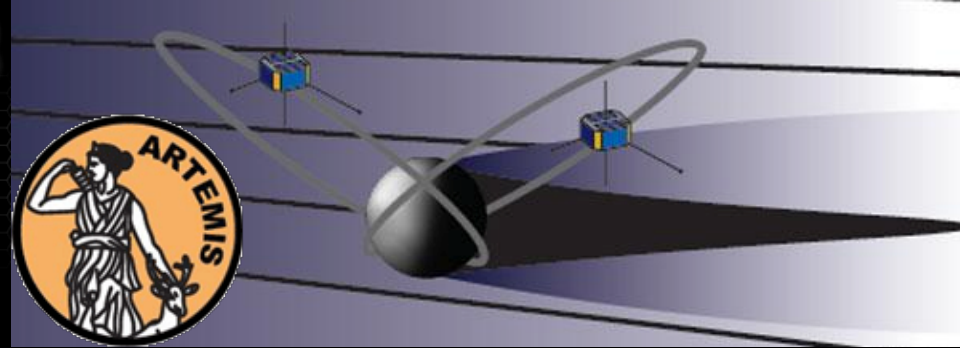


DREAM2



Dynamic Response of the Environments
at Asteroids, the Moon, and moons of Mars



The Plasma Environment of the Moon

J.S. Halekas [jasper-halekas@uiowa.edu]

Department of Physics and Astronomy, University of Iowa

The Moon is a Keystone

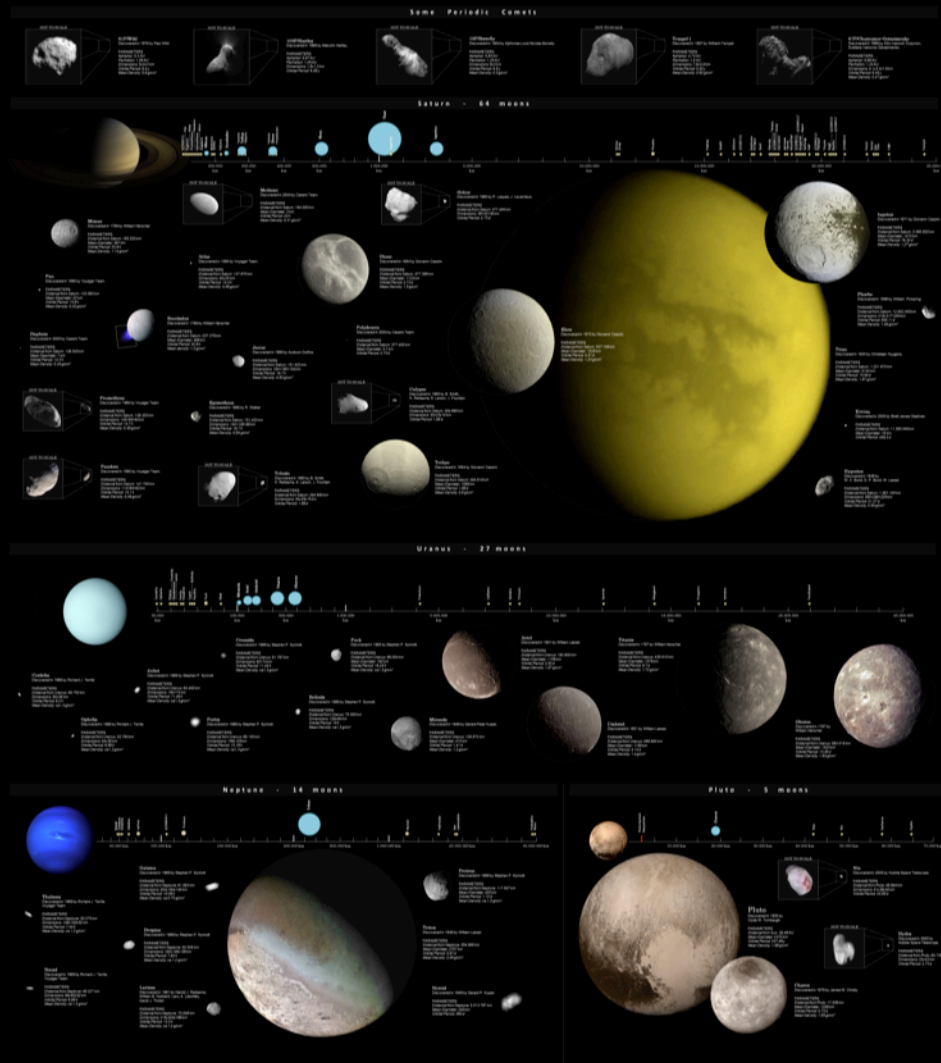
Non-Planet of the Solar System to scale

Dwarf Planets (Ceres & Pluto) – Moons of Planets and Dwarf Planets – Asteroids – Comets

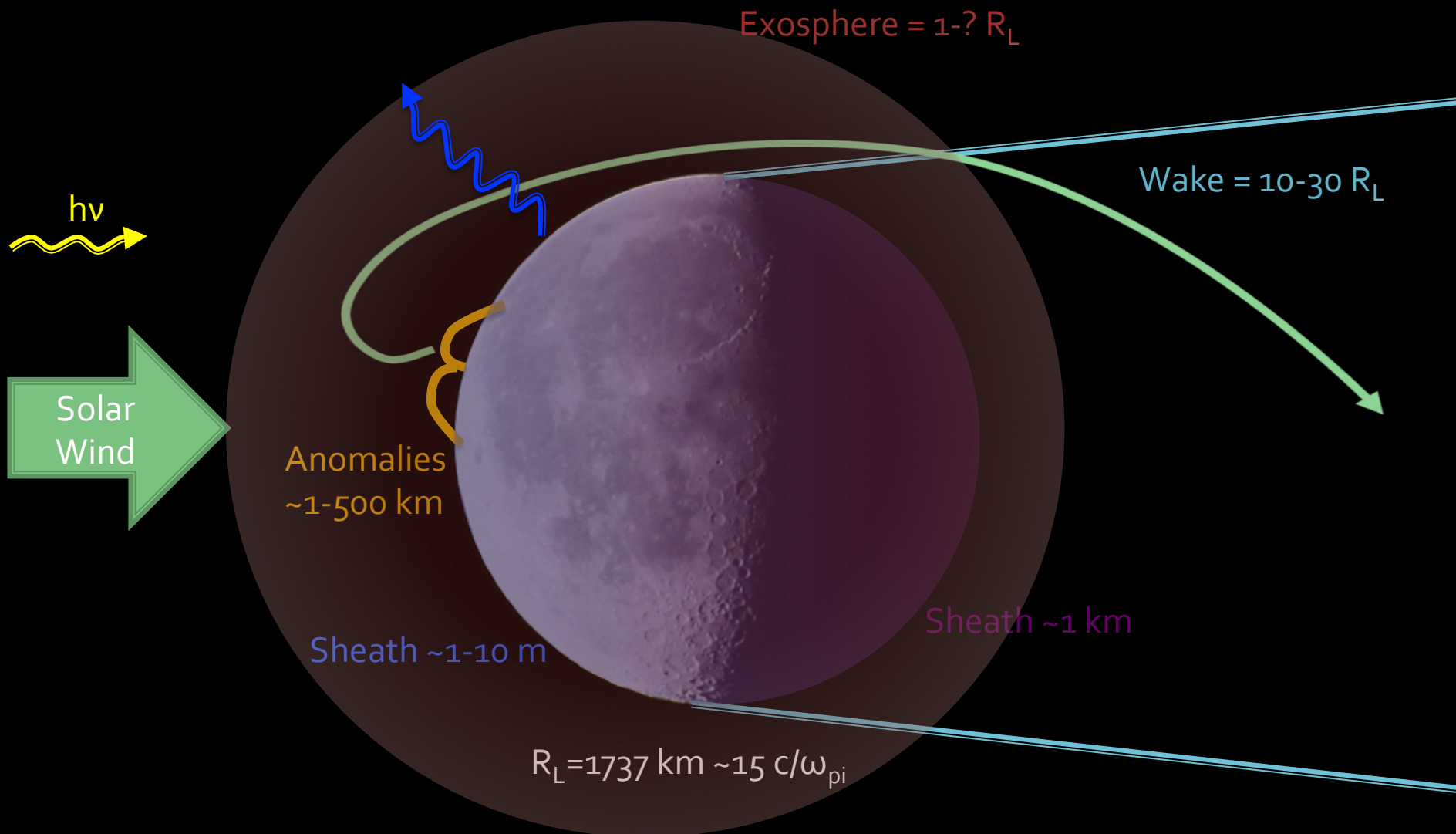
Images from Missions:

Voyager 1 – 2, Hubble Space Telescope, Mars Reconnaissance Orbiter, Deep Impact-EPOXI, Stardust, Galileo, Near-Shoemaker, Cassini, Rosetta, Dawn, New Horizons

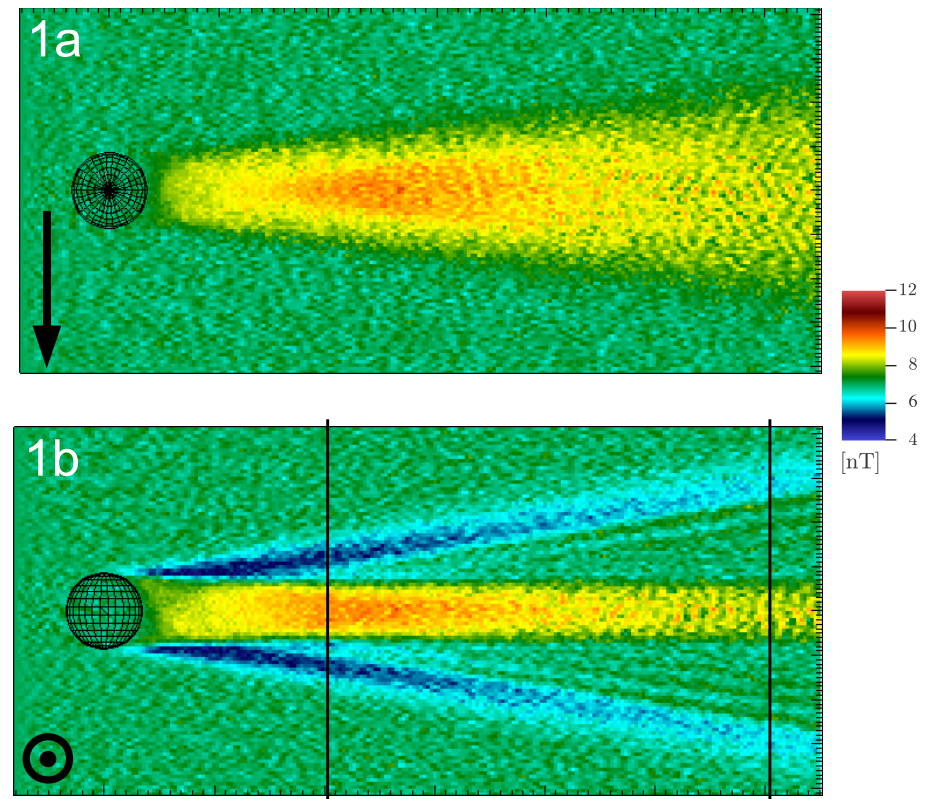
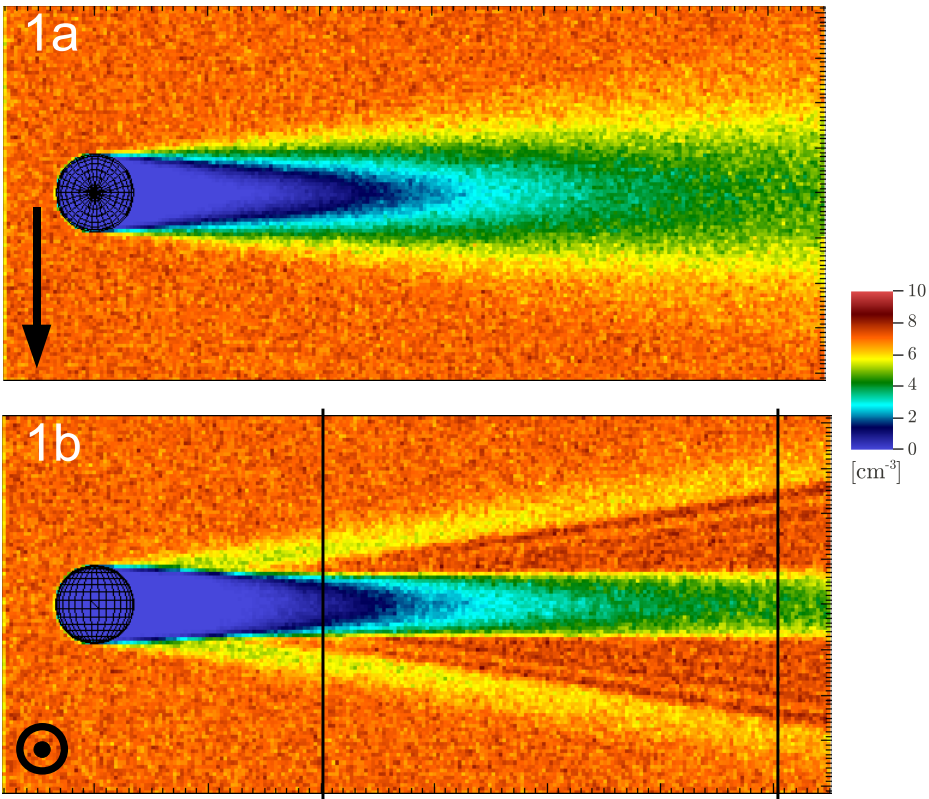
THE REPRESENTATION BETWEEN MOONS & PLANET ON DISTANCE LINE AND PLANET & PLANET OF DISTANCE LINE IS NOT TO SCALE



