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Observations of the lunar plasma wake from the WIND spacecraft on December 27, 1994

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Abstract. On December 27, 1994, the WIND spacecraft crossed the lunar wake at a distance of 6.5 lunar radii (R_L) behind the moon. The observations made were the first employing modern instruments and a high data rate. The SWE plasma instrument on WIND observed new aspects of the interaction between the solar wind and unmagnetized dielectric bodies. The plasma density decreased exponentially from the periphery of the wake towards its center as predicted by simple theory. Behind the moon two distinct cold ion beams were observed refilling the lunar cavity. The ions were accelerated along the direction of the magnetic field by an electric field of the order 2×10^{-4} volts/m. The region of plasma depletion was observed to extend beyond the light shadow, consistent with a rarefaction wave moving out from the wake into the undisturbed solar wind.

Introduction

The first orbital measurements of the plasma and magnetic field signatures of the moon were made between 1967 and 1972 by Explorer 35 and by the Apollo sub-satellites (see Schubert and Lichtenstein, [1974] and many references therein). They showed conclusively that the moon behaves as a non-conducting dielectric sphere that absorbs the solar wind falling upon its surface. Minor magnetic disturbances close to the limb were thought to result from the abrupt interruption in the flow [Krall and Tidman, 1969; Ness and Schatten, 1969] or from local weakly magnetized regions in the moon [Sonett and Mihalov, 1972; Ness and Whang, 1972].

Numerous close flybys have shown the moon to possess a plasma wake, with a density decrease on the anti-sunward side. This paper presents the first high resolution ion and electron measurements in and near the wake of the moon made with modern instrumentation [Lepping et al., 1995; Ogilvie et al., 1995].

The WIND spacecraft is destined for a halo orbit surrounding the forward Lagrangian point, some 200 Earth radii upstream of Earth in the solar wind. Prior to its halo orbit insertion, the spacecraft follows double lunar swing-by orbits which require that it approach close to the moon for gravity-assisted orbit changes [Acuna et al., 1995]. During these approaches the spacecraft passes behind the moon. We report in this paper observations on December 27, 1994 at a downstream distance of 6.5 lunar radii, R_L ($R_L \approx 1738$ km). Earlier wake crossings by other spacecraft discussed by Schubert and Lichtenstein [1974] occurred at smaller distances ($\approx 2R_L$) from the moon.

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Instrumentation and Data

The SWE plasma instrument on the WIND spacecraft has been described in detail by Ogilvie et al. [1995]. In brief, it consists of a Faraday cup subsystem, which measures the vector velocity, number density, and temperature of proton and helium components of the solar wind, together with a tri-axial ion and electron spectrometer (VEIS), which performs 3-D measurements of electrons, and in some modes, of the subsonic ion population. In this paper we discuss observations of the complete 3-D electron velocity distribution function made in one 3 second spacecraft rotation and repeated every 6s by the VEIS in its electron mode. The electron distribution function is obtained by measuring the electron energy spectrum, consisting of 16 energies, 6 times per rotation for each of the 6 detectors. The velocity distributions are thus approximated by 576 points. Moments calculated from these distributions give a time series, at 6s. spacing, for bulk flow velocity components, density, temperature, temperature anisotropy, etc. For the results reported here, each measurement of the ion velocity distribution requires about 30s to accumulate, with measurements repeated every 87s (29 spacecraft spins).

The early trajectory of the WIND spacecraft, following its launch on November 1, 1994 until the end of January 1995, consisted of four phasing orbits about the Earth with apogees beyond the lunar orbit, after which the spacecraft passed across the lunar wake at a distance of 6.5 lunar radii, R_L from the center of the moon on December 27, 1994.

