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Final Technical Report

Project Title: "Solar Wind Effects on Atmospheres of the Weakly Magnetized Bodies: Mars, Titan and the Moon"
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Summary of Accomplishments

The atmospheres of planetary bodies without significant intrinsic magnetic fields exhibit unique featues because they interact with the external plasma flows in their space environments. The plasma interactions also have the potential of altering the evolutionary paths of these atmospheres since the processes (such as ion pickup and sputtering) that lead to loss of constituents have effects unlike those of other escape mechanisms. This ongoing investigation has been concentrating on the characterization of the plasma interactions and the associated plasma physical escape processes at Mars and Titan. The results are relevant to both mission planning and the interpretation of data from past and future Mars and Lunar missions, and to tour and mission operations planning for the Cassini Orbiter. They also contribute to our general understanding, from a comparative planetology standpoint, of the role that planetary magnetic fields play in determining the state and fate of a planetary atmosphere. This project has now been transferred under a new account number (NAGW-4600) to the PI's new institution at the University of California, Berkeley where the work is continuing.

The PI has for many years led efforts to understand the Mars-solar wind interaction using analogies with the Venus-solar wind interaction (Luhmann, 1995, describes some of these). During the period covered by this report the PI worked with Phobos-2 plasma investigation team members in Europe to model the plasma environment of Mars. Our analyses showed that the solar wind flows around the Martian obstacle, to a first approximation, very much as it does at unmagnetized Venus (Kallio et al., 1994). The principal author of the results of this work has now joined us at Berkeley to work on some models of atmospheric ion pickup at Mars both for Phobos-2 retrospective study and in preparation for the Mars-96 mission. In addition, the PI has been invited to collaborate on the Swedish-built Mars-96 ion spectrometer data analysis. The access to this data will allow us to determine whether the physical processes important in the solar wind interaction with Mars are the same as at Venus, and to use our models to make estimates of the global loss-rates of atmsopheric constituents from escaping ion observations along the spacecraft orbit.

One of our goals was to improve the plasma environment model that we use for atmosphere scavenging studies. We obtained the results from a global MHD simulation of the solar wind interaction with a conducting sphere from J. Lyon of Dartmouth College that we will soon incorporate into our ion scavenging models. This past year we also worked with D. De Zeeuw, A. Nagy and T. Gombosi on interpretation of their independent global MHD model which utilizes a high resolution adaptive grid. The case considered as a first application was for interplanetary magnetic field aligned with the solar wind flow. We provided corresponding Pioneer Venus Orbiter magnetometer observations that illustrate how well the model approximates the solar wind interaction under these special conditions. The comparison tells us that the model's simulated wake region vortices in the flow and field can explain the previously uninterpreted measurements. The paper on this result in Journal of Geophysical Research (de Zeeuw et al., 1996), shows how synergistic modeling and data analysis can lead to new understanding.

In connection with attempting to understand the Titan plasma-atmosphere interaction for comparison, we reanalyzed magnetic field data from the Voyager 1 pass through Titan's wake in 1980 and modeled the observed magnetic perturbation in terms of a pickup ion current signature. These results, which show yet another aspect of atmosphere-plasma interaction signatures, may influence some operations planning for the Cassini tour. They have been presented at the 1995 DPS meeting and submitted to Journal of Geophysical Research (Luhmann, 1996).

Finally, as parts of the general activity in accord with this project's goals, we presented an invited lecture at the AGU Chapman Conference on the Physics of the Magnetopause to provide a contrasting look at solar wind boundaries from the unmagnetized planet perspective (Luhmann, 1995), completed and revised a book chapter on "Global Models of the Venus-Solar Wind Interaction" that will be published in VENUS II by the University of Arizona Press this year (Luhmann et al., 1996), and represented Mars aeronomy science by invitation at the Intermarsnet Planning Workshop in Capri in October, 1995. The lunar aspect of this project has been given lower priority because of the current level of interest in Mars and Titan. However, in the next year we plan to supply J. Lyon and/or T. Gombosi with a lunar atmosphere model to install in their MHD codes. This would allow the first quantitative assessment of the effect of the lunar atmosphere on the solar wind interaction. Indications of its significance would open the way for comparative analyses between the model and both the archived lunar data and the new data from the lunar flybys of the WIND spacecraft.

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Patents or Inventions Resulting

None.

