Icarus 250 (2015) 238–248

Contents lists available at ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

Electrons on closed field lines of lunar crustal fields in the solar wind wake

Masaki N. Nishino [a,*], Yoshifumi Saito [b], Hideo Tsunakawa [c], Futoshi Takahashi [d], Masaki Fujimoto [b], Yuki Harada [e], Shoichiro Yokota [b], Masaki Matsushima [c], Hidetoshi Shibuya [f], Hisayoshi Shimizu [g]

[a] Solar-Terrestrial Environment Laboratory, Nagoya University, Furocho, Chikusa-ku, Aichi 464-8601, Japan
[b] Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, 3-1-1 Yoshinodai, Chuo-ku, Sagamihara, Kanagawa 252-5210, Japan
[c] Department of Earth and Planetary Sciences, Tokyo Institute of Technology, Ookayama, Meguro-ku, Tokyo 152-8551, Japan
[d] Department of Earth and Planetary Sciences, Faculty of Science, Kyushu University, 6-10-1 Hakozaki, Higashi-ku, Fukuoka 812-8581, Japan
[e] Space Sciences Laboratory, University of California, Berkeley, CA 94720, USA
[f] Kumamoto University, 2-39-1 Kurokami, Kumamoto 860-8555, Japan
[g] Earthquake Research Institute, The University of Tokyo, 1-1-1 Yayoi, Bunkyo-ku, Tokyo 113-0032, Japan

ARTICLE INFO

Article history:
Received 5 September 2014
Revised 3 November 2014
Accepted 2 December 2014
Available online 11 December 2014

Keywords:
Moon
Solar wind
Magnetic fields

ABSTRACT

Plasma signature around crustal magnetic fields is one of the most important topics of the lunar plasma sciences. Although recent spacecraft measurements are revealing solar–wind interaction with the lunar crustal fields on the dayside, plasma signatures around crustal fields on the night side have not been fully studied yet. Here we show evidence of plasma trapping on the closed field lines of the lunar crustal fields in the solar–wind wake, using SELENE (Kaguya) plasma and magnetic field data obtained at 14–15 km altitude from the lunar surface. In contrast to expectation on plasma cavity formation at the strong crustal fields, electron flux is enhanced above Crisium Antipode (CA) anomaly which is one of the strongest lunar crustal fields. The enhanced electron fluxes above CA are characterised by (1) occasional bi-directional field-aligned beams in the lower energy range (<150 eV) and (2) a medium energy component (150–300 eV) that has a double loss-cone distribution representing bounce motion between the two footprints of the crustal magnetic fields. The low-energy electrons on the closed field lines may come from the lunar night side surface, while supply mechanism of medium-energy electrons on the closed field line remains to be solved. We also report that a density cavity in the wake is observed not above the strongest magnetic field but in its vicinity.

1. Introduction

Although the Earth's Moon does not possess a global intrinsic magnetic field, a large fraction of its surface is magnetised (e.g. Dyal et al., 1974; Purucker, 2008; Richmond and Hood, 2008; Tsunakawa et al., 2010). For example, the crustal magnetic field directly measured at one of the Apollo landing sites is stronger than 300 nT (e.g. Dyal et al., 1974). With a recent remote-sensing technique, it has been revealed that the magnetic fields in the northwest region of the South Pole-Aitken basin on the farside are as strong as 500 nT at the surface (Tsunakawa et al., 2014). These localised crustal magnetic fields are strong enough to interact with the ambient space plasma. When the Moon is in the solar wind, the crustal magnetic fields on the dayside are deformed by the solar–wind dynamic pressure (Dyal et al., 1972) as well as show complicated interaction with the incident plasma (e.g. Saito et al., 2012). In particular, solar wind ion deflection (and/or reflection) is one of the most prominent features detectable over the strong crustal fields (Saito et al., 2010, 2012; Lue et al., 2011), which suggests that the strong crustal magnetic fields may prevent the solar wind protons from accessing the lunar surface. Formation of plasma cavity around the strong crustal fields on the dayside has been reported in an observational study (Halekas et al., 2008a) and simulation studies (e.g. Deca et al., 2014). Low reflectance ratio of energetic neutral atoms also provided evidence that the strong crustal fields prevent the incident solar wind protons from directly coming into the 'mini-magnetosphere' (Wieser et al., 2010). Both observational studies of the possible plasma cavity formation mentioned above (Halekas et al., 2008a; Wieser et al., 2010) focused on the Crisium Antipode (CA) anomaly which is located around Latitude 15°S to 25°S and Longitude ~235°E in the ME coordinate system.

* Corresponding author.
E-mail address: mnishino@stelab.nagoya-u.ac.jp (M.N. Nishino).

http://dx.doi.org/10.1016/j.icarus.2014.12.007
0019-1035/

Meanwhile, a tenuous region called lunar wake is formed on the lunar night side along the solar wind flow (e.g. Bosqued et al., 1996). When the crustal magnetic fields are in the tenuous region of the wake, they are unlikely to show a significant interaction with the ambient tenuous plasma (e.g. Kurata et al., 2005). A previous study reported observations of magnetic fields and electrons at 25 km height in the vicinity of the CA anomaly in the wake, showing a large peak in magnetic field magnitude and a density drop there (Halekas et al., 2008a). However, more detailed observations of plasmas at lower altitude around the strong crustal fields in the wake has been awaited.

