Surface radiation environment of Saturn's icy moon Mimas

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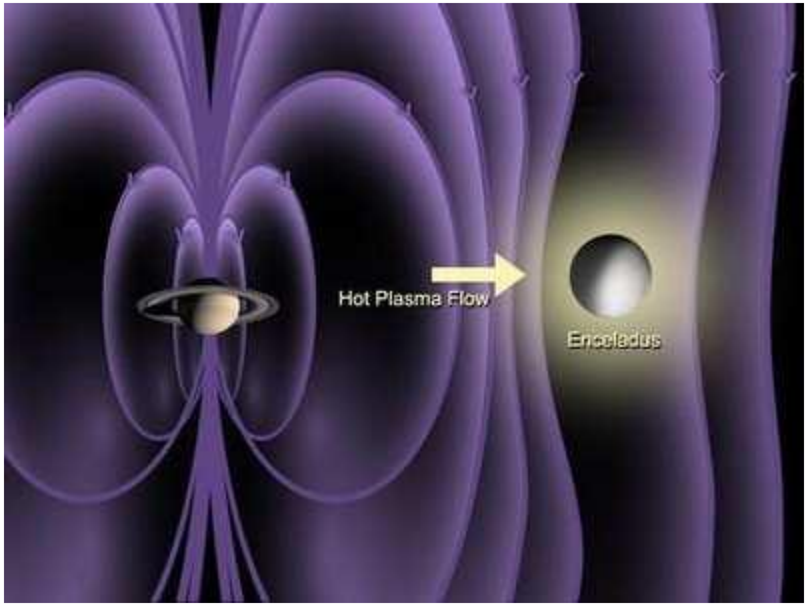
Moon environments

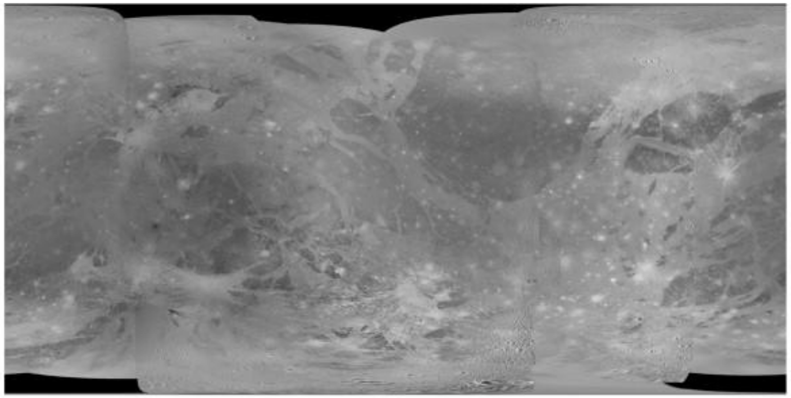
- A large number of moons orbit inside the magnetospheres of the giant planets
- The magnetospheric environment is characterized by populations of trapped charged particles
  - From co-rotational thermal plasma to energetic electrons, protons and heavier ions.
  - Moons continously interacting with these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

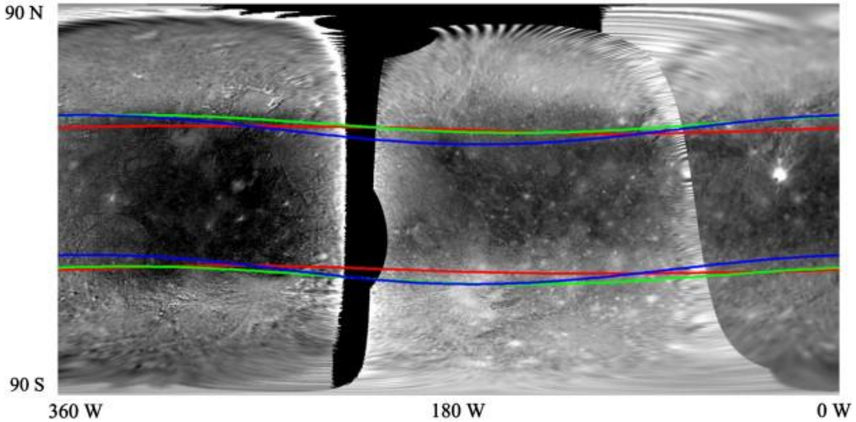


NASA/JPL

Charged particle interactions with moon surfaces

- Moon surfaces are continously 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


(a)

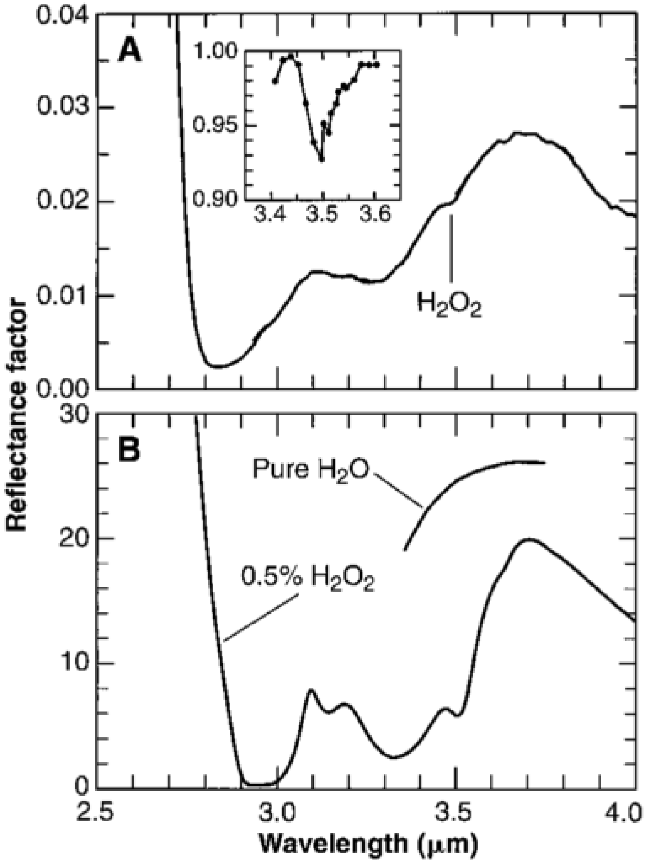


(b)

