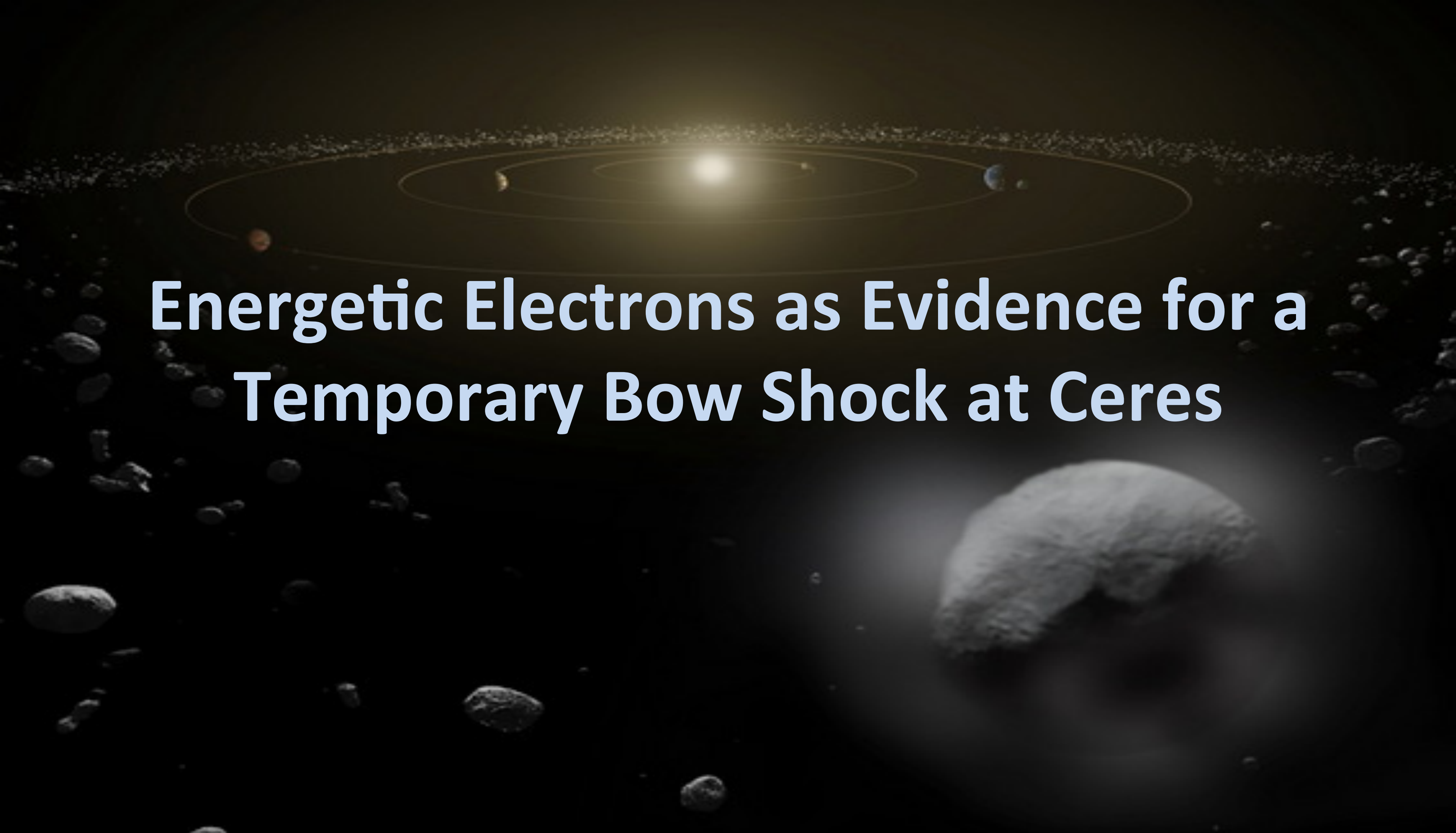


Energetic Electrons as Evidence for a Temporary Bow Shock at Ceres

M. N. Villarreal, C. T. Russell, Y. D. Jia, T. H. Prettyman, N. Yamashita

January 13th, 2017

Outline

1) Ceres & Dawn Overview

2) Electron Burst Detections
    - Timeseries
    - Electron Identification
    - Burst locations

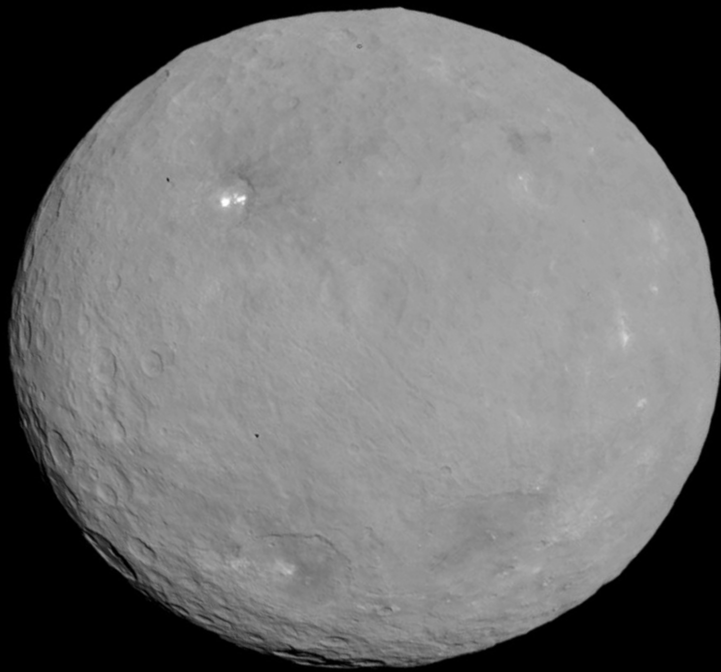
3) Fast-Fermi Acceleration & Electron Foreshock Geometry

4) Single-Fluid MHD Model

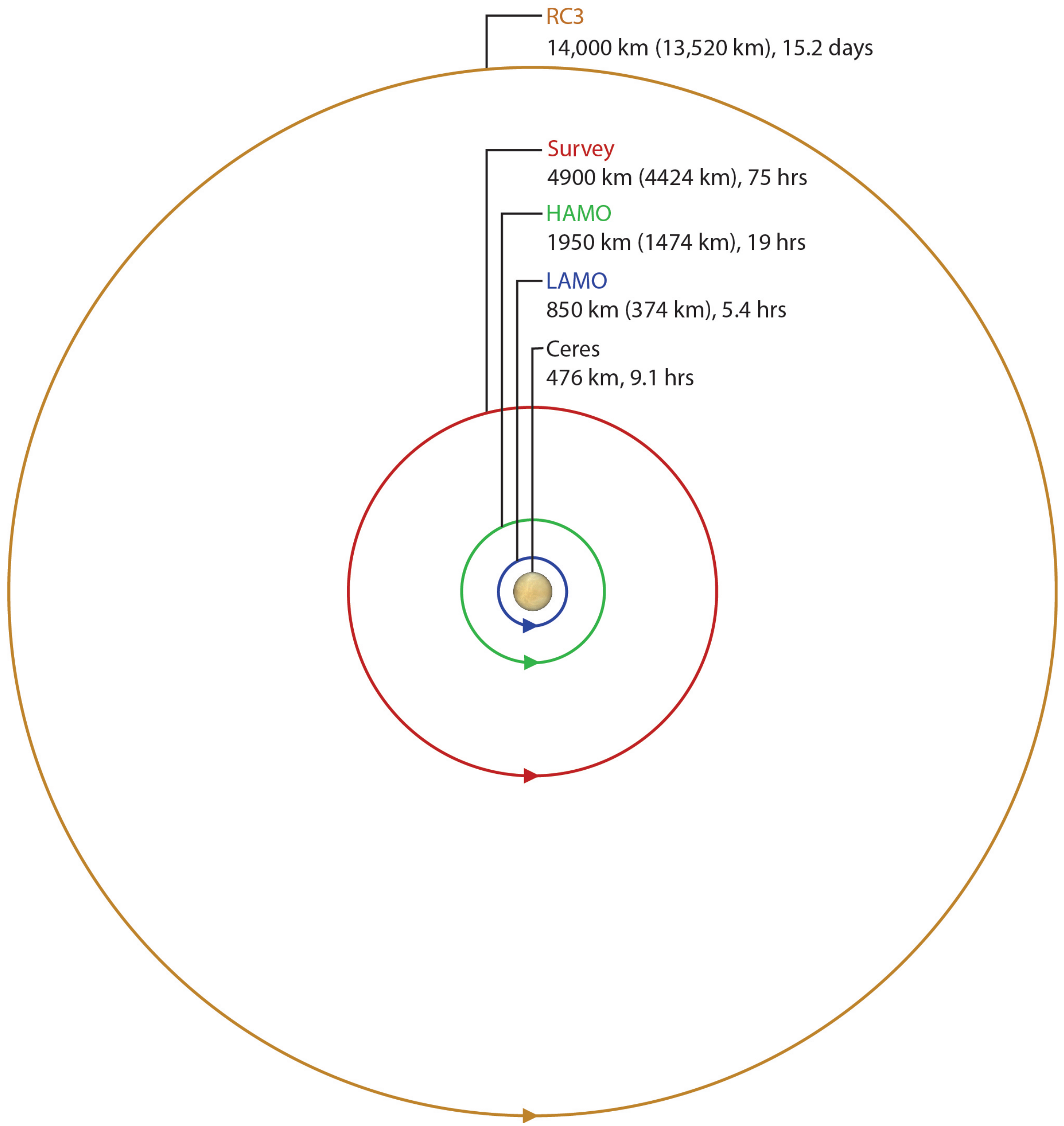
5) Summary

Ceres

- Dwarf planet with a radius ~470 km located in the asteroid belt at ~2.8 AU.
- Ceres has a low mean density at 2,160 kg/m^3 [Russell et al., 2016].
- Exposed ice patches have been detected at Oxo crater [Combe et al., 2016].
- Surface ice has also been detected in cold traps [Platz et al., 2016].
- Global ice table within 1 m depth of the surface [Prettyman et al., 2016.
- Ceres is known to have a transient atmosphere [A'Hearn & Feldman (1992), Rousselot et al. (2011), Küppers et al. (2014)].

