Title: Three-dimensional structure of the boundary current in a mini-magnetosphere above a lunar magnetic anomaly

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Abstract

We studied the three-dimensional structure of the boundary current in a mini-magnetosphere created above the magnetic anomaly on the lunar surface by performing electromagnetic particle-in-cell simulations. The size of a magnetic anomaly can be characterized by the distance L from the center of the magnetic dipole to the position where the pressure of the local magnetic field becomes equal to the dynamic pressure of the solar wind under the magnetohydrodynamics (MHD) approximation. In this study, we focused on a magnetic anomaly which has L smaller than the local ion Larmor radius r_{iL} observed at the distance of L from the dipole center. In the simulation results for the case $r_{\mathrm{iL}}/L = 4$, we confirmed that a mini-magnetosphere is formed by the interaction of the magnetic anomaly with the incoming solar wind plasma. As examined in the previous studies, we also found an asymmetric density profile of the mini-magnetosphere with respect to the solar wind direction. At the boundary layer of the magnetosphere, intense boundary current is observed. We found that the boundary current is mainly due to cross-field motions of electrons whose Larmor radius is much smaller than L. Considering that intense outward electric field is induced by the charge separation between the magnetized electrons and the weakly magnetized ions at the boundary layer, the solar wind electrons encountering the magnetic anomaly region make the E $\times$ B drift motion in perpendicular to the magnetic dipole. In the case where the direction of the magnetic field is southward in the dayside region, the electron drift motion is in the dawn-to-dusk direction in the low to mid-latitude region. At the high latitude region, on the other hand, the direction of the electron cross-field motion changes and it becomes from the dusk to the dawn side. It is because of the curvature of the dipole field and the direction of the magnetic field lines becomes locally different in the high latitude region from that in the equatorial plane while the induced electric field basically points outward at the boundary layer. We revealed that this two-layer structure of electron flow between the low and mid-latitude and the high latitude is very characteristic in the mini-magnetosphere created above magnetic anomaly.

Keywords

Three to ten keywords representing the main content of the article.

Background (or Introduction)

The lunar plasma environment has been intensively investigated with the recent in situ observation by scientific spacecraft such as KAGUYA[参考文献] and Chandrayaan-1[参考文献]. In addition to the macroscopic structure of plasma distribution such as the wake structure with low density of plasma formed in the downstream region, small-scale perturbation of plasma distribution and fields are newly observed in the dayside region mostly over the crustal magnetic anomalies found on the lunar surface. In the KAGUYA spacecraft observations, more than 10% of solar wind protons are reflected at 100km over the magnetic anomalies [Saito et al., 2010]. Chandrayaan-1 found the deflection of the solar wind protons with high efficiency more than 10% [Lue et al., 2011] and it also observed the backstreaming ions over the magnetic anomalies [Wieser et al., 2010]. In association with the plasma variation, plasma wave activities are also enhanced over the magnetic anomalies [???]. To understand these solar wind responses, double layer structure at the dayside magnetopause was proposed from the observational point of view [Lue et al., 2011], [Saito et al., 2012]. These observational facts suggest that the plasma and field disturbances over the magnetic anomalies are caused by the solar wind interactions with the local magnetic fields of the magnetic anomalies. Unlike the case of the Earth 's magnetosphere, however, the dipole moment of the magnetic anomalies on the lunar surface is very weak and the resulting dipole field region is much smaller than the characteristic spatial scale of the solar wind such as the ion inertial length and the ion's Larmor radius r_{iL}. When we define L as the typical scale of a magnetic dipole, L can be an equilibrium point with the MHD approximation where the plasma dynamic pressure balances to the local magnetic pressure of the dipole field. In the situation of the lunar magnetic anomalies, L can be less than 100km and becomes smaller than r_{iL} of the solar wind proton. In such a situation, the protons are assumed unmagnetized and the interactions with the dipole field becomes loose because the finite Larmor radius effect cannot be ignored. Then the ions dynamics can be little affected by the local field of magnetic anomalies. However, as stated above, variation of ion dynamics such as the ion reflection are obviously observed by spacecraft. Plasma flow response to such a small-scale magnetic dipole has been examined in different situations. When L is comparable to or smaller than r_{iL} but large enough in comparison with the electron Lamor radius r_{eL} we call this range meso-scale. As one of the feasibility studies of a future interplanetary flight system called magneto-sail, the solar wind interactions with a meso-scale magnetic dipole artificially created by a superconducting cold equipped at a spacecraft has been examined with two-dimensional particle-in-cell plasma simulations [Moritaka et al., 2012]. They confirmed a clear formation of a magnetosphere even in a meso-scale regime. In the interactions between the solar wind and a meso-scale magnetic dipole, it can be assumed that electrons are magnetized while ions are not much at the magnetopause. Then electric field is induced at the dayside magnetosphere by charge separation due to the momentum difference between electrons and ions. The plasma responses to the induced electric field were also examined in the previous simulation studies using particle model [Harnett and Winglee, 2002; Kallio et al., 2012; Poppe et al., 2012; Deca et al., 2015]. Laboratory experiments associated with the plasma interactions with small-scale magnetic dipole were also conducted and electric potential and electric field in the interactions were examined [Wang et al., 2013] [Bamford et al., 2012] [??????, boulder 2015] . As pointed in many previous studies, plasma kinetics should be included in modeling the interactions between the solar wind and the magnetic anomalies because L is smaller than r_{iL}. In this letter, by performing three-dimensional electromagnetic particle-in-cell simulations we will describe the spatial structure of the boundary current layer in the mini-magnetosphere formed above a magnetic anomaly. The boundary current in the mini-magnetosphere mainly consists of electron current. Therefore we particularly focus on the electron dynamics in the boundary layer in the three-dimensional simulation results. In Section II, we describe the simulation model used in this study. In our model we mainly examined a case of $r_{\mathrm{iL}}/L = 4.$ for the magnetic anomaly. In Section III, we describe the spatial variation of plasma density and the current density obtained in the simulations. We also examine the electron dynamics in the boundary layer in the three-dimensional domain. In Section IV, we summarize the results.