Observations and Interpretation

Shown in Figure 1 are some of the plasma parameters derived from the measurements made by SWE as well as the magnetic field magnitude and longitude from measurements made by the WIND MFI instrument (R. P. Lepping principal investigator) as WIND crossed the lunar wake. The ion and electron number densities both show reductions clearly associated with the moon. The minimum densities measured are about 20 times lower than the solar wind densities measured just before entry into the wake. While the electron temperature increases in the wake by a factor of about four, the ion temperature remains fairly constant. The magnetic field strength rose in the wake as reported previously [Ness et al. 1968; 1969]. Within the region where the plasma is significantly depleted, two distinct proton distributions are simultaneously detected. Each appears as a cold beam, narrow in velocity space, one

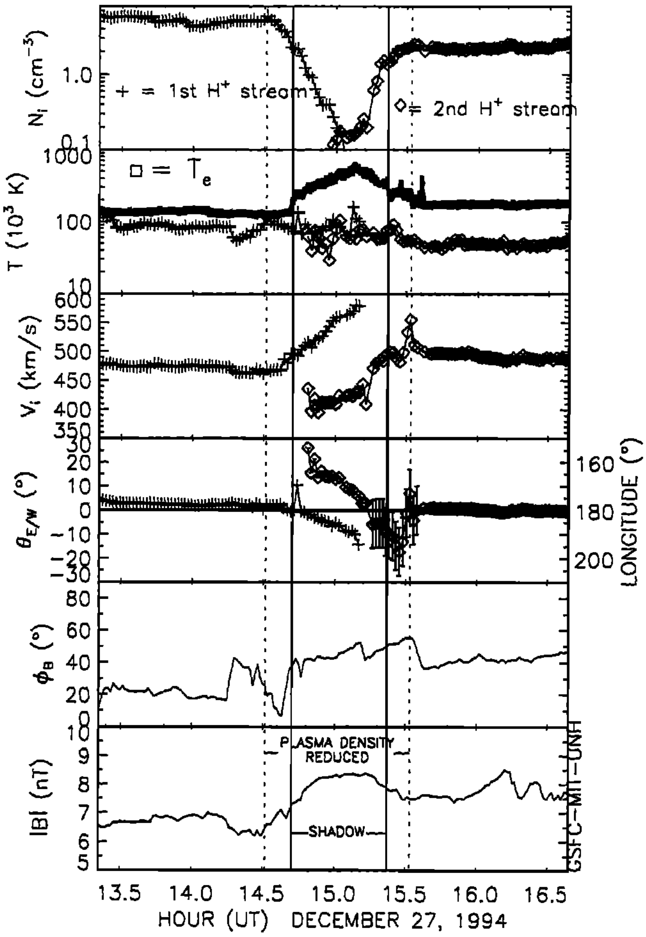

Figure 1. Plasma and magnetic field parameters for lunar wake crossing. "+" indicates entry-side proton parameters, diamonds indicate exit-side parameters. From the top panel to the bottom: proton density, proton and electron temperatures, proton speed, plasma east/west flow angle (>0 is from west of sun), the longitude of **B** (0° is sunward), and |**B**|. On right, flow angle shown with longitude scale to allow comparison with **B**. Vertical lines mark the times bounding the light shadow and the region in which plasma density is reduced from ambient solar wind values. Larger uncertainty in east/west angle between 15:15 and 15:37 UT caused by the cumulative effect of satellite spin rate change in the shadow: an angle offset developed between the desired optimal and the actual Faraday cup pointing directions, resulting in a less accurate flow angle determination during that time interval.

convecting with a speed slightly faster than the ambient solar wind, and the other convecting slightly slower.

The appearance of inter-penetrating proton beams in the lunar wake is illustrated in Figure 2, which presents a time sequence showing observed current (which is proportional to particle flux) versus energy/charge scans from a SWE Faraday cup. The detector is pointing in roughly the same near-sunward direction for each scan. The upper (earliest) panel shows a large peak associated with solar wind protons, and a smaller peak at higher energy/charge due to alpha particles. In succeeding panels, the alpha signal disappears, and solar wind proton peak becomes lower in amplitude while moving to higher energies. By the time of the fourth panel (14:58 UT), a second proton signal at lower energy/charge is clearly present. As time proceeds, the first proton signal diminishes, while the second proton peak grows in amplitude, moves to higher energy/charge, and appears to evolve into what is the unperturbed solar wind proton peak by the time of the last panel, when WIND has moved beyond the wake.

The measurements show that ambient solar wind conditions changed somewhat during WIND's lunar encounter: when WIND emerged from the wake, the solar wind speed was higher and the density lower (see Figure 1) and the alpha particle flux was much lower (see Figure 2). Thus, one must keep in mind that the wake may have undergone some slight temporal changes due to solar wind variations during the spacecraft crossing. Nonetheless, these observations show important overall features that are most probably characteristic of a steady-state wake structure.

