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Solar wind proton reflection at the lunar surface: Low energy ion measurement by MAP-PACE onboard SELENE (KAGUYA)

Y. Saito,[1] S. Yokota,[1] T. Tanaka,[1] K. Asamura,[1] M. N. Nishino,[1] M. Fujimoto,[1] H. Tsunakawa,[2] H. Shibuya,[3] M. Matsushima,[2] H. Shimizu,[4] F. Takahashi,[2] T. Mukai,[1] and T. Terasawa[5]

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[1] Interaction between the solar wind and objects in the solar system varies largely according to the settings, such as the existence of a global intrinsic magnetic field and/or thick atmosphere. The Moon's case is characterized by the absence of both of them. Low energy ion measurements on the lunar orbit is realized more than 30 years after the Apollo period by low energy charged particle analyzers MAP-PACE on board SELENE(KAGUYA). MAP-PACE ion sensors have found that 0.1%∼1% of the solar wind protons are reflected back from the Moon instead of being absorbed by the lunar surface. Some of the reflected ions are accelerated above solar wind energy as they are picked-up by the solar wind convection electric field. The proton reflection that we have newly discovered around the Moon should be a universal process that characterizes the environment of an airless body. **Citation:** Saito, Y., et al. (2008), Solar wind proton reflection at the lunar surface: Low energy ion measurement by MAP-PACE onboard SELENE (KAGUYA), *Geophys. Res. Lett.*, *35*, L24205, doi:10.1029/2008GL036077.

1. Introduction

[2] While the lunar plasma environment was monitored by the lunar orbiters and landers in 1960∼70s [*Lyon et al.*, 1967; *Colburn et al.*, 1967; *Anderson et al.*, 1972; *Howe et al.*, 1974; *Neugebauer et al.*, 1972; *Clay et al.*, 1972; *Hills et al.*, 1972], understanding it from the plasma physics point of view via three-dimensional particle distribution function data was difficult. Most of the subsequent lunar missions were dedicated to the global mapping of the lunar surface [*Nozette et al.*, 1994; *Binder*, 1998; *Foing et al.*, 2006]. After 90s, observations by the WIND spacecraft during its Moon fly-by showed the features of the lunar wake [*Ogilvie et al.*, 1996]. Three-dimensional low energy electron measurements by Lunar Prospector revealed the lunar plasma environment including plasma interactions with crustal magnetic fields, surface charging, and wake structure [*Lin et al.*, 1998; *Halekas et al.*, 2005, 2007]. Remote detection of the lunar ions [*Hilchenbach et al.*, 1993; *Mall et al.*, 1998; *Futaana et al.*, 2003], lunar electrons [*Futaana et al.*, 2001], and ULF waves generated by electron beams around the lunar wake [*Nakagawa et al.*, 2003] were also reported. Due to these curious features seen in the data, the expectation of comprehensive three-dimensional plasma measurements around the Moon has been high. We will show the results from the first in-situ measurements of low energy ions at 100 km altitude by a Moon polar orbiter SELENE (KAGUYA).

