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Lunar energetic neutral atom (ENA) spectra measured by the interstellar boundary explorer (IBEX)

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ABSTRACT

The solar wind continuously flows out from the Sun, filling interplanetary space and directly interacting with the surfaces of small planetary bodies and other objects throughout the solar system. A significant fraction of these ions backscatter from the surface as energetic neutral atoms (ENAs). The first observations of these ENA emissions from the Moon were recently reported from the Interstellar Boundary Explorer (IBEX). These observations yielded a lunar ENA albedo of ~10% and showed that the Moon reflects ~150 metric tons of neutral hydrogen per year. More recently, a survey of the first 2.5 years of IBEX observations of lunar ENAs was conducted for times when the Moon was in the solar wind. Here, we present the first IBEX ENA observations when the Moon is inside the terrestrial magnetosheath and compare them with observations when the Moon is in the solar wind. Our analysis shows that: (1) the ENA intensities are on average higher when the Moon is in the magnetosheath, (2) the energy spectra are similar above ~0.6* solar wind energy but below there are large differences of the order of a factor of 10, (3) the energy spectra resemble a power law with a "hump" at ~0.6 * solar wind energy, and (4) this "hump" is broader when the Moon is in the magnetosheath. We explore potential scenarios to explain the differences, namely the effects of the topography of the lunar surface and the consequences of a very different Mach number in the solar wind versus in the magnetosheath.

1. Introduction

The Interstellar Boundary Explorer (IBEX) (McComas et al., 2009a) was launched on Oct. 19, 2008 and has been delivering a number of exciting results ever since. Aside from its goals to study the global interactions between the heliosphere and the local interstellar medium using energetic neutral atom (ENA) imaging, IBEX also observes nearby objects (McComas et al., 2011a), namely the terrestrial magnetosphere (e.g., McComas et al., 2011b, 2012; Petrinec et al., 2011; Fuselier et al., 2010) and the Moon (McComas et al., 2009; Rodriguez et al., 2012; Funsten et al., 2013).

IBEX has two single-pixel, high-sensitivity ENA imagers (or sensors), IBEX-Lo and IBEX-Hi, that have overlapping energy ranges from ~0.01 to 2 keV and from ~0.3 and 6 keV, respectively. Both sensors use a similar detection technique: a collimator to define the field-of-view (FOV) and repel charged particles, a charge conversion system to convert the ENAs into charged particles, an energy analyzer to filter the ionized ENAs by energy and to block UV radiation, and a coincidence detection section. For the charge conversion system, IBEX-Lo utilizes a very smooth conversion surface (e.g., Scheer et al., 2006), whereas IBEX-Hi utilizes an ultra-thin carbon foil (e.g., Funsten et al., 1993; McComas et al., 2004). Their FOVs are similar (~$7^\circ \times 7^\circ$ FWHM) and their look directions are on opposite sides of the spacecraft, perpendicular to the spin axis, such that they both sample the same swath in the sky over a full spacecraft spin. Both IBEX sensors resolve energy ($\Delta E/E$~0.7 FHWM in eight steps for IBEX-Lo and ~0.5 to 0.7 FHWM in six steps for IBEX-Hi). More detailed information on these sensors can be found in the respective instrument papers (Fuselier et al., 2009; Funsten et al., 2009). IBEX also has a background monitor (IBaM for IBEX Background Monitor) (Allegrini et al., 2009) that is used to infer the ion background environment and to identify time intervals when the

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background signal is above an energy and flux threshold. The IBaM makes an integral measurement of protons intensities above ~14 keV.

The first report of ENAs from the Moon (McComas et al., 2009b) used IBEX-Hi observations taken in December 2008, during the first IBEX-Hi commissioning orbit. This study established that the ENAs were solar wind backscattered from and neutralized by the surface of the Moon. The reflected portion, or ENA albedo, was estimated to be ~10% based on this one observation of the Moon.

Soon after, Wieser et al. (2009) reported the first observations of ENAs measurements from the Chandrayaan-1 Energetic Neutral Atom (CENA) (Kazama et al., 2007) sensor part of the SARA instrument (Bhardwaj et al., 2005; Barabash et al., 2009). CENA is based on the conversion surface technique, similar to IBEX-Lo (Wurz, 2000). Chandrayaan-1 was in a polar orbit around the Moon at 100 km altitude. CENA measured an ENA albedo of ~16–20% in the energy range ~40 to 650 eV. Using a large collection of CENA measurements, Schaufelberger et al. (2011) determined a scattering function of lunar ENAs over this energy range. Contrary to what is observed with atomically smooth surfaces for which forward scattering is favored, the results showed that backscattering was favored in the case of the lunar regolith, probably because of the large porosity. Using the full energy range of CENA (10–3300 eV), Futaana et al. (2012) reported ENA energy spectra. They found that the best fit to their spectra was with Maxwell–Boltzmann distributions and with the only correlation between the fit parameters and the upstream solar wind parameters was the solar wind speed with the characteristic energy of the ENAs.

Recently, Rodríguez et al. (2012) reported IBEX-Lo observations of lunar ENAs. They derived an ENA albedo of ~0.09. Building on Schaufelberger et al. (2011) scattering function, Saul et al. (2013) recalculated the ENA albedo from the IBEX-Lo measurements and found an albedo about 25% higher, i.e., 0.11.

