 2a, the $H/R_0 = 0.11$ case, implies that gas dynamic model is inadequate below at least $1.2 R_v$ in the SZA range of 0° - 30° . In Figure 2b, the $H/R_0 = 0.03$ case, it is apparent that when the ionopause is forced to fit (instead of the shock position), the gas dynamic model over-estimates the pile-up of the field against the obstacle. This feature is, of course, a consequence of the gas dynamic model assumption of no magnetic pressure effects on the compression of the medium together with the frozen-field approximation. Figure 3 summarizes the comparison in the SZA range of 30° to 90° divided into four bins. There are several features apparent in Figure 3a, the $H/R_0 = 0.11$ case. First, the radius where the gas dynamic model becomes invalid

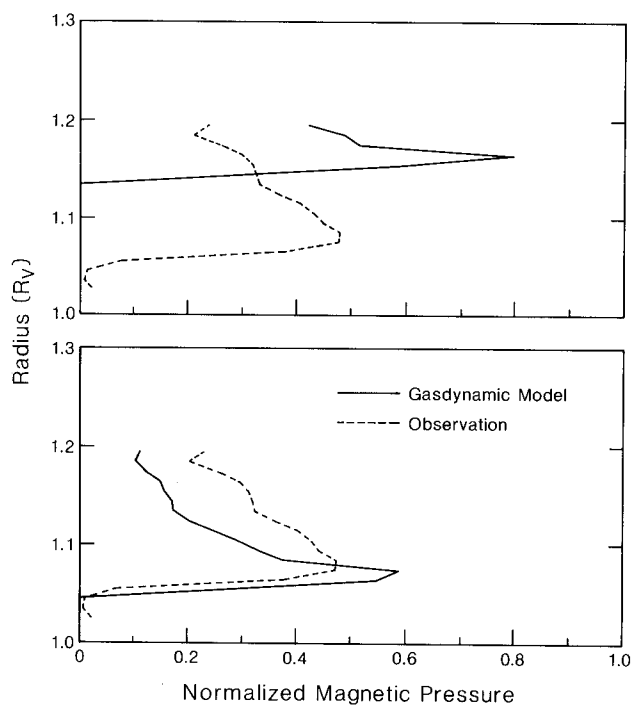


Fig. 2. Comparison of the normalized magnetic pressure from the gas dynamic simulation and observations in the subsolar region (SZA 0° - 30°). The solid line is from the gas dynamic model and the dashed line is from observations. In the top panel the ratio of the ionospheric scale height H to the subsolar obstacle radius, R_0 is 0.11. In the bottom panel H/R_0 is 0.03. The former scale height produces a match in the bow shock position; the latter a match in the ionopause position.

increases as the SZA increases. Near the subsolar region (left hand panel of Figure 3a), the gas dynamic model still agrees with the observations at a radius as low as $1.3 R_V$ in the inner magnetosheath. However, at the terminator (right hand panel of Figure 3a), the model departs from the observations at a radius of $1.5 R_V$. Secondly, the obstacle position of the model is higher than the observed ionopause position, as noted above. Nevertheless, if we added the magnetic barrier on top of the ionopause and compared the position of the upper boundary of the magnetic barrier with the effective obstacle size in the model, the differences would be significantly reduced (see Zhang et al., 1991). Other factors, e.g., the ion pickup effect, may also result in a discrepancy between the location of the obstacle in the observations and the model. Figure 3b shows similar plots for the $H/R_0 = 0.03$ case. Here the discrepancy, as in Figure 2b, lies mainly in the amount of compression of the field against the obstacle as well as in the deficient shock distance. The field strength in the model in the altitude range above the region of maximum pile-up also appears to be systematically lower than the observed field strength, a feature that may also be explainable by magnetic forces or mass-loading effects.

Conclusions

The gas dynamic model has been used extensively in the modeling of the Venus bow shock and pickup ion effects.

