GEOPHYSICAL RESEARCH LETTERS, VOL. 33, L22104, doi:10.1029/2006GL027684, 2006

Whistler waves observed near lunar crustal magnetic sources

J. S. Halekas,[1] D. A. Brain,[1] D. L. Mitchell,[1] and R. P. Lin[1]

Received 26 July 2006; revised 16 October 2006; accepted 24 October 2006; published 28 November 2006.

[1] We present Lunar Prospector Magnetometer (LP MAG) observations of monochromatic circularly polarized low frequency waves at frequencies of 0.4–4 Hz near the Moon. We observe such waves on about 6.6% of LP orbits in the solar wind, outside of the lunar wake. About a third of them occur on orbits when we also observe external magnetic enhancements ("limb shocks"), and most are clearly associated with lunar crustal magnetic sources, indicating an origin related to solar wind interaction with lunar magnetic fields. The inferred propagation vectors and polarizations of these waves are consistent with the expected characteristics of whistler-mode waves. These observations could indicate either upstream whistler waves produced at shock surfaces above lunar crustal magnetic sources, or phase-standing whistler wakes formed by direct solar wind interaction with lunar crustal magnetic fields.
Citation: Halekas, J. S., D. A. Brain, D. L. Mitchell, and R. P. Lin (2006), Whistler waves observed near lunar crustal magnetic sources, *Geophys. Res. Lett.*, *33*, L22104, doi:10.1029/2006GL027684.

1. Introduction

[2] Low-frequency circularly or elliptically polarized waves have been observed upstream of bow shocks at Mars [*Brain et al.*, 2002], Earth [*Fairfield*, 1974], and other solar system bodies, including Mercury and Venus [*Orlowski et al.*, 1990]. These waves have frequencies of one to a few Hertz and, though often observed with left-handed polarization in the spacecraft frame, are usually identified as right-handed whistler-mode waves that have been Doppler-shifted. Their origin has been debated, with a variety of scenarios proposed for their formation.

[3] Recent interest in upstream whistler waves has been spurred by observations of magnetic perturbations near the asteroids Gaspra and Ida [*Wang et al.*, 1995], which were suggestive of a "whistler wake" generated by electrons interacting with a magnetic obstacle too small to perturb the fluid flow of the solar wind and produce ion-scale waves or shocks. 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 can be generated by solar wind interaction with electron-scale magnetic obstacles, producing circularly polarized perturbations which can extend upstream from the obstacle (due to the high group velocity of whistlers). They also predict that whistlers should be confined to propagate in specific regions. For fields parallel or anti-parallel to solar wind velocity, whistlers will propagate into the entire upstream hemisphere, while for perpendicular fields whistlers will only propagate downstream from the obstacle, near the plane formed by magnetic field and solar wind velocity vectors (the B-v plane) [*Gurnett*, 1995]. For intermediate angles, whistlers will propagate in an asymmetric region bounded on the upstream side by a caustic surface with the same relative orientation to the solar wind as the magnetic field, and confined near the B-v plane.

[4] Whistler-mode waves have previously been observed near the Moon by Wind and Geotail, associated with magnetic connection to the lunar wake, and likely produced by electrons interacting with the electrostatic potential associated with the lunar wake [*Farrell et al.*, 1996; *Nakagawa et al.*, 2003]. Probable whistler-mode waves have also been observed previously by Lunar Prospector (LP), associated with lunar external magnetic enhancements (LEMEs, or "limb shocks") formed by the interaction of the solar wind with lunar anomalies [*Lin et al.*, 1998; *Halekas et al.*, 2006]. We now conduct a systematic study of the distribution and properties of monochromatic low frequency waves near the Moon, using LP Magnetometer (LP MAG) data.

