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Solar wind interaction with lunar crustal magnetic anomalies

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Abstract

Using Lunar Prospector data, we review the magnetic field and electron signatures of solar wind interaction with lunar crustal magnetic sources. Magnetic field amplifications, too large to represent direct measurements of crustal fields, appear in the solar wind over strong crustal sources, with the chance of observing these amplifications depending on upstream solar wind parameters. We often observe increases in low-energy ($\lesssim$100 eV) electron energy fluxes simultaneously with large magnetic field amplifications, consistent with an increase in plasma density across a shock surface. We also often observe low frequency wave activity in the magnetic field data (both broadband turbulence and monochromatic waves), often associated with electron energization, sometimes up to keV energies. Electron energization appears to be correlated more closely with wave activity than with magnetic amplifications. Detailed studies of the interaction region will be necessary in order to understand the physics of the Moon–solar wind interaction. At present, the Moon represents the only natural laboratory available to us to study solar wind interaction with small-scale crustal magnetic fields, though simulation results and theoretical work can also help us understand the physical processes at work.

Keywords: Moon; Magnetosphere; Crustal magnetism

1. Introduction

1.1. The lunar plasma environment

The present-day Moon has a minimal atmosphere and no global magnetic field, so when the Moon's orbit takes it outside of the terrestrial magnetosphere (~75% of the time), its surface is directly exposed to the solar wind. To first order, solar wind magnetic fields pass relatively unimpeded through the Moon, while charged particles impact the surface and are absorbed, leading to the formation of the lunar plasma wake (Halekas et al., 2005). However, regions of remanent crustal magnetization ranging in size from a few km or less to hundreds of km cover portions of the lunar surface, with magnetic fields at 20–30 km altitude as high as 30 nT, and surface fields as high as several hundred nT (Halekas et al., 2001; Hood et al., 2001). Crustal magnetic fields perturb the basic Moon–solar wind interaction, producing magnetic amplifications variously termed limb shocks, limb compressions, or lunar external magnetic enhancements (LEMEs) (Ness et al., 1968; Colburn et al., 1971; Russell and Lichtenstein, 1975; Lin et al., 1998; Halekas et al., 2006a). These features are only sporadically observed, with solar wind conditions apparently playing a role in their formation and extent.

1.2. Solar wind interaction with localized magnetic fields: solar system context

Localized crustal magnetic fields are also present on other solar system bodies, with a range of magnetic field strengths and scale sizes. However, crustal fields at Mars and Earth are protected from direct incidence of the unshocked solar wind by planetary atmospheres and, in the case of the Earth, a global dynamo field. Meanwhile, the existence of crustal sources on asteroids remains controversial. Magnetic perturbations near the asteroids Gaspra and Ida have been reported (Wang et al., 1995), but simulation results disagree over whether these features indicate the

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presence of asteroidal magnetic fields (Wang and Kivelson, 1996; Omidi et al., 2002). Meanwhile, a direct observation of an asteroidal magnetic field was claimed for the asteroid Braille (Richter et al., 2001), but only one such observation exists. At present, therefore, the Moon may represent the only available laboratory for investigating solar wind interaction with small-scale crustal magnetic fields.

1.3. Solar wind interaction with localized magnetic fields: simulations

Interest in solar wind interaction with small-scale magnetic fields has been spurred by the observations at Gaspra and Ida (Wang et al., 1995), which some authors interpreted as "whistler wakes" generated by electrons interacting with magnetic obstacles too small to perturb the fluid flow of the solar wind and produce ion-scale waves or shocks. As a result, a number of authors have performed detailed theoretical calculations and simulations of solar wind interaction with small magnetic obstacles (Gurnett, 1995; Wang and Kivelson, 1996; Omidi et al., 2002). These results indicate that phase-standing whistler wakes could be generated by solar wind interaction with electron-scale magnetic obstacles, producing magnetic perturbations (probably circularly polarized) which extend upstream from the obstacle (due to the high group velocity of whistlers).