The moon absorbs solar wind, carving out a plasma cavity in the downstream wake; the solar wind acts to refill that cavity. The physical processes and phenomena involved in the expansion of plasma into a vacuum are described in the review by Samir et al. [1983] and references therein. Initially, because they are lighter, more mobile, and have a greater thermal speed, the electrons attempt to fill in ahead of the ions. The resulting ambipolar electric field accelerates the ions into the cavity. Because the solar wind is collisionless, particles filling in the plasma cavity are restricted to move only along magnetic field lines. The ambipolar electric field and the ion acceleration resulting from that field are directed along the magnetic field lines. Thus, the plasma does not fill the wake from all directions at once, but instead fills it from two opposite "sides" whose locations are determined by the magnetic field orientation. The variations of the plasma parameters observed as WIND crossed the lunar wake are similar in character to the one-dimensional analytical solutions for the expansion of plasma into vacuum discussed by Samir et al. [1983]. Because the direction of the filling motion is restricted by the field, a model which is one-dimensional is nonetheless quite useful.

The principal characteristics of plasma expansion into vacuum are demonstrated in the solution for the simplest case: a sin-

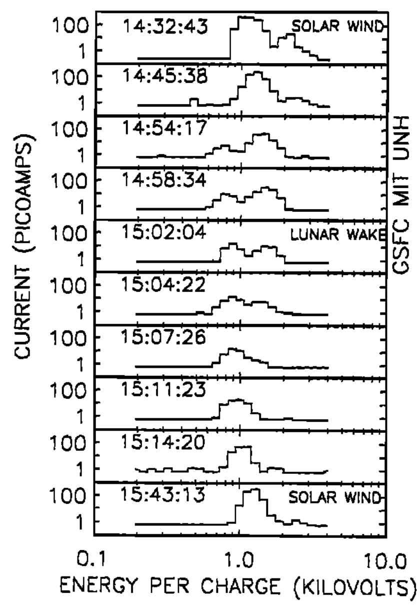

Figure 2. Time sequence of Faraday cup current versus energy/charge spectra as WIND crossed the wake. At 14:32 UT, signal peaks are due to solar wind H^+ and H_e^{++}, with (density H_e^{++})/(density H^+) = 0.025. At 15:02 UT there are two H^+ signal peaks. At 15:43 UT, peak signals due to solar wind H^+ and a small flux of H_e^{++}.

gle ion species and Maxwellian electrons. Given a plasma at time $t = 0$ of density N_o in the region $x < 0$, and a vacuum in the region $x > 0$, the solutions for the ion and electron densities, N_i and N_e, and for the ion speed V_i are as follows:

$$N_e = N_i = N_o \exp[-((x/S_o t)+1)] \tag{1}$$

$$V_i = S_o((x/S_o t)+1) \tag{2}$$

where S_o is the sound speed, approximated here as $\sqrt{T_e/M_i}$; T_e is the electron temperature and M_i is the ion mass. The solutions are valid for times $t > 0$ and $x > -S_o t$.

These equations describe several important features. First, a region of decreased density propagates back into the plasma as a rarefaction wave with speed S_o (Equation 1). Second, at any fixed time $t = t_o > 0$, the density decreases exponentially as a function of $x + S_o t$, the distance from the rarefaction wave front at $x = -S_o t$ (Equation 1), while the ion filling-in speed V_i increases linearly with distance from the wave front (Equation 2). The region of decreased plasma density is referred to as the expansion region. The exponential decrease in density, the rarefaction wave, and the linearly increasing ion speed are all evident in the WIND lunar wake measurements, as will be explained below.

As the solar wind encounters and flows past the moon, plasma begins to expand into the lunar wake cavity, while at the same time continuing to convect away from the sun. There is a rough correspondence between the distance downstream from the moon, and variable t in the above equations - the time for plasma to expand into the wake. Moreover, a spacecraft which crosses the wake at a fixed distance downstream, is scanning the plasma as a function of the position variable x, while the expansion time t is kept fixed. WIND crossed the wake at a distance of $\approx 6.5\ R_L$ from the moon, while the solar wind flow speed was ≈ 475 km/s, giving a fixed expansion time of ≈ 24s. It follows that there is a correspondence between the measurement time shown in Figure 1, and the variable x in Equations 1 and 2, so the variation of the measured density and speed versus time can be compared to the dependence on x of N_i and V_i in Equations 1 and 2. Since the expansion is restricted to occur along the magnetic field **B**, a correction is made to take into account the fact that **B** makes an angle of about 45° to the solar wind flow direction.