2. Observations

[5] We present example wave observations in Figures 1 and 2. Figure 1 shows magnetic field components (in Selenocentric Solar Ecliptic (SSE) coordinates, analogous to GSE but Moon-centered) and a power spectrum of magnetic field magnitude, as well as a color bar indicating whether the spacecraft is in sunlight or shadow, and a color bar showing whether a straight-line magnetic field trace from LP intersects the lunar surface (and if so, with what polarity). We observe an LEME (peaked at ~19:47) produced by the interaction of the solar wind with lunar crustal magnetic fields [*Halekas et al.*, 2006]. After this magnetic field increase, we see a dip in magnetic field magnitude, identifiable as a rarefaction wave associated with the lunar wake boundary [*Halekas et al.*, 2005]. When LP is in the solar wind or wake boundary region and magnetically connected to the surface (~19:55–20:05), we observe sporadic broadband (0–2 Hz) magnetic turbulence. Similar magnetic turbulence when connected to the surface is very commonly observed by LP, regardless of the presence of a magnetic enhancement. We observe monochromatic waves at frequencies of just above 1 Hz from 19:40–19:46 and 19:51–19:55. Monochromatic waves, unlike broadband fluctuations, are rarely observed by LP.

[6] In Figure 2, we present an analysis of six seconds of magnetic field data during the event described above. We

[1]Space Sciences Laboratory, University of California, Berkeley, California, USA.

0094-8276/06/2006GL027684$05.00

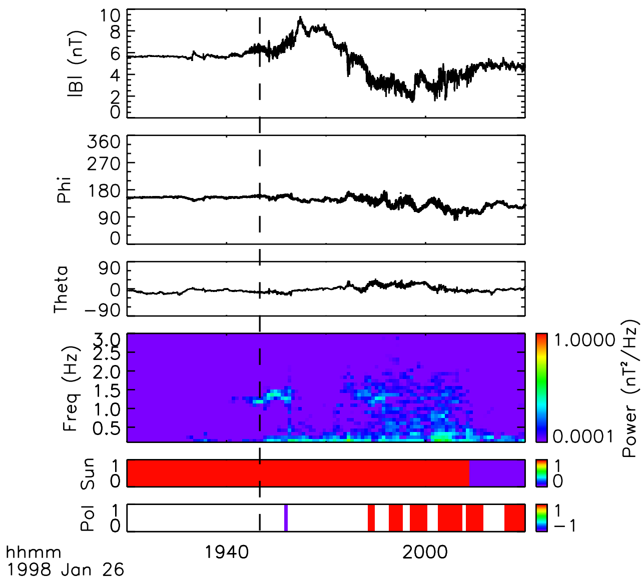

Figure 1. Magnetic field magnitude, direction angles, and power spectrum, with sun/shadow bar and magnetic connection bar (described in text). Dashed line indicates time of observations shown in Figure 2.

subtract the mean magnetic field, and use minimum variance analysis [*Song and Russell*, 1999; *Sonnerup and Cahill*, 1967] on the residuals to determine eigenvalues of λ = [0.12, 0.11, 0.002], indicating nearly circular wave polarization and a well-determined propagation direction (since $\lambda_1 \sim \lambda_2$ and $\lambda_3 \ll \lambda_2$). The power spectrum and hodogram also indicate nearly monochromatic circularly polarized waves. The inferred wave propagation direction lies at an angle of 65° to the magnetic field, with the usual ambiguity in the sign of propagation. The sense of polarization is left-handed with respect to the magnetic field, as measured in the spacecraft frame. As pointed out by many authors [e.g., *Fairfield*, 1974], this is consistent with right-handed whistler waves. In most cases the whistler group velocity is higher then the solar wind velocity, allowing upstream propagation, but the phase velocity is lower, and the resulting Doppler shift often results in left-handed polarization in the spacecraft frame (except for waves which propagate nearly perpendicular to the solar wind velocity).

