Solar-wind proton access deep into the near-Moon wake


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We study solar wind (SW) entry deep into the near-Moon wake using SELENE (KAGUYA) data. It has been known that SW protons flowing around the Moon access the central region of the distant lunar wake, while their intrusion deep into the near-Moon wake has never been expected. We show that SW protons sneak into the deepest lunar wake (anti-subsolar region at ~100 km altitude), and that the entry yields strong asymmetry of the near-Moon wake environment. Particle trajectory calculations demonstrate that these SW protons are once scattered at the lunar dayside surface, picked-up by the SW motional electric field, and finally sneak into the deepest wake. Our results mean that the SW protons scattered at the lunar dayside surface and coming into the night side region are crucial for plasma environment in the wake, suggesting absorption of ambient SW electrons into the wake to maintain quasi-neutrality. Citation: Nishino, M. N., et al. (2009), Solar-wind proton access deep into the near-Moon wake, Geophys. Res. Lett., 36, L16103, doi:10.1029/2009GL039444.

1. Introduction

[2] Studying interaction between the solar wind (SW) and the Moon is important for understanding the lunar plasma environment. The near-Moon space environment is characterized by a tenuous tail-like region formed behind the Moon along the SW flow, which is called the lunar wake [Lyon et al., 1967]. Concerning the near-Moon wake environment, it has been believed that high-energy component of the SW electrons can approach the lunar nightside surface while the SW protons are unlikely to approach the lunar nightside region, because the thermal speed of SW protons is much lower than the SW bulk speed. According to previous models, the electron-rich status of the lunar wake yields bipolar (inward) electric field at the wake boundary where SW protons gradually intrude toward the wake center along the interplanetary magnetic field (IMF) in the distant wake [Ogilvie et al., 1996; Bosqued et al., 1996; Trávníček et al., 2005].

[3] Although signatures of electrons and magnetic fields in the near-Moon wake have been fairly well understood [Halekas et al., 2005], proton behaviors in the near-Moon wake were not known because there were no observation data. Recently, a Japanese lunar orbiter SELENE (KAGUYA) performed comprehensive measurements of the plasma and electromagnetic environment around the Moon; in particular, entry of SW protons into the near-Moon wake was found [Nishino et al., 2009]. The SW protons are accelerated by the bipolar electric field around the wake boundary and come into the near-Moon wake by their Larmor motion in the direction perpendicular to the IMF. This entry mechanism, which we call ‘Type-I entry’, lets the SW protons come fairly deep into the wake (solar zenith angle (SZA) 150°) at 100 km height.

[4] Another outstanding feature of the lunar plasma environment found by SELENE observations is scattering/reflection of the SW protons at the lunar dayside surface (hereafter, we simply refer it as scattering). About 1 percent of the SW protons that impact against the lunar dayside surface are scattered and then picked-up by the SW to obtain at most 9 times the original kinetic energy [Saito et al., 2008a]. This energization, which is called ‘self-pick-up’ process, occurs on the dayside, and the destination of the self-picked-up protons has never been known.

[5] The phenomenon that we deal with in this paper is an unexpected detection of the SW protons in the deepest (anti-subsolar, low-altitude) region of the near-Moon wake. Because Type-I entry cannot let the SW protons come into the deepest wake, another entry mechanism must be at work for this phenomenon. In the present study, we show that the SW protons scattered at the lunar dayside surface access the deepest wake, which should be categorized as ‘Type-II entry’.