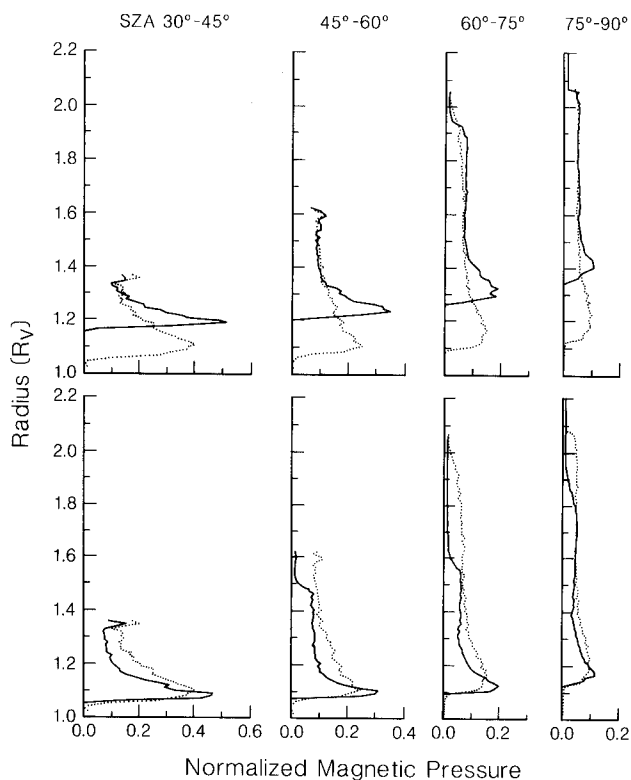


Fig. 3. Comparison of the normalized magnetic pressure from the gas dynamic simulation and observations in the SZA ranges of 30° - 45° , 45° - 60° , 60° - 75° and 75° - 90° . The solid line is from the gas dynamic model and the dashed line is from observations. In the top panels the scale height ratio H/R_0 has been chosen to be 0.11 and in the bottom panels, 0.03.

With the extensive database from the Pioneer Venus magnetometer now available we have been able to test whether this model provides a good "fluid" approximation for these modeling studies. Our results show that one can choose to fit either the inner magnetosheath or the shock and the outer magnetosheath. Whichever choice is made, the resulting model magnetosheath will be thinner than that observed and the peak magnetic field strength will be less. Since these differences may be important in several of the applications in which the model has been used, caution should be exercised in interpreting the results. The attempt to improve the model through mass addition did not significantly thicken the magnetosheath and move the shock location outward when mass loading rates appropriate for Venus were used [Moore et al., 1991]. For improved model comparisons and applications, either MHD or hybrid simulations are ultimately required.

Acknowledgments. The work at UCLA was supported by the National Aeronautics and Space Administration under research grant NAG2-501.

References

- Luhmann, J. G., C. T. Russell, J. R. Spreiter, and S. S. Stahara, Evidence for mass-loading of the Venus magnetosheath, *Adv. Space Res.*, 5, 307-311, 1985.

- 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*, 3001-3010, 1986.
- Mihalov, J. D., J. R. Spreiter, and S. S. Stahara, Comparison of gas dynamic model with steady solar wind flow around Venus, *J. Geophys. Res.* *87*, 10363-10371, 1982.
- Moore, K. R., The role of pickup ions in the solar wind interaction with Venus as deduced from observations and numerical simulations, Ph.D. thesis, UCLA, 1990.
- Moore, K. R., D. J. McComas, C. T. Russell, S. S. Stahara, and J. R. Spreiter, Gas dynamic modeling of the Venus magnetotail, *J. Geophys. Res.*, *96*, 5667-5681, 1991.
- Phillips, J. L., J. G. Luhmann, W. C. Knudsen, and L. H. Brace, Asymmetries in the location of the Venus ionopause, *J. Geophys. Res.*, *93*, 3927-3941, 1988.
- Slavin, J. A., R. E. Holzer, J. R. Spreiter, S. S. Stahara, and D. S. Chausee, Solar wind flow about the terrestrial planets, 2. Comparison with gasdynamic theory and implications for solar-planetary interactions, *J. Geophys. Res.*, *88*, 19, 1983.
- Spreiter, J. R. and S. S. Stahara, Solar wind flow past Venus: Theory and comparisons, *J. Geophys. Res.*, *85*, 7715-7738, 1980.
- Tatralay, M., C. T. Russell, J. G. Luhmann, A. Barnes, and J. D. Mihalov, On the proper Mach number and ratio of specific heats for modeling the Venus bow shock, *J. Geophys. Res.*, *89*, 7381-7392, 1984.
- Zhang, T.-L., J. G. Luhmann, and C. T. Russell, The magnetic barrier at Venus, *J. Geophys. Res.* *96*, 11145-11153, 1991.
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(Received December 30, 1992;
accepted January 27, 1993.)