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Equations with line numbers can be written as

$$\sin^2\theta + \cos^2\theta = 1, \tag{1}$$

between `\begin{linenomath}` and `\end{linenomath}`.

Methods

We performed three-dimensional, full kinetic, electromagnetic PIC simulations to examine the boundary layer of a mini-magnetosphere above a magnetic anomaly. In the simulation, Reiner Gamma, which is one of the typical magnetic anomalies on the lunar surface, is refereed to as a model of magnetic anomaly. In the Reiner Gamma case, the magnetic dipole moment is almost parallel to the lunar surface. The dipole center is approximately located at a depth of 10 km under the ground. The amount of the dipole moment is ***. Figure 1 shows a three-dimensional simulation model. In the positive x direction, we have a plasma flow representing the solar wind. The static magnetic field representing IMF is also introduced in the simulation domain. In this study, the direction of IMF is northward. The Mach number M which is a ratio of the plasma flow velocity $V_{\rm flow}$ to the Alfven velocity $V_{\rm A}$ is 5. The values used for the plasma flow parameters are as follows. Instead of using actual measured physical values, we used scaled ones. To reduce the calculation time, we set the mass ratio to be a value between the mass of an ion and that of an electron, $m_{\rm i}/m_{\rm e} = 100$ （これ梅沢モデルだよね。。）. We set the ratio of the speed of light V_c to V_{flow} to be 25, although the actual ratio is about 600. We set the ratio of the electron thermal velocity $V_{\rm th}$ to $V_{\rm flow}$ to be 2.5, which is almost the same as the actual ratio for the solar wind. When $r_{\rm iL}/L = 4$, the ratio of the electron plasma frequency to the cyclotron frequency, ω pe/Ω pe, was set to be 250 at a distance L from the dipole center. The simulation domain consists of $256 \times 256 \times 256$ cells, and the length of each side of the domain was approximately $5L$. The cell size dx corresponds to $\lambda_{\rm D}$, where $\lambda_{\rm D}$ denotes the Debye length in the solar wind plasma. The time increment dt was chosen to satisfy the Courant condition, $dx/dt > 1.73V_c$, in three dimensions. The plasma flow typically consists of 4×10^9 macroparticles in the simulation space. In the center of the simulation domain, we set an ideal dipole magnetic field with a magnetic moment M. The magnetic moment is arranged in the z direction, and the resulting magnetic field was taken into account in the equation of motion when the velocity of each particle was updated. Absorbing boundary conditions were used for the electromagnetic field on all of the outer boundaries. We flow plasma particles into the simulation domain to the lunar surface at the velocity of $V_{\rm flow}$ with a thermalized distribution. Particles leaving the simulation domain are eliminated from the calculation. Since we assumed space plasma, we assumed there were no collisions between particles. We performed the simulation to iterate until the spatial variation of the plasma density reached a steady state.