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, H_2O_2, O_2, 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 H_2O_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 continous 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

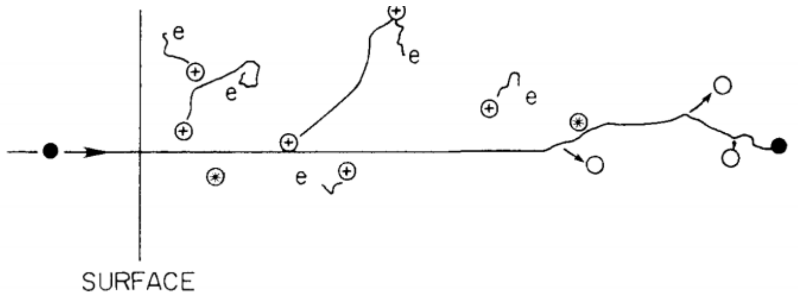
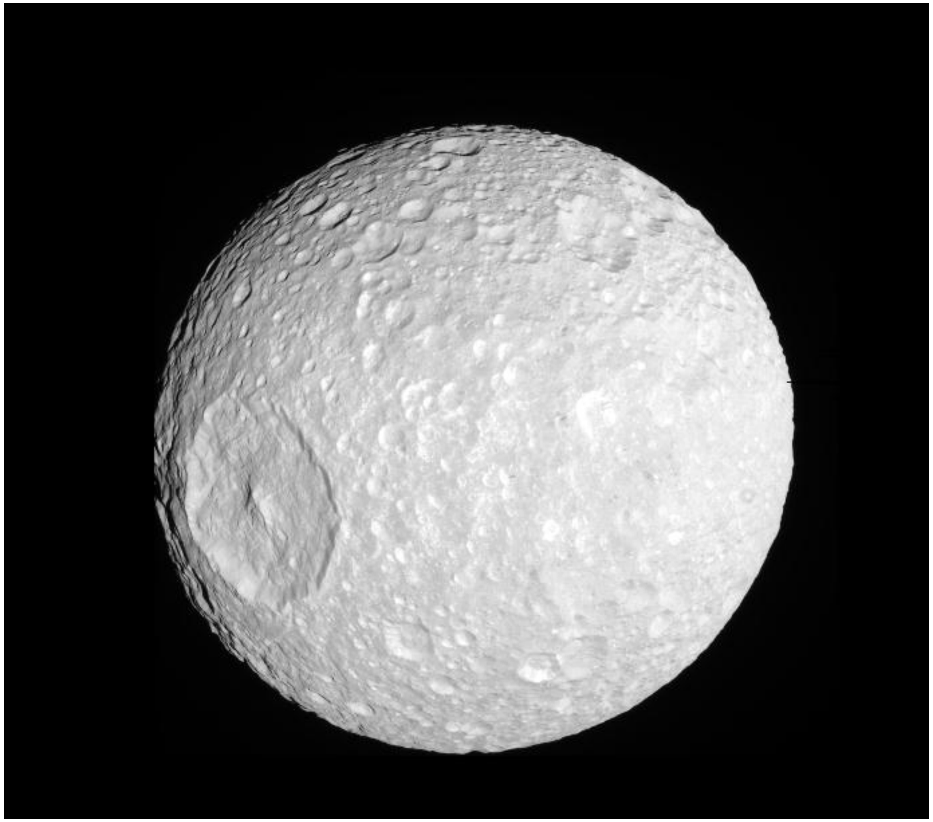


Fig. 1.10. Schematic diagram of events along ion path. Fast incident ion produces ionizations ⊕ with corresponding secondary electrons (*e*). In addition some excitations ⊛ are produced as well as secondary atoms, ○, by direct collisions. Finally the incident particle stops, that is, implanted in the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

Johnson et al, 1990

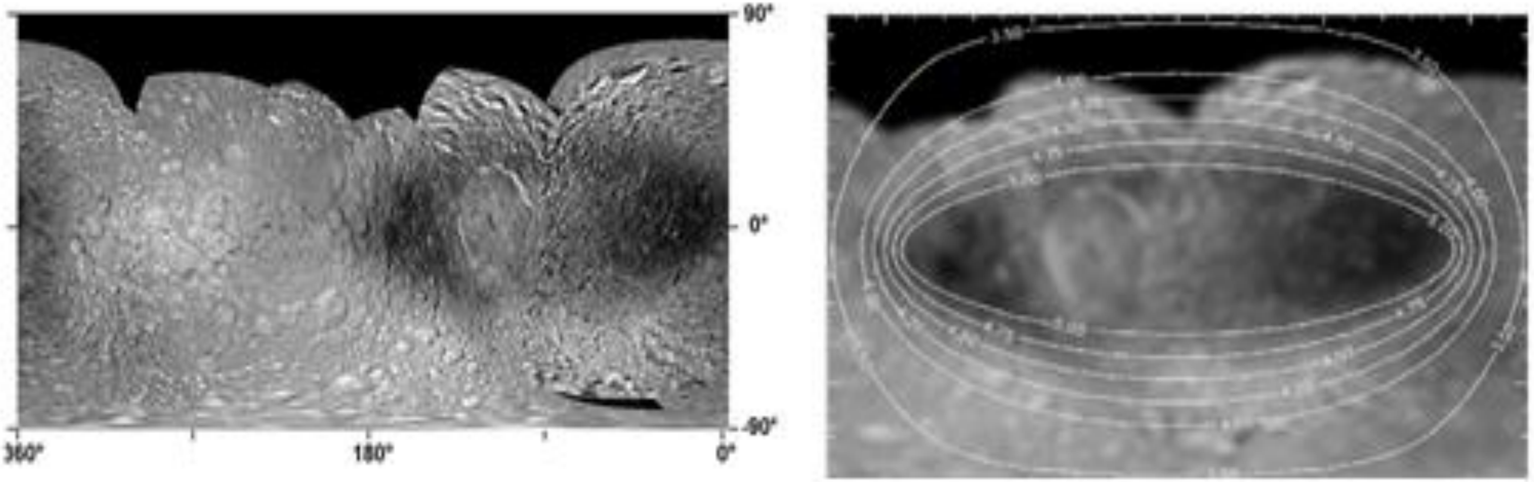
Mimas

- 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 ~1/40th 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 – Februrary 13th, 2010