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A new axisymmetric MHD model of the interaction of the solar wind with Venus

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Abstract. A new two-dimensional axisymmetric MHD model is used to study the interaction of the solar wind with Venus under conditions where the interplanetary field is approximately aligned with the solar wind velocity. This numerical model solves the MHD transport equations for density, velocity, pressure, and magnetic field on an adaptively refined, unstructured grid system. This use of an adaptive grid allows high spatial resolution in regions of large density/velocity gradients and yet can be run on a workstation. The actual grid sizes vary from about 0.06 R_v near the bowshock to 2 R_v in the unperturbed solar wind. The results of the calculations are compared with observed magnetic field values obtained from the magnetometer on the Pioneer Venus Orbiter, at a time when the angle between the solar wind velocity vector and the interplanetary magnetic field (IMF) was only 7.6^o. Good qualitative agreement between the observed and calculated field behavior is found. The overall results suggest that the induced magnetotail disappears when the IMF is radial for an extended time period and implies that it weakens when the field rotated through a near-radial orientation.

Introduction

The initial flyby observations of Venus by Veneras 4 and 6 and Mariners 2, 5, and 10 initiated a great deal of interest in the physical processes controlling the interaction of the solar wind with Venus. It soon became obvious that the obstacle to the supersonic magnetized solar wind is the ionosphere, because of the very weak or nonexistent intrinsic magnetic field of Venus. Early models of these global interaction processes were based on gasdynamic calculations. *Spreiter et al.* [1966] studied the interaction of an inviscid supersonic flow with a nonabsorbing, blunt obstacle appropriate for the terrestrial magnetosphere case. A few years later they carried out similar calculations appropriate for nonmagnetic planets such as Venus and Mars [*Spreiter et al.*, 1970]; the gas dynamic calculations were later somewhat improved and extended [*Spreiter and Stahara*, 1980; *Stahara et al.*, 1987; *Belotserkovskii et al.*, 1987; *Moore et al.*, 1991a]. These gasdynamic models were reasonably successful in predicting the shape and location of the bow shock. They have also been used to estimate the magnetic field configuration inside the magnetosheath and to a lesser extent in the magnetotail, assuming "frozen-in" flow [*Luhmann et al.*, 1986; *Moore et al.*, 1991a]. One of the major shortcomings in the applications of these models to "nonmagnetic" planetary obstacles has been their minimal attention to the wake region, where nongasdynamic forces are likely to play a major role in any case.

Semikinetic (hybrid) particle simulations and MHD models have been introduced recently to better simulate the true situation around nonmagnetic bodies such as Venus, Mars, or comets. The hybrid code used for these studies treats the ions as individual particles, but the electrons are assumed to be a massless fluid [*Brecht*, 1990; *Brecht and Ferrante*, 1991; *Moore et al.*, 1991b; *Brecht et al.*, 1993]. This approach allows the effects of finite gyroradius, particle wave interactions, mass loading, and Hall currents to be examined. The published hybrid model simulations have thus far only treated the dayside interaction with a spherical conducting obstacle. The major conclusions obtained from these studies were that there are asymmetries in both the magnetic structure in the dayside magnetosheath and shock lo-

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Proton flow in the Martian magnetosheath

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Abstract. The Automatic Space Plasma Experiment with a Rotating Analyzer (ASPERA) measurements on board the Phobos 2 spacecraft gave, for the first time, a three-dimensional (3-D) picture of the proton flow around Mars. The measurements from the circular orbits of Phobos 2 are well suited to study the bow shock at the terminator region, the nightside magnetosheath, and the tail region. Moreover, measurements from the elliptical orbits offer dayside magnetosheath data. In this work, all circular orbits (11) where there was enough information for 3-D velocity calculations are analysed. The solar wind deflection at the bow shock and the disappearance of the flow near the optical shadow of Mars are found to be typical features on all circular orbits. A dawn-dusk asymmetry is detected in many cases as well. When the results are compared to a gasdynamic model, the locations of the observed boundaries and the general behavior of the flow are found to be quite consistent with the model. The region where proton particle flux decreases significantly, referred to as a magnetopause near the optical shadow of Mars, was typically found near the magnetic field maximum. The magnetopause was thus inside the so-called magnetic tail boundary, which is defined to be at the broad magnetic minimum between the bow shock and the central current sheet. The magnetic tail boundary may be related to the O^+ pick-up ions because the mass loading boundary also lies between the shock and the magnetopause. Because the proton flow may behave differently in the dayside than in the nightside magnetosheath, the 3-D velocities are calculated on two elliptical orbits as well. However, in these cases the nature of the flow is not possible to determine as reliably as near the terminator.