[7] The properties of the waves shown in Figures 1 and 2 are similar to those of waves previously observed by Wind and Geotail near the Moon [*Farrell et al.*, 1996; *Nakagawa et al.*, 2003]. However, those waves were observed when magnetically connected to the lunar wake boundary, downstream of the Moon. The waves presented in this paper are found near the dayside lunar surface, and different physical processes may produce them. Wake-related whistlers are likely generated by interactions of electrons with ambipolar electric fields created at the wake boundary (due to faster solar wind electrons attempting to fill in the wake cavity before the slower ions, resulting in a charge separation electric field). The currently observed waves, on the other hand, are likely generated by the solar wind interacting with lunar crustal magnetic fields. Charge separation electric fields may still be involved, but in this case they could instead be associated with a shock structure or with separation of solar wind electrons and ions interacting with lunar crustal fields.

3. Spatial and Temporal Distribution of Waves

[8] We searched the entire LP MAG data set (January 1998 to July 1999) for similar examples of monochromatic waves by dividing MAG data into 30 s time intervals and calculating magnetic field power spectra. We flagged all examples where there was an order of magnitude increase in wave power at a given frequency, as compared to a half-Hz wide frequency band below the peak frequency. The LP spin period is 5 s, and we often observe a tone at 0.4 Hz (corresponding to a half-spin period), so we only searched for waves with frequencies above 0.4 Hz. We only selected examples where a peak was found for four or more 30 s time intervals during a four minute time period, thereby eliminating short-duration turbulent fluctuations that otherwise contaminated the data set. We found 3934 thirty second time periods with monochromatic waves, on 253 different orbits. Monochromatic waves were only observed in the solar wind, when LP was outside of the lunar wake. Our search spanned 3813 orbits where LP entered the solar wind; waves were observed on 6.6% of these orbits. Our search criteria were stringent, so this is certainly an underestimate of the percentage of time that monochromatic waves are present, but this allowed us to ensure that we excluded more common broadband magnetic turbulence from contaminating our data set. Visual inspection of data confirms that our selection algorithm works adequately in separating monochromatic waves from broadband turbulence.

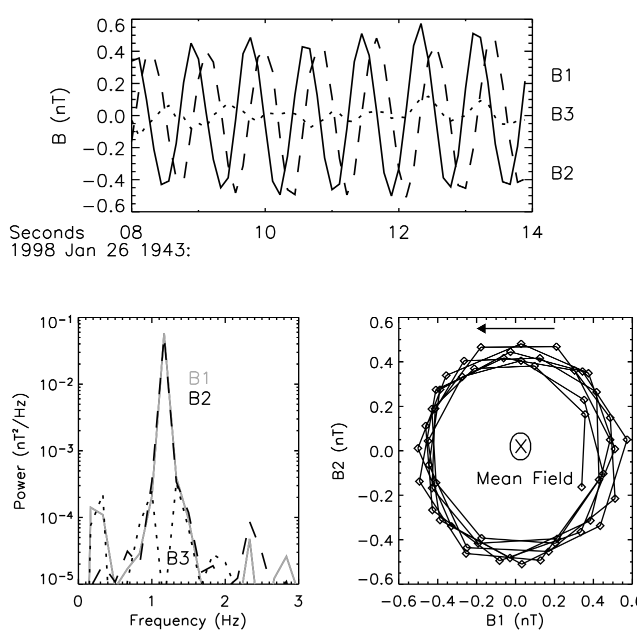

Figure 2. Magnetic field (with mean field subtracted) in minimum variance coordinates, power spectrum of all three components, and hodogram of first and second components.

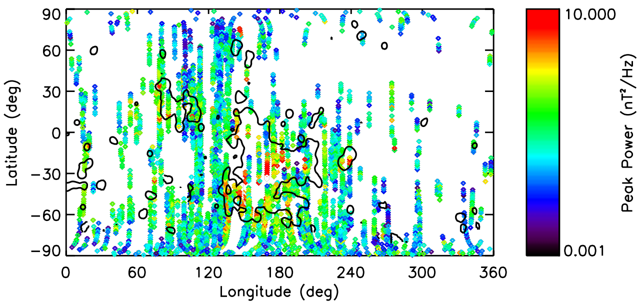

Figure 3. Selenographic distribution of monochromatic wave observations, colored by peak total wave power. Contour indicates 20 nT surface magnetic field level.