Overview: A Moon of Many Scales



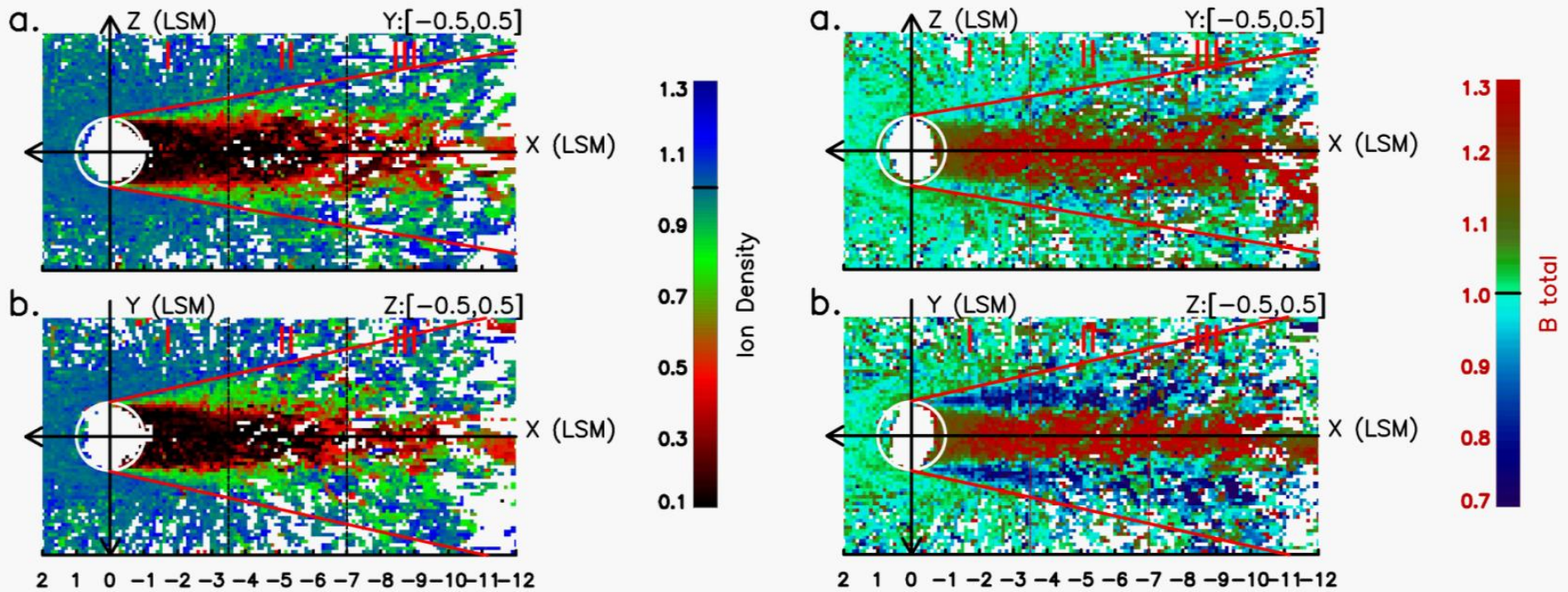
The Wake: Simulations



Holmstrom et al., 2012

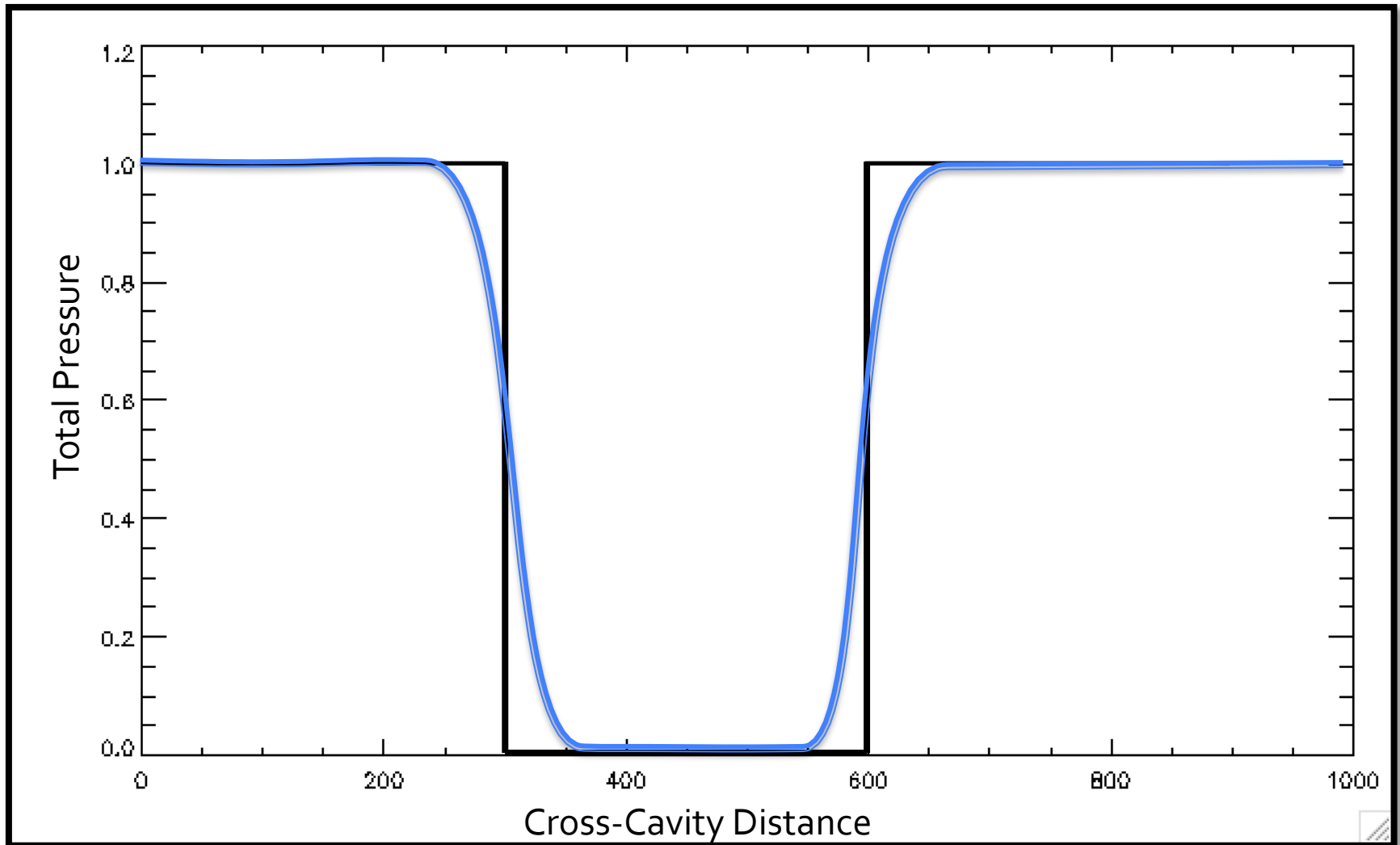
The Wake: Observations

Upstream B in X-Z plane

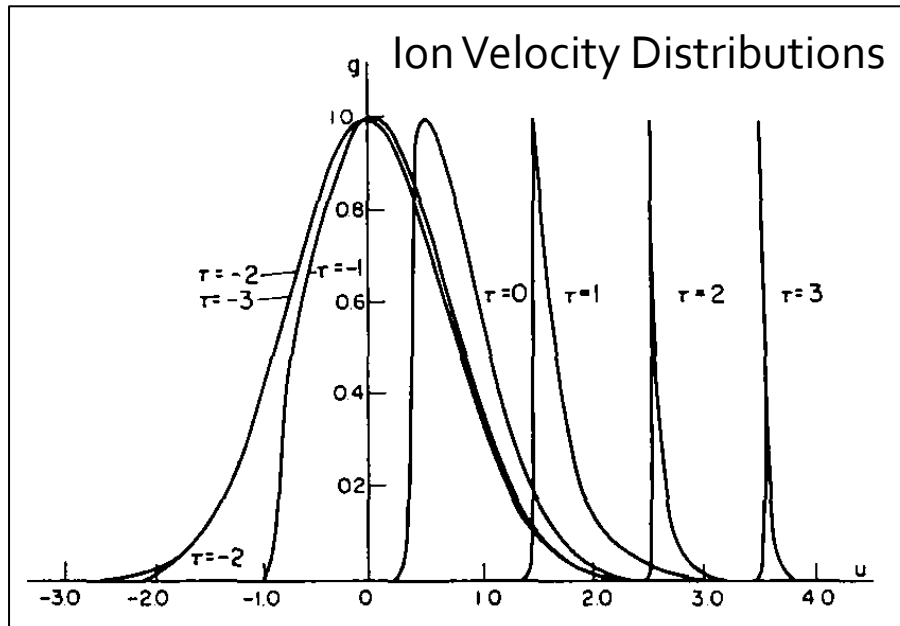


Zhang et al., 2014

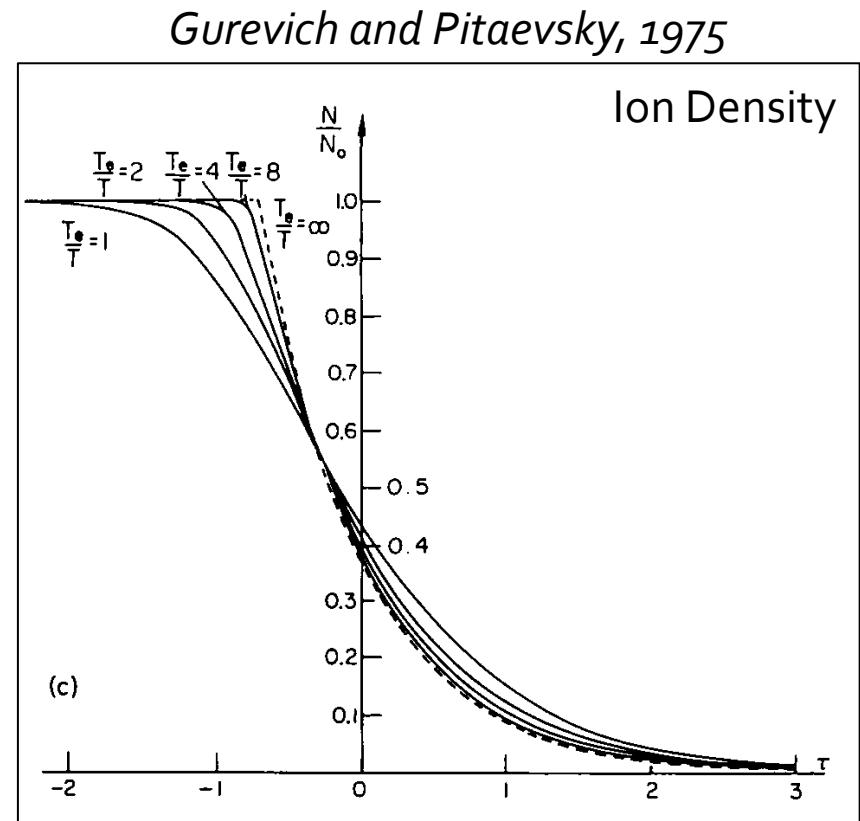
Parallel Expansion



Parallel Expansion Theory

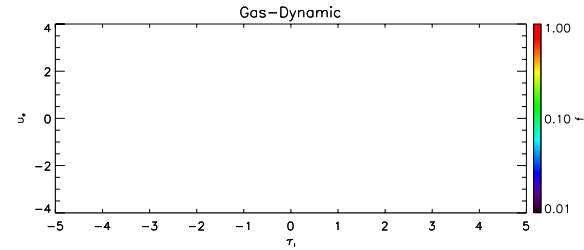
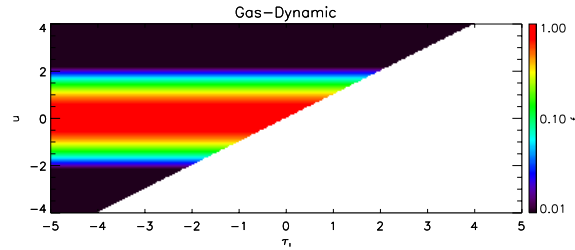


Electric field maintains quasi-neutrality – retards electrons and accelerates ions into wake

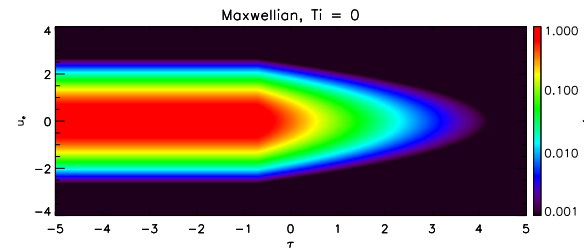
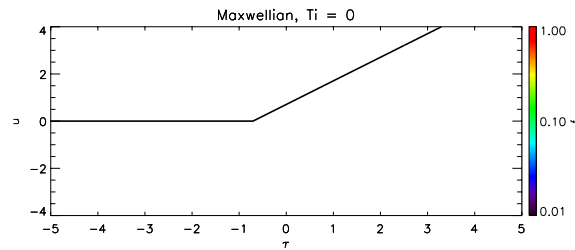


Parallel Expansion Theories

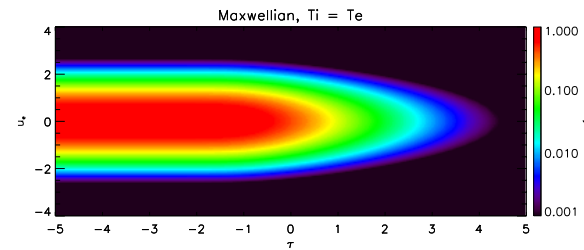
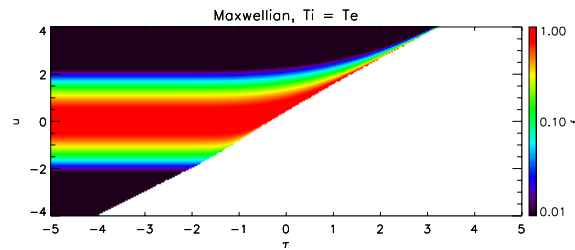
Gas-Dynamic



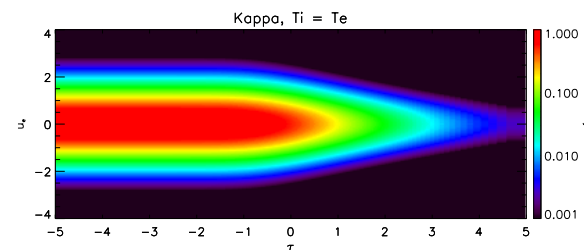
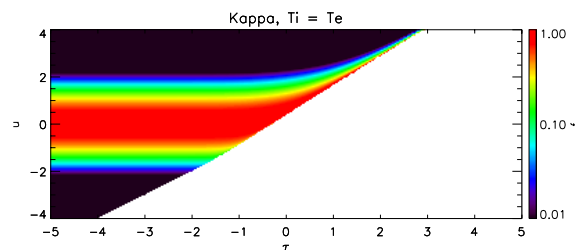
Cold Ion Plasma



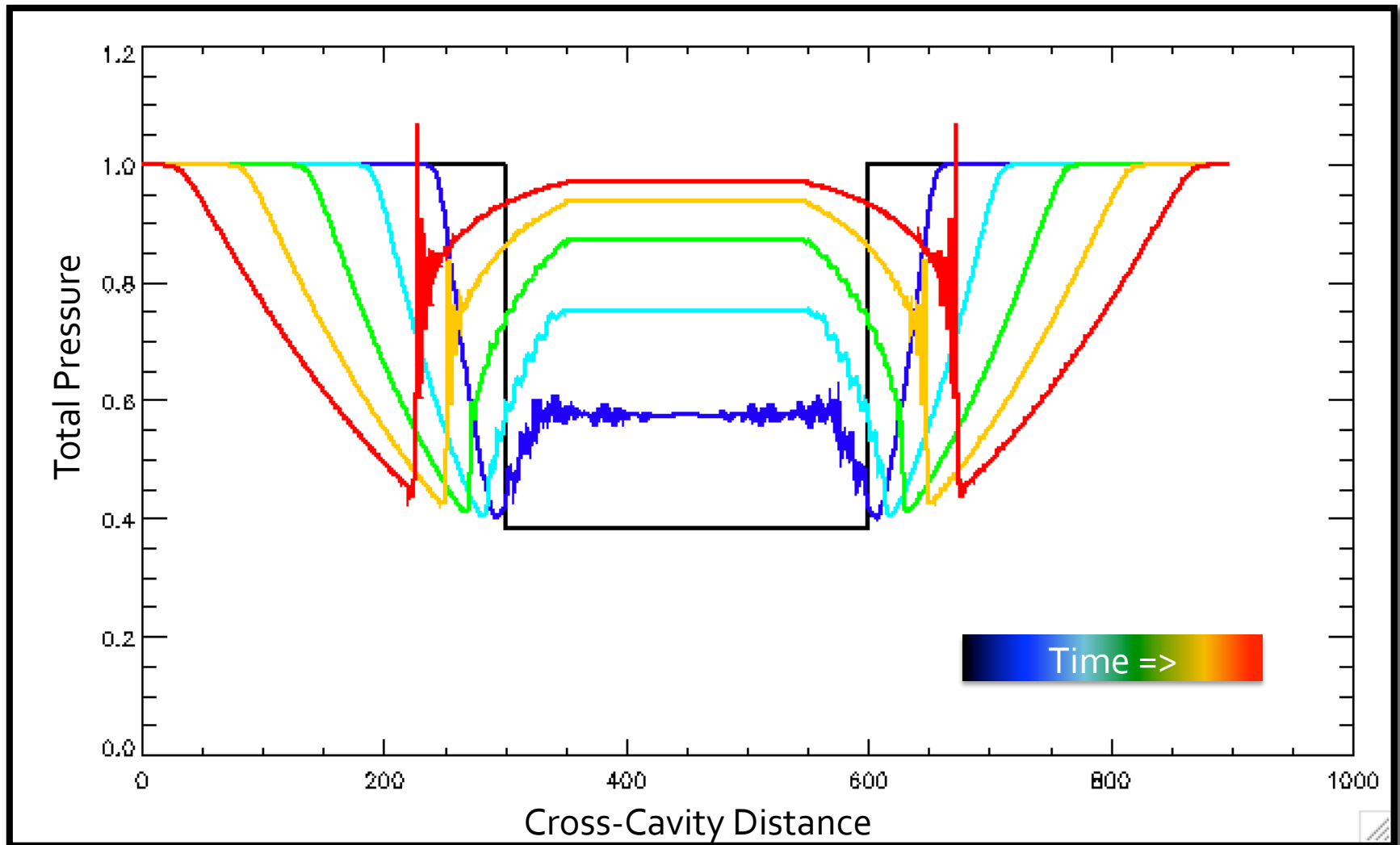
Warm Ions



Warm Ions, Kappa Electrons

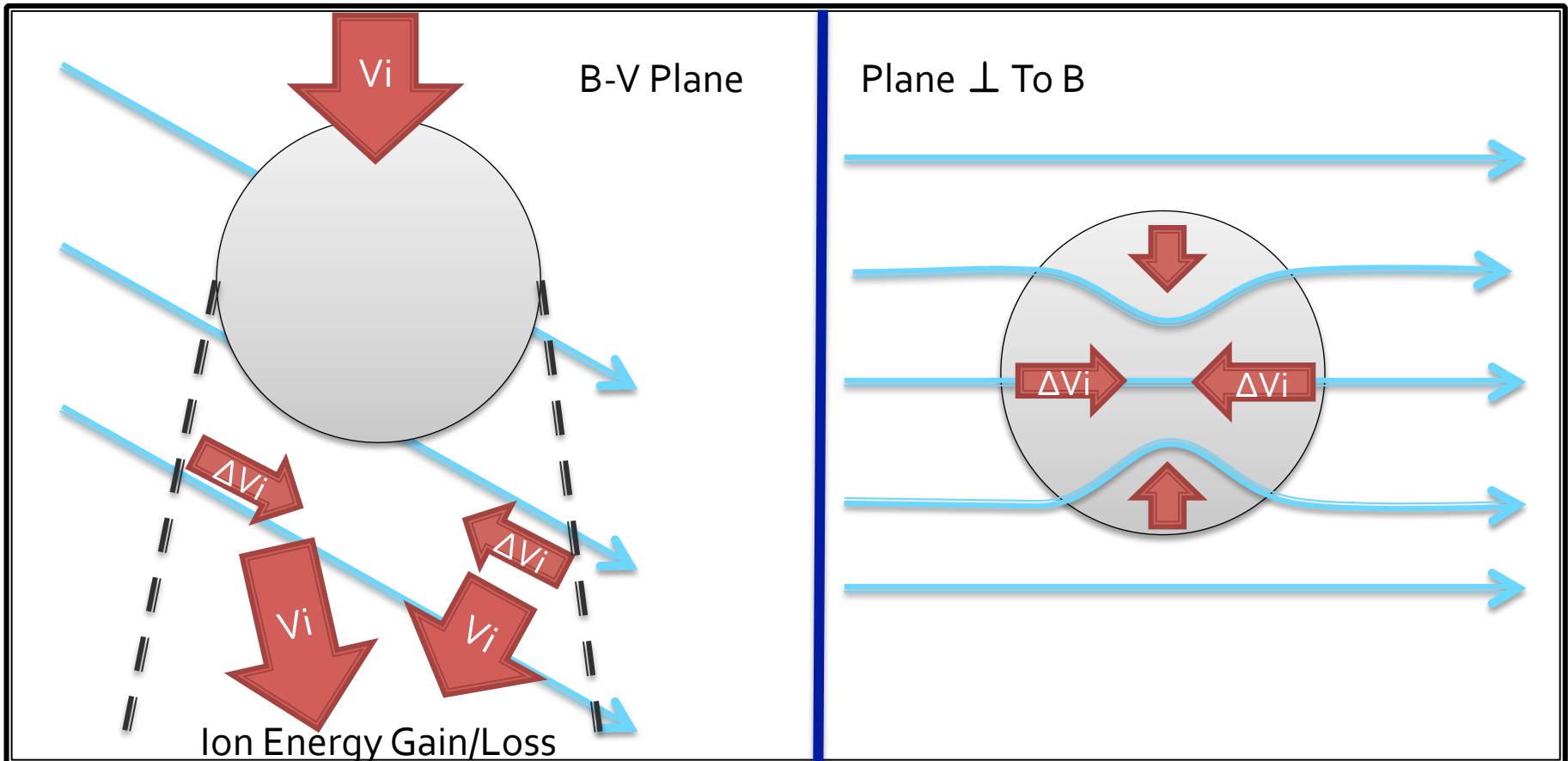


Perpendicular Expansion

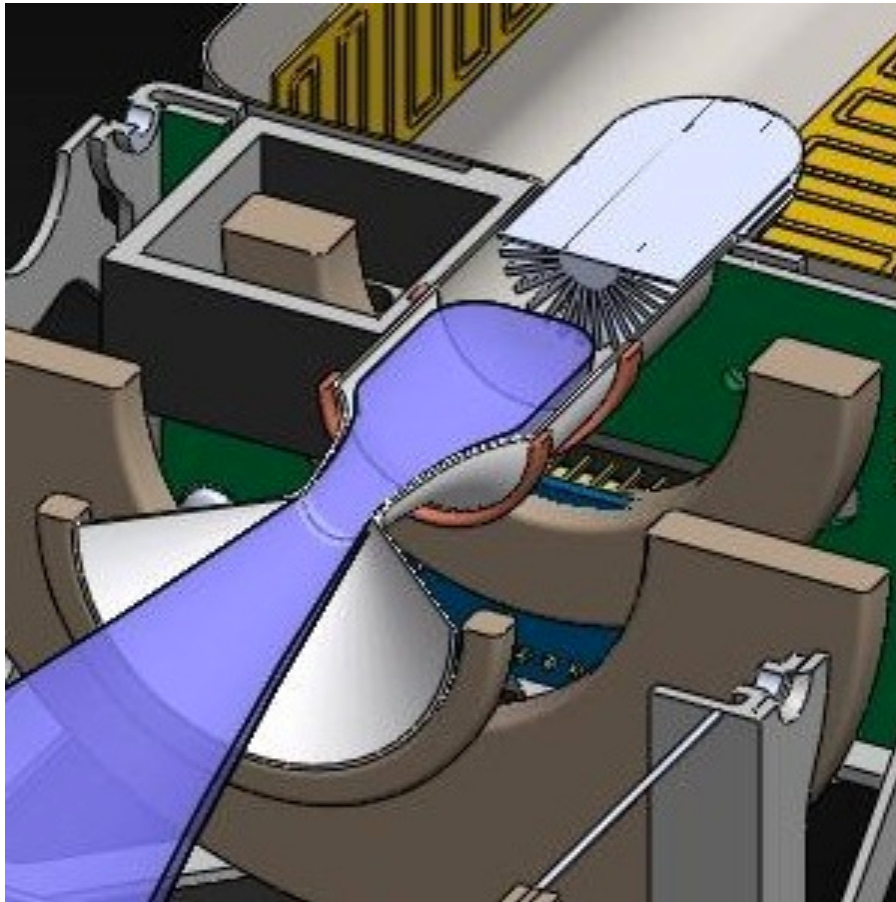


Role of Magnetic Field

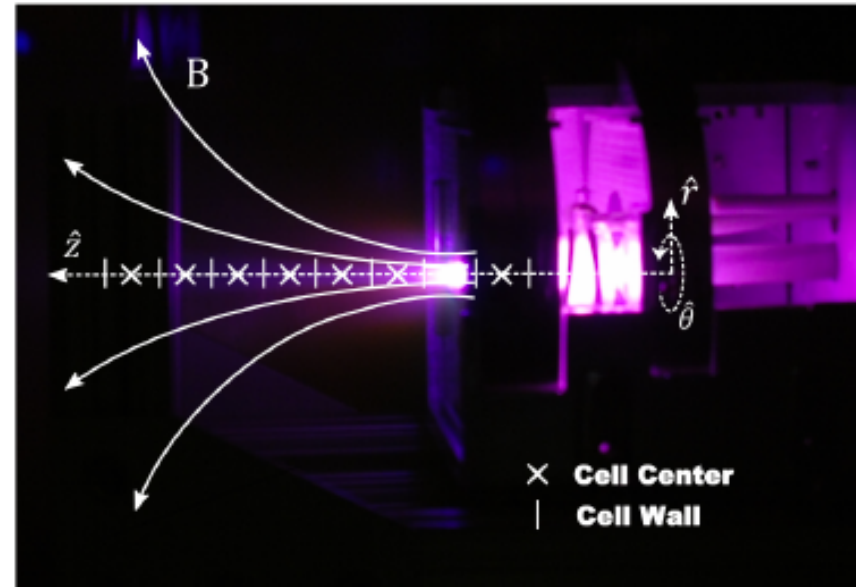
- $R_i \ll R_m \Rightarrow$ particles flow along magnetic field
- If [particle pressure]/[magnetic pressure] significant, magnetic field can be compressed by perpendicular flows