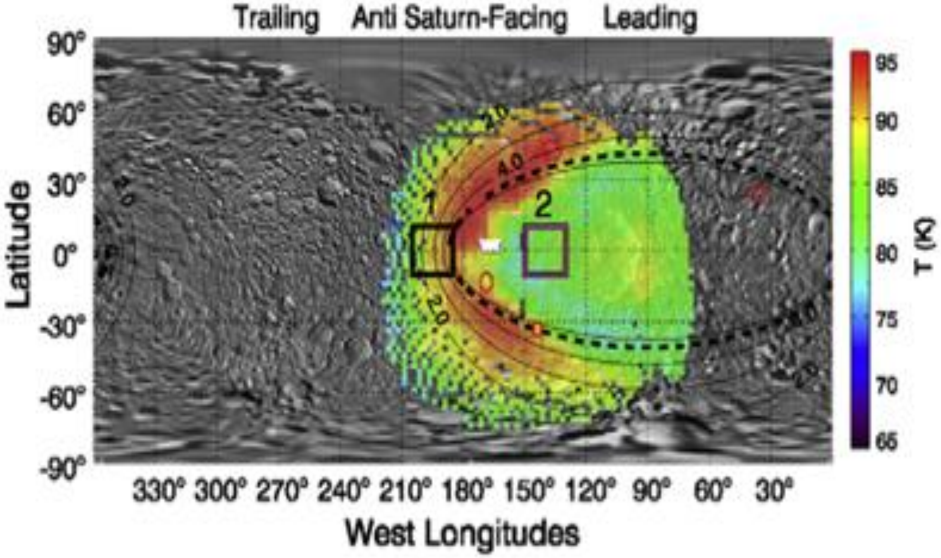
Mimas from ISS – IR/UV



Schenk et al, 2011

- 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)

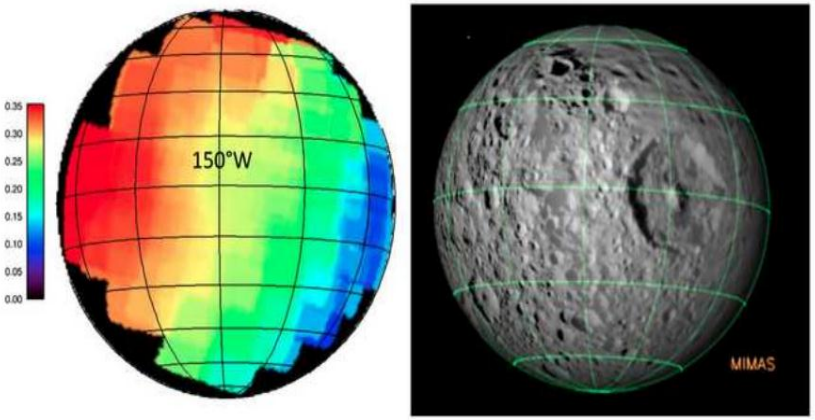
Mimas from CIRS – Thermal infrared



Cassini CIRS - Howett et al, 2011

- 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

Mimas from UVIS – Ultraviolet

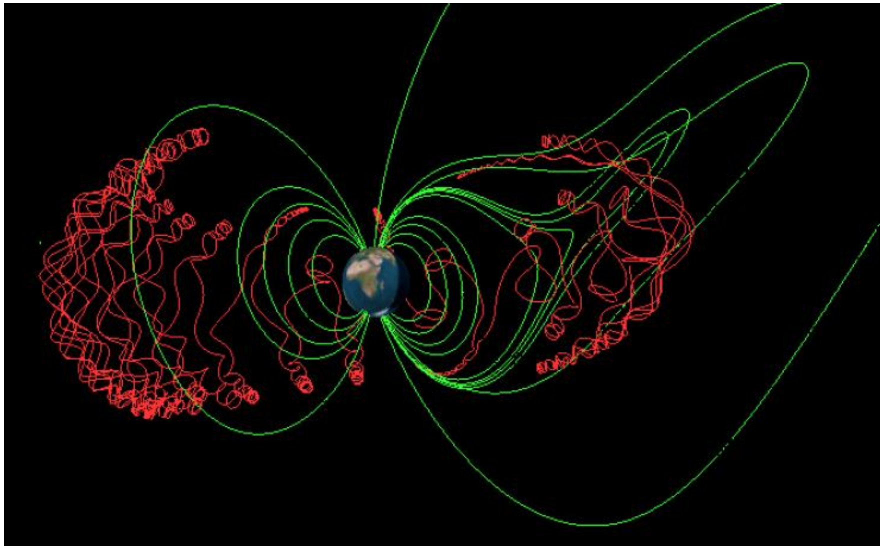


Hendrix et al, submitted

- Far-ultraviolet (170-190nm) observations show an albedo variation pattern
- Darkening at the leading hemisphere, most prounounced 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)

