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The lunar wake at 6.8 R_L: WIND magnetic field observations

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Abstract. We report on WIND magnetic field observations at ~6.8 R_L downstream of the moon on 27th December 1994. The moon was in the solar wind during the encounter. IMP-8 observations are used to determine baseline IMF conditions, and therefore determine those features in the WIND data which are related to its proximity to the moon. Previous Explorer 35 observations suggest that the lunar wake is not detectable beyond a downstream distance of ~4 R_L. However, despite the distance of WIND from the moon, we observe a slight decrease in field intensity just prior to the spacecraft entering the optical shadow, a slight field strength enhancement whilst in shadow, and perhaps a weak depression once the spacecraft re-emerges into sunlight. These signatures closely resemble, but are weaker than, the previous observations. We conclude that a lunar wake did extend to these distances at the time of this encounter. We also note a rotation in field direction some distance outside of the wake signature which may be attributed to the crossing of the lunar mach cone boundary. We discuss the observations in terms of simple models of the solar wind interaction with an insulating body.

1. Introduction

Much of our current observational understanding of the solar wind lunar interaction is based on data from Explorer 35 in the late 1960's (see review by Ness [1972] and references therein), which showed the moon has no significant intrinsic magnetic field [Ness et al., 1967], and therefore no bow shock or magnetosheath when located in the solar wind [Colburn et al., 1967; Ness et al., 1967]. Solar wind plasma simply impinges on and is absorbed by the lunar surface, thus creating a plasma cavity on the downstream side [Lyon et al., 1967]. Ness et al. [1967] reported magnetic field magnitude increases in the region corresponding to this plasma umbra, and decreases on either side, in a plasma penumbra. The field direction was perturbed by < 20°. Some cases also exhibited an additional penumbral increase in the |B| [Colburn et al., 1967; Ness et al., 1968]. In his review of the Explorer 35 observations, Ness [1972] pointed out there was no evidence of the wake beyond 4 lunar radii (R_L) downstream from the moon, implying that solar wind plasma fills the cavity by this distance, such that there are no residue magnetic signatures.

A number of models of the solar wind-lunar interaction were subsequently published. Colburn et al. [1967] explained the observations in terms of diamagnetic currents on the surface of the plasma cavity. These create a |B| enhancement inside the cavity, and a depression just outside. This is equivalent to assuming pressure balance across the cavity boundary in a fluid treatment, in which the dips in |B| outside the cavity are associated with a density decrease created by solar wind plasma expanding into the cavity [e.g., Whang, 1967; 1968, Johnson and Midgeley, 1968; Michel, 1968; Wolf, 1968; Siscoe et al., 1969; Spreiter et al., 1970]. Occasional observations of |B| enhancements outside the prenumbral decrease have also been addressed by Siscoe et al., [1969], Whang [1969; 1970], Whang and Ness [1970; 1972] and Catto [1974]. A review of the various studies associated with the Explorer 35 observations can be found in Schubert and Lichtenstein [1974].

WIND was launched in November 1994. To deflect the spacecraft into the upstream region, a lunar encounter occurred on December 27, 1994, with a closest approach of ~6.8 R_L on the "nightside" of the moon. We present WIND magnetometer data [Lepping et al., 1995], and concurrent magnetic field observations from IMP-8, located in the solar wind, in the same local time sector, but closer to the Earth. We show that a wake signature was indeed observed by WIND at this time.

2. Observations

Figure 1 shows the positions of WIND and IMP-8 in the x-y GSE plane on December 27, 1994. In the left panel, spacecraft trajectories for the period 12-18 UT are shown in the Earth reference frame. Both spacecraft are on the dawn side of the Earth and outside the mean bow shock (BS) and magnetopause (MP) locations. During this interval WIND moved from z_{GSE} = -1.0 R_E to -1.4 R_E, and IMP-8 from -14.2 to -14.8 R_E. The right panel shows the WIND trajectory for the same time period in lunar-centric coordinates. The spacecraft passed through the lunar shadow, with a closest approach of ~6.8 R_L.

