Satellite-magnetosphere interactions at Jupiter and Saturn

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Outline

- **Magnetospheres**
- **Satellites of Saturn**
- **Data and models: the impact of satellites on the magnetosphere**
- **Data and models: the impact of the magnetosphere on satellites**
- **References**

The magnetic field lines around Earth are similar to a bar magnet inside the planet. The "closed" (both foot-points on Earth) field lines on the left are able to trap charged particles on them for long periods of time. The Van Allen radiation belts are such a trapped population (Williams et al. 1999).
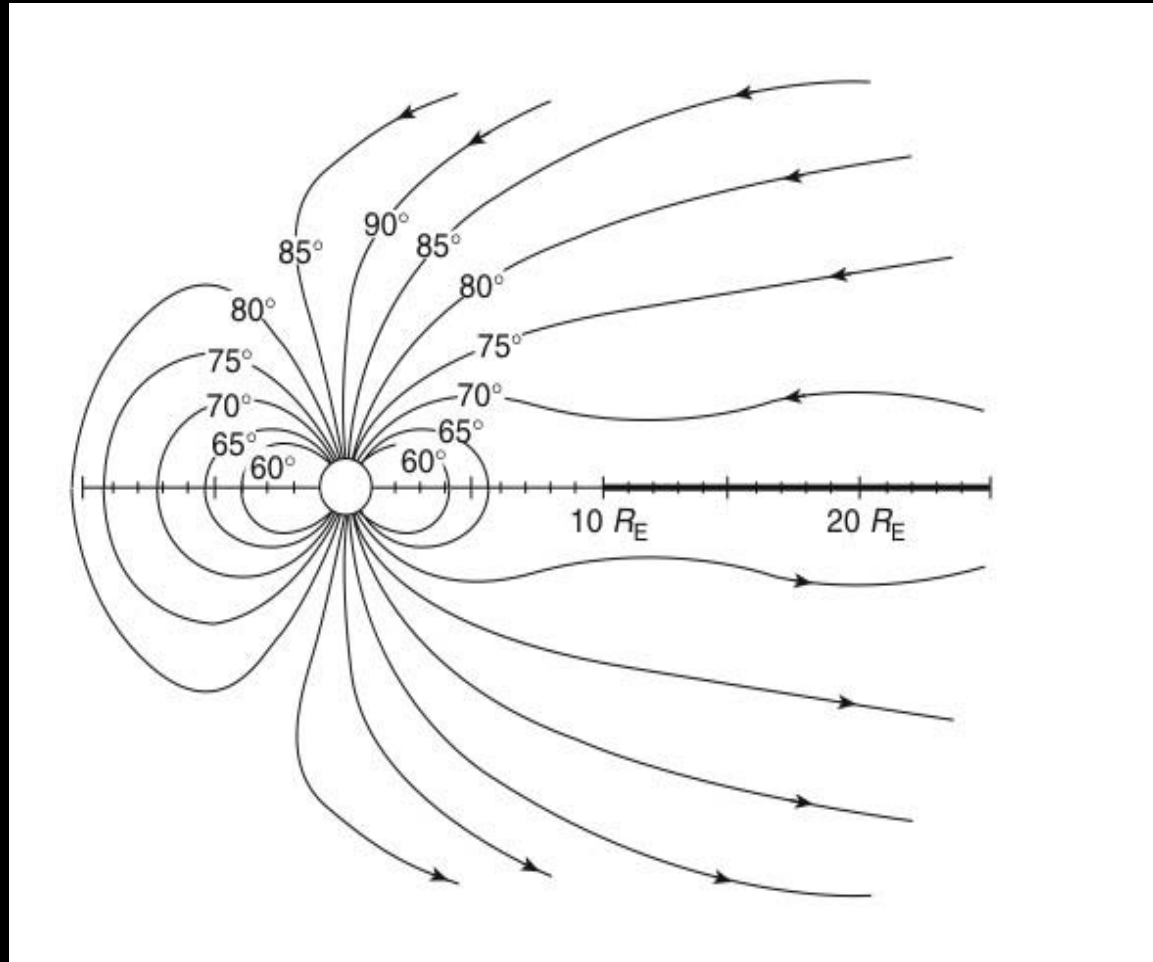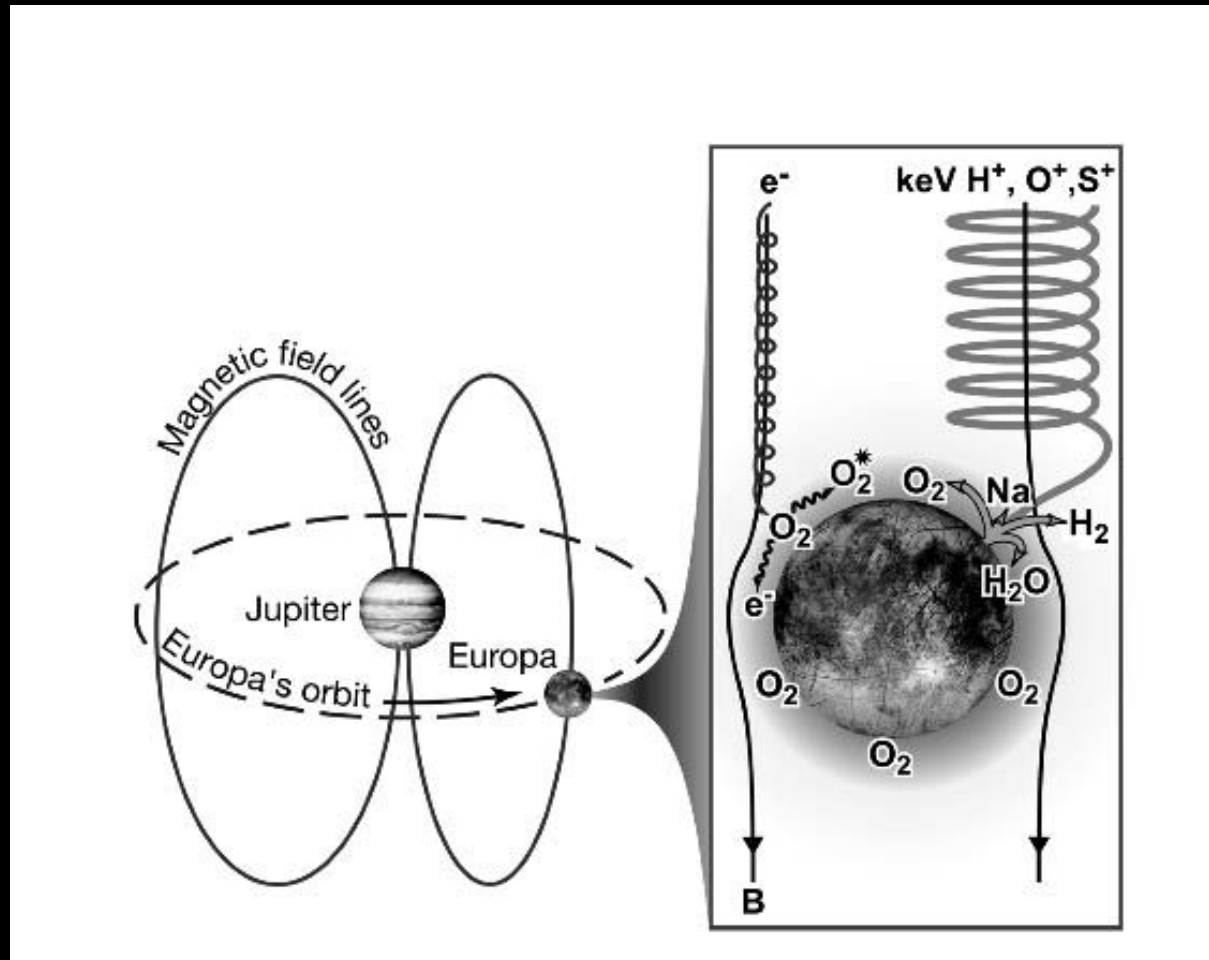
Relative sizes of the magnetospheres of the Solar System (Williams et al. 1998)
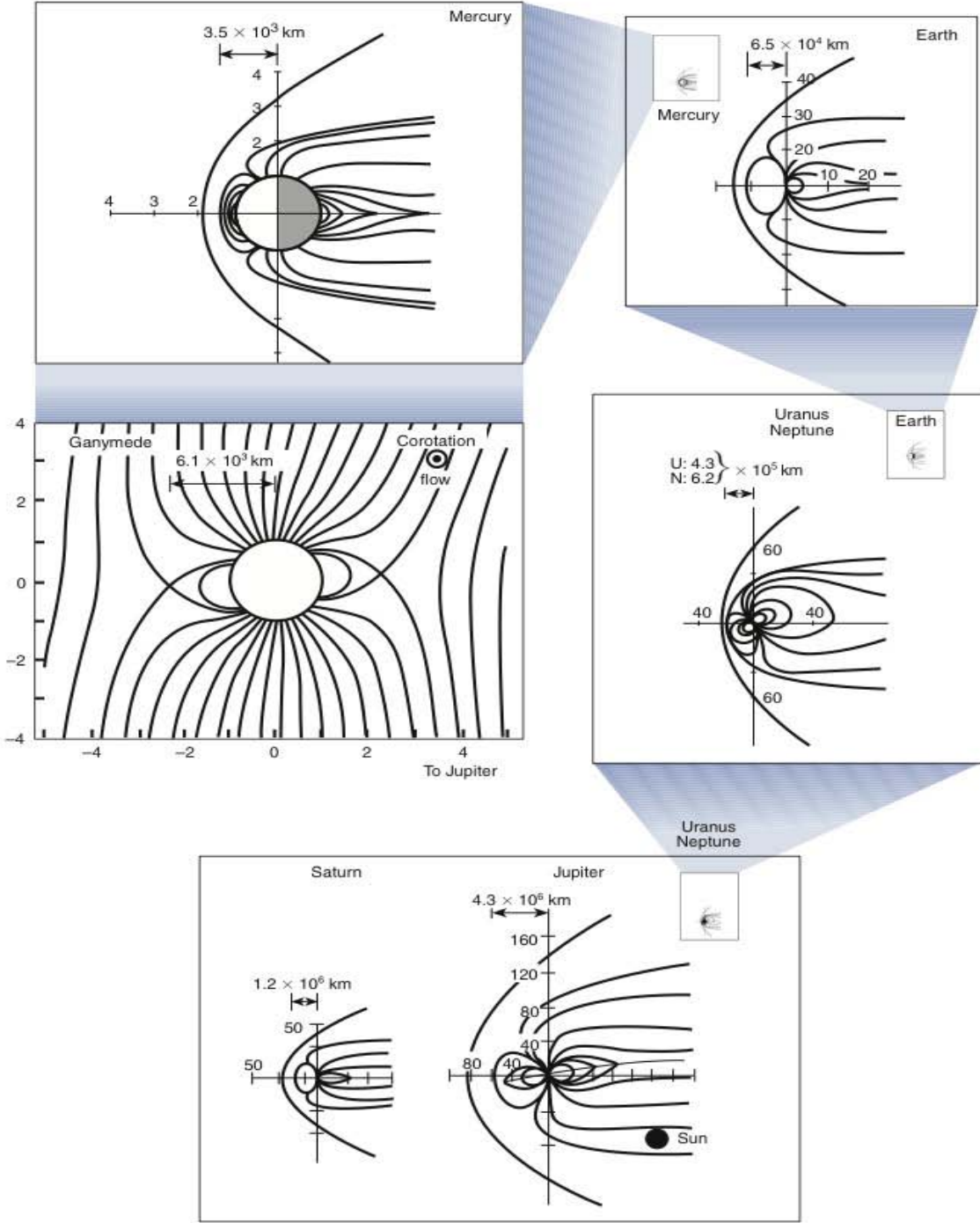
Why are particles trapped?