Quantifying energy deposition – Geant4 modeling

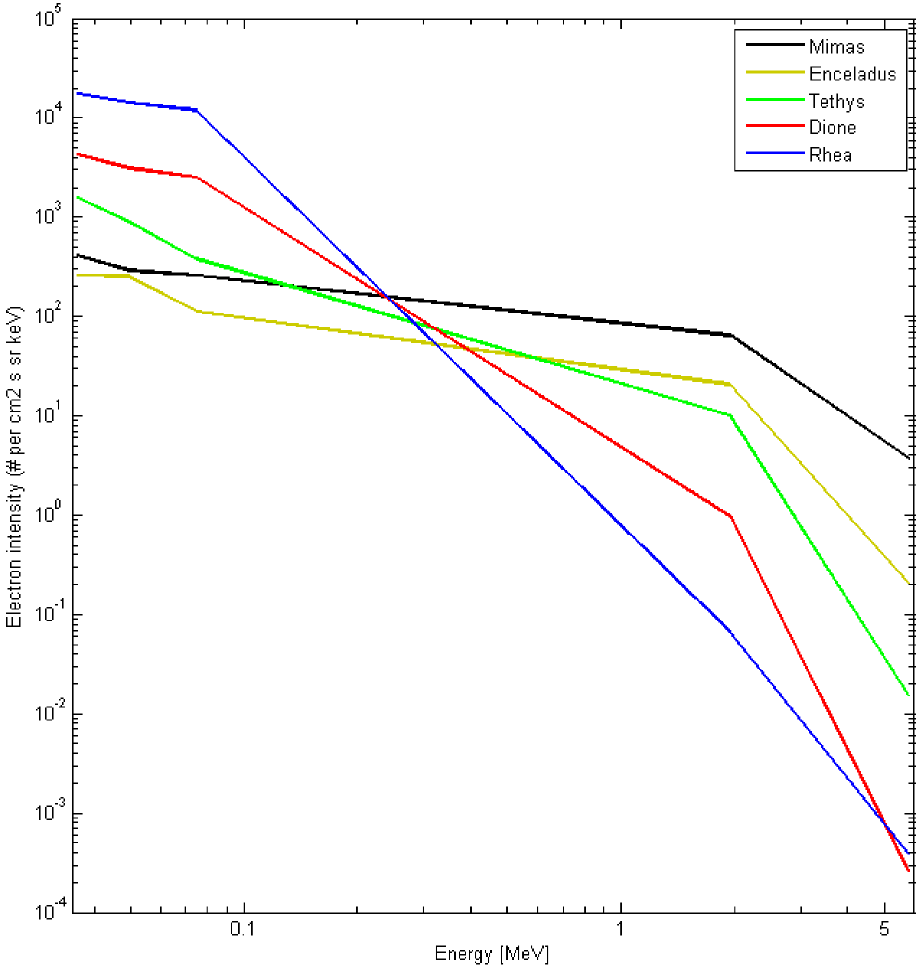
- Goal: To quantify energy deposition into surface by particle species and energy.
- Geant4 – Monte Carlo toolkit developed by CERN to simulate the passage of particles through matter
- Large development community
- Core physics has been extensively validated
- Simulation implemented using the Planetocosmics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