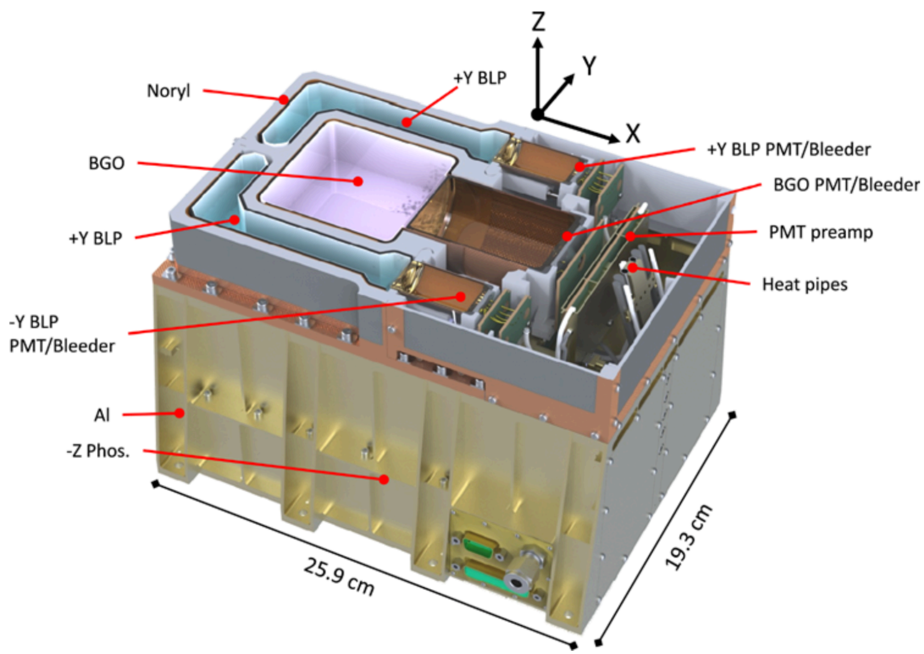


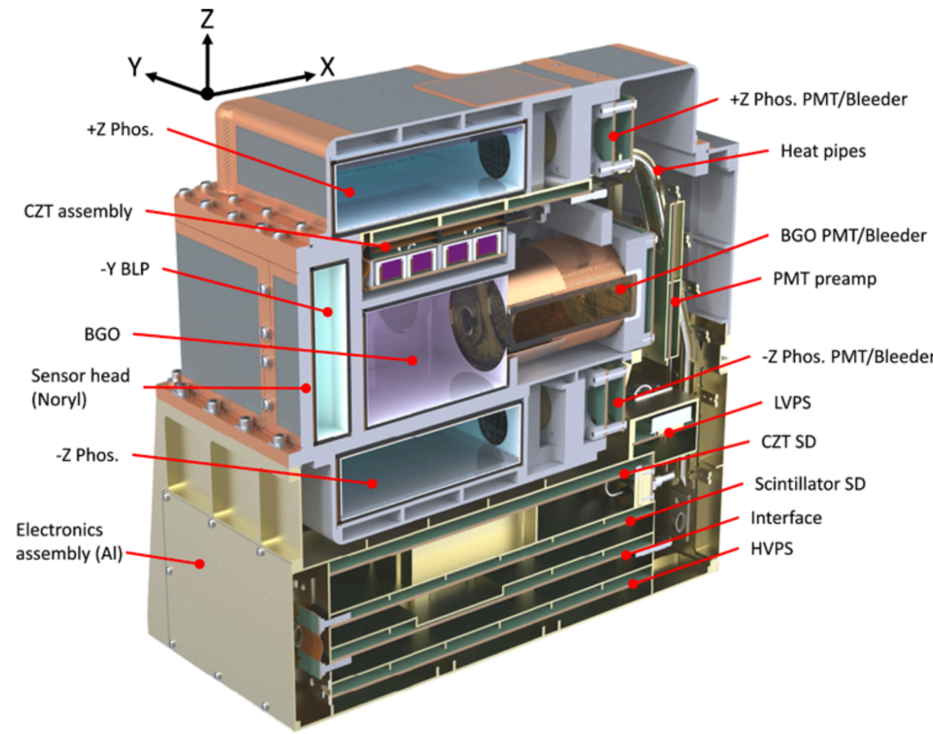
Dawn Orbit



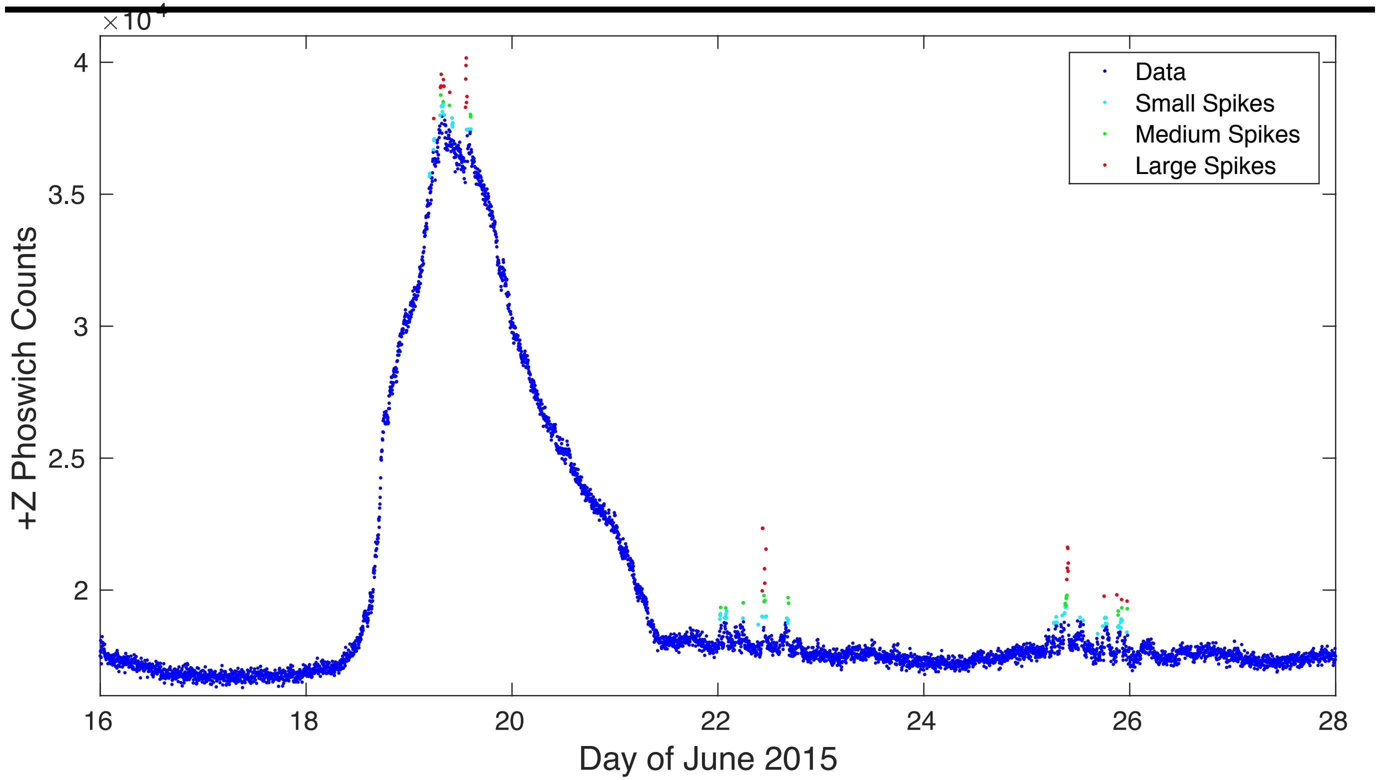
RC3
14,000 km (13,520 km), 15.2 days
Survey
4900 km (4424 km), 75 hrs
HAMO
1950 km (1474 km), 19 hrs
LAMO
850 km (374 km), 5.4 hrs
Ceres
476 km, 9.1 hrs

Gamma Ray and Neutron Detector



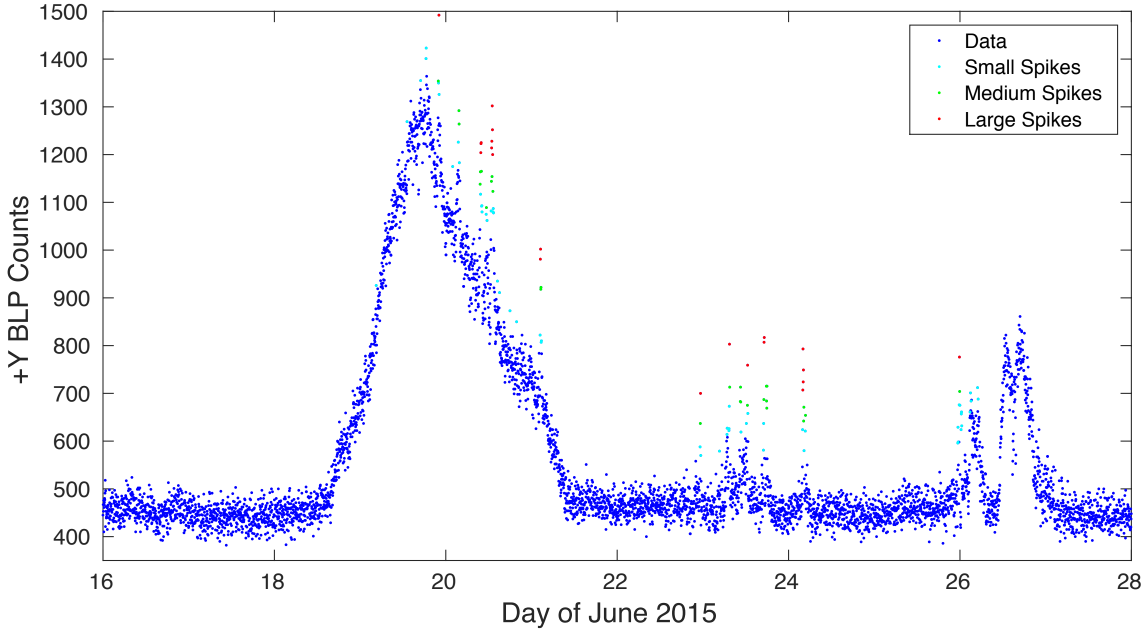


Particle Bursts

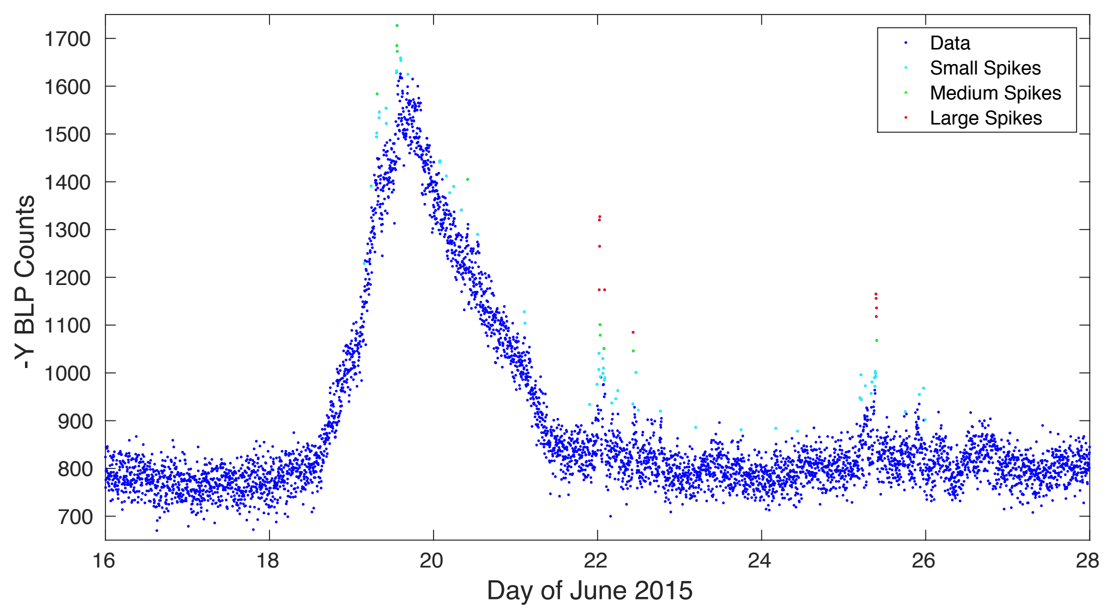


- GRaND saw distinct bursts in its exterior scintillators between June 18th-26th
- Dawn was at a distance of ~10 R_C away from Ceres (4,400 km alt)
- First appearance of spikes concurrent with a solar energetic particle event
- Individual bursts typically lasted ~20 min.

