Induced magnetospheres

J.G. Luhmann a, *, S.A. Ledvina a, C.T. Russell b

a Space Sciences Laboratory, University of California, Grizzly Peak Blvd, Centennial Drive, Berkeley, CA 94720, USA
b Institute of Geophysics and Planetary Physics, University of California, Los Angeles, CA 90095-1567, USA

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Abstract

Induced magnetospheres occur around planetary bodies that are electrically conducting or have substantial ionospheres, and are exposed to a time-varying external magnetic field. They can also occur where a flowing plasma encounters a mass-loading region in which ions are added to the flow. In this introduction to the subject we examine induced magnetospheres of the former type. The solar wind interaction with Venus is used to illustrate the induced magnetosphere that results from the solar wind interaction with an ionosphere.

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1. Introduction

Most readers are familiar with the traditional picture of a magnetosphere, illustrated in Fig. 1(a). Its dipolar magnetic field from an internal planetary dynamo is distorted by the solar wind flow into a blunt obstacle shape, surrounded by a magnetosheath of shocked, de- exed solar wind plasma with its draped, frozen-in magnetic field. It is defined as the region of space in which the magnetic field lines have at least one end connected to the source of the internal field. The magnetopause is the outer boundary of this topological domain. In contrast, an induced magnetosphere occurs in plasma interactions with nonmagnetic bodies, and is the less well-defined region in which magnetic forces dominate the dynamics of the plasma. The word "induced" in this context refers to the general process of creating an effective magnetic obstacle through the plasma interaction. The induced magnetic fields include the classical field perturbations resulting from electromagnetic induction, but also the field perturbations from the flow interaction. The obstacle producing the induced magnetosphere can be an electrically conduct-

* Corresponding author. Tel.: +1-510-642-2345; fax: +1-510-643-8302.
E-mail address: gjluhman@berkeley.edu (J.G. Luhmann).

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magnetic fields associated with the induced currents are generally configured so as to exclude the external field from the conductor. The disturbed field regions in fast flows include a magnetosheath and an induced magnetic net that is essentially an extension of the magnetosheath into the wake. Fig. 1(b) illustrates these features for an ionospheric obstacle, and the contrast to the traditional magnetosphere in Fig. 1(a).

The existence of a bow shock at the upstream boundary of an induced magnetosphere's magneto sheath depends on the combination of magnetic parameter. Much number of the relative external flow, the importance of ion pickup from any extended atmosphere of the obstacle, and the importance of finite- ion gyroradius effects. In particular, mass loading by ion pickup from an extended atmosphere can gradually slow the external flow, making a shock flow transition unnecessary. Ion pickup can moreover dominate a plasma interaction to the extent that induced currents are unimportant compared to mass loading of the surrounding plasma by the pickup ions. Comets exhibit induced magnetotails in the solar wind, but they are primarily due to localized slowing of the solar wind in the space surrounding the nucleus by production of water and other heavy ions on passing interplanetary magnetic flux tubes. For this reason cometary interactions are placed in a separate category, to be discussed elsewhere in this volume by T.E. Cravens. The importance of the dynamic pressure of the cometary gas outflow in defining the cometary obstacle (Lindgren et al., 1997) also distinguishes comets from most planetary induced magnetospheres (with the possible exception of Pluto, see Bagenal et al., 1998).

Similarly, for discussion of finite-ion gyroradius effects, which can prevent the formation of an MHD shock if the subflow magneto sheath thickness is comparable to or less than the ion's gyroradius, we refer the reader to a later paper by Ledvina et al. (also this volume).