2. Instrumentation

[3] SELENE was successfully launched on 14 September 2007 by H2A launch vehicle from Tanegashima Space Center in Japan. MAP-PACE(MAgnetic field and Plasma experiment - Plasma energy Angle and Composition Experiment) [*Saito et al.*, 2008] is one of the 14 science instruments onboard. Since SELENE is a three-axis stabilized spacecraft, a pair of sensors, each having a half-sphere field of view in the opposite direction from each other, is necessary for obtaining three-dimensional particle distribution functions. The pair for measuring electrons below 15 keV is ESA (Electron Spectrum Analyzer)-S1 and ESA-S2, and the other pair for ions below 28 keV/q is IMA (Ion Mass Analyzer) and IEA (Ion Energy Analyzer), respectively. IMA is capable of identifying mass species of ions [*Yokota et al.*, 2005]. Figure 1a shows how the ion sensors are installed. Figures 1c and 1d show the E-t spectrograms from IEA and IMA, respectively. The vertical scale is the energy of ions while the horizontal axis is the time. The color of each bin depicts the ion counts in each energy bin at the time of observations. Since IMA is installed on the spacecraft panel facing the Moon surface, it mostly measures ions from the Moon. On the other hand, IEA is installed on the opposite side and measures mostly ions going into the Moon. In order to measure the main component of the solar wind ions without saturation, IEA is operated with 1/50 sensitivity below 2.5 keV/q and 1/1 sensitivity above 2.5 keV/q. Therefore the minimum detectable ion flux is different between the energy range above and below 2.5 keV/q that causes some data gap at 2.5 keV/q in the E-t spectrogram of IEA. It is the simultaneous measurements on the dayside orbits of solar wind ions by IEA and of the ions from the Moon by IMA that enable us to make the discovery reported here. Magnetic field data are measured by a magnetometer MAP-LMAG (Lunar Magnetometer) [*Shimizu et al.*, 2008].

3. Solar Wind Proton Reflection at the Lunar Surface

[4] Data in Figure 1 show typical lunar plasma obtained in a day along the polar orbit that is close to the noon-

[1]Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, Sagamihara, Japan.
[2]Department of Earth and Planetary Sciences, Tokyo Institute of Technology, Tokyo, Japan.
[3]Department of Earth Science, Kumamoto University, Kumamoto, Japan.
[4]Earthquake Research Institute, University of Tokyo, Tokyo, Japan.
[5]Department of Physics, Tokyo Institute of Technology, Tokyo, Japan.

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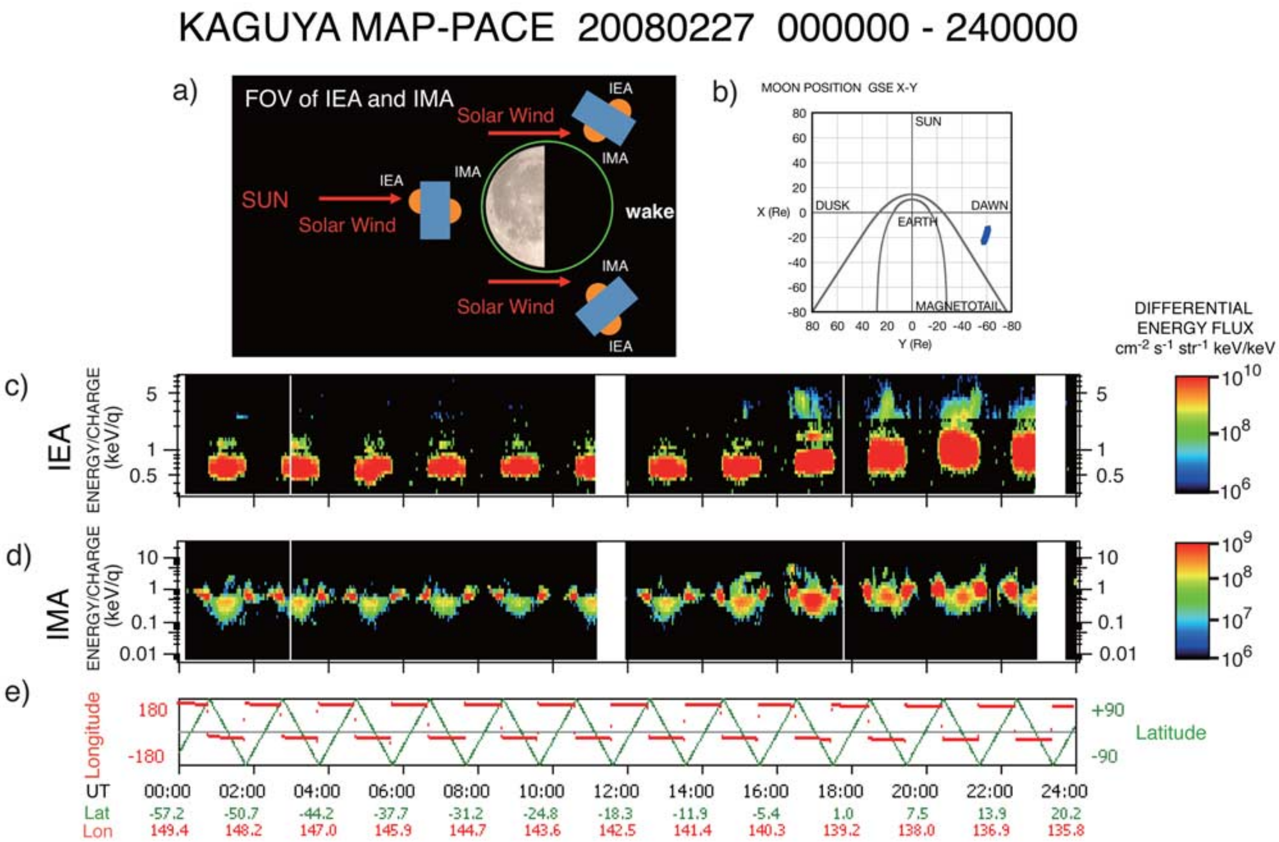