Since the first report of lunar ENA measured by IBEX-Hi, Funsten et al. (2013) analyzed many more observations when the Moon was in the solar wind. They derived key properties of the lunar ENAs, and in particular found that the albedo varies from about 0.08 to 0.20 depending on solar wind speed. It is lowest for the highest solar wind speed and is empirically fitted with the function $R_N = 1/(2.3 + 6.3\ E_{SW}\ [\mathrm{keV}])$. They also found strong evidence of an ENA spectral distribution at energies greater than ~250 eV that decreases linearly with increasing energy up to the solar wind energy.

There are times, however, when the Moon is in the magnetosheath as it transits IBEX's FOV. In the magnetosheath, the plasma incident on the Moon is different from the solar wind input of previous studies. Specifically, the solar wind is slowed, compressed and heated at the bow shock, and flow is diverted around the magnetosphere. This contrasts to direct exposure to the solar wind, which is generally beam-like. Some parameters, such as the Mach number, are changed in the magnetosheath and that may result in a different reflection coefficient because more of the surface visible from IBEX could be exposed to the solar wind.

In this study, we combine for the first time IBEX-Lo and -Hi observations of lunar ENAs to create spectra over the broad energy range from ~14 eV to ~4.1 keV for the viewings when the Moon is in the magnetosheath or in the solar wind. We then compare these spectra and evaluate the differences between observations when the Moon is in the magnetosheath and the solar wind.

2. Data selection

We examine all data intervals, when the Moon is either in the solar wind or in the magnetosheath, in which IBEX observes statistically significant counts in both IBEX-Lo and -Hi. Specifically, the number of counts attributed to lunar ENAs is larger than one standard deviation in more than one energy step (total of eight steps for IBEX-Lo and six for IBEX-Hi). The driver for good intervals is usually the IBEX-Lo sensor because IBEX-Hi is more sensitive than IBEX-Lo. We end up with a total of nine viewings from orbit 11 (end of December 2008) up to orbit 139 (mid September 2011), four of them being when the Moon is in the solar wind, and five when the Moon is in the magnetosheath. Table 1 lists the intervals and Fig. 1 shows two examples of the configuration when (a) the Moon is in the solar wind (orbit 58, December 2009) and (b) when the Moon is in the magnetosheath (orbit 136a, August 2011). We use a model of the magnetosphere to determine if the Moon is in the magnetosheath (more details are given below).

Table 1
Time intervals in UT of the lunar viewings. The abbreviations of the location are SW for solar wind and MS for magnetosheath.

orbit	Date start yyyy/mm/dd	Time start hh:mm:ss	Date stop yyyy/mm/dd	Time stop hh:mm:ss	Location
29	2009/05/16	13:43:28	2009/05/17	02:01:36	SW
43	2009/08/30	21:46:51	2009/08/31	10:01:22	MS
44	2009/09/07	20:21:02	2009/09/08	23:52:50	MS
58	2009/12/21	15:32:16	2009/12/22	03:50:24	SW
72	2010/04/08	11:54:40	2010/04/08	22:41:04	SW
126	2011/05/24	09:38:08	2011/05/24	17:18:56	SW
136a	2011/08/17	00:01:50	2011/08/17	13:47:59	MS
138b	2011/09/07	11:40:15	2011/09/07	22:22:55	MS
139b	2011/09/15	03:05:15	2011/09/16	15:54:08	MS

Figs. 2 and 3 show examples of data for the orbit arc 136a for IBEX-Lo and -Hi, respectively. The counts per time bin (923 s bin for IBEX-Lo and 919 s bin for IBEX-Hi) are color-coded and plotted in angle from north ecliptic pole (NEP) versus time for each energy step on the right-hand side. The orange vertical bars represent the time intervals of the lunar viewing. The top panel displays the background monitor counts in the same representation for the full angle range. The rectangle corresponds to the range of angles covered in the lower panels. Times when the background monitor rates are above a defined threshold or when the Moon is outside the magnetosheath (for a magnetosheath interval) are disregarded as indicated by the gray shading. The counts are then integrated over the time interval and plotted as a function of angle from NEP on the right-hand side.

IBEX's FOV is ~$7^\circ \times 7^\circ$ FWHM with a roughly triangular transmission function. IBEX data are binned in histograms of sixty six-degree bins. From IBEX's point-of-view, the Moon's full disk in the FOV ranges from ~0.55° to 2.1° for the selected viewings. Therefore, the lunar ENA counts appear at most within three consecutive angle bins.

To extract the lunar counts from a residual background (that can be partly attributed to heliospheric signal) we fit an empirical second-degree polynomial (dark blue curve) to the pixels (green dots) on each side of the peaks (red dots) and subtract it from the counts in the peaks. The total lunar ENA counts with background subtracted are indicated as well as the one-sigma uncertainty for each energy step.

3. Results

3.1. Lunar ENA energy spectra

The lunar ENAs counts for IBEX-Lo and -Hi are then converted into rates and subsequently into fluxes using the respective geometric factors for hydrogen (see Table 2). The fluxes for IBEX-Lo are