As the scale of magnetic obstacles compared to the solar wind proton inertial length increases, simulations show that the interaction should change from a phase-standing whistler wake, to a magnetosonic wake, to a shock, and finally to a fully magnetosphere-like interaction (Omidi et al., 2002). For the lunar case (Halekas et al., 2006a), where the altitude at which crustal magnetic field obstacles can balance the solar wind pressure should usually be relatively small ($\lesssim$10 km) compared to the proton inertial length (on the order of 100 km), these simulations predict that a magnetosonic wake might form, but that a fully formed shock is unlikely. However, this work utilized simulations with a single dipole, and other simulations show that the decidedly non-dipolar character of lunar crustal sources should increase the efficiency of their interaction with the solar wind (Harnett and Winglee, 2003). Furthermore, recent theoretical work suggests that strong magnetic perturbations and/or shock waves can sometimes be created (especially for low Mach numbers) even in cases where the solar wind is not completely reflected from crustal magnetic anomalies (Borisov and Mall, 2003). It is therefore likely that a range of different modes of interaction may be observed at the Moon, depending on the strength of specific crustal sources and solar wind parameters.

2. Lunar external magnetic enhancements

2.1. LEME morphology

Fig. 1 shows an example of a large LEME, measured by Lunar Prospector (LP), and discussed in detail in Lin et al. (1998). This LEME is located above (and slightly downstream from) the strongest lunar crustal sources, on the southern far side. As detailed in previous papers (Lin et al., 1998; Halekas et al., 2006a), before and after LEMEs, magnetic field directions and magnitudes measured at the Moon by LP are consistent with solar wind fields measured upstream by Wind (when time-shifted appropriately in order to take into account the solar wind convection time). Meanwhile, during LEMEs, magnetic field rotations are usually moderate ($\lesssim$30°), consistent with solar wind magnetic field draping rather than direct measurement of crustal fields. During LEMEs, the magnetic field magnitude can increase by a significant factor (in this case, almost three). The magnetic field amplifications observed cannot be explained by direct measurement of crustal magnetic fields. In this case, for instance, the altitude is ~100 km, where crustal fields reach a maximum of only a few nT, while the LEME field is over 30 nT.

During the time period when we observe this LEME, the average solar wind magnetic field is 14 nT, the velocity is 363 km/s, the dynamic pressure is 2.6 nPa, and the magnetosonic Mach number is ~3.4. A magnetic field of ~80 nT should be required to balance this dynamic pressure, and this value can only be reached relatively near the surface ($\lesssim$10 km) even above the strongest crustal sources. Meanwhile, the solar wind proton inertial length is ~67 km, implying that the formation of a shock is unli-

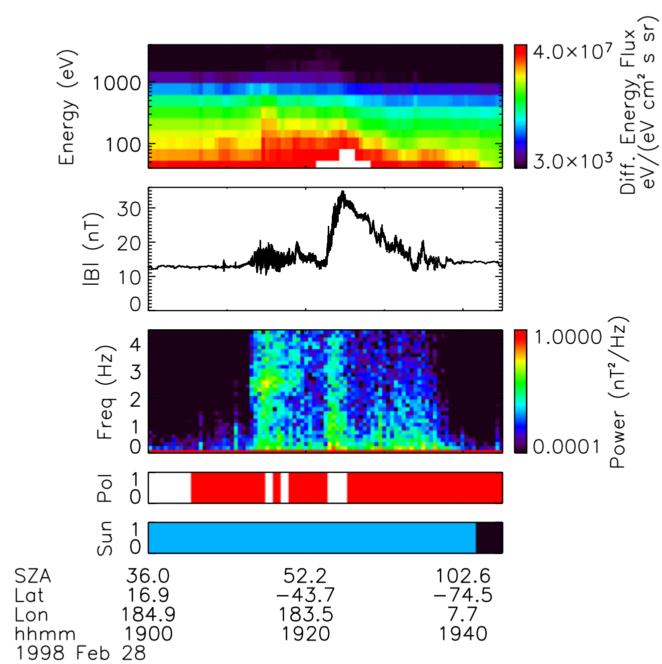

Fig. 1. LEME measured on February 28, 1998. Panels show electron differential energy flux, magnetic field magnitude, FFT of magnetic field, bar showing whether a straight line magnetic field trace from the spacecraft intersects the surface (red, positive polarity; black, negative), and bar showing sun (blue) or shadow (black). Labels below plot indicate solar zenith angle and planetary longitude and latitude of spacecraft. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

kely. Nonetheless, the significant magnetic amplification we observe suggests that a fully formed shock may actually exist.