Figure 1. (a) Schematic diagram showing the ion measurement configuration. (b) Position of the Moon in the GSE coordinate system. A nominal magnetopause and bow shock boundary positions are also shown. (c) and (d) E-t spectrograms from PACE sensors for the 24-hour interval. (e) Position of the SELENE spacecraft in the selenographic coordinates system.

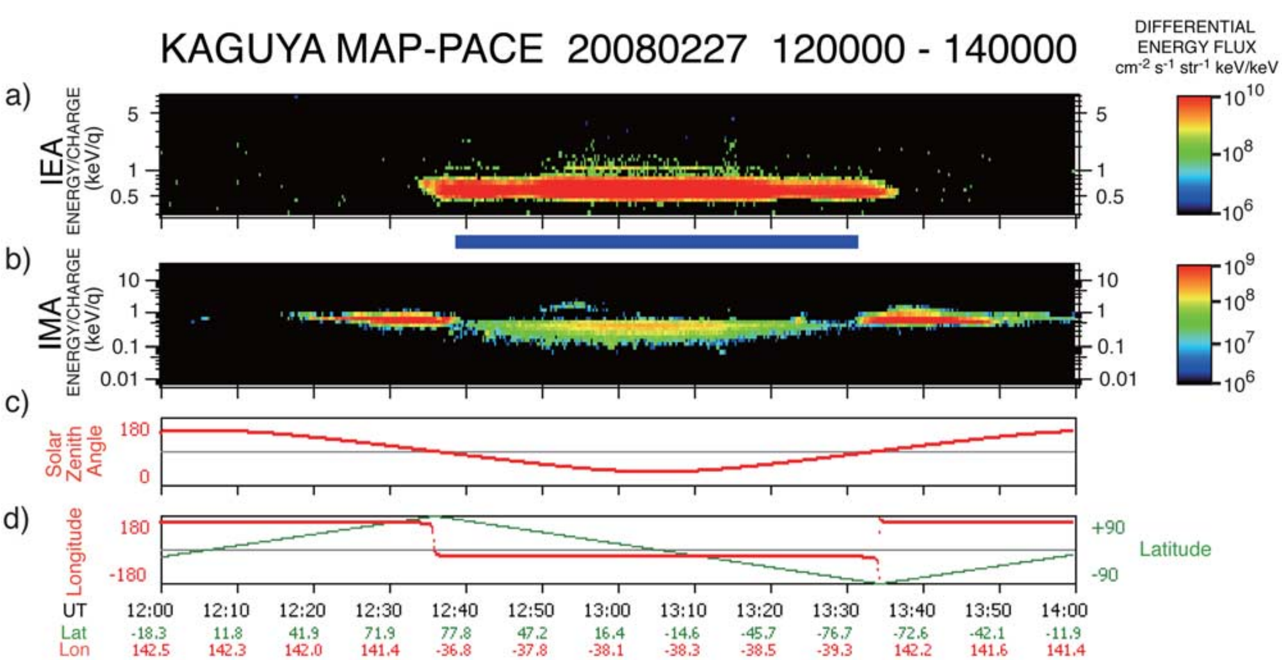

Figure 2. (a) E-t spectrogram of IEA observed between 1200 UT and 1400 UT. The enhanced counts at ∼0.6 keV between 1240 and 1330 UT were the solar wind detected when SELENE was on the dayside. (b) E-t spectrogram of IMA observed between 1200 UT and 1400 UT. (c) Solar zenith angle location of the SELENE spacecraft. (d) Position of the SELENE spacecraft in the selenographic coordinate system.