The lifetime of the classical induction currents contributing to the induced magnetosphere depends on the electrical conductivity of the material involved and the dimensions of the body in which these currents are generated, together with the frequency of the external magnetic field changes. For planets or planetary satellites, these currents may flow in parts of the interior body and on the surface of conductors such as molten core material or liquid layers such as oceans. They can also flow in the ionosphere if an atmosphere is present, in a current layer or ionopause boundary layer where the external magnetized plasma and ionospheric plasma balance. While we do not usually think of these currents as classically induced, the ionopause effectively acts as a conducting surface. The currents associated with pressure balance with a completely collisionless ionosphere can last indefinitely, as long as the pressure gradients at the boundary are maintained by the flowing external plasma and the ionosphere is maintained by solar EUV. If the ionosphere is resistive at the pressure balance altitude, the "shielding" current spreads as the magnetic field diffuses into the ionosphere. We note that if the solar wind interacted with an atmosphereless planet the body of the planet was molten metal with a very high electrical conductivity, a shielding current would flow on the outer surface of the metal planet and a similar induced magnetosphere would be created.
It was once thought that the Earth's Moon would produce an induced magnetosphere in the solar wind. The dipole field that would be classically induced in its conducting interior by interplanetary magnetic field variations is illustrated in Fig. 2(a) for the simplified case of an external vacuum field. In the fast-flowing plasma of the solar wind the magnetic configuration would be more like that shown in Fig. 2(b), with an upstream bow shock bounding the perturbed field. However, the early relations to the moon found it lacked the necessary bulk conductivity to produce such effects. Instead, the solar wind was absorbed, merely creating a flow wake and hardly perturbing the interplanetary magnetic field (e.g., Spreiter et al. 1970; Russell et al., 1974). The moon has an electrically conducting "core", but it is so small that instead of doubling the external field as in Fig. 2(a), the perturbed surface field was enhanced by only a few percent. The moon also lacks a substantial atmosphere, and hence enough of an ionosphere to produce the alternative pressure balance obstacle. In contrast, ionospheric pressure balance currents dominated the solar wind interaction with Venus observed during the Pioneer Venus Orbiter missions, whose main features are those illustrated in Fig. 1(b). Perturbation magnetic fields associated with induced currents of either kind can exclude the external fields from the interior space of the obstacle, as suggested by both Fig. 2(b) and 2003. Parallel exclusion of the external flow and field occurs if the induced currents are insufficient or are inside the body (such as or the core) rather than on its surface. At Venus, this effect was seen as nearly field-free ionosphere beneath the ionopause when the solar wind pressure balance occurred well above the exobase at ~200 km altitude. A magnetized ionosphere was observed when the solar wind pressure exceeded the ionospheric pressure near the exobase. Under those conditions, the Venus obstacle apparently does not deflect all of the incident solar wind (Zhang et al., 1990), and the external magnetic fields diffuse into the ionosphere (e.g., Lahmann and Cravens, 1991 and references therein).

In general, an induced magnetosphere induces a wake in the form of an induced magnetotail under Alfvén wing. As mentioned earlier in connection with Venus, the induced magnetotail is composed of inner magnetosphere flux tubes that slip over the obstacle to fill the flow wake (see Fig. 1(b)). The horn Alfvén wing describes the perturbations due to field-aligned currents from a conductor moving in a magnetized plasma. These currents transfer momentum between the conductor and the plasma in an effort to force them to move at the same speed. In a planetary situation field-aligned currents can also result from currents in the detached external medium. The Alfvén wing occurs when some flux tubes threading the obstacle connect to the external magnetic field. These become an effective extension of the obstacle to the external flow (see the review of satellite interactions by Kivelson, this volume). In fact, the boundary of an induced magnetosphere is less well defined than the boundaries of the traditional magnetosphere, although it can be argued that reconnection

Fig. 2. (a) Illustration of the configuration of the magnetic field around a conducting sphere, resulting from classical induction - in this case a switched-on internal external field. The perturbation field is that of an opposing dipole, which causes the external field to drop around the sphere. 20 Field lines are shown in a simulation of the solar wind interaction with a conducting spherical Venus' ionosphere, for comparison. In this case a flowing magnetized plasma encounters the obstacle boundary where magnetic field and plasma flow normal components are forced to vanish.