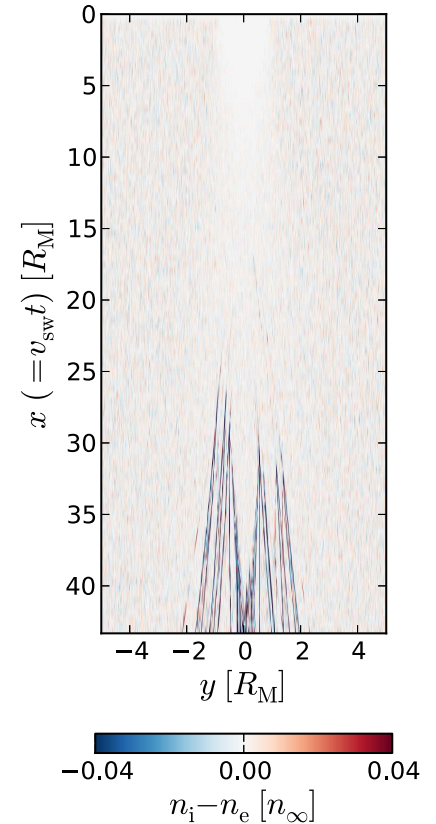
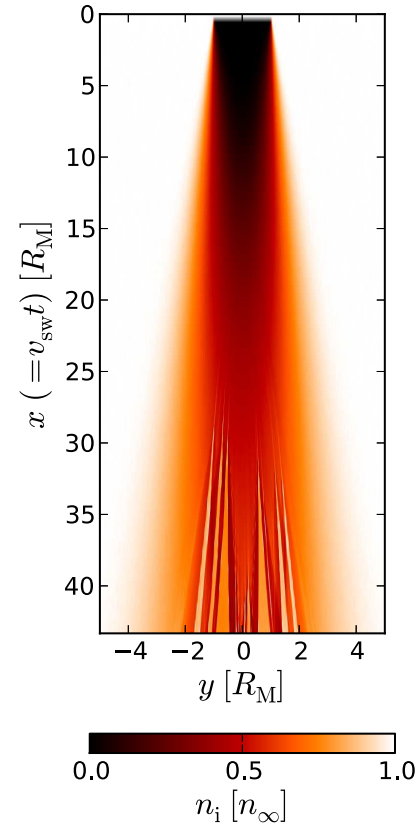
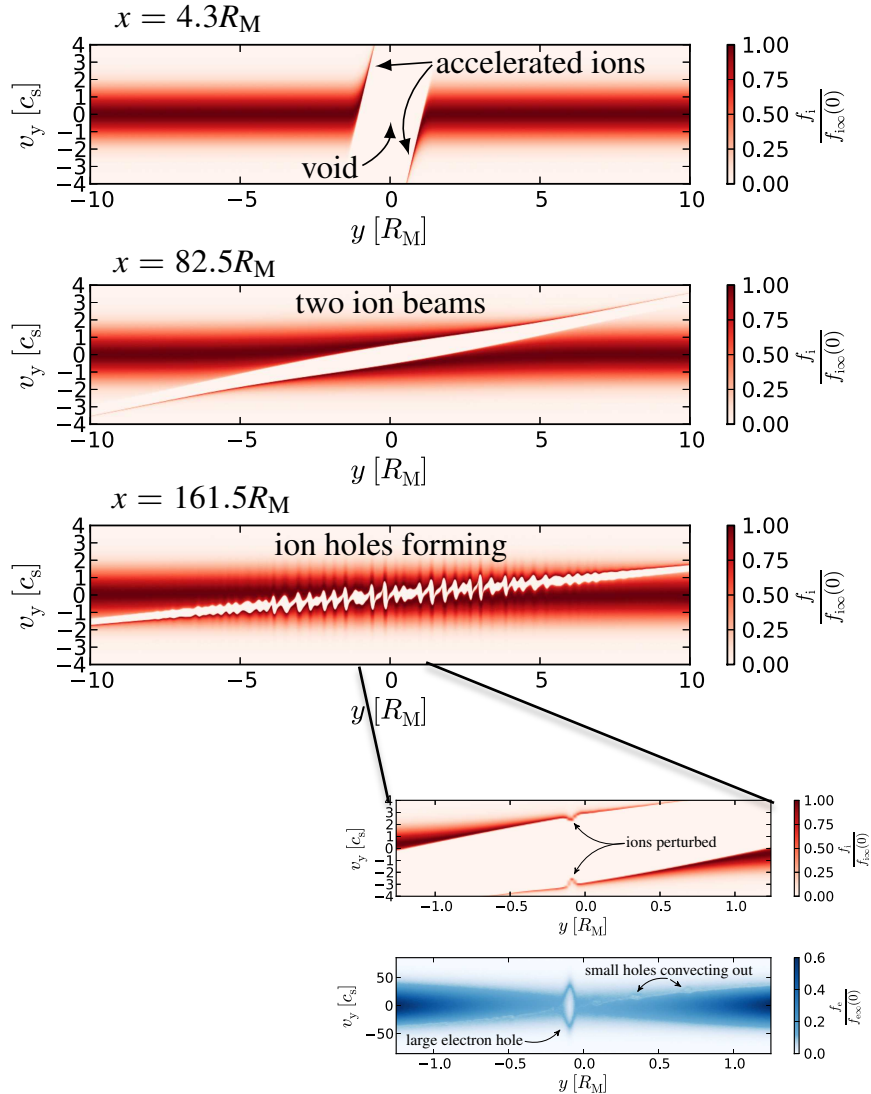
Plasma Expansion into a Vacuum



“Cubesat Ambipolar Thruster”

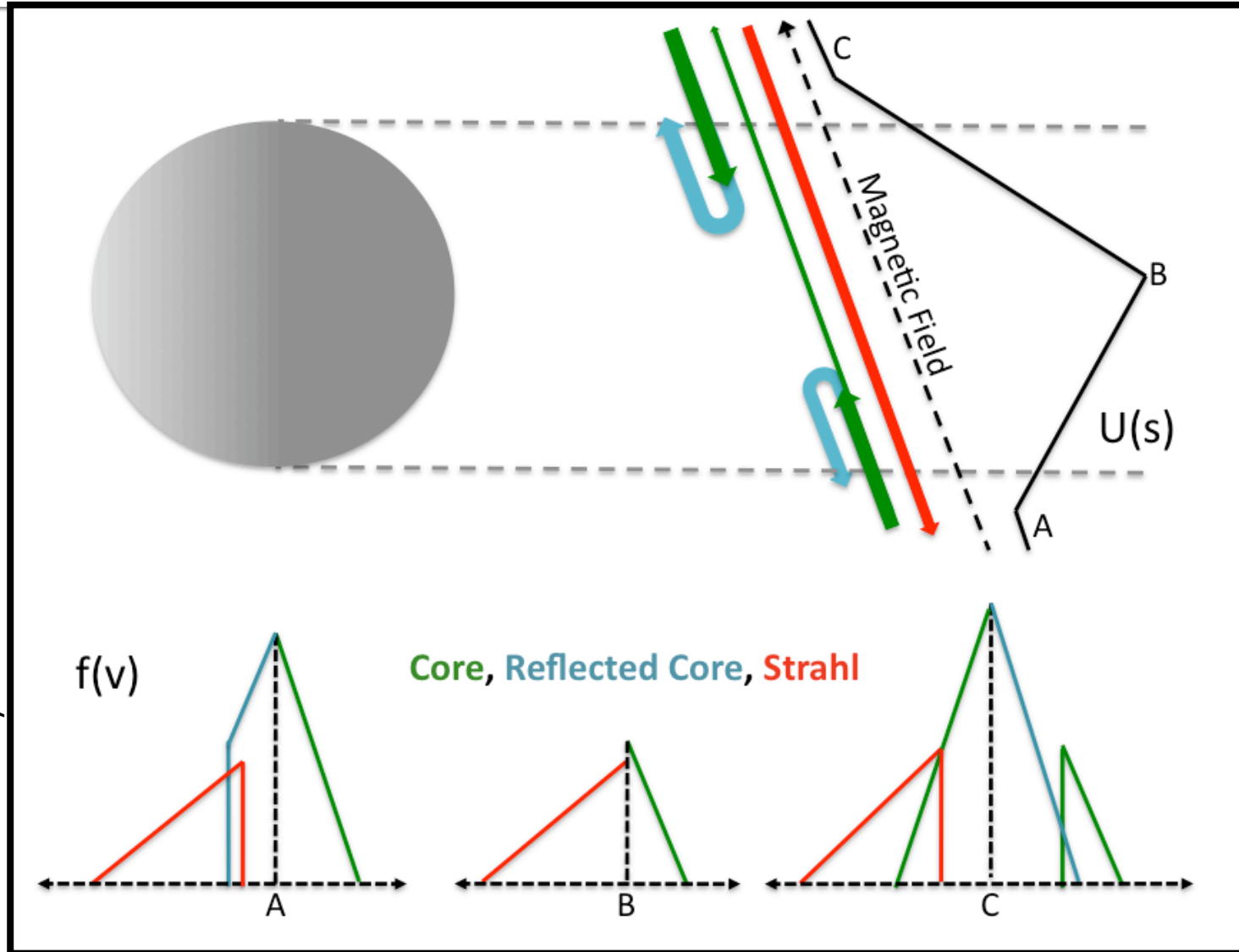


The Wake: An Instability Generator



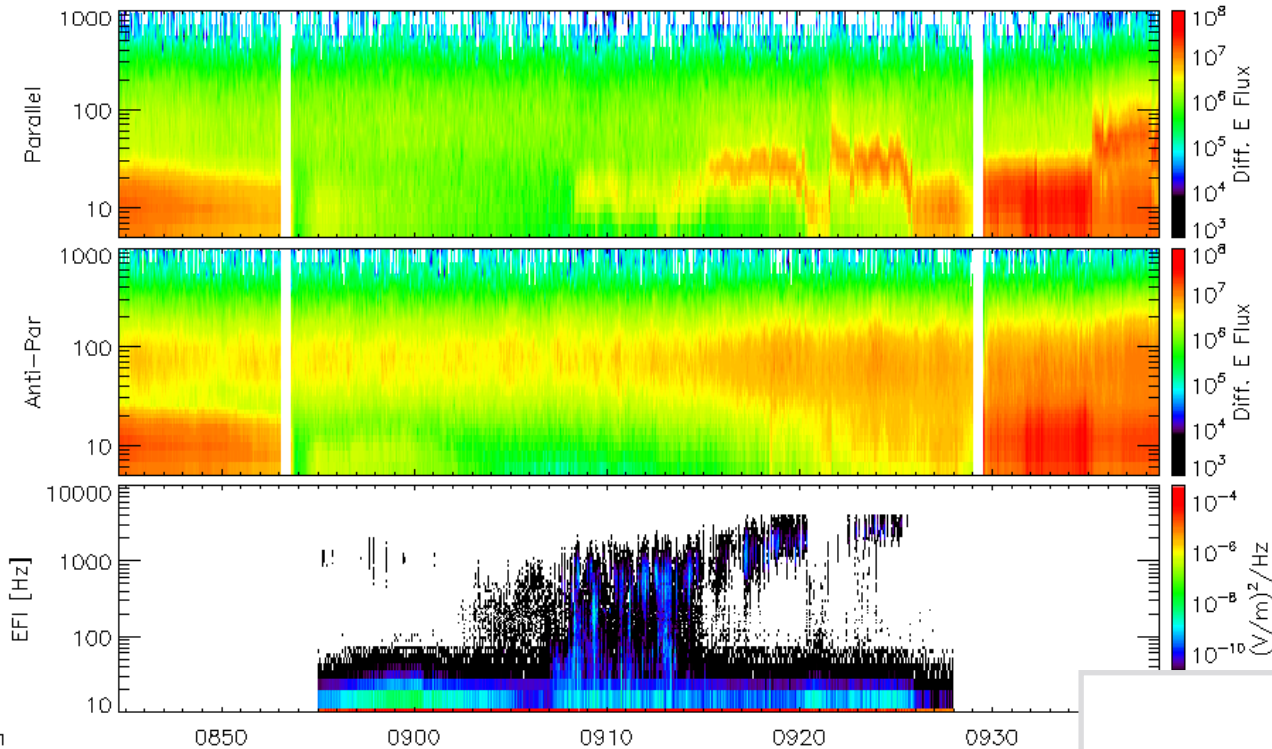
Haakonsen et al., 2015

Velocity-Filtered Electrons

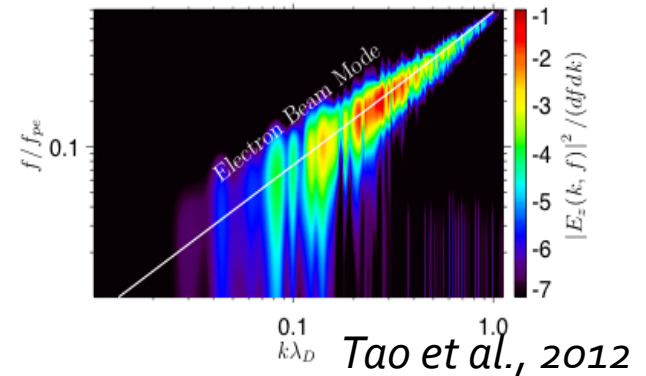
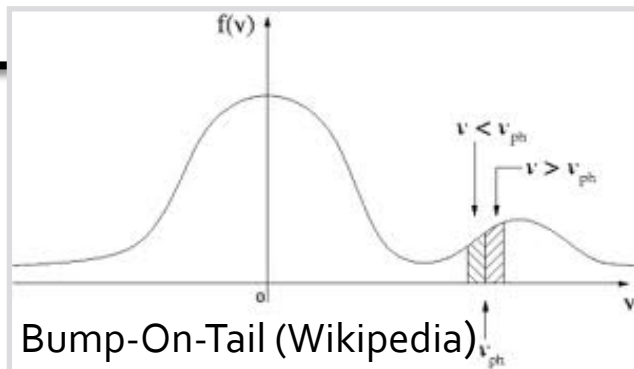


Halekas et al., 2011

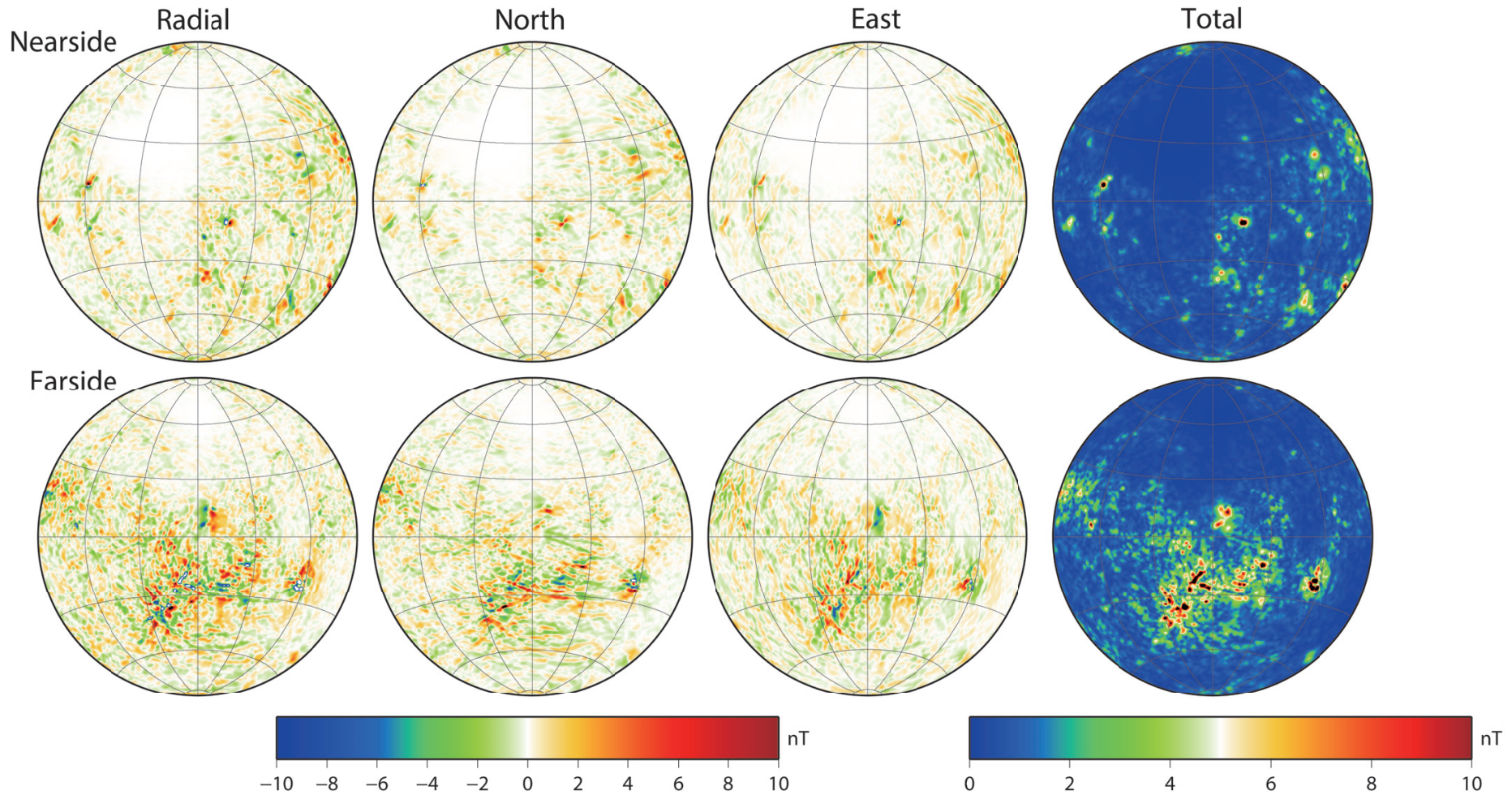
Streaming Instabilities



Halekas et al., 2011



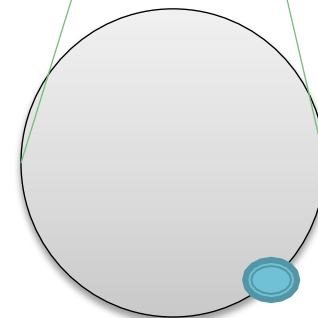
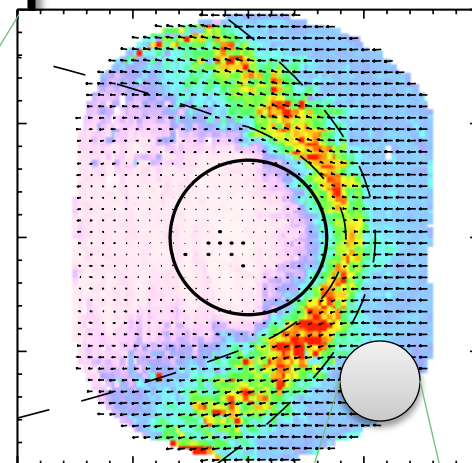
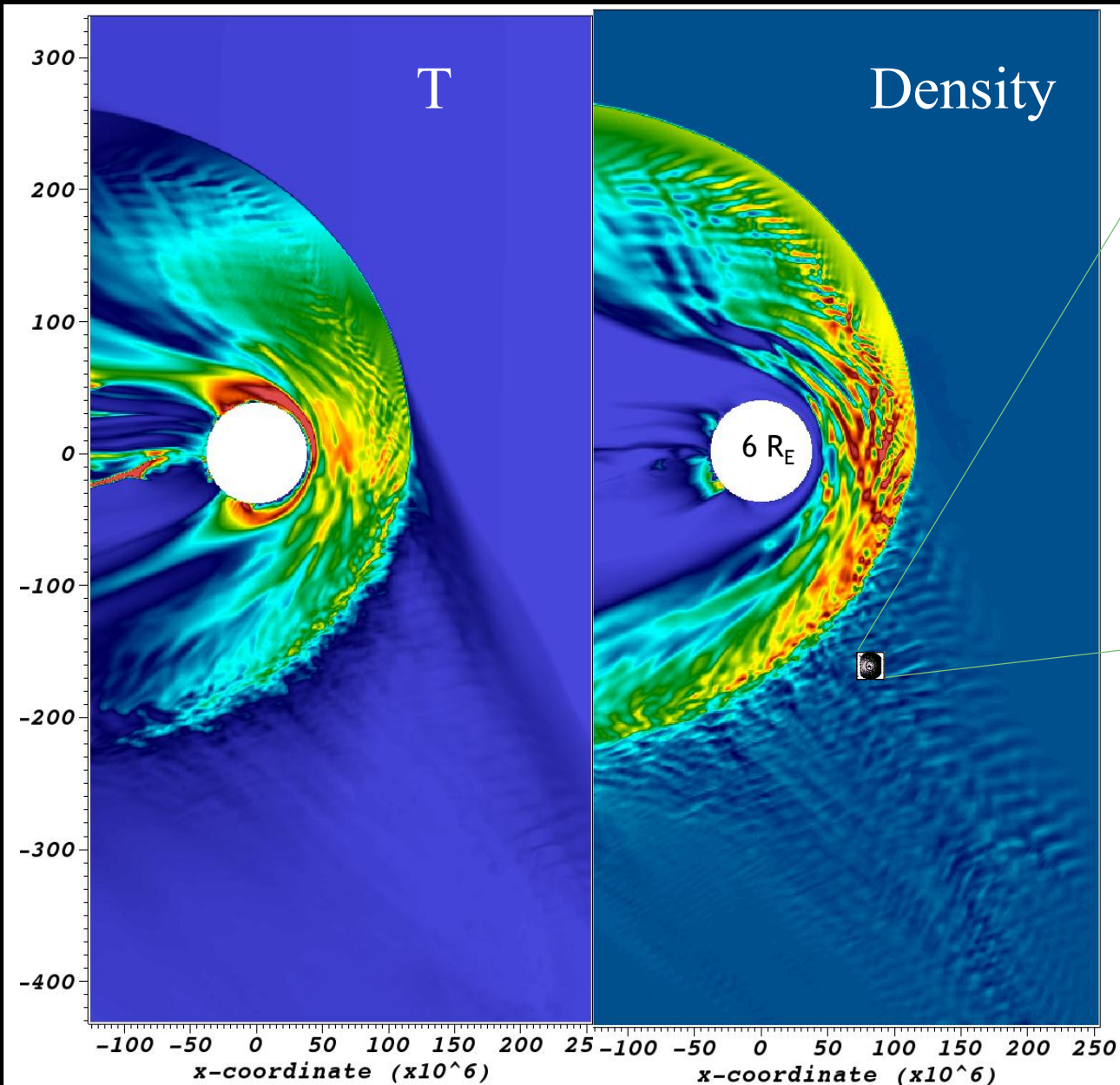
Lunar Magnetic Anomalies



