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Biogenic oxygen from Earth transported to the Moon by a wind of magnetospheric ions

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For five days of each lunar orbit, the Moon is shielded from solar wind bombardment by the Earth's magnetosphere, which is filled with terrestrial ions. Although the possibility of the presence of terrestrial nitrogen and noble gases in lunar soil has been discussed based on their isotopic composition[1], complicated oxygen isotope fractionation in lunar metal[2,3] (particularly the provenance of a ^{16}O-poor component) remains an enigma[4,5]. Here, we report observations from the Japanese spacecraft Kaguya of significant numbers of 1–10 keV O^+ ions, seen only when the Moon was in the Earth's plasma sheet. Considering the penetration depth into metal of O^+ ions with such energy, and the ^{16}O-poor mass-independent fractionation of the Earth's upper atmosphere[6], we conclude that biogenic terrestrial oxygen has been transported to the Moon by the Earth wind (at least 2.6×10^4 ions cm^{-2} s^{-1}) and implanted into the surface of the lunar regolith, at around tens of nanometres in depth[3,4]. We suggest the possibility that the Earth's atmosphere of billions of years ago may be preserved on the present-day lunar surface.

In 2008, the Moon and the Japanese lunar orbiter Kaguya both lay within the Earth's plasma sheet for tens of minutes to a few hours per month (Fig. 1, Table 1). When the Moon moved into the central magnetosphere on 21 April 2008, Kaguya measured plasma sheet ions with an energy of several kiloelectronvolts during the periods of 0:50–1:10 UT and 8:00–16:00 UT, and detected a weak signature of cold lobe ions in the remaining period (Fig. 2). Moonward-moving magnetospheric ions were observed by the Ion Energy Analyzer (IEA), whereas the Ion Mass Analyzer (IMA) measured both the ions coming from the Moon (anti-moonward ions) and the magnetospheric ions by means of a wide energy field of view (FOV)[7].

Figure 1 illustrates the geometrical setting of solar wind, Earth, Moon and Kaguya and the direction of the mass spectrometer (for details, see Methods). The IEA is not equipped with a mass analyser, and thus the moonward energy spectra include the signatures of all ions mixed together (Fig. 2a). In the case of the anti-moonward ions, in contrast, we were able to disentangle the H^+ and the O^+ contributions (Fig. 2b,c). The temporal evolution of the moonward energy spectra (Fig. 2a) is very similar to (Fig. 2b), because ions in the plasma sheets are mainly H^+ and are dense, hot and almost isotropic. The O^+ anti-moonward energy spectra exhibit a series of low-energy signatures below ~1 keV, which appear only when Kaguya is in the dayside region. These signatures have been observed before[8]

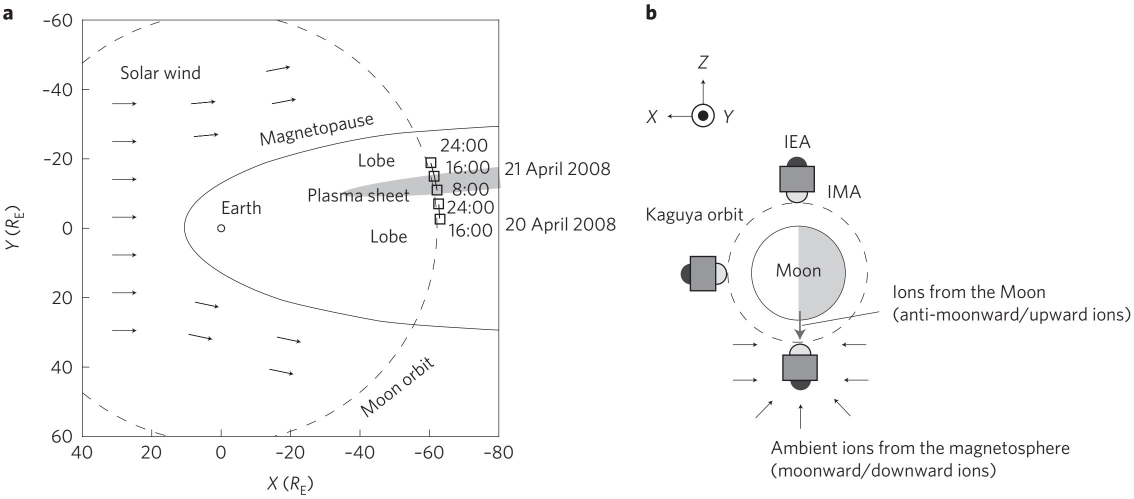

Figure 1 | Geometrical setting of the instrumental apparatus. a, The solar wind, Earth, Moon and Kaguya, within the geocentric solar ecliptic coordinate system. The squares indicate the position of Kaguya during the measurements analysed in this paper. The grey area is the position of the plasma sheet. The arrows schematize the direction and behaviour of the solar wind around the Earth's magnetosphere. R_E, Earth radius. **b**, Position of the two Kaguya ion sensors, IEA and IMA, with respect to the Moon.