with the external field at the magnetopause, and ionosphere-magnetosphere coupling also compromise the traditional version. To accommodate such uncertainties, we here state our working definition of an induced magnetosphere as everything between an outer boundary outside of which the obstacle has no effect on the external medium, and an inner boundary inside of which there is no effect of the external conditions. Note that if we identified the ionopause as the inner boundary of Venus' induced magnetosphere, it would be more analogous to the inner boundary of Earth's magnetopause, not its magnetosphere. On the other hand, the ionopause is not always impenetrable to external plasma and field, so that boundary identification even requires caution.

The adjustment of planetary ionospheres to dynamic pressure changes, and run/ wake side asymmetries, greatly complicates the separation of classical electromagnetic induction effects in induced magnetospheres. As mentioned earlier, the external magnetic field can diffuse into the ionosphere if the solar wind dynamic pressure is high (or the ionospheric pressure is weak, as at solar minimum at Venus). If magnetic fields reach the solid planet surface, conducting material in or on the body can contribute to the induced field perturbations. In the flow wake created by the external flow deflection by the obstacle, and possibly some absorption, reflowing occurs due to a variety of processes. Charge separation electric fields resulting from the differing mobilities of ions and electrons in the plasma, fluid-like instabilities from the density and velocity gradients at the wake edges, and MHD and possibly even gravitationally forces may all contribute. The resulting magnetic field topology of the induced magnetotail, like that of the magnetosphere, is influenced by these reflowing processes as well as by mass loading by ionospheric ions as the incident flux tubes slip through the upper atmosphere. Together with the upstream deflection of the oncoming flow by the obstacle, the wakes alter the uniformity of the external magnetic field to which the conducting material of the obstacle is exposed. In addition, the conductors involved are often in nonsymmetrical shapes with nonuniform conductivities. For example, a typical ionosphere is a partially conducting hemispherical shell produced on the sunlit face of the obstacle. It is moreover time variable and subject to control by forces and factors with mass loading to the ionosphere (e.g., solar wind, collisions, atmospheric chemistry, neutral winds, episodic production increases, and plasma pressure gradients). The isolation of the classically induced magnetic field perturbations in such settings requires careful modeling and detailed measurements. In addition some crustal remnant magnetization is present, as at Mars (Acuña et al., 1999), all perturbation currents are affected by the distribution and strength of those permanent localized fields.

It is worth noting that the classically induced magnetospheres apparently generated at some of the Galilean satellites, and studied later in this volume by Kivelson, are not usually described in terms of induced magnetospheres. In these cases the induction is by a small oscillating equatorial component of the local jovian magnetic field, resulting in an induced field perturbation that deflects the incident corotating plasma, but does not make the satellite an effective flow obstacle. Clearly there is some ambiguity about what qualifies as an induced magnetosphere.

Below we consider our simplest and best-observed example of an induced magnetosphere at Venus. A numerical simulation of the solar wind interaction with a conducting sphere, representing the ionosphere, reproduces the basic features observed by the Pioneer Venus magnetometer in the magnetosheath and magnetotail. We consider the possibility that under certain circumstances some time-dependent external fields leak into the interior and electromagneticly induced field perturbations in Venus' core that oppose interplanetary field changes. The signatures of this classically induced contribution, and its potential for telling us about the interior of Venus, provides some food for thought on retrospective and future studies of induced magnetospheres in the solar system.

