Planetary and Space Science 57 (2009) 2132–2134

Contents lists available at ScienceDirect

Planetary and Space Science

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

Rapid Communication

Extremely high reflection of solar wind protons as neutral hydrogen atoms from regolith in space

Martin Wieser [a,*], Stas Barabash [a], Yoshifumi Futaana [a], Mats Holmström [a], Anil Bhardwaj [b], R. Sridharan [b], M.B. Dhanya [b], Peter Wurz [c], Audrey Schaufelberger [c], Kazushi Asamura [d]

[a] Swedish Institute of Space Physics, Box 812, SE-98128 Kiruna, Sweden
[b] Space Physics Laboratory, Vikram Sarabhai Space Center, Trivandrum 695 022, India
[c] Physikalisches Institut, University of Bern, Sidlerstrasse 5, CH-3012 Bern, Switzerland
[d] Institute of Space and Astronautical Science, 3-1-1 Yoshinodai, Sagamihara, Japan

ARTICLE INFO

Article history:
Received 10 June 2009
Received in revised form
29 August 2009
Accepted 14 September 2009
Available online 20 September 2009

Keywords:
Solar wind interaction with regolith
Energetic neutral atoms
Moon
Chandrayaan-1
Sub-keV Atom Reflecting Analyzer

ABSTRACT

We report on measurements of extremely high reflection rates of solar wind particles from regolith-covered lunar surfaces. Measurements by the Sub-keV Atom Reflecting Analyzer (SARA) instrument on the Indian Chandrayaan-1 spacecraft in orbit around the Moon show that up to 20% of the impinging solar wind protons are reflected from the lunar surface back to space as neutral hydrogen atoms. This finding, generally applicable to regolith-covered atmosphereless bodies, invalidates the widely accepted assumption that regolith almost completely absorbs the impinging solar wind.

1. Introduction

In the Solar System, space weathering results in most surfaces of atmosphereless bodies being covered by regolith, a layer of loose, heterogeneous material of small grain size (Clark et al., 2002). In the absence of an atmosphere, plasma interacts directly with the surface, e.g. solar wind with the lunar regolith, and it has been tacitly assumed that the plasma is almost completely absorbed ($<1\%$ reflected) in the surface material (e.g. Crider and Vondrak, 2002; Schmitt et al., 2000; Feldman et al., 2000; Behrisch and Wittmaack, 1991). Regolith reaches hydrogen saturation on a geologically very short timescale of at most 10^4 years (Johnson and Baragiola, 1991). Once saturated, for every impinging proton a hydrogen atom is removed from the surface by sputtering, a scatter or desorption process. Here we present measurements that invalidate the widely accepted assumption that regolith almost completely absorbs the impinging solar wind. A large fraction of up to 20% is reflected as energetic neutral hydrogen atoms back to space.

2. Instrumentation

The Sub-keV Atom Reflecting Analyzer (SARA) instrument (Barabash et al., 2009) onboard the Indian Chandrayaan-1 spacecraft (Goswami and Annadurai, 2009) orbiting the Moon in a 100 km polar orbit measures the neutral atom flux from the lunar surface and simultaneously monitors the impinging flux of solar wind protons. The SARA instrument consists of two sensors: the Solar Wind Monitor (SWIM) (McCann et al., 2007) measures solar wind ions and the Chandrayaan-1 Energetic Neutrals Analyzer (CENA) (Kazama et al., 2007) measures energetic neutral atoms (10 eV–3 keV) arriving from the direction of the lunar surface. Both sensors provide angular and mass resolution SWIM has a field-of-view of $7.5^\circ \times 180^\circ$ divided into 16 angular pixels covering directions from nadir to zenith on the sun-facing side of the spacecraft. The orbital motion of Chandrayaan-1 is used to scan the SWIM field-of-view across the full solar wind angular distribution. The center of the CENA field-of-view is nadir-pointing and in total 160° cross-track times 7° along-track in size, divided into 7 angular pixels. Mass resolution m/dm of both sensors is 2–3, depending on sensor, angular pixel and mass. The geometric factor for SWIM is $5 \times 10^{-5}\,cm^2\,sr\,eV/eV$ for 500 eV protons. The geometric factor of CENA is $5 \times 10^{-8}\,cm^2\,sr\,eV/eV$ for 500 eV neutral hydrogen. Both values are for a single angular pixel at the center of the field-of-view.