Figure 2(a) shows 15.36 s averages of the magnetic field in GSE coordinates measured at IMP-8 for the period 12-18 UT. Except for 3 intervals (1340-1355, 1420-1440, and after 1740 UT) the field is moderately strong (~7 nT) and steady. B_X and B_Y are both positive for most of this interval, each with average magnitude of ~5 nT, while the average B_Z component is rather smaller (~1 nT). The field thus lies approximately in the ecliptic plane, at an angle of ~45° to the Earth-Sun line, pointing sunward and duskward, as also indicated by the heavy arrow in the left panel of Figure 1. This orthospiral field direction implies that neither IMP-8 nor WIND are magnetically connected to the bow shock, which might have been expected were the IMF in a more typical Parker spiral orientation. Two exceptions to this are the 1340-1355 UT event at IMP-8, when B_Y becomes small, and a similar, briefer event at 1425 UT. The field orientation probably does connect IMP-8 to the bow shock during these periods, which would explain the noiser data. However, for the most part these data represent pristine IMF conditions, and are free from complications of processes occurring in the foreshock region [e.g., Fairfield et al.,1990].

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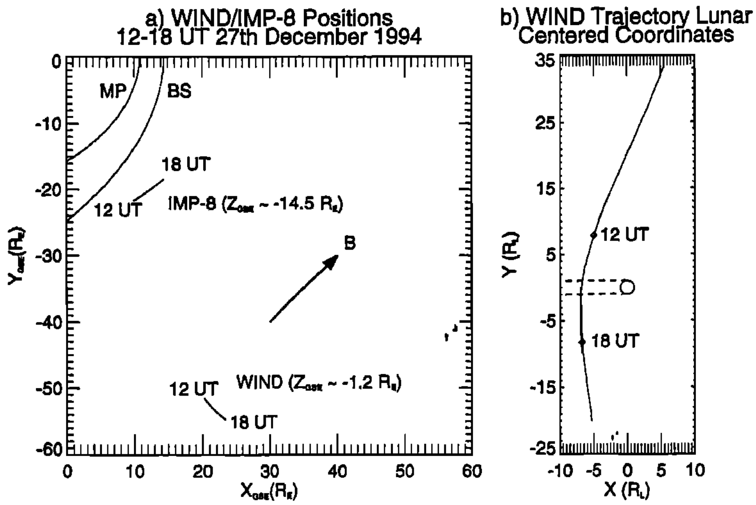

Figure 1. a) The trajectories of WIND and IMP-8 between 12 and 18 UT on 27th December 1994. Both spacecraft were in the solar wind in the same local time sector. Orthospiral IMF configuration meant neither spacecraft was connected to the bow shock (BS). b) The trajectory of WIND in a lunar-centric coordinate system. The spacecraft passes through the optical shadow of the moon at a downstream distance of 6.8 R_L.

Figure 2(b) shows WIND inboard magnetic field observations for the same time period, at 3 s resolution. The period that the spacecraft was in lunar optical shadow is bounded by the dashed lines at 1441 UT and 1523 UT. The data during this period have been corrected for errors in the spacecraft attitude due to loss of the spacecraft sun pulse during eclipse, using a method similar to that of Taylor et al., [1968]. We have also corrected for changes in the zero level offsets due to contamination arising from thermoelectric currents which occur when the spacecraft decouples from the solar thermal input during eclipse. Concentrating first on the bottom panel, we note a smooth signature consisting of a slight depression of |B| beginning ~25 min prior to eclipse, an enhancement during the shadow itself, and a less clear depression after the spacecraft re-enters sunlight. The field magnitude peaks at the shadow center at ~1 nT above the pre-event value of ~7 nT observed prior to ~1415 UT. The beginning of the slight preumbral depression in field magnitude at 1415 UT appears associated with a rotation of the field in the x-y plane. A reverse of this feature in the B_X and B_Y components appears in the outbound leg at ~1535 UT, but this does not appear to be associated with a significant depression in |B|. However, any post-eclipse signature may be obscured by the slight general increase in |B| between the pre- and post-encounter periods (e.g., compare |B| prior to 14 UT to that after 16 UT).