- **Particle motion in a dipolar magnetic field (such as in the previous slid) can be understood by** $F=ma$ **where forces are electromagnetic so that the equation is,**
  - **F=q ($E + v \times B$) where E and B are the electric and magnetic fields that are generated by the planet and v and q are the velocity and charge of the particle these fields act upon**
- **On a closed dipole field line (the solution of the equation** dl **x** B **=0), the strength of the magnetic field increases toward the planet (the location of the bar magnet)**
- **It is easy to show from the above equation that particles attempting to access the stronger field along magnetic field lines are turned around and reflected back (e.g. Walt 1994)**
- **This leads to a "magnetic bottle" effect that traps charged particles on closed magnetic field lines**
- **We will be looking at such trapped particles and how they interact with satellites in this presentation**

Sketch of particle trapping in a magnetosphere and the precipitation of particles onto Europa (Johnson et al. 2004)
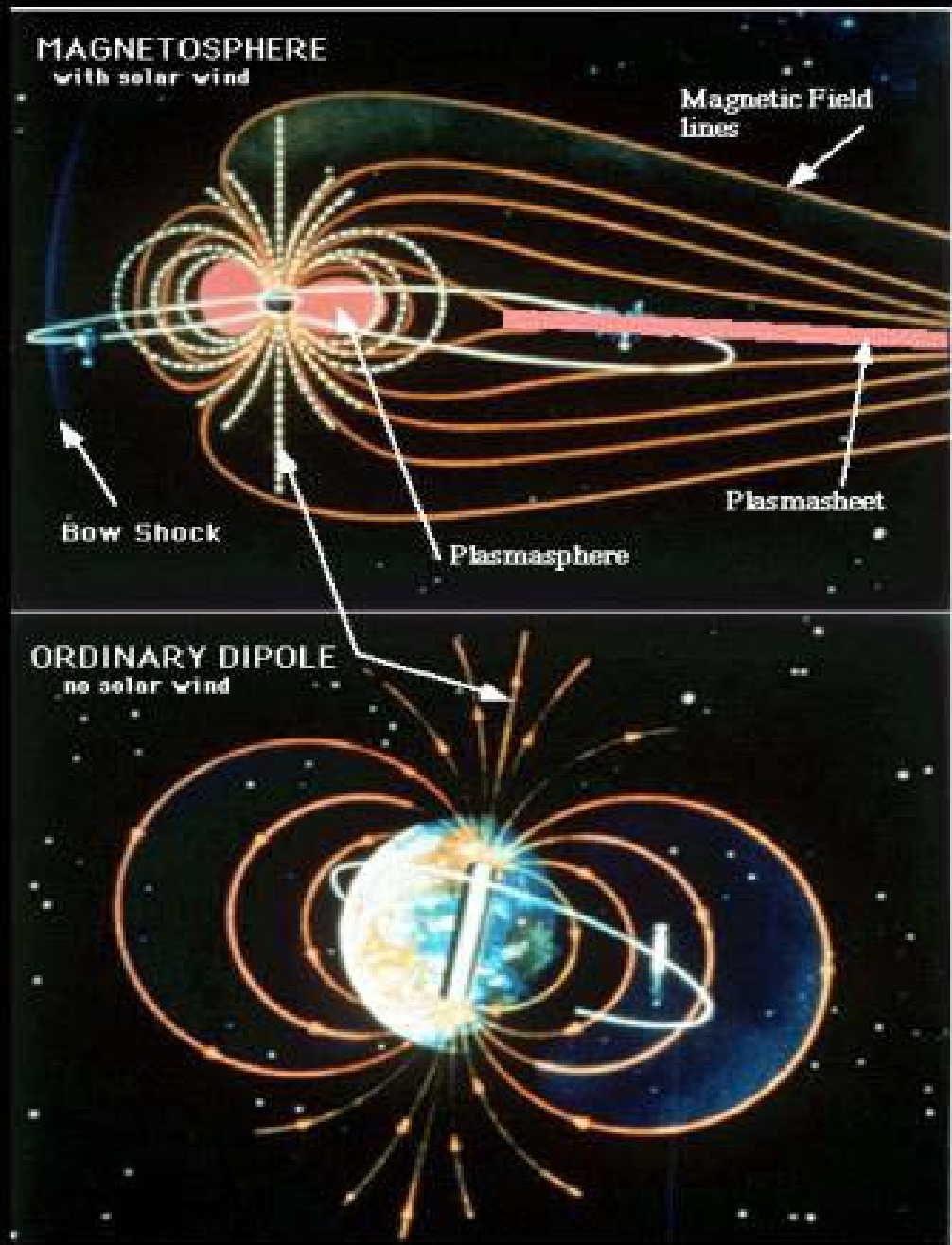
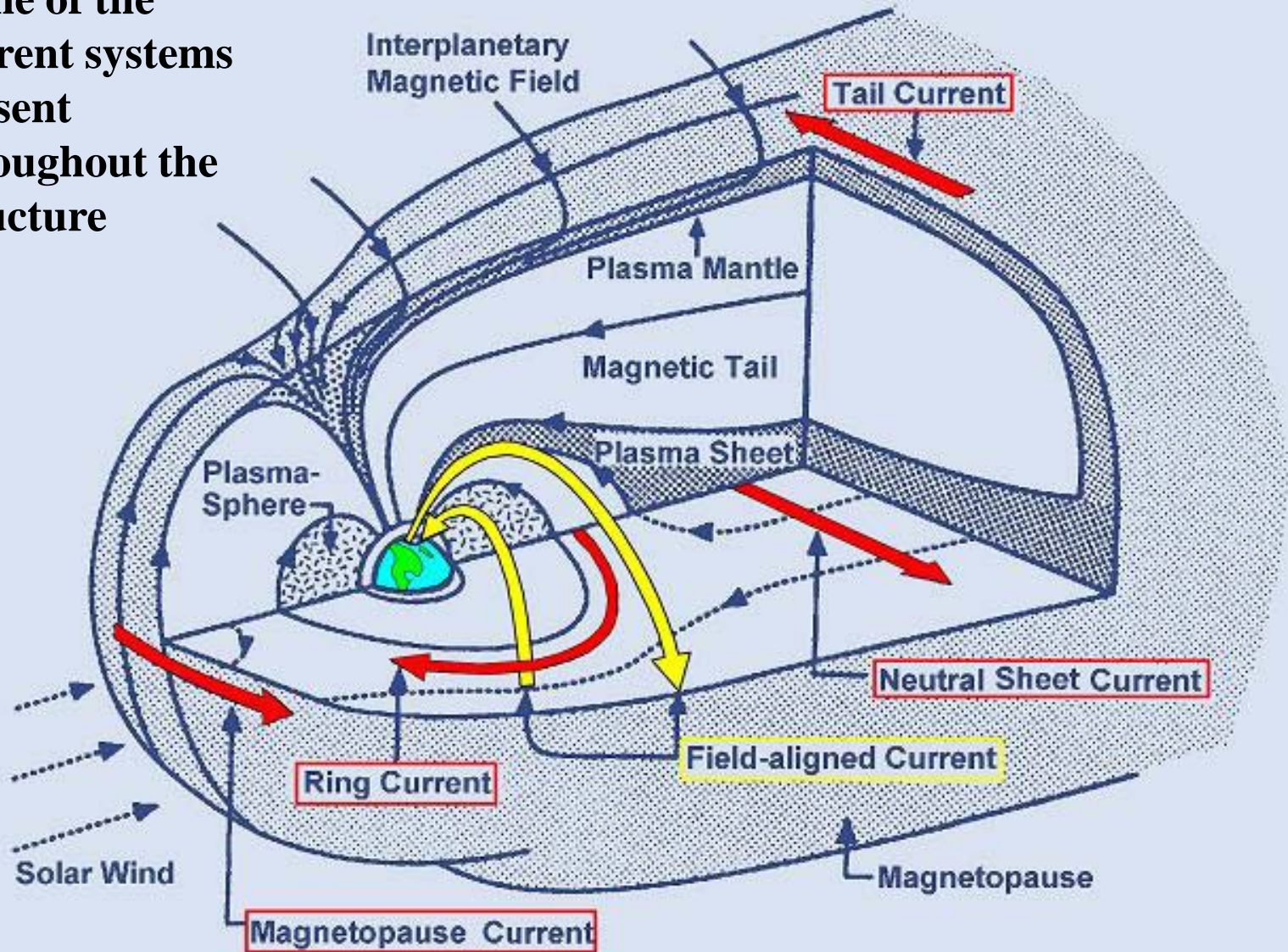More detailed pictures of magnetospheres.

