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Control of lunar external magnetic enhancements by IMF polarity: A case study

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ABSTRACT

We study an interaction between the solar wind and crustal magnetic fields on the lunar surface using SELENE (Kaguya) data. It has been known that magnetic enhancements are at times detected near the limb external to the lunar wake, which is thus called lunar external magnetic enhancement (LEME), as a result of direct interaction between the solar wind and lunar crustal fields. Although previous observational studies showed that LEMEs in the high solar zenith angle region favor stronger interplanetary magnetic field (IMF) and higher solar wind density, the relation between the IMF and the crustal field orientation has not been taken into account. We show evidence that the relation between the IMF and crustal field orientation is also one of the key factors that control the extent of LEME, focusing on one-day observations at 100 km altitude that include data above strong crustal fields around South Pole-Aitken (SPA) basin. Strong LEMEs are detected at 100 km altitude around SPA basin under the stronger and northward IMF condition, while they weaken under southward IMF. All LEME's peaks are located in the region where unperturbed crustal fields at 300 km altitude are directed northward while they are less related to unperturbed crustal fields at 100 km or lower, which suggests that lunar crustal fields are compressed by the solar wind dynamic pressure, and its large scale component parallel to the IMF is essential to the formation of the LEME.

1. Introduction

Although the Moon has no global magnetic field, a non-negligible fraction of its surface is locally magnetized and can interact with the ambient magnetic field and plasma (Dyal et al., 1972). The spatial scale sizes of the crustal magnetic fields are from less than 1 km to several hundreds of km, and its strength ranges from a few nT to several hundreds nT at the surface (e.g. Halekas et al., 2006; Mitchell et al., 2008; Purucker, 2008; Tsunakawa et al., 2010). The strength of the crustal fields rapidly decreases with altitude to be only a few nT at most at 100 km (Tsunakawa et al., 2010) which is the altitude of typical lunar orbiters. The spatial scale and strength of the crustal fields would put their interactions with the solar wind in an intermediate regime between fluid-type and kinetic ones (Halekas et al., 2006).

One of the most prominent features of interactions between the solar wind and lunar crustal magnetic fields is magnetic enhancements, which have been observed by lunar orbiters (Halekas et al., 2011 and references therein). Magnetic enhancements near the limb external to the lunar wake were found in initial observations by Lunar Prospector and termed limb shocks or limb compressions, because they were thought to be a manifestation of a shock-like interaction or compressional wave excitation that resulted from direct interactions between the solar wind flow and lunar crustal magnetic fields (Lin et al., 1998). In later years magnetic enhancements including the limb shocks/compressions are generalized and termed Lunar External Magnetic Enhancements (LEMEs) (Halekas et al., 2006). Their statistical study revealed that locations of LEMEs are indeed related to the crustal fields; magnetic fields detected above the regions around the strong crustal fields were very strong (say ~ 30 nT), which is much stronger than unperturbed crustal field components at the altitude (1–2 nT at 100 km altitude) and also 2–3 times as strong as the original interplanetary magnetic field (IMF). Another important finding is that occurrence condition of LEMEs depends on its solar zenith angle (SZA); At high SZA ($>60^{\circ}$), stronger IMF and higher solar wind density (i.e. smaller gyroradius and smaller inertial length) are favorable for LEME

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formation, which suggests that the high-SZA LEME is manifestation of a fluid-like interaction between the solar wind and the crustal magnetic fields. At low SZA ($<60^\circ$), on the other hand, preferred conditions for LEME formation are stronger IMF and higher Alfvén speed that enable a larger stand-off distance of a fast-mode shock from an obstacle and thus suggest a more shock-like interaction.

Meanwhile, one of the strongly magnetized regions is located near the northern edge of South Pole-Aitken (SPA) basin in the southern hemisphere on the farside (e.g. Halekas et al., 2006; Mitchell et al., 2008; Tsunakawa et al., 2010). The spatial scale of the magnetized region is as wide as several hundreds km in both longitudinal and latitudinal directions, which possibly enables a fluid-type (or shock-like) interaction between the solar wind and the crustal fields. Since many LEMEs in the statistical study by Halekas et al. (2006) are located around the strong crustal field region near the SPA basin, LEMEs around the SPA basin may result from typical interaction between the solar wind and the crustal fields.

Then, how does a particular strong crustal field respond to various solar wind conditions? To know this will let us obtain a clue toward understanding the formation mechanism of LEMEs. In this paper we focus on one-day observations above the SPA basin to examine what controls the extent of magnetic enhancements.

2. Instrumentation and coordinates

We use magnetometer data obtained by MAP (MAgnetic field and Plasma experiment)-LMAG (Lunar MAGnetometer) onboard a Japanese spacecraft SELENE (Kaguya) which orbits the Moon in a polar orbit at ~ 100 km altitude with a 2 h period. The time resolution of the raw data is 32 Hz (Shimizu et al., 2008; Takahashi et al., 2009), and we use 1-s averaged data and 1-min averaged data in this paper. The solar wind ion data at the lunar orbit are obtained by MAP-PACE(Plasma energy Angle and Composition Experiment)-IEA (Ion Energy Analyzer) which looks upward to detect SW ions on the dayside with a hemispherical field of view (Yokota et al., 2010). The energy-per-charge range of IEA used in this paper is 0.3 keV/q–8 keV/q, and its time resolution is 16 s or 2 s. As the solar wind data far upstream of the Moon, we use ACE MAG and SWE data. We use the geocentric solar ecliptic (GSE) coordinate system, the selenocentric solar ecliptic (SSE) coordinate system, and the mean Earth/polar axis (ME) coordinate system.