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and were mainly attributed to ions of lunar origin, produced by the photoionization of exospheric particles and/or ion emission from the lunar surface, and then accelerated by the electrical potential difference between the lunar surface and the spacecraft. This potential difference causes the cutoff energy to be about 1 keV in the energy distribution[8,9]. Our new finding in this study is the higher-energy O^+ (1–10 keV) ions during almost the entire period of the plasma sheet encounters (Fig. 2c), which were not detected when the Moon was outside the magnetosphere[9]. Figure 3 shows the energy distributions of H^+ and O^+ before, during and after the plasma sheet encounter, clearly illustrating the enhancement of high-energy O^+ (1–10 keV) ions during plasma sheet encounters (Fig. 3b) in comparison with those in the lobe (Fig. 3a and c). The calculated density and net flux of the magnetospheric O^+ during the plasma sheet encounter were 1.2×10^{-3} cm^{-3} and 2.6×10^{4} cm^{-2} s^{-1}, respectively, which are consistent with the previous GEOTAIL observation[10] of 2.1×10^{4} ions cm^{-2} s^{-1} at approximately 75–150R_E, where R_E is the Earth radius (for the flux calculation, see Methods).

Here, we investigate the possibility that the high-energy O^+ contribution observed when Kaguya is within the plasma sheet comes from the solar wind. In general, solar wind oxygen is mainly in the form of multi-charged ions because of the high temperature of the solar corona, according to the CHIANTI database[11]. In reality, solar wind fluxes of O^{5+}, O^{6+}, O^{7+} and O^{8+} were observed by the ACE space satellite, but the flux of O^+ was negligible compared with the detection limit of typical ion analysers[12]. Indeed, when the Moon was outside the magnetosphere (and therefore in the solar wind), Kaguya observed a negligible flux of high-energy (>1 keV) O^+, but did observe significant low-energy O^+ originating from the Moon[9]; in other words, high-energy O^+ (>1 keV) only appears in the plasma sheet. Moreover, conversion from solar wind multi-charged oxygen ions to O^+ rarely occurs because the cross-sections with the geocorona are too small (~10^{-15} cm^2)[13] for multiple collisions with electrons to occur. Another possibility is that when solar wind oxygen reaches the lunar surface, it converts to O^+, which may then move from the surface to the detector. In this case, this component can be distinguished by its low energy (<1 keV) because the electrical potentials between the lunar surface and the Kaguya satellite correspond to energies below 1 keV. Such low-energy O^+ ions are actually detected both inside the magnetopause (this study) and outside[9]. Further evidence against a solar wind origin for the high-energy O^+ is that the average abundance ratio of O^+/H^+ for the period of 8:00–16:00 UT was 2.4% (Table 1), which is similar to previous observations of the Earth's magnetosphere[14,15] and an order of magnitude higher than the elemental ratio O/H of the solar wind[16] (the O^+/H^+ ratio of the solar wind is much lower because most of the oxygen ions are multi-charged[12]). For these reasons, the possibility of a solar wind origin is excluded, and we conclude that the observed 1–10 keV O^+ ions during the plasma sheet originated from the Earth's ionosphere. In this study, terrestrial nitrogen ions were not observed, possibly because of the low abundance ratio of N^+/O^+ (for example, 0.05–0.1 for the outflow from the ionosphere[17] and 0.05 for the outflow from the polar magnetosphere[18]).

Interestingly, the stratospheric ozone (O_3) is mass-independently fractionated and significantly enriched in ^{18}O and ^{17}O, depending on the altitude (up to 400‰ at 32 km)[19]. Such ^{16}O-poor stratospheric ozone is considered to be chemically produced when O_3 is formed from molecular oxygen[7]. In general, the production rate of atomic oxygen in the upper atmosphere is considered proportional to both the density and absorption cross-section of ozone (O_3) and/or oxygen molecules (O_2). Because the abundance ratio of O_3/O_2 is 10^{-4} at around 0–100 km altitude and the absorption cross-section of O_3 is 10^6–10^7 times higher than that of O_2, the photolysis of O_3 mainly produces atomic oxygen above 60 km (immediately above the ozone layer). Although most of the oxygen atoms re-combine to reform ozone, a portion of atomic oxygen would be photo-ionized by ultraviolet radiation. Consequently, a portion of O^+ in the ionosphere might have a positive $\Delta^{17}O$ composition, as suggested by a one-dimensional chemical model[20], although more rigorous quantum mechanical treatment of photo-dissociation processes would be necessary for quantitative discussion. Finally, O^+ will escape from the Earth towards the magnetosphere because of heating and acceleration by the electric fields and/or plasma waves[14,21].