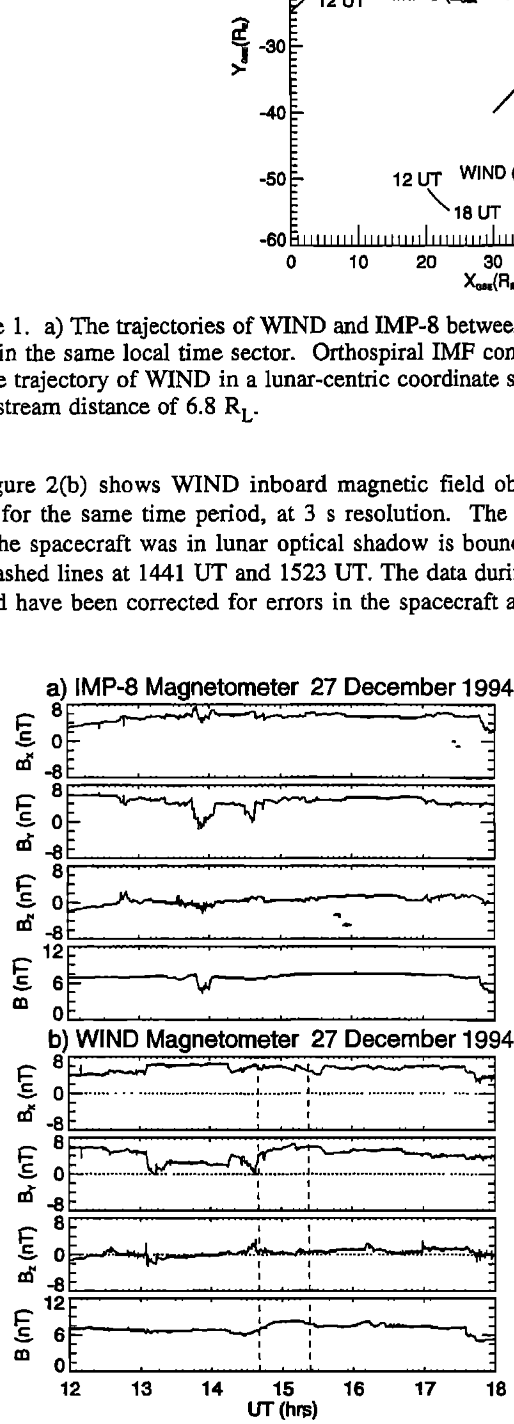

Figure 2. a) Imp-8 magnetic field observations for the period 12-18 UT on 27th December 1994. b) WIND magnetic field observations for the period 12-18 UT on 27th December 1994. The period in which the spacecraft was in eclipse is marked by the dashed vertical line. The enhancement in the field strength within the shadow and depression just outside are the magnetic signature of the lunar wake. Rotations in B_X and B_Y at 1415 UT and 1540 UT may be associated with the lunar mach cone.

To confirm these signatures are those of an observable wake at these distances from the moon, we need to make direct comparison with the IMP-8 measurements which provide the baseline IMF conditions during the encounter. During the period displayed in Figure 3, the solar wind speed (not shown) determined by the SWE instrument varied only slightly, being ~490 km s^{-1} around the time of the lunar encounter. The GSE y-component of the flow was ≤ 20 km s^{-1}, indicating a closely radial flow (deflections ≤ 2.5° towards dusk). Considering the spacecraft separation, we would expect features in the plane perpendicular to the solar wind flow to arrive at IMP-8 ~2.5 min after they were detected at WIND. The step-like feature evident in the WIND B_X and |B| at ~1740 UT appears consistent with this, appearing at IMP-8 ~2-3 min later. Similarly, features contained in the plane of the magnetic field and perpendicular to the ecliptic would be expected at IMP-8 ~7.5 min after their arrival at WIND. Finally, features in the plane perpendicular to the magnetic field should arrive at IMP-8 ~3.25 min before arriving at WIND. Unfortunately the two other features that the eye might naturally be drawn to do not seem consistent with any of these simple possibilities. The feature evident in the WIND B_Y component between 1305 and 1325 UT is similar to that at IMP-8 between 1337 and 1357 UT, a delay of ~32 min. The IMP-8 signature also has a depression in field strength. Unfortunately variance-analysis directions for these features are not well determined, and with the long delay it is difficult to draw conclusions about these signatures beyond their subjective similarities. Also, as mentioned above, the field orientation at this time probably connects IMP-8 to the bow shock. The second B_Y feature at IMP-8, between 1420 and 1440 UT appears similar to the WIND feature at 1430 and 1450 UT, analysis of which suggests the minimum variance direction is only 34° away from the x-direction. This appears inconsistent with a presumption that this is the same feature observed at both s/c, which requires the normal to the plane of the feature to be tilted sharply out of the ecliptic and/or towards perpendicular to the flow for the structure to be observed at IMP-8 prior to WIND. Thus none of the predominant features observed at each spacecraft can be confidently related to features observed at the other. However, except for the events at 1337-1357 UT and ~1740 UT, |B| at IMP-8 is very steady, as a result of the fortuitous situation of orthospiral fields disconnecting the s/c from the foreshock. Hence, despite the difficulty in obtaining a clear lag time between observations at each spacecraft, the WIND observations in and around the shadow are local (no similar signature at IMP-8) and can be ascribed to the lunar wake with some certainty.