3. Observations

3.1. An overview

We examine SELENE and ACE data on September 3, 2008. On this day the Moon was located around (44, 43, -5) R_E in GSE, being exposed to the solar wind in the region far upstream of the Earth's bow shock.

ACE is located at $X_{\mathrm{GSE}} = 243\ R_E$ and observed the solar wind. The IMF is very weak ($\sim 1-3$ nT) until 03:55 UT, while it changed to be stronger than 10 nT after 5 UT (Fig. 1a). The solar wind density was higher than 10 cm^{-3} except several hours after 17 UT (Fig. 1c). These solar wind conditions after 4 UT are suited for occurrence of LEMEs at higher SZA regions (SZA $> 60^\circ$) (Halekas et al., 2006).

On the day the orbital plane of SELENE has an inclination of roughly 35 $^\circ$ with respect to the noon-midnight meridian plane, with duskside passes on the dayside and dawnside ones on the nightside. During first two passes no magnetic enhancement is observed even above strong crustal fields, while strong magnetic enhancements in the southern hemisphere on the lunar dayside are repeatedly detected after 5 UT (Fig. 1a). All of the enhancements occur around the northern edge of the SPA basin (Table 1) under the strong IMF (>10 nT) and relatively high solar wind density.

Meanwhile, the extent of magnetic enhancement after 5 UT (i.e. passes from #3 to #12) varies event by event, although the solar wind conditions do not show clear variations and the spacecraft flew above the almost same region. To examine what controls the extent of the magnetic enhancements, three typical cases are studied in the following section.

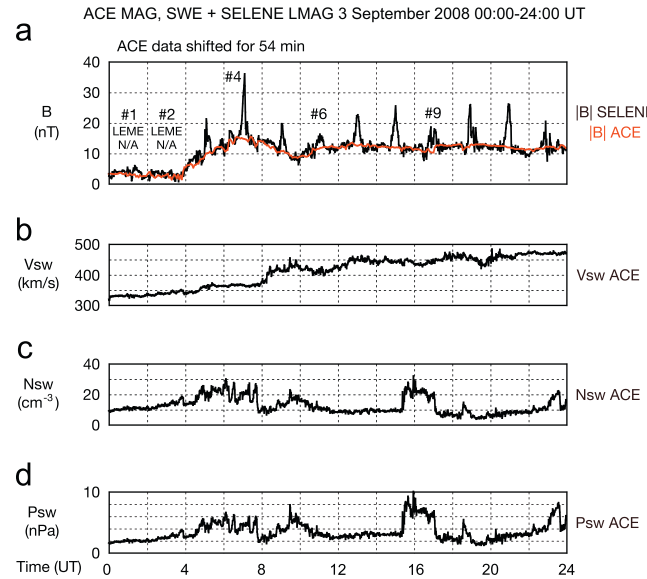

Fig. 1. An overview of LEME observations on 3 September 2008. Upstream solar wind data obtained by ACE and magnetic field strength measured by SELENE on the day are shown. From the top: (a) magnetic field strength measured by SELENE (black) and ACE (red, time shifted), (b) SW density, (c) SW speed, and (d) SW dynamic pressure are presented. For simplicity, convection period from ACE to the Moon is fixed to be 54 min in this figure. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

3.2. A strong LEME

We first examine a typical LEME around 7 UT when the magnetic field at SELENE is the strongest observed on this day (Fig. 2). After passing over the South Pole around 06:57 UT, SELENE goes to the north on the dayside and detects a strong enhancement of the magnetic field between 06:57 and 07:11 UT. The footprint of SELENE for the LEME period is along longitude 177°E and its latitude ranges from 90°S to 47°S. The LEME in the wide region with higher SZA is similar to those reported in the previous study (See Fig. 2 in Halekas et al., 2006).

To avoid influence of low frequency waves above the crustal fields, we use 1-min averaged SELENE/LMAG data to find the peak of the LEME. The peak of the magnetic enhancement takes place around 07:08 UT when the latitude of the spacecraft is $\sim 55^\circ$S and its SZA is $\sim 61^\circ$. The magnetic field strength at the LEME peak is 36 nT while the IMF at ACE is 14.7 nT, which means that magnetic enhancement ratio is $\sim$ 2.5 and magnetic field increase (δB) is 21.3 nT. Because the contribution of unperturbed crustal fields at 100 km altitude is ~ 2 nT at most (Tsunakawa et al., 2010), the observed magnetic enhancement shows that the IMF is piled-up above the crustal fields. After the peak at 07:08 UT the magnetic field at SELENE immediately decreases for 3 min until 07:11 UT, which shows very steep magnetic fields in the edge on the low-SZA side of the LEME.