These are some views of the magnetosphere that are available publicly on the internet (so not specifically attributed here).
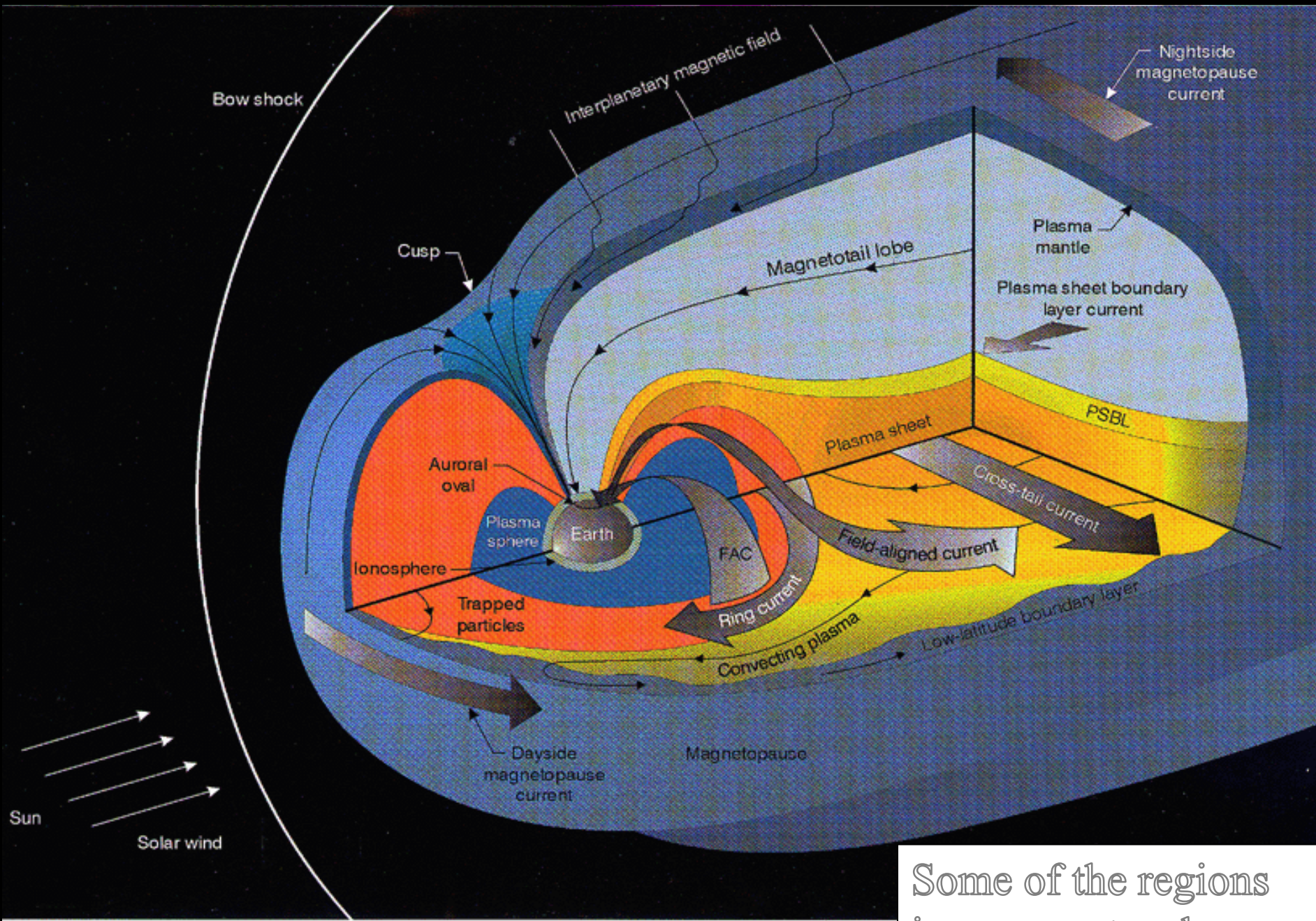
These show the magnetic fields, currents, trapped plasma, and other structural boundaries of magnetospheres….

Effect of the solar wind on a planetary dipole (top)

Some of the current systems present throughout the structure

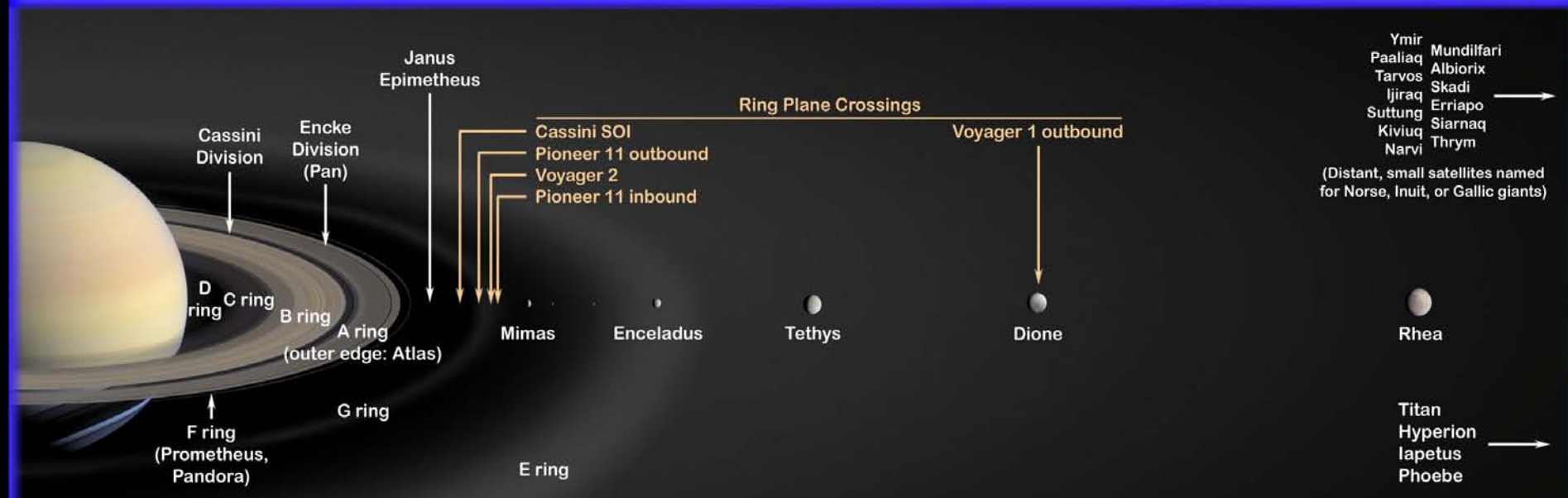Interplanetary Magnetic Field

Tail Current

Plasma Mantle

Magnetic Tail

Plasma Sheet

Plasma-Sphere

Neutral Sheet Current

Field-aligned Current

Ring Current

Solar Wind

Magnetopause

Magnetopause Current

Some of the regions
in a magnetosphere

THE SATURNIAN SYSTEM

Pan*   Atlas*   Prometheus   Janus   Methone*   Telesto*   Polydeuces*
Pandora   Epimetheus   Pallene*   Calypso*   Helene*

Mimas   **Enceladus**   **Tethys**   **Dione**   **Rhea**   **Hyperion**   **Iapetus**   **Phoebe**

Titan

SATURN

All bodies are to scale except for the eight small, starred (*) bodies whose sizes have been exaggerated by a factor of 5.

