Planetary and Space Science 115 (2015) 57–63

Contents lists available at ScienceDirect

Planetary and Space Science

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

Imaging the South Pole–Aitken basin in backscattered neutral hydrogen atoms

A. Vorburger [a,*], P. Wurz [b], S. Barabash [c], M. Wieser [c], Y. Futaana [c], A. Bhardwaj [d], K. Asamura [e]

[a] Division of Physical Sciences, American Museum of Natural History, New York, USA
[b] Physikalisches Institut, Universität Bern, Sidlerstrasse 5, CH-3012 Bern, Switzerland
[c] Swedish Institute of Space Physics, Box 812, SE-98128 Kiruna, Sweden
[d] Space Physics Laboratory, Vikram Sarabhai Space Center, Trivandrum 695 022, India
[e] Institute of Space and Astronautical Science, 3-1-1 Yoshinodai, Sagamihara, Japan

ARTICLE INFO

Article history:
Received 29 August 2014
Received in revised form
4 January 2015
Accepted 11 February 2015
Available online 21 February 2015

Keywords:
Moon
South Pole–Aitken basin
Energetic neutral atoms
Backscattering

ABSTRACT

The lunar surface is very efficient in reflecting impinging solar wind ions as energetic neutral atoms (ENAs). A global analysis of lunar hydrogen ENAs showed that on average 16% of the solar wind protons are reflected, and that the reflected fraction can range from less than 8% to more than 24%, depending on location. It is established that magnetic anomalies reduce the flux of backscattered hydrogen ENAs by screening-off a fraction of the impinging solar wind. The effects of the surface properties, such as porosity, roughness, chemical composition, and extent of weathering, were not known.

In this paper, we conduct an in-depth analysis of ENA observations of the South Pole–Aitken basin to determine which of the surface properties might be responsible for the observed variation in the integral ENA flux. The South Pole–Aitken basin with its highly variable surface properties is an ideal object for such studies. It is very deep, possesses strikingly elevated concentrations in iron and thorium, has a low albedo and coincides with a cluster of strong magnetic anomalies located on the northern rim of the basin. Our analysis shows that whereas, as expected, the magnetic anomalies can account well for the observed ENA depletion at the South Pole–Aitken basin, none of the other surface properties seem to influence the ENA reflection efficiency. Therefore, the integral flux of backscattered hydrogen ENAs is mainly determined by the impinging plasma flux and ENA imaging of backscattered hydrogen captures the electrodynamics of the plasma at the surface. We cannot exclude minor effects by surface features.

1. Introduction

The Moon, not being protected by a global magnetic field nor by an atmosphere, is constantly bombarded by solar wind ions. Until a few years ago, it was commonly assumed that the impinging solar wind ions are almost completely absorbed by the lunar surface (e.g. Crider and Vondrak, 2002; Feldman et al., 2000). This assumption has been invalidated by several recent observations conducted by Nozomi (Futaana et al., 2003), Kaguya (Saito et al., 2008), Chandrayaan-1 (Wieser et al., 2009; Lue et al., 2011), the Interstellar Boundary Explorer (IBEX) (McComas et al., 2009), Chang'E-1 (Wang et al., 2010) and Artemis (Halekas et al., 2013).

In particular, observations by Kaguya and Chandrayaan-1 showed that in fact on average between 0.1% and 1% of the impinging solar wind ions are reflected back from the lunar surface as ions, with local values ranging from 0% to more than 50% (Saito et al., 2008; Lue et al., 2011). Moreover, IBEX and Chandrayaan-1 observations showed that on average 16% of the impinging solar wind protons are backscattered as neutral hydrogen atoms from the lunar surface (McComas et al., 2009; Wieser et al., 2009; Vorburger et al., 2013). Mapping of the complete Chandrayaan-1 dataset showed that this backscatter percentage can range from less than 8% to more than 24% (Vorburger et al., 2013).

While an in-depth analysis of several observations of local magnetic anomalies showed that these influence the amount of solar wind flux reaching the lunar surface (e.g. Lin et al., 1998; Wieser et al., 2010; Saito et al., 2010; Lue et al., 2011; Vorburger et al., 2012), influences of other surface properties on the ion–surface interaction have not been investigated. We thus chose to analyze the ENA measurements in a region that exhibits very distinct features in as many surface properties as possible.

* Corresponding author. Tel.: +1 212 796 5082.
E-mail address: avorburger@amnh.org (A. Vorburger).

http://dx.doi.org/10.1016/j.pss.2015.02.007

With the South Pole–Aitken basin exhibiting distinct variability of several properties potentially affecting the ion–surface interaction (visible albedo, topography, chemistry, mineralogy, magnetism), it poses a choice location for analyzing the interaction between the solar wind and the lunar surface. By comparing an ENA integral flux map to variations in the different maps, we can determine what surface properties ENAs are sensitive to. This helps us to shed more light onto the still poorly understood backscattering process of plasma ions from regolith covered planetary surfaces.