3. Observations

During nominal solar wind conditions SARA observed that up to 16–20% of the proton flux impinging on the lunar surface is

* Corresponding author. Tel.: +46 980 79198.
E-mail address: wieser@irf.se (M. Wieser).

0032-0633/$ - see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.pss.2009.09.012

reflected back to space as energetic neutral hydrogen atoms. SARA persistently detects high-intensity fluxes of energetic neutral hydrogen atoms propagating from the lunar surface, while the latter is illuminated by the solar wind. The reflected neutral atom flux changes consistently with the change in solar wind incident angle (Fig. 1), with the reported numbers having reached at the lunar equator. No significant energetic neutral atom flux is observed on the night side. As the intensity of the impinging solar wind proton flux changed orbit by orbit, the intensity of the reflected neutral atom flux changed correspondingly and consistently (Fig. 2). The reflected neutral hydrogen observed had an energy spectrum with a distinct upper energy of 300 eV,

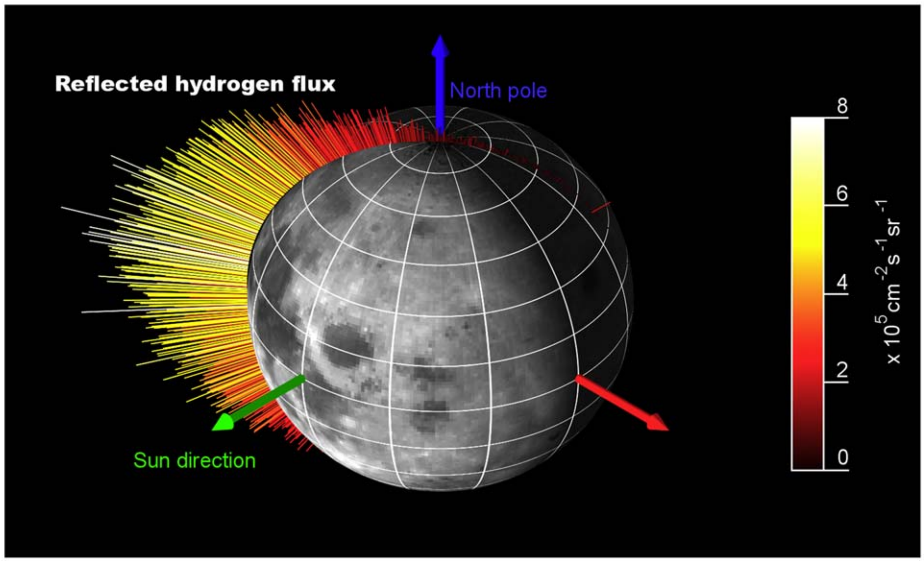

Fig. 1. Neutral hydrogen measurements recorded during three consecutive orbits on 6 February 2009. The flux from the surface seen with the nadir-looking sensor pixel is shown by thin colored zenith-pointing lines. Data from three orbits covering an area around 8°W lunar longitude on the lunar dayside are superimposed. Color and the line length depict the flux intensity. Solar wind ions impinge onto the lunar surface approximately from the Sun direction indicated by the green axis. A clear dependence of the flux on solar zenith angle is seen on the dayside. Small fluxes on the night side correspond to the instrument background. The lunar surface map is taken from Clementine image data.