Table 1 | Densities of the magnetospheric ions measured by IEA, abundance ratios of the magnetospheric O^+/H^+ measured by IMA and net fluxes of the magnetospheric O^+ to the lunar surface during the plasma sheet crossing of Kaguya in 2008.

	Density of ions (10^{-2} cm^{-3})	Abundance ratio O^+/H^+ (%)	Net flux of O^+ ions (10^4 cm^{-2} s^{-1})
21 January 14:49–15:10	5.3	1.3	2.3
22 January 02:05–02:20	3.5	2.9	3.2
22 January 09:25–12:07	3.6	2.0	2.2
20 March 03:14-08:48	5.4	1.0	1.7
20 March 10:24–11:46	6.6	1.1	2.4
22 March 12:45–20:52	5.8	1.0	1.9
20 April 04:09–04:47	4.2	3.2	4.2
20 April 05:44-10:55	5.3	2.0	3.0
21 April 08:24–15:17	5.1	2.4	2.6
18 May 13:16–14:01	5.0	–	
18 May 16:10–22:48	5.4	–	
19 May 11:03–11:56	4.3	–	
19 May 17:01–17:25	4.7	–	
19 May 21:54–23:42	4.3	–	
18 June 00:24–01:04	4.0	2.7	3.8
19 June 06:05–13:26	3.7	–	
16 July 19:10–19:45	5.4	1.1	1.8
16 July 22:57–23:53	5.5	1.5	2.3
17 July 01:03–02:17	4.2	0.9	0.99
19 July 02:47–13:40	5.1	1.6	2.6
14 September 03:36–04:11	7.4	2.3	3.9
14 September 05:03–06:16	6.3	1.5	2.7
15 September 00:25–03:03	6.6	–	
12 November 05:47–05:55	9.2	1.4	2.8
12 November 08:21–08:27	5.9	1.1	1.8

In all the events, continuous (≥5 min), hot (widely distributed over 1 keV) and dense ($\geq1.0\times10^{-2}$ cm^{-3}) plasma sheet ion signatures were found in the central region of the Earth's magnetosphere ($|Y|\leq15R_E$ in Geocentric Solar Ecliptic coordinates). A dash indicates that no mass analysis data were available, because IMA was working in the other mode. The magnetospheric O^+ fluxes were estimated by using H^+ fluxes from the IEA data and O^+/H^+ ratios from the IMA data. February, August, October and December each had a couple of days on which observation was suspended in the magnetosphere for operational reasons such as the eclipse. Time is UT.

To sum up, we have discovered relatively high-energy (1–10 keV) O^+ ions that appear only when the Moon and Kaguya cross the plasma sheet. Such an energy range for the Earth wind corresponds to a penetration depth of several tens of nanometres for metal grains, according to the Stopping and Range of Ions in Matter (SRIM) model[22] (from 3–4 nm for 1 keV to 30–40 nm for 10 keV), which is consistent with the observation of high-concentration ^{16}O-poor components at shallow depth in the lunar regolith (~8 wt%; $\Delta^{17}O = +26\pm4$‰ and $+33\pm3$‰)[4]. Until now, the provenance