Results and Discussion

Figure 2 shows contour maps of the number densities of electrons and ions and the charge density obtained at the steady state in the meridian plane which includes the sunward direction. As shown in the left two panels, a clear magnetosphere which is a plasma evacuated region is created above the magnetic anomaly region as studied in the previous works such as *******. In panel (a) which shows the electron density, the boundary of the magnetosphere seems very clear along the dipole fields and the density becomes relatively high in the high latitude regions because of the convergence of the magnetic fields. In panel (b) indicating the ion density, we also recognize the magnetosphere as shown in the electron density map. However, the boundary does not seem so clear as in the electron case. Across the electron boundary region shown in panel (a), some ions reach the inner magnetosphere where no electrons exist. The magnetosphere itself seems compressed along the horizontal axis corresponding to the solar wind direction. The ion density is also relatively high in the high latitude regions. In comparison between panels (a) and (b), the spatial profiles of the magnetosphere are similar to each other. However, because there are some differences in the density profiles as stated above, we found a spatial variation in terms of charge density as shown in the contour map in panel (c). Since the charge density variation causes the electric potential, we superimpose arrays of the resulting electric field on the contour map. The contour map in panel (c) shows that ions are rich in the inner magnetosphere as shown in red region while the boundary layer surrounding the ion rich region is shown in blue indicating electrons are relatively rich. Because of this charge separation at the boundary layer, intense electric field is induced as shown in the arrows pointing radially to the outward direction to the magnetosphere. (2015/09/11)

Figure 3 shows contour maps of f the number densities of electrons and ions and the charge density in the equatorial plane in the same manner as in Figure 2. One of the interesting features we notice is asymmetric profile of the magnetosphere. As shown in panels (a) and (b), a high density region is created at the upper side of the boundary of the magnetosphere which corresponds to the dawn side. Panel (c) shows the charge density. The profile is overall similar to that in panel (c) in Figure 2. Ions which have larger inertia than electrons reach the inner magnetosphere and an ion rich region is created. As shown in panels (a) and (b), the charge density also has an asymmetric profile. In the dawn region, electron rich region is locally created near the lunar ground. Due to this charge separation in the boundary region of the magnetosphere, intense electric field pointing outward is also found in the equatorial plane. Because of the electron rich region at the dawn side near the surface, some electric fields point there.

Figure 4 shows the contour maps of the total current density at the different latitudes. Panels (a) and (b) show the profiles in the equatorial plane and in high latitude plane of z=*** respectively. The vector arrays of the current components in the $x-y$ plane are superimposed on the contour maps. In the equatorial plane shown in panel (a), the current density is intense at the boundary layer of the magnetosphere. The direction of the current is along the positive y direction which corresponds to the dawn direction. As shown in the density profile, the current density profile is also asymmetric and intense current is found at the dawn side. In panel (b), however, the direction of the most intense current is different from that in panel (a). It is observed near the lunar surface pointing to the dust side. To examine the detail of the current, we decompose the total current into electron current and ion current as shown in Figure 5. We plot the electron and ion current densities measured along a line of $y = 0$ in black and red, respectively. Panels (a) and (b) show the profiles in the different latitudes in the same manner as shown in the previous figure. As shown in the both panels, the ion current shown in red is relatively small in comparison with the electron current. It implies that the boundary current is dominated by the electron current. In panel (a), the ion current has a peak at the inner magnetosphere where almost no electrons are found. The current flows in the positive y direction. In panel (b) corresponding to the high latitude region, the electron current has two peaks in the opposite directions. One found around x=*** point to the positive y direction while the other found around $x = **$ which is close to the ground has a much higher peak pointing to the negative y direction. These profiles agree with the vector plots shown in Figure 4. To see the overall profile of the boundary current, we plot a all sky view of the electron current with the vector arrays in Figure 5 which is observed from the ground in the magnetic anomaly region. As shown in the figure, two current volteces are found in each hemisphere. In the l

Subsection

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Conclusions

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Appendix A. An example of appendix

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Endnotes

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