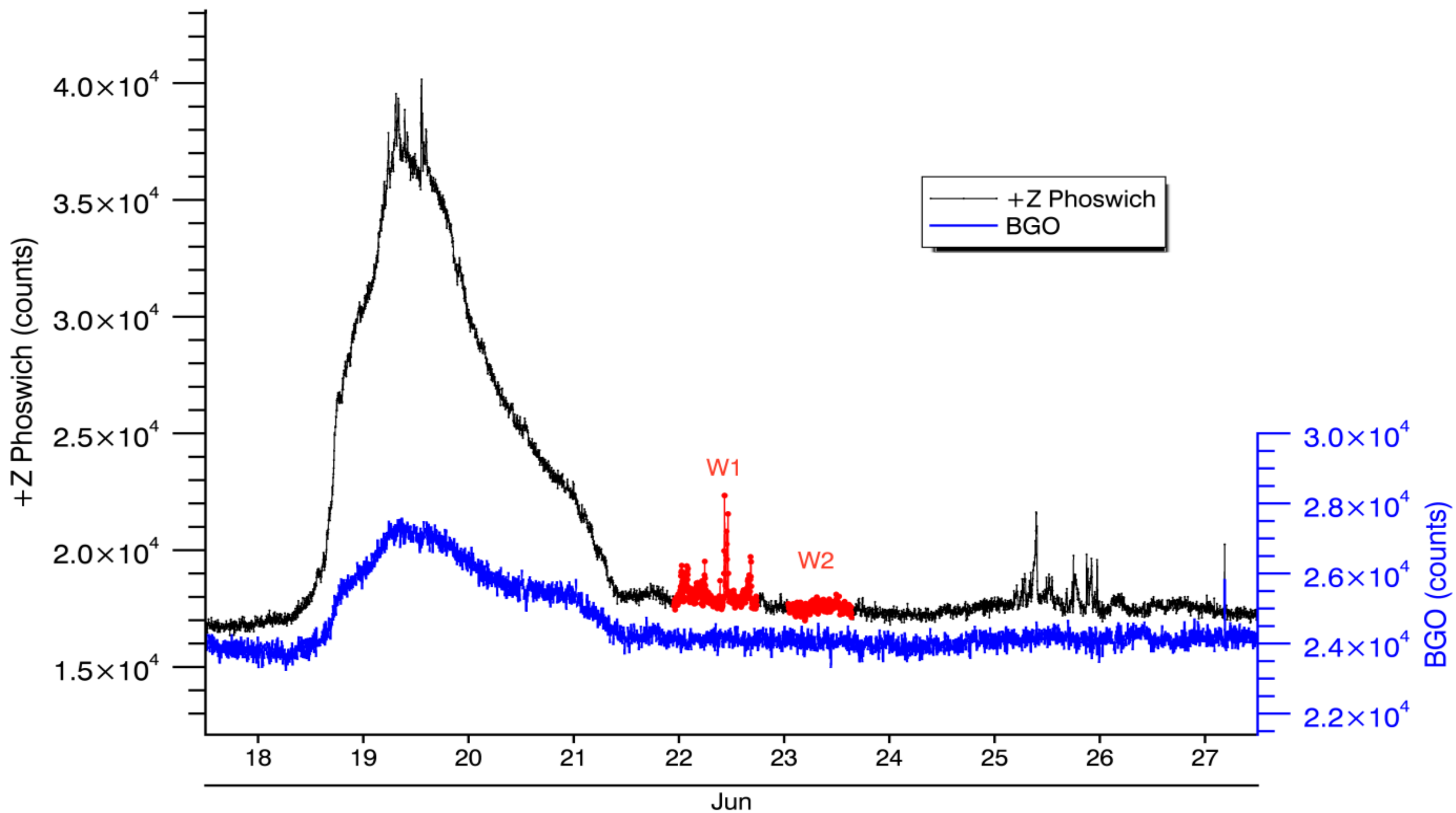
+/- Y BLP Detections



Boron Loaded Plastic (BLP) side scintillators

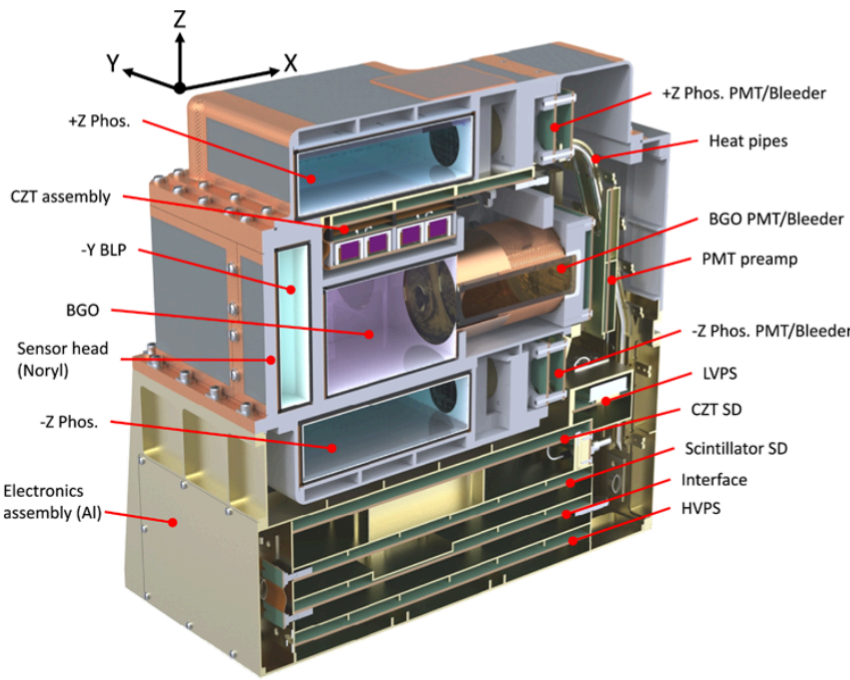


BGO Scintillator Comparison



The bursts appear in the exterior detectors but are absent from the BGO.

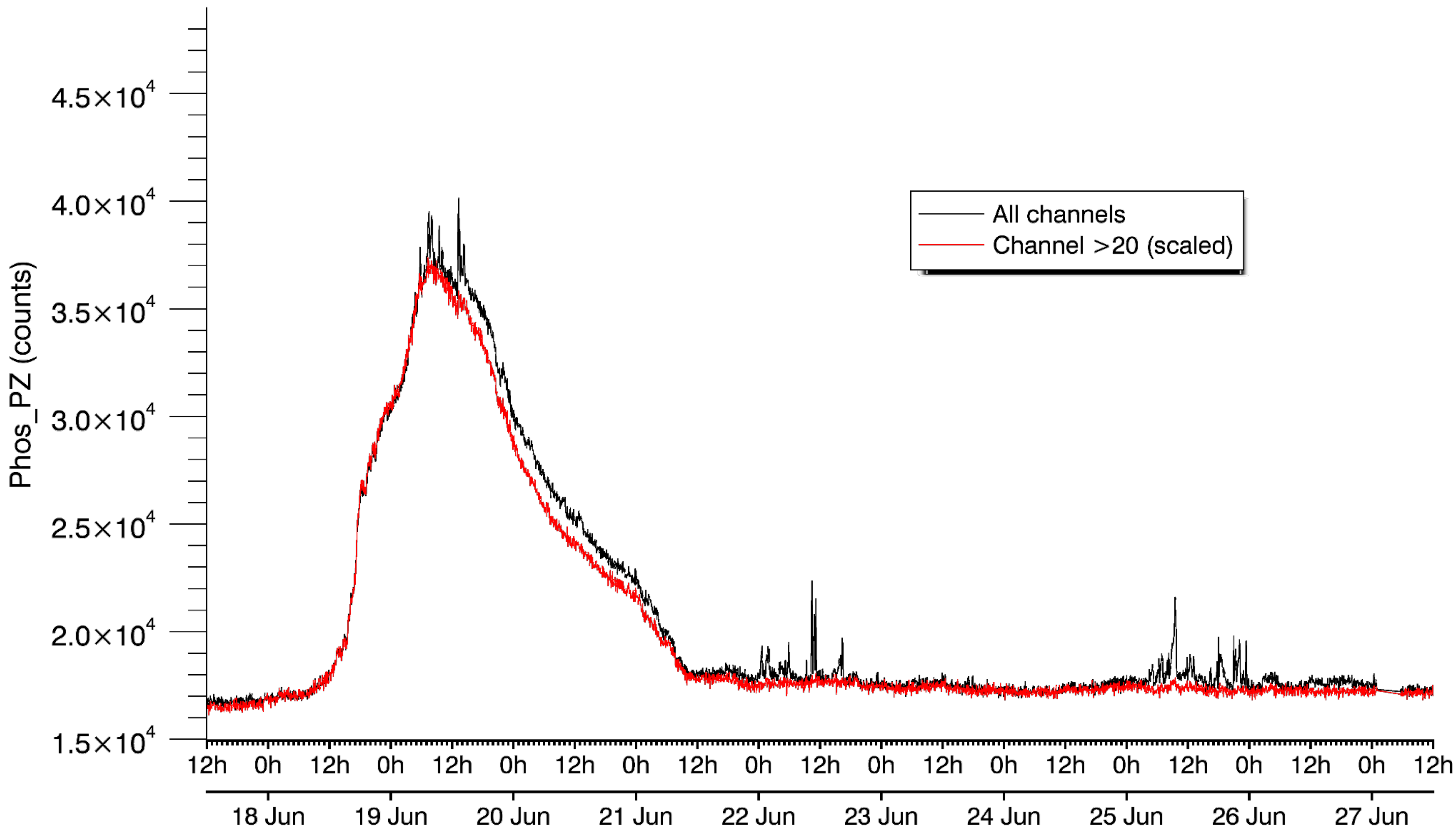
Identification of Electrons



- **NOT CAUSED BY PROTONS**: a 4 MeV proton is needed to penetrate GRaND's housing. A proton with this energy would result in an increase in the 4.4 MeV (C+O) and 6.1 MeV gamma peaks in the BGO spectrum→ not seen.

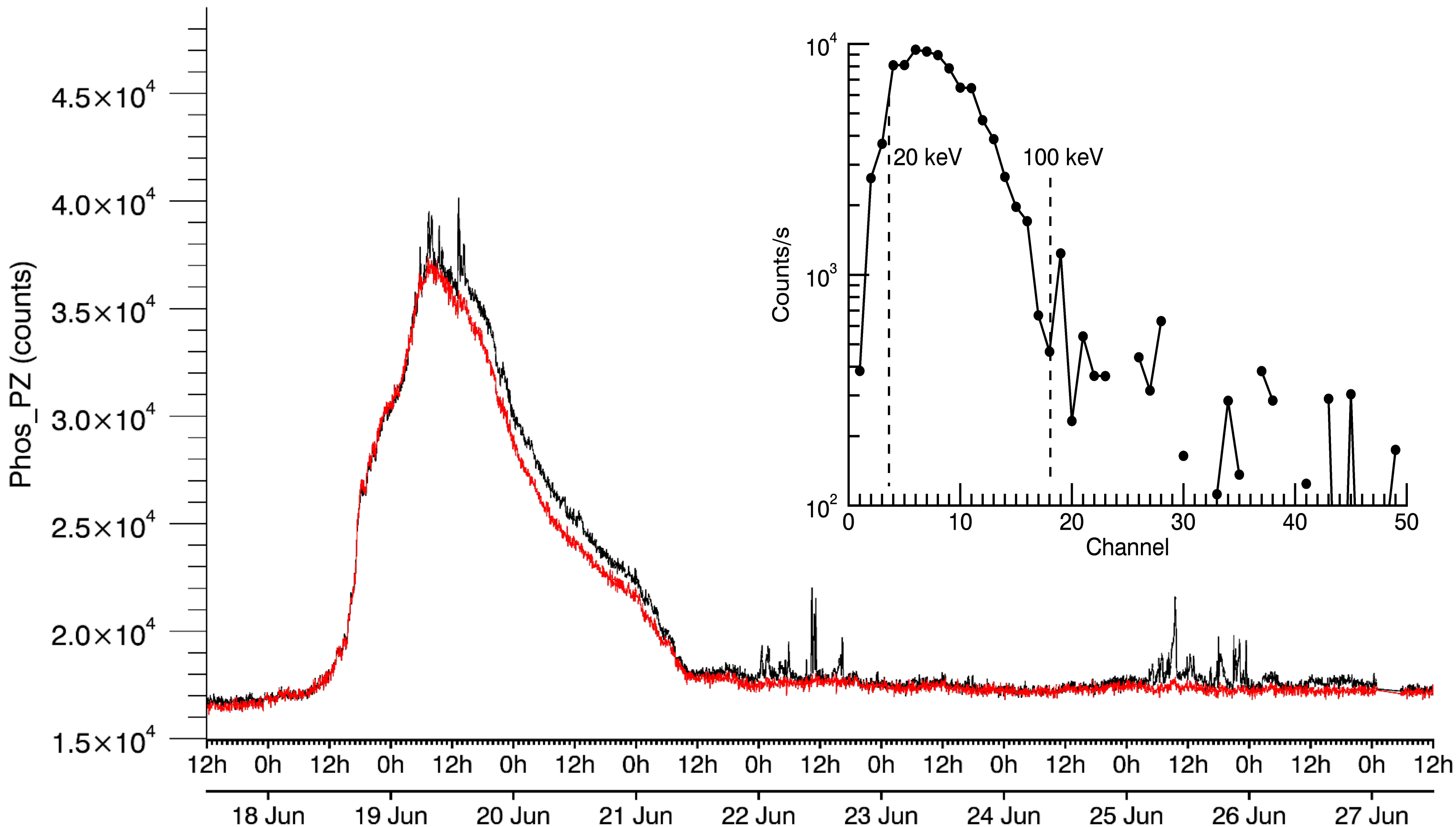
- Electrons greater than 20 keV can cause bursts in the outside scintillators without causing additional effects to the BGO.

Identification of Electrons



- Based on the channels the bursts are located, **ELECTRON ENERGIES ARE BETWEEN 20-100 keV**.