For the orbit segment shown in Fig. 1, we progress from upstream at the left, to downstream at the right. Far upstream, we observe relatively quiet electron distributions and magnetic fields. Slightly upstream from the LEME (at ~19:10 UT), we first see perturbations in both the electron distribution and the magnetic field, with significant electron energization and broadband magnetic field turbulence beginning at ~19:13. Interestingly, we observe the strongest wave turbulence and electron energization upstream from the LEME itself. At ~19:24, we observe a sharp increase in magnetic field magnitude (the LEME), and a simultaneous significant increase in low-energy electron energy fluxes – enough to saturate the LP electron reflectometer (ER). Both of these signatures are consistent with the presence of a shock. Meanwhile, broadband magnetic turbulence persists until ~19:40. During most of the interval, a straight line magnetic field trace from LP intersects the surface, indicating possible magnetic connection to the strongly magnetized region lying below the LP spacecraft. At ~19:42, LP passes into the shadow of the Moon and the lunar plasma wake.

2.2. LEME distribution and solar wind control

Previous investigations indicate that LEMEs are clearly associated with lunar crustal magnetic sources, occurring either directly over them or somewhat downstream (Russell and Lichtenstein, 1975; Halekas et al., 2006a). LEMEs are more often observed by spacecraft near the lunar limb (thus the terminology of "limb shocks" and "limb compressions"). Two factors likely combine to explain this observational bias. First, the average solar wind dynamic pressure on a crustal source is minimized near the limb, due to geometrical considerations, which ensure less direct solar wind incidence on the surface at high solar zenith angle (SZA) and therefore allow LEMEs to more easily extend to spacecraft altitude. Second, at high SZA a compressional disturbance generated at the lunar surface and convected downstream from its source (forming a magnetosonic wake) can sometimes be observed at spacecraft altitude. On the other hand, at lower SZA, for us to observe a disturbance at spacecraft altitude it must extend well upstream from regions where magnetosonic waves can propagate, requiring waves to steepen and form a coherent shock that extends upstream from its source (Lin et al., 1998). Simulation results indicate that a larger magnetic source (relative to the solar wind proton inertial length) is required to form a shock than to form a magnetosonic wake (Omidi et al., 2002), ensuring that this interaction should be less commonly observed. Even smaller magnetic sources can likely form phase-standing whistler wakes, but these should not produce the large coherent magnetic enhancements seen in many LEMEs.

Changes in solar wind conditions should affect several of the factors which influence the likelihood of observing an LEME. Lower dynamic pressure and Mach number should allow more LEMEs to be observed at spacecraft altitude, while lower proton inertial lengths and proton gyroradii should allow LEMEs to more easily form over a given crustal magnetic source. Observational results have proven roughly consistent with these expectations. LP observations of 990 LEMEs demonstrate that LEME observations, especially at low SZA, are most likely during time periods with low solar wind magnetosonic Mach number and proton temperature, low beta, and low gyroradius (Halekas et al., 2006a). All of these factors increase the likelihood that a fluid description of solar wind interaction with crustal sources remains appropriate, likely a necessary precondition for the formation of a shock.

3. Electron energization

3.1. Electron energization and compression during LEMEs

Fig. 1 demonstrates that, for this example, enhanced electron fluxes representing energization up to ~1 keV begin (and are most significant) slightly upstream from the LEME itself. We commonly observe electron energization associated with large LEMEs, but it does not always precede the main LEME in this manner. As discussed in Lin et al. (1998), the relative timing may depend largely on geometric considerations, and the specifics of how LP's orbit intersects the surface of the interaction region. In any case, for most LEMEs electron energization corresponds most closely with wave activity in the magnetic field, suggesting an association between electron energization and wave processes, rather than with the magnetic amplification itself.

For the orbit in Fig. 1, the electron energy flux below ~100 eV increases dramatically during the LEME. This is a general feature of most large LEMEs, and likely indicates an increase in electron density simultaneously with the magnetic field amplification (the lowest energy measured by the LPER is ~40 eV, making a direct measurement of the total electron density impossible), as we would expect for a shock-like interaction where a fluid approximation remains valid.

3.2. LEMEs without electron energization

Not all LEMEs are associated with significant electron energization, as demonstrated in Fig. 2. This LEME lies close to the south polar regions, where several moderate crustal magnetic sources occasionally produce LEMEs. For the orbit segment shown in Fig. 2, we proceed from downstream at the left to upstream at the right, the opposite sequence from that in Fig. 1. Unlike for the LEME shown in Fig. 1, we find no clear electron energization signatures associated with this LEME. We do, however, observe significant wave activity, extending well upstream

