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Statistical analysis of monochromatic whistler waves near the Moon detected by Kaguya

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Abstract. Observations are presented of monochromatic whistler waves near the Moon detected by the Lunar Magnetometer (LMAG) on board Kaguya. The waves were observed as narrowband magnetic fluctuations with frequencies close to 1 Hz, and were mostly left-hand polarized in the spacecraft frame. We performed a statistical analysis of the waves to identify the distributions of their intensity and occurrence. The results indicate that the waves were generated by the solar wind interaction with lunar crustal magnetic anomalies. The conditions for observation of the waves strongly depend on the solar zenith angle (SZA), and a high occurrence rate is recognized in the region of SZA between 40° to 90° with remarkable north-south and dawn-dusk asymmetries. We suggest that ion beams reflected by the lunar magnetic anomalies are a possible source of the waves.

Keywords. Magnetospheric physics (Solar wind interactions with unmagnetized bodies) – Radio science (Waves in plasma) – Space plasma physics (Waves and instabilities)

1 Introduction

Monochromatic whistler waves around the Moon have been detected by WIND (Farrell et al., 1996) and Geotail (Nakagawa et al., 2003) as narrowband magnetic fluctuations observed at frequencies close to 1 Hz when magnetic field lines connect the spacecrafts to the Moon. From the statistical analysis of the Lunar Prospector (LP) data set, Halekas et al. (2006a) reported that the intense monochromatic whistler waves were frequently observed near the lunar crustal magnetic anomalies, which have spot-like configurations of the order of 100 km in the horizontal scale with the magnetic field strength of a few nT at 100 km altitude. They suggested that these waves may be generated at shocks or wakes formed around the lunar crustal magnetic anomalies by the solar wind interaction. However, the generation process of the waves has not been fully understood.

Similar monochromatic whistler waves have been observed in the upstream region of bow shocks of many solar system bodies including Mercury, Venus, Earth, Mars, and Saturn (Orlowski and Russell, 1995; Brain et al., 2002). These waves are called "upstream whistler waves" or simply "1 Hz waves". The peculiar wave spectra are characterized by upstream whistler-mode waves propagating against the solar wind (cf. review by Russell, 2007). The spectral density of such waves is concentrated at a certain frequency corresponding to the condition where the group velocity equals the solar wind velocity. Since the phase velocity is smaller than the solar wind velocity at that frequency, the waves are largely Doppler-shifted and mostly left-hand polarized. That is, the fundamental characteristics of the group and phase velocities of whistler-mode waves lead to their peculiar spectra. Although upstream whistler waves from bow shocks have been extensively studied for several decades, the generation process of the waves has not been identified yet.

To clarify the generation process of monochromatic whistler waves near the Moon, we have performed a detailed statistical analysis of the spatial distributions using the Kaguya observations. Especially, the average intensity and occurrence rate of the waves were separately analyzed, which respectively correspond to the wave source and the condition required for the observation that have not been studied in previous works.

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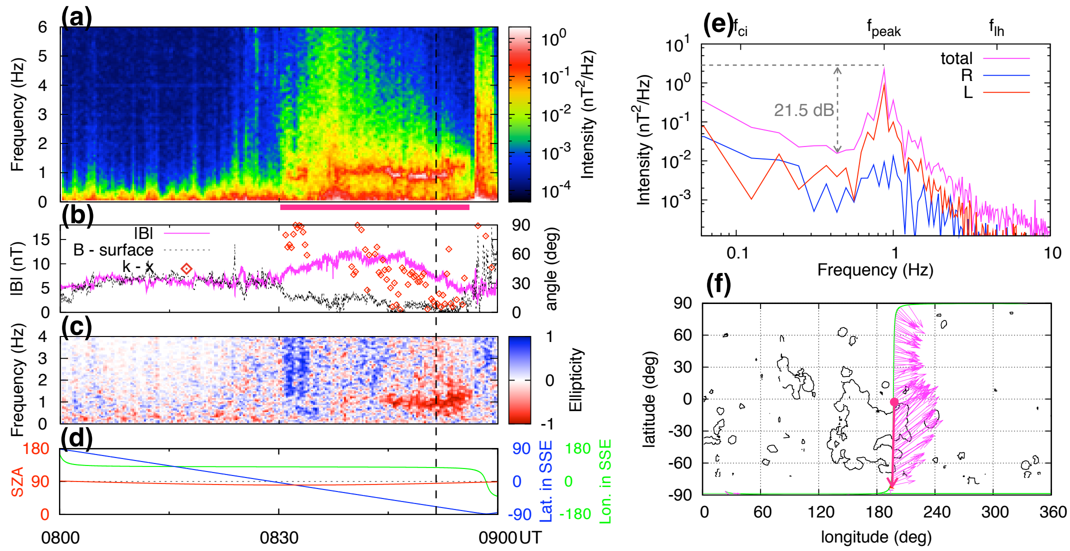