Identification of Electrons



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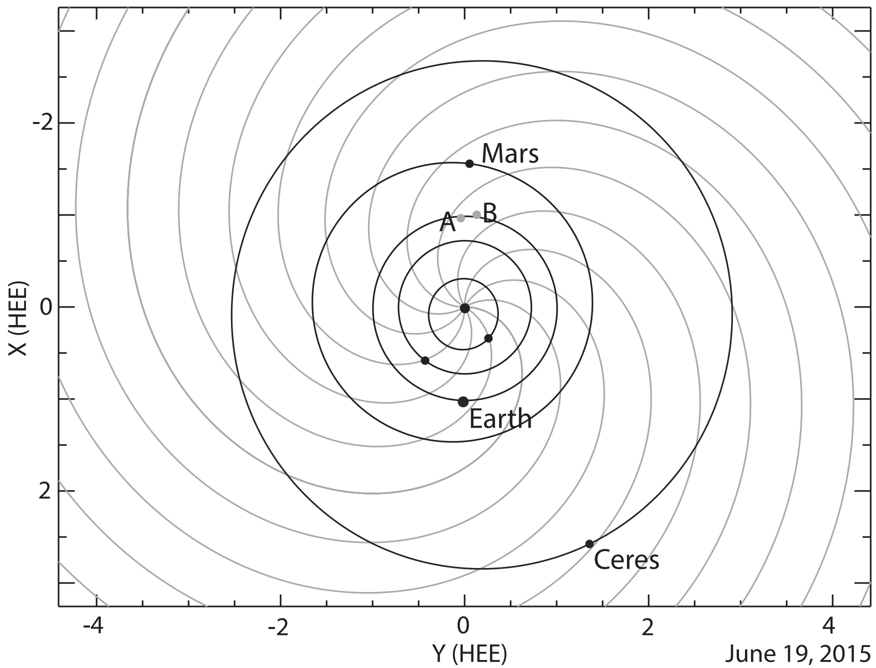
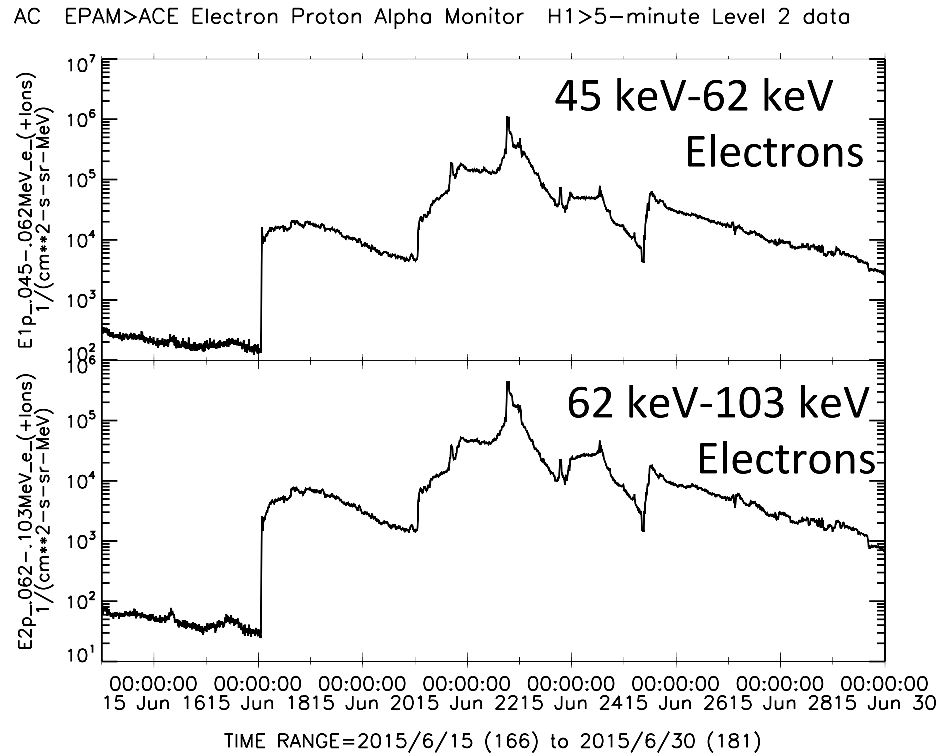
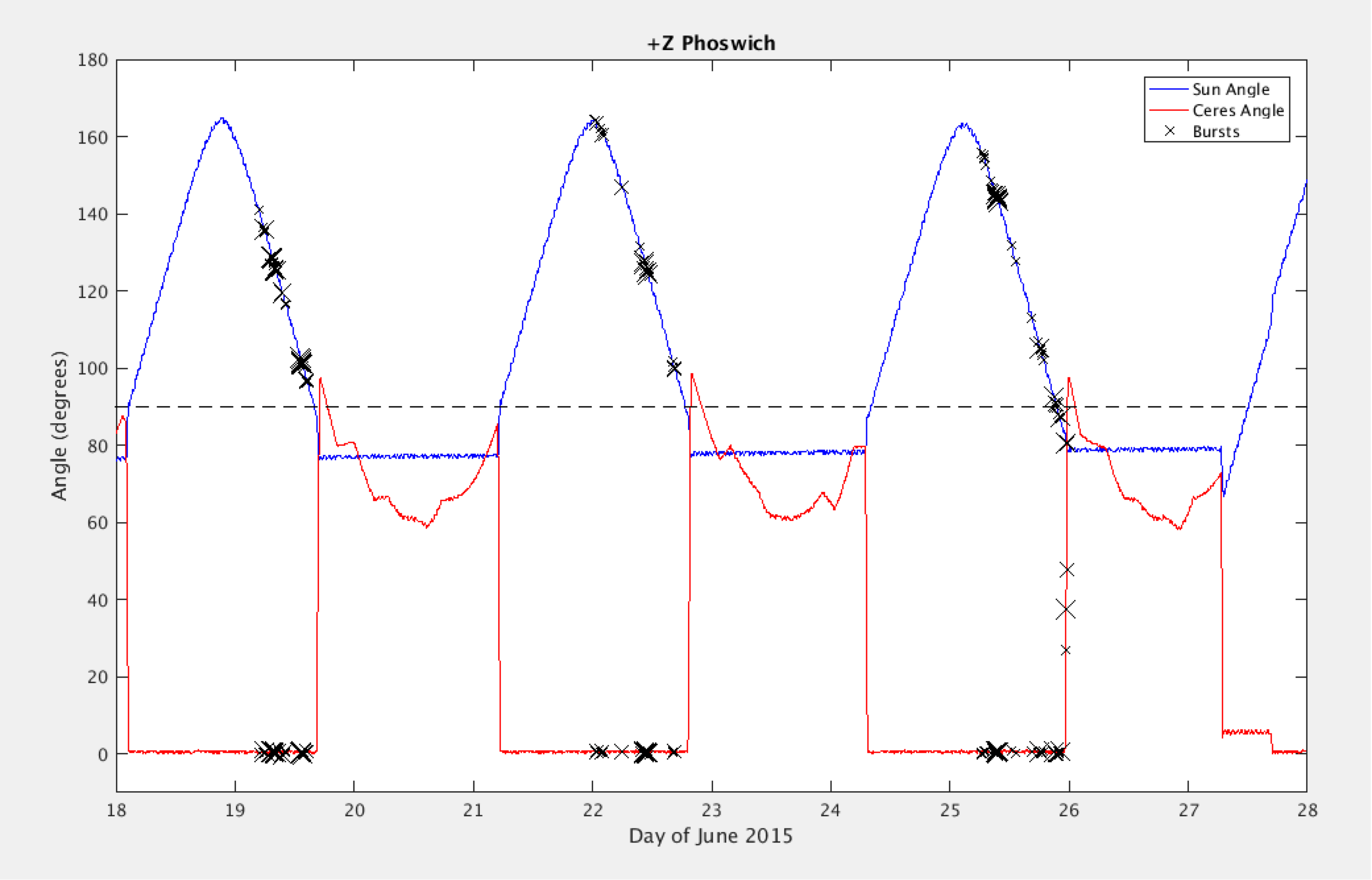
ACE Electron Data



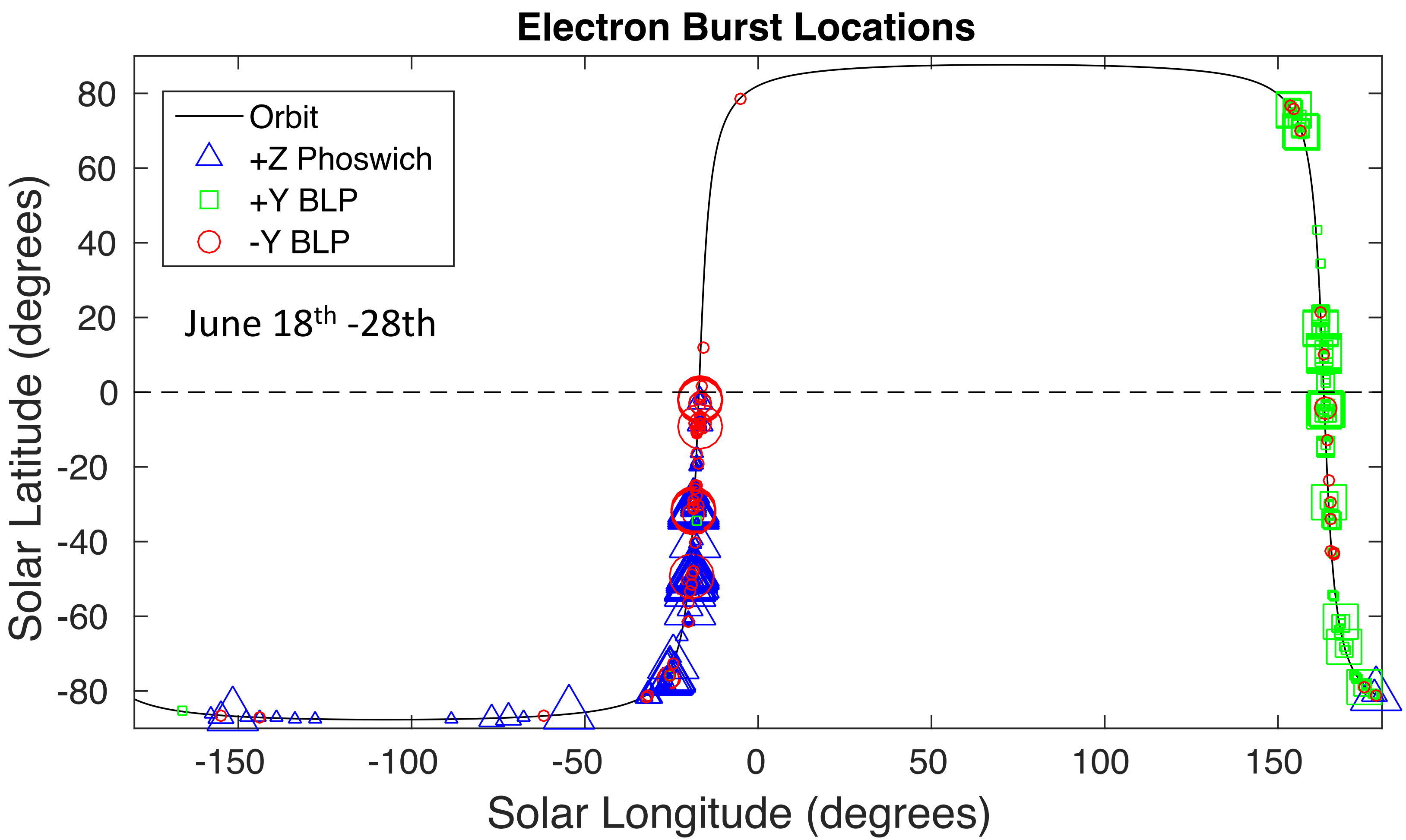


June 19th, 2015

Field of View



Location of Bursts



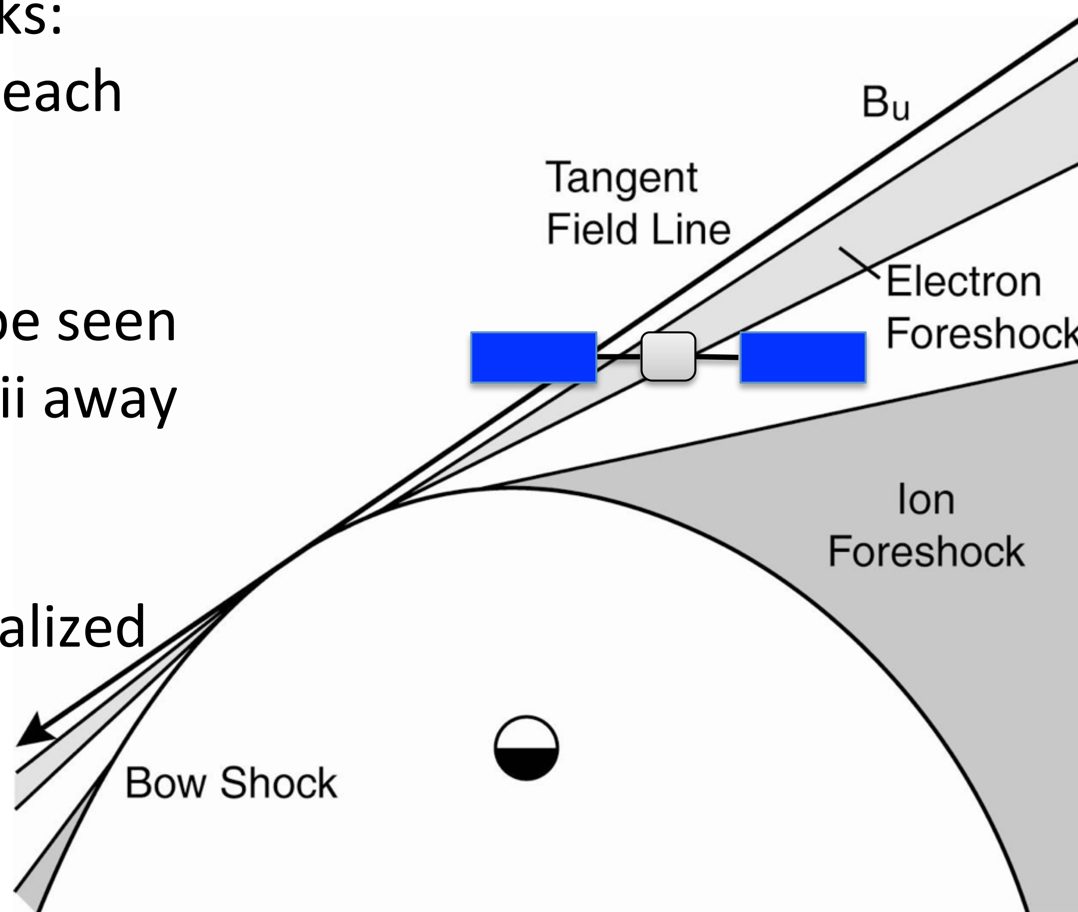
- Bursts occur at the same locations in solar coordinates on consecutive orbits for each scintillator.
- There is no correlation of the burst locations with surface features.