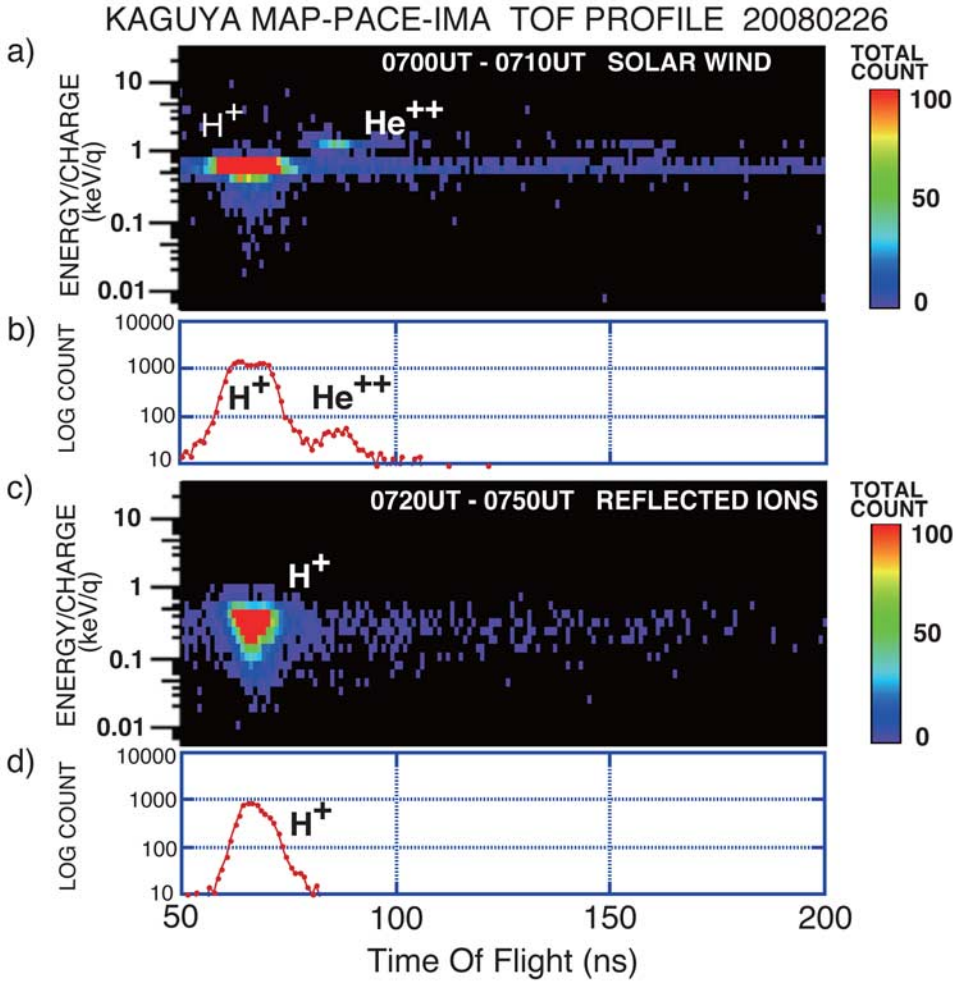

Figure 3. (a) and (b) TOF (Time Of Flight) profile of solar wind ions. Since IMA is a TOF-type mass spectrometer that identifies ion species by measuring the flight time of ions inside the spectrometer, the TOF profile corresponds to the mass profile. The profile is made with data obtained between 0700 UT and 0710 UT on the previous day (26 February) when PACE IMA was in the TOF mode and when SELENE was crossing the day-night terminator. (c) and (d) TOF profile of the ions observed between 0720 UT and 0750 UT when PACE IMA was in the TOF mode and when SELENE was on the dayside.