Fig. 1. Monochromatic whistler waves detected by Kaguya on 13 January 2008. Left panels are **(a)** the fast Fourier transform (FFT) spectrum, **(b)** magnetic field strength ($|B|$), angle of magnetic field to lunar surface, and angle of the wave vector ($\boldsymbol{k}$) to the sunward direction (x), **(c)** ellipticity spectrum, and **(d)** position of the spacecraft in solar zenith angle (SZA) and Selenocentric Solar Ecliptic (SSE) coordinates (Lat.: latitude, Lon.: longitude). Ellipticity is defined as $(\mathrm{R}-\mathrm{L})/(\mathrm{R}+\mathrm{L})$, where R and L represent the intensities of the right- and left-hand polarized component of the waves, respectively. The right top panel **(e)** shows the intensities of the total, right-, and left-hand polarized component of the waves at 08:52 UT (this time is indicated by a dashed line in the left panels). The right bottom panel **(f)** illustrates the spacecraft orbit during 08:00–09:00 UT and magnetic field vectors in the selenographical coordinates. The contour indicates 20 nT surface magnetic field strength obtained from LP observations (courtesy of J. S. Halekas). The thick red arrow superposed on the orbit represents the period indicated by a bar just below the FFT spectrum panel **(a)**.

2 Instruments and observations

Kaguya (SELENE) is a Japanese spacecraft orbiting the Moon. During the constancy phase (December 2007–September 2008), Kaguya is in a nearly polar orbit at about 100 km altitude with a 2-h period. We use 32 Hz time series of the magnetic field data set obtained by the Lunar Magnetometer (LMAG) on board Kaguya, which has a triaxial ring-core type fluxgate sensor (Tsunakawa et al., 2010). From the ground and in-orbit calibrations (Shimizu et al., 2008; Takahashi et al., 2009), and the electromagnetic compatibility conditions (Matsushima et al., 2010), the noise level is estimated to be less than 0.1 nT. We applied the fast Fourier transformation (FFT) to every 16 s time interval to obtain the wave spectra of 0.125–16 Hz. For the waveform analysis, the wave normal direction is estimated by the minimum variance analysis (Sonnerup and Cahill Jr., 1967). In addition, we divided the component of the waves oriented perpendicular to the mean field into right- and left-hand polarized wave components.

An example of monochromatic whistler waves detected by Kaguya-LMAG is shown in Fig. 1. Narrowband magnetic waves at ∼1 Hz were seen from 08:32 to 08:55 UT. Figure 1e shows the frequency spectrum for a time section of 08:52 UT, where the peak intensity is ∼2.0 $\mathrm{nT}^2\,\mathrm{Hz}^{-1}$ at a frequency of 0.9 Hz (“the peak frequency”, hereafter we call f_{peak}), which is 21.5 dB higher than the weakest intensity in a frequency domain lower than f_{peak} (hereafter we call this value as the drop level). Since the ellipticity of the waves is close to -1 from 08:43 to 08:55 UT, the waves are almost circularly left-hand polarized (Fig. 1c). During this period the angle between the wave normal and sunward directions (which is approximately parallel to the solar wind velocity) approaches 0° (Fig. 1b), indicating that the waves are largely Doppler-shifted in the spacecraft frame. The frequency range and these wave properties are consistent with those of previously reported monochromatic whistler waves around the Moon (Halekas et al., 2006a). For more detailed conditions of the observation, the solar zenith angle (SZA) during this event was 80°–90°, that is, close to the terminator region (Fig. 1d), while Kaguya orbited over the lunar magnetic anomaly cluster in the South Pole Aitken (SPA) basin (Fig. 1f). The magnetic field strength above the SPA region was enhanced by about 2.5 times compared with that in the Northern Hemisphere. The spacecraft is considered to have not been connected to the lunar surface by magnetic field lines during this event, since the angle between the local magnetic field and the lunar surface was less than 20° (Fig. 1b). Moreover, some examples show that the monochromatic waves are not necessarily detected with the magnetic enhancement, that is the same result as reported in the LP observation (Halekas et al., 2008), and others are observed far away from magnetic