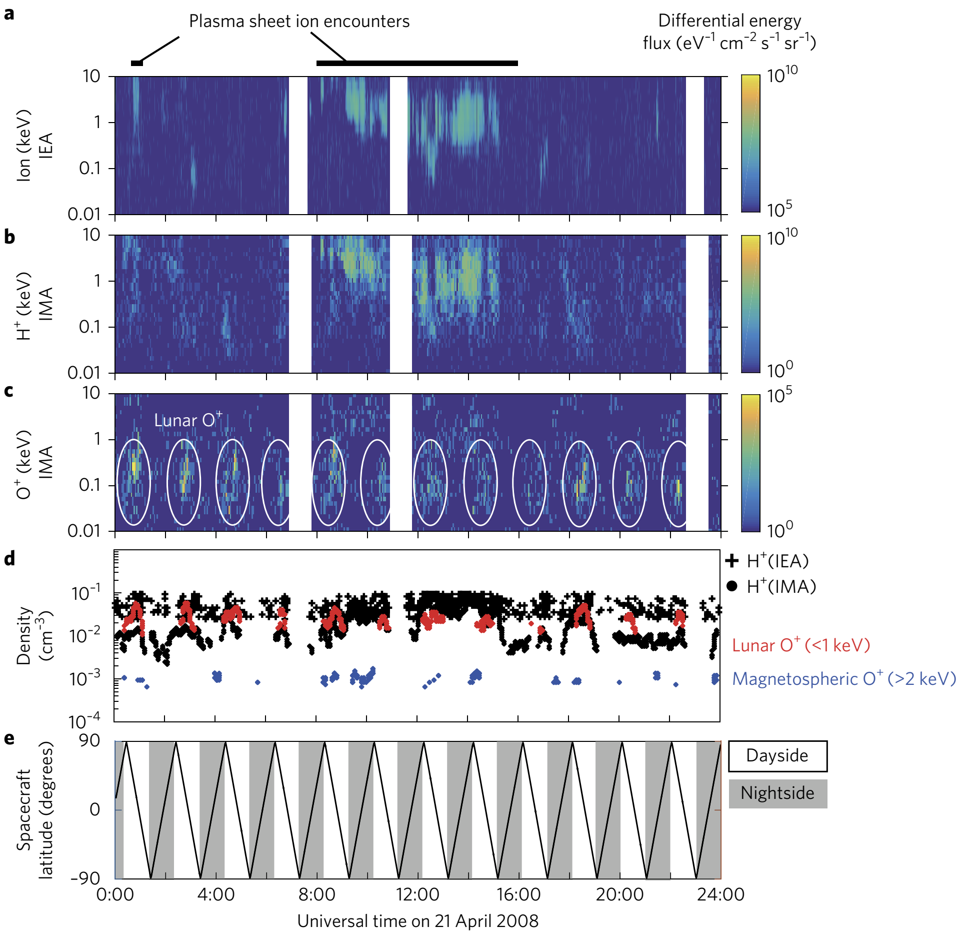

Figure 2 | Kaguya ion observations in the Earth's magnetosphere on 21 April 2008. The Moon encountered plasma sheet ions during the periods of 0:50–1:10 UT and 8:00–16:00 UT, which are indicated by the thick black lines at the top of the figure. **a**–**c**, Energy–time spectra of ions observed by the IMA and IEA instruments. The colour indicates the differential energy flux. **a**, Moonward ions measured by IEA. **b**,**c**, Anti-moonward H$^+$ and O$^+$ ions measured by the IMA. The measured O$^+$ consisted of lunar ions below ~1 keV (marked by white ellipses in Fig. 2c) and magnetospheric ions in the higher energy range, particularly during the plasma sheet crossing. **d**, Densities of H$^+$ and O$^+$ ions. The H$^+$ ions are derived from the IEA (black plus) and IMA (black dot) data. Low-energy (<1 keV) O$^+$ ions coming from the Moon are marked in red, and high-energy (>2 keV) magnetospheric O$^+$ in blue. **e**, Lunar latitude of the spacecraft that orbited near noon and midnight. The magnetospheric ions were measured in both the dayside and nightside (grey) regions, whereas the lunar O$^+$ was only measured in the dayside region.

of ^{16}O-poor oxygen in the shallow lunar regolith layer has been enigmatic because the observed oxygen concentration is 5–10 times higher than the solar wind concentrations[4]. If we consider that a series of oxygen isotope measurements[2–4] of lunar soils are experimentally valid, based on our Kaguya observation, we can interpret the complicated oxygen mass-independent fractionation of the lunar soils as a mixing of three components. First, there is an 'intrinsic' lunar oxygen, with the same isotopic distribution as that of the Earth[23] ($\Delta^{17}O \approx 0$). Then there is a ^{16}O-rich component, coming from the solar wind when the Moon is outside the magnetosphere, which penetrates 200–2,000 nm below the sampled surface[2]. This component is characterized by a negative $\Delta^{17}O$, similar to the observation by the Genesis mission[24]. Finally, there is a ^{16}O-poor oxygen component, originating from the Earth wind, that is implanted when the Moon is in the plasma sheet and has a positive $\Delta^{17}O$ similar to that of stratospheric ozone. A consequence of this finding is that the entire lunar surface can be contaminated with biogenic terrestrial oxygen, which has been produced by photosynthesis over a few billion years (with an estimate of 4×10^{36} O$^+$ ions for about 2.4 billion years after the Great Oxygenation Event[25]). This hypothesis does not exclude the possibility that the Earth wind component originated from oxygen molecules in the Earth's atmosphere, whose isotopic composition is 'normal' ($\Delta^{17}O \approx 0$). Indeed, most lunar metals (more than 30 out of 38 grains)[4] show 'normal' isotopic compositions, and only two metal grains show meaningful ^{16}O-poor signatures, although the normal isotopic composition of lunar metal could also indicate that an unresolved small silicate grain sits in the analysed area[4].

