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Coupling of earth's magnetosphere, solar wind and lunar plasma environment

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Abstract

The Moon does not have significant atmosphere and magnetic field. So it was considered like a passive absorber of incoming plasma. The latest observation revealed that the significant deflected proton fluxes exist over magnetic anomalies at lunar surface. Such deflection implies that the magnetic anomalies may act as magnetosphere-like obstacles (mini-magnetospheres), modifying the upstream plasma.

The present paper is aimed to describe one possible deflection mechanism and its relations to solar wind conditions. It was obtained that for considered conditions the suggested mechanism gives too low density of deflected protons. However for the big anomaly it can give amount of deflected protons in accordance with the observations.

Keywords: Moon; Mini-magnetosphere; Solar wind

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. As the Moon does not have any significant atmosphere and global magnetic field it seems that the solar wind must be absorbed by lunar regolith. However there are regions of enhanced crustal magnetic field so called magnetic anomalies, where a magnetic field may reach till several hundred nT (Coleman et al., 1972; Lin, 1979; Lin et al., 1998). The observations of Kaguya and Chandrayaan revealed that significant deflected proton fluxes exist over magnetic anomalies at the lunar surface (Holmström et al., 2010; Saito et al., 2008; Saito et al., 2012; Wieser et al., 2009). 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 (Futaana et al., 2006; Wieser et al., 2010).

The measurements by Lunar Prospector show that the surface magnetic field may be represented by dipole and in interaction with the solar wind shock-like structure should be formed (Lin et al., 1998). If the reflection takes place on such structure it may be similar to the reflection on the shock wave (see discussion in Lin et al. (1998), where the authors have shown that for the Imbrium anomaly some kind of shock wave can exist). However many observations show that the mini-magnetosphere in many cases does not form (Halekas et al., 2008).

We take the observation performed by Chandrayaan and described in paper Lue et al. (2011). For this case we examine the conditions in solar wind and estimate plasma parameters in solar wind and in crustal magnetic field. Then we make the estimation of the possibility of mini-

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magnetosphere and shock-like structure formation. Also we apply our calculations to the case of big anomaly.

The structure of the paper is following. In Section 2 we describe the proton deflection, in Section 3 parameters of the solar wind are investigated. Section 4 is devoted to interaction model and necessary estimation. The conclusion is in the Section 5.

2. Proton deflection

For the parameters of proton deflection we use the results described in paper Lue et al. (2011). The authors used data received by Solar Wind Monitor (SWIM) (McCann et al., 2007), which was carried by Chandrayaan-1. There was drawn map of observed deflected protons in the 200 eV–1.7 keV energy range. In paper Lue et al. (2011) the deflection efficiencies were estimated. For the entire hemisphere it was at $\sim 1\%$, for the whole anomaly region $\sim 10\%$ and for the strongest anomaly $\sim 50\%$. Such values correspond to efficiencies obtain in other studies (Saito et al., 2010; Wieser et al., 2010).

However in paper Lue et al. (2011) only one case of deflection was presented in details. All our calculations were made for this case. The data were received on 29 April 2009 in time interval between 04:58 and 05:56 UT over the Imbirium antipode magnetic anomalies. The whole proton flux peak value may be estimated as $> 10^8$ protons $\cdot\, \mathrm{cm}^{-2} \cdot \mathrm{s}^{-1} \cdot \mathrm{sr}^{-1}$. The magnetic field at 30 km altitude estimated by Purucker (2008) model (Lue et al., 2011) has 12 nT peak value.

3. Solar wind

Solar wind observations was taken on board WIND spacecraft (courtesy of CDAweb). Fig. 1 shows the magnetic field magnitude, solar wind speed, ion density, ion thermal velocity, electron temperature and dynamic pressure on April 29, 2009. To take the valid time interval (between 04:58 and 05:56 UT) one should take into account time lag about 1 h 20 min. It is seen that the observations at the Moon for time under consideration are made under relatively low solar wind dynamic pressure and velocity. It is seen that observations at Moon are made at peculiar interplanetary conditions when interplanetary magnetic field is practically negligible (of about 0.5 nT), i.e. the solar wind plasma is unmagnetized. So, for considered case we have interaction of the unmagnetized plasma with magnetic obstacle.

4. Estimation of deflection

The observation of the particle deflection over magnetic anomaly was reported by Saito et al. (2012) where Hall-MHD was used for the estimation of the deflection efficiency. However the physical origin of the electric field is the subject of discussion. Suggesting that some kind of shock structure is formed (for example a bow-shock Lin et al. (1998) or a limb-shock), we can use the simple model of deflection of unmagnetized flow from a shock structure and obtain that an electric field in shock structure should exist.

From data presented in previous sections we obtain and use the following values for characteristic parameters. Solar wind velocity is $V_{SW} = 310$ km/s, dynamic pressure is $p = 1.5$ nPa, model magnetic field in anomaly is taken from the model of Purucker (2008) which was used in (Lue et al., 2011) and is equal $B_0 = 12$ nT. Using these values we found the magnitudes of characteristic frequencies and length. In anomaly cyclotron electron frequency is $\omega_{ce} = 2100\ \mathrm{s}^{-1}$, cyclotron ion frequency is $\omega_{ci} = 1.5\ \mathrm{s}^{-1}$, cyclotron electron radius is $r_{ce} = 0.8$ km and cyclotron ion radius is $r_{ci} = 270$ km. Also suggesting that the magnetic field of anomaly has quasi-dipolar form, we can estimate the “magnetopause” radius (balance between magnetic pressure in anomaly and dynamic pressure of solar wind). It is equal $r_M \sim 19$ km.

So we see that in anomaly the electrons become magnetized but ions remain unmagnetized. As a consequence the charge separation should occur. That’s why we perform to check the next scenario (Lue et al., 2011). Magnetized electron are deflected by magnetic field and as protons are unmagnetized and set up a charge separation. An ambipolar electric field may be estimated as

$$E \sim 4\pi enL, \tag{1}$$

where $L > v_{Te}/\omega_{pe} \sim 10$ m (v_{Te} is a thermal electron velocity and ω_{pe} is a plasma frequency).

The crude exaggerated estimate for the amount of deflected protons may be made from the next suggestions. If we suggest that a mini-magnetosphere forms, we should also suggest the existence of some boundary surface. The incident electrons deflect from this boundary and electric field should be created. The maximum amount of deflected protons is equal to the amount of the deflected electrons. As the solar wind flow is almost unmagnetized (see Fig. 1) we use the model by Leroy and Mangeney (1984); Wu (1984) and obtain for the deflected protons (n_r)

$$\frac{n_r}{n} < \left(1 - \frac{B_{SW}}{B_0}\right)^{1/2} \exp\left[-\frac{B_{SW}}{B_0}\frac{L^2}{\lambda_{De}^2}\right], \tag{2}$$

where λ_{De} is the electron Debye length.

For considered conditions in anomaly, with the help of the parameters described above, we obtain $n_r/n_0 < 0.0001$ which is too low to explain observed fluxes.

However it should be mentioned that for Imbrium antipode anomaly surface magnetic field strength is approximately 100 nT (Mitchell et al., 2008). Taking the pressure balance for the cited parameters we obtain that magnetic field strength B_0 on the mini-magnetosphere boundary is $B_0 = 45$ nT. Putting this value to the Eq. (2) we obtain $n_r/n_0 < 0.49$ which is coincide with observations by Lue et al. (2011).

Let us discuss the applicability of the Eq. (2). The characteristic time for electron reflection is ω_{ce}^{-1} and is enough to create the electric field and to maintain the ion reflection