As WIND enters the wake, the log of the density decreases approximately linearly (see Figure 1), in agreement with the exponential behavior of Equation 1. The density decrease matches Equation 1 reasonably well for $S_o \approx 40$ km/s, while $\sqrt{T_e/M_i}$ using the measured T_e is somewhat less (35 km/s). The density recovery on exit from the wake is less smooth, and does not follow an exponential dependence so well over such a large spatial distance, possibly because of solar wind temporal changes during lunar wake crossing. If only the final portion of the recovery is considered, between about 15:22 and 15:32, the density variation appears somewhat less steep than that seen on wake entry, consistent with a somewhat higher sound speed at that time. $\sqrt{T_e/M_i}$ at wake exit was 40 km/s, a value greater than that seen at entry.

Evidence for a rarefaction wave is found by comparing the time period during which the density was below ambient solar wind values, to the time period for which WIND was within the light shadow of the moon. Figure 1 shows the times of entry and exit for the plasma depletion region, and for the light shadow; the density depleted region is larger than the geometric shadow. These four times can be used to determine the angle between the rarefaction wave and the light shadow (the sunward direction) on each side of the wake. As WIND entered the lunar wake, that angle was about 5° to the sunward direction, while on the exit side the angle was about 4.4°. At the time of entry the solar wind was flowing from a direction approximately 2.5° to the west of the solar direction (in a moon-fixed reference frame). Correcting for the solar wind flow, the angle of the rarefaction wave to the aberrated wake axis is about 2.5°, which is somewhat less than the 3.1° expected based on $S_o \approx \sqrt{T_e/M_i}$. At the time of exit, no angle correction is required; the solar wind flow direction was nearly anti-sunward. The observed exit-side wave angle is somewhat larger than the 3.1° expected from $\sqrt{T_e/M_i}$ on that side. Taking into account any aberration due to the solar wind flow direction, we find on both sides rarefactions consistent with waves propagating outward from the lunar wake at roughly the expected angles.

Next we examine the velocity profiles for the two proton streams: the first stream which is related to solar wind filling in the wake from the entry side, and the second stream which is related to solar wind filling in the wake from the exit side. The speeds and flow angles for each are shown in Figure 1. The speed of the first stream increases linearly as WIND moves into the expansion region. From Equation 2 we see that by knowing the rate of change of V_i with x one can estimate the expansion time t: $\Delta V_i/\Delta x = 1/t$. Determining the rate of change of the speed profile for the first proton stream we obtain an expansion time of 22s, a value similar to our estimate given above. The