midnight meridian. As shown in Figure 1b, the Moon was exposed to the solar wind. Then the two-hour orbital period of SELENE produces the repeated signatures in the E-t spectrograms. Focusing into a two-hour interval between 1200 UT and 1400 UT, the high counts located at the energy of ∼0.6 keV detected by IEA for the ∼one-hour interval centered around 1300 UT is the signature that IEA detected the solar wind when SELENE was on the dayside, moving from the north-pole to the south-pole via the noon-equator. Regarding IMA, although it mostly measures ions from the Moon, it also detects the solar wind for a short interval encompassing the day-night terminator crossing. This is seen as the high counts at slightly below 1 keV around 1230 UT and 1340 UT.

[5] What is central to this study is the high count rate feature of IMA for the ∼one-hour interval centered around 1300 UT, when SELENE was on the dayside and when IMA was looking into the dayside lunar surface. The zoom-in to this two-hour interval is shown in Figure 2. On the dayside between 1240 UT and 1330 UT, IMA measured ions coming from the direction of the Moon whose energy was slightly lower (<∼0.5 keV) than that of the solar wind ions (indicated by a blue line in Figure 2). These ions started to appear immediately after the day-night terminator crossing at the north-pole and continued until the other crossing on the other pole. While the maximum energy of these ions was constant at slightly lower than the solar wind proton energy, the lowest energy end gradually decreased as the spacecraft moved from the north-pole to the equator and then gradually increased as the spacecraft left the equator to the south-pole. We propose that these newly observed ions from the dayside lunar surface, whose energies are slightly lower than that of the solar wind proton, evidence the solar wind proton reflection at the lunar surface. We have found that the angular distribution of the newly observed ions is much broader than that of the solar wind ions. Therefore the observed ions are not specularly reflected but rather scattered at the lunar surface. The 30% reduction in the energy