The role of crustal magnetic fields on the lunar surface for the observation of these ENAs is that the plasma physical interaction of the solar wind plasma with the surface magnetic fields governs actual access of ions to the surface, as has been demonstrated in several papers before (Vorburger et al., 2012, 2013). Scattering of atoms and ions at solid surfaces is a complex process where the interaction of the impinging particles with the surface atoms is determined by the topmost surface of the solid, its chemical composition, and its roughness (Niehus et al., 1993). Variations in visible albedo of the Moon can have several causes, for example an increased roughness of the surface at scales commensurate with optical wavelengths can cause a lower visible albedo or a different chemical (or mineralogical) composition. Both of these effects will cause differences in the particle scattering from the surfaces: increased roughness will reduce the efficiency of particle reflection to space because of multiple scattering at the fractal surfaces and higher probability of absorption of a particle, and a different chemical composition changes the scattering partners for the reflection since this interaction is to first order a single or a few binary collisions. The South-pole Aitken basin is the oldest recognized topographical feature on the lunar surface. With its size of about 2500 km and a depth of about 12 km it indicates that a substantial amount of material has been removed from the surface during the impact forming this basin. Thus, the material on the floor of this basin might be different from the material outside this basin. The chemical and mineralogical composition of the South-pole Aitken basin is different from typical highland regions, as recorded in data from the Galileo, Clementine and Lunar Prospector missions (e.g. Lawrence et al., 1998, 2002), thus possibly affecting the ENA albedo. In terms of mineralogy, the basin floor is much richer in clinopyroxene (monoclinic crystal) and orthopyroxene (orthorhombic crystals) minerals than the surrounding highlands that are largely anorthositic (mostly plagioclase feldspar with minor mafic contributions). Pyroxenes are Si- or Al-oxide based minerals with ions of Ca, Na, Mg, Fe and other elements, many of heavier mass than in the anorthositic highlands, again, which might affect the ENA albedo. The remote sensing observations indicate that the floor of this basin has slightly elevated abundances of iron, titanium, and thorium. The enrichment in several heavier elements, which may represent lower crust material, will affect the particle scattering properties.

In Section 2 we briefly describe the instrument and the observations that were used for this analysis. In Section 3 we discuss the different surface features in which the South Pole–Aitken basin is distinguished from the surrounding terrain, and present two maps showing the ENA observations of that region. In Section 4 we thoroughly discuss the correlation between the ENA map and local surface features and thus deduced implications as to what mechanisms can cause the observed ENA depletions. Section 5 presents our conclusions and discusses where else our results might be applicable.

2. Observations and instrumentation

For this study we analyzed measurements conducted by the Chandrayaan-1 Energetic Neutrals Analyzer (CENA) (Kazama et al., 2007), which is a part of the Sub-keV Atom Reflecting Analyzer (SARA) instrument (Bhardwaj et al., 2005; Barabash et al., 2009) on board Chandrayaan-1 (Goswami and Annadurai, 2009). CENA measured ENAs originating from the lunar surface within the energy range 10 eV to 3.3 keV and with an energy resolution of $\Delta E/E \approx 50\%$. Even though CENA allows crude mass analysis to identify H, He, and O (Vorburger et al., 2014), we only analyzed hydrogen measurements in this study because the hydrogen counts by far exceed the counts in all other mass bins combined, thus they offer the statistically most robust measurement by far. CENA's field-of-view is spanned by seven angular sectors, which provide information about the arrival direction of the measured ENAs. The central sector is nadir pointing, i.e., its bore-sight crosses the lunar surface at the sub-spacecraft point. The other six sectors are symmetrically arranged around the central sector in the azimuth direction covering a swath of the full size of the Moon perpendicular to the orbit motion (see Fig. 1 in Wieser et al., 2010 for an illustration). Measurements by the outermost two sectors were disregarded in this study because they not only record measurements from the lunar surface but also from the lunar limb. The surface projections of the remaining five sectors are given in Table 1.

The Chandrayaan-1 mission operated from October 2008 until the end of August 2009. The spacecraft's circular polar orbit was initially set at an altitude of 100 km and was raised to 200 km at the end of May 2009. Discarding the period when the Moon was inside Earth's magnetosphere, we were left with 163 orbits, 64 of which passed directly over the South Pole–Aitken basin (i.e. the instrument's boresight crossed the South Pole–Aitken basin). Since each orbit gives us 5 datasets (one for each angular sector), we had in total 815 datasets to analyze, about 250 of which contained measurements from the South Pole–Aitken basin.

3. The South Pole–Aitken basin

3.1. The South Pole–Aitken basin in ENAs

Fig. 1 shows two different ENA reflection ratio maps centered on the South Pole–Aitken basin. The reflection ratio is defined as the ratio of ENA flux backscattered from the lunar surface for CENA's complete energy range and all exit angles (hemisphere) to the impinging solar wind ions:

$$R = \frac{J_{ENA}}{J_{SW}}, \quad (1)$$

where J_{ENA} is the reflected ENA flux over the zenith hemisphere (the 2π sphere) and J_{SW} is the impinging solar wind flux observed at the Moon. The solar wind values were taken from the WIND spacecraft time-shifted according to the distance between WIND and Chandrayaan-1 as well as the plasma's velocity.

Since a single ENA observation is only able to measure the flux backscattered in a certain direction (i.e., towards the instrument's field of view), we first had to deduce the total ENA flux released over the complete zenith hemisphere (J_{ENA}) from the directional measurement ($j_{ENA}(\mathrm{SZA}, \phi, \theta)$). This was accomplished by fitting the measurements with the scattering function presented in

Table 1
Surface projections of the central five sectors given in lunar longitude/latitude as well as kilometers for two nominal spacecraft altitudes (100 km and 200 km).

Sector	lon × lat @ 100 km	lon × lat @ 200 km	km × km @ 100 km	km × km @ 200 km
1	5.57° × 0.36°	13.72° × 0.76°	169 × 11 km^2	416 × 23 km^2
2	3.20° × 0.36°	6.53° × 0.76°	97 × 11 km^2	198 × 23 km^2
3	2.74° × 0.36°	5.54° × 0.76°	83 × 11 km^2	168 × 23 km^2
4	3.20° × 0.36°	6.53° × 0.76°	97 × 11 km^2	198 × 23 km^2
5	5.57° × 0.36°	13.72° × 0.76°	169 × 11 km^2	416 × 23 km^2