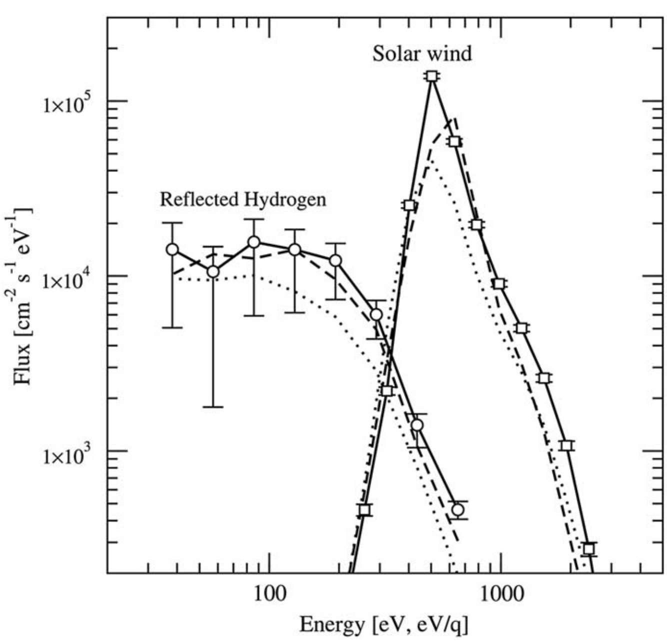

Fig. 2. Energy spectra of the solar wind (right side, open squares) and of the corresponding reflected energetic hydrogen (left side, open circles). Data from the same three orbits on 6 February 2009 as used in Fig. 1 are shown, with dayside equator crossings at 05:22 UTC (solid lines), 07.20 UTC (dashed lines) and 09:18 UTC (dotted lines). Measurements were taken shortly after the Moon crossed the Earth's bow shock to the downstream direction, resulting in a broadening of the energy spectrum of the solar wind protons. Note the good correlation between the reflected energetic neutral flux and the solar wind flux variations. The reflection yield when crossing the equator is 0.16–0.20, depending on the orbit. Taking uncertainties arising from detector efficiency into account and assuming an isotropic angular scatter distribution of the energetic hydrogen atoms, the average values over several orbits are, with 95% confidence, between 0.03 and 0.35. The isotropic angular scattering distribution on the surface assumed for calculating the total reflected flux is based on data obtained from pixels looking in non-nadir directions. Error bars shown represent knowledge of the instrument geometric factor (1σ).

roughly half the measured central energy (540 eV) of the impinging protons. Upon reflection from the surface, solar wind particles experience an average energy loss of more than 50%.

4. Discussion and conclusions

Ions with solar wind energies interacting with surfaces are likely to be neutralized, e.g. by resonant or Auger neutralization, before being absorbed or reflected (e.g. Niehus et al., 1993). We observe that up to 20% of solar wind protons are reflected from the lunar surface back to space as energetic neutral hydrogen atoms with energies larger than 25 eV (Fig. 2). These energetic neutral hydrogen atoms were also observed by the Interstellar Boundary Explorer (IBEX), at a much larger distance from the Moon (McComas et al., 2009) The high reflection invalidates the previous assumption that regolith almost completely absorbs the impinging solar wind. On a saturated surface the sum of all loss processes equals the solar wind precipitation, the high reflection yield reduces thus the amount of hydrogen available for release by other processes such as sputtering or desorption, both mechanisms predominantly producing neutrals with energies of only a few eV (Betz and Wien, 1994). Since the energy of the reflected energetic neutral hydrogen is much higher than the escape energy, escaping atoms propagate on ballistic trajectories. They can be used for detailed remote imaging of the solar wind–surface interaction (Bhardwaj et al., 2005, Futaana et al., 2006). The average energy loss of more than 50% when interacting with the surface is likely due to several mechanisms. A simple classical binary collision model (Niehus et al, 1993) gives an energy loss between 10% and 20%. This indicates the presence of other loss mechanisms, such as multiple scattering processes or interaction with the crystal lattice. Another possible loss process is retarding of impinging solar wind ions by a positive surface potential on the dayside (Vondrak, 1992), before the ions interact with the regolith surface. The observed lunar energetic neutral hydrogen component with an energy of up to 300 eV should also be visible in measurements of Doppler-shifted Lyman alpha emissions (Gott and Potter, 1970). The rate of implantation of solar wind ^{4}He and ^{3}He in the lunar regolith has to be reconsidered as well, because it can be expected that helium will have a similar reflection rate as hydrogen. Helium ions are efficient in creating hydrogen recoils when impinging on the surface (Niehus et al., 1993), a process that will additionally remove hydrogen from the lunar surface. It is expected that high solar wind reflection occurs on similar bodies in the Solar System as well, e.g. on Mercury, planetary satellites such as Phobos or Deimos, or on asteroids. Finally, the high neutral hydrogen reflection implies a lower hydrogen implantation rate in the regolith. Earlier work on the hydrogen influx on the lunar surface assumed almost complete absorption of solar wind ions (Crider and Vondrak, 2002, Schmitt et al., 2000, Feldman et al., 2000, Behrisch and Wittmaack, 1991), a finding that has to be revisited in the light of the present results: in equilibrium conditions, escaping and trapped hydrogen must equal the impinging hydrogen from solar wind. The efficient reflection process reduces the possible trapping rate, e.g. at the lunar poles. This makes it less likely that hydrogen at the poles is entirely of solar wind origin.

