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Effect of solar-wind proton entry deep into the lunar wake

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Abstract

We study effect of the solar wind (SW) proton entry deep into the near-Moon wake that was recently discovered by the SELENE mission. Because previous lunar-wake models are based on electron dominance, no effect of SW proton entry has been taken into account. We show that the type-II entry of SW protons forms proton-governed region (PGR) to drastically change the electromagnetic environment of the lunar wake. Broadband electrostatic noise found in the PGR is manifestation of electron two-stream instability, which is attributed to the counter-streaming electrons attracted from the ambient SW to maintain the quasi-neutrality. Acceleration of the absorbed electrons up to ~1 keV means a superabundance of positive charges of 10^{-5}~10^{-7} cm^{-3} in the near-Moon wake, which should be immediately canceled out by the incoming high-speed electrons. This is a general phenomenon in the lunar wake, because PGR does not necessarily require peculiar SW conditions for its formation.

1. Introduction

The near-Moon space environment is characterized by formation of a plasma cavity region on the night side along the solar wind (SW) flow, which is called the lunar wake [1]. Because the Moon obstructs the SW plasma flow, the wake region is much more tenuous than the ambient SW region. The plasma environment of the lunar wake has been considered as follows; Because high energy SW electrons can easily access the night side region while SW protons cannot, the wake region should be negatively charged. The electron-rich status of the lunar wake yields ambipolar (inward) electric field at the wake boundary where SW protons gradually come to the wake center along the interplanetary magnetic field (IMF) in the distant wake [2−4].

It has been reported that the SW entry into the distant wake gives rise to plasma waves. Broadband electrostatic noise (BEN) was detected by the Wind spacecraft in the distant wake (~10,000 km from the Moon) [5]. The excitation of the BEN was attributed to ion two-stream instability owing to the SW proton beams that were accelerated/decelerated into the wake by the ambipolar electric fields [6]. It was also attributed to electron two-stream instability that is expected to occur around the wake boundary region [7]. However, such instabilities were not anticipated to occur in the near-Moon wake (say, ~100 km altitude), because it has been believed that a major part of the SW particles cannot access the deepest wake so that any plasma effects would be inoperative there.

2. SELENE observations

Recently, a Japanese lunar orbiter SELENE (Kaguya) performed comprehensive measurements of the plasma and electromagnetic environment around the Moon at ~100 km altitude. Concerning the night-side region, two mechanisms of SW proton entry into the near-Moon wake were found [8,9] and called type-I and type-II, respectively. The type-I entry lets SW protons come fairly deep into the near-Moon wake (Solar zenith angle (SZA) ~150 deg.) at 100 km altitude of the SELENE spacecraft. This entry mechanism is based on SW proton gyro motion and the acceleration/deceleration by the ambipolar electric field around the wake boundary. The type-II entry, which becomes evident when the non-radial IMF component is dominant, is closely related to `self-pickup' process of protons that were once scattered on the lunar dayside surface or magnetically reflected around the magnetic anomalies [9,10]. This mechanism lets protons access the deepest region of the wake, namely, 150<SZA<180 deg at the 100 km altitude of the SELENE orbit. It has been pointed out that this proton entry may form a proton-governed region (PGR) in the lunar wake, which attracts ambient SW electrons along the IMF to maintain the quasi-neutrality [9]. We show that such a coupling of dynamics initiated by the type-II entry leads to excitation of BEN at the bottom of the lunar wake [11].

During a wake pass, typical type-II proton entry was detected. It was accompanied by an enhancement of electron flux and BEN signals. The electron distribution was counter-streaming along the magnetic field, and their energy range was from several hundred eV to 1 keV. This energy is much higher than the typical energy of SW thermal electrons, which shows that acceleration operates as they are attracted from the SW to maintain the quasi-neutrality. Both ends of the magnetic field at the SELENE location were connected to the SW region, which is advantageous to the absorption of SW electrons from both ends into the PGR. The counter-streaming electrons give rise to two-stream instability that results in the excitation of electrostatic solitary waves (ESWs) in the PGR.

We also estimate the positive superabundance in the PGR of the deepest wake that yields outward electric field to attract the ambient electrons. The obtained number density (10^{-5}~10^{-7} cm^{-3}) is orders-of-magnitude lower than the proton density in the PGR (~0.05 cm^{-3}). This means that the quasi-neutrality is well maintained in the PGR, and that such a tiny superabundance of positive charges can give rise to the prominent feature seen in the electron and plasma wave data.

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