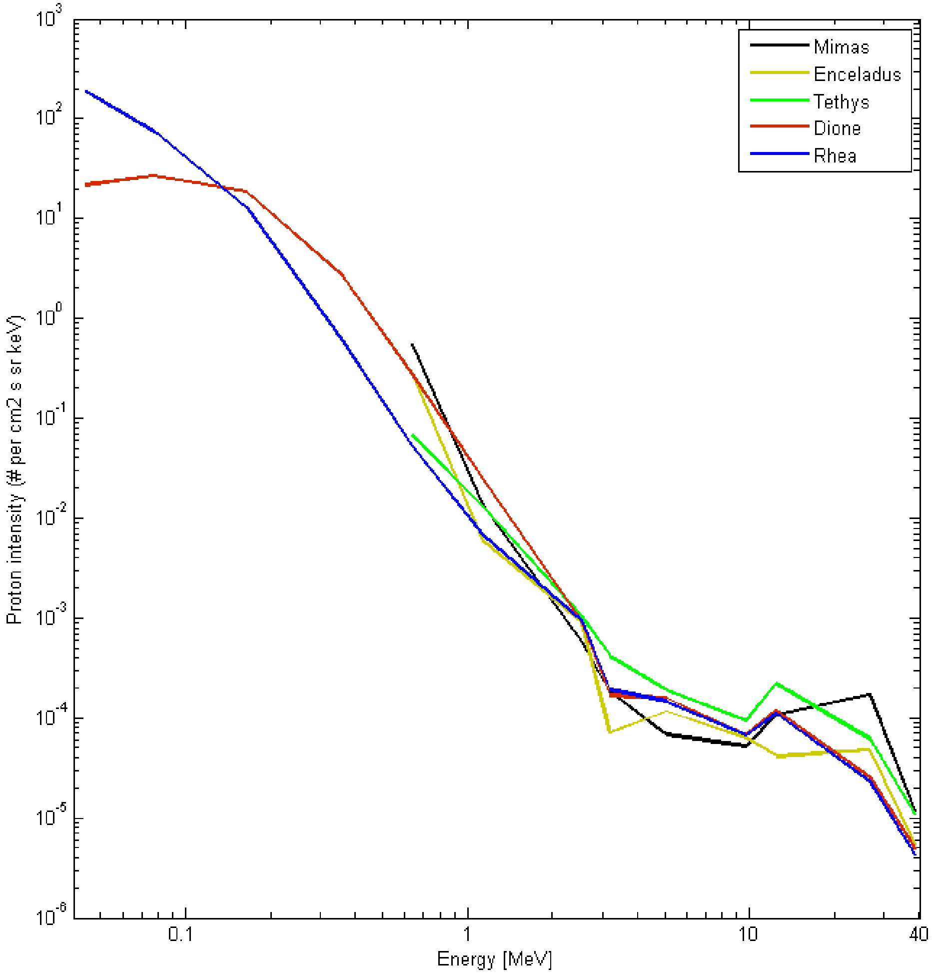
Planetocosmics – Desorgher et al, 2006

Mimas energetic particle environment

Electrons

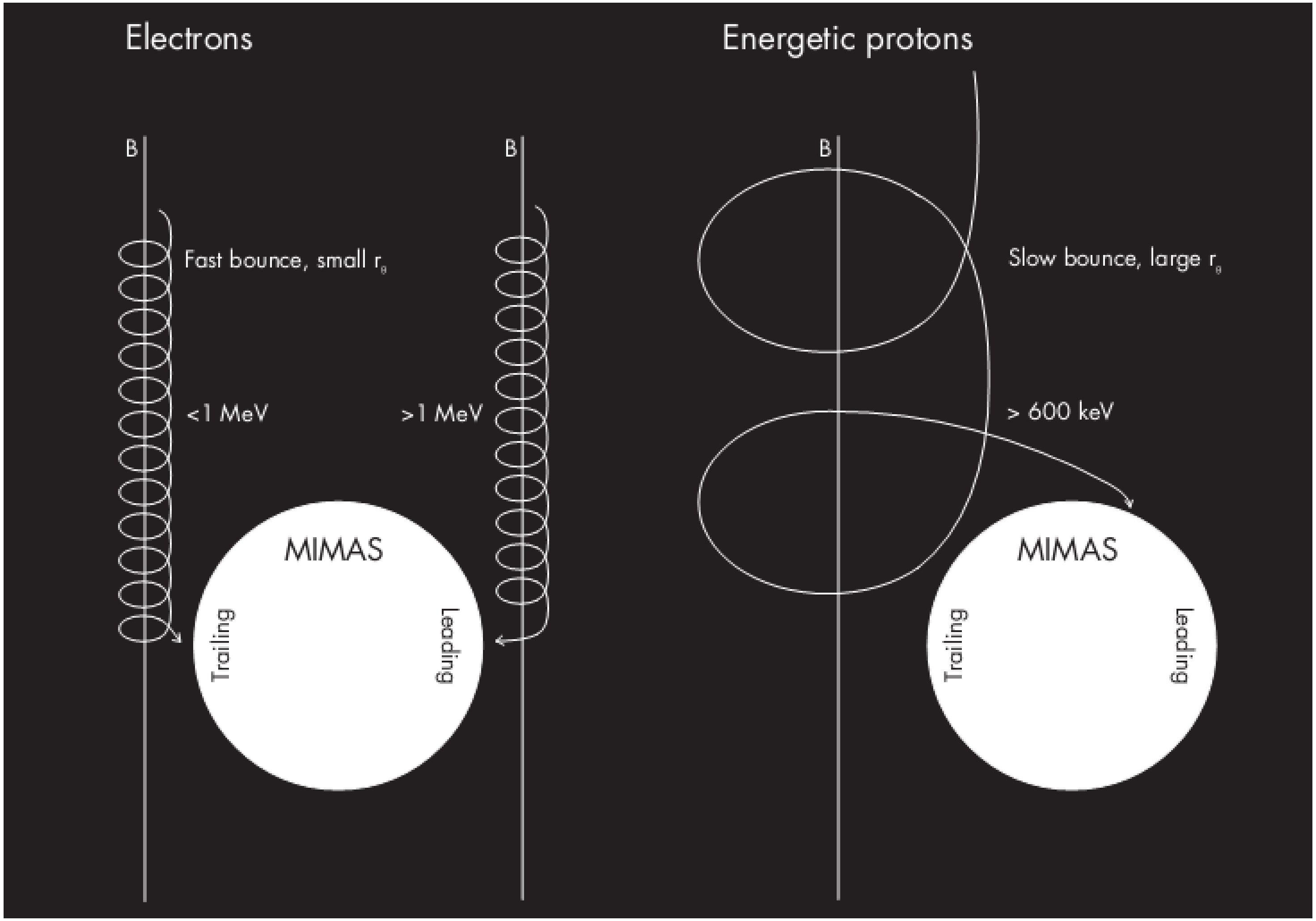


Protons

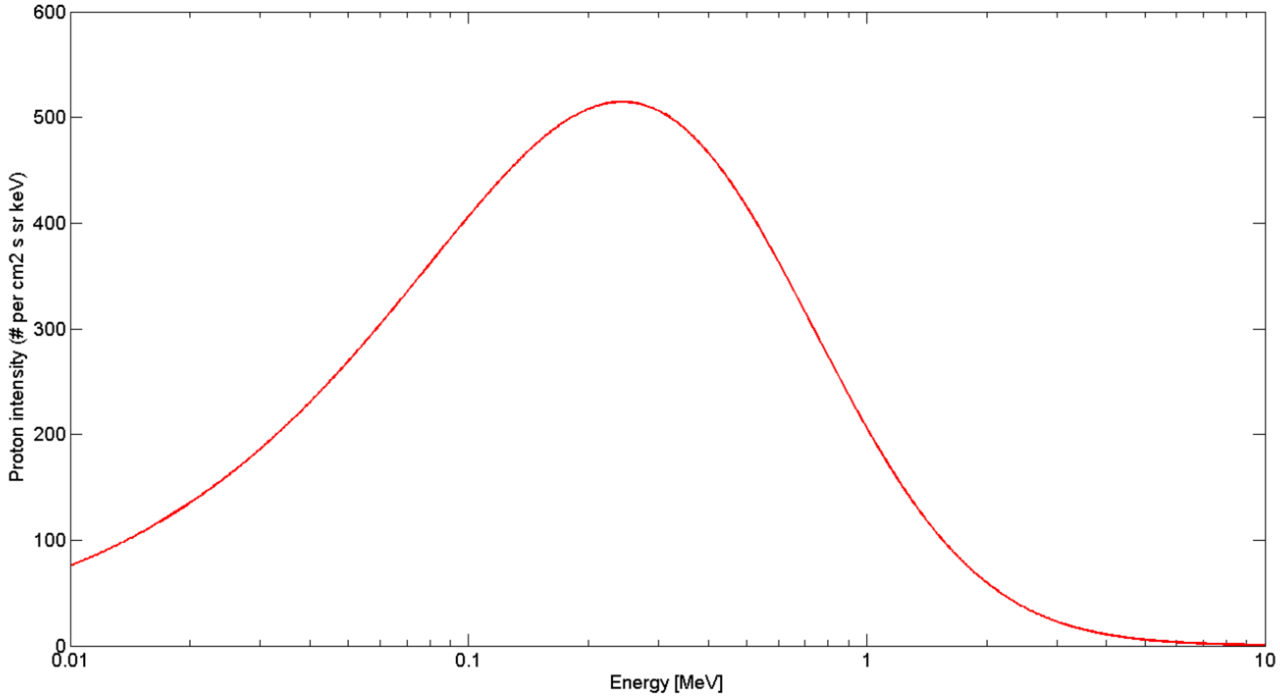


Adapted from Paranicas et al, 2012