References

Barabash, S., Bhardwaj, A., Wieser, M., Sridharan, R., Kurian, T., Varier, S., Vijayakunar, E., Abhirami, V., Raghavendra, K.V., Mohankumar, S.V., Dhanya, M.B., Thampi, S., Asamura, K., Andersson, H., Futaana, Y., Holmstrom, M., Lundin, R., Svensson, J., Karlsson, S., Piazza, R.D., Wurz, P., 2009. Investigation of the solar wind–moon interaction onboard Chandrayaan-1 mission with the SARA experiment. Current Science 96 (4), 526.

Behrisch, R., Wittmaack, K., 1991. Introduction. In: Behrisch, R., Wittmaack, K. (Eds.), Sputtering by Particle Bombardment III. Springer-Verlag, New York, pp. 1–13.

Betz, G., Wien, K., 1994. Energy and angular distributions of sputtered particles. International Journal of Mass Spectrometry and Ion Processes 141.

Bhardwaj, A., Barabash, S., Futaana, Y., Kazama, Y., Asamura, K., Sridharan, R., Holmström, M., Wurz, P., Lundin, R., 2005. Low energy neutral atom imaging on the moon with the SARA instrument aboard Chandrayaan-1 mission. Journal of Earth System Sciences 114 (No.6), 749–760.

Clark, B.E., Hapke, B., Pieters, C., Britt, D., 2002. Asteroid space weathering and regolith evolution. In: Bottke Jr., W.F., Cellino, A., Paolicchi, P., Binzel, R.P. (Eds.), Asteriods III. University of Arizona Press, Tucson, pp. 585–599.

Clementine image data available at ⟨http://www.cmf.nrl.navy.mil/clementine/⟩.

Crider, D.H., Vondrak, R.R., 2002. Hydrogen migration to the lunar poles by solar wind bombardment of the moon. Advances in Space Research 30 (8), 1869–1874 October.

Feldman, W.C., Lawrence, D.J., Elphic, R.C., Barraclough, B.L., Maurice, S., Genetay, I., Binder, A.B., 2000. Polar Hydrogen deposits on the Moon. Journal of Geophysical Research 105 (E2), 4175–4196 02.

Futaana, Y., Barabash, S., Holmström, M., Bhardwaj, A., 2006. Low energy neutral atoms imaging of the Moon. Planetary and Space Science 54, 132–143.

Goswami, J.N., Annadurai, M., 2009. Chandrayaan-1: India's first planetary science mission to the moon. Current Science 96, 4 25 February.

Gott, J.R., Potter Jr., A.E., 1970. Lunar atomic hydrogen and its possible detection by Scattered Lyman-α Radiation. Icarus 13, 202–206.

Johnson, R.E., Baragiola, R., 1991. Lunar surface: sputtering and secondary ion mass spectrometry. Geophysical Research Letters 18, 2169.

Kazama, Y., Barabash, S., Wieser, M., Asamura, K., Wurz, P., 2007. Development of an LENA instrument for planetary missions by numerical simulations. Planetary and Space Science 55, 1518–1529.

McCann, D., Barabash, S., Nilsson, H., Bhardwaj, A., 2007. Miniature ion mass analyser. Planetary and Space Science 55 (No.9), 1190–1196.

McComas, D.J., Allegrini, F., Bochsler, P., Frisch, P., Funsten, H.O., Gruntman, M., Janzen, P.H., Kuchareck, H., Möbius, E., Reisenfeld, D.B., Schwadron, N.A., 2009. Lunar backscatter and neutralization of the solar wind: First observations of neutral atoms from the Moon. Geophysical Research Letters 36, L12104.

Niehus, H., Heiland, W., Taglauer, E., 1993. Low-energy ion scattering at surfaces. Surface Science Reports 17, 213–303.

Schmitt, H.H., Kulcinski, G.L., Santarius, J.F., Ding, J., Malecki, M.J., Zalewski, M.J., 2000. Solar wind hydrogen at the lunar poles, in: Proceedings of Space 2000: the Seventh International Conference and Exposition of Engineering, Construction, Operations, and Business in Space, February 27–March 2, Albuquerque, NM, USA, pp. 653–660, doi:10.1061/40479(204)79.

Vondrak, R.R., Lunar base activities and the lunar environment. In: Proceedings of the second Conference on Lunar Bases and Space Activities, NASA Johnson Space Center, September 1992, vol. 1, pp. 337–345 (SEE N93-17414 05-91), 1992lbsa.conf.337V.