THE MOON OBSERVED IN ENERGETIC NEUTRAL ATOMS: REVIEW OF THE SCIENTIFIC FINDINGS FROM SARA/ CENA ON BOARD CHANDRAYAAN-1

A. Vorburger[1], P. Wurz[1], S. Barabash[2], M. Wieser[2], Y. Futaana[2], A. Bhardwaj[3], M. B. Dhanya[3], K. Asamura[4]

[1] University of Bern, Space Research and Planetary Sciences, Bern, Switzerland (vorburger@space.unibe.ch);
[2]Swedish Institute of Space Physics, Kiruna, Sweden
[3]Space physics Laboratory, Vikram Sarabhai Space Center, Trivandrum, India
[4]Institute of Space and Astronautical Science, Sigamihara, Japan

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INTRODUCTION:

The Moon, not being protected by a global magnetic field or an atmosphere, is under constant bombardment 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 (< 1% reflection; see for example [1, 2]). Recent observations by IBEX and the Sub-keV Atom Reflecting Analyzer (SARA) onboard Chandrayaan-1 invalidated this assumption, though, showing that lunar surface very efficiently reflects impinging solar wind protons as Energetic Neutral Atoms (ENAs), with reflection ratios typically between 10% and 20% (e.g. [3, 4]). With such high ENA fluxes coming from the lunar surface, ENA monitoring offers a powerful method for investigating the solar wind interaction with the lunar surface. Herein we present a review of all scientific findings from SARA's ENA sensor.

INSTRUMENTATION:

We report here on scientific measurements based on measurements conducted by the Chandrayaan-1 Energetic Neutrals Analyzer (CENA) [5], which is a part of the SARA instrument [6] onboard Chandrayaan-1 [7]. CENA measured ENAs originating from the lunar surface within the energy range 10 eV to 3.3 keV and an energy resolution of $\Delta E / E \sim 50\%$. CENA was capable of mass discrimination, being able to distinguish H and O from heavier elements. CENA's field of view consisted of seven angular sectors (five of which were purely surface pointing), with surface-projected footprints of approximately 100 – 400 km × 10 – 20 km, depending on the sector number and spacecraft altitude.

RESULTS & DISCUSSION:

Figure 1 presents an overview of the most significant scientific findings based on measurements conducted by CENA. Panel a) shows that there is a substantial flux of reflected, neutralized hydrogen coming from the lunar surface. The plot shows a clear cosine-correlation with solar zenith angle, as is expected for pure geometrical reasons. A global analysis showed that on average 16% of the impinging solar wind protons are reflected as neutral hydrogen atoms, with a standard deviation of 5%. The ENA reflection ratio is rather featureless over the lunar surface, showing only strong variations at local crustal magnetic fields due to the interaction of the plasma with so-called mini-magnetospheres. An example of such a mini-magnetosphere ENA image is shown in Panel b): There is a clear void of ENAs coming from the centre of the magnetic anomaly, where the surface is shielded from the impinging solar wind ions, whereas there is an enhanced ring surrounding the void, denoting the region where the ions have been deflected to.

CENA measurements were also used to identify a large, positive electric potential associated with the magnetic anomaly. This electric potential was expected based on charge separation in the impinging plasma, where ions can penetrate further into the mini-magnetosphere region than electrons, which are deflected by the magnetic field. The charge separation produces an outward-facing electric field. The ENA energy spectrum in general resembles a Maxwell Boltz-