Electron Foreshocks

Fast-Fermi acceleration is currently the best candidate to explain observations.

In Planetary Electron Foreshocks:

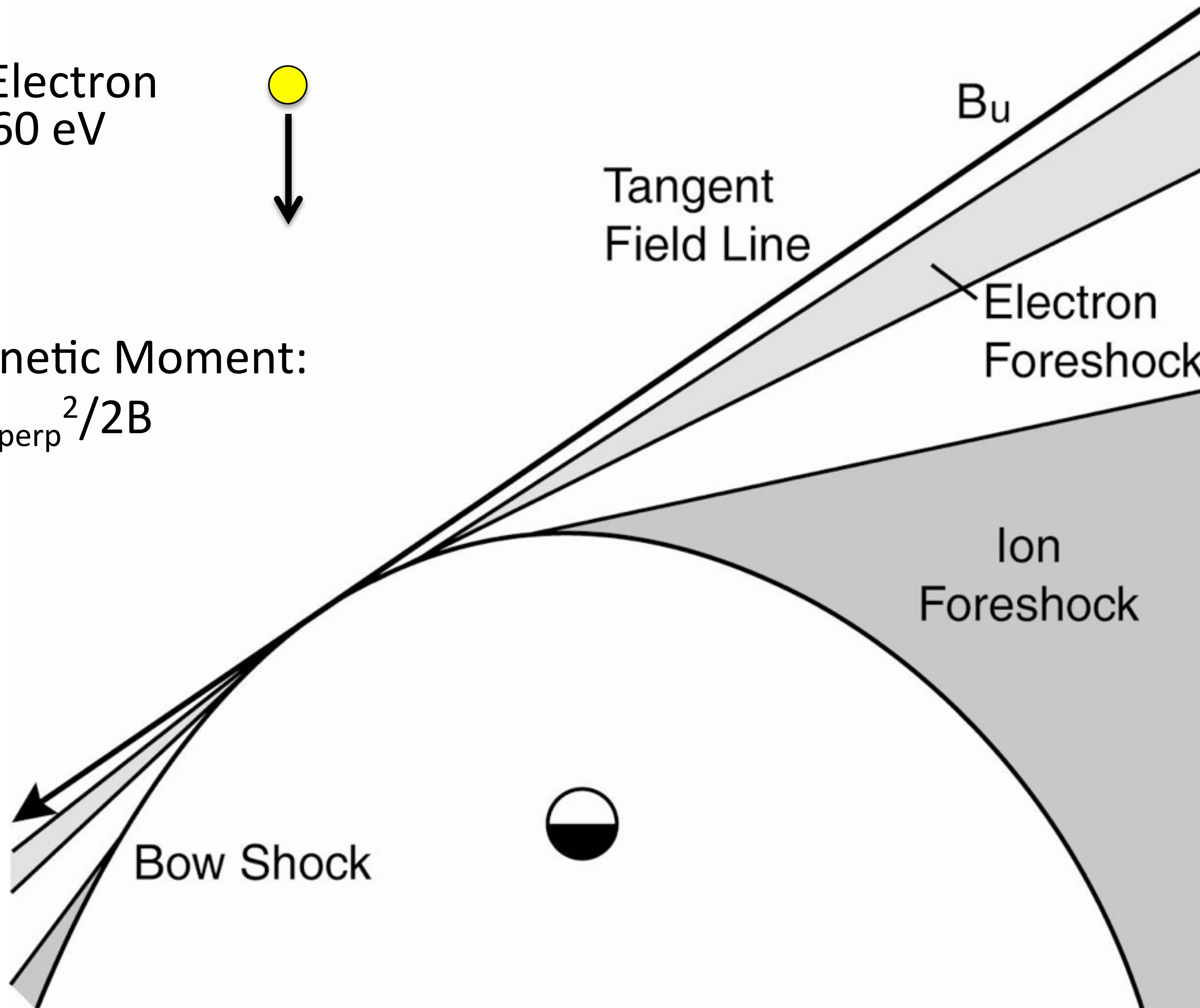
- Reflected electrons can reach tens of keV
- Energetic electrons can be seen as far as hundreds of radii away from the planets
- Electrons detected in localized regions dictated by the magnetic field



Fast-Femi Acceleration

Solar Wind Electron
Start: 10-60 eV

Conserves Magnetic Moment:
$\mu = m v_{perp}^2 / 2B$



Fast-Fermi Acceleration

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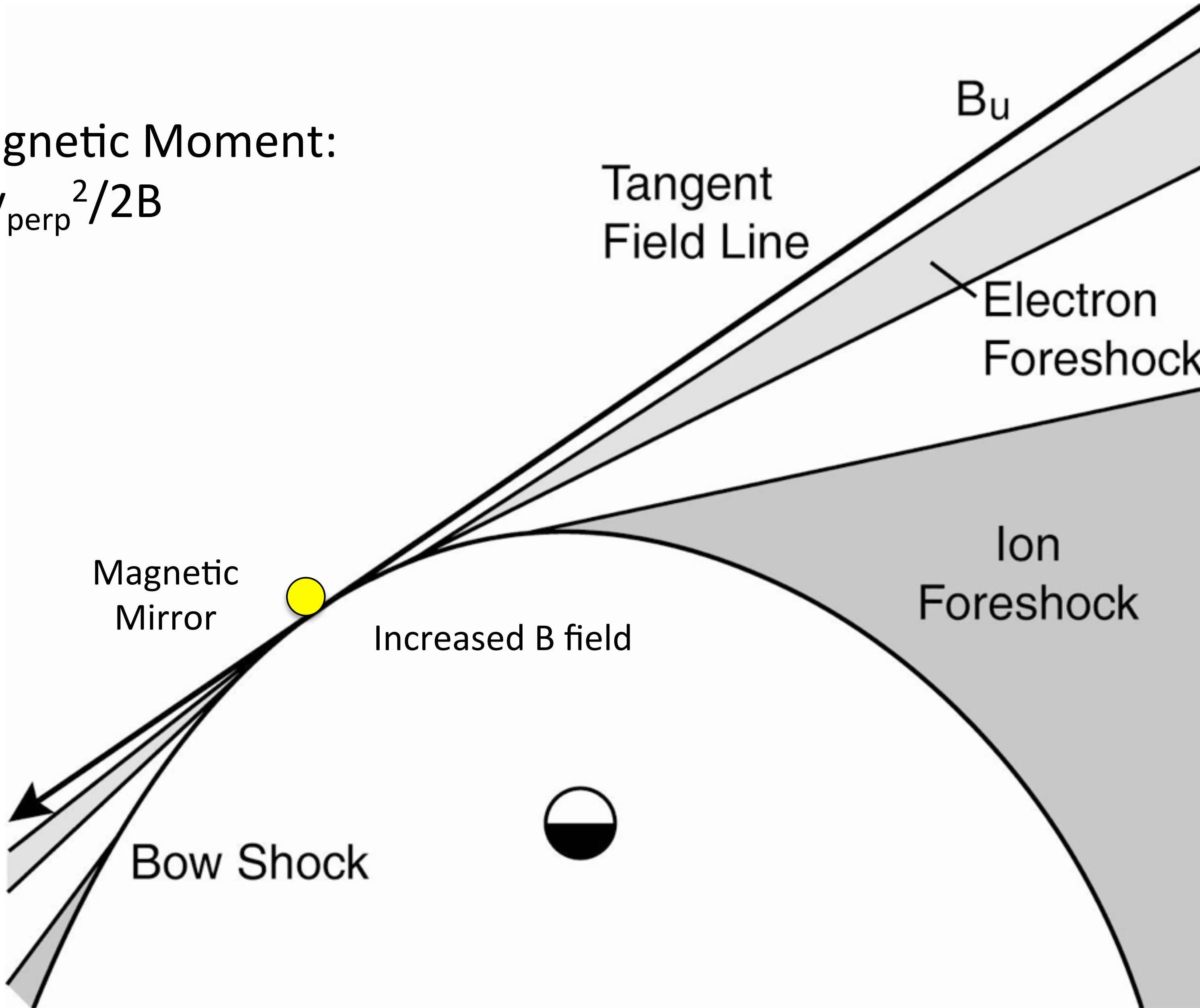
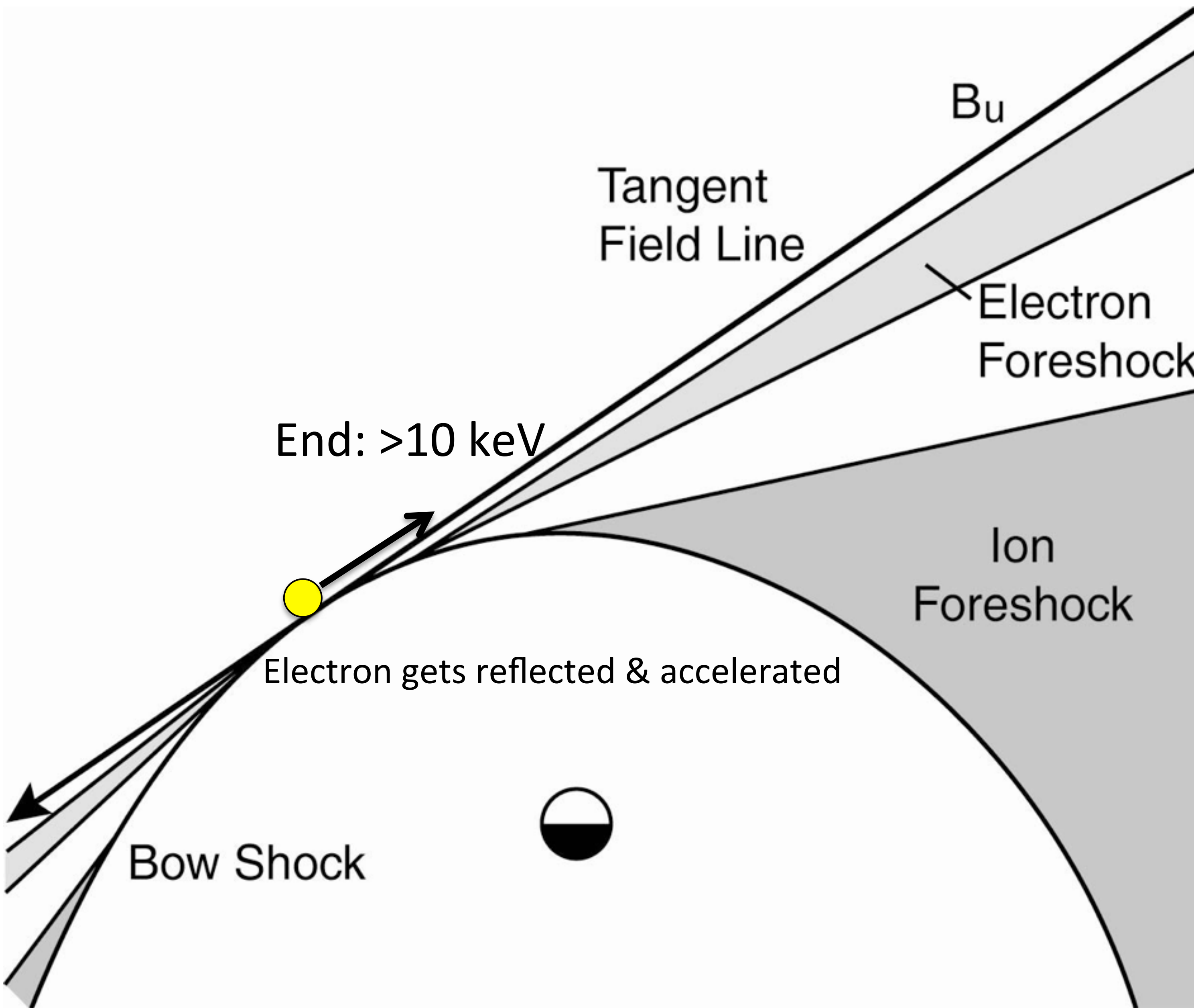