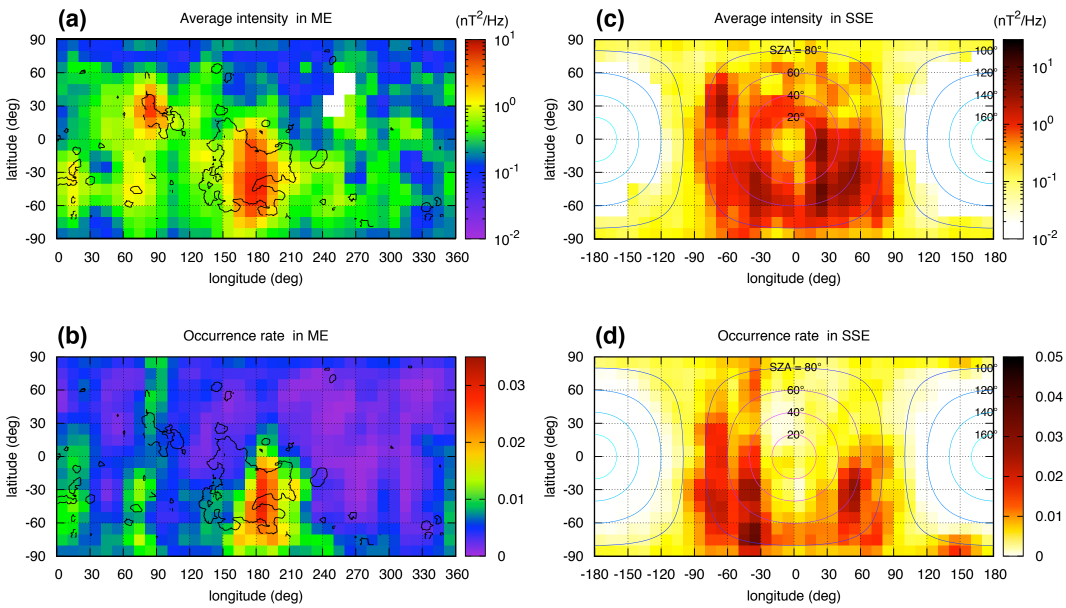

Fig. 2. Distributions of **(a)** average intensity and **(b)** occurrence rate of the monochromatic whistler waves in the selenographical (Mean Earth/polar axis, ME) coordinates with 20 nT of surface magnetic field strength contour (same as Fig. 1f) and **(c)** average intensity and (d) occurrence rate of the waves in the Selenocentric Solar Ecliptic (SSE) coordinates with SZA contours shown for every 20°. The average intensity is calculated by dividing the sum of the peak intensities of the waves by the number of events in each $10^\circ \times 10^\circ$ bin. The occurrence rate is obtained by dividing the number of events by the number of 16 s interval data points for all orbits in each $10^\circ \times 10^\circ$ bin. SSE longitude corresponds to local time (e.g., 0° longitude in SSE corresponds to local noon), SSE latitude almost corresponds to selenographical latitude because of the small (a few degrees) inclination of the Moon's axis.

anomalies. To explore the association of the monochromatic whistler waves with the magnetic anomalies, we performed a statistical analysis in the following section.

3 Statistical analysis

3.1 Event selection

We have analyzed the LMAG data set of the solar wind region during the constancy phase of 10 months. To limit our investigation to the period when the Moon was outside the Earth's magnetosphere and to discard waves originating from the Earth's bow shock, we selected the period when the azimuthal angle of the spacecraft position in the Geocentric Solar Ecliptic (GSE) coordinates ranged from $-3/4\pi$ to $3/4\pi$. We applied three selection criteria of the monochromatic waves: (1) $f_{\mathrm{peak}} = 0.4$–4 Hz, (2) the peak intensity $>0.01\,\mathrm{nT}^2\,\mathrm{Hz}^{-1}$, and (3) the drop level >20 dB. The first criterion is the same as that employed by Halekas et al. (2006a). We note that the local proton cyclotron frequency (f_{cp}) is less than 0.4 Hz at 100 km altitude even above the largest magnetic anomaly. The second criterion is adopted to avoid noise contamination. The third criterion is related to enhancement of the waves, and a threshold of 20 dB is taken in the present study (see Fig. 1e). Applying these criteria, we selected 6638 events (one event represents a 16 s time interval), which correspond to 0.54 % of the analyzed period. Using the data set of selected events, we have conducted a statistical study of the monochromatic whistler waves.

3.2 Distributions of the waves

The peak intensity and the occurrence rate of the waves averaged within a $10^\circ \times 10^\circ$ bin in the selenographical coordinates, as shown in Fig. 2a and b, respectively, together with 20 nT contours of the surface intensities of the lunar magnetic anomalies. It is seen in Fig. 2a that the average intensities higher than $\sim 3\,\mathrm{nT}^2\,\mathrm{Hz}^{-1}$ are clearly associated with the locations of lunar magnetic anomalies, however, relatively weak average intensities are distributed more widely than the magnetic anomalies. This wide distribution is attributable to the modulation caused by variations in the direction of the ambient magnetic field during the observation periods, because the magnetic field direction is one of the controlling factors for the wave propagation properties. The high occurrence rate regions are also nearly coincident with the locations of magnetic anomalies as shown in Fig. 2b, but appear to be shifted from those of the high average intensity regions (Fig. 2a). Particularly in the SPA region, the distribution of very high occurrence rate is shifted eastward.