May 2005

Cassini Division   Encke Division (Pan)   Janus Epimetheus

Ring Plane Crossings

Cassini SOI   Voyager 1 outbound
Pioneer 11 outbound
Voyager 2
Pioneer 11 inbound

D ring   C ring   B ring   A ring (outer edge: Atlas)

Mimas   **Enceladus**   **Tethys**   **Dione**   **Rhea**

F ring (Prometheus, Pandora)   G ring

E ring

Ymir   Mundilfari
Paaliaq   Albiorix
Tarvos   Skadi
Ijiraq   Erriapo
Suttung   Siarnaq
Kiviuq   Thrym
Narvi

(Distant, small satellites named for Norse, Inuit, or Gallic giants)

Titan
Hyperion
Iapetus
Phoebe

Hendrix 2010

There are clues about the interactions of satellites and magnetospheres in various kinds of data.

These are some of the effects of satellites on the magnetosphere....

Footprints of the satellites appear in the planetary auroral region of Jupiter. There has been a lot of work on understanding how the satellites generate these distant signatures. Some of the polar emission is caused by processes of "spinning up" the Iogenic plasma. This is an image from the HST imaging spectrograph of Jupiter's polar region in the UV that appears in Paranicas et al. (2005)
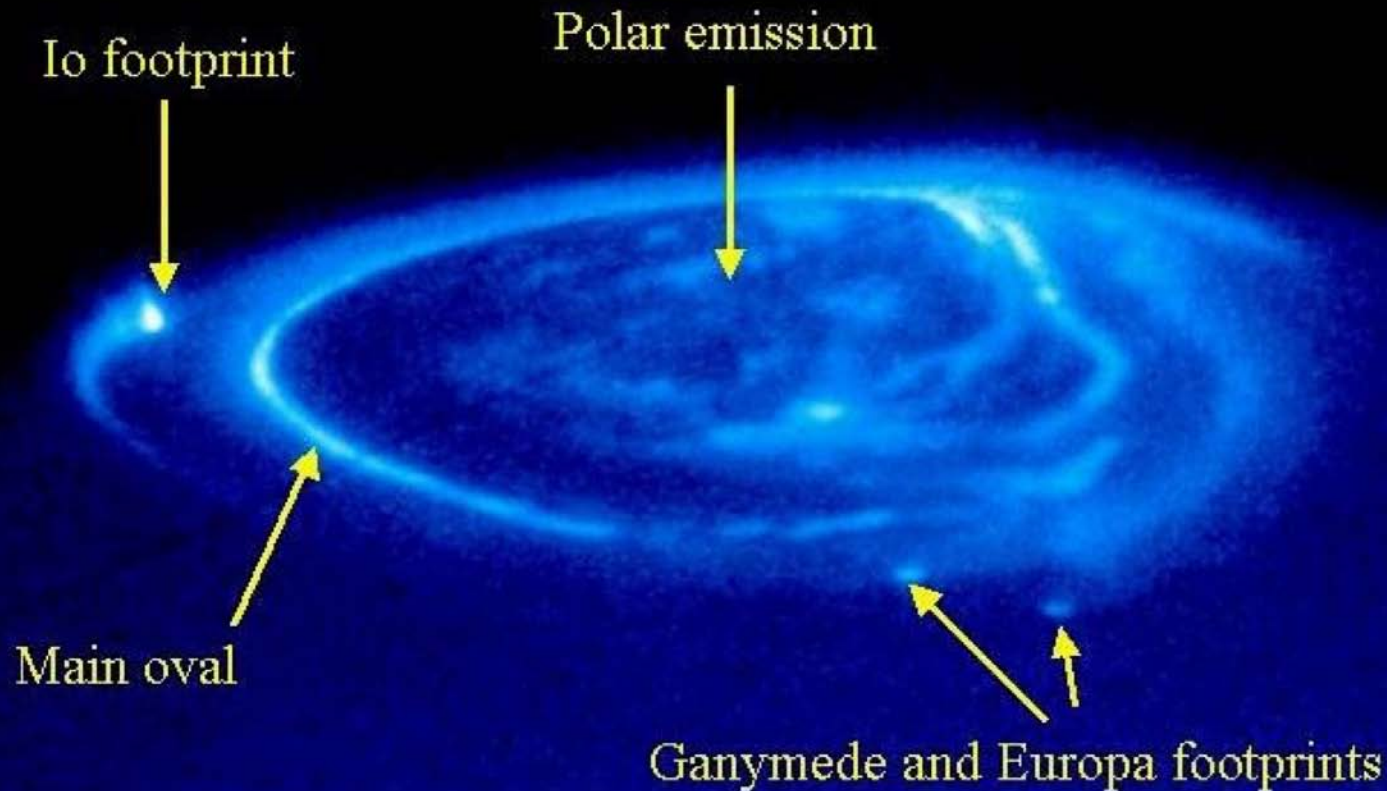
To explain the presence of these satellite footprints in the aurora, investigators have studied the satellite/magnetosphere interaction region. The main point is to know what electric potential changes or electric currents are generated by the interaction. For instance, the figure below from the book chapter by Kivelson et al. (2004) shows an Alfven wing current system set up by the plasma flow (from the left) and the body.
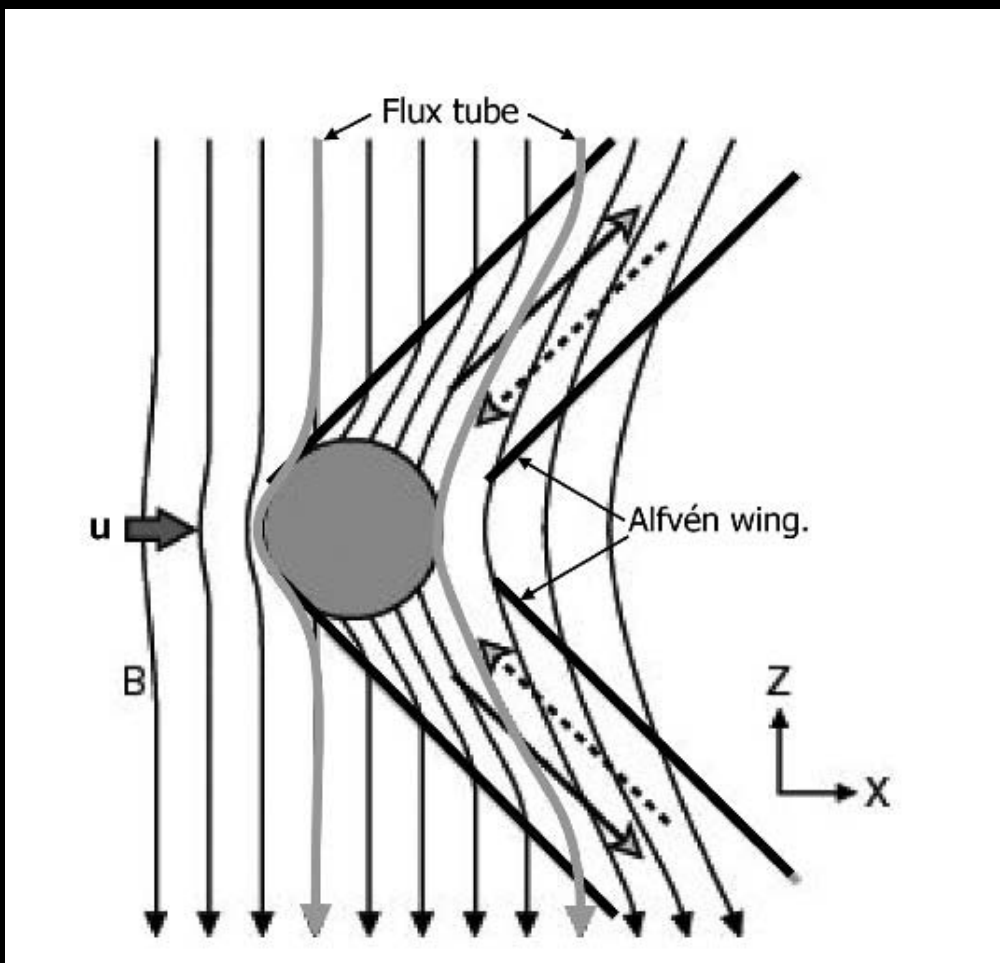
Kivelson et al. (2004) have suggested a useful ordering for moon-magnetosphere interactions.