1. Introduction

Solar wind diversion around a planetary object depends on the underlying deflection mechanism. The knowledge of the characteristic features of the flow may thus give detailed information about the interaction process between the flow and the object. Such information is particularly valuable in the case of Mars because, in spite of in situ measurements near Mars since 1965, some basic questions still lack answers. For example, we do know that a shocklike structure exists upstream of Mars, indicating that Mars forms an effective obstacle which deflects a significant portion of the solar wind flow around the planet. However, we do not know how strongly the Martian intrinsic magnetic field, its ionosphere, atmosphere, or neutral corona affect the formation of the obstacle.

In frequently used terminology [e.g., *Cravens*, 1989], we do not know how strongly the Mars-solar wind interaction is Earth-like, Venus-like, or comet-like, for several reasons. A discrepancy exists concerning the strength of the Martian intrinsic magnetic field [e.g., *Lundin et al.*, 1990, and references therein] even though it certainly is very weak compared to the Earth's intrinsic field. Moreover, in situ ionospheric measurements made by Viking 1 and 2 landers gave rather different ionospheric profiles, and it is not clear how strongly the Martian ionosphere can deflect the solar wind flow [*Zhang and Luhmann*, 1992]. In addition, there is a hot neutral corona around Venus, but so far no hot neutral corona has been observed around Mars [*Nagy et al.*, 1990]. The corona together with the thermal upper atmosphere of a planet adds mass to the solar wind when neutral atoms are ionized. The newly born ions are picked up by the solar wind electric field thereby decreasing the solar wind flow speed [*Lundin et al.*, 1991].

Gasdynamic models have frequently been used to study the main features of the flow deflection around planetary bodies. For example, *Russell et al.* [1984] analyzed MARS 3 spacecraft magnetic field data, and later *Luhmann et al.* [1986] analyzed Pioneer Venus Orbiter (PVO) magnetic field data. In both studies a quite good correspondence between the data and the model was found. Earlier, *Mihalov et al.* [1982] compared the PVO plasma data from the Venusian magnetosheath near the terminator and found that the calculated values were similar to the observed plasma properties. The ability of the gasdynamic model to describe the PVO observations was also discussed by many other authors [*Slavin et al.*, 1983; *Tatrallyay et al.*, 1984; *Moore et al.*, 1991; *Zhang et al.*, 1993; *Brecht and Ferrante*, 1991].

Recently, for the first time, three-dimensional (3-D) proton bulk velocity determination around Mars has been made using in

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OUTSTANDING PROBLEMS IN MARS AERONOMY

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ABSTRACT

Although the Phobos-2 spacecraft recently obtained important results relevant to some of the major remaining questions in Mars aeronomy, much remains to be done. In particular, not since the Viking Landers have we made in-situ measurements of aeronomical quantities such as atmospheric and ionospheric densities and temperatures below 400 km altitude. We have never made magnetic field measurements at these altitudes. Without such measurements we cannot unambiguously resolve arguments concerning issues such as the significance of the planetary magnetic field in the solar wind interaction, or understand the atmospheric cycle that leads to escape to space. With the trio of future orbiters including Mars Observer, Mars-94, and Planet-B we should see a veritable explosion of new knowledge, but some gaps in aeronomical science coverage will still remain. This paper briefly reviews some of the major unsolved problems in Mars aeronomy, and points out which are expected to remain outstanding after this flotilla of missions.

INTRODUCTION

While there have been significant advances in Mars aeronomy since the Viking spacecraft first probed the upper atmosphere and ionosphere of Mars, many aeronomy issues remain open. In particular, certain outstanding questions can at best be partially addressed at this time due to a lack of low altitude (< 400 km) in-situ information. Among these are the continuing uncertainty regarding the nature and importance of the Martian magnetic field, the related issues