Mimas energetic particle environment



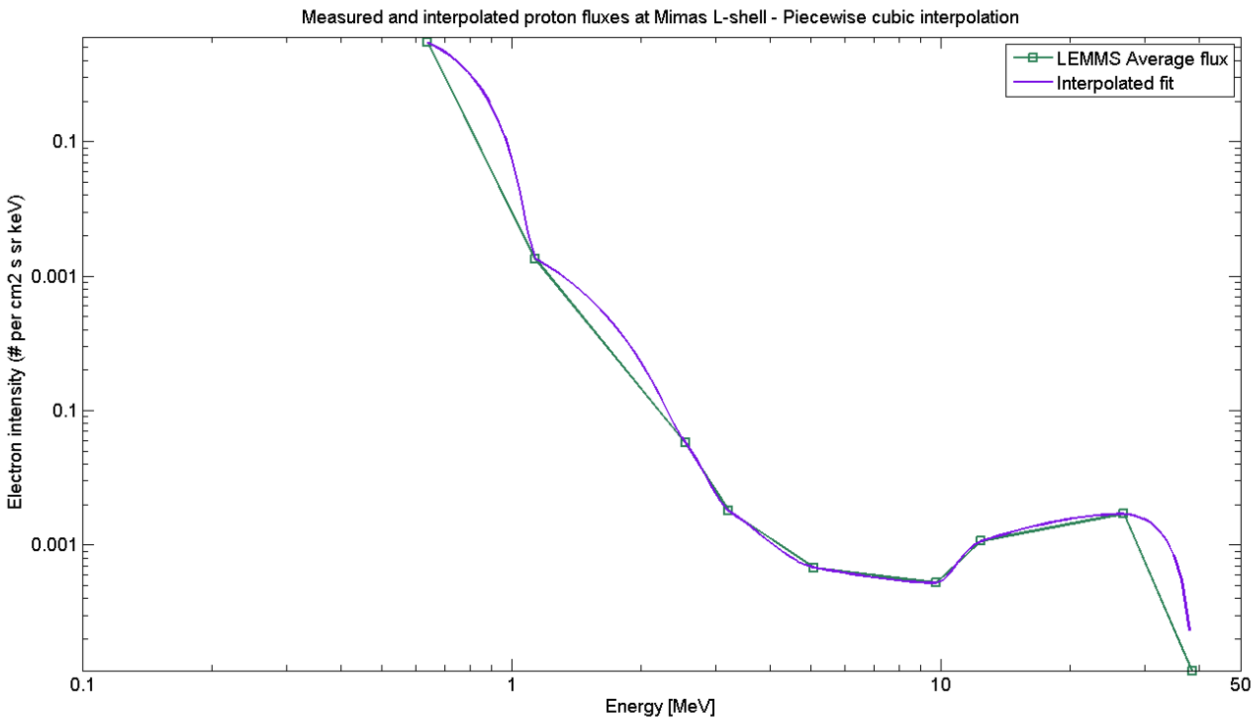
Input spectra: Electrons



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

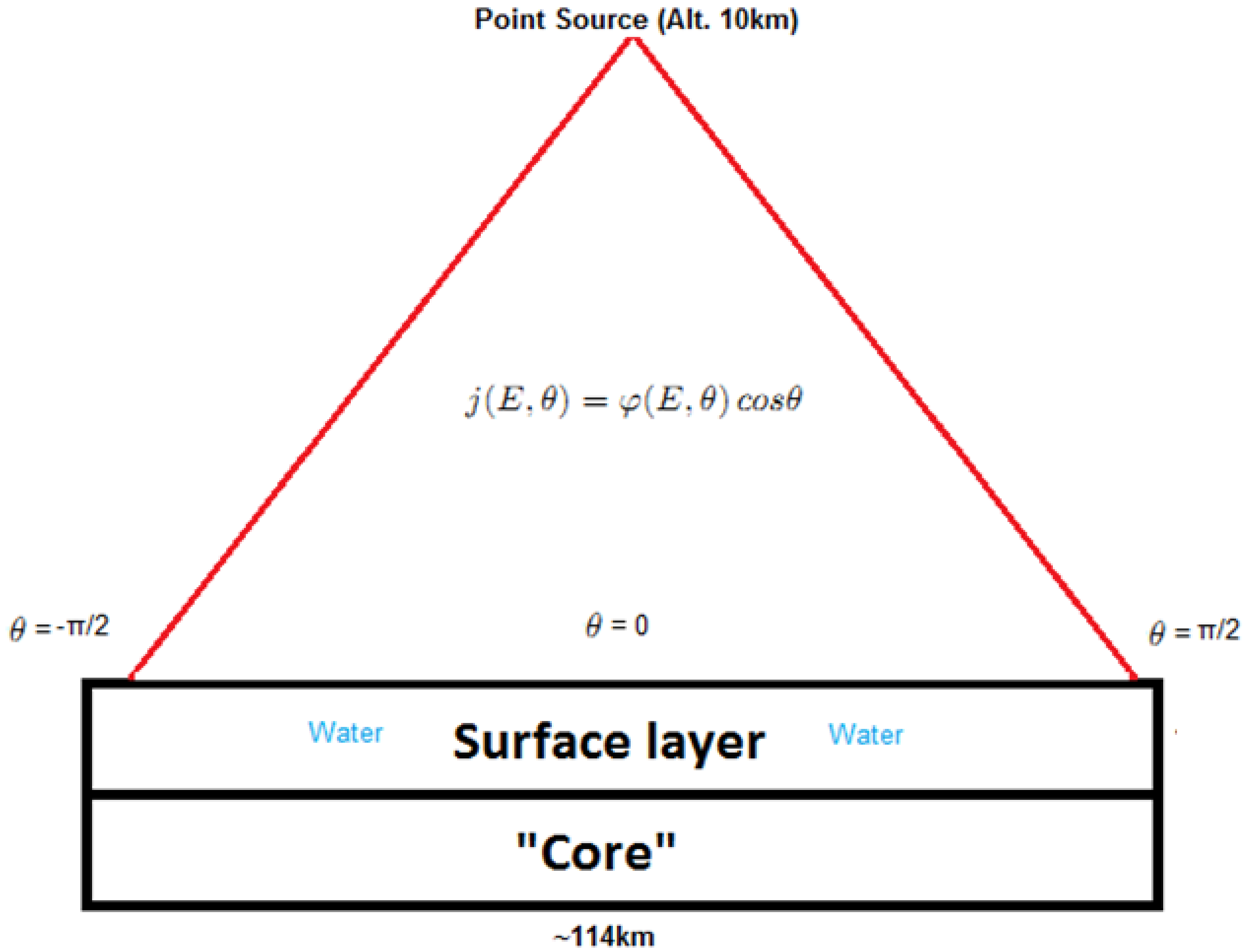
$$j = j_0 E^a \left(1 + \left(\frac{E}{E_0}\right)\right)^b$$

