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IBEX-Lo Observations of Energetic Neutral Hydrogen Atoms Originating from the Lunar Surface

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Abstract

We present quantitative results of observations of energetic neutral atoms (ENAs) originating from the lunar surface. These ENAs, which are hydrogen atoms, are the result of the solar wind protons being reflected from and neutralised at the surface of the Moon. These measurements were made with IBEX-Lo on NASA's IBEX satellite. From these measurements we derive the energy spectrum of the ENAs, their flux, and the lunar albedo for ENAs (i.e., the ratio of ENAs to the incoming solar wind protons). From several orbits we derived an average global albedo of $A_H = 0.09\pm0.05$.

The observed energy spectrum provides a generic spectrum for unshielded bodies in the solar wind. This spectrum clearly shows that the origin of the ENAs is directly from the solar wind via backscattering, and that they are not sputtered atoms.

1. Introduction

NASA's Interstellar Boundary Explorer (IBEX) mission was designed to investigate the interaction of the heliosphere with the surrounding interstellar medium via the observation of Energetic Neutral Atoms (ENAs) from a near Earth vantage point [4]. The IBEX payload consists of two single-pixel ENA sensors with large geometric factors, IBEX-Lo and IBEX-Hi, and a single Combined Electronics Unit (CEU) that controls these sensors, stores data, and is the payload interface to the spacecraft bus [4]. Because the Moon has no atmosphere or strong magnetic field to protect its surface from external influences, the solar wind directly interacts with the lunar surface. The solar wind ions are partially absorbed by the lunar regolith but a fraction of them is scattered back to space, with most of these backscattered particles being neutralised in the process to form energetic neutral atoms (ENAs). These large fractions of reflected and neutralised solar wind challenged previous assumptions about almost complete adsorption of solar wind ions impinging on the lunar surface [8]. The observations of the backscattering and neutralisation processes of solar wind on the lunar surface is important for the analysis of plasma interaction with the lunar surface, which is also important for all other celestial bodies that have no atmosphere.

2. Instrumentation

The IBEX-Lo sensor is a single pixel, large geometric factor camera [2]. It detects 10 eV to 2 keV neutral atoms from the heliosphere and from the interplanetary medium in 8 broad energy bands. The IBEX-Lo sensor uses surface reflection and conversion to convert neutrals into negative ions and then accelerates the ions so that they can be deflected away from the viewing direction to efficiently suppress background from ambient particles and photons [9]. The ions are energy and mass analysed and registered with high efficiency. The sensor uses a triple coincidence TOF mass spectrometer, which separates hydrogen, helium, and oxygen.

3. Observations

There are only selected time periods during a few orbits when the Moon is in the field-of-view (FOV) of the IBEX sensors [1]. To determine what orbits could be used to calculate the energy spectrum of ENAs from the Moon, we used several selection criteria, which meant that not all the orbits where the Moon was in the FOV were chosen for further analysis. To remove the background from the signal in the selected orbits, we took samples from two observations before and after the lunar viewing. By subtracting this background from the signal directly we avoid here a more rigorous accounting of the background source [9]. After removing background, the lunar signal was corrected for cross-talk from other energy bins. We calculated the ENA flux from the lunar surface from the corrected counts of an observation recorded by the IBEX-Lo. Knowing the ENA fluxes, for each energy bin, in addition to the distance of the IBEX satellite from the Moon, we can deduce the ENA flux produced at the lunar surface. When the Moon is outside the magnetosphere the observation angle is $\phi_{SW} \sim 90°$ with respect to the solar wind direction, thus only half of the Moon visible to IBEX is illuminated by solar wind ions. When the Moon is inside the magnetosphere the observation angle is different ($\phi_{SW} \neq 90^o$). Also the plasma parameters, i.e., the density and flow velocity, are different from the solar wind plasma parameters. This analysis was done with the help of the BATS-R-US [3], a magnetosphere model of Community Coordinated Modeling Center (CCMC).

From the emitted lunar ENAs fluxes we estimate the ENAs albedo using the incident solar wind flux on the surface of the Moon. We obtained the average of this flux ratio (average global ENA albedo) over all orbits of 0.09±0.05. The derived value of the global albedo is limited to the range of energy bins covered by the IBEX-Lo sensor, although we can assume that most of the lunar ENA flux is registered by IBEX-Lo based on the energy spectra. The value for the global ENA albedo is an average value for the lunar surface since the angular size of the Moon during the IBEX observations is smaller than the angular resolution of IBEX-Lo.

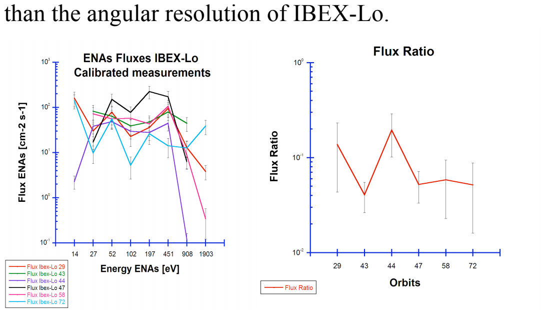

Figure 6. a. ENA flux as function of energy for selected orbits. The ENA fluxes are roughly constant up to an energy near the solar wind energy. Above the solar wind energy, they drop steeply. Similar energy dependences are observed for all orbits. b. Variation of lunar ENA flux ratio for the different orbits of IBEX-Lo.

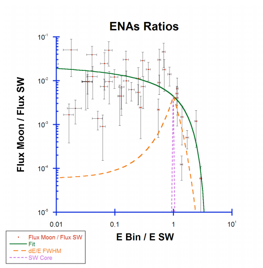

Figure 9. Flux ratio of all the orbits in this work. The error bars come from propagation of error of counting statistics and uncertainty in the geometric factor of IBEX-Lo. For comparison the core solar wind is shown, and a distribution with a FWHM equal to that of the IBEX-Lo Energy response, both normalized to the observed flux ratio at the solar wind energy. The solid line shows the best fit to our generic ENA spectrum described in the text.

4. Discussion and conclusions

We report observations of lunar hydrogen ENAs over the full IBEX-Lo energy range down the lowest energy bin (14 eV centre energy, spanning from 10 to 18 eV). This means that IBEX-Lo almost completely covers the energy spectrum of the ENAs from the lunar surface for typical solar wind speeds <500 km/s. The spectrum of lunar ENAs represents a typical spectrum emitted from such unshielded bodies, assuming that the surface properties are similar to the lunar regolith. The observations of lunar ENAs show a very flat spectrum extending down to small fractions of the solar wind energy, unlike those measured from laboratory surfaces under bombardment by mono-energetic ion beams (e.g. [6,7]). One explanation of this feature is that the lunar surface is rough, leading to more frequent multiple scatterings. We could also observe the behaviour of the variable energy H-ENA albedo (Flux Ratio), correlated with the solar wind. In our study with IBEX-Lo we determine a total global value for the flux ratio, with an average flux ratio of $A_H \approx 0.09\pm0.05$ [1], which is compatible with the earlier measurements of the global albedo based on IBEX-Hi data of $A_H \sim 0.1$ [5], and the local value of $A_H = 0.16$ to 0.20 at the lunar equator derived by [8], from Chandrayaan-1 / SARA data. The study of data from the lunar hydrogen ENAs, i.e., the backscattered and neutralised solar wind, is very relevant to planetary science since many planetary surfaces are not shielded from the influence of the solar wind, and these ENAs are a source of energetic hydrogen atoms in the solar system.

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