Recently, the MAVEN spacecraft observed that Mars, despite its weak magnetosphere[26], also has a plasma sheet, which consists of heavy ions, mainly oxygen[27]. This suggests that, even when the geomagnetic field was less developed or absent in ancient times[28], the Earth's plasma sheets could have existed and led to effective transportation from the Earth's atmosphere to the lunar surface. This mechanism would be enhanced if the distance between the Earth and the Moon was much smaller than today, as it seems it was[29]. In addition, the escape rate from the Earth would be intensified by sporadic solar activity, as a recent MAVEN observation revealed by monitoring the response of the Martian atmosphere to interplanetary coronal mass ejection[30]. Thus, our Kaguya observation of significant Earth wind from the current geomagnetic field strengthens the hypothesis that information on the lost ancient atmosphere of the Earth could be preserved on the surface of lunar soils, as predicted based on nitrogen and noble gas isotopes[1].

However, realistically, it is difficult to distinguish the old Earth wind from long-duration solar wind, because we have no method of dating the exact time at which the sample reached the surface.

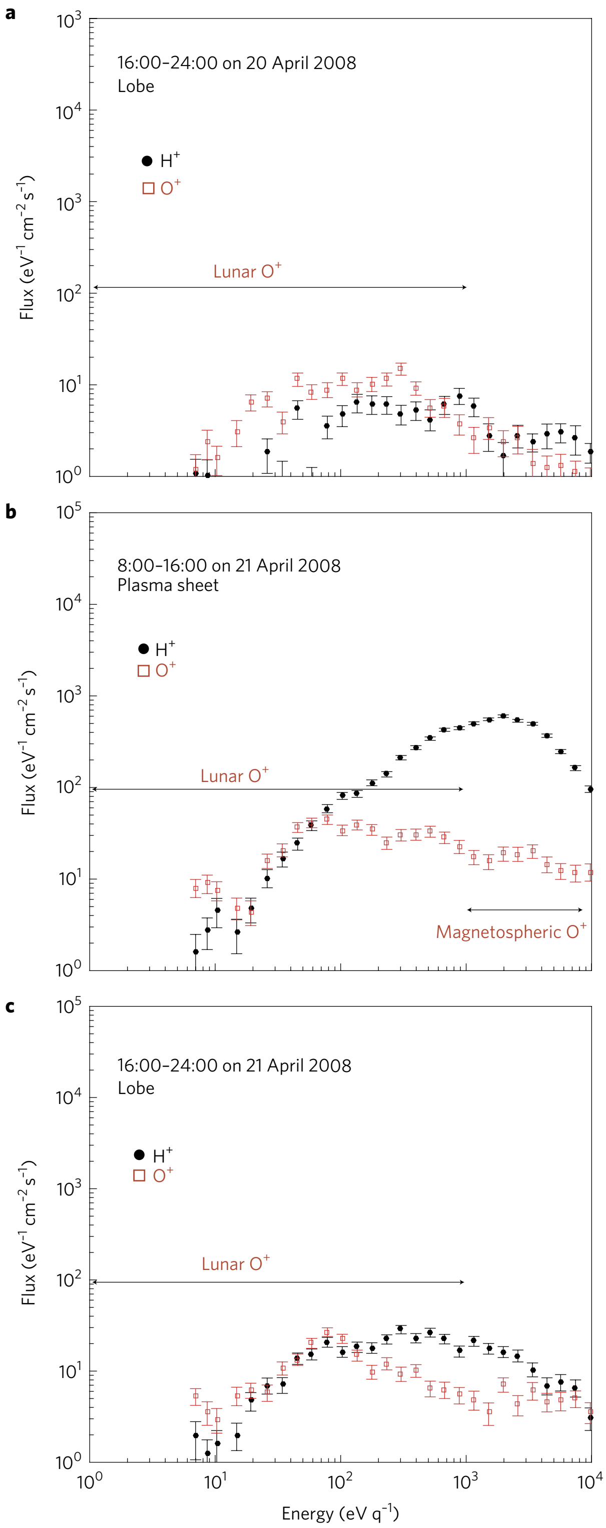

Figure 3 | Energy distributions of H^+ (black dot) and O^+ (rectangle) measured by IMA on 20 April 2008. Distributions were obtained at 16:00–24:00 UT on 20 April 2008 in the lobe (**a**); 8:00–16:00 UT on 21 April 2008 in the plasma sheet (**b**); and 16:00–24:00 UT in the lobe (**c**). Only in the plasma sheet (**b**) are significant magnetospheric O^+ ions in the energy range 1–10 keV observed. The error bars were determined by the number of data points.