3. Venus: the prototypical induced planetary magnetosphere

The exploration of Venus by the long-lived Pioneer Venus Orbiter (PVO) in the 70s and 80s provided a first close look at the details of the solar wind interaction with an essentially unmagnetized planet. Fig. 1(b) was essentially derived from the PVO magnetometer data and complementary plasma measurements (Russell and Vaisberg, 1983; Luhmann, 1986). The draped magnetic fields of the magnetosheath and the induced magnetotail are its key attributes. The occurrence of the primary mission of PVO during active solar conditions provided the opportunity to probe Venus' induced magnetosphere in its simplest state. Especially important in this regard were the location of the boundary where the ionospheric pressure balanced incident solar wind dynamic pressure in the practically collisionless region of the upper atmosphere, and the existence of a significant equatorial ionosphere. The ~10 km thick ionopause boundary layer, at ~350 km altitude, carried essentially all of the current required to deflect the solar wind and shield the lower atmosphere and solid planet from the interplanetary field. Classical induction in the solid planet apparently played no significant role. To first order, Venus at solar maximum is a spherical conducting obstacle in the magnetized solar wind, with its ionospheric pressure producing the flow obstacle.
The magnetosheath of Venus was analyzed using the best tool available at the time, the Sprites and Stahura gas-dynamic frozen-field magnetosphere model for hypersonic flow around a blunt obstacle (Luhmann et al., 1986; Phillips et al., 1986; Spriter and Stahura, 1992). In general, the daytime fields up to the terminator plane bore remarkable resemblance to the three-dimensional magnetic field described by that model. The exception was the magnetic barrier region immediately adjacent to the ionopause, where the computed interplanetary field plus the dynamically induced field from the ionopause currents assumed all of the incident solar wind dynamic pressure (e.g. Zhang et al., 1990). This feature is not part of the gasdynamic description because the magnetic field exerts control over the plasma here. Such domains are the counterpart of the plasma depletion layer in Earth's magnetosheath, and a key attribute of induced magnetospheres in the solar wind.

The PVO observations of the Venus wake were restricted to low (-3 Venus radii, Rv) and high altitude (10-12 Rv) segments due to the orbit sampling along the highly elliptical path of PVO. Several overviews of the PVO measurements of plasma and field structure in that region can be found in reviews by Phillips and Mccomas (1991), and Slavin et al. (1989). Luhmann et al. (1991), and Luhmann and Granat (1992) analyzed the PVO magnetometer observations of the low altitude wake, while Saunders and Russell (1986), and Mccomas et al. (1986), concentrated on its high altitude behavior in the magnetotail proper. The comet tail-like draped fields of Fig. 10b were clearly seen in the observations, but the near-wake fields which are most affected by the induced currents "internal to" the Venus ionospheric obstacle, required more interpretation. The lack of a wake limited the applications of the gas dynamic model to the study of the Venus magnetotail (although Moore et al. 1991) made some adaptations to mimic wake closure in the gas dynamic flow, and Luhmann et al. (1991) experimented with insertion of a comet-like field structure. These limitations do not exist in recent global MHD numerical simulations, described below.

The observed near-wake of Venus exhibited two kinds of magnetic features. One was characterized by nearly antisolar field inclinations within powered low-density ionospheric regions, observed during the high solar activity primary mission (Braum et al., 1983). These features are referred to as nighttime ionospheric hole: due-to-their low density. The details of their generation are still not understood (e.g. Luhmann and Russell, 1992), although their fields appear to be oriented toward and away from the Sun like the prevailing draped fields of the induced magnetotail. The second type of feature was large-scale magnetization, which occurred at the PVO periaxis altitudes when the incident solar wind pressure was unusually high. These cases can be interpreted as the broadening of the ionospheric layer carrying the pressure balance currents, and correspond to the daytime magnetized ionospheres (e.g. Luhmann and Cravens, 1991). From their properties Luhmann (1992) deduced that the induced magnetic fields around Venus were toroidal, consistent with nearly-complete wrapping of solar wind fields around the planet as in Fig. 2b), rather than poloidal or deflected around the obstacle x Fig. 2a). An implication of the magnetized ionosphere is that the pressure balance currents flow in part in the collisional ionosphere, where they cause atmospheric ionospheric modifications and may not shield the surface from the externally imposed magnetic fields (Luhmann, 1991). However, for the first global simulations of Venus' induced magnetosphere, the most ideal approximation where the ionopause carries all of the necessary currents, as on a surface, provided the best model.