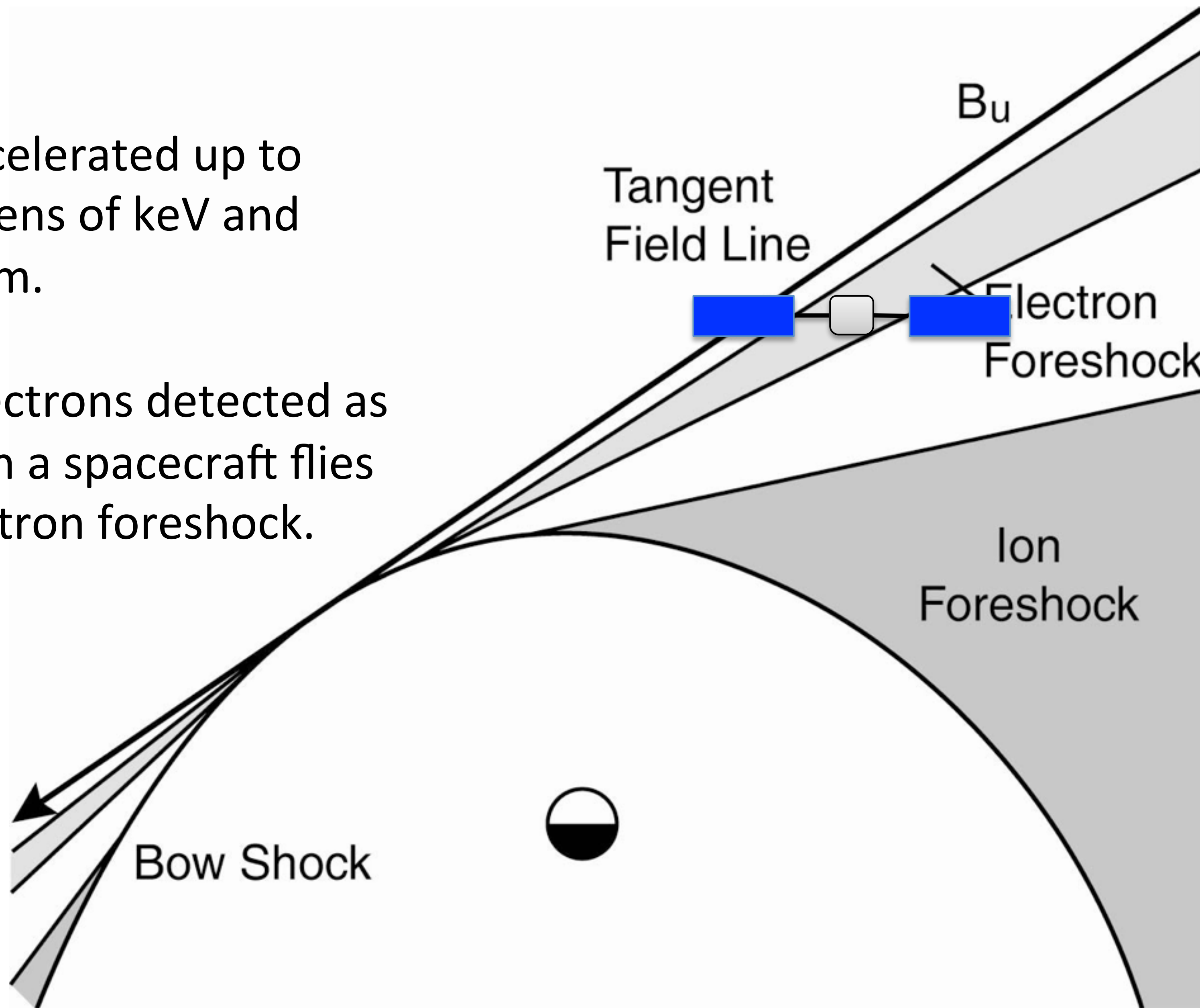
Fast-Fermi Acceleration



Fast-Fermi Acceleration

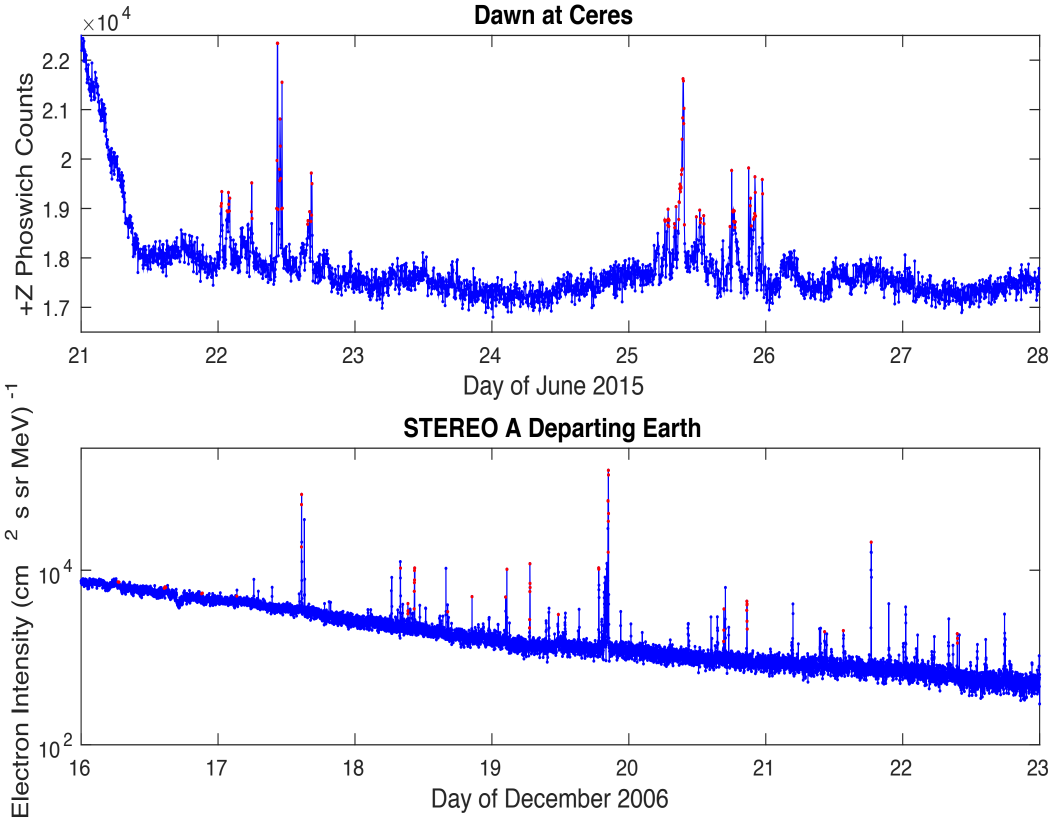
Electrons accelerated up to energies of tens of keV and create a beam.

Energetic electrons detected as 'bursts' when a spacecraft flies through electron foreshock.



Electron Foreshock at Earth

- Comparison of STEREO A as it is ~100 R_E from Earth.
- Data is from STEREO's SEPT instrument: electron energies 60-100 keV plotted.
- Both occur on relatively short timescales. However, in the Earth case, the duration is several minutes, while the Dawn cases can last up to an hour.



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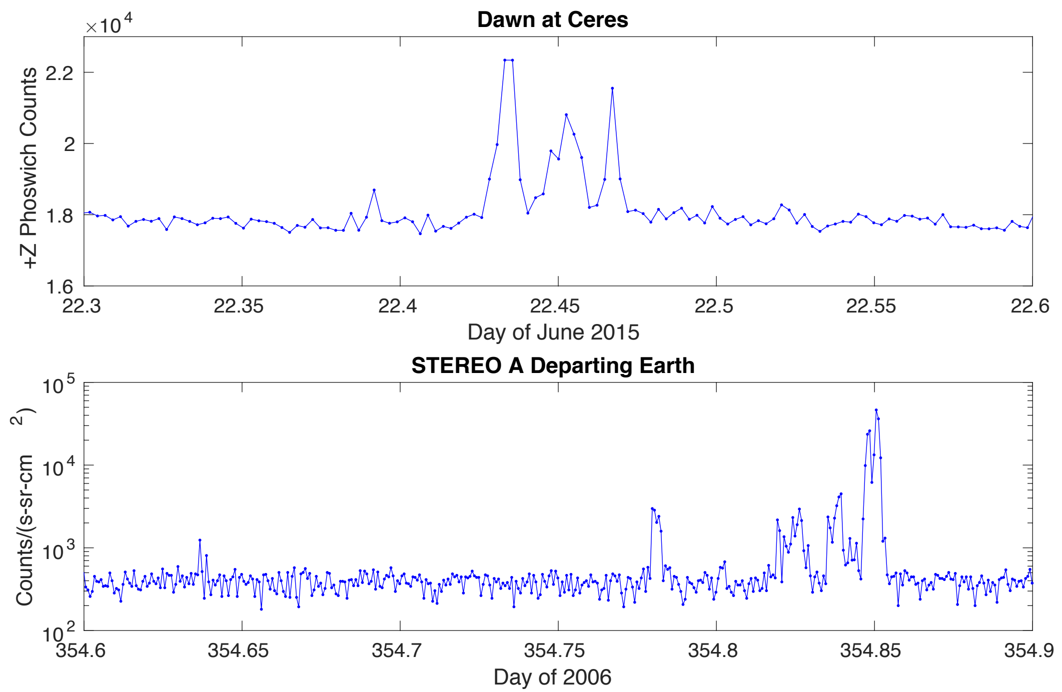
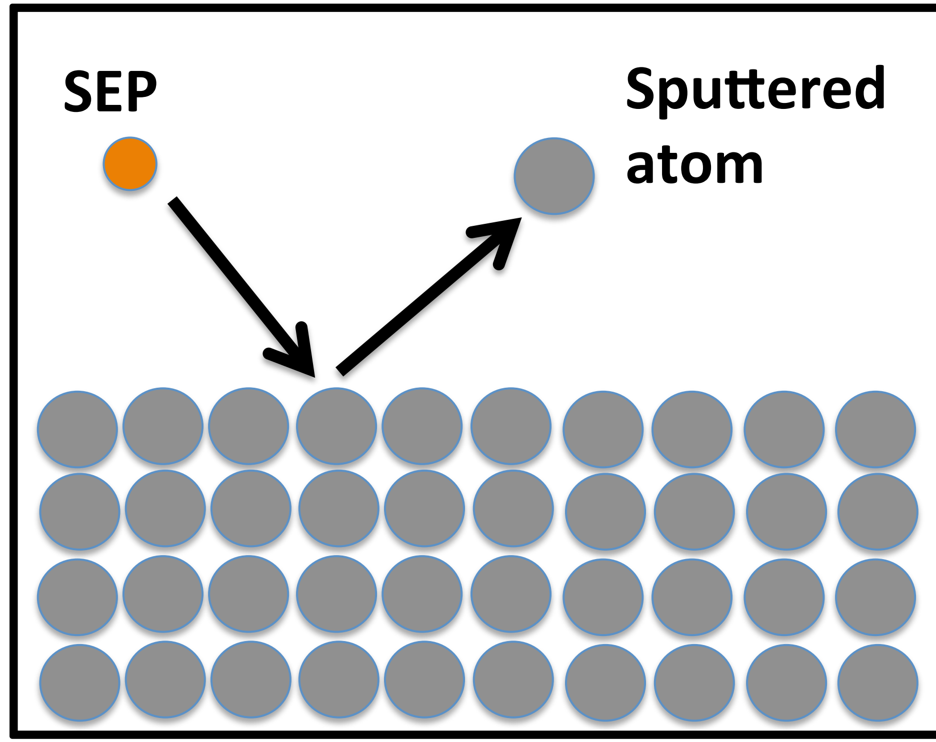


Transient Exosphere

- Increased solar energetic particle (SEP) bombardment can induce a transient atmosphere via sputtering of the ice on Ceres' surface.
- Water vapor has been detected at Ceres on several occasions [A'Hearn & Feldman (1992), Kuppers et al. (2014)].



- Formisano et al. (2016) predicts a transient atmosphere can last about 10 days, which is the same timescale over which the electron bursts occur.