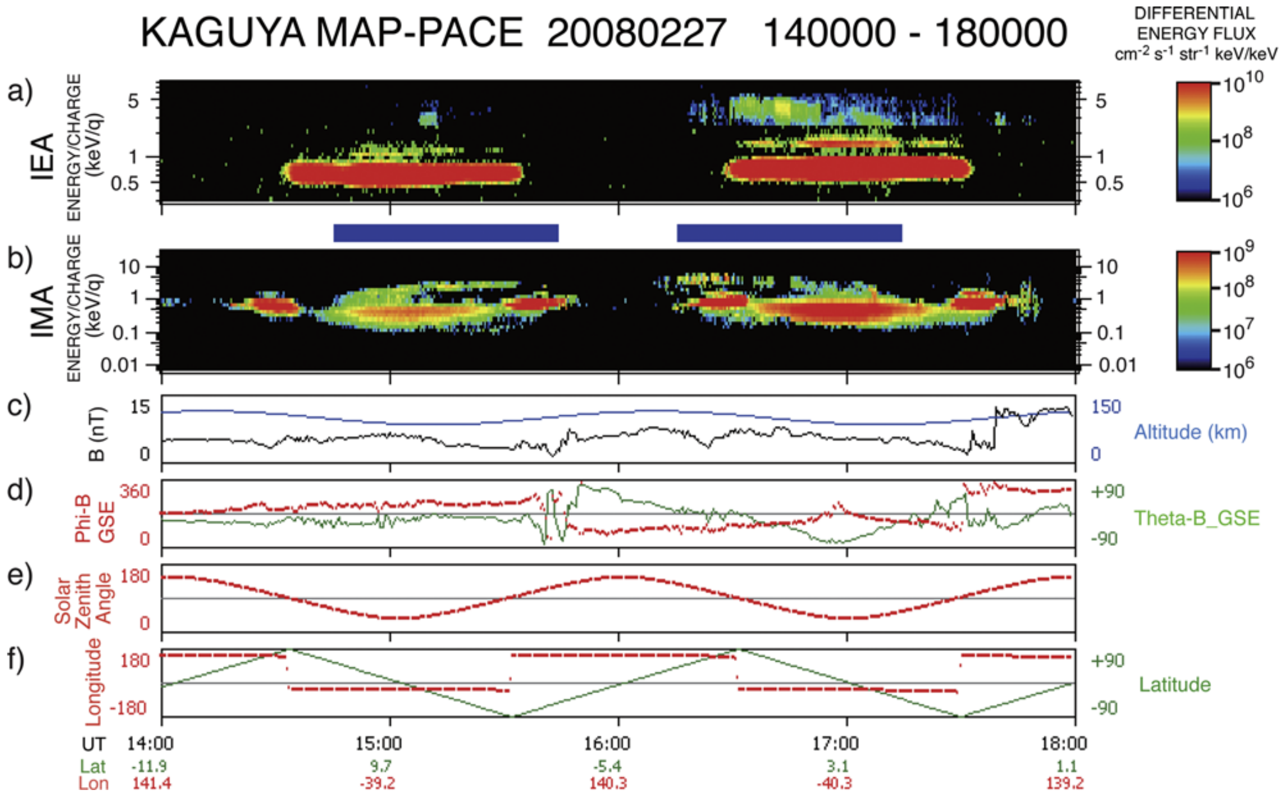

Figure 4. (a) and (b) E-t spectrograms of IEA and IMA showing ions subject to self-pick-up process obtained in the two consecutive revolutions between 1400 UT and 1800 UT on 27 February 2008. (c) and (d) Magnetic field data observed by MAP-LMAG. (e) Solar zenith angle location of the SELENE spacecraft. (f) Position of the SELENE spacecraft in the selenographic coordinate system.

is taken to denote the energy loss upon interaction at the surface.

[6] The ion mass information from IMA, which requires a special operational mode and is not always available, was obtained from an orbit on the previous day when IEA and IMA were showing the same features described above. The mass profiles are shown in Figure 3. Figures 3a and 3b are from an interval when IMA detected the solar wind upon a day-night terminator crossing and Figures 3c and 3d are from a dayside interval when IMA was detecting ions from the lunar surface, respectively. Although both protons and alpha particles are identified in the solar wind (Figure 3a), the ions from the lunar surface consist mostly solely of protons (Figure 3c). This is supporting evidence that these ions are indeed due to the solar wind reflection at the lunar surface. The ionization ratio of the hydrogen in collisional interaction with some materials is much higher than that of helium [*Souda et al.*, 1995], and the ion component of helium species is not expected after reflection. The reflected proton flux is about 0.1%∼1% of the original solar wind ion flux and is not negligible in studying the lunar exosphere.

4. Pick-Up Acceleration of the Reflected Solar Wind Protons

[7] The newly discovered solar wind reflection at the lunar surface can give birth to various new phenomena. Self-pick-up acceleration is one of them. IMA has detected ions coming from the Moon whose energies are higher than that of the solar wind. A pair of illustrative examples is obtained during the two consecutive revolutions 1400 UT–1800 UT (Figure 4). In addition to the solar wind ions and reflected solar wind ions, we can see a clear signature of ion acceleration in the E-t spectrogram of IMA (see 1445 UT–1545 UT and 1615 UT–1715 UT indicated by the blue lines). For the 1445–1545 UT interval, the accelerated ions emerged out of the reflected component and showed increase in their energies as the spacecraft moved from north to south. On the contrary, between 1615 UT and 1715 UT the accelerated ions decreased their energies during the dayside north-to-south traversal to merge with the reflected component at the end of the dayside interval. The energy of the solar wind protons observed by IEA is ∼0.75 keV/q while the maximum energy of the accelerated ions is ∼5 keV/q, that is, acceleration by a factor of ∼6 is identified. A mass profile obtained on the previous day from a similar event shows that the accelerated ions were protons. Simultaneously observed magnetic field data show that the magnetic field and thus the solar wind convection electric field changed their directions between the two intervals, with the electric field being southward for the first interval and northward for the second.