Starting in the early 90s, several authors published results from the numerical MHD simulation of the solar wind interaction with a conducting sphere representing Venus' ionopause. In these simulations, the shielding currents flow where the external medium makes contact with the sphere. Simulations by Tanaka (1992, 1993) gave detailed insight on how the draped magnetic fields close on the nightside, but also drapes and slip over the surface of the sphere from the poles, eventually forming the central induced magnetotail. Murawski and Stenofsen (1996) showed how the magnetic fields in the wake of the sphere could, in the presence of some diffusion, form a X-point at the anti-solar region that separated a toroidal band of low altitude field from a comet-like magnetotail structure. They found that the induced magnetotail probably requires some contribution from ionospheric mass loading of the inner magnetosphere flux tubes to produce sufficiently draped fields. DeZeeuw et al. (1996) simulated a case where the external field was aligned with the flow, an untypical situation in the solar wind at Venus, but nonetheless one that is observed on occasion. Kalil et al. (1998) showed that the magnetosheath field magnitude and bow shock shape are well represented by an MHD simulation. Each study produced a picture of an induced magnetosphere that qualitatively resembles what was inferred from the PVO observations.

The magnetic field lines in Fig. 2b) represent the global external field configuration from the particular MHD simulation described by Kelil et al. (1998). The perturbation fields are from currents both on the conducting sphere representing Venus, and in the deflected external plasma representing the solar wind. The parameters of this particular case study, carried out using methods developed for Earth magnetosphere simulations (Lyons, 2000), are: 14 nT interplanetary magnetic field (in this model perpendicular to the upstream flow direction), a magnetosonic Mach number of 4.5, and flow speed 400 km/s. The ionopause of the presumed
perfectly conducting ionosphere is represented by zero normal field and flow boundary conditions at the spherical obstacle surface (inclusion of an ionosphere, as in Tanaka and Murawski (1997) broadens the current carrying knee and introduces ionospheric plasma tail rays, but does not change the gross behavior of the surrounding induced magnetosphere.) The dayside fields external to the sphere in Fig. 2(b) closely resemble those draped around the classically induced dipole field (Fig. 2(a)). The most obvious exception is that the draped fields cross the terminator plane, producing a degenerate version of the induced dipole field configuration. The cusps at the poles in Fig. 2(a) were folded back into the wake of the obstacle, one would obtain field lines similar to the simulation field geometry.

To visualize the differences between the magnetic fields generated in the simulated MHD flow interaction and the classically induced dipole case in Fig. 2(a), in Fig. 3 we subtract the background (perpendicular solar wind) field from the simulation field. As mentioned earlier, this residual field represents a combination of the field from currents on the conducting obstacle, and currents due to flow distortions of the frozen-in magnetic field. (In principle one could separately determine the field from the current on the obstacle-flow interface by computing curl of B on the sphere.) The net result is similar to the "anipolar generator" fields envisioned by Sonett and Cahill (1968), and calculated by Horne and Schubert (1974) early in the history of magnetized planet exploration. Although in this steady-state model, there is no explicit counterpart at the classically induced currents on a conducting sphere in a time-varying field, the simulation setup for such a case study would be identical. However, the results would differ because the external field produces an asymmetric MHD interaction. At any time the magnetosphere and induced magnetotail fields would be influenced by a variety of external field orientations - as well as their associated current sheets that could give rise to reconnection sites.

The subsequent Venus-induced magnetosphere simulations carried out by Tanaka and Murawski (1997)...

![Fig. 3. 3D Projections of selected magnetic field lines from the simulation of the solar wind interaction with a conducting sphere, representing Venus (also see Fig. 2(a)). The lines are traced from the selected specimen starting points. The left panels show the field simulation field looking down on the plane of the external field (top), from the Sun (middle), and along the external field direction (bottom). The right panels show the corresponding perturbation fields in the same view, obtained by subtracting the usual external field.]