We re-plotted the average intensity and the occurrence rate of the waves in the Selenocentric Solar Ecliptic (SSE) coordinates, which are analogous to the GSE coordinates but

Moon-centered (Fig. 2c and d, respectively). The average intensity gradually increases at SZA = 20°–80° with a broad distribution on the dayside (Fig. 2c). There is a bias between the Northern and Southern Hemispheres for the distribution of high average intensities, especially those higher than 1 $nT^2 Hz^{-1}$. This is because a larger number of strong magnetic anomalies are distributed in the Southern Hemisphere than in the Northern Hemisphere, and high average intensity regions are distributed in accordance with the distributions (see Fig. 2a). In Fig. 2d, the occurrence rate abruptly increases in the region of SZA between 40° to 90° with significant north-south and dawn-dusk asymmetries. The waves are more frequently observed in the south than in the north, and at dawn than at dusk. Few events are observed in the lunar wake due to absence of the solar wind interaction. The north-south asymmetric distribution shown in Fig. 2d is again explained by the magnetic anomaly and occurrence rate distributions in the selenographical coordinates in Fig. 2b, in the same way as for the average intensity distribution in Fig. 2c.

Figure 2 clarified that the distributions of the average intensity and the occurrence rate are clearly related to the locations of magnetic anomalies, while the regions of the high intensity and the high occurrence rate are differently distributed around anomalies in both latitude and longitude. These results provide important clues for understanding the wave properties and their generation process. Based on previous studies of the upstream whistler waves from planetary bow shocks for which the wave intensity decreases with distance from the source region (Orlowski and Russell, 1991), the distribution of the high average intensity (Fig. 2a and c) indicates the intense wave source region. On the other hand, the distribution of the high occurrence rate (Fig. 2b and d) indicates regions satisfying the conditions for observation of the waves. Figure 2a suggests that magnetic anomalies are intense wave sources, and the high average intensity on the dayside shown by Fig. 2c indicates that solar wind interactions with lunar magnetic anomalies generate the intense waves. Figures 2b and d show that the conditions to observe the waves are satisfied both near magnetic anomalies and in the region of SZA between 40° to 90°. The clear dependence on SZA shown in Fig. 2d raises a possibility that SZA is a stronger constraint for determining the occurrence rate distribution than the influence of magnetic anomalies.

4 Discussion and summary

We report monochromatic whistler waves near the Moon observed by LMAG on board the Kaguya spacecraft. It is confirmed from statistical analysis that the intense waves are generated by the solar wind interaction with the lunar magnetic anomalies. High occurrence rates of the waves are found in the region of SZA between 40° to 90° with remarkable north-south and dawn-dusk asymmetries in the SSE coordinates. The north-south asymmetry can be explained by the biased distributions of the magnetic anomalies in the selenographical distributions, but the mechanisms to cause the abrupt peak of wave occurrence in the region of SZA between 40° to 90° and the dawn-dusk asymmetry are not yet fully understood and they will be clarified in our future study. We expect that these wave properties contain helpful information regarding the wave generation.

As a possible source of wave generation, we propose ions reflected from lunar magnetic anomalies. Because reflected ions have nearly the same energy as the solar wind ions and a flux of more than 10 % of the incident solar wind ion flux (Saito et al., 2010), they can be a source of free energy for wave generation. Other generation processes proposed to explain upstream whistler waves from bow shocks, such as shock front perturbation (Baumgärtel and Sauer, 1995) and reflected or energized electrons (Sentman et al., 1983), are unlikely to be the case for the Moon, because the spatial scale of lunar magnetic anomalies is comparable to the ion scale, i.e., proton gyro radius ∼66 km, proton skin depth ∼102 km in a typical solar wind condition near the Moon (number density = 5 cm^{-3}, magnetic field strength = 5 nT, proton temperature = 1.2×10^5 K). This means that the solar wind interaction with lunar magnetic anomalies is not expected to maintain a conventional shock structure. Although magnetic enhancements have been observed near the lunar limb when the solar wind interacts with the magnetic anomalies in a more fluid manner (Halekas et al., 2006b), the compressional ratio is generally 1 to a few value and too small to form a shock. Despite the lack of conventional shock structures around the Moon, it is interesting that lunar magnetic anomalies play a role in supplying reflected ions. Although the mechanism of the ion reflection is not fully revealed, the properties of the reflected ions around anomalies would provide important clues for understanding the wave properties reported in the present statistical study and the generation process.

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