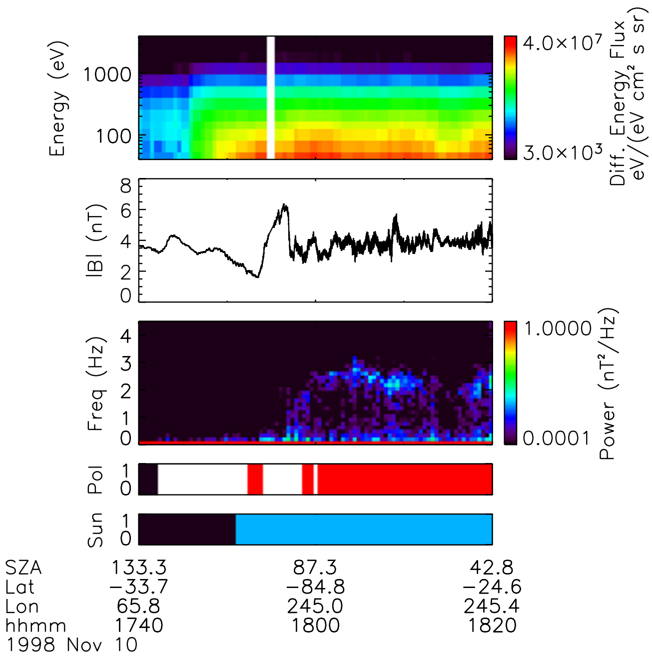

Fig. 2. LEME measured on November 10, 1998. Panels are the same as for Fig. 1.

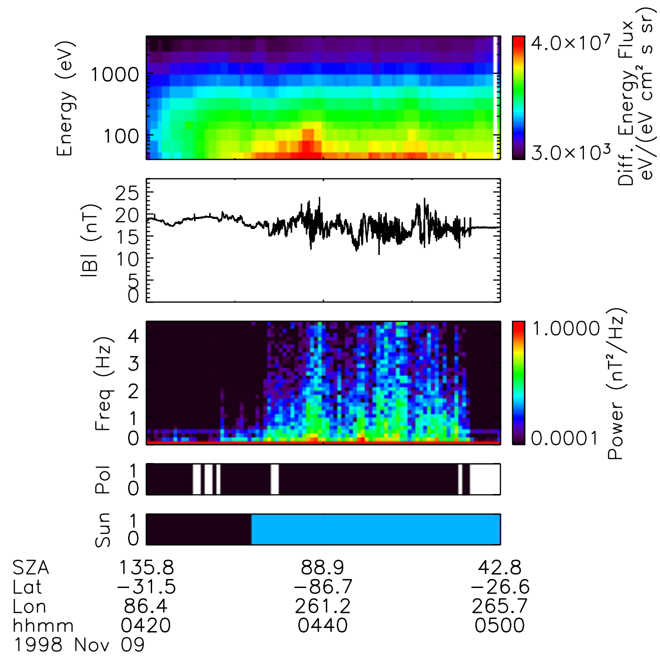

Fig. 3. Orbit on November 09, 1998 without an LEME. Panels are the same as for Fig. 1. Magnetic field fluctuations at 0.4 Hz throughout this time period are likely a spacecraft artifact corresponding to twice the spacecraft spin frequency.

from the LEME. This wave activity, unlike the primarily broadband turbulence in Fig. 1, consists mainly of ∼2–3 Hz monochromatic left-handed circularly polarized waves (most likely Doppler-shifted intrinsically right-handed whistler-mode waves, as described in Halekas et al., 2006b). We do observe some changes in the electron spectra associated with these waves, but they are not as significant as those in Fig. 1, and are not clearly associated with the LEME itself. We find no significant increase in low-energy electrons during this small LEME, though such an increase could still occur at energies below the lowest energy measured by the ER (∼40 eV).

3.3. Electron energization without LEMEs

On the other hand, electron energization can occur in the absence of an LEME at spacecraft altitude, as demonstrated in Fig. 3. This orbit occurred on the day before that shown in Fig. 2, and lies over a similar region of the lunar surface. The solar wind had a higher speed (495 km/s, as compared to 405 km/s), magnetic field (18.5 nT, as compared to 3.9 nT) and dynamic pressure (4.2 nPa, as compared to 1.8 nPa) during this orbit than during that in Fig. 2. All of these factors make it more likely that any LEME will not extend above spacecraft altitude, therefore potentially explaining why we do not observe an LEME on this orbit. The solar wind magnetosonic Mach number is lower (∼3.8, as compared to ∼6.6), but apparently not low enough to have an effect. However, despite the absence of an LEME at spacecraft altitude, we do still observe significant broadband magnetic turbulence, and some electron energization (up to a few hundred eV), peaking at ∼04:38 and ∼04:50, nearly simultaneously with the periods of strongest wave activity. This wave activity and electron energization could be generated below the spacecraft altitude, so it could still potentially be associated with an LEME lying below the LP orbit.