To summarize the observations, it appears that WIND does detect a recognizable signature of the lunar wake at ~6.8 R_L, in contrast to previous results that suggested that the wake had disappeared beyond 4 R_L. The signature itself consists of an enhancement in the magnetic field strength in the optical shadow of the moon, and a depression in the field strength on at least the inbound pre-shadow region, and possibly on the outbound. Antisymmetric deflections in B_X and B_Y occur ~22 min prior to entry into the optical shadow and ~13 min after exit. No penumbral increases in |B| of the type occasionally observed by Explorer 35 were observed by WIND at this time.

3. Discussion

In this section we outline qualitative models to explain, to first order, the observations of the lunar magnetic field wake presented above and in previous Explorer 35 work. We assume that the |B| variations immediately around the lunar eclipse period can be described entirely by means of diamagnetic effects operating at the boundary of the plasma cavity formed by the moon standing in the solar wind flow. We assume the moon is a perfect insulator, absorber and neutralizer of the solar wind particles incident on its sunlight face. Magnetic flux tubes are assumed to pass unhindered through the moon without developing a significant draping component. These field lines emerge into the plasma cavity which gradually refills via field aligned diffusion. Density gradients within the wake support a system of diamagnetic currents on and around the surface of the cavity in the solar wind flow. These currents are driven by gradient anisotropy drifts of ions and electrons in opposite directions, and the moon itself must be considered part of the cavity to understand the closure of the currents.

Figure 3 presents a cartoon of the currents formed within the system and the consequence for the global magnetic field structure in and around the lunar wake. The top panel (a) shows a cut through the lunar system in the x-z plane, where the negative x-axis is assumed parallel to the solar wind flow and, for simplicity, the magnetic field has only a y-component, pointing out of the plane of the paper. Extension of the arguments to include a magnetic field component in the direction parallel/antiparallel to the solar wind flow is relatively straightforward. At the "dayside" of the moon, the particles are perfectly absorbed and neutralized, and a current is set up within 1 larmor radius of the surface due to gradient anisotropy drifts of ions (electrons) in the negative (positive) z-direction at the subsolar point. This current is continuous with similarly formed components along the flanks of the plasma shadow, in the positive (negative) x-direction on the "dawn" ("dusk") side. The current loop is closed by more diffuse currents across the plasma shadow some way downstream, these being associated with the more gradual density gradient anisotropies formed by the refilling of the plasma cavity.

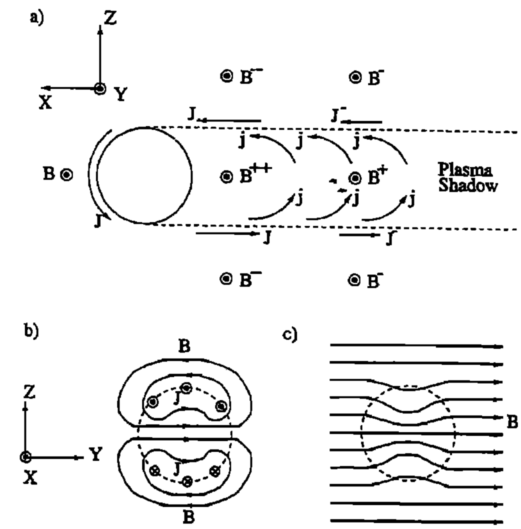

Figure 3. Sketch of the currents flowing around the lunar plasma cavity (upper panel) and the resulting changes in the magnetic field structure around the cavity (lower panel).

The lower panels of Figure 3 show cuts through the plasma cavity in the y-z plane. Panel (b) shows a schematic of the form of the magnetic field resulting from the diamagnetic currents described above if taken in isolation of the global system. This current system produces loops of magnetic field which are generally aligned parallel (antiparallel) to the positive y-axis inside (outside) the plasma cavity (bounded by the dashed circle). The magnetic field inside the cavity is also parallel to the undisturbed IMF, such that the combined local and global fields give a net magnetic field of the form shown in panel (c). The field strength inside (outside) the cavity is enhanced (reduced) with respect to the undisturbed IMF and there are slight deflections of the magnetic field direction within the system. This is the general nature of the WIND observations presented above, and those presented previously. The exact signature observed by a spacecraft depends on its trajectory relative to the wake and the background IMF direction. Also, the magnitude of the effect depends on distance downstream from the moon. Close to the moon, where little infilling of the plasma cavity can have occurred, the diamagnetic currents are well confined and strong, such that large, abrupt variations in field strength should be observed during passes across this region, as was the case in some Explorer 35 observations. Further downstream, where significant infilling may have taken place, the gradients in plasma density, and hence the diamagnetic currents, are more diffuse, such that smoother, less extreme variations might be anticipated, as is the case with the present WIND observations. Hence the lunar wake observations can be explained in terms of simple diamagnetic currents around the moon and the plasma cavity lying immediately downstream. A more rigorous treatment, including the second order effects of the gradient and curvature drift currents can be found in Ness et al., [1968].