[8] These findings lead us to explain the newly discovered ion acceleration phenomenon in terms of pick-up

acceleration. Pick-up acceleration process itself has been well known, for example, in the cometary environment [*Mukai et al.*, 1986; *Coates*, 2004]. At comets, a neutral particle almost at rest is photoionized and starts to gyrate about the magnetic field that convects with the solar wind. In other words, the photoionized ion starts a cycloid motion and the maximum velocity (energy) is twice (four-times) the solar wind velocity (energy). Similar pick-up acceleration of the photo-ionized neutrals at the Moon was reported by *Manka and Michel* [1973]. In the present case, the maximum energy is higher because of the difference in the initial velocity. As we described before, the initial velocity of the ion that is to be accelerated is the reflection velocity from the lunar surface, which is directed opposite to, but is reduced only slightly in magnitude from, the solar wind velocity. Then the pick-up process elevates the maximum velocity (energy) up to three (nine) times the solar wind velocity (energy). Thus the observed energy gain of a factor of ∼6 is within the achievable range. The opposite trend in the E-t spectrograms obtained in the two consecutive revolutions (Figure 4) is also consistent with the pick-up acceleration scenario. A picked-up ion has the highest energy when it moves most in the direction of the solar wind convection electric field during its cycloid motion. The southward (northward) electric field for the first (second) revolution makes the highest energy ions to appear at the southern (northern) end of the dayside orbit, which is what is indeed observed. We also note that the lunar pick-up acceleration process is so to speak a ‘‘self-pick-up acceleration’’ in the sense that the ions subject to acceleration by the solar wind electric field are originally from the solar wind itself. The newly discovered proton reflection at the lunar surface is the key element for this to be realized.

5. Summary and Discussion

[9] MAP-PACE ion sensors onboard SELENE have found that 0.1%∼1% of the solar wind protons are reflected back from the Moon instead of being absorbed by the lunar surface. Some of the reflected ions are accelerated above solar wind energy as they are picked-up by the solar wind convection electric field.

[10] In laboratory, there is a technique called LEIS (Low-energy ion scattering spectroscopy) for analyzing the composition and structure of a solid surface by injecting ion beams with 500 eV–20 keV at a surface and measuring the directions and energies of the ions scattered from the surface. The ion reflection we have observed is similar to LEIS, though the injected ion beams are the solar wind ions and the lunar surface is much more complicated than the solid surface target of LEIS. We have quantitatively measured the solar wind proton reflection/scattering at the lunar surface for the first time in space.

[11] The ion sputtering is the well-known important process in considering the plasma interaction with an airless body (such as Jupiter's satellite Europa and Mercury). The proton reflection that we have newly discovered around the Moon should be an equally important universal process that characterizes the environment of airless bodies in space.

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K. Asamura, M. Fujimoto, T. Mukai, M. N. Nishino, Y. Saito, T. Tanaka, and S. Yokota, Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, 3-1-1 Yoshinodai, Sagamihara 229-8510, Japan. (saito@stp.isas.jaxa.jp)

M. Matsushima, F. Takahashi, and H. Tsunakawa, Department of Earth and Planetary Sciences, Tokyo Institute of Technology, 2-12-1 Ookayama, Tokyo 152-8551, Japan.

H. Shibuya, Department of Earth Science, Kumamoto University, Kumamoto 860-8555, Japan.

H. Shimizu, Earthquake Research Institute, University of Tokyo, 1-1 Yayoi, Tokyo 113-0032, Japan.

T. Terasawa, Department of Physics, Tokyo Institute of Technology, 2-12-2 Okayama, Tokyo 152-8551, Japan.