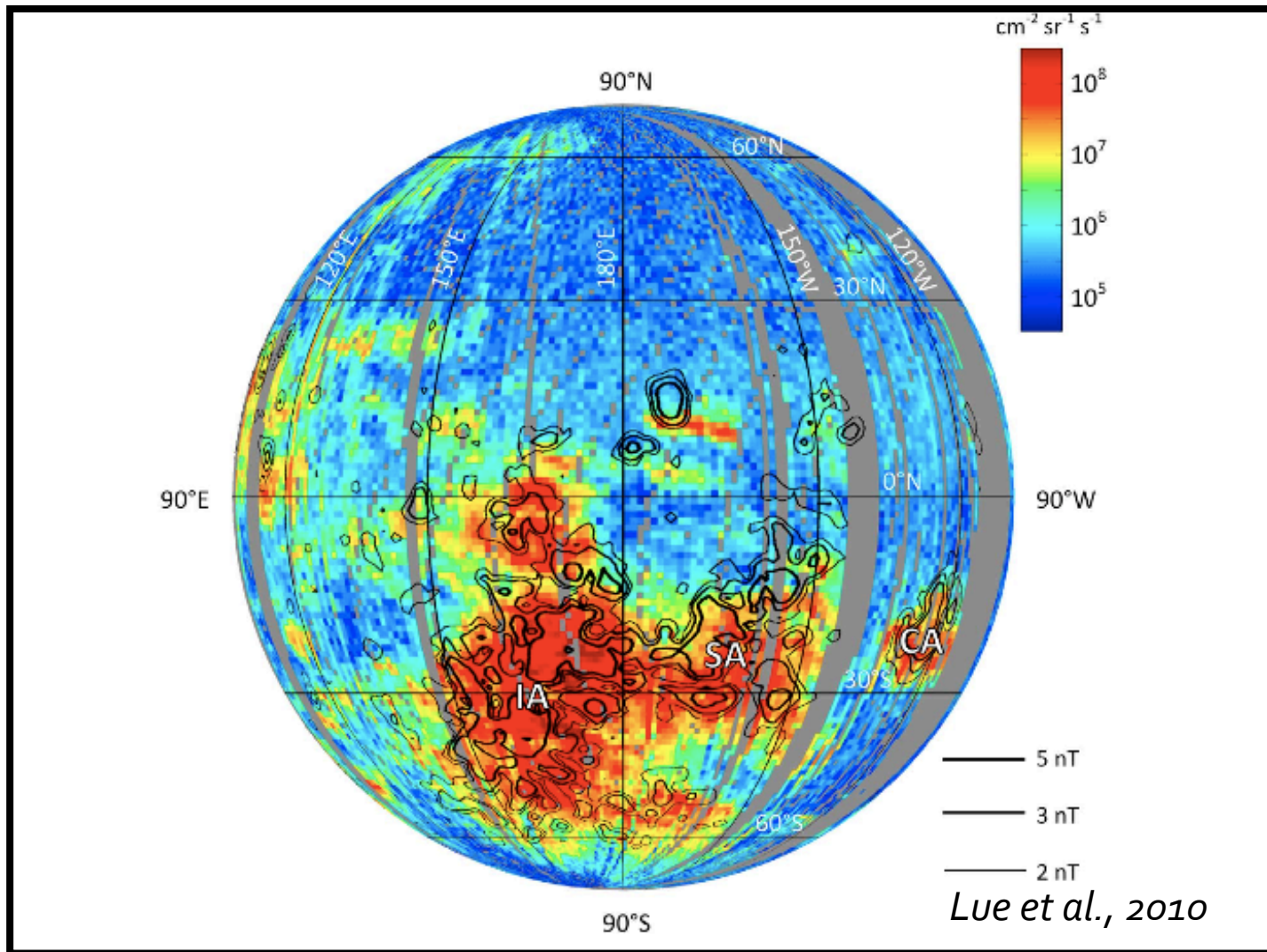
30 km altitude

[Tsunakawa et al., 2015]

The Moon is Small

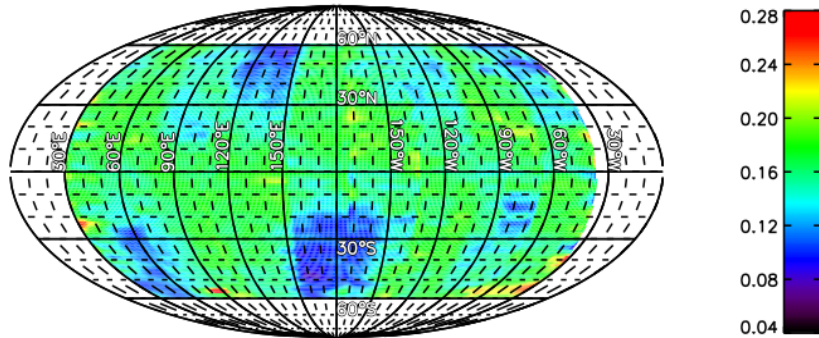


Solar Wind Reflection

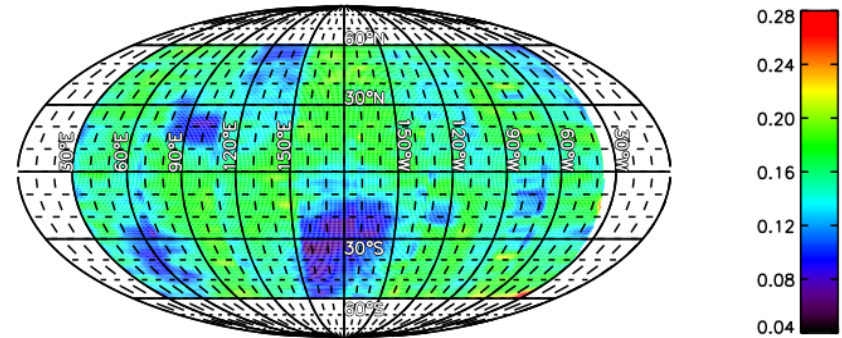


Solar Wind Reflection

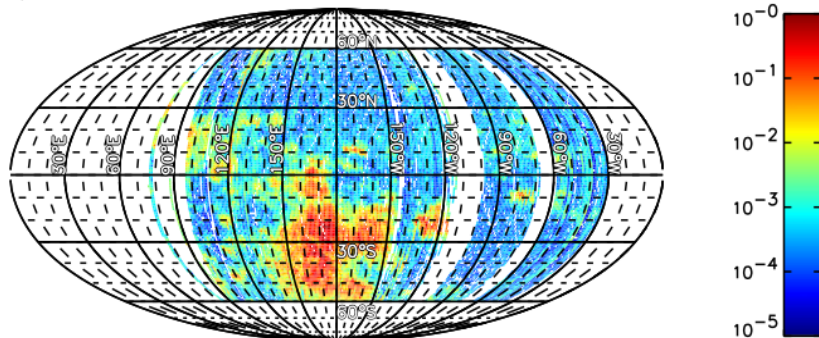
a) Low energy ($<30\% E_{\text{solar wind}}$) ENAs



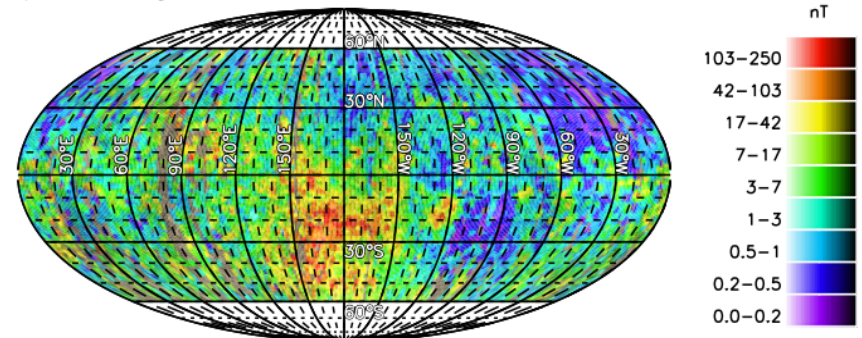
b) High energy ($>30\% E_{\text{solar wind}}$) ENAs



e) Proton deflection ratio

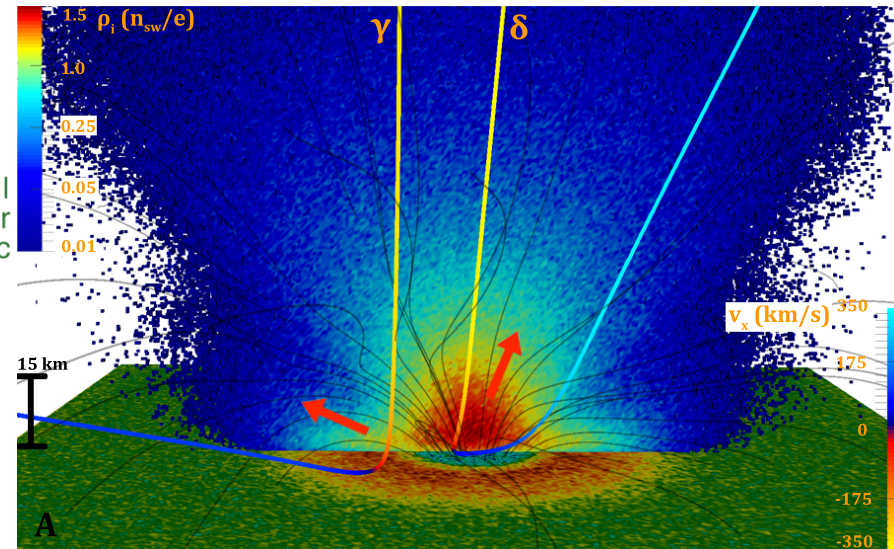
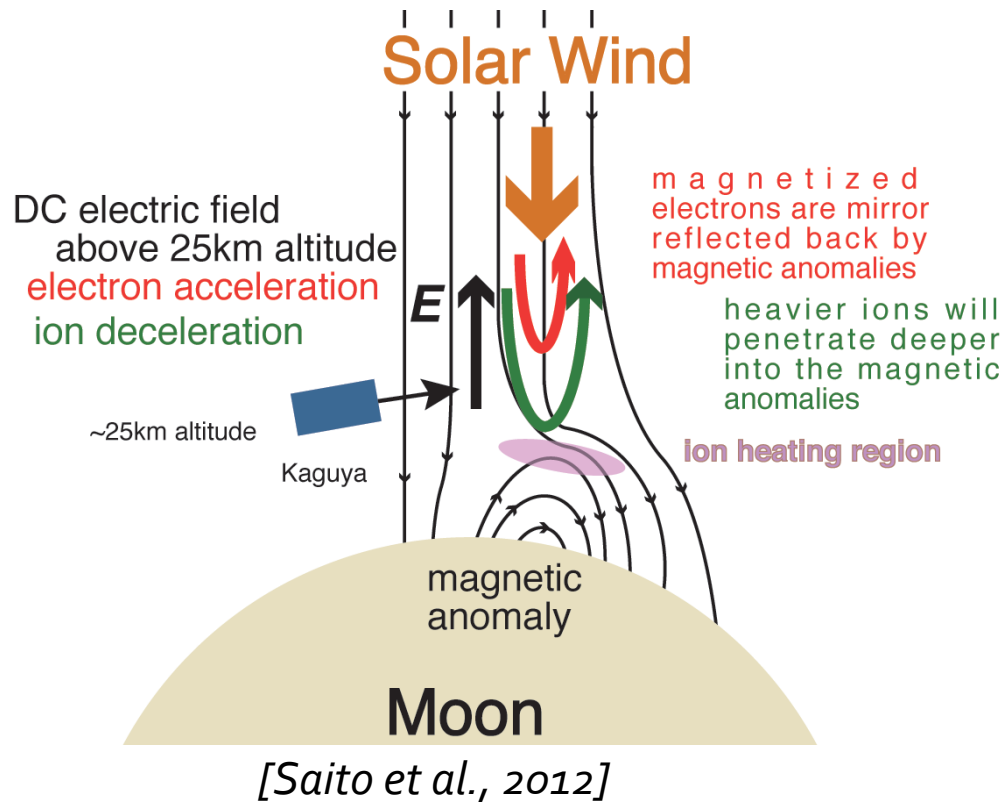


f) Measured magnetic surface field



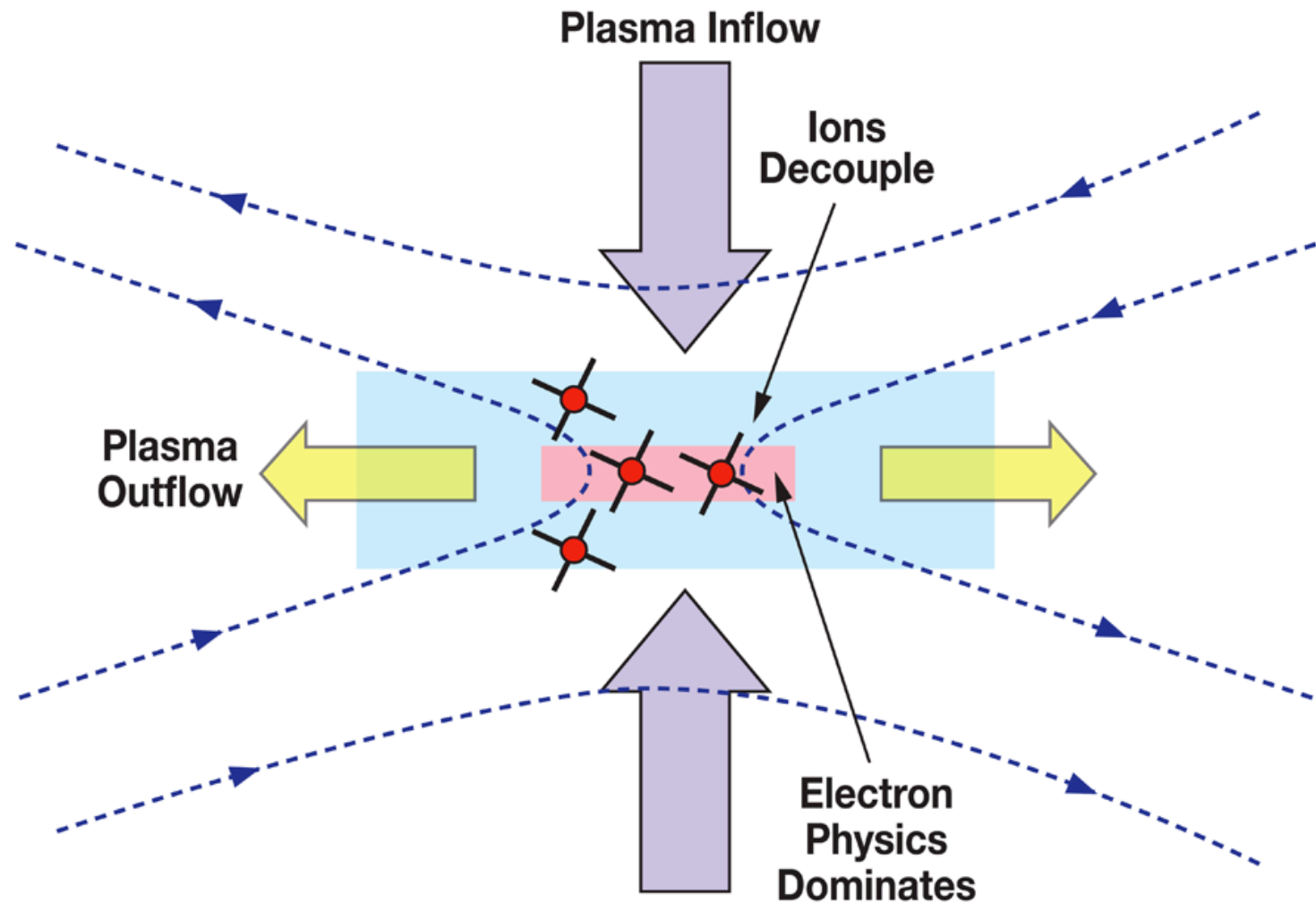
Low Altitude Microphysics

It's all in the E!



[Deca and Divin, 2016] (and many others)

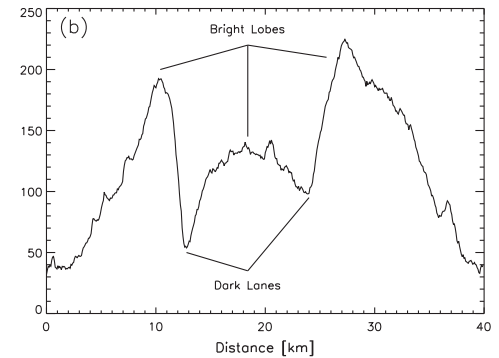
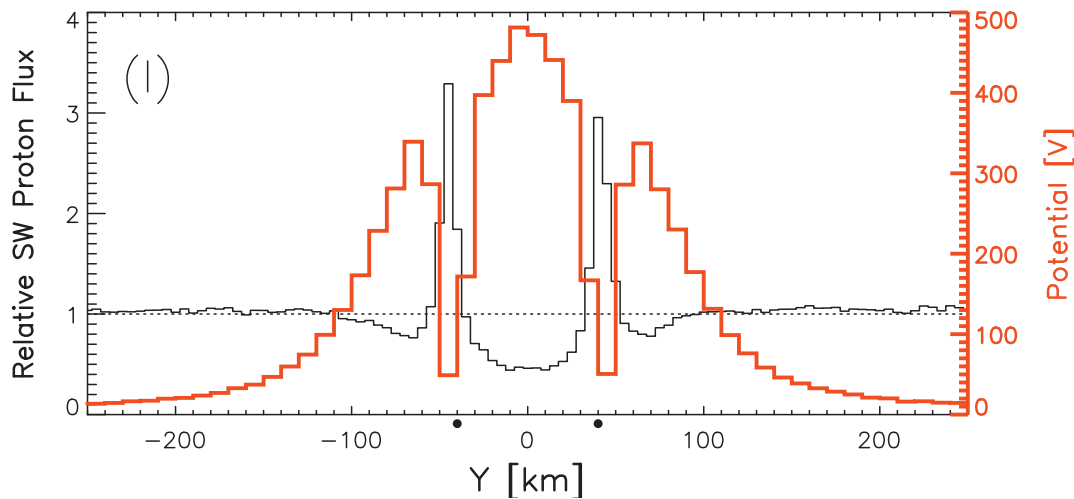
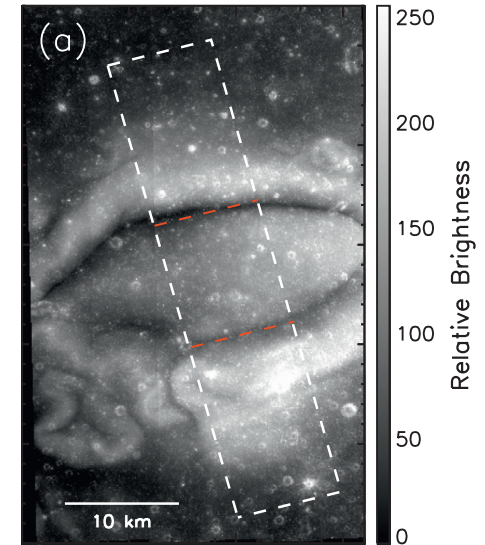
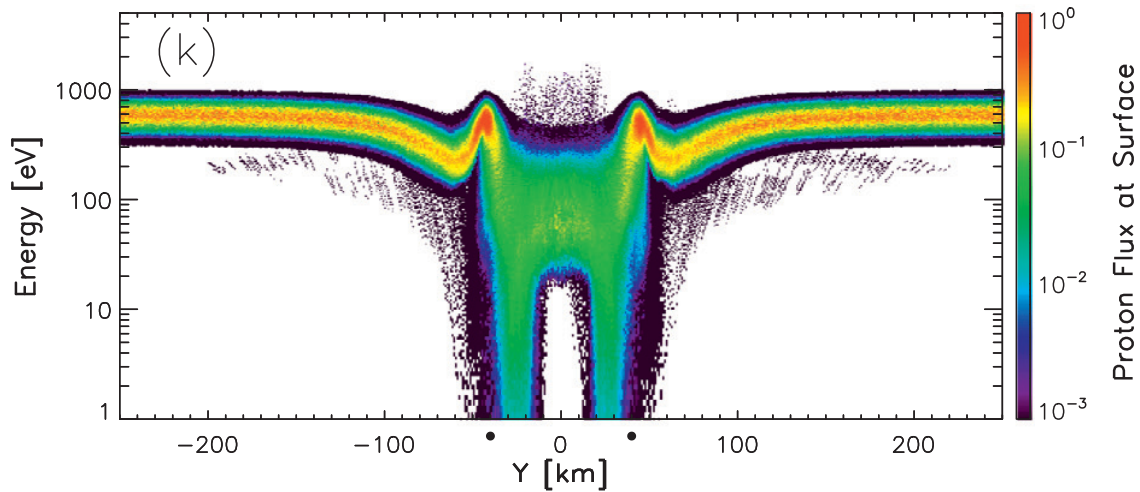
Electron-Scale Magnetic Gradients