Methods

IMA and IEA on Kaguya. The lunar orbiter Kaguya was launched on 14 September 2007 and had a nominal observation of 1 year at an altitude of 100 km. The Magnetic field and Plasma experiment/Plasma energy Angle and Composition experiment (MAP-PACE) on the Kaguya spacecraft performed the first direct ion measurements of three-dimensional energy and mass information[7]. In this study, we used the data of MAP-PACE available in the Kaguya Data Archive (http://l2db.selene.darts.isas.jaxa.jp/). MAP-PACE consists of four sensors: two electron sensors and two ion sensors. The two ion sensors are the IMA and the IEA. The IMA, the IEA and the two electron sensors have hemispherical FOVs and cover the full three-dimensional phase space of low-energy ions and electrons (Fig. 1b). Although the energy ranges of the IMA and IEA are 0.005–28 keV per unit charge (keV q^{-1}), the maximal full FOVs are ~10 keV q^{-1}. Because Kaguya is a three-axis stabilized satellite, the IMA continuously faces the Moon. Thus, it measures ions that mostly come from the Moon, whereas the mounted IEA on the opposite side of the spacecraft measures ions from outer space, such as the Earth's magnetosphere. In other words, the IMA and IEA mainly measure anti-moonward (upward) and moonward (downward) ions, respectively. Although the FOV of the IMA is 60% covered by the Moon at a 100-km altitude, the IMA can measure ions from outer space by means of the marginal FOV. High-temperature (isotropic) magnetospheric ions were measured by both IEA and IMA, whereas only the nadir-pointing IMA effectively detects the ions that originate from the Moon[31] and obtains mass-identified ion energy spectra[8,9].

KAGUYA observation on 20–21 April 2008. The Moon and Kaguya were within the plasma sheet for tens of minutes to a few hours per month in 2008 (Table 1). As a typical example, the Kaguya observation data on 21 April show that when the Moon was in the central magnetosphere, both IMA and IEA measured dense-plasma-sheet ions with an energy of several keV during the periods of 0:50–1:10 UT and 8:00–16:00 UT and detected low numbers of cold lobe ions in the remaining period (Fig. 2a,b). Low-energy (<1 keV) O^+ of lunar origin was measured during each period of passing above the dayside region, because the solar ultraviolet radiation causes the photoionization and emission of lunar particles (Fig. 2c). In addition, the IMA measured magnetospheric O^+ in a wider energy range, particularly in the plasma sheet.

In the magnetospheric lobe, the O^+ energy distribution shows a low-energy (<1 keV) flux of lunar O^+ similar to previous observations[8,9], and negligible flux of high-energy (>1 keV) O^+, comparable to the detection limit of the IMA (Fig. 3a). However, the energy distributions in the plasma sheet indicate one component of magnetospheric H^+ and two components of O^+: lunar O^+ (<1 keV) and significant magnetospheric O^+ up to 10 keV (Fig. 3b). These magnetospheric H^+ and O^+ were measured in both dayside and nightside regions, and even around the polar regions, for four orbiting times of 8 hours (Fig. 2e), because the ion temperature was sufficiently hot compared with the bulk velocity. Thus, in the plasma sheet with thickness typically greater than that of the Moon, the magnetospheric ions that contain O^+ hit the entire lunar surface. In the other magnetospheric lobe (Fig. 3c), high-energy O^+, for which data were obtained immediately after the plasma sheet was encountered (Fig. 1a), is non-negligible, possibly because of the flapping of the plasma sheet.

Estimation of the flux and density of magnetospheric O^+ in the plasma sheet. Differential energy fluxes in the energy–time spectra, densities and net fluxes were computed on the ground using the calibration data[32] obtained in pre-flight testing and in-flight calibration operations[9]. The abundances of H^+ and O^+ in the measured fluxes were also derived on the ground from the IMA data in the mass analysis mode, which contained the flight-time (that is, mass) profiles[7]. We selected the data for H^+ and O^+ from the full width at half maximum of the calibration curves.