2. Instrumentation

[6] We use data obtained by a Japanese spacecraft SELENE (KAGUYA) which is orbiting the Moon in a polar orbit at ~100 km altitude with 2-hour period. The MAP (MAgentic field and Plasma experiment) instrument onboard SELENE performs a comprehensive diagnosis of electromagnetic and plasma environment in the near-Moon space by means of in-situ measurements of electrons, ions, and magnetic field. MAP-PACE (Plasma energy Angle and Composition Experiment)-IMA faces the lunar surface to measure up-going positive ions whose energy per charge is between 7 eV/q and 29 keV/q with a half-sphere field of view (FOV) [Saito et al., 2008b]. MAP-PACE ESA (Electron Spectrum Analyzer)-S1 with a similar FOV as IMA is for measurement of electrons with energy between 5 eV and 10 keV. The time resolutions of IMA and ESA-S1 data in the present study are 32 sec and 16 sec, respectively. Although IMA is originally designed for detecting tenuous ions from the lunar surface, it also measures SW ions...
around the day-night terminator and near the wake boundary because of its large FOV (Figure 1). Magnetic field is measured by MAP-LMAG (Lunar MAGnetometer) with a time resolution of 32 Hz [Shimizu et al., 2008].

3. Observation

On 24 September 2008 the Moon was located at \((X, Y, Z) = (28, -51, 1)\) \(R_E\) in the GSE coordinate system, interacting with the SW flow upstream of the Earth’s bow shock. The SW speed observed by the Wind spacecraft was \(\sim 300\) km/s (\(\sim 0.47\) keV for protons), and the IMF whose strength was about 5 nT was dominated by the negative \(B_Y\) component. On the day the SELENE spacecraft flew near the noon-midnight meridian plane, orbiting from south to north on the dayside and going through the tenuous wake on the nightside (Figure 1). We first mention proton signatures observed by SELENE between 09:10–11:10 UT. Before 09:38 UT the protons scattered at the lunar dayside surface [Saito et al., 2008a] were detected by IMA (Figure 2a). The spacecraft passed above the North Pole (NP) at 09:37 UT and crossed the boundary between sunlit and shadowed regions at 09:44 UT. Between 09:36–09:51 UT SELENE observed SW proton entry near the NP, which is categorized into ‘Type-I entry’ [Nishino et al., 2009] by which SW protons come deep into nightside (deepest at SZA 150°). After SELENE passed through the almost vacuum region in the northern hemisphere, it began to detect protons around 10:08 UT in the deepest wake (SZA 168°) that SW protons are not anticipated to access. The proton flux in the deep wake was the largest around 10:12 UT, and its energy ranged broadly between 0.1–1 keV. Between 10:20–10:40 UT the proton energy was higher than the original SW energy, and took a peak energy of \(\sim 3\) keV around 10:34–10:38 UT near the South Pole (SP). The increase in energy (factor \(\sim 6\)) over the SW is consistent with previous observations by SELENE [Saito et al., 2008a]. Between 10:20–10:30 UT, Type-I entry of the SW protons was again observed, which seems to be unrelated to the protons found in the deepest wake.

When the protons were observed in the deep wake, the magnetic field was dominated by the \(B_Y\) component (Figure 2c). The averaged magnetic field between 10:08–
access into the deepest wake was accompanied by an intrusion of the electrons (Figure 2b). The energy of the electrons in the deep wake was ~0.2–0.3 keV which is higher than that of the original SW electrons, and the electron distribution function in the deep wake showed counter-streaming beams along the magnetic field. The physical meaning of the electron signature will be discussed later. Such enhancement of counter-streaming electron beams in the wake were observed during similar SW proton entry events.

[10] Noting the fact that the protons were continuously detected from the deepest wake to the dayside region, we propose that the protons scattered at the lunar dayside surface are picked up by the SW and come into the deepest wake. (Hereafter, we call this mechanism ‘Type-II entry’.)

4. Model Calculations

[11] To examine the origin of the protons coming into the deepest wake, we perform following particle trajectory calculations. Because the observed event occurred under dominant negative $B_T$ condition, we assume the simple IMF configuration with only $B_T$ component and the SW speed similar to the observation:

\[
\begin{align*}
B_{SW} &= (0, -5.6, 0) \text{ nT} \\
V_{SW} &= (-300, 0, 0) \text{ km/s (i.e. 0.47 keV).}
\end{align*}
\]

[12] Because the IMF observed in the lunar wake was slightly stronger than the original IMF, we assume the magnetic field in the shadowed region to be 1.2 times stronger than the ambient IMF in order to be consistent with the observations and the previous statistical result [Halekas et al., 2005]. Inward electric fields around the wake boundary are ignored because the energy of protons of our interest is much larger than the wake potential.