Reflection: Observed vs. Simulated

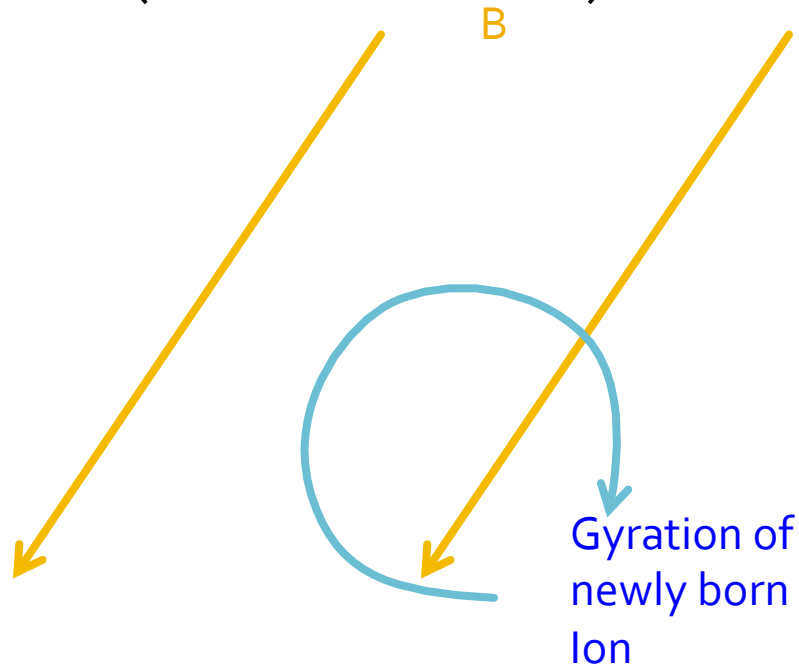
- Observed:
 - >50% locally [*Saito et al., 2010; Lue et al., 2011*]
- Simulated:
 - 10% [*Deca et al., 2014*]
 - <10%? [*Jarvinen et al., 2014*]
 - <5% [*Giacalone et al., 2015*]
 - 50% for 10,000 nT field [*Poppe et al., 2012*]
 - 50-100% in very small (sub-km) regions [*Zimmerman et al., 2014*]

Connecting to the Surface

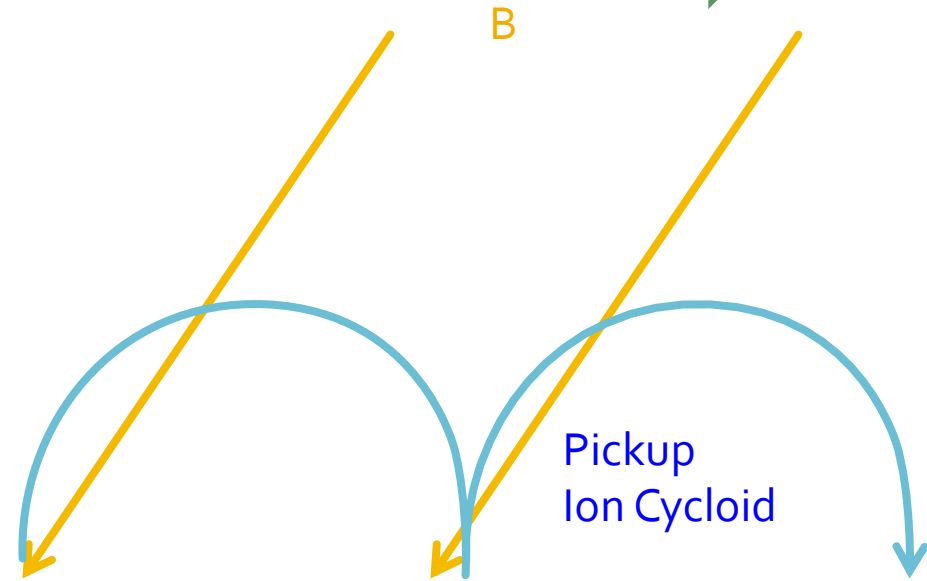
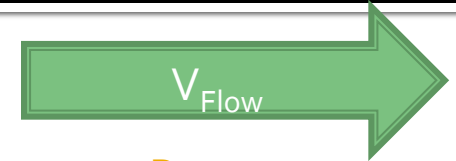


Pickup Ion Physics

Drift Reference Frame
(No flow across B)



$$V_{\text{initial}} = -V_{\text{Drift}}$$



Pickup
Ion Cycloid

$$V_{\text{initial}} = 0$$

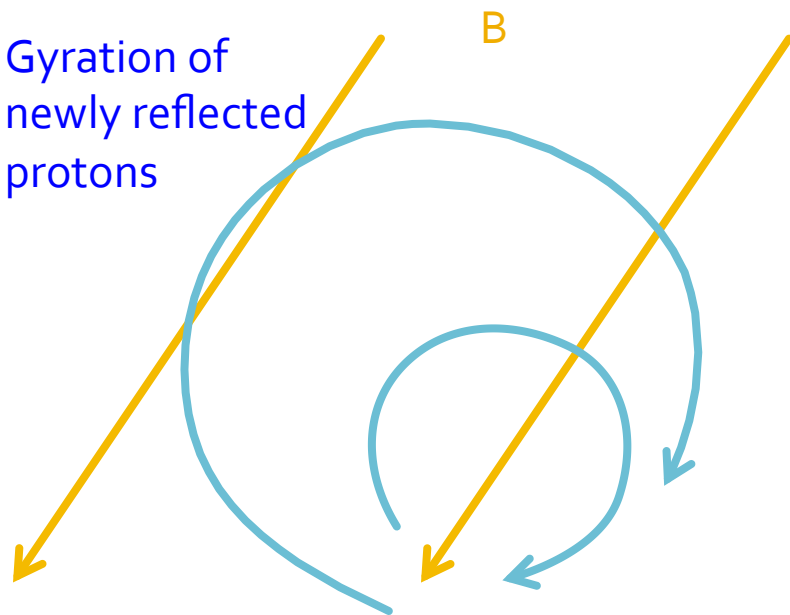
Motional Electric Field

$$-V_{\text{Flow}} \times B$$

Reflected Proton Physics

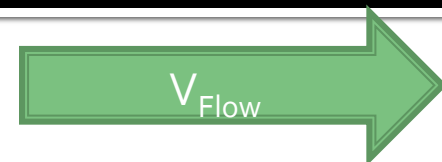
Drift Reference Frame
(No flow across B)

Gyration of
newly reflected
protons

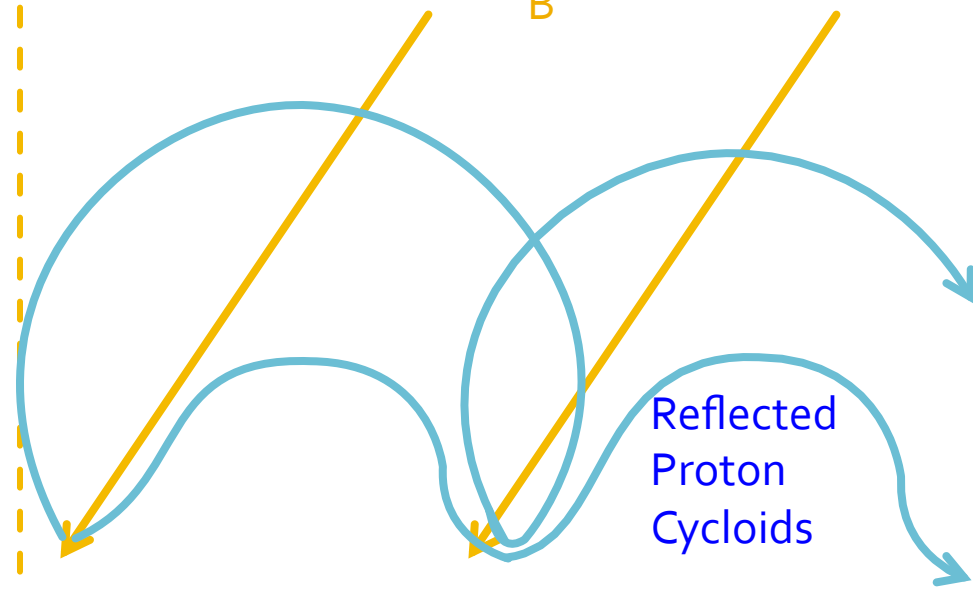


$$V_{initial} = -V_{Drift} + V_{Ref}$$

+ Constant $V_{||}$

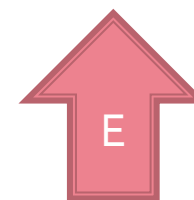


B



Reflected
Proton
Cycloids

$$V_{initial} = V_{Ref}$$

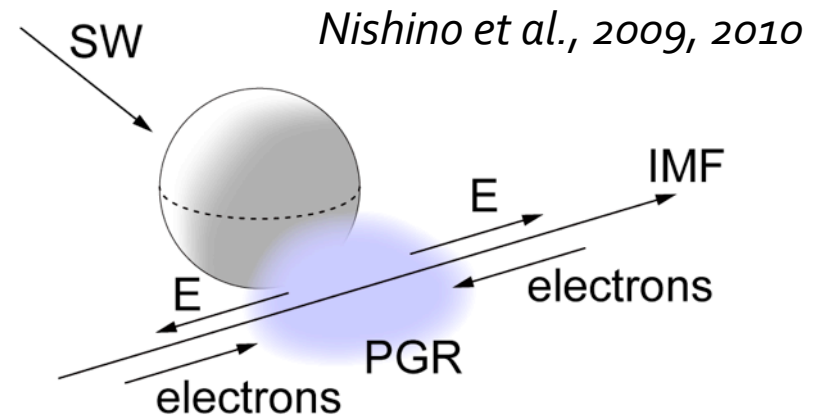
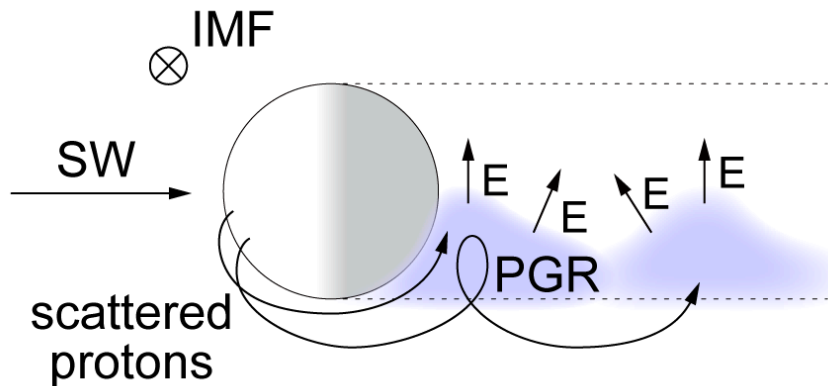
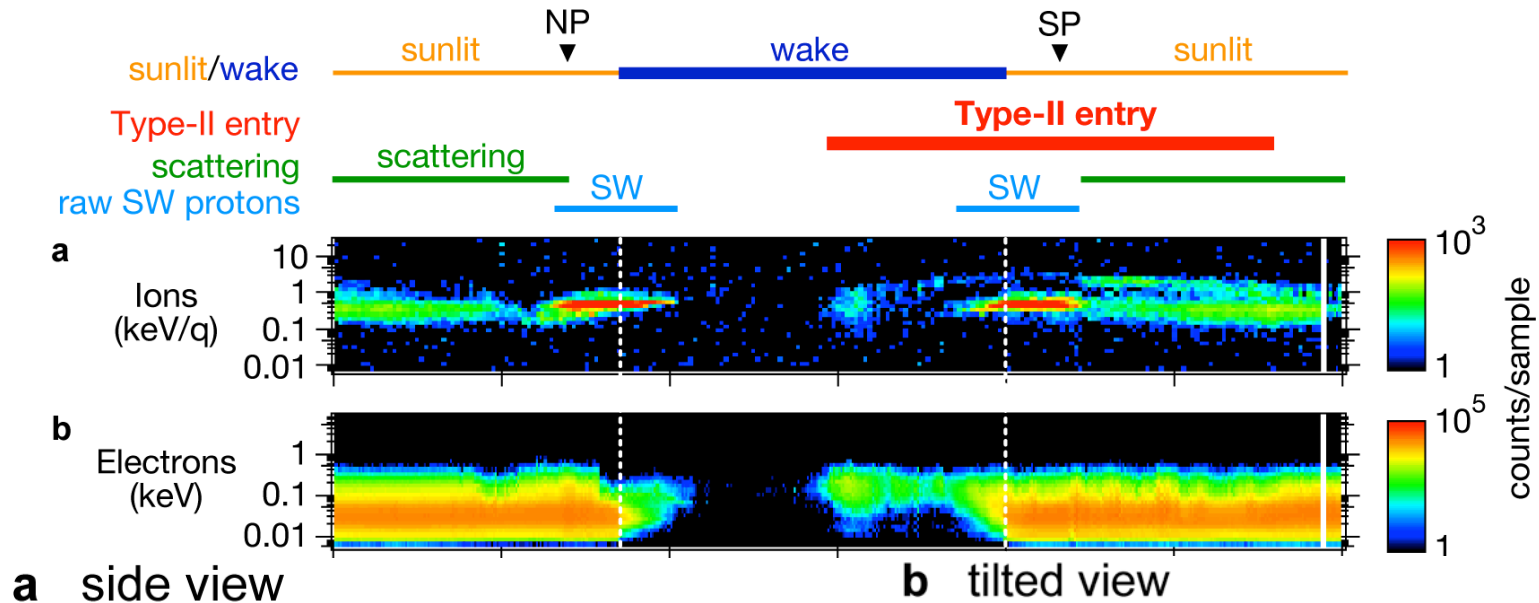