Single-Fluid MHD Models

Equations & Numerical Set-up

Fluid Equations:

$$\partial \rho/\partial t + \nabla \cdot (\rho \mathbf{u}) = Q_\rho$$

$$\partial(\rho \mathbf{u})/\partial t + \nabla \cdot (\rho \mathbf{u}\mathbf{u}) = \rho \mathbf{g} - \nabla p + ne\mathbf{u} \times \mathbf{B} + \mathbf{Q}_{\rho \mathbf{u}}$$

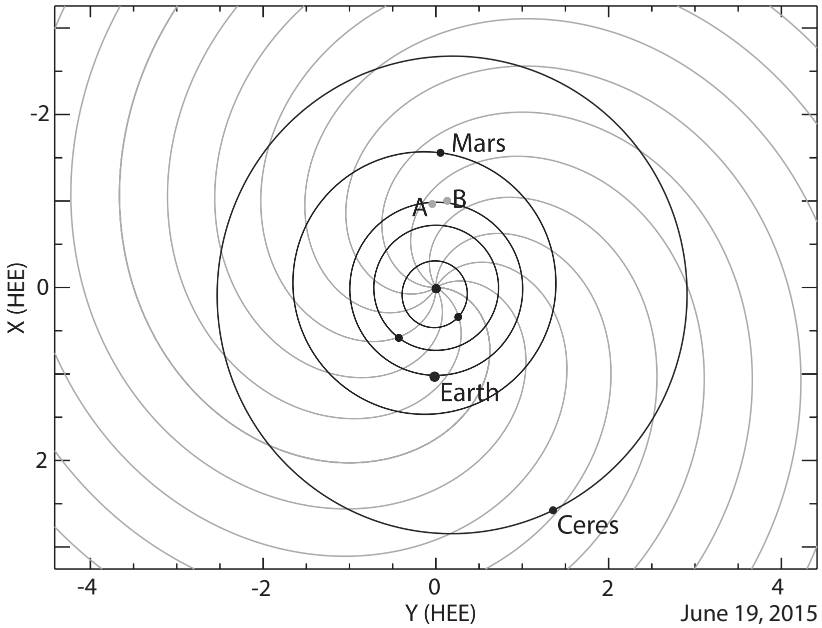
$$\partial p/\partial t + \nabla \cdot (p\mathbf{u}) = -(\gamma - 1)\, p\, (\nabla \cdot \mathbf{u}) + Q_p$$

- Q includes ions added to and removed from the calculation domain via photoionization, charge exchange, and dissociative recombination between water group ions and neutrals.
- Cartesian grid with a resolution of 1/12 R_C
- The outer boundaries use solar wind inflow on the subsolar side, and outflow on the 5 other sides.
- The inner boundary is located on Ceres' surface.

Solar Wind Inputs

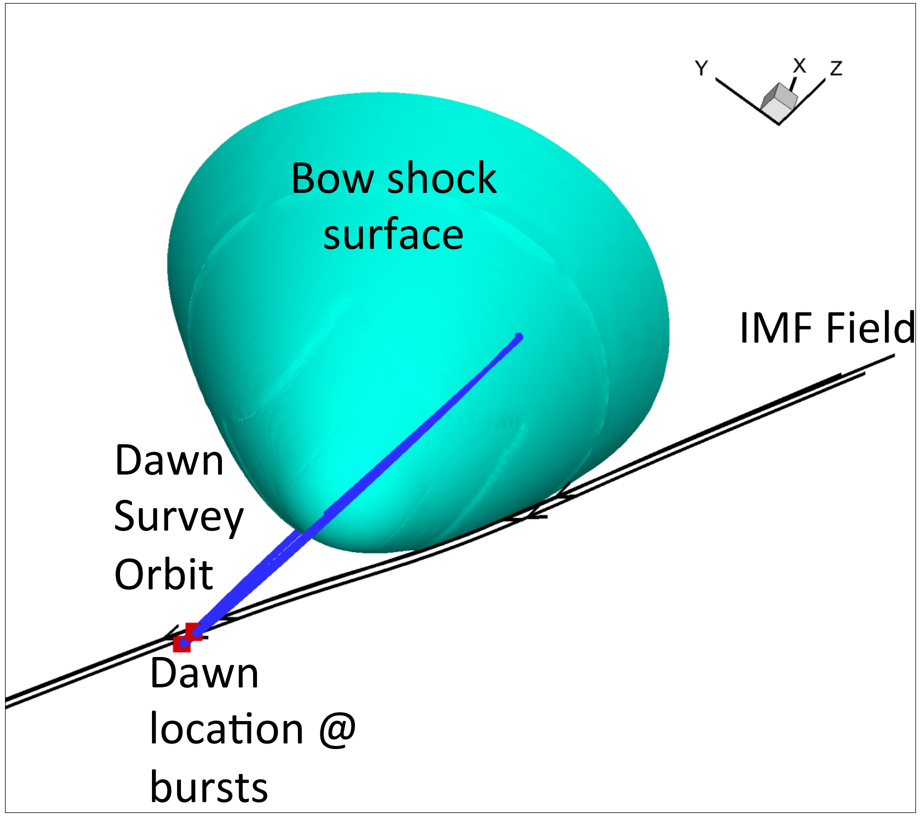
Earth was near Ceres at the time of the electron burst detections, so ACE data are used to extrapolate solar wind conditions at Ceres.

Goal: want to understand what atmospheric densities are needed to create a bow shock and how the shape depends on the source



Variables	values
Solar wind density n_{sw}	1.3 cm^{-3}
Solar wind velocity u_{sw}	500 km/s
Solar wind temperature T_{sw}	2×10^5 K
IMF $(Bx, By, Bz)_{sw}$	(-1.2, 0.88, -0.45) nT
Plasma β	2.

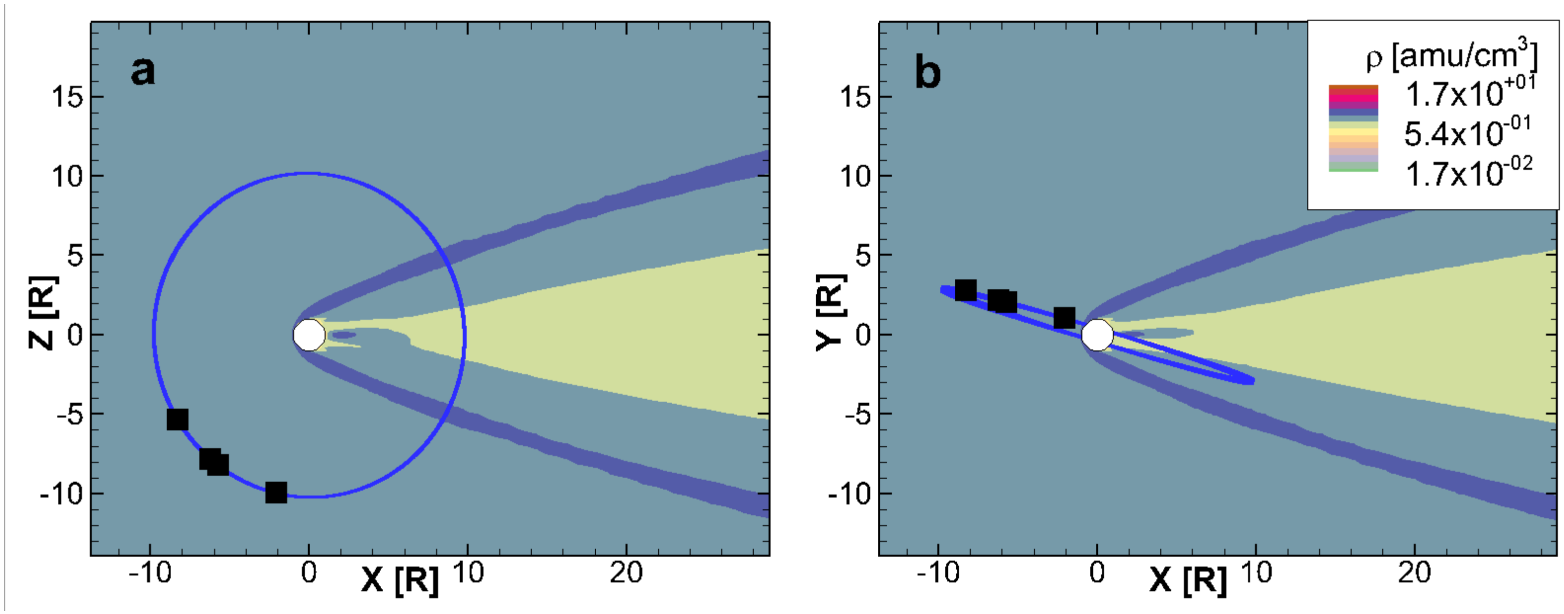
Geometry



Electrons will travel from the bow shock to Dawn along the magnetic field line that is tangent to the bow shock.

For Dawn to see energetic electrons, must be outside of the bow shock surface.

Case 1: Exospheric Lower Limit

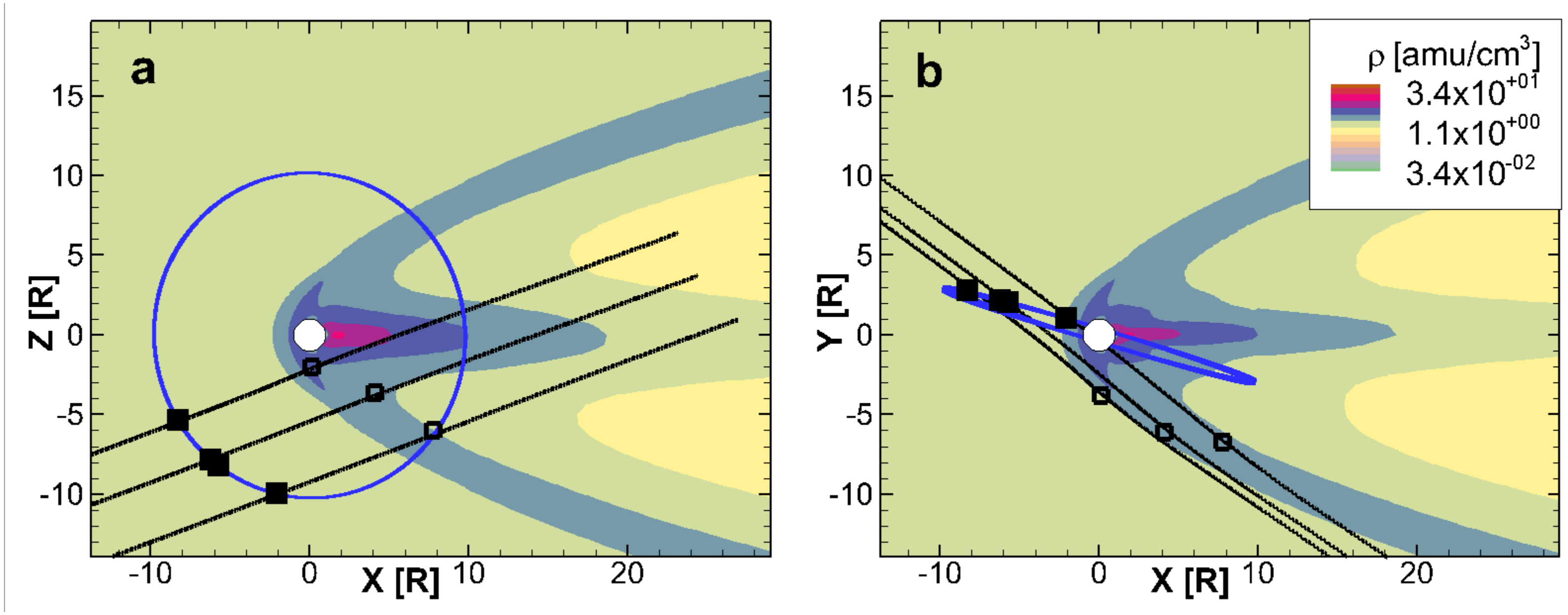


What is the minimum global exospheric density needed to produce a bow shock?

Lower limit vapor production rate to produce a bow shock from a single fluid model gives a rate of $6x10^{25}$ s^{-1} (1.8 kg/s).

Should easily form a bow shock for vapor production rates reported for Ceres.