In this paper we focus on the observations of plasmas at very low altitude (~14–15 km) right above the CA anomaly region in the wake to show electron behaviours on the magnetic field lines there.

2. Instrumentation and coordinate systems

We use electron, ion, and magnetic field data from a Japanese spacecraft SELENE (Kaguya) which circles the Moon in a polar orbit. The orbital period is about 113 min, and the height from the lunar surface is in the range of ~14–72 km. Electrons are detected with MAP (MAgnetic field and Plasma experiment)–PACE (Plasma energy Angle and Composition Experiment)–ESA (Electron Spectrum Analyzer)-S1 facing upon the lunar surface and ESA-S2 looking up the space, both of which has a hemispherical field of view so that three-dimensional distribution function can be obtained (Saito et al., 2008, 2010). Ions are detected with a surface-facing sensor IEA (Ion Energy Analyzer) and a space-looking sensor IMA (Ion Mass Analyzer) (Saito et al., 2008, 2010). The energy range of ESA-S1 and S2 used in this study is 24 eV–9 keV and 26 eV–16 keV, respectively. The energy ranges are divided into 32 different steps and swept every 16 s, and data at one energy step are obtained in a 0.5 s period. The energy-per-charge range of IEA and IMA in this study is 0.3 keV/q–8 keV/q and 18 eV/q–28 keV/q, respectively. (These energies are central values in lowest and highest energy bins.) Magnetic field along the orbit is measured by MAP-LMAG (Lunar MAGnetometer) with a time resolution of 32 Hz (Shimizu et al., 2008; Takahashi et al., 2009; Tsunakawa et al., 2010), and 1-s averaged data are used in this study.

Solar wind data from Wind spacecraft around the L1 point far upstream of the Moon are used. 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. We also use the spacecraft (SC) coordinate system in which $+Z$ is directed toward the nadir (i.e. lunar surface), $+X$ (or $-X$) is the travel direction of the spacecraft, and Y completes the right-handed coordinate system. The elevation angle of the magnetic field in the SC coordinate system is defined as $\theta_{B_{SC}}$.

3. Observations

We study plasma and magnetic field data on 29 May 2009 when the SELENE spacecraft flies at 14–15 km altitude over the strongest crustal fields at the CA anomaly on the night side. The Moon is

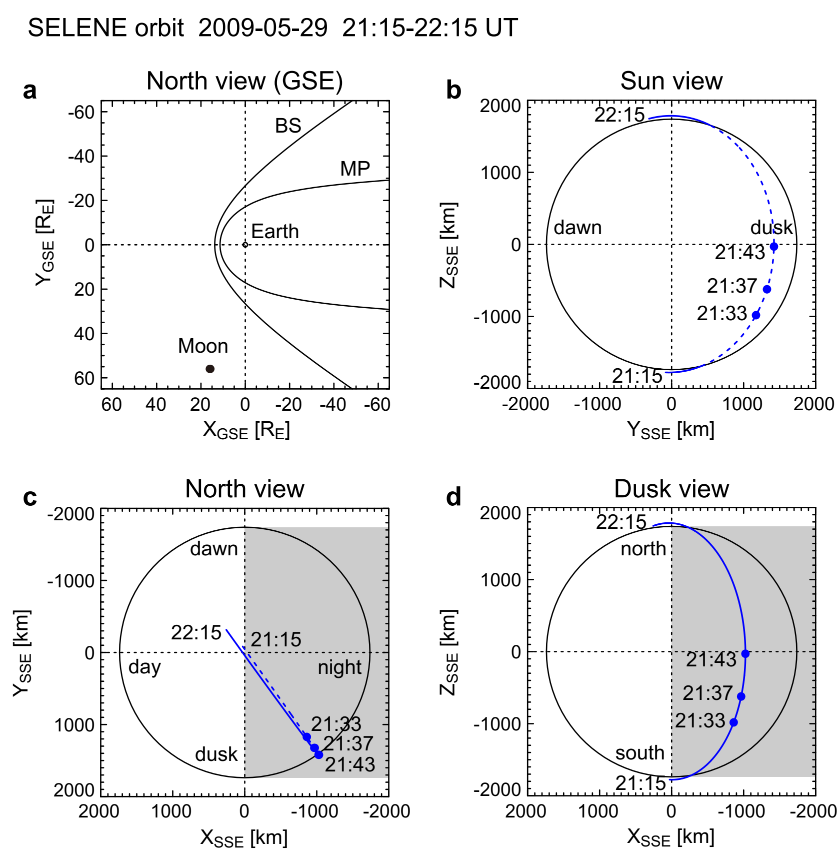

Fig. 1. (a) Location of the Moon in GSE coordinate viewed from the north. Two black solid curves in this panel show the typical locations of the Earth's bow shock (BS) (Slavin and Holzer, 1981) and magnetopause (MP) (Shue et al., 1997). (b–d) SELENE orbit in the SSE coordinate system for 1 h between 21:15–22:15 UT on 29 May 2009 which includes a northward path in the wake. The locations of the spacecraft at 21:33, 21:37, and 21:43 UT (see Fig. 2 and the main text) are shown by larger blue circles. Solid portions of the orbit show that the spacecraft is in front of the Moon, while dotted portions show that it is behind the Moon. The grey zones in north-view and dusk-view panels display the optical shadow of the Moon. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)