Motional Electric Field

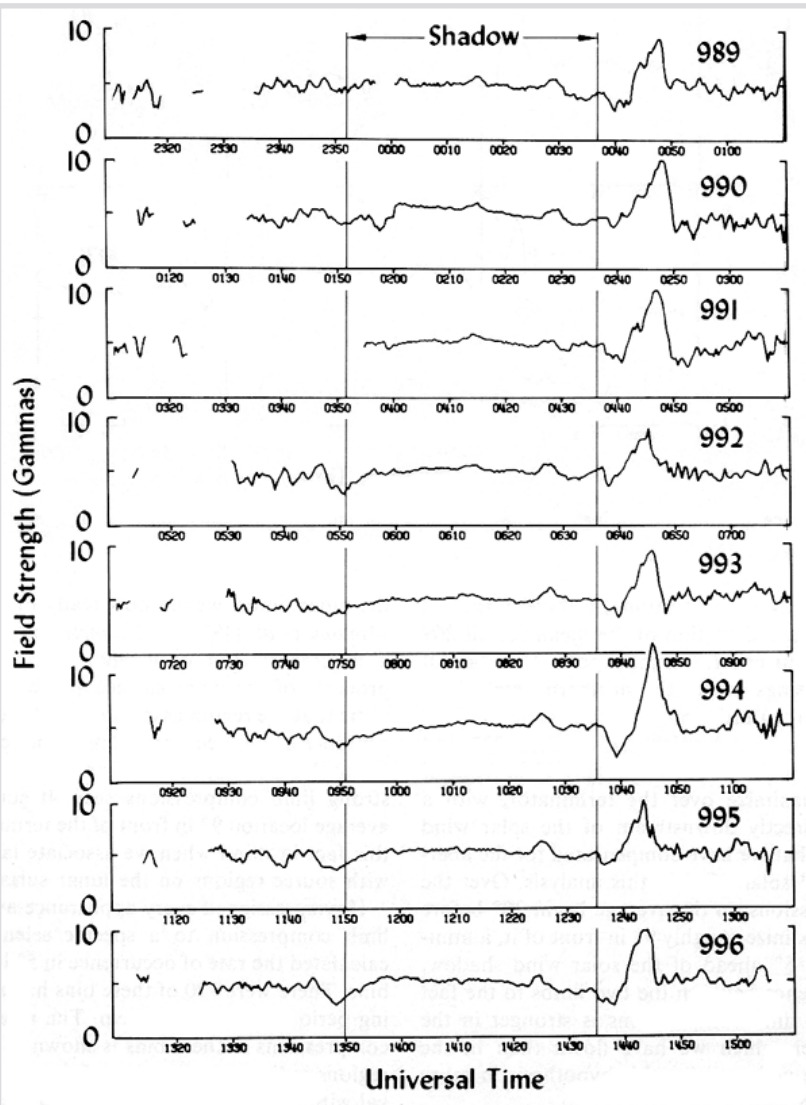
$$-V_{Flow} \times B$$

Type-II Entry

SELENE PACE and LMAG September 24, 2008 09:10-11:10 UT

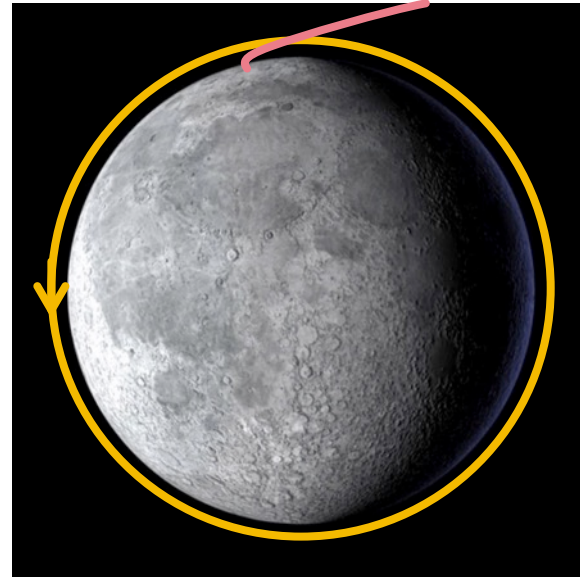


Macroscopic Interactions

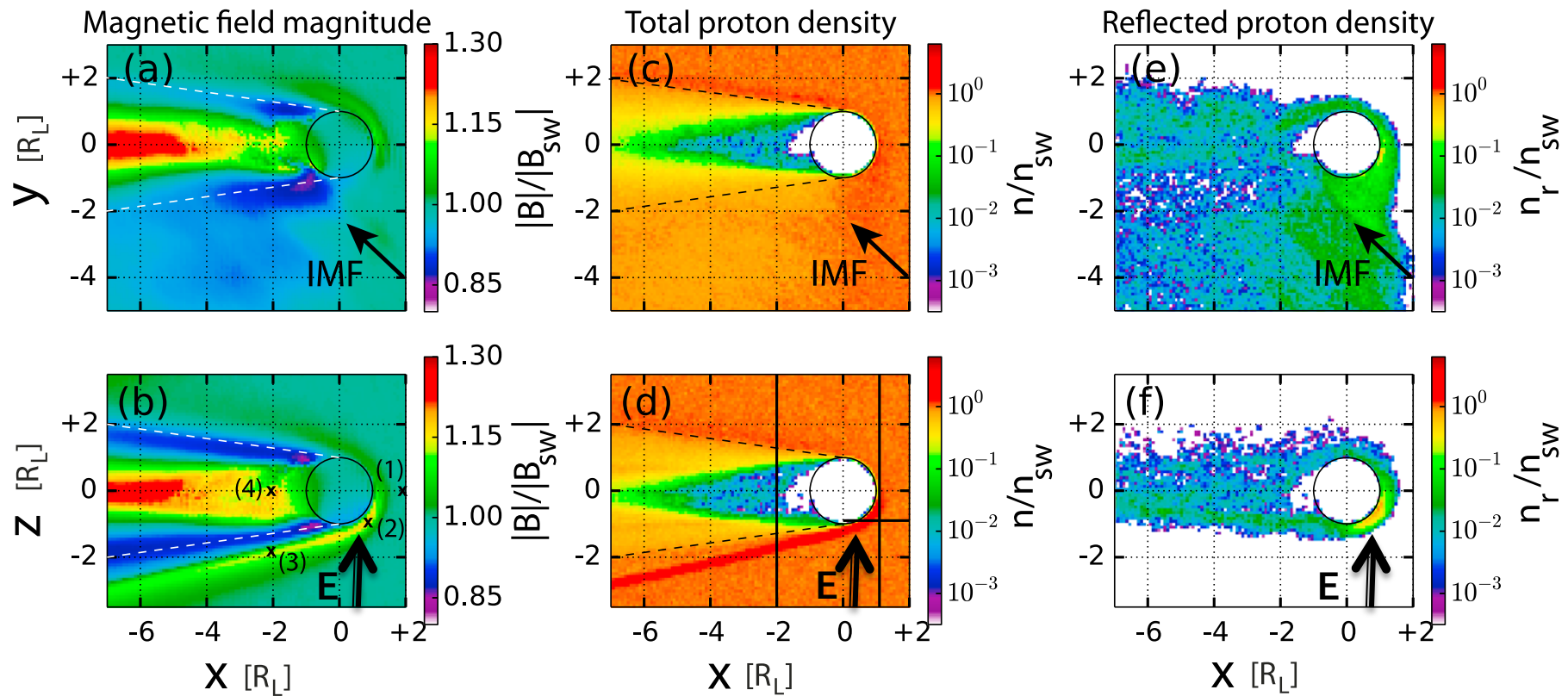


Limb Shocks? *Limb Compressions?*

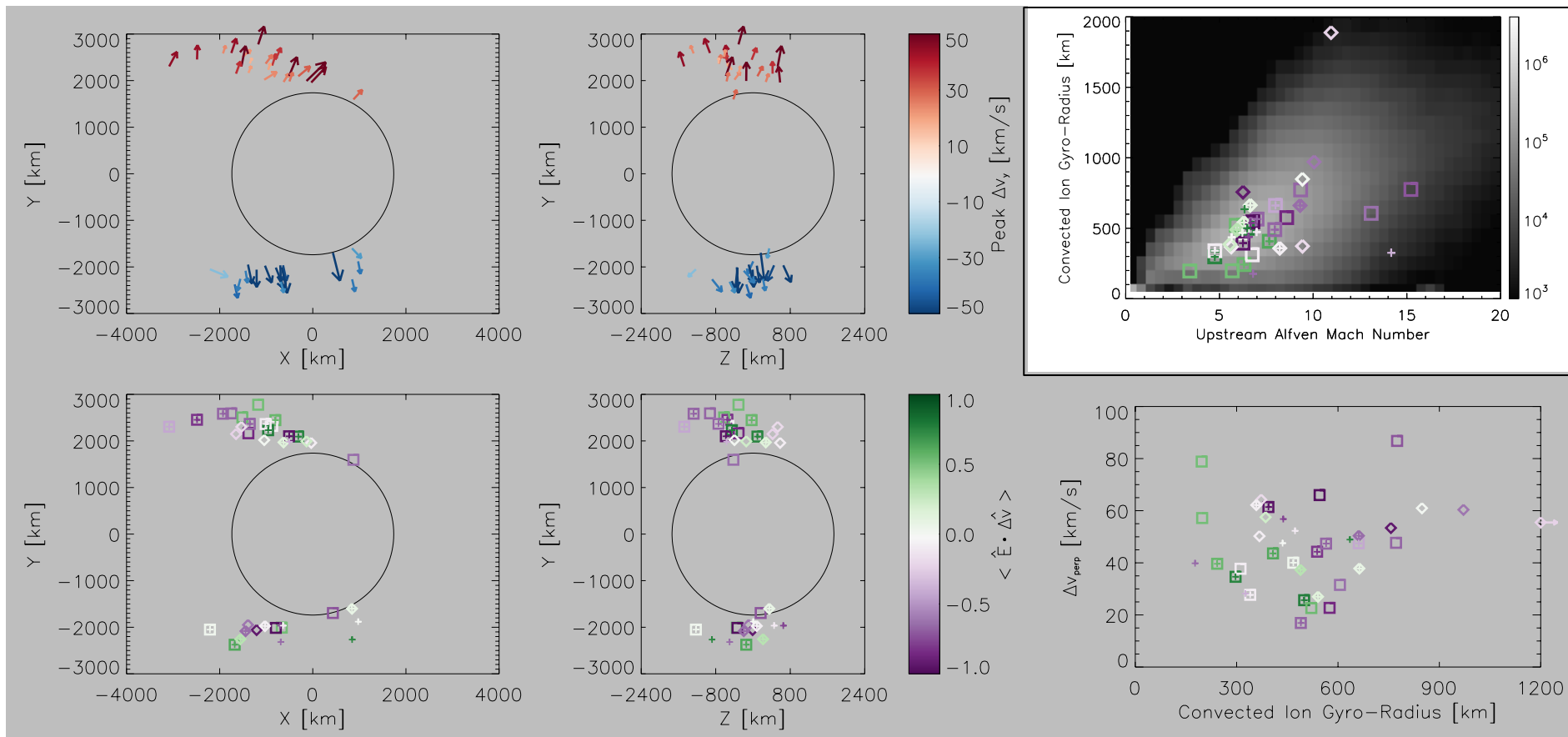
“there is no evidence that the plasma is shocked on passage through the features”
[Russell and Lichtenstein, 1975]



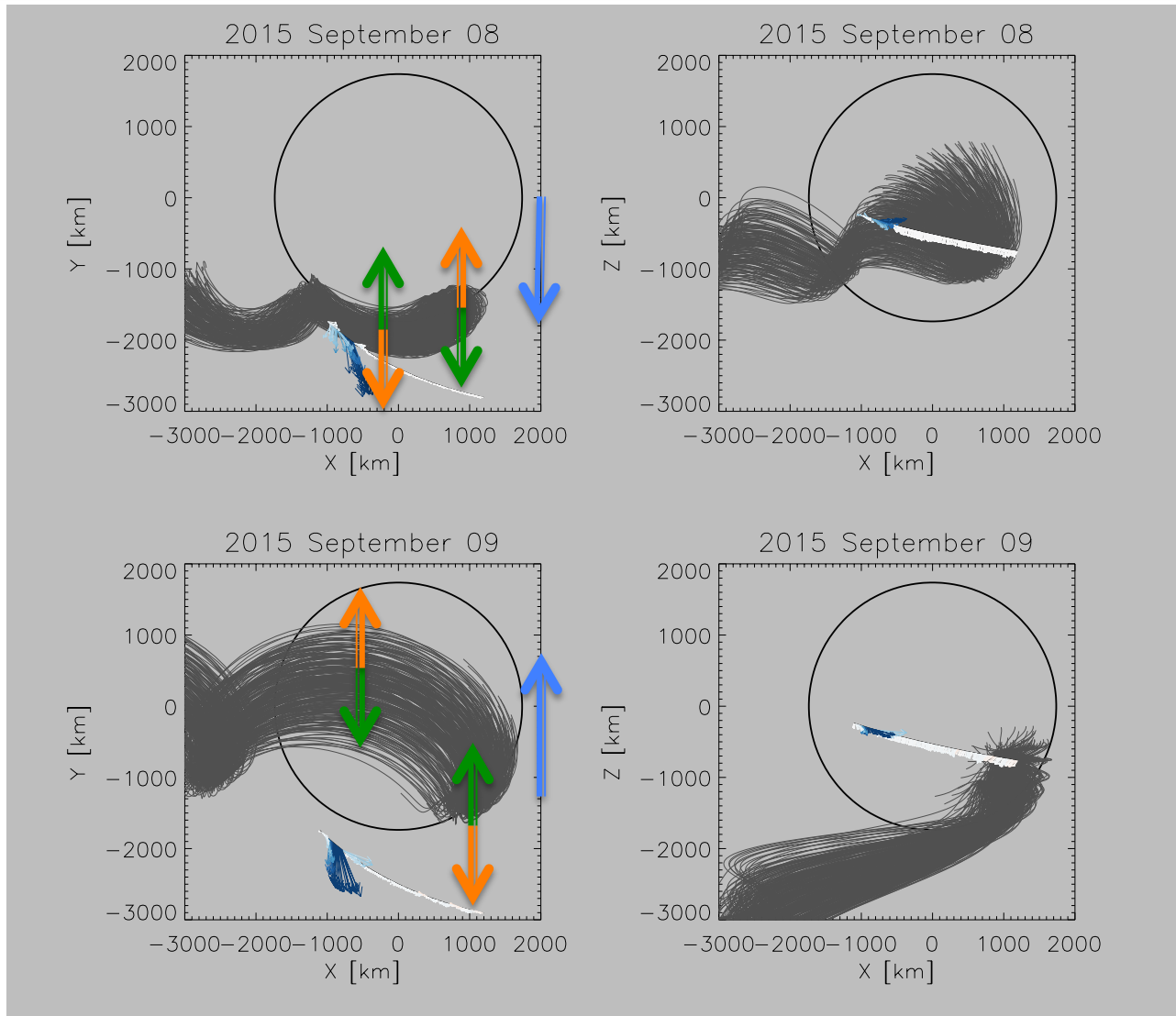
Connecting Microphysics to Macroscopic Effects



Two Kinds of "Limb Shocks"



Two Kinds of “Limb Shocks”

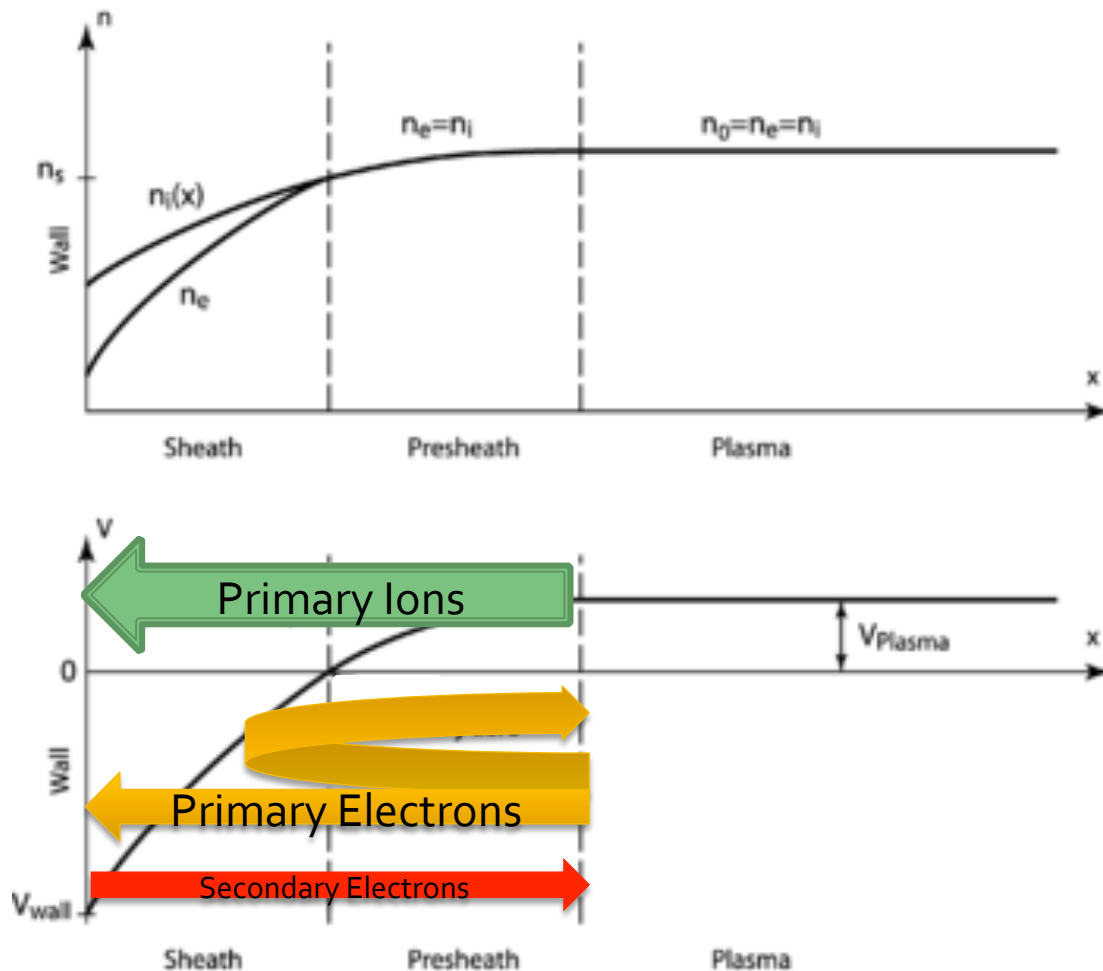


Upstream Motional
Electric Field

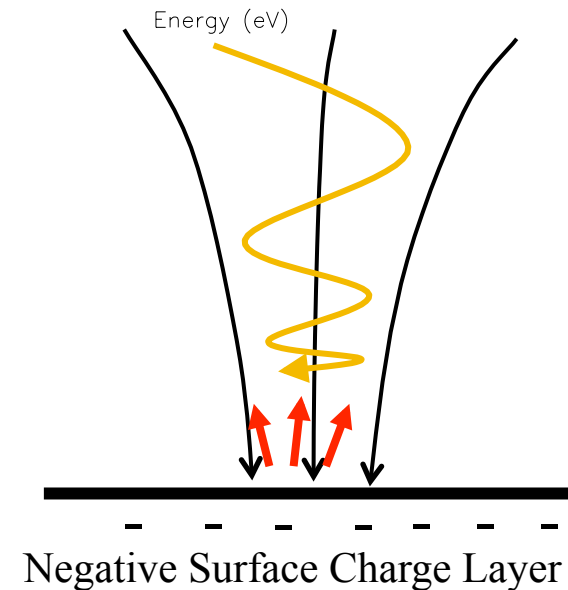
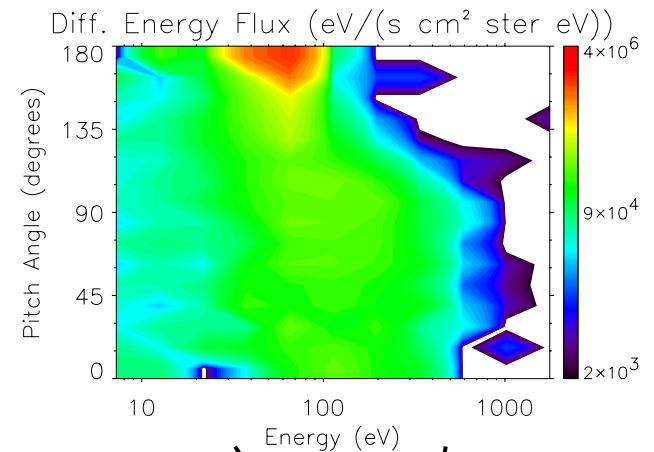
Force on Reflected
Protons