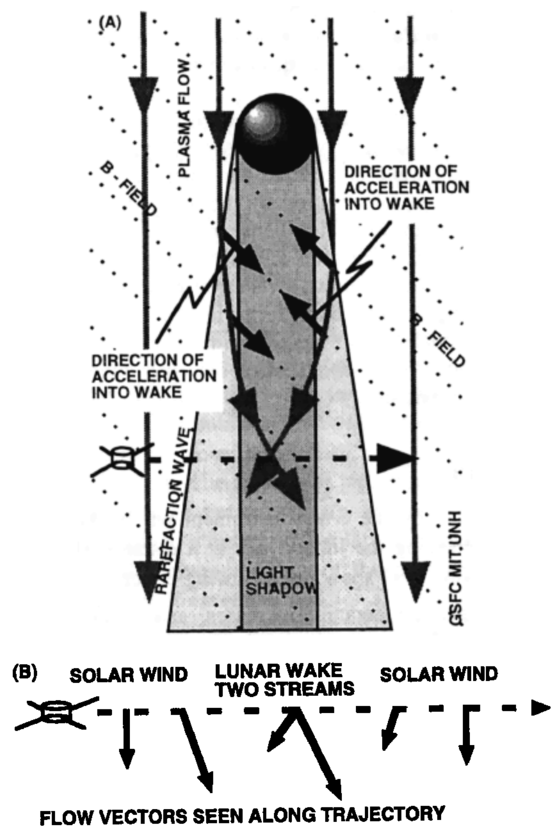

Figure 3. (a) The schematic representation of lunar wake on Dec 27, 1994. Region of plasma depletion propagates out from wake as a rarefaction wave. Streamlines of plasma flow are shown entering the wake from the satellite entry and exit side. The ion acceleration is directed along magnetic field lines as shown; flow speeds up on the entry side and slows down on the exit side. **(b)** Illustrative schematic to show behavior of the ion flow vectors measured as Wind crossed the wake. Does not accurately show the actual changes in relative magnitude or direction of vectors.

acceleration of ions into the wake occurs along **B**, which is at an angle of about 45° to the undisturbed solar wind flow direction (see Figure 3). This field angle requires the ion acceleration to have a component parallel to the initial solar wind flow, causing ions to speed up. The acceleration deflects the flow into the wake from the entry side.

In the middle of the wake, the second stream is slower than that from the entry side, and it increases in speed rather than decreases as WIND moves away from the middle of the wake (see Figure 1)! The velocity of the second stream can be understood as follows. As on the entry side, the ion acceleration into the wake must occur along **B** on the exit side. However, because the field is 45° to the flow, the acceleration on the exit side has a component anti-parallel to the initial solar wind flow, causing the ions to slow down as they move into the wake (see Figure 3).

The description presented of ions accelerated into the wake electrostatically is consistent with the fact that the ion temperature remains steady across the wake. The observed velocity change from solar wind to wake center corresponds to an electrostatic potential change of about 400 volts over an expansion distance on the order of 2000 km. From these rough figures, we get a crude estimate of 2×10^{-4} volts/m for the time-averaged electric field acting on the ions. The oblique angle of B causes the wake to refill asymmetrically. In the wake center, where two streams of different velocity are seen simultaneously, the velocity difference ($\mathbf{V}_1-\mathbf{V}_2$) between the two must lie along **B**. In order to verify that alignment, the cosine of the angle between ($\mathbf{V}_1-\mathbf{V}_2$) and **B** was determined, and found to be ≥0.96 for every case.

In an accompanying paper by Farrell et al. [1996] in this issue, the presence of ULF waves observed by the magnetometer just outside the wake is reported and interpreted. These waves coincided with the observation by the VEIS of counter streaming electrons with velocities between 5×10^3 and 2×10^4 km/s. Though no effects were seen in the moment plots, the electron distribution functions, shown by Farrell et al. [1996], were noticeably distorted from their form in the nearby solar wind. The bi-directional flow of electrons in this period is easily visible on the entry side, and though less pronounced, was also present on the exit side.

Conclusions

Observations by the SWE instrument on the WIND spacecraft while crossing the lunar wake at a distance of 6.5 R_L on December 27th, 1994 show the following effects:

1. The electron temperature increases, and as predicted by a simple theory, the density decreases exponentially as the spacecraft moves across the wake from its edge towards its center.

2. An ambipolar electric field set up by the subsonic solar wind electrons accelerates the ions towards the center of the wake along the magnetic field. The electric field is of the order 2×10^{-4} volts/m. This acceleration has the effect of increasing the total velocity of the plasma from the entrance side of the wake, and reducing the total velocity of the plasma from the exit side. We thus observed two ion streams, one with velocity greater and one with velocity less, than the solar wind. The temperature of the ions remained unchanged, consistent with an electrostatic acceleration of the ions.

3. The region of plasma depletion extends beyond the lunar light shadow, consistent with a rarefaction wave moving out from the wake into the undisturbed solar wind. The entry-side and exit-side waves were slightly differently directed with respect to the wake because of changes in the solar wind flow direction and sound speed during the wake traversal.

4. ULF waves were observed adjacent to the entrance to the wake. Although no effects were noticed in the plot of the electron moments, bi-directional electron flow was readily apparent in the velocity distribution function plots. Bi-directional flow also appeared on the exit side of the wake, but to a less pronounced extent.

Several lunar encounters will occur during the remainder of the WIND mission. We intend to use data from all of these to perform a more extensive study of the lunar wake, with the intent of determining the variation of the wake signature with distance from the moon.

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