To distinguish between magnetospheric and lunar O^+, we used the cutoff energy of the measured lunar ions. The cutoff energy was determined by the electrical potential differences between the lunar surface and the spacecraft. Kaguya only measured lunar ions above the dayside surface, because the photoionization of the lunar exosphere and ion emission from the surface require solar ultraviolet[33]. The sunlit surface and spacecraft are expected to be positively charged below 10 V because of photoelectron emission[34]. The surrounding electric fields in the magnetosphere are typically below 1 mV m^{-1} and can provide a potential difference that is less than a few hundred volts[8]. Therefore, we computed the densities of lunar and magnetospheric O^+ from the IMA data of O^+ below 1 keV and over 2 keV, respectively, to distinguish clearly between the two origins of O^+ (Fig. 2d).

The densities of magnetospheric H^+ were computed from both IEA and IMA data (Fig. 2d). The H^+ densities from the IMA were occasionally lower than those from the IEA because the IEA effectively measured ambient magnetospheric ions. Thus, we calculated the net fluxes of magnetospheric O^+ based on the densities from the IEA data and the abundance ratio of magnetospheric O^+/H^+ from the IMA data (Table 1). In the period of 8:00–16:00 UT on 21 April 2008, the average abundance ratio of magnetospheric O^+/H^+ was 2.4%, which is similar to previous observations[10,15]. Assuming that the magnetospheric ions with a density of 5.1×10^{-2} cm^{-3} from the IEA data maintained the abundance ratio of 2.4%, the density and net flux of magnetospheric O^+ were $1.2\times10^{-3}\,cm^{-3}$ and $2.6\times10^{4}\,cm^{-2}\,s^{-1}$, respectively. Finally, from all events detected during the encounters with the plasma sheet in 2008 (Table 1), a 1-year supply of terrestrial O^+ of $4.0\times10^{9}\,cm^{-2}$ was calculated. The total 1-year O^+ supply to the entire lunar surface area was 1.5×10^{27} ions. Here, it should be noted that the O^+ 1-year supply is a lower limit, because Kaguya sometimes suspended its ion observation, and some observations were performed without the mass analysis mode in the Earth's magnetosphere. In addition, a solar minimum occurred around 2008, which resulted in stable and quiet solar and geomagnetic activities.

Data availability. The data that support the plots within this paper and other findings of this study are available from the corresponding author upon reasonable request.