This is by characterizing the parameters of the cold plasma overtaking the moons in their prograde orbits
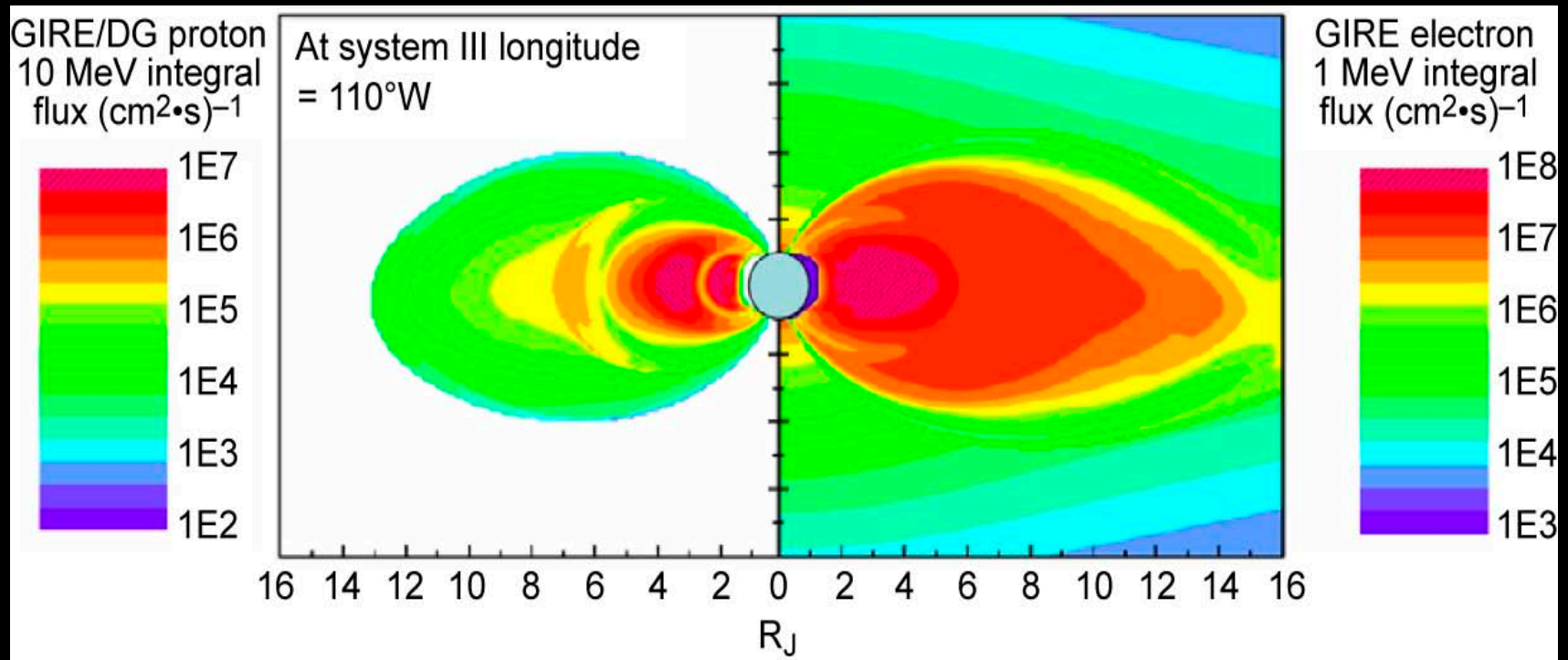
For example, the Alfven Mach number (u/v_A) near the satellites is a good indicator of whether information can propagate upstream (see table on next slide from Kivelson et al. 2004)

At Io, Europa, and Ganymede, the flow is not expected to be super-Alfvenic although it sometimes is at Callisto and there a shock can form

Symbol (units), Physical property	Io	Europa	Ganymede	Callisto	Ref
Plasma and field parameters of the ambient magnetospheric plasma					
B_o(nT), jovian magnetic field, av. min (max)	1720 (2080)	370 (460)	64 (113)	4 (42)	1
n_e(elns cm^{-3}), eq. av. (range) eln. density	2500 (1200-3800)	200 (18-250)	5 (1-10)	0.15 (0.01-0.70)	2
$<Z>$, eq. av. (lobe) ion charge	1.3 (1.3)	1.5 (1.5)	1.3 (1)	1.5 (1)	3
$<A>$, eq. av. (lobe) ion mass in m_p	22 (19)	18.5 (17)	14 (2)	16 (2)	3
n_i(ions cm^{-3}), av. (range) ion no. density	1920 (960-2900)	130 (12-170)	4 (1-8)	0.10 (0.01-0.5)	3
ρ_m(amu cm^{-3}), av. (range) ion mass density	42,300(18,000-64,300)	2,500(200-3,000)	54 (2-100)	1.6 (0.02-7)	3
kT_i (eV), equator (range) ion temperature	70 (20-90)	100 (50-400)	60 (10-100)	60 (10-100)	3
kT_e(eV), electron temperature	6	100	300	500	4
$p_{i,th}$(nPa), eq. (range) pressure thermal plasma	22 (3-42)	2.1 (0.10-11)	0.04 (0.002-0.12)	0.001 (0.00-0.01)	3
$p_{i,en}$(nPa) (20 keV – 100 MeV ions)	10	12	3.6	0.37	5
p_e(nPa) (both "cold" and "hot" electrons)	2.4	3.2	0.2	0.01	
p(nPa), eq. (max) total pressure	34 (54)	17 (26)	3.8 (3.9)	0.38 (0.39)	3, 5
v_{cr}(km s^{-1}), local corotation velocity	74	117	187	328	6
v_s(km s^{-1}), satellite orbit velocity	17	14	11	8	6
v_ϕ(km s^{-1})s plasma azimuthal vel. (range)	74 (70-74)	90 (70-100)	150 (95-163)	200 (130-280)	7
u(km s^{-1}), relative velocity (range), v_ϕt v_s	57 (53-57)	76 (56-86)	139 (84-152)	192 (122-272)	
v_A(km s^{-1}), eq. (range) Alfvén speed	180 (150-340)	160 (145-700)	190 (130-1700)	70 (30-6500)	8
c_s(km s^{-1}), eq. (range) sound speed	29 (27-53)	92 (76-330)	280 (190-1400)	500 (230-4400)	9
$B_o^2/2\mu_o$(nPa), eq. (lobe) magnetic pressure	1200 (1700)	54 (84)	1.6 (5)	0.006 (0.7)	1
ρu^2(nPa), eq. av. (max) ram pressure	230 (350)	24 (38)	1.7 (4.1)	0.10 (0.90)	
ρu^2(nPa), lobe ram pressure	100	2.5	0.08	0.002	

Next we discuss some other impacts of the satellites on the magnetosphere. These are impacts on the population of energetic charged particles (not the cold plasma)

In the JPL model of Jupiter's radiation belts, the particle flux changes or decreases at the locations of the planetary moons. For example, at about 6 RJ on the left, the presence of Io on the flux is modeled (e.g. Paranicas et al. 2010)

