Surface radiation environment of Saturn’s icy moon Mimas

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Moon environments

- A large number of moons orbit inside the magnetospheres of the giant planets
- The magnetospheric environment is characterized by populations of trapped charged particles
  - From co-rotational thermal plasma to energetic electrons, protons and heavier ions.
  - Moons continuously interacting with these particles.
- Trapped particles will experience gyration, bounce and drift motions
  Saturn’s magnetic field
  - Energy, mass and charge dependent.
  - Leads to asymmetric bombardment profiles.
Charged particle interactions with moon surfaces

- Moon surfaces are continuously exposed to charged particle weathering
- Over geological timescales this could be a significant contributor to surface chemistry
- It is therefore important to quantify the energy deposition of magnetospheric particles into the surface

Khurana et al, 2007
Radiolysis and surface chemistry

• The energy deposited by incident particles can lead to the breakup of chemical bonds in the material
  - This, as well as subsequent reactions can lead to the formation of new molecules
  → Radiolysis
  - Typical products in water ice, $\text{H}_2\text{O}_2$, $\text{O}_2$, $\text{O}_3$
• Charged particle weathering may also amorphize surface ice
• Can lead to the production of sputter-induced exospheres
  - Europa, Ganymede, Callisto
  - Dione, Rhea

Detection of $\text{H}_2\text{O}_2$ at Europa (Carlson et al, 1999)
Charged particle interactions with solids

- Incident ions and electrons lose energy to the material by
  - Ionizations
  - Excitations
  - Collisions
  - Secondary production
  - Bremsstrahlung photon emission

- The energy deposition profile can be estimated by assuming a continuous energy loss function

- However, this does not take into account the discrete interactions that occur during the particle’s path into the material
  - This is why we want to use Monte Carlo codes to simulate energy deposition

Johnson et al, 1990

Fig. 1.10. Schematic diagram of events along ion path. Fast incident ion produces ionizations $\oplus$ with corresponding secondary electrons (e). In addition some excitations $\ominus$ are produced as well as secondary atoms, $\circ$, by direct collisions. Finally the incident particle stops, that is, implanted in the material (gas, liquid, or solid)
Mimas

- Saturn’s innermost large icy moon
- Orbital distance ~3.1 Rs
- Receives the highest radiation flux of any of the large Saturnian moons
- Electron flux ~1/40\textsuperscript{th} that of Europa
- Remote sensing data in the visible, UV and infrared show striking surface patterns that have been attributed to magnetospheric input

Cassini ISS – February 13th, 2010
Mimas from ISS – IR/UV

- Displays bulls-eye pattern on trailing hemisphere (possibly due to bombardment by cold, co-rotational plasma)
- Equatorial lens feature on leading hemisphere (possibly due to bombardment by energetic electrons)

Schenk et al, 2011
Mimas from CIRS – Thermal infrared

- Thermal inertia anomaly at the leading hemisphere
- Corresponds well with lens feature seen in ISS and calculated bombardment profiles for energetic electrons
- Suggested magnetospheric origin

Cassini CIRS - Howett et al, 2011
Mimas from UVIS – Ultraviolet

- Far-ultraviolet (170-190nm) observations show an albedo variation pattern
- Darkening at the leading hemisphere, most pronounced in the south
- General darkening of the surface
- Possibly due to combined effect of radiolytic and photolytic (UV) processing and the presence of Hydrogen Peroxide
- UV darkening has been associated with Hydrogen Peroxide at Europa, Ganymede and Callisto (Carlson et al, 1999)

Hendrix et al, submitted
Quantifying energy deposition – Geant4 modeling

- Goal: To quantify energy deposition into surface by particle species and energy.
- Geant4 – Monte Carlo toolkit developed by CERN to simulate the passage of particles through matter
- Large development community
- Core physics has been extensively validated
- Simulation implemented using the Planetocosmics Geant4 package

Planetocosmics – Desorgher et al, 2006
Mimas energetic particle environment

Electrons

Adapted from Paranicas et al, 2012

Protons

Adapted from Paranicas et al, 2012
Mimas energetic particle environment
Input spectra: Electrons

- Spectrum generated using fit function of Paranicas et al (2012) based on MIMI-LEMMS
- 10 keV to 10 MeV in 100 log-spaced bins

\[ j = j_0 E^a \left( 1 + \left( \frac{E}{E_0} \right) \right)^b \]
Input Spectra: Protons

- Representative average fluxes for protons in the 638 keV to 38 MeV range at the Mimas L-shell
- Negligible anisotropy – fluxes not filtered by pitch angle
- Negligible counts for particles below 638 keV
  - Ring current particles (100s of keV) CE easily with neutrals
  - Problems with penetrating radiation
- Interpolated to 100 log-spaced bins by a cubic spline fit
Simulation geometry

\[ j(E, \theta) = \varphi(E, \theta) \cos \theta \]

\[ \theta = -\pi/2 \quad \theta = 0 \quad \theta = \pi/2 \]

Water

Surface layer

"Core"

\( \sim 114 \text{km} \)
Simulation set-up

- Flat ‘slab’ approach
- Source follows cosine law to capture full angular distribution
- Simulation divided into
  - Trailing hemisphere: Electrons 10 keV to 1 MeV
  - Leading hemisphere: Electrons 1 MeV to 10 MeV
  - Isotropic: Protons from 638 keV to 38 MeV

nb=10 x 10^6 primary particles
Model results for Mimas

Deposited dose vs depth in surface water ice for energetic particles at Mimas

- Electrons 1 - 10 MeV
- Electrons 10 keV - 1 MeV
- Protons 0.638 - 38 MeV

Depth in water: 1 μm to 100 mm
Model results for Mimas

- Separate dose-depth profiles for leading and trailing hemispheres
- Provided in time to reach chemically significant dose (100 eV/16 amu)
  - Can be used directly with published values for radiolytic production and destruction in materials
Model results for Mimas

- Protons and low energy (keV) electrons will dominate the uppermost portion of the subsurface.
- Very energetic (MeV) electrons dominate below ~300um.
- Highest dose expected at the uppermost region of the trailing hemisphere.
- However, Mimas orbits at the inner edge of the E-ring – icy material from Enceladus.
  - Remote sensing instruments could be seeing radilolytically altered E-ring grains on the surface.
- Over geological timescales, meteroid impact gardening could be significant.
Conclusions

• Model provides a method for assessing depth-dependent radiolytic dose in icy moon surfaces
• Can be used to investigate radiolytic production and destruction of materials with depth
• Overall dose is dominated by energetic electrons
• However, protons and keV energy electrons will dominate the uppermost (<300um) portion of the subsurface
  – Relevant to Cassini optical remote sensing measurements
• Care must be taken when interpreting results, as E-ring deposition and micrometeroid bombardment also modifies the surface

Future work
• Improve particle input spectra using data from the Cassini Plasma Spectrometer (CAPS) to extend to lower energies
• Extend study to include Saturn’s other major icy moons
• Include more detailed bombardment patterns
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