![Fig. 4. Illustration from Tanaka (1993) of the gas pressure (P), magnetic pressure (B^2/2), and dynamic pressure (RAM) along the magnetic field lines. The Venus interaction simulation that included an ionosphere. The simulation does not separate the solar wind and ionospheric gas pressure, thus the shock heated solar wind makes a significant thermal pressure contribution over the total range shown - within the magnetosphere. The lower panel represents the optical solar maximum Venus interaction where currents in the ionosphere layer, at the top of the ionosphere, shield the external flow and field. The upper panel represents a periodic or steady-state pressure, where the interplanetary field diffuses and connects lines, possibly through the ionosphere in the surface.]

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that included the ionospheric plasma provided more insight into the variety that the real solar wind interaction exhibits. These simulations reproduced the magnetization of the ionosphere that was observed to occur on PVO when incident solar wind magnetic pressure pushed the ionopause downward (e.g. see Luhmann and Cravens, 1991). The associated altitude profiles of the simulated pressure along the stagnation streamline, showing the trade-off from solar wind dynamic pressure to magnetic barrier pressure to ionospheric pressure are reproduced in Fig. 4. The magnetic field extends to the surface in the high solar wind dynamic pressure case (top panel), raising the question of what happens on Venus on such occasions. While the lowest altitude field structure is probably not spatially resolved in the simulation shown, calculations by Luhmann (1991), based on the PVO peripapsis field measurements, indicate that some field is probably present at the surface on occasion. Perhaps, as mentioned earlier and suggested by the sequence of sequentially stronger interaction concepts in Fig. 5, classical inductors in the core of Venus produces an additional magnetic field perturbation. In theory, this perturbation could be measured on the surface to gain information about Venus' core, if it could be separated from the surface fields due to currents in the ionosphere and above. Of course this illustration presumes there are no additional good conductors on the Venus surface or in the crust and mantle.

4. Concluding remarks

While the idea of an induced magnetosphere at first seems straightforward, the discussion here suggests it's not a particularly well-constrained concept when applied to even the simplest solar system cases, as at Venus. At Venus we are at least fortunate to have a substantial observational picture of what appears to first-order the interaction of the solar wind with a conducting sphere. Global MHD simulations suggest how the combination of ionopause boundary currents, and distributed currents from the external plasma flow deflection, lead to the field perturbations that characterize Venus’ induced magnetosphere. Yet we have only scratched the surface of even this simplest planetary example. Observations within the Venus ionosphere, and on its surface, under a range of solar wind and ionospheric conditions, would be necessary to truly characterize the breadth of characteristics of Venus' induced magnetosphere. Perhaps more easily, the numerical simulations could be further exploited to explore the numerous possible scenarios of the Venus solar wind interaction that must occur.

The Venus induced magnetosphere will be revisited with modern instruments by Venus Express, planned for launch in 2005. The induced magnetospheres at Mars and Titan, which are further complicated by strong crustal remnant fields (e.g. Liu et al., 1999) and finite iron gyroradii effects (Brecht et al., 2000; Ledvina et al., this volume), respectively, are the new frontier. Observations from the Mars Express mission starting in 2004 are expected to shed light on the Mars-solar wind interaction, while the Cassini Orbiter will repeatedly fly by Titan with a full complement of particles and fields instruments. Broadly viewing induced magnetospheres in terms of their systems of classically and dynamically induced currents resulting from their magnetized plasma interactions, one could also study these cases in some detail by using numerical simulations to experiment with possible scenarios (e.g. as done by Ledvina et al., this volume, for Titan in the solar wind). Indeed, the combination of observations and simulations is required to explore the physical complexity and variety of plasma interactions that induced magnetospheres encompass.
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References

Kallio, E., Luhmann, J.G., Lyon, J.G. Magnetic field near Venus: a comparison between Pioneer Venus Orbiter magnetic field observa