GIRE/DG proton 10 MeV integral flux (cm²•s)−1

At system III longitude = 110°W

GIRE electron 1 MeV integral flux (cm²•s)−1

1E7	1E8
1E6	1E7
1E5	1E6
1E4	1E5
1E3	1E4
1E2	1E3

16 14 12 10 8 6 4 2 0 2 4 6 8 10 12 14 16

R$_J$

These are energetic proton data with MeV energies from Cassini/MIMI showing a notch in the trapped flux level at the locations of the Saturnian satellites (Krupp et al. 2009)
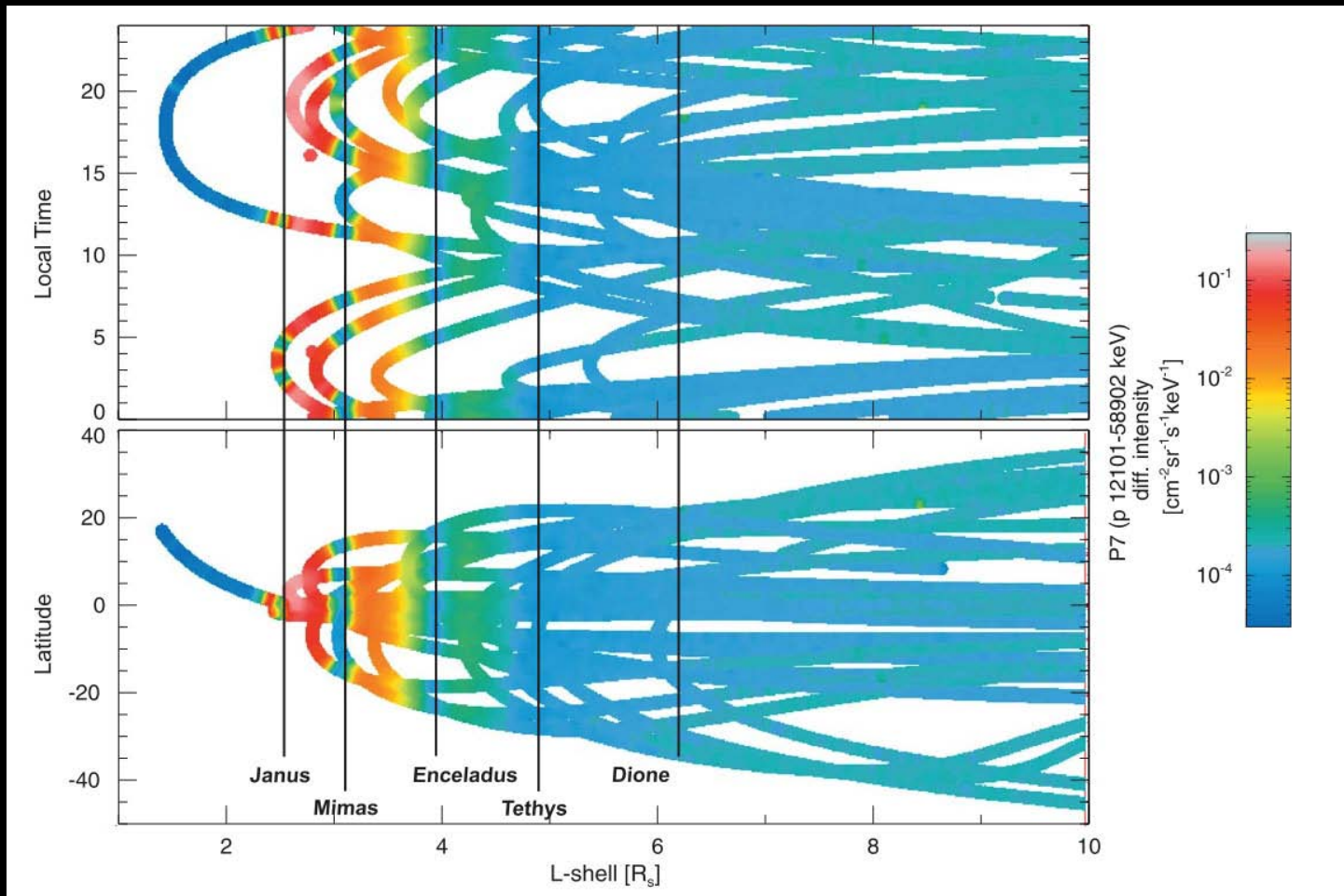
Averaged MIMI data by distance from Saturn's center in a meridian view showing the notches of satellites in the trapped particles (Roussos et al. 2008)
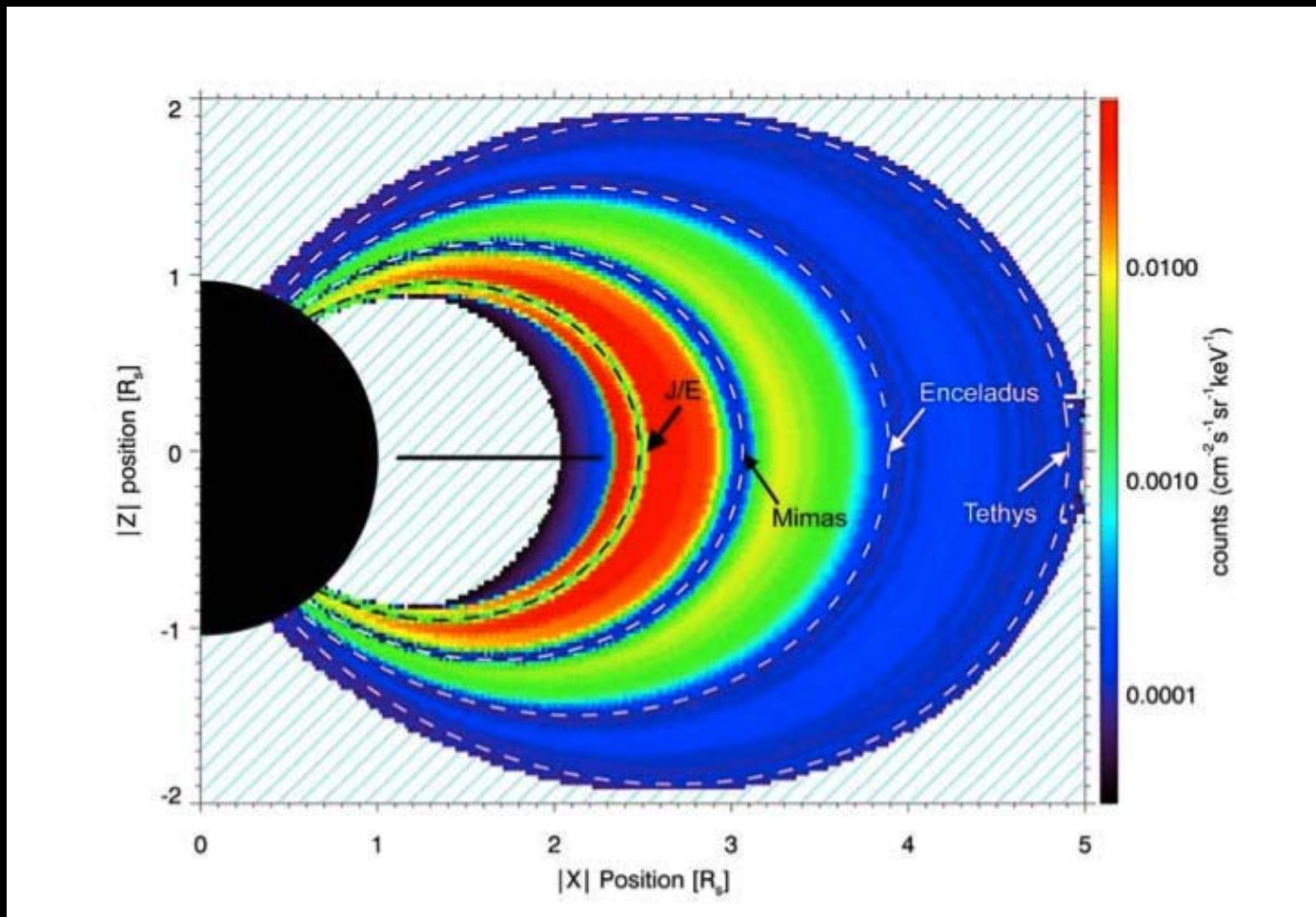
The next slides show some views of an inert satellite interacting with the particles trapped in a magnetosphere

For cold plasma, flowing like a fluid past an obstacle, it is expected that some kind of wake would form on the downstream side of the moon

This cold plasma wake would fill in over time

For some particle species/energies, the wake can occur upstream of the moon, can fill in slowly, etc.