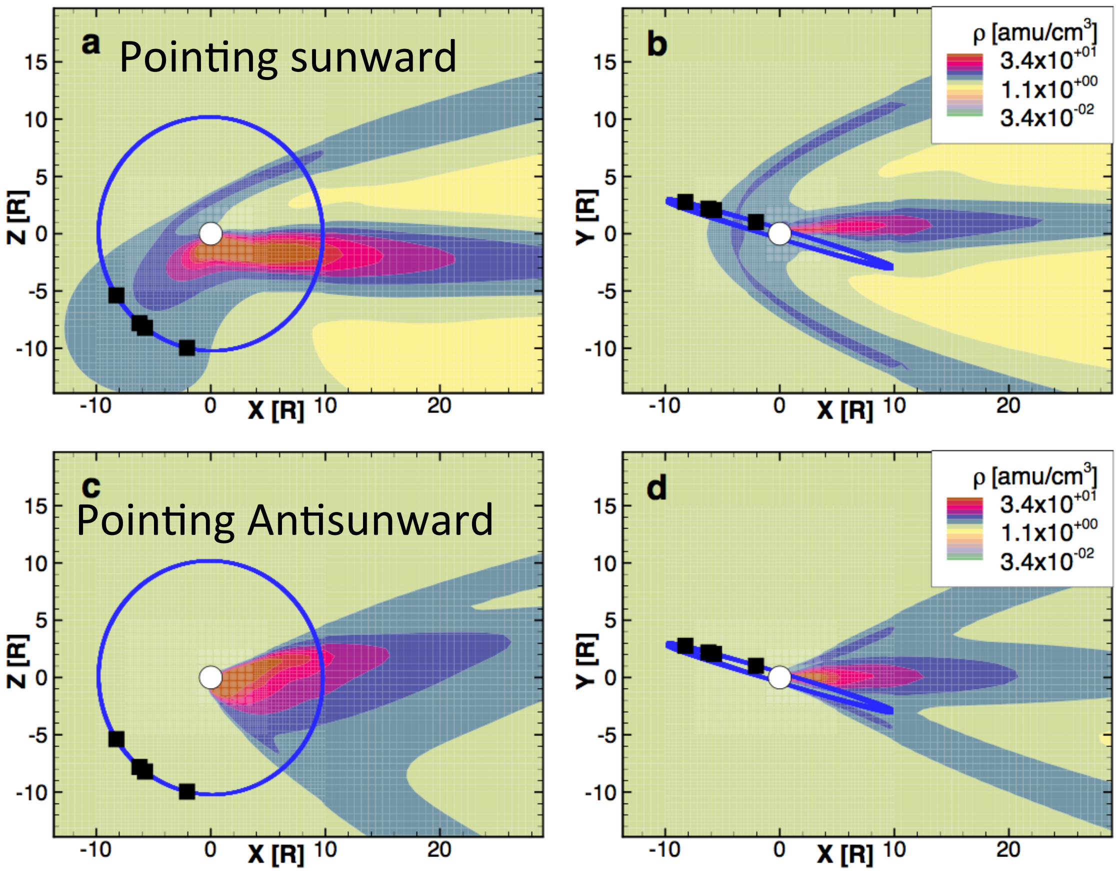
Case 2: Q=9 kg/s



The gas around Ceres is modeled as a spherically symmetric water vapor exosphere with a constant flux of Q = 9 kgs^{-1}.

Location of the bursts are consistent with Dawn being magnetically connected to the bow shock surface.

Case 3: Localized Source



Localized source, Q=4.5 kg/s

Bow shock shape asymmetric

Concentrated gas plume causes a stronger shock

Can have a gas loss rate less than $1.5x10^{25}$ s^{-1} to create a bow shock if the source is localized

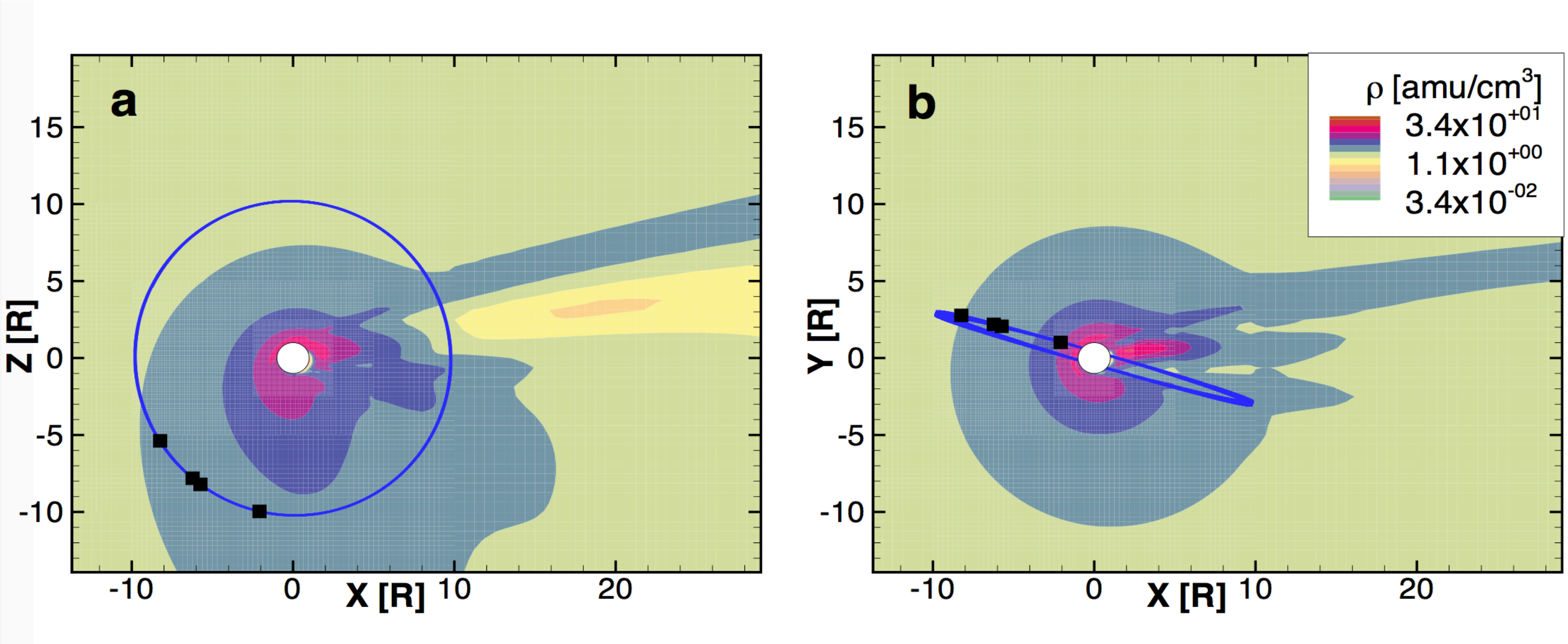
*These models represent extreme end members and do not take into account rotation. The actual bow shock will be something in between.

Summary

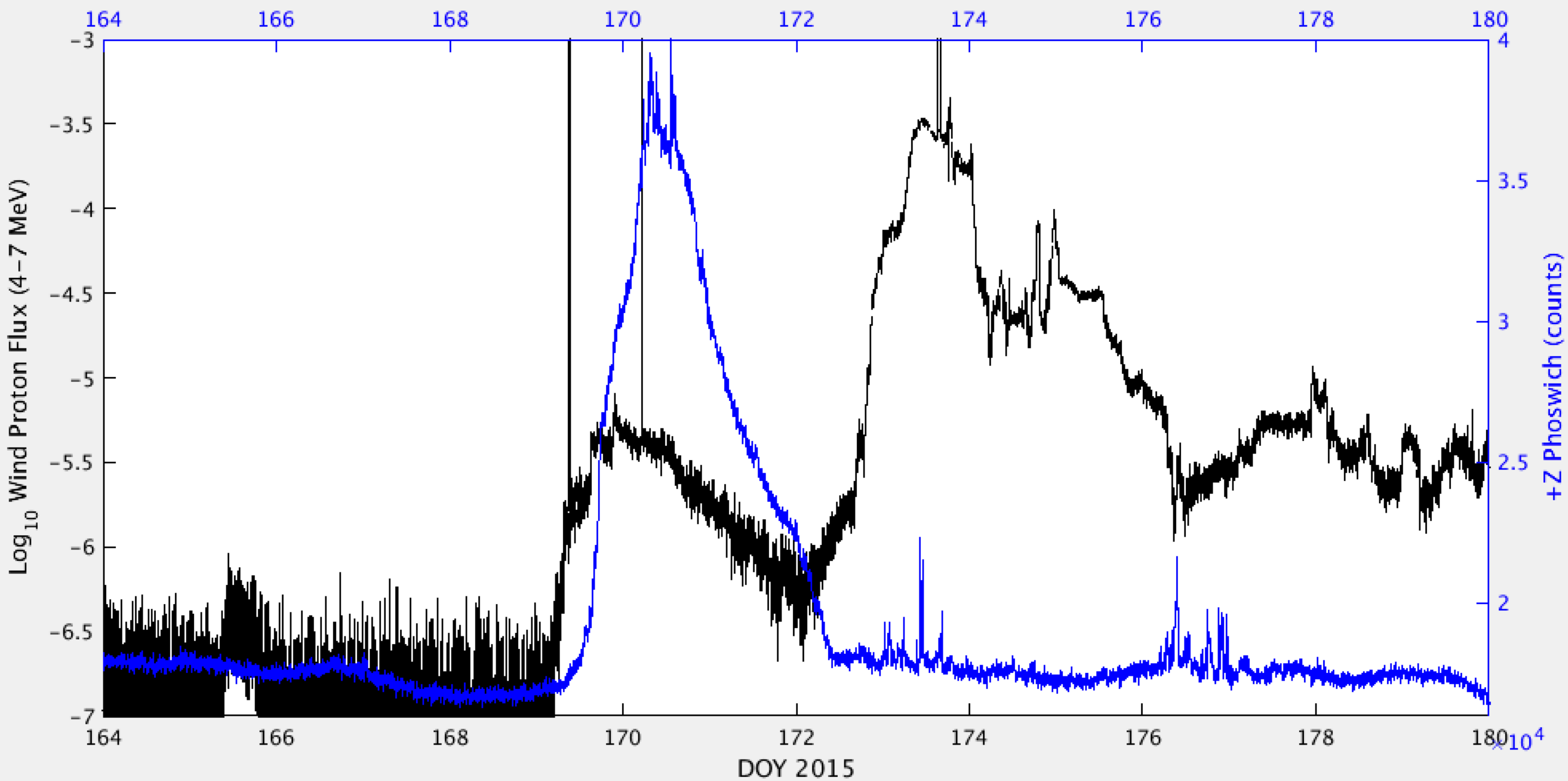
- Dawn observed highly energetic electrons in its exterior GRaND scintillators during Survey orbit.
- Bursts of electrons with these characteristics have been observed in planetary electron foreshocks and are energized by their respective bow shocks.
- The temporary atmosphere than would be needed to replicate the geometry observed by Dawn is similar to the vapor production rates that have been previously reported for Ceres.

Back-Up Slides

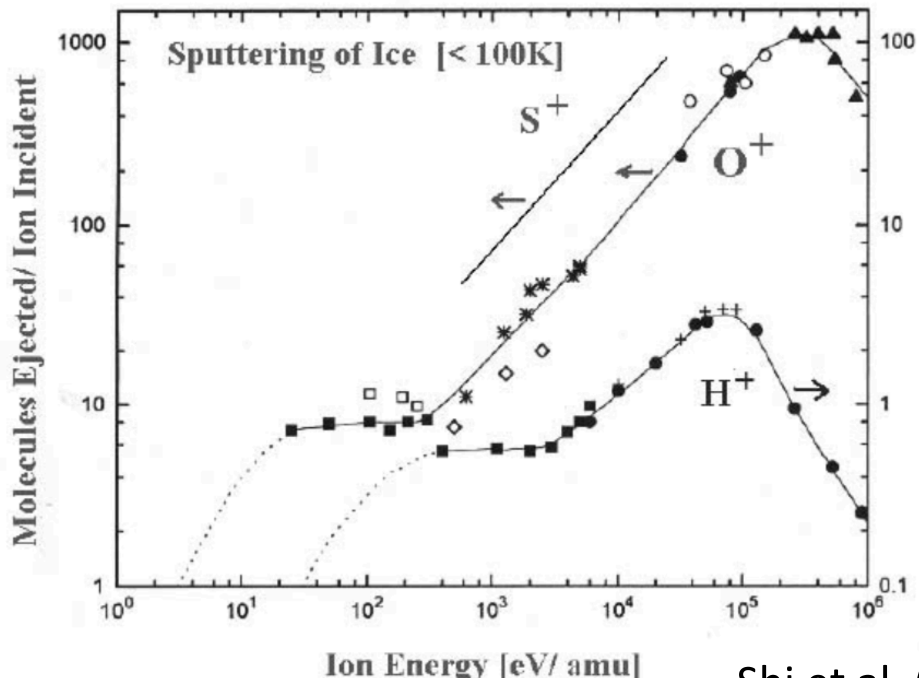
Multi-fluid Model



Proton comparison



Solar protons are important because they can sputter water ice from the surface.



Shi et al. (1995)

Figure 1. The sputtering yield (equivalent H_2O molecules ejected per ion incident) for water ice at ~77K for incident O^+, S^+ (left hand axis) and H^+ ions (right hand axis). Lines are model fits of data indicated by points.

At Ceres, protons with energies ~ 1 keV-1 MeV will be important for sputtering water ice (peak at 10^5 eV). In the solar wind, it is the higher energy protons that are the most variable.