[9] We found waves at all solar zenith angles <110° (roughly corresponding to the lunar wake boundary at 100 km altitude) and at all altitudes (∼15–100 km). The distribution in SZA is non-random, with 13% of observations at SZA < 40°, 20% at 40° < SZA < 60°, 40% at 60° < SZA < 80°, and 27% at 80° < SZA < 110°. Beyond this preference for SZA near or slightly upstream of the limb, the distribution of waves is relatively random in solar coordinates. In selenographic coordinates, on the other hand, the distribution is highly non-random. Figure 3 shows this distribution, with color corresponding to total wave power (in all magnetic field components) at the peak frequency. We observe waves clustered in regions with crustal magnetic fields, with the highest wave powers associated with the strongest crustal fields. The distribution of wave observations, in concert with the fact that we only observe waves in the solar wind, provides strong evidence that the wave generation mechanism is related to solar wind interaction with lunar crustal magnetic fields. We do not see the previously observed wake-related whistlers [*Farrell et al.*, 1996; *Nakagawa et al.*, 2003], presumably because they are only generated further downstream from the Moon.

[10] A natural question is: Are these whistler waves associated with external magnetic enhancements (LEMEs)? It is difficult to answer this question conclusively. We find that 85 of the 253 orbits also have LEMEs, so there is only clear evidence for an association between waves and LEMEs for about one third of the wave orbits. However, it is quite likely that LEMEs could also exist on other orbits, but below spacecraft altitude. The association with crustal magnetic sources and the preference for locations near the limb for both waves and LEMEs strongly suggests that monochromatic waves may be associated with LEMEs. If LEMEs are truly shocks, which is not completely clear [*Halekas et al.*, 2006], this tentative association might indicate that the waves discussed in this paper are analogous to "1 Hz waves" observed upstream from the bow shocks of many planets [*Brain et al.*, 2002; *Orlowski et al.*, 1990]. On the other hand, simulations predict that similar upstream whistlers could be produced merely by the interaction of the solar wind with small crustal sources, with no shock structure necessary [*Wang and Kivelson*, 1996; *Omidi et al.*, 2002]. In this interpretation, the waves presented in this paper could be considered manifestations of a phase-standing whistler wake. Observationally distinguishing between these two possibilities may be quite difficult, since the expected upstream whistler propagation should be the same – only the generation mechanism would differ.

4. Wave Propagation Directions and Polarizations

[11] We wish to determine if the locations and times where we observe monochromatic waves are consistent with the expected propagation characteristics of whistler-mode waves. To accomplish this, we conduct the same minimum variance analysis presented in Figure 2 for all wave observations, using 10 s intervals of data (three intervals for each 30 s interval already identified). This analysis allows us to determine polarizations and propagation directions. We find that the observed monochromatic waves propagate at all angles to the magnetic field, with the largest percentage of inferred propagation angles near ∼40°. Only about 11% of our wave observations satisfy the most stringent criteria for precisely determining propagation directions using minimum variance analysis ($\lambda_1 \sim \lambda_2$, $\lambda_3 < 0.1 * \lambda_2$). However, the properties of this subset of data are nearly indistinguishable from those for all wave observations. This is the case for all tests we have performed – it appears that even when eigenvalue ratios indicate that the results of minimum variance analysis are less well-constrained, inferred propagation direction results remain robust. Therefore, we show results for all wave observations in subsequent analyses.