4. Waves

4.1. Broadband turbulence

Regardless of the presence or absence of an LEME at spacecraft altitude, we often observe broadband magnetic field turbulence (like that shown in Figs. 1 and 3) whenever a straight line trace in the direction of the measured magnetic field indicates that the field line passing by the LP spacecraft likely intersects the surface (especially over regions with significant crustal fields). It seems likely that this broadband turbulence is produced by solar wind plasma interacting with crustal sources near the surface. It is not clear whether the presence of a shock is required to generate the magnetic turbulence, since though we often observe turbulence in the absence of an LEME signature at spacecraft altitude, the shock surface could simply lie below spacecraft altitude at those times.

4.2. Monochromatic waves

Though more rare than broadband magnetic turbulence, we also sometimes observe monochromatic low frequency waves in the magnetic field, as shown in Fig. 2. As discussed in Halekas et al. (2006b) we observe these monochromatic waves at frequencies of ~0.5 to 3 Hz near the Moon, with monochromatic waves observed on ~6.6% of LP orbits in the solar wind. About a third of them occur on orbits with clear LEME signatures (though, as for broadband turbulence, LEMEs could simply lie below spacecraft altitude for other observations), and most are clearly associated with lunar crustal magnetic sources. The inferred propagation vectors and polarizations of these waves are consistent with the expected characteristics of intrinsically right-hand polarized waves propagating upstream from their source. Similar waves (commonly referred to as "1 Hz waves") have been observed upstream of bow shocks at Earth (Fairfield, 1974), Mars (Brain et al., 2002), and other solar system bodies, including Mercury and Venus (Orlowski et al., 2002). The association of monochromatic waves with crustal sources strongly suggests that these waves are produced by solar wind interaction with lunar magnetic fields, but they could either be upstream whistlers produced at a shock surface, or could represent a phase-standing whistler wake structure directly generated by solar wind interaction with small-scale crustal fields (Halekas et al., 2006b).

4.3. Waves and electron energization

As shown in Figs. 1–3, and in general for LEME observations, electron energization is most clearly associated with low frequency wave activity observed in the magnetic field, either broadband or monochromatic in form. The association of electron energization with wave activity is generally closer than with the magnetic amplification of the LEME itself. This suggests a causal connection, but does not indicate how the causality may operate. In fact, there are at least three possibilities: (1) Waves and energized electrons could both be produced by solar wind interaction with crustal sources, possibly at a shock surface. (2) Waves could be produced by solar wind interaction with crustal sources, either in the form of a whistler wake generated at low altitude and extending upstream or in the form of upstream waves produced at a shock surface, and could then energize electrons. (3) Electrons could be energized by the solar wind interaction with crustal sources, possibly at a shock surface, and could then generate waves. Detailed studies of the interaction region will be necessary in order to distinguish between these possibilities.

5. Conclusions

When the solar wind interacts with lunar crustal magnetic sources, it produces a variety of electron and magnetic field effects, which we observe in LP data. Magnetic field amplifications, too large to represent direct measurements of crustal fields, often appear in the solar wind over the stronger crustal sources. We observe these LEMEs directly above and/or somewhat downstream from their apparent sources. Many of those near the limb could be explained as magnetosonic wakes ("limb compressions"), but those at lower SZA can likely only be explained by shocks which extend well upstream from their sources ("limb shocks"). The chance of observing LEMEs appears to depend on upstream solar wind parameters.

We usually observe increases in low-energy ($\lesssim 100$ eV) electron energy fluxes simultaneously with large LEMEs, consistent with an increase in plasma density across a shock surface. We also often observe low frequency wave activity in the magnetic field data, often associated with electron energization, sometimes up to keV energies. We observe both broadband magnetic turbulence (more common) and monochromatic whistler-mode waves (less common). Electron energization appears to be correlated more closely with wave activity than with magnetic amplifications. Waves and electron energization are also observed in the absence of LEME signatures at spacecraft altitude, though LEMEs could be present below the LP orbit.

Detailed studies of the interaction region will be necessary in order to understand the physical processes at work. At present, the Moon represents the only natural laboratory available to us to understand solar wind interaction with small-scale crustal magnetic fields, though simulations and theoretical work should continue to guide our efforts in understanding the physical processes at work.

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