Multiple wakes of Enceladus, from Jones et al. (2006)
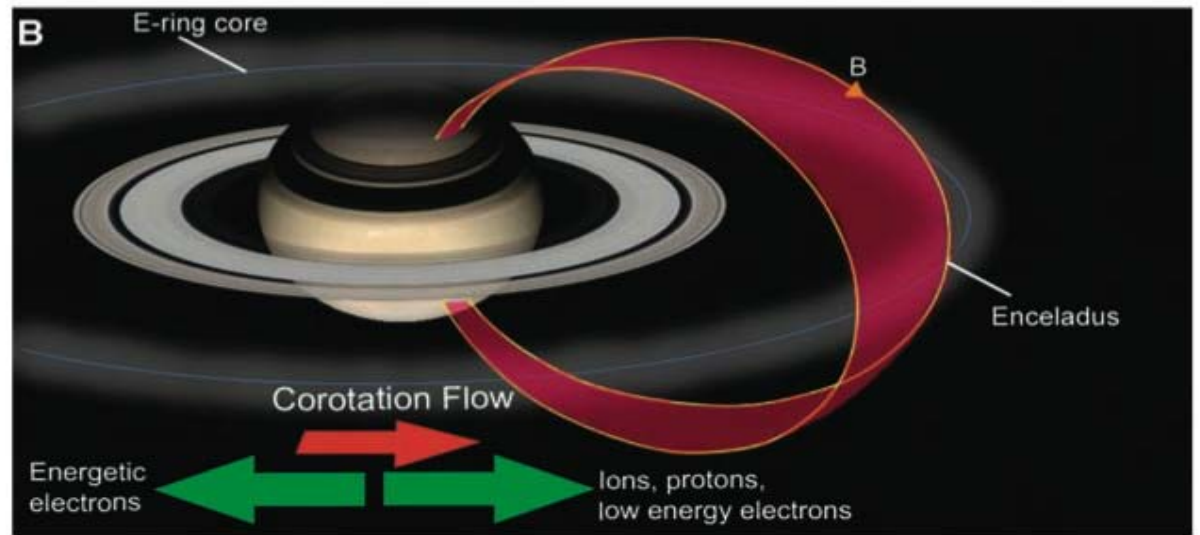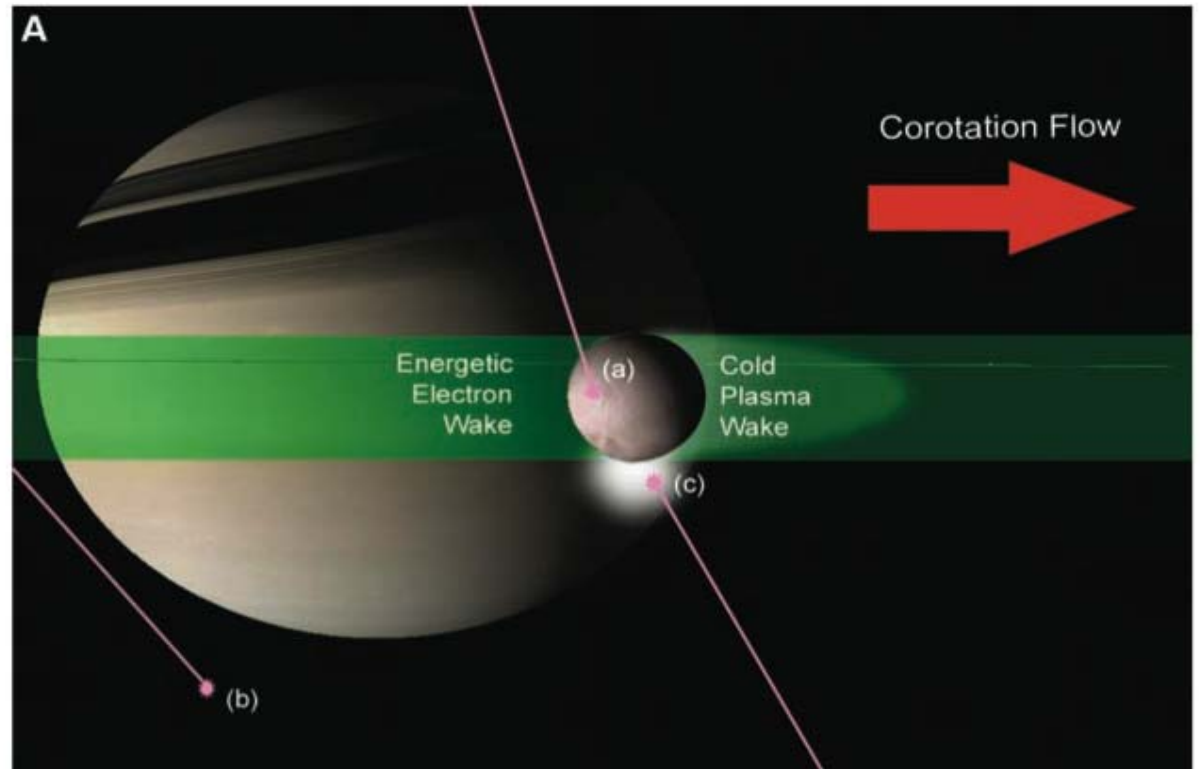
Satellite wake in a population of energetic charged particles (z axis) as itfills in in longitude. The L value describes a radial coordinate (Paranicas et al. 1997).
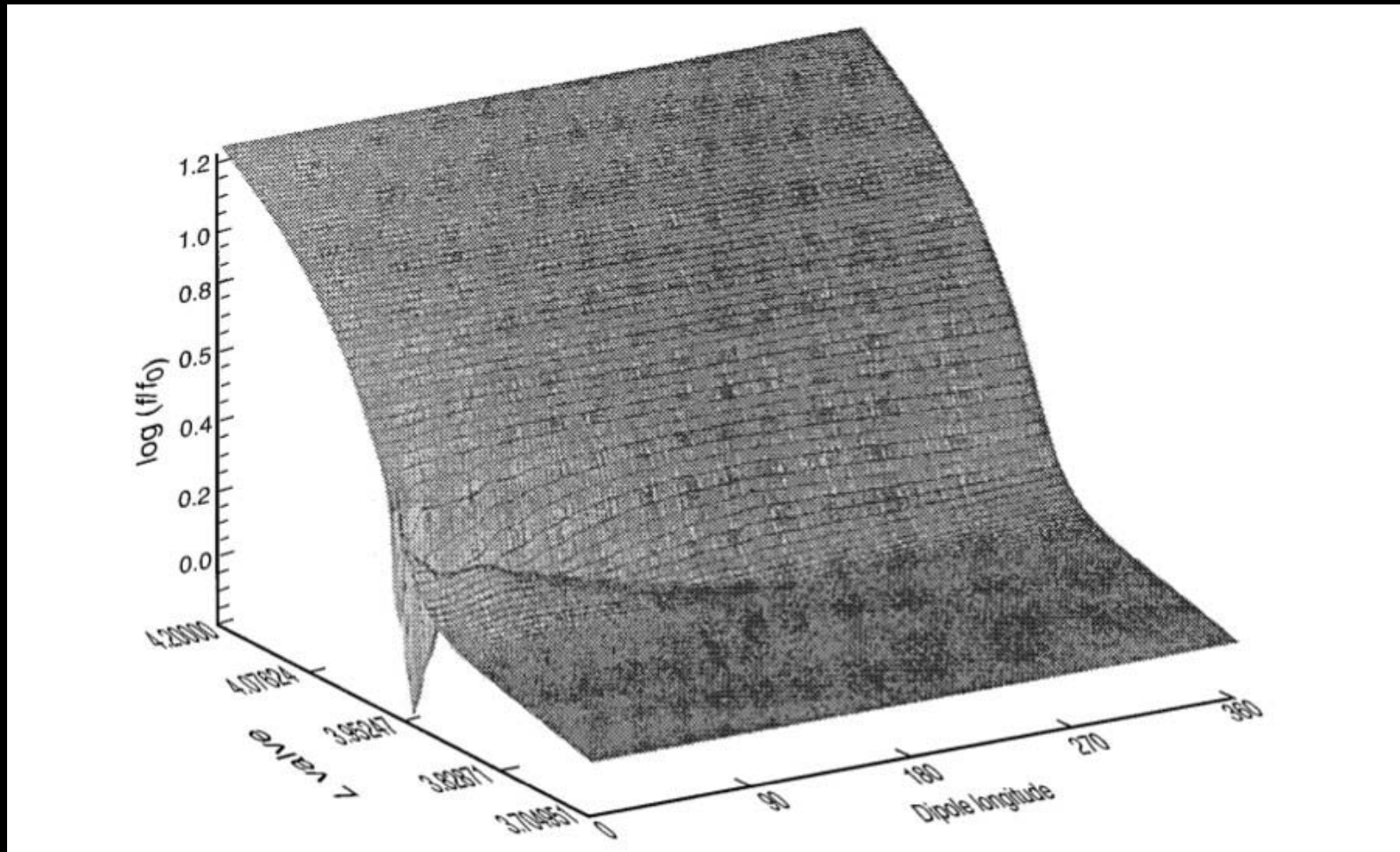
Cassini/MIMI data taken in the Enceladus wakes. Flux depletion (moon absorptions) are seen both in the up- and down-stream plasma regions (Jones et al. 2006)
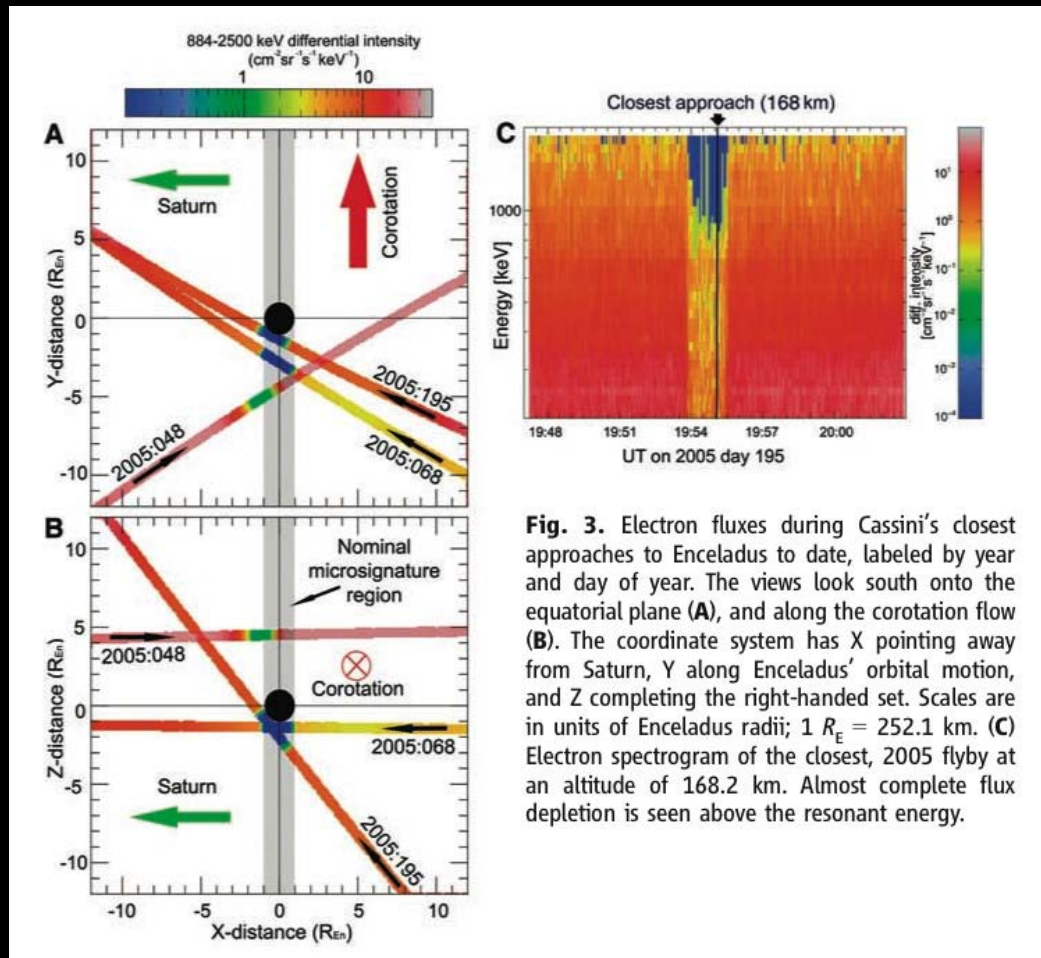