Input Spectra: Protons



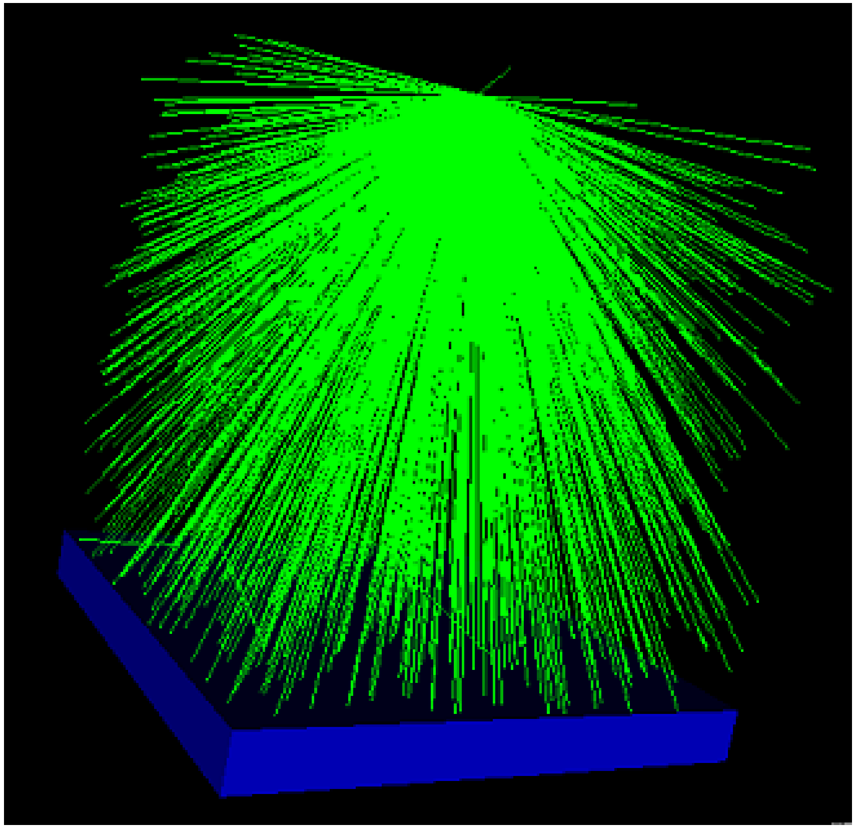
- Representative average fluxes for protons in the 638 keV to 38 MeV range at the Mimas L-shell
- Negligible anisotropy – fluxes not filtered by pitch angle
- Negligible counts for particles below 638 keV
  - Ring current particles (100s of keV) CE easily with neutrals
  - Problems with penetrating radiation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