[12] In Figure 4, we plot peak frequency versus the angle between solar wind velocity and inferred propagation direction (the propagation direction is ambiguous in sign, so all angles are referenced to the range of 0–90°), for all observations. The gap below 0.4 Hz is an artifact of our selection criteria. The upper range of the observations is determined by the Nyquist frequency of 4.5 Hz, since LP MAG data is sampled at 9 Hz. We observe almost all waves with left-handed polarization in the spacecraft frame, except for cases when the propagation direction and solar wind velocity are nearly perpendicular. This is consistent with whistlers which propagate upstream and are Doppler-shifted, since we should more often observe

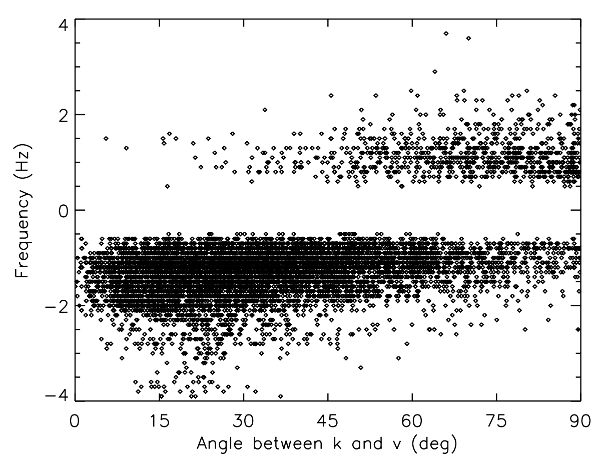

Figure 4. Frequency (negative values indicate left-handed polarization) versus angle between propagation direction and solar wind velocity.

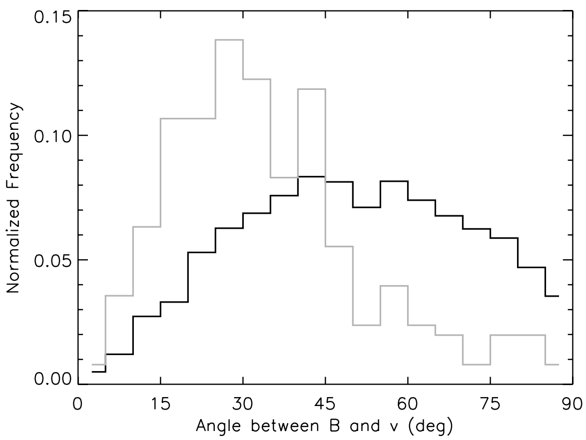

Figure 5. Distributions of the angle between solar wind velocity and magnetic field for all LP orbits (black) and orbits where waves are observed (grey).

the waves with their intrinsic right-handed polarization when they propagate close to perpendicular to the solar wind [*Fairfield*, 1974].

[13] Theoretical calculations and simulations demonstrate that whistlers are more able to propagate in the upstream direction the closer to parallel (or anti-parallel) that the magnetic field is to the solar wind velocity, and that for most magnetic field angles whistlers are constrained to propagate near the B-v plane [*Gurnett*, 1995; *Wang and Kivelson*, 1996]. To test this, in Figure 5 we show histograms of the angle between solar wind velocity and magnetic field (the distribution is symmetric, so all angles are referenced to angles of 0–90°) for all 3813 LP orbits in the solar wind and for the 253 orbits where we observe monochromatic waves. For all LP orbits, the distribution is peaked at ~45°, consistent with the expected Parker spiral direction at the Moon. For the subset of orbits when waves were observed, on the other hand, the distribution is peaked at ~25°. Furthermore, we find that 91% of inferred wave propagation vectors lie within 30° of the B-v plane. Our observations are therefore consistent with simulations and theoretical predictions for upstream whistler propagation.

5. Conclusions

[14] We observe monochromatic circularly polarized waves on many LP orbits in the solar wind, outside of the lunar wake. These waves are clearly associated with crustal magnetic fields, and about a third of them are also associated with LEMEs observed at spacecraft altitude. These observations strongly suggest that most waves are created either directly or indirectly by solar wind interaction with lunar crustal magnetic fields. Inferred wave propagation vectors and polarizations are completely consistent with the expected characteristics of whistler-mode waves propagating upstream. These waves 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. In order to distinguish between these two possibilities, it may be necessary to investigate the low-altitude source region in detail.