Force on Solar Wind

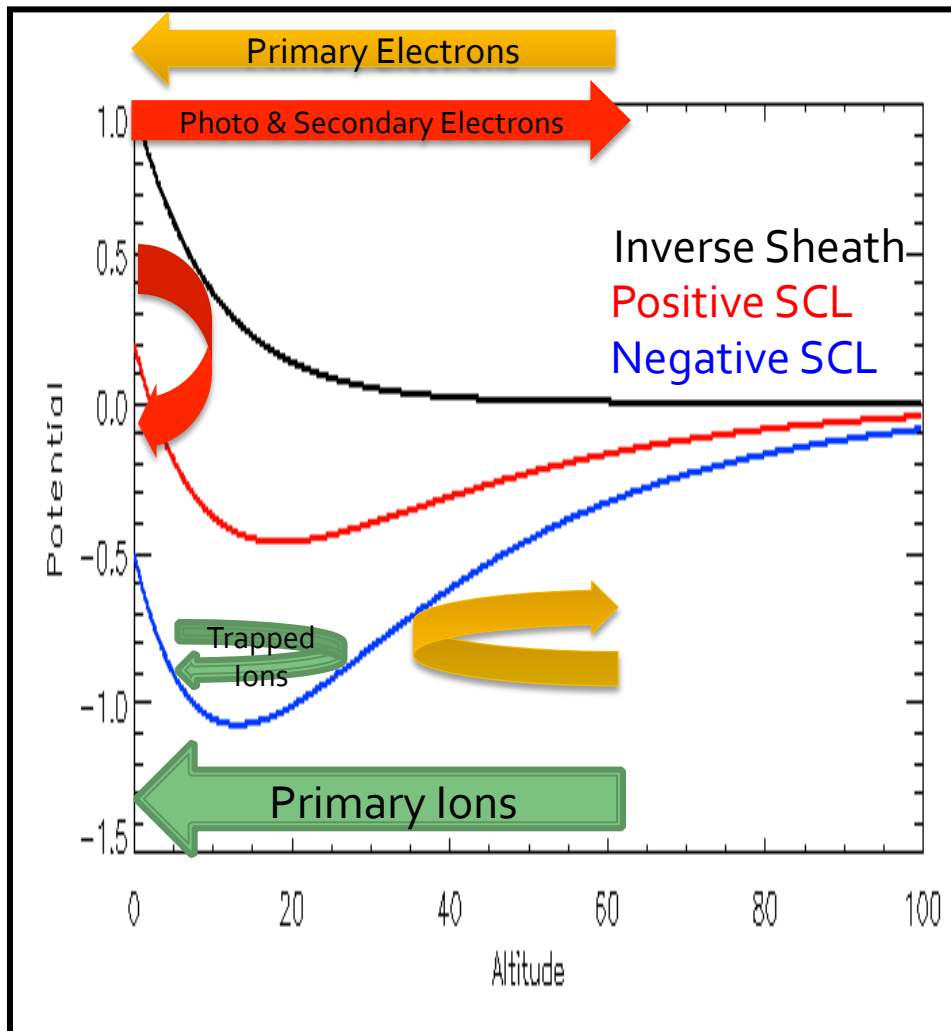
Night Side: Ion Sheath



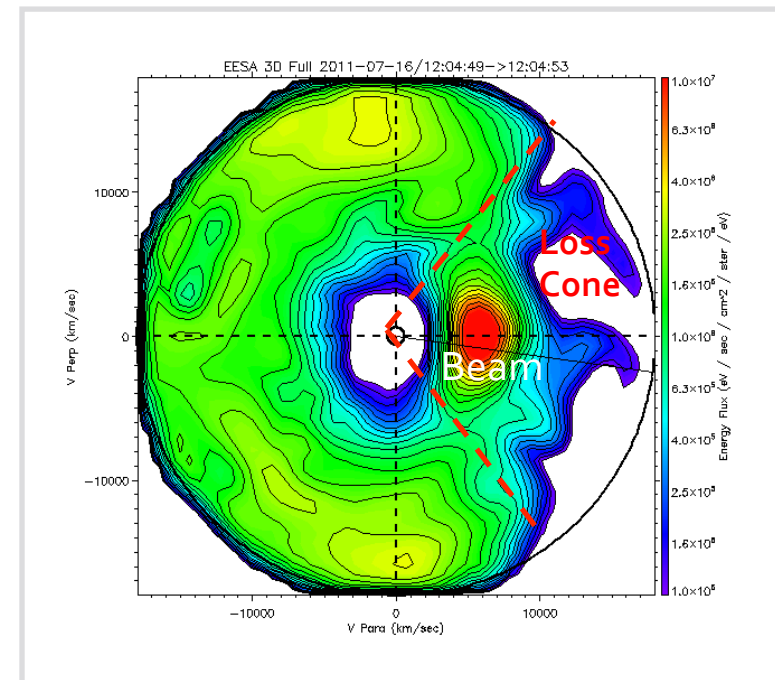
Halekas et al., 2002



Day Side: Photoelectron Sheath

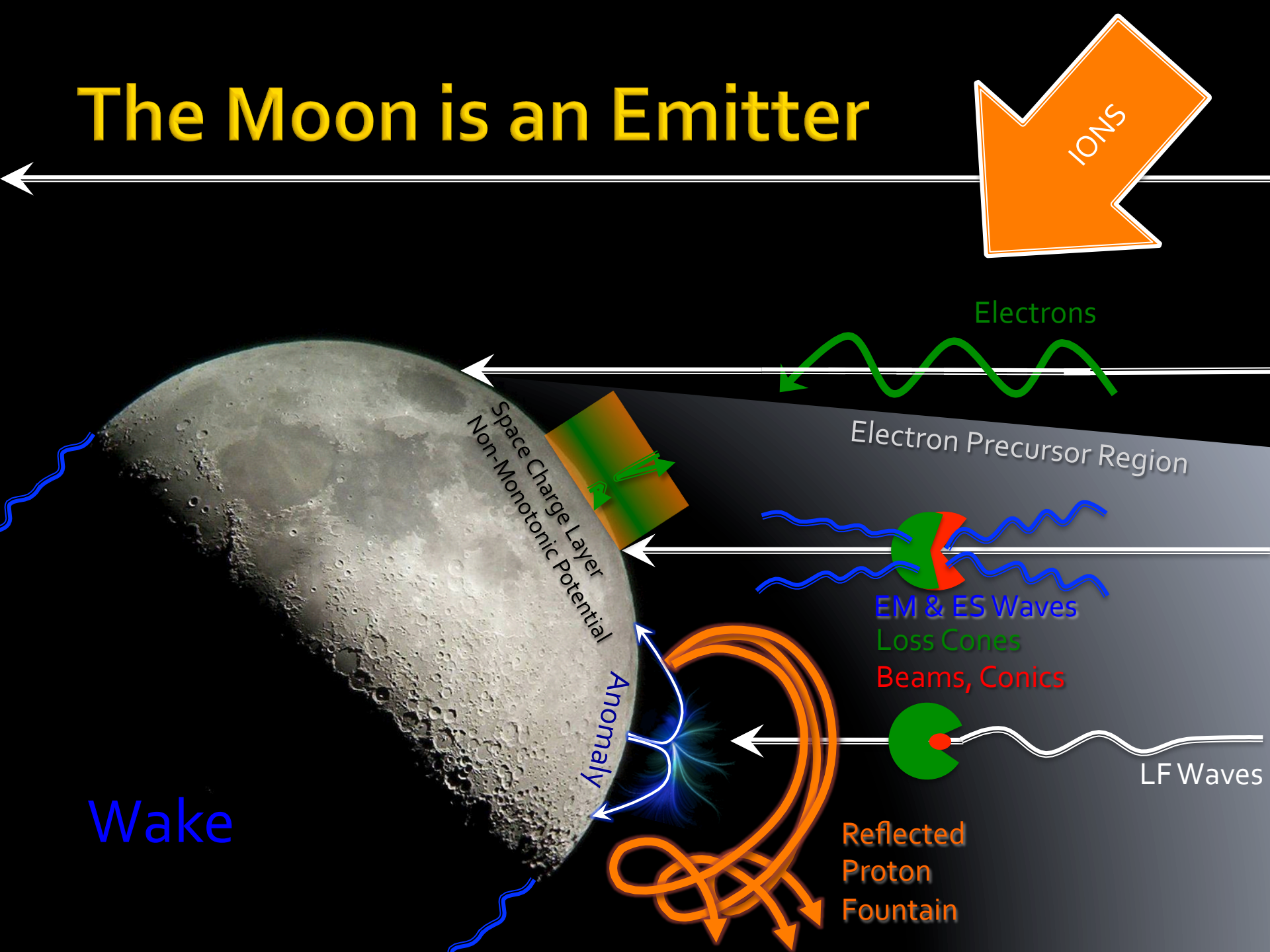


Halekas et al., 2011

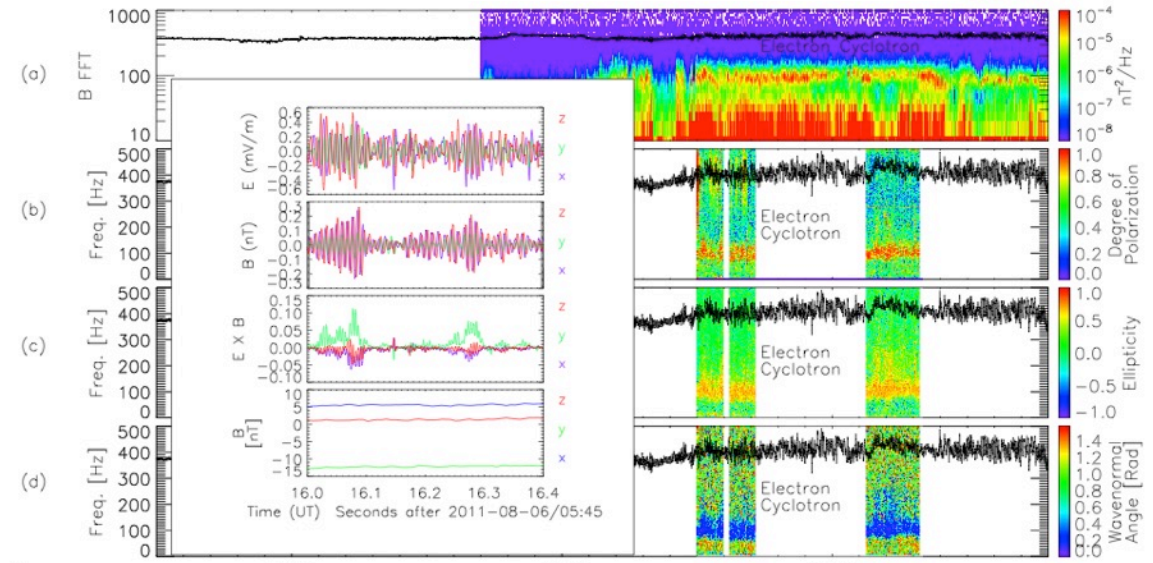
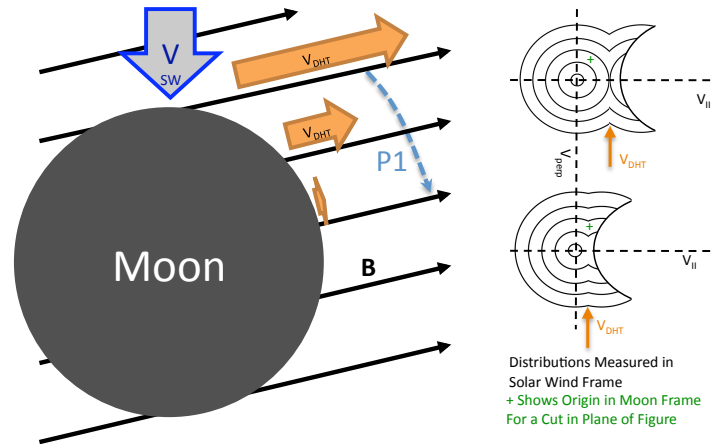
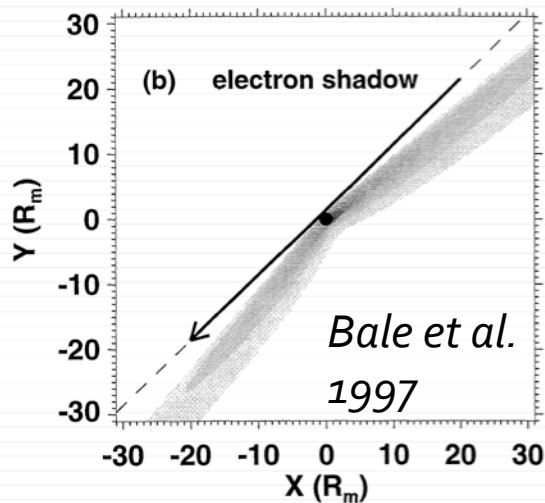
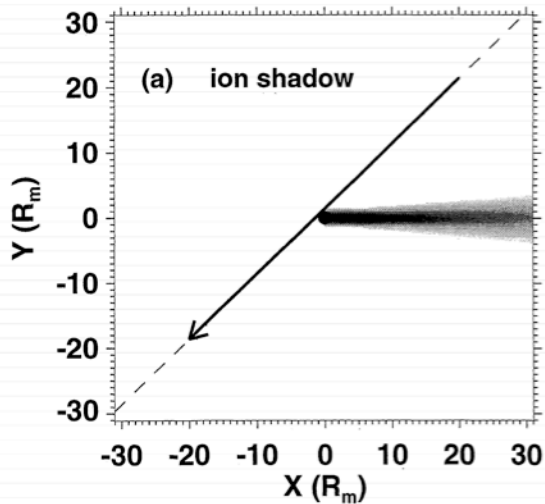


Beam + Loss Cone: Produced By Combined
Magnetic & Electrostatic Effects Near Surface

The Moon is an Emitter



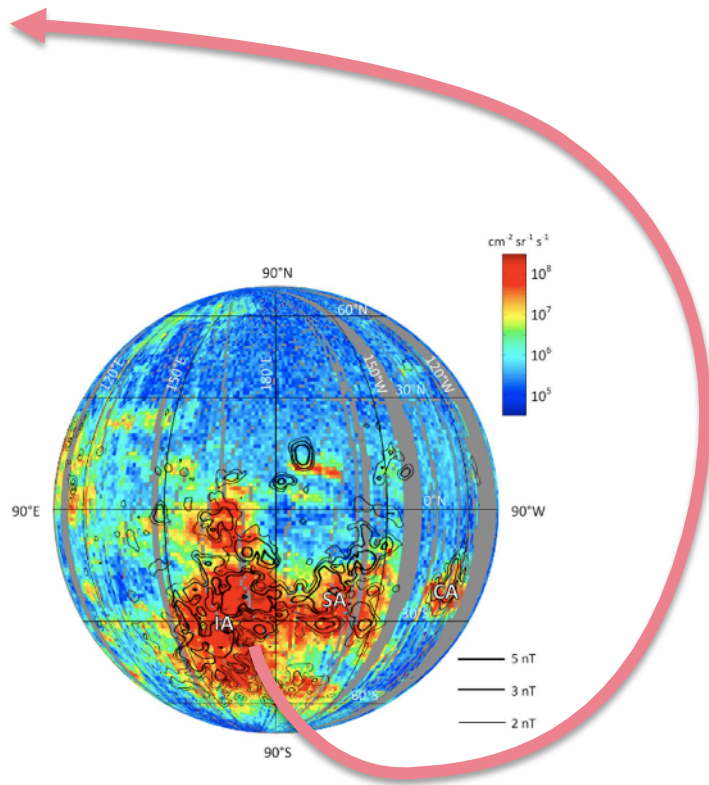
Electron-Driven Waves in the "Foremoon" and "Forewake"



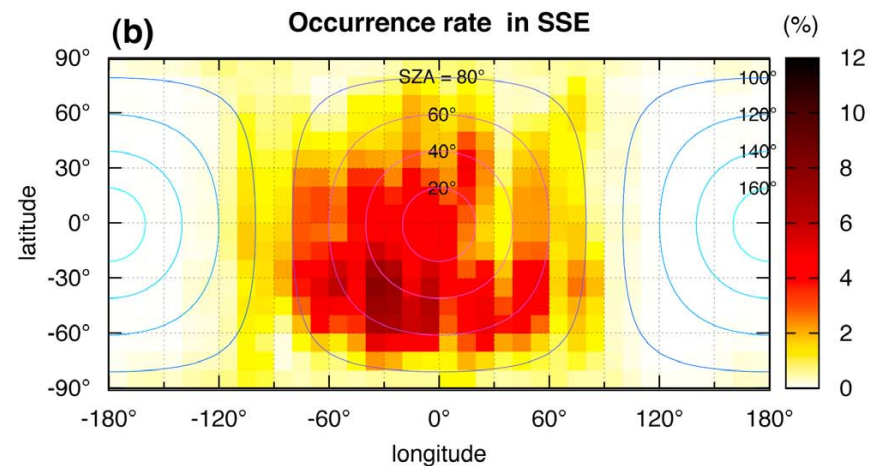
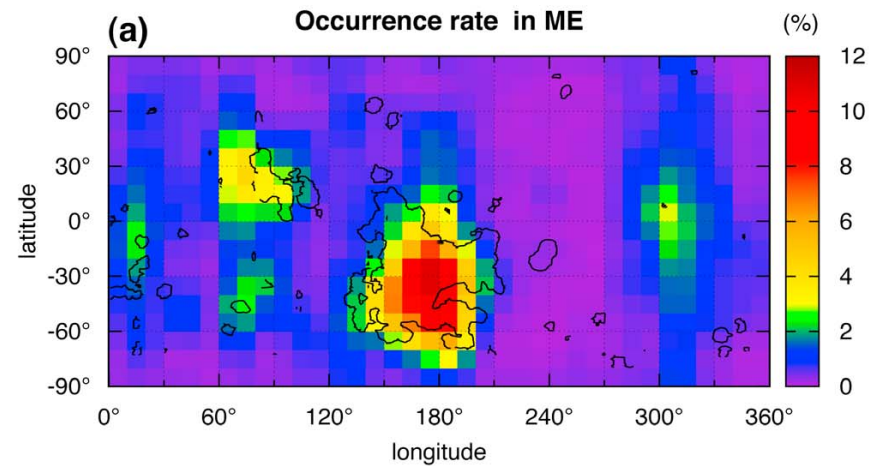
hhmm
2011 Aug 06

Halekas et al., 2012

Ion-Driven Low Frequency Waves

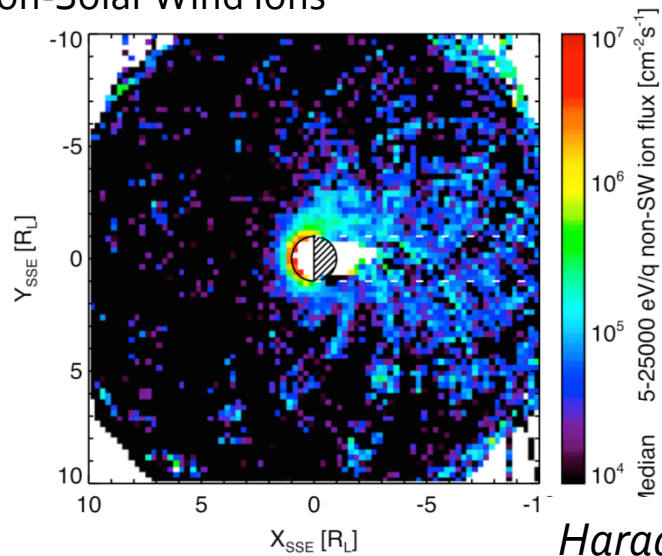


$$\omega \mp \mathbf{k} \cdot \mathbf{V}_{ion} = \Omega_i$$

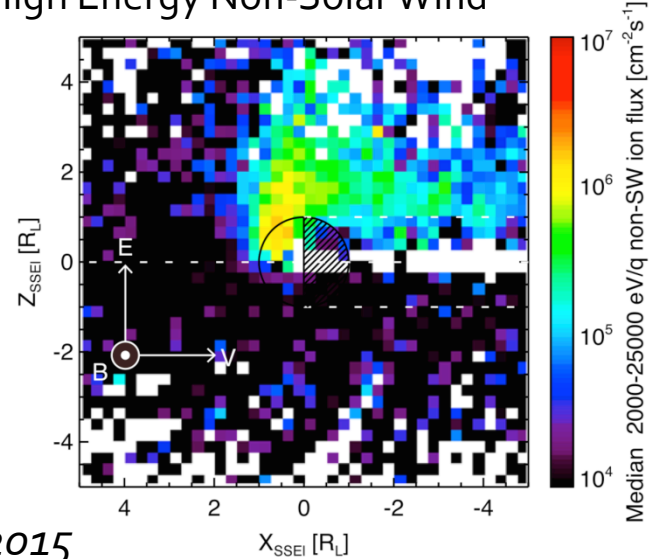


Widespread Lunar Influence

Non-Solar Wind Ions

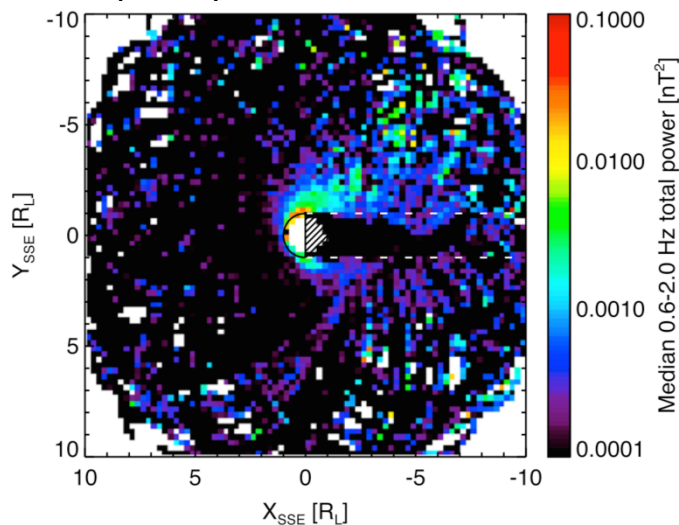


High Energy Non-Solar Wind

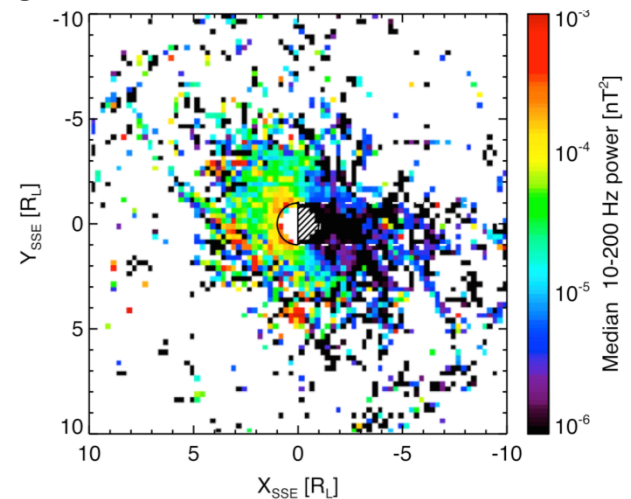


Harada et al., 2015

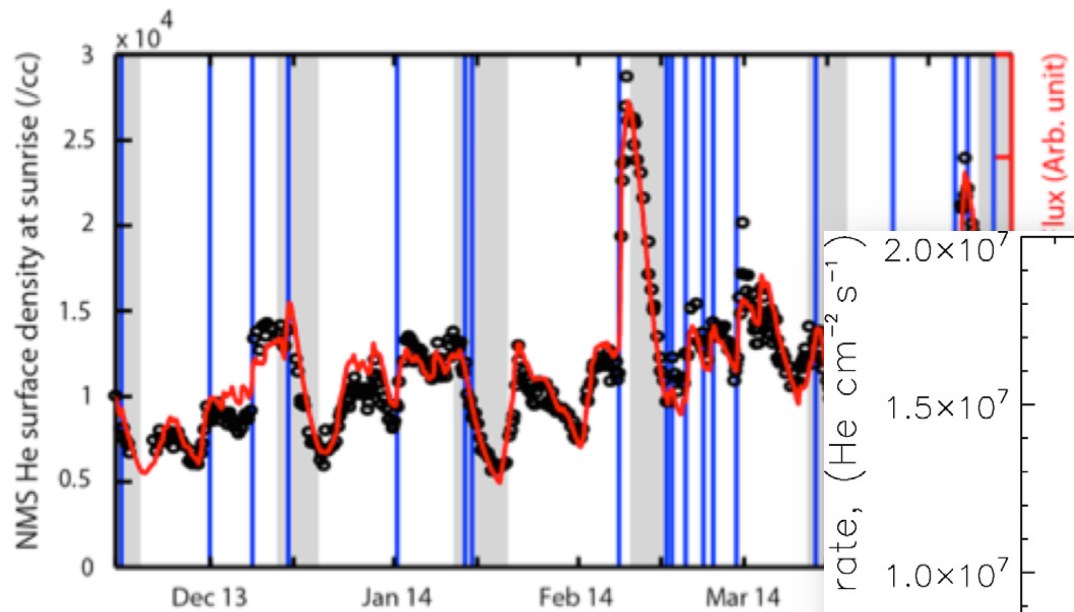
Low Frequency Waves



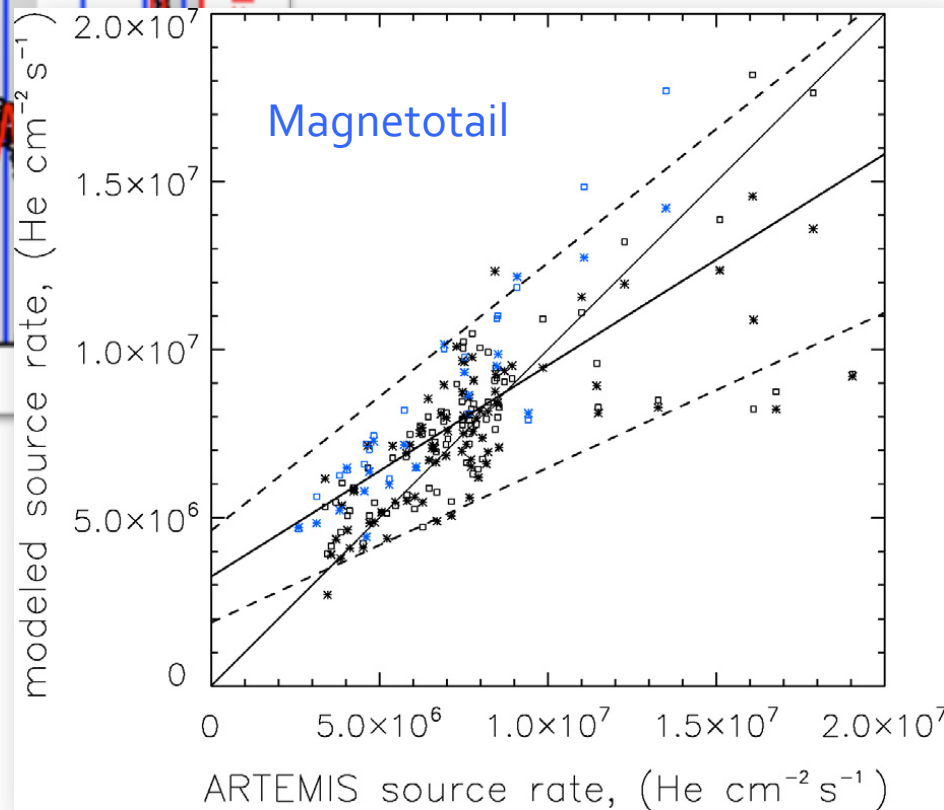
High Frequency Waves (Connected)