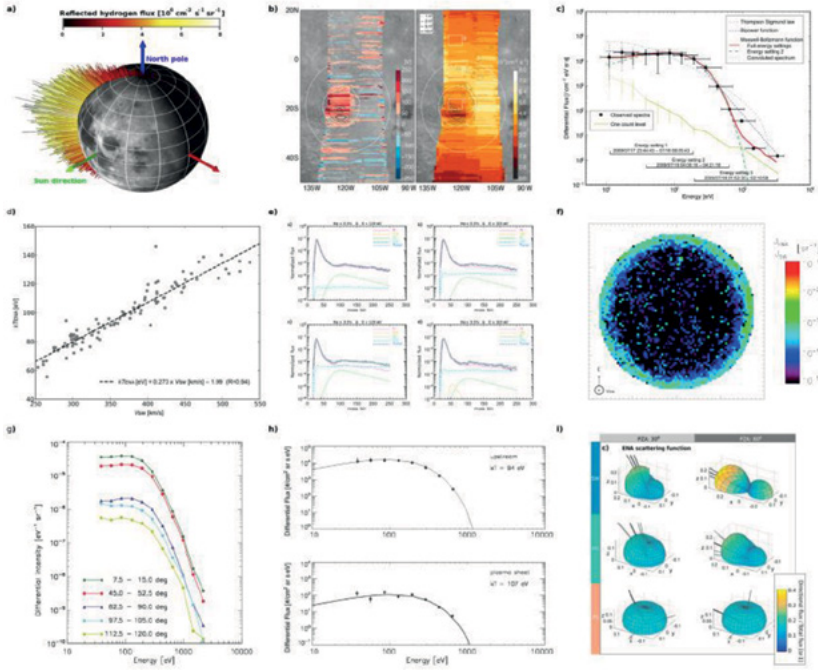

Fig. 1. Scientific results based on measurements conducted by CENA. Panel a): Reflected neutral hydrogen flux measured during one orbit of Chandrayaan-1. Panel b): Electric potential and reflection ratio imaging of a mini-magnetosphere above a lunar magnetic anomaly. Panel c): Energy spectrum of measured ENAs and best fitting Maxwell Boltzmann Function. Panel d): Correlation between ENA characteristic energy and solar wind velocity. Panel e): Mass spectra recorded during flight containing neutral hydrogen, oxygen, and helium. Panel f): Lunar nightside energy spectrum exhibiting a ~20° broad ring parallel to the terminator. Panel g): Energy spectrum of dayside and nightside ENAs showing the similarity of the two. Panel h): Energy spectrum of ENAs measured in the solar wind and in the terrestrial plasma sheet. Panel i): Scattering function of ENAs measured upstream, in the magnetosheath, and in the terrestrial plasma sheet.

mann distribution (see Panel c), a fact still not completely understood, because the energy loss observed does not agree with the ENAs having been thermalized. An additional mystery is the correlation between the characteristic energy and the solar wind velocity, and not the solar wind energy, a fact hinting at the backscattering processes at the surface being controlled by the momentum of the impinging particle velocity rather than its energy (see Panel d).

Whereas all these findings were based on energetic neutral hydrogen measurements, other mass groups were also observable by CENA. CENA presented first direct measurements of sputtered lunar oxygen, with surface densities of ~$1.3 \cdot 10^7$ m^{-3} and column densities of ~$1.6 \cdot 10^{13}$ m^{-2}. In addition, backscattered helium was detected in the CENA data set (see Panel e), but due to uncertainties in the instrument's geometric factor, no surface or column densities could be derived.

Nightside ENA measurements showed that a significant fraction of the solar wind plasma is able to reach much further into the lunar nightside wake than the proton temperature would allow: CENA measured a 30° broad ENA ring parallel to the terminator, with a flux of ~1.5% of the dayside flux (see Panel f). Energy analysis showed, that whereas the nightside ENAs' energy spectrum clearly resembles the dayside backscattered ENAs' energy spectrum, their characteristic energy is slightly lower (by about 4 eV), hinting at the plasma having been decelerated in the lunar wake (see Panel g).

CENA measurements in the terrestrial plasma sheet (Panel h) revealed that the characteristic energy and the backscatter ratio in Earth's plasma sheet is similar to the upstream solar wind case. In contrast to the upstream observations, though, no ENA void was observed over large and strong magnetized lunar surface regions. Analyses suggest that the magnetic shielding of the lunar surface in the plasma sheet is less effective in the terrestrial plasma sheet than in the solar wind, probably due to the broad velocity distributions of the plasma sheet ions.

A final analysis included lunar ENAs recorded when the Moon was located inside the terrestrial magnetosheath (see Panel i). As in the upstream solar wind and in the terrestrial plasma sheet case, on average 10% to 20% of the impinging protons are reflected back as neutral hydrogen atoms in Earth's magnetosheath. Similar to the upstream solar wind case, and contrary to the terrestrial plasma sheet case, clear signatures of plasma shielding by magnetic anomalies were observed. Overall, the scattering process seems unchanged in the Earth's magnetosheath, with the only exception being that in the terrestrial magnetosheath the energy spectrum becomes broader and less peaked, probably due to the increase in plasma temperature.

Overall, CENA was exceptionally successful. The instrument not only achieved all its set science goals but also revealed several hitherto unknown and unexpected properties of the solar wind interaction with the lunar surface.

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