[15] **Acknowledgment.** This work was supported by NASA grant NNG05GJ24G.

References

Brain, D. A., F. Bagenal, M. H. Acuña, J. E. P. Connerney, D. H. Crider, C. Mazelle, D. L. Mitchell, and N. F. Ness (2002), Observations of low-frequency electromagnetic plasma waves upstream from the Martian shock, *J. Geophys. Res.*, *107*(A6), 1076, doi:10.1029/2000JA000416.
Fairfield, D. H. (1974), Whistler waves observed upstream from collisionless shocks, *J. Geophys. Res.*, *79*, 1368–1378.
Farrell, W. M., R. J. Fitzenreiter, C. J. Owen, J. B. Byrnes, R. P. Lepping, K. W. Ogilvie, and F. Neubauer (1996), Upstream ULF waves and energetic electrons associated with the lunar wake: Detection of precursor activity, *Geophys. Res. Lett.*, *23*, 1271–1274.
Gurnett, D. A. (1995), The whistler-mode bow wave of an asteroid, *J. Geophys. Res.*, *100*, 21,623–21,629.
Halekas, J. S., S. D. Bale, D. L. Mitchell, and R. P. Lin (2005), Electrons and magnetic fields in the lunar plasma wake, *J. Geophys. Res.*, *110*, A07222, doi:10.1029/2004JA010991.
Halekas, J. S., D. A. Brain, D. L. Mitchell, R. P. Lin, and L. Harrison (2006), On the occurrence of magnetic enhancements caused by solar wind interaction with lunar crustal fields, *Geophys. Res. Lett.*, *33*, L08106, doi:10.1029/2006GL025931.
Lin, R. P., D. L. Mitchell, D. W. Curtis, K. A. Anderson, C. W. Carlson, J. McFadden, M. H. Acuña, L. L. Hood, and A. Binder (1998), Lunar surface magnetic fields and their interaction with the solar wind: Results from Lunar Prospector, *Science*, *281*, 1480–1484.
Nakagawa, T., Y. Takahashi, and M. Iizima (2003), GEOTAIL observation of upstream ULF waves associated with lunar wake, *Earth Planets Space*, *55*, 569–580.
Omidi, N., X. Blanco-Cano, C. T. Russell, H. Karimabadi, and M. Acuña (2002), Hybrid simulations of solar wind interaction with magnetized asteroids: General characteristics, *J. Geophys. Res.*, *107*(A12), 1487, doi:10.1029/2002JA009441.
Orlowski, D. S., G. K. Crawford, and C. T. Russell (1990), Upstream waves at Mercury, Venus and Earth: Comparison of the properties of one Hertz waves, *Geophys. Res. Lett.*, *17*, 2293–2296.
Song, P., and C. T. Russell (1999), Time series data analyses in space physics, *Space Sci. Rev.*, *87*, 387–463.
Sonnerup, B. U. Ö., and L. J. Cahill Jr. (1967), Magnetopause structure and attitude from Explorer 12 observations, *J. Geophys. Res.*, *72*, 171–183.
Wang, Z., and M. G. Kivelson (1996), Asteroid interaction with solar wind, *J. Geophys. Res.*, *101*, 24,479–24,493.
Wang, Z., M. G. Kivelson, S. Joy, K. K. Khurana, C. Polanskey, D. J. Southwood, and R. J. Walker (1995), Solar wind interaction with small bodies: 1. Whistler wing signatures near Galileo's closest approach to Gaspra and Ida, *Adv. Space. Res.*, *16*, 47–57.

D. A. Brain, J. S. Halekas, R. P. Lin, and D. L. Mitchell, Space Sciences Laboratory, University of California, Berkeley, CA 94720, USA. (jazzman@ssl.berkeley.edu)