The B_X and B_Y variations observed 22 min before and 13 min after the optical shadow can perhaps be explained in terms of the spacecraft crossing a rarefaction wave front (a lunar mach cone) [e.g. Whang and Ness, 1970]. This wave front is launched from the lunar surface as a result of the effective deflection of the solar wind flow *towards* the sun moon line, associated with the refilling of the plasma cavity. (Occasionally Explorer 35 observed a penumbral increase in |B|, which we do not see in this case. Siscoe et al., [1969] postulated that this signature corresponds to an additional, compressive wave front launched under conditions in which magnetic anomalies on the lunar surface are able to stand off the solar wind and thus deflect it *away* from the sun-moon line.) The timing of these variations suggest they occur at distances of $\sim 1R_L$ and $\sim 2/3\ R_L$ outside the edge of the optical shadow respectively. Since the spacecraft is $\sim 6.8\ R_L$ downstream, this implies the mach cone angles for the inbound and outbound passages are $\sim \tan^{-1}(1/6.8) = 8.4^o$ and $\sim \tan^{-1}(1/10.4) = 5.6^o$ respectively. These angles are not inconsistent with the average value of $\sim 8^o$ for 28 Explorer 35 crossings published by Whang and Ness [1970]. Moreover, we can check these angles for consistency with the solar wind parameters. The background field strength is ~7 nT, the electron density from the SWE instrument [Ogilvie et al., this issue] is $\sim 4\ cm^{-3}$, suggesting an Alfven speed $V_A \sim 76\ km\ s^{-1}$. The ion thermal velocity is $\sim 30\ km\ s^{-1}$, the electron temperature $\sim 3 \times 10^5$ K, implying a sound speed $V_S \sim 50\ km\ s^{-1}$. Fast mode waves travel along the field direction at the Alfven speed, and perpendicular to the field at a speed given by $V_F = \sqrt{(V_A^2 + V_S^2)} = 91\ km\ s^{-1}$. The angle ϕ_B between the field and the moon-sun line is 70° and 45° before and after encounter respectively. For the inbound crossing the furthest extent of the fast mode wavefront at a given point downstream is approximately determined by field aligned propagation. We thus estimate an inbound mach cone angle of ~8.7°. For the outbound crossing, the furthest extent of the wavefront is determined by propagation perpendicular to the field. We obtain a value for the outbound angle of ~8.6°.

Finally, we consider why a wake signature was observed by WIND at this distance from the moon. The signature may be expected to disappear once the solar wind has refilled the plasma cavity. The distance downstream that flux tubes convect before refilling is complete and the wake disappears depends on the ratio of the plasma thermal velocities to the solar wind flow speed, as well as the background field orientation. Since ions diffuse along the field into the cavity at a speed of order V_S, while convecting antisunward at the solar wind speed V_{SW}, the inflow angle of solar wind plasma (equivalent to a slow mode wavefront) is $\sim \tan^{-1}(V_S \sin \phi_B / V_{SW})$. In the case of the WIND observations, $V_S/V_{SW} \sim 1/10$ and $\phi_B \sim 45^o$. Hence we expect the plasma cavity and wake signatures to exist as far as 14 R_L downstream. The plasma cavity will be about half filled at 6.8 R_L downstream, the WIND traversal distance.

4. Summary

We have presented observations from the magnetic field instrument on WIND for the period surrounding the close approach to the moon in December 1994. WIND passed through the optical shadow and plasma cavityof the moon at a downstream distance of 6.8 R_L. A distinct signature is observed in |B| which is centered on the optical shadow. This is despite the fact that, on the basis of Explorer 35 results, no wake signatures are expected at this distance. The lunar wake signature can be interpreted in terms of diamagnetic currents flowing on the surface of the plasma cavity producing an enhancement to the field strength inside the cavity, and a reduction just outside. The boundaries of the reduction in field strength appear to be associated with a small rotation in B_X and B_Y, and are located close to the expected position of the lunar mach cone. Comparison of solar wind thermal and flow speeds for this case suggest that a plasma cavity and wake should exist to a distance of ~14 R_L downstream.

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