[13] We first examine motions of scattered protons in the noon-midnight meridian plane. Protons scattered at the sub-solar point without energy loss are picked-up by the SW, pass over the SP, and finally reach the anti-subsolar region (Figure 3a). However, all of them have downward velocity in the deepest wake and impact against the nightside surface, and thus they cannot be detected by IMA which looks down on the Moon. Because energy loss accompanied by the scattering at the dayside surface does not change proton trajectories so much (Figure 3b), we hereafter consider cases without loss of kinetic energy. Protons scattered in the northern hemisphere do not reach the nightside region (Figure 3c), and those scattered in the southern hemisphere far from the equatorial region come into the southern wake but do not access the deepest wake (Figure 3d).

[14] Next we investigate motions of protons scattered at the location off the noon-midnight meridian plane. We find that some of protons scattered at (Lat. 0°, Lon. 30°E) can reach anti-subsolar region and have upward velocity there (Figures 3e and 3f). Such obliquely-going protons have smaller velocity in the direction perpendicular to the magnetic field than protons without field-aligned velocity, having smaller Larmor radius that fits into the effective lunar radius along the trajectories. Part of these protons
reach the deepest wake and have upward velocity there, because they turn upward just near the nightside surface. The calculation also shows that the source areas of the protons that access the deepest wake are the dayside equatorial regions off the subsolar point.

Finally, we try to reproduce an Energy-time (E-t) scatter plot along the virtual spacecraft orbit at 100 km height in the noon-midnight meridian plane. For simplicity, we assume scattering location at the grid points every 5 degrees in the region of 70°N–70°S, 70°E–70°W. Concerning scattering angle, every 2 degrees in the both longitudinal and latitudinal directions are assumed. Energy loss by scattering at the dayside surface is not considered in the calculations. To simulate proton detection by IMA which faces upon the Moon, we accumulate protons that have upward velocity at every locations along the virtual spacecraft orbit. The calculated E-t plot shows patterns similar to the observations related to scattering on the dayside and Type-II entry (Figure 3g); that is, protons in the deepest wake, high-energy protons around the SP, and scattered SW protons on the dayside are reproduced. The resultant outward electric field generated around the PGR absorbs the ambient SW electrons into the wake along the magnetic field.

5. Summary and Discussion

In the present study we reported unexpected SW proton coming into the deepest lunar wake. The key mechanisms of this phenomenon, which we call Type-II entry, are scattering of the SW protons at the lunar dayside surface and their self-pickup by the SW [Saito et al., 2008a]. Part of scattered and self-picked-up protons with the specific Larmor radius suitable for the spatial scale of the Moon can access the deepest lunar wake. In other events of Type-II entry, the suitable combination of the IMF direction, its strength, and the SW speed results in detection of proton access to the deepest wake.

We propose that Type-II entry forms the proton-governed region (PGR) in one hemisphere of the near-Moon wake, giving rise to a strong asymmetry of the near-Moon wake environment (Figure 4). In the case with dominant negative $B_y$, the protons scattered on the dayside come into the southern hemisphere, while they cannot access the northern hemisphere. To maintain quasi-neutrality, the PGR yields outward electric fields to absorb the ambient SW electrons, which are detected as the counter-streaming distribution. This idea is supported by the fact that both ends of the wake magnetic field at the SELENE location are thought to be connected to the ambient SW. Previous models predicted governance of the high-energy electron on the lunar wake environment and negative charging on the lunar nightside surface [Halekas et al., 2002, 2005; Stubbs et al., 2006], while our results show that SW protons also play an important role in the electromagnetic environment there. The SW proton access deep into the near-Moon wake would significantly change the electric field configuration and motions of charged particles (including charged dust particles) in the lunar nightside region.

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