Simulation geometry



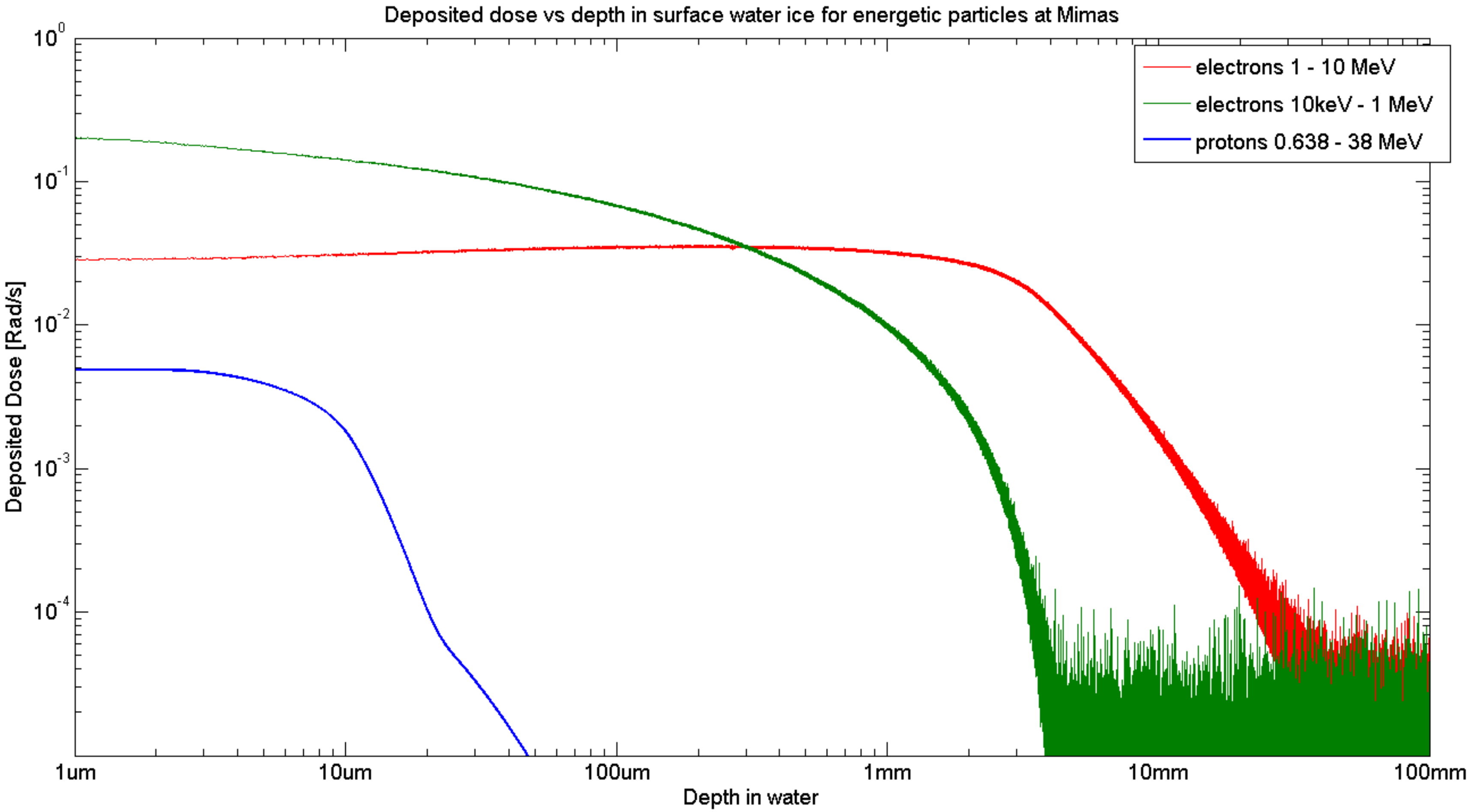
Simulation set-up

- 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

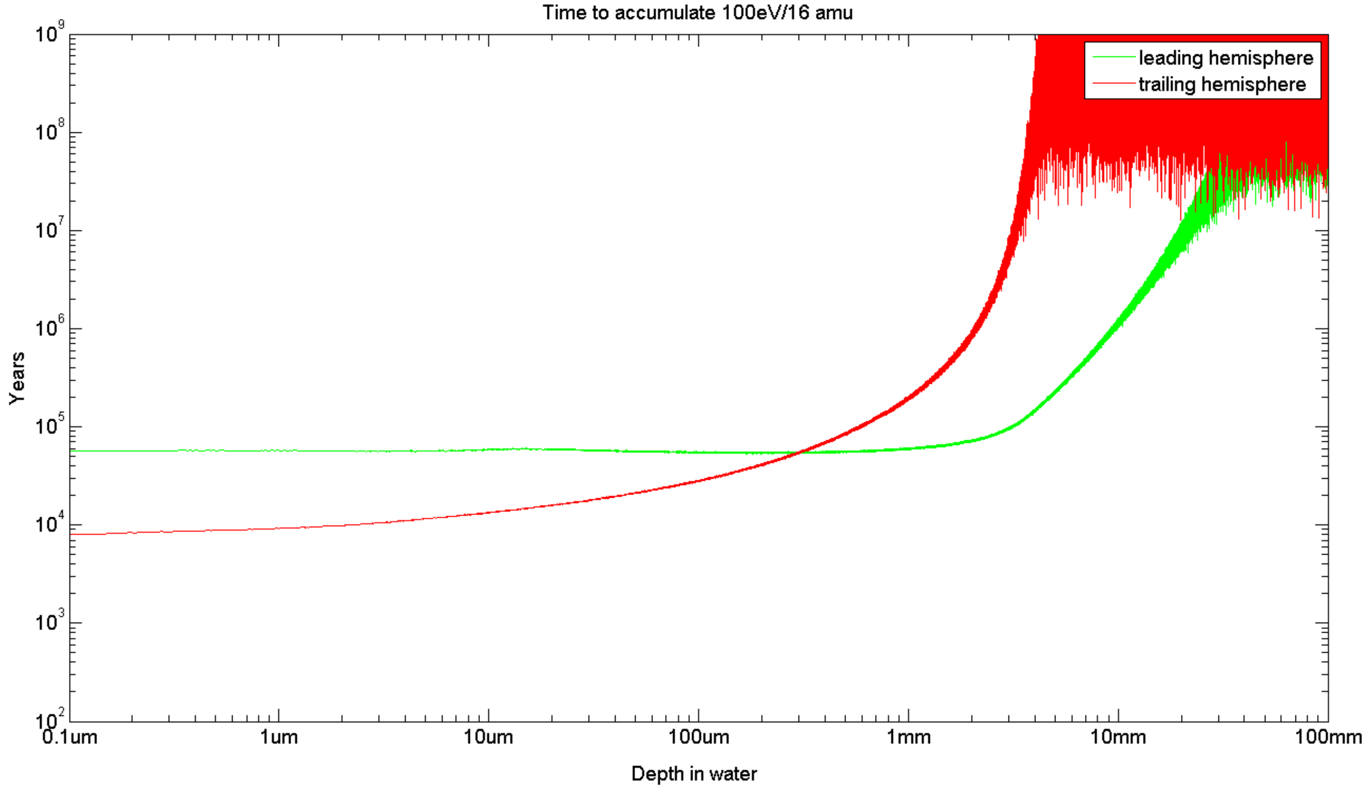


nb=10 x 10^6 primary particles

Model results for Mimas

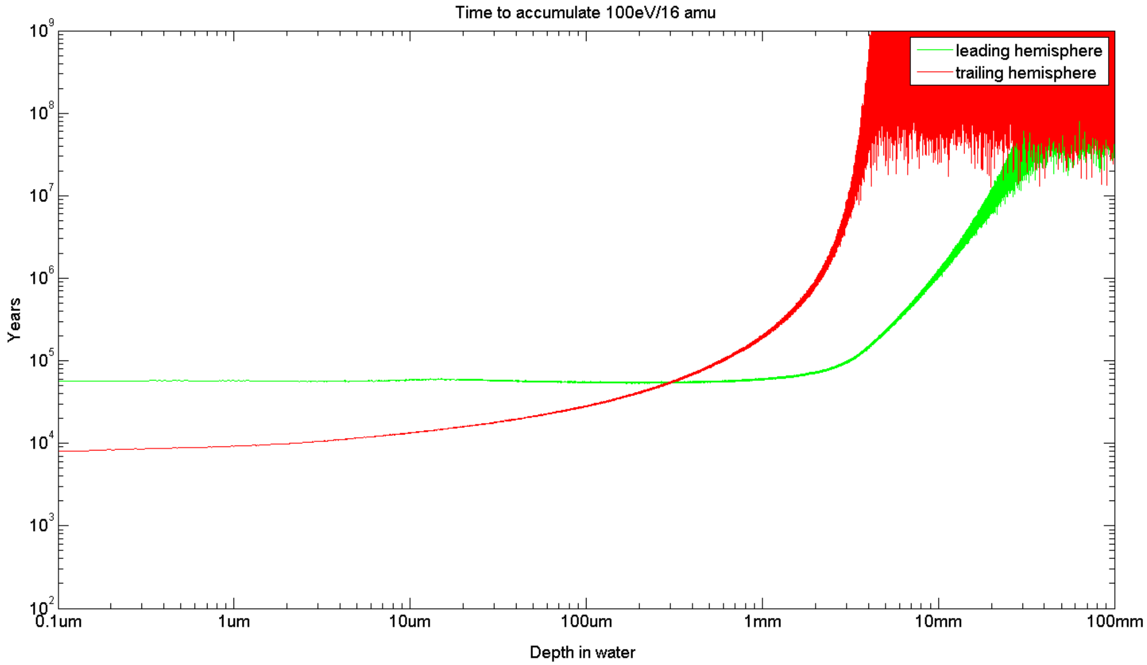


Model results for Mimas



- Seperate 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 asessing 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

Many thanks to the ESA Education Office for supporting my attendance at ESLAB.