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References

1. Ozima, M. *et al.* Terrestrial nitrogen and noble gases in lunar soils. *Nature* **436,** 655–659 (2005).
2. Hashizume, K. & Chaussidon, M. A non-terrestrial ^{16}O-rich isotopic composition for the protosolar nebula. *Nature* **434,** 619–622 (2005).
3. Ireland, T. R., Holden, P., Norman, M. D. & Clarke, J. Isotopic enhancements of ^{17}O and ^{18}O from solar wind particles in the lunar regolith. *Nature* **440,** 776–778 (2006).
4. Hashizume, K. & Chaussidon, M. Two oxygen isotopic components with extra-selenial origins observed among lunar metallic grains — in search for the solar wind component. *Geochim. Cosmochim. Acta* **73,** 3038–3054 (2009).
5. Ozima, M., Yin, Q.-Z., Podosekc, F. A. & Miura, Y. N. Toward understanding early Earth evolution: Prescription for approach from terrestrial noble gas and light element records in lunar soils. *Proc. Natl Acad. Sci.* **105,** 17654–17658 (2008).
6. Thiemens, M. H. Atmospheric science: Mass-independent isotope effects in planetary atmospheres and the early solar system. *Science* **283,** 341–345 (1999).
7. Saito, Y. *et al.* In-flight performance and initial results of Plasma energy Angle and Composition Experiment (PACE) on SELENE (Kaguya). *Space Sci. Rev.* **154,** 265–303 (2010).
8. Tanaka, T. *et al.* First *in situ* observation of the Moon-originating ions in the Earth's magnetosphere by MAP-PACE on SELENE (Kaguya). *Geophys. Res. Lett.* **36,** L22106 (2009).
9. Yokota, S. *et al.* First direct detection of ions originating from the Moon by MAP-PACE IMA onboard SELENE (Kaguya). *Geophys. Res. Lett.* **36,** L11201 (2009).
10. Seki, K., Elphic, R. C., Hirahara, M., Terasawa, T. & Mukai, T. On atmospheric loss of oxygen ions from Earth through magnetospheric processes. *Science* **291,** 1939–1941 (2001).
11. Del Zanna, G. *et al.* CHIANTI — an atomic database for emission lines. Version 8. *Astr. Astrophys.* **582,** A56 (2015).
12. Gloeckler, G. *et al.* Investigation of the composition of solar and interstellar matter using solar wind and pickup ion measurements with SWICS and SWIMS on the ACE spacecraft. *Space Sci. Rev.* **86,** 497–539 (1998).
13. Wargelin, B. J. *et al.* Chandra observations of the 'dark' Moon and geocoronal solar wind charge transfer. *Astrophys. J.* **607,** 596–610 (2004).
14. Seki, K. *et al.* Statistical properties and possible supply mechanisms of tailward cold O^+ beams in the lobe/mantle regions. *J. Geophys. Res.* **103,** 4477–4489 (1998).
15. Kistler, L. M. *et al.* Escape of O^+ through the distant tail plasma sheet. *Geophys. Res. Lett.* **37,** L21101 (2010).
16. Reisenfeld, D. B. *et al.* Elemental abundances of the bulk solar wind: Analyses from Genesis and ACE. *Space Sci. Rev.* **130,** 79–86 (2007).
17. Ilie, R. & Liemohn, M. W. The outflow of ionospheric nitrogen ions: A possible tracer for the altitude dependent transport and energization processes of ionospheric plasma. *J. Geophys. Res. Space Phys.* **121,** 9250–9255 (2016).
18. Yau, A. W., Abe, T. & Peterson, W. K. The polar wind: Recent observations. *J. Atmos. Sol. Terr. Phys.* **69,** 1936–1983 (2007).
19. Mauersberger, K. Measurement of heavy ozone in the stratosphere. *Geophys. Res. Lett.* **8,** 935–937 (1981).
20. Hiraki, Y., Yamada, A., Kasai, Y., Seta, T. & Ozima, M. Evaluation of isotopic fractionation of oxygen ions escaping from terrestrial thermosphere. *Geochim. Cosmochim. Acta* **84,** 525–533 (2012).
21. Chappell, C. R. *et al.* The adequacy of the ionospheric source in supplying magnetospheric plasma. *J. Atmos. Sol. Terr. Phys.* **62,** 421–436 (2000).
22. Ziegler, J. F. SRIM-2003. *Nucl. Instrum. Meth. Phys. Res. B* **219–220,** 1027–1036 (2004).
23. Young, E. D. *et al.* Oxygen isotopic evidence for vigorous mixing during the Moon-forming giant impact. *Science* **351,** 493–496 (2016).
24. McKeegan, K. D. *et al.* The oxygen isotopic composition of the Sun inferred from captured solar wind. *Science* **332,** 1528–1532 (2011).
25. Anbar, A. D. *et al.* A whiff of oxygen before the great oxidation event? *Science* **317,** 1903–1906 (2007).
26. Acuña, M. H. *et al.* Magnetic field and plasma observations at Mars: Initial results of the Mars Global Surveyor Mission. *Science* **279,** 1676–1680 (1998).
27. Harada, Y. *et al.* Marsward and tailward ions in the near-Mars magnetotail: MAVEN observations. *Geophys. Res. Lett.* **42,** 8925–8932 (2015).
28. Hale, C. J. The intensity of the geomagnetic field at 3.5 Ga: Paleointensity results from the Komati Formation, Barberton Mountain Land, South Africa. *Earth Planet. Sci. Lett.* **86,** 354–364 (1987).
29. Kahn, P. G. K. & Pompea, S. M. Nautiloid growth rhythms and dynamical evolution of the Earth–Moon system. *Nature* **275,** 606–611 (1978).
30. Jakosky, B. M. *et al.* MAVEN observations of the response of Mars to an interplanetary coronal mass ejection. *Science* **350,** 6261 (2015).
31. Yokota, S., Saito, Y., Asamura, K. & Mukai, T. Development of an ion energy mass spectrometer for application on board three-axis stabilized spacecraft. *Rev. Sci. Instrum.* **76,** 014501 (2005).
32. Saito, Y. & Mukai, T. The method of calculating absolutely calibrated ion and electron velocity moments. *ISAS Res. Note* **815,** 1–23 (2007)
33. Yokota, S. & Saito, Y. Estimation of picked-up lunar ions for future compositional remote SIMS analyses of the lunar surface. *Earth Planet. Space* **57,** 281–289, (2005).
34. Halekas, J. S., Saito, Y., Delory, G. & Farrell, W. M. New views of the lunar plasma environment. *Planet. Space Sci.* **59,** 1681–1694 (2011).

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Author contributions

K.T. and S.Y. wrote the manuscript. S.Y. also analysed the data, and contributed to the observations and data processing. Y.S., K.A. and M.N.N. contributed to the observations and data processing. N.K. contributed to the discussion.

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Competing interests

The authors declare no competing financial interests.