Fig. 3. Electron fluxes during Cassini's closest approaches to Enceladus to date, labeled by year and day of year. The views look south onto the equatorial plane (A), and along the corotation flow (B). The coordinate system has X pointing away from Saturn, Y along Enceladus' orbital motion, and Z completing the right-handed set. Scales are in units of Enceladus radii; 1 R_E = 252.1 km. (C) Electron spectrogram of the closest, 2005 flyby at an altitude of 168.2 km. Almost complete flux depletion is seen above the resonant energy.

MIMI data obtained in the Tethys wake and a model of diffusive fill-in (Roussos et al. 2007)
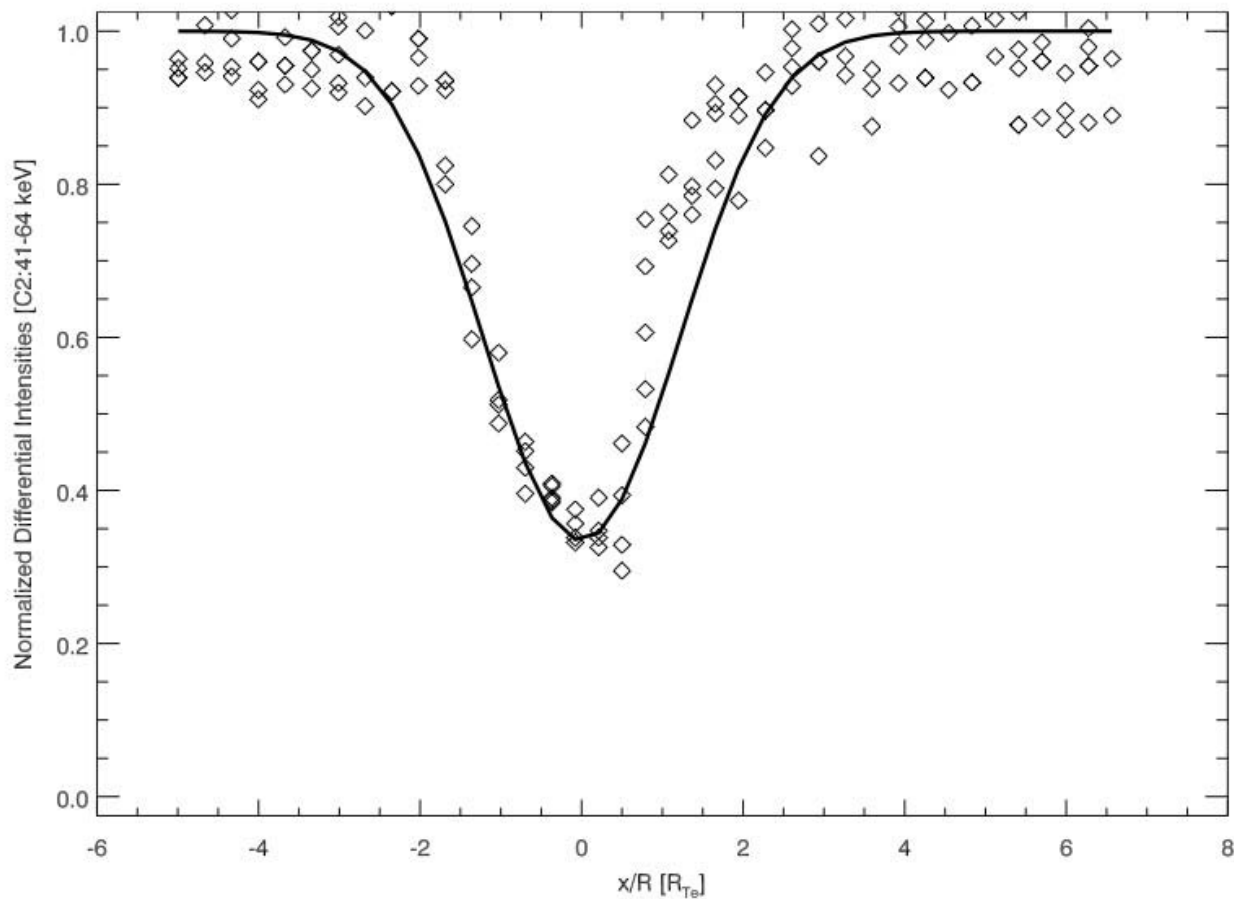
The discovery of the Enceladus plume showed that the environment of the body is often perturbed from the purely inert case (Dougherty et al. 2006)
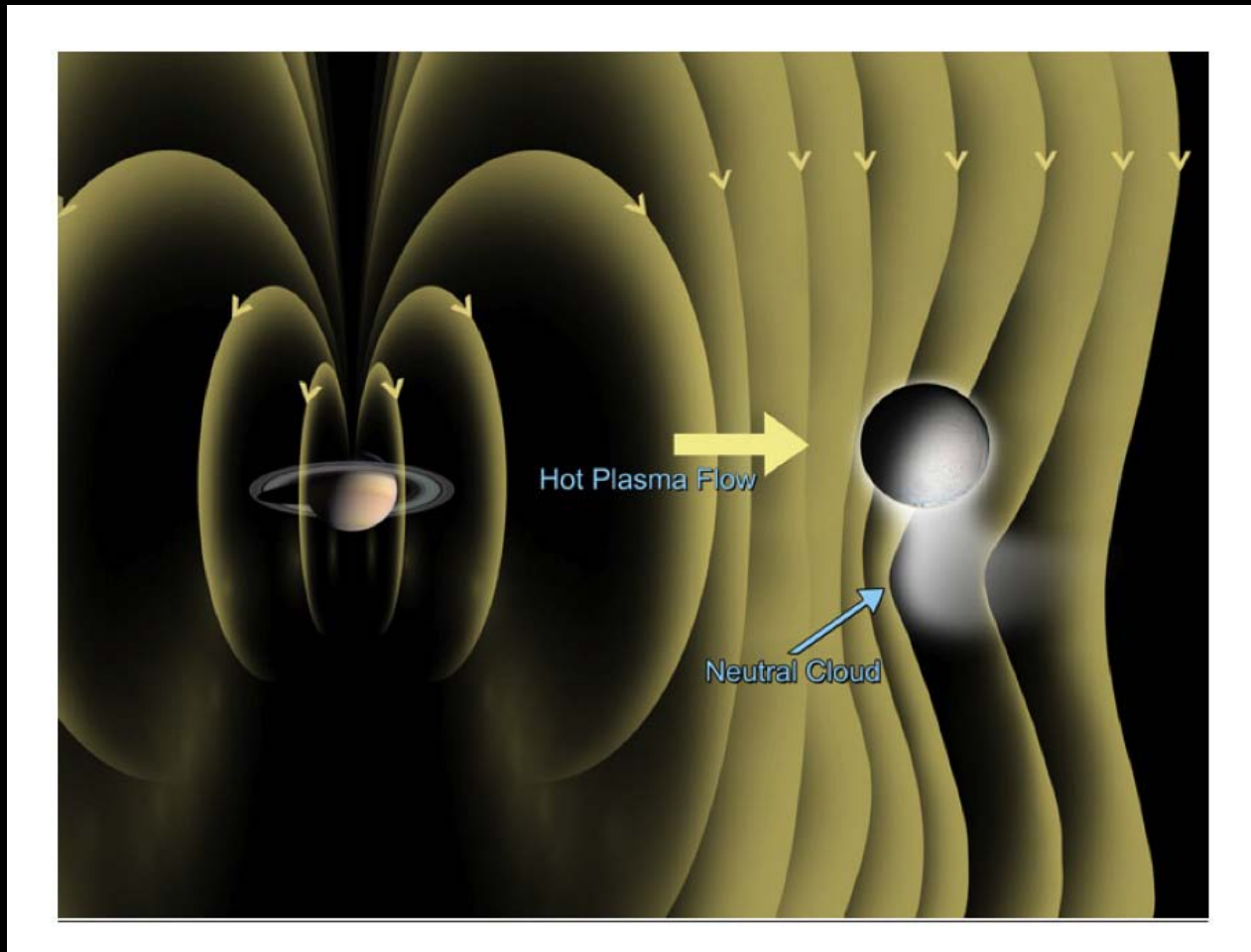