Plasma as an Exospheric Source



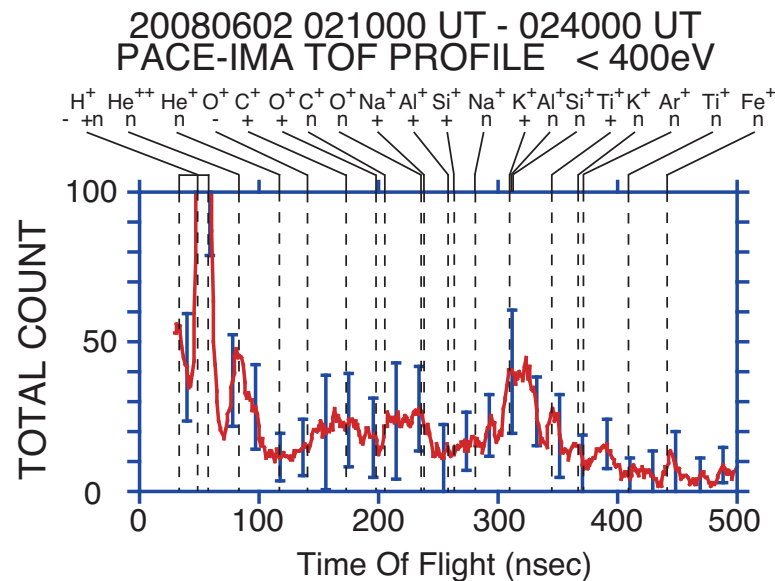
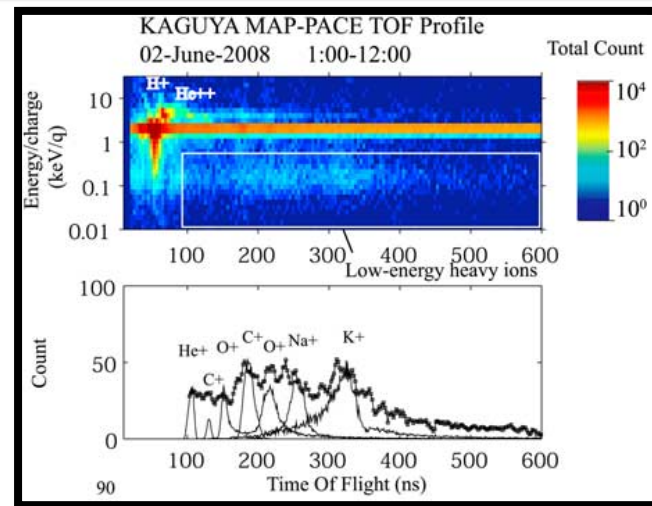
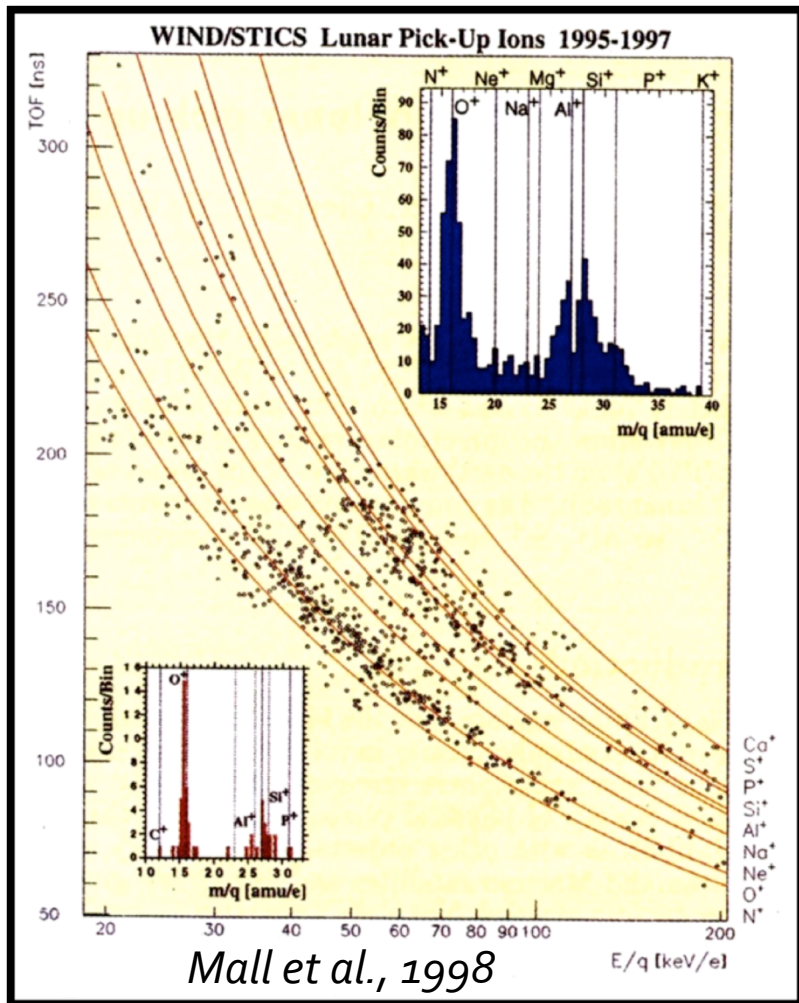
Benna et al., 2015



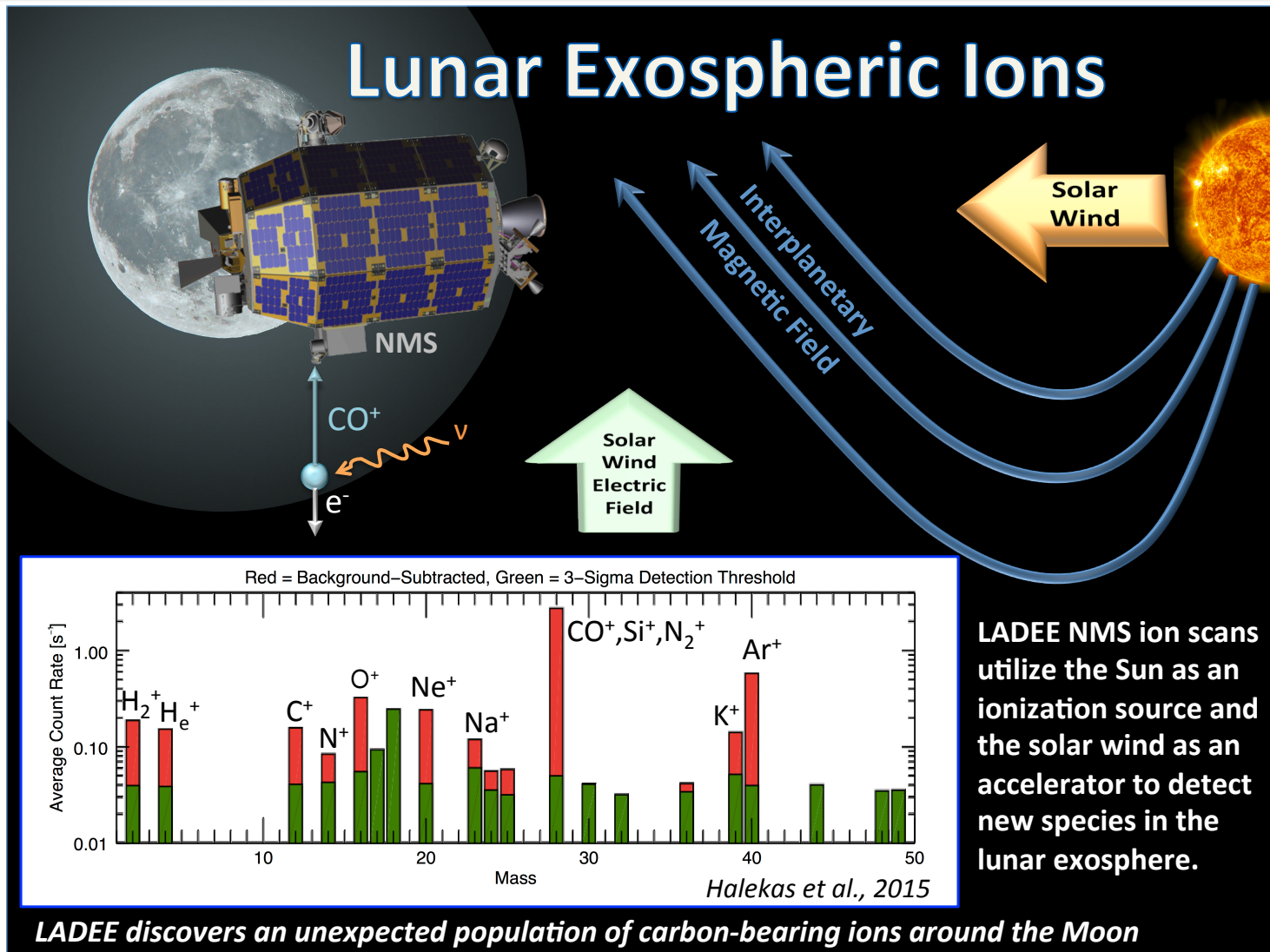
Hurley et al., 2016

Also See: Solar Wind Sputtering...

Plasma as an Exospheric Sink



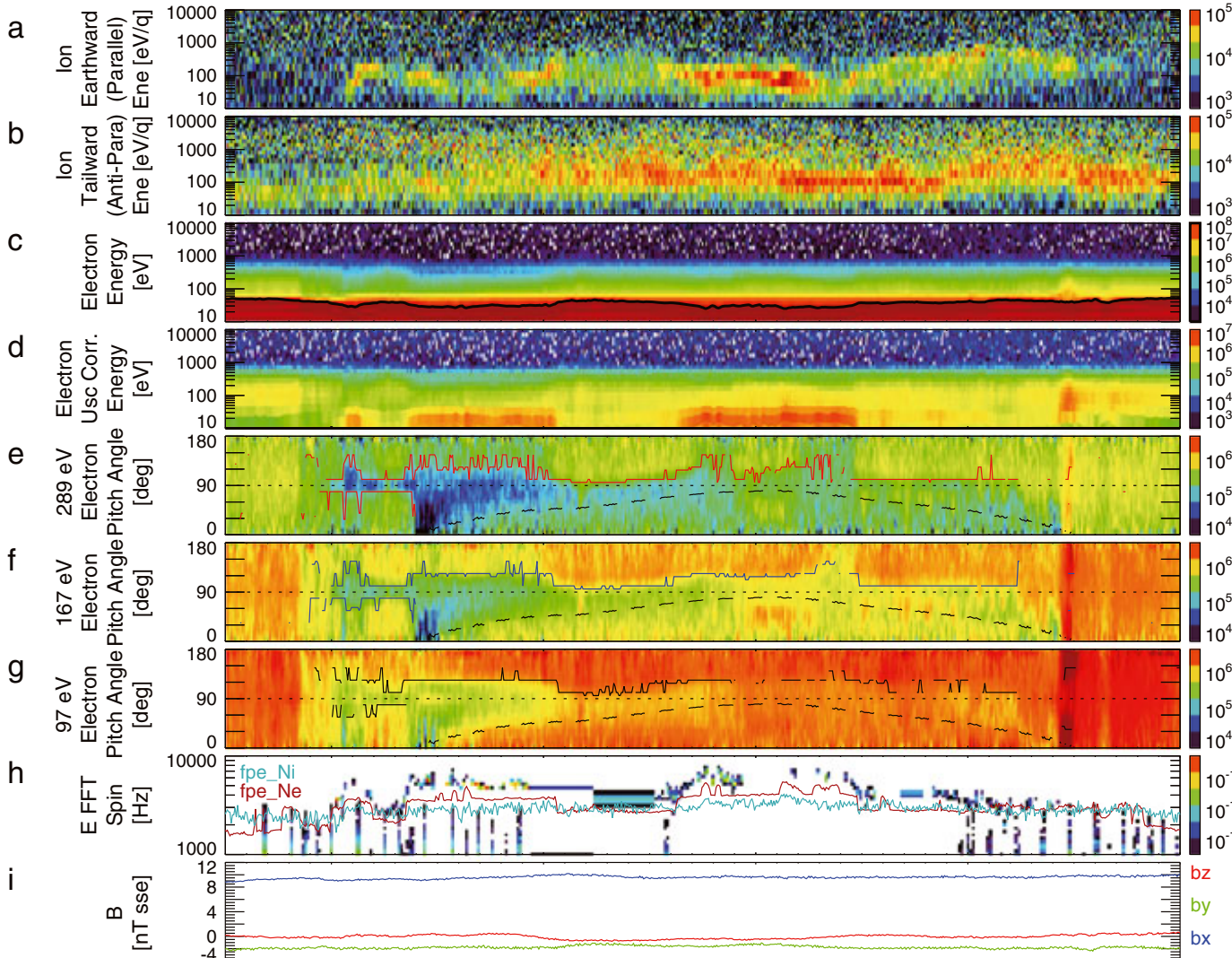
Plasma as an Exospheric Sink



Weirdness: Moon in Magnetotail

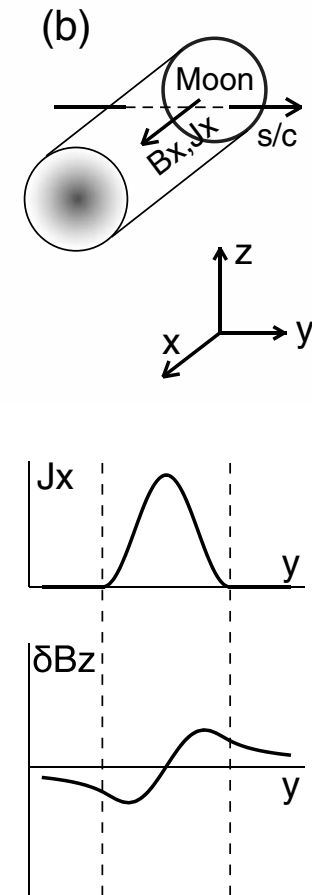
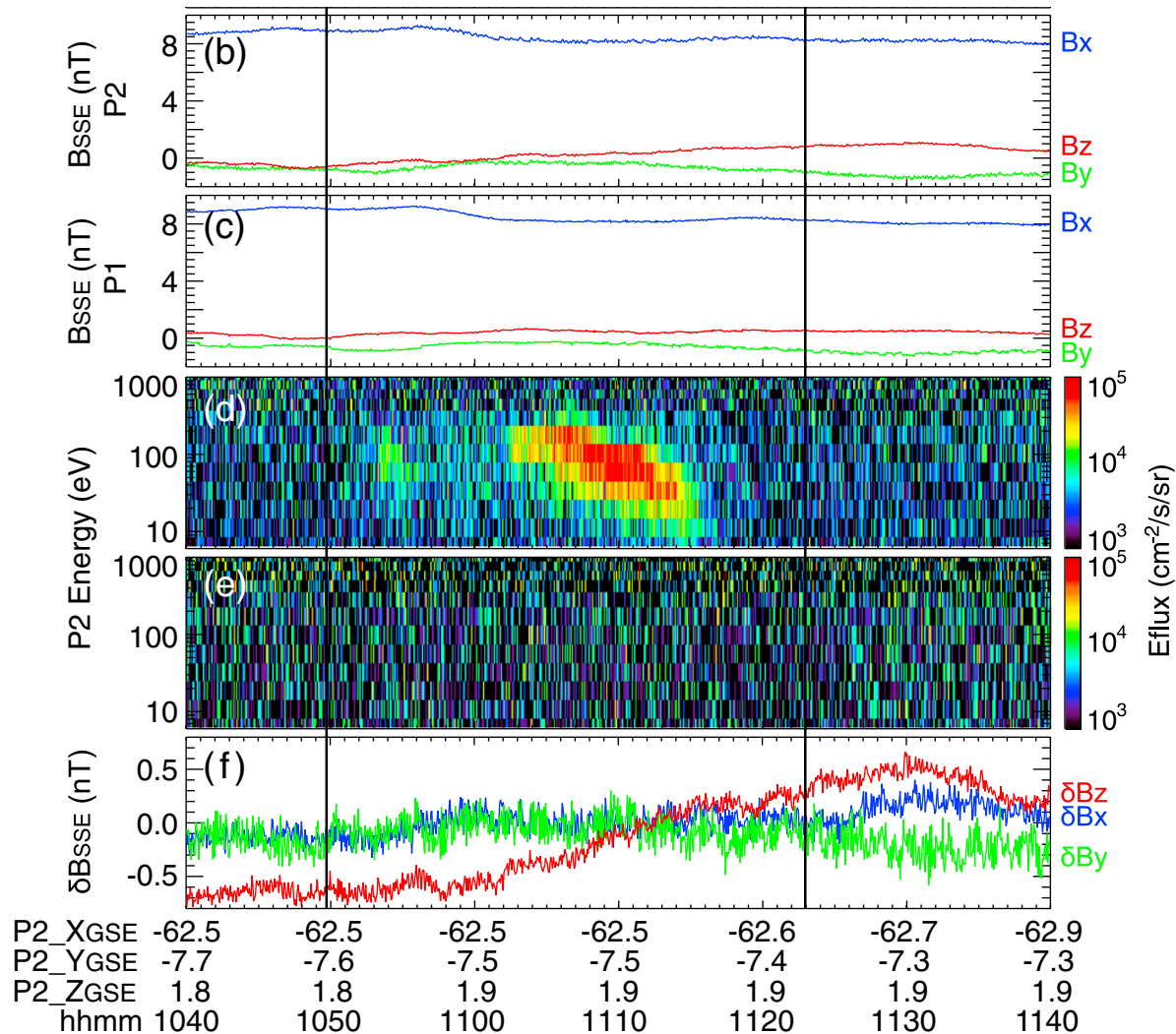
ARTEMIS P2

Harada et al., 2013



- Lunar Ions
- Cold Electron Enhancements
- 90° Dropouts in Energetic Electrons
- Dens. Increases
- Few Magnetic Perturbations

Weirdness: Moon in Magnetotail



Moon in Magnetotail: Some Thoughts

- The Moon in the magnetotail is **not** a “pickup” situation
 - The density of lunar exo-ions **exceeds** that of the lobe plasma
- The Moon is more like a comet...
 - But, it's a very very low-beta comet
 - The dominant force on lunar ions in the magnetotail should probably be $\mathbf{J} \times \mathbf{B}$ (*not* $-\mathbf{v} \times \mathbf{B}$!)

Frontiers

[Paraphrased from Schubert and Lichtenstein, 1974]

- What properties of the solar wind or lunar surface are responsible for the highly variable nature of the interaction?
- What is the structure of the lunar cavity far downstream from the Moon?
- What are the sources of the limb disturbances?
- The physics of the Moon-magnetosheath and the Moon-plasma sheet interactions.
- Possible upstream influences of the Moon in the solar wind, especially at high frequencies
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“New Frontiers”

- What is the time-dependent 3-d electric field structure of the wake?
- How do lunar interactions compare with other small-scale magnetic field gradients (e.g. RX diffusion regions, shocks) in the heliosphere?
- How does the presence of the surface and sheath affect the magnetic anomaly interaction?
- What is the composition of lunar exo-ions and what do they tell us about the exosphere and/or surface?
- How does the Moon interact with the Earth’s magnetotail?