Magnetic fluctuations of 0.1-10 Hz frequency range detected by Kaguya/LMAG

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1. Introduction

The solar wind interaction with the moon generates wave activities around the moon. Whistler waves were reported in association with the magnetic connection to the lunar wake (Farrell et al., 1996; Nakagawa et al., 2003), or with the lunar external magnetic enhancements (LEME) or the lunar crustal magnetic field (Halekas et al., 2006a). They were nearly monochromatic, circularly polarized waves propagating along the magnetic field against the solar wind flow.

On the other hand, the 0.03-5 Hz fluctuations are detected by Kaguya on the solar side surface of the moon, regardless of the crustal magnetic field. They were not observed deep in the wake. Halekas et al. (2006b) also noted the Lunar Explorer observation of sporadic broadband (0-2Hz) magnetic turbulence in the solar wind or wake boundary region when the spacecraft was magnetically connected to the surface of the moon. The aim of this paper is to present the properties of the non-monochromatic waves observed on the dayside surface of the moon and their probable relationship with the reflected protons, and to examine the resonance condition between them.

2. Observation

The magnetic field data used in this study were obtained by MAP-LMAG magnetometer (Shimizu et al., 2008; Takahashi et al., 2009) onboard Kaguya on its orbit encircling the moon at an altitude of 100 km. Figure 1 shows an example of the Kaguya orbit on March 8, 2008, when the moon was in the solar wind. The period of the orbital motion was about 118 min at the altitude. The magnetic field vectors were obtained with sampling frequency of 32Hz.

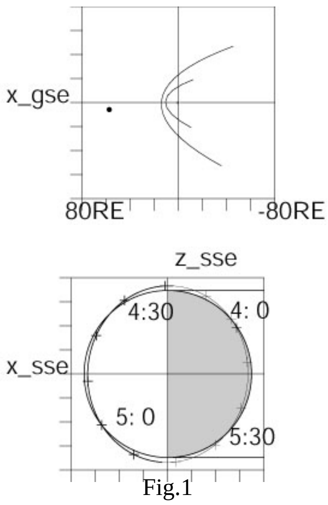

Fig.1

Figure 2 shows an example of the magnetic fluctuations observed on the orbit shown in Figure 1. The curves on the top 4 panels of Figure 2 appear to be broad during the period from 4:10 to 5:30, due to the magnetic fluctuations. The spacecraft was on the solar side of the moon during the period from 4:20 to 5:20. The bottom panel of Figure 2 is an example of the dynamic spectrum of *By* component. The level of fluctuations rose during the period from 4:10 to 5:30. The frequency extended up to 5 Hz for the period 4:10-5:10, and then up to 10 Hz for 5:10-5:27. Although the fluctuations were most intense in the weak-field region around 5:20-5:27 just behind of an LEME observed at 5:10-5:20, for the most part of the time (4:10-5:10), the magnetic fluctuations were observed far from the LEME, and seem to have nothing to do with the LEME.

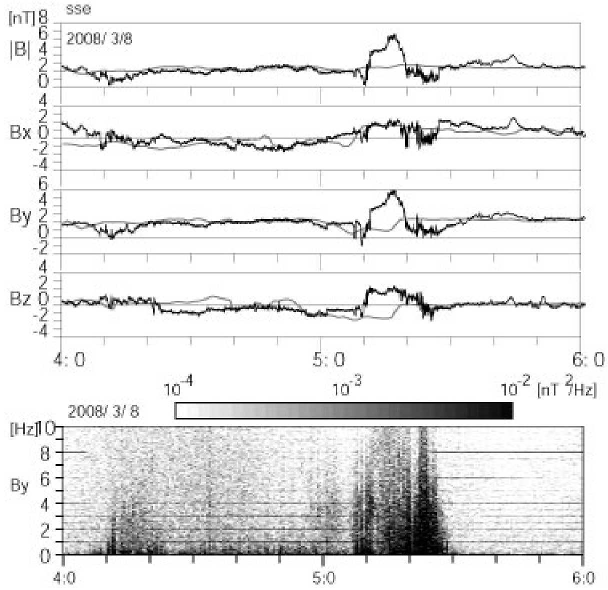

Fig.2

The 0.03-5 Hz fluctuations appeared repeatedly when the spacecraft was on the dayside of the moon or in the wake boundary, and they disappeared as the spacecraft went into the center of the wake. Figure 3 shows an example of the dynamic spectrum for a 24-hour period on January 4, 2008. The alternating pattern of presence and absence of the 0.03-5 Hz fluctuations repeated every 2 hours.

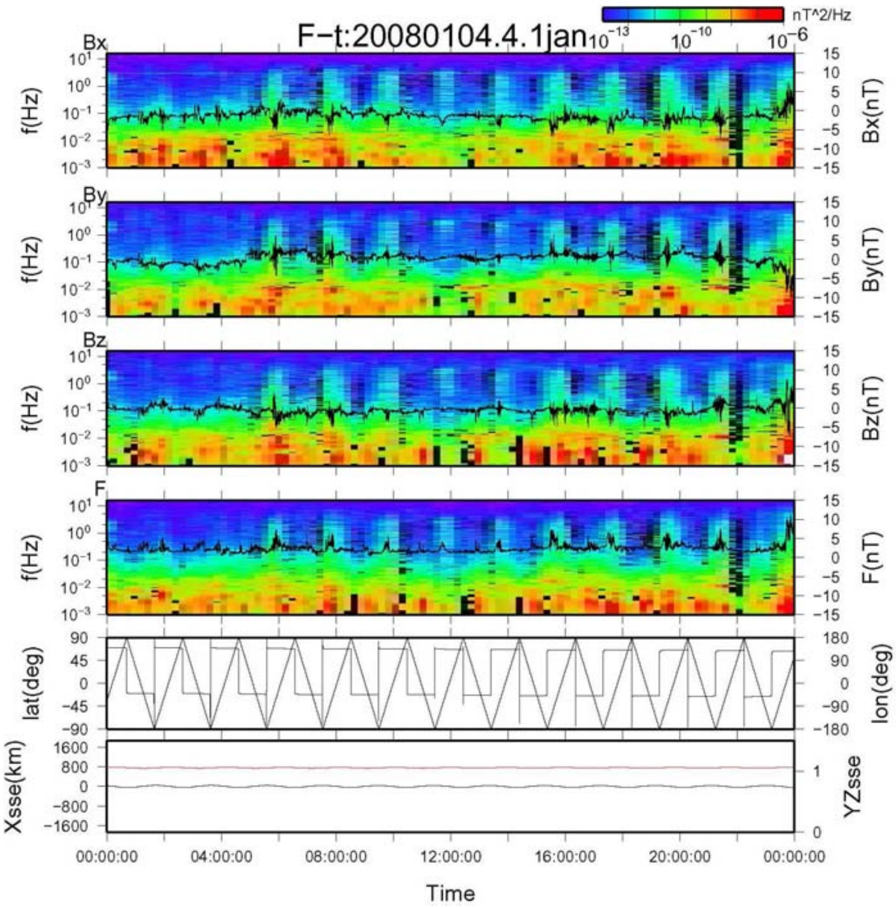

Fig.3

3. Resonance condition

The non-monochromatic waves as described above were not related with any specific local structures on the moon. The only characteristic of occurrence is that they appeared almost always on the dayside surface of the moon. It would be natural to think that they were generated on the dayside surface of the moon and propagate upstream against the solar wind to be detected by Kaguya at 100 km above the lunar surface. There is another possibility that they were generated at upstream of the spacecraft by plasma particles which would have traveled upstream past the spacecraft after their reflection at the lunar surface, and convected down by the solar wind flow.

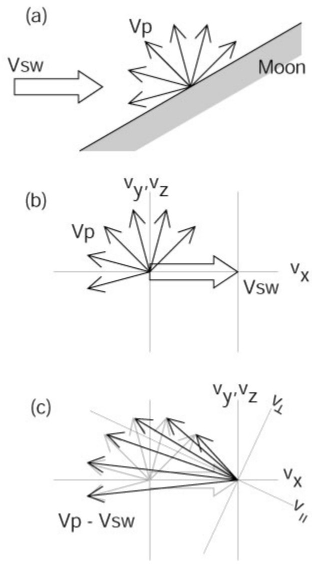

Fig.4

If we assume upstream propagation of a wave generated near the lunar surface, the most probable candidate is the whistler wave which can propagate against the solar wind with group velocity higher than the solar wind speed. A whistler wave with an angular frequency ω and a wave number vector **k** in the solar wind frame of reference would be detected at lower frequency

$$\omega_{obs} = \omega - | kV_{sw} \cos\theta_{kS} |$$

by a spacecraft in the rest frame, where *Vsw* is the solar wind velocity with respect to the moon and θ_{kS} is the angle between the wave number vector and the direction of the solar wind velocity.

A particle with the velocity **V**p measured in the rest frame would be injected into the solar wind plasma with the velocity **V**p – **V**sw in the solar wind frame of reference (Fig.4). If we assume the particles as ions or electrons reflected by or emitted by the surface of the moon, they would start gyration after the injection into the solar wind magnetic field, and the velocity component parallel to the magnetic field would contribute to the Doppler shift of the whistler waves as observed from the particles. The condition of the cyclotron resonance of the upstream-propagating whistler wave and the reflected particles would be

$$\omega - | k(V_e - V_{sw})_{\|} \cos\theta_{kB} | = \Omega_e$$

for electrons, and

$$\omega - | k(V_i - V_{sw})_{\|} \cos\theta_{kB} | = -\Omega_i$$

for ions, where Ω is the cyclotron frequency and θ_{kB} is the angle between the wave number vector and the background magnetic field. The resonance with electrons is impossible because the angular frequency of the whistler wave is smaller than the electron cyclotron frequency and can never become equal to Ω_e subtracted by $| k(V_e - V_{sw})_{\|} \cos\theta_{kB} |$. Thus the resonant particles must be protons.

Figure 5 compares the non-monochromatic waves with the reflected protons detected by MAP-PACE Ion Mass Analyzer (IMA) onboard Kaguya (Saito et al., 2008). It is reported that 0.1-1 % of the solar wind protons were reflected back from the moon instead of being absorbed by the lunar surface. Enhancement of magnetic fluctuations occurred during the period from 12:27 to 13:40, covering the period of detection of reflected protons between 12:40 and 13:30 as recognized at <0.5 keV in the IMA spectrogram. According to Saito et al. (2008), the protons were scattered into various directions, rather than reflected specularly. It should be noted in Fig.4(c) that the velocity component parallel to the magnetic field would be distributed over a significant range. In the ω-k space in Figure 6, the resonant condition is represented by the lines with variable inclination $|k(V_i - V_{sw})_{\parallel} \cos\theta_{kB}|$.

The lines cross the curve of the dispersion relation of the whistler wave at different angular frequencies depending on the inclination. Thus it is expected that not a monochromatic but broadband wave activities would be produced by the scattered protons.

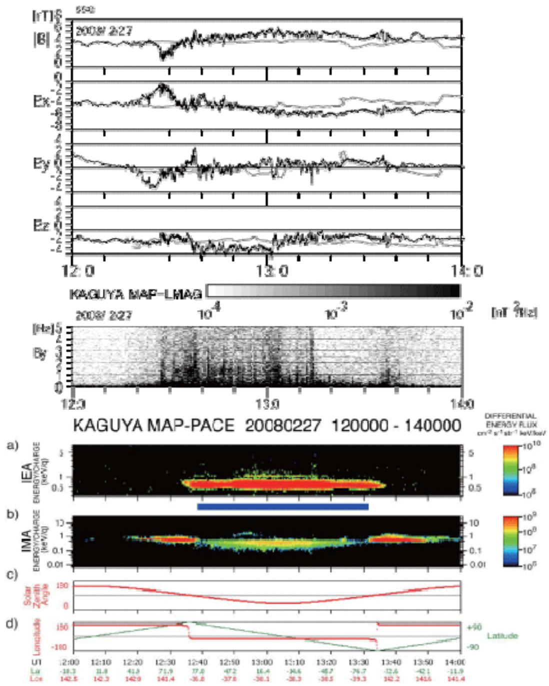

Fig.5

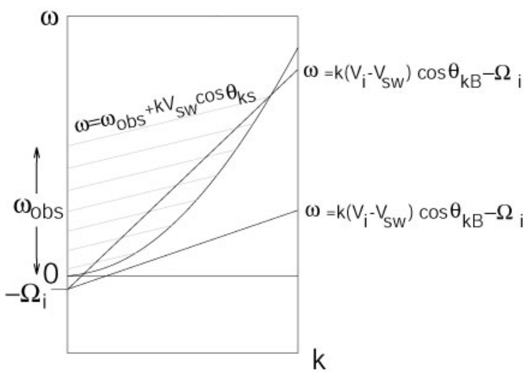

Fig.6

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