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Wave phenomena at Moon: the solar wind–magnetic anomalies interaction

A. Skalsky and **A. Sadovski**
Space Research Institute of Russian Academy of Sciences (IKI RAS) (asadovsk@iki.rssi.ru / Fax: +7-495-3331248)

Abstract

One of the most interesting effect of solar wind interaction with Lunar surface is the formation of such called mini-magnetosphere above the anomalous magnetic regions. The anomalies magnetic field and forming magnetic field discontinuity (shock structure) may reflect solar ind ions and electrons. We perform the review of different mechanisms for the wave generation in plasma environment near such mini-magnetosphere regions.

1. Introduction

The lunar plasma environment seems to be very simple matter but the observations of the interaction in Moon-plasma system has proven that the physical processes are complex and varied. Especially it should be noted that the interaction have a kinetic nature and must be studied using kinetic theory.

One of important processes is the solar wind interaction with Moon surface. There are regions of enhanced crustal magnetic field so called magnetic anomalies, where a magnetic field may reach till several hundred nT [1, 2, 3]. The observations of Kaguya and Chandrayaan revealed that significant deflected proton fluxes exist over magnetic anomalies at the lunar surface [4, 5, 6, 7]. Such deflection may imply that the magnetic anomalies may act as magnetosphere-like obstacles (mini-magnetospheres), modifying the upstream plasma. Moreover the observations of energetic neutral atoms showed that the enhanced fluxes of deflected particles may exist [9, 8].

We perform the review of different mechanisms for the wave generation in plasma environment near such mini-magnetosphere regions.

2. Solar wind interaction with magnetic field anomalies

The interaction of the solar wind with magnetic anomalies may result in formation of miniature magnetosphere. The main observational features revealing such concept are the existence of the MHD waves with 40–80 km/s speed in the solar wind reference frame, the growth of the plasma density.

The possibility of the minimagnetosphere formation depends upon two conditions:

- the magnetic field pressure should be big enough to balance the solar wind dynamic pressure;
- the characteristic minimagnetosphere size should be bigger than the proton gyroradius.

For typical solar wind conditions magnetic field necessary for the mini-magnetosphere formation should be 7–230 nT. The magnetic field in magnetic anomalies may be more than 20–27 nT. In papers [10, 11] authors presented the simple model for the ion reflection from anomaly. The main conclusion was that the some shock structure may forms and great deflection of electrons is possible. However, presented model of reflection may be appropriate only for strong magnetic anomalies and the amount of deflected ions should be very sensitive to the solar wind conditions.

However if we estimate the solar wind electron energy after shock it appears to be equal $E_e \sim 3 \times 10^{-12}$ erg/nuc. Maximum energy, that may be gained to proton deceleration is $E_i \leq 10 E_e$, but the energy of proton solar wind component is $E_{SW} \sim 9 \times 10^{-10}$ erg/nuc. So the energy gain is too low to stop the protons and they fill the magnetic cavity.

3. Wave activity near the Moon

Variety of electric fluctuations was observed during the passage of Wind spacecraft across the lunar wake: langmuir waves, electrostatic modes above electron cyclotron frequency, whistlers [12]. The investigations by Kuncic and Cairns [13] revealed emissions on plasma frequency and its first harmonic. Electron reflection at quasi-shock at leading edge of magnetic anomaly could drive the electric field oscillations. The generation mechanism is similar to that known for foreshock of planetary bow shock.

In KAGUYA [14] and Lunar Prospector [15] missions the monochromatic whistlers near the Moon were observed as narrow band magnetic fluctuations with frequencies close to 1 Hz, and are mostly left-hand polarized in the spacecraft frame. The waves are 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. It is suggested that ion beams reflected by the lunar magnetic anomalies are a possible source of the waves.

Also large-amplitude monochromatic ULF waves were observed on Kaguya spacecraft [16]. The dominant periods of waves are of 120–100 s. The amplitude was as large as 3 nT. The occurrence rate is high above the terminator and on the dayside surface. The direction of the propagation is not exactly parallel to the interplanetary magnetic field, but shows a preference to the direction of the magnetic field and the direction perpendicular to the surface of the moon below the spacecraft. The sense of rotation of the magnetic field was left-handed with respect to the magnetic field in 53% of the events, while 47% showed right-handed polarization. The possible generation mechanism is the cyclotron resonance of the magnetohydrodynamic waves with the solar wind protons reflected by the moon. Most of events occur in the southern hemisphere of the Moon over region of lunar magnetic anomalies.

Non-monochromatic fluctuations of the magnetic field over the frequency range of 0.03-–10 Hz were detected by Kaguya [17] at an altitude of 100 km above the lunar surface. The fluctuations were almost always observed on the solar side of the moon, irrespective of the local lunar crustal field. They were also detected just nightside of the terminator (SZA $< 123°$), but were absent around the center of wake. The level of the fluctuation enhanced over the wide range from 0.03 to 10 Hz, with no clear peak frequency. The fluctuations had the compressional component, and the polarization was not clear. The fluctuations were supposed to be whistler waves generated by the protons reflected by the lunar surface.

4. Summary and Conclusions

Waves occur in wide frequency range from f_{ci} to f_{pe}. Observations of wide band electric noise (above f_{ce}) seem to be related to short electric spikes. Wave phenomena observed at Moon are mostly associated with the wake boundary and lunar crust magnetic anomalies. Most of emissions are detected simultaneously with enhanced fluxes of reflected from the Moon surface (crust anomaly) ions and electrons.

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