The Magnetopause Counterpart at the Weakly Magnetized Planets: The Ionopause

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In commonly accepted terminology, a magnetopause is the pressure balance boundary that forms at the interface of a magnetosheath composed of inflowing solar wind plasma, and a magnetosphere dominated by internal magnetic field pressure. The corresponding boundary observed on the dayside at the weakly magnetized planets like Venus has been called the ionopause to distinguish it from the magnetopause. The dayside ionopause forms where the magnetosheath (sometimes called ionosheath in this case) plasma and field comes into pressure balance with the ionosphere. On the nightside there is a magnetosheath/obstacle boundary with a more magnetospheric character in that the internal pressure is supplied by the fields in the lobes of the induced magnetotail. The dayside ionopause responds to solar wind pressure like the magnetopause under circumstances where the latter is exceeded by the peak ionospheric plasma pressure, albeit with less sensitivity due to the small ionospheric scale height. For excessive incident solar wind pressures, or weak ionospheres, the ionopause definition becomes ambiguous because magnetosheath field and plasma can penetrate into the ionospheric "obstacle". At these times collisional processes related to the presence of the atmosphere bring into play diffusion processes that are unique to the ionopause boundary. Other unique features related to the atmospheric nature of the interaction include planetary ion production in the magnetosheath and possible kinetic effects from the small obstacle size.

1. INTRODUCTION

The words "magnetosheath" and "magnetopause" are often used to describe features of the solar wind interaction at the essentially nonmagnetic obstacles Venus and Mars. The use of magnetosheath terminology seems justified based on the similar physical origins and observed characteristics of the Earth and Venus sheaths (the latter of which is sometimes called an ionosheath). To a first approximation, at least at solar maximum, the Venus sheath is well-described by the gas-dynamic models of *Spreiter and Stahara* [1980]. Evidently, under these circumstances Chapman-Ferraro-like currents are induced on the pressure balance boundary, the "ionopause", between the ionospheric plasma and the incident solar wind plasma, that closely approximate those on the ideal closed magnetopause. The magnetic fields associated with this boundary current system in effect cancel interplanetary fields inside of the pressure balance or obstacle surface. However, this ideal picture does not always prevail. Boundary layer physics that has no Earth counterpart, such as mass-loading by planetary ions, collisional diffusion into the obstacle, and solar wind plasma kinetic effects related to the small obstacle size, distinguish the nonmagnetic obstacle boundaries. Even the most magnetopause-like part of the boundary in the wake is characterized by normal components controlled by the interplanetary field orientation rather than by reconnection with an intrinsic tail lobe field.

Here the characteristics of the magnetopause counterpart at the weakly magnetized planets are briefly reviewed. Because we know much more about the Venus example, due especially to the Pioneer Venus Orbiter (PVO) mission, those observations form the basis of much

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Titan's ion exosphere wake: a natural ion mass spectrometer?

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Abstract

According to one possible picture of the Titan atmosphere interaction with Saturn's magnetosphere, newborn exospheric pickup ions may exhibit a marked asymmetry with respect to the corotation wake due to their large gyroradii in the local ~5 nT magnetic field. These finite gyroradius effects should persist until the ions are scattered by wave-particle interactions (a scale length that is presently unknown). To the extent that simple test-particle-like motion is maintained, the combination of the small (on the scale of most ion gyroradii) size of Titan and the small, steady local magnetic field at ~20 Saturn Radii provides a natural ion mass spectrometer configuration. The resulting spatial dispersion of the pickup ion trajectories can be used for both analyzing the composition of the Titan exosphere and determining the ionization rates of its various constituents. Possible evidence of this ion mass spectrometer effect may be visible as a magnetic field perturbation in the Voyager 1 Titan flyby data.

Page Proof

GLOBAL MODELS OF THE SOLAR WIND INTERACTION WITH VENUS

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In-depth observational analyses of the Venus-solar wind interaction over the last decade have both stimulated and responded to the synergistic development of global theoretical models. The latest global models include mass-loaded gas dynamic magnetosheath models, MHD models of the solar wind interaction with conducting spheres representing the planetary ionosphere, hybrid models in which both solar wind and planetary ion kinetics are included, and test particle models wherein ions are introduced into prescribed global field models. Each gives somewhat different but complementary insights into the physical consequences of the solar wind interaction with a planetary atmosphere. In particular, the gas dynamic magnetosheath and MHD models allow us to interpret the interplanetary magnetic field and solar wind flow disturbances created by the Venus obstacle. They also give us background fields to be used in test particle investigations of the characteristics of the planetary pick-up ion population. The global hybrid simulations uniquely combine self-consistent aspects of both, although they are constrained to lower spatial resolutions by current computational constraints. Several of these models are capable of evolving to include more realistic treatment of the "soft" solar wind-ionosphere interface, thus providing the possibility of a combined or coupled model of both the magnetotail/magnetosheath region and the ionopause/ionosphere. These models, and their future further-developed counterparts, will be of great value in the comparative study of the Venus and Mars solar wind interactions expected in the coming era of renewed Mars exploration.