Solar Wind Reflection from the Lunar Surface


DAP-2012 Meeting, June 6-8, 2012
Interaction of the Solar Wind with the Lunar Regolith

- Solar wind: primarily H\(^+\), \sim 1\ \text{keV}, beam-like

**Sputtering:** <50 eV
- Wehner et al., Planet. Space Sci. 1963
- Hapke, Icarus, 1986
- Elphic et al., GRL 1991
- Johnson and Baragiola, 1991

** Implanted SW**
- Pillinger et al, Rep Prog Phys, 1979
- Crider and Vondrak, JGR, 2000

**Reflected SW:** Up to SW energy
- **Ions:** Saito et al, GRL, 2008
- **Neutrals:**
  * McComas et al., GRL, June 2009

**Solar Wind Ions**
The IBEX-Hi ENA Imager

- Sensitivity: detect ENA flux of $0.02 \text{ (cm}^2 \text{ s sr keV)}^{-1}$
  - Large, single pixel camera
  - $6.8^\circ$ FWHM FOV
- Energy Range: 0.3 – 6 keV
  - Ultrathin carbon foil charge conversion subsystem
- Background and noise: control $<3.8 \times 10^{-2}$ cnts/s at the foil entrance surface

3: ENA Emission from the Moon
Orbit 8: First Light, Lots of Action

Orbit 8: Start UTC 2008:337:10:13 (Dec 2)

- ESA 1
- ESA 2
- ESA 3
- ESA 4
- ESA 5
- ESA 6

Solar Wind background

"120°" Feature Part of Ribbon!

"340°" Feature Part of Ribbon!

Magnetosheath

X-ray source in Background Monitor

Moon!

McComas, et al., GRL

Spacecraft Spin Angle

N, 360°
Retrograde, 270°
S, 180°
Prograde, 90°
N, 0°

4: ENA Emission from the Moon
Orbit 83: Lunar View

ESA 1: 0.45 keV
ESA 2: 0.71 keV
ESA 3: 1.1 keV
ESA 4: 1.7 keV

Time [hrs]
Counts
Viewing geometry:
- IBEX views only the 1\textsuperscript{st} or 3\textsuperscript{rd} quarter Moon
- Nearly identical to illuminated quarter sphere (SW terminator ≠ optical terminator)
  - $FOV = 6.8$ deg FWHM
  - Energy range: 0.4 to 6 keV
Observations include only events in which the Moon was in the pristine solar wind (not in the magnetosphere)
Orbits 29, 83, 126: Solar wind speed and density relatively constant

Points = observation, Lines = simulation based on IBEX-Hi response function

Moon location in IBEX field-of-view matches IBEX collimator response model
9: ENA Emission from the Moon

Effects of SW Aberration Angle

\[ \theta_A = \tan^{-1}\left( \frac{29.78 \text{ km/s}}{v_{SW}} \right) \]

\[ A_I = 0.5 \pi r_L^2 \left( 1 \pm \sin(\theta_A + \theta_{IBEX}) \right) \]

Illuminated Fraction of Lunar Disk

\[ 29 \text{ km/s} \]

8°/orbit

\[ \theta_A \]

v_{SW}
SRIM Simulations

Simulations:
• Assume monoenergetic proton beam
• Assume random angle of incidence ($0^\circ - 90^\circ$) of ion relative to microscopic surface
• Track fraction of ions backscatters exiting the surface with a scatter angle $77^\circ - 87^\circ$ (1st quarter Moon) relative to incident ion trajectory
• Vary stoichiometry; 80% highlands/20% mare, representative of both 1st and 3rd quarter illuminated moon
• SRIM uses binary encounter approximation, ideal for amorphous solids like the regolith
• Critical angle: $\beta = \text{viewing angle of IBEX relative to the Solar Wind}$
• Upper estimate for albedo: 0.25-0.3
• Likely to be less due to porosity [Cassidy and Johnson, 2005]
SRIM Simulations

Energy Distribution of Backscatters

- At higher energies of IBEX-Hi, can estimate backscatter yield as linearly decreasing with increasing solar wind energy.
- Analytic differential flux (lines, and below) derived for 0.5-3.5 keV SW, 80º-100º angle of IBEX relative to SW direction.
- Simulated energy distribution of ENAs is convolved with the energy response of IBEX-Hi.

\[
F_{BS} = 5.22 \times 10^{-6} \frac{E_{SW}^{-1}}{E_{BS}} \left\{ -0.111 \\
\quad + \left( 0.94 - \frac{E_{BS}}{E_{SW}} \right) [37.2 - 1.53\beta] + (1 - 0.0223 \beta) \\
\quad \times (-61.1 E_{SW} + 9.79E_{SW}^2)] \\
\quad + \left( 0.94^2 - \left( \frac{E_{BS}}{E_{SW}} \right)^2 \right) [-66.6 + 2.24 \beta] \\
\quad + (1 - 0.0223 \beta) \times (59.4E_{SW} - 9.18E_{SW}^2) \right\}
\]
$C_i = R \int_0^{E_{SW}} \phi_{SW} F_{BS}(E_{SW}, E, \beta) \frac{A_I}{d_s^2} G_i(E, \Omega) \, dE$

$A_I = 0.5 \pi r_L^2 \left(1 \pm \sin(\theta_A + \theta_{IBEX})\right)$

$G_i(E, \Omega) \equiv IBEX$ - Hi Geometric Factor

$F_{BS}(E_{SW}, E, \beta) \equiv \text{Differential backscattered flux, from SRIM Results}$

$R = \frac{C_{i,\text{Measured}}}{C_{i,\text{Modeled}}}$

$R$ is the “comparison parameter” between model and observations. We expect $R < 1$ because:

- The Moon is micro/macroscopically porous
  - Some areas of the Moon observed by IBEX are shadowed from SW illumination
  - IBEX lies in the shadow of some areas of the Moon illuminated by the SW
- Some backscattered hydrogen are ionized
  - $\sim 1\%$ (Saito et al., GRL, 2008)
Example: Orbit 83

Counts/48 Spins

Note: these axes are flipped relative to what follows

Orbit 83

Measured ENA Count Rate [Cts/48 spins]
R-factor by Orbit

$R \sim 0.95$ for the viewing geometry of IBEX
- $R > 1$ for ESA 1: within uncertainty of ESA 1 response function
- $R \sim 0.96$ for the viewing geometry of IBEX
Fraction Backscattered, $R = 0.95$

- Ionized fraction of backscatters is $\sim 1\%$ (Saito et al., GRL, 2008)
- Shadowing effects are therefore small ($\sim 4\%$)
- Results obtained at the unique viewing geometry of IBEX relative to the SW suggest an absolute albedo of 0.23 for 1 keV SW
- Albedo per unit solid angle is a complicated function of viewing geometry; assuming uniform emission over $2\pi$ sr, albedo is 0.036/sr for 1 keV SW
Moon in the Magnetosheath
Future Study, Allegrini et al.

Moon in the Magnetosheath!

Orbit 43

18: ENA Emission from the Moon
Conclusions

• We find that, at the unique viewing geometry of IBEX relative to the SW, the observed ENA flux is $\sim$ 95% of the simulated ENA flux.

• By scaling the simulation results (over all backscattered energies over all viewing angles) by 0.95, the **absolute ENA albedo** from the Moon as a function of SW energy $E$ [keV] is:

$$Y_{\text{ENA}} = 0.23 - 0.056 \ln(E)$$

• For solar wind at 1 keV, this corresponds to 0.23.

• Applies to SW interaction with solar system objects from tiny dust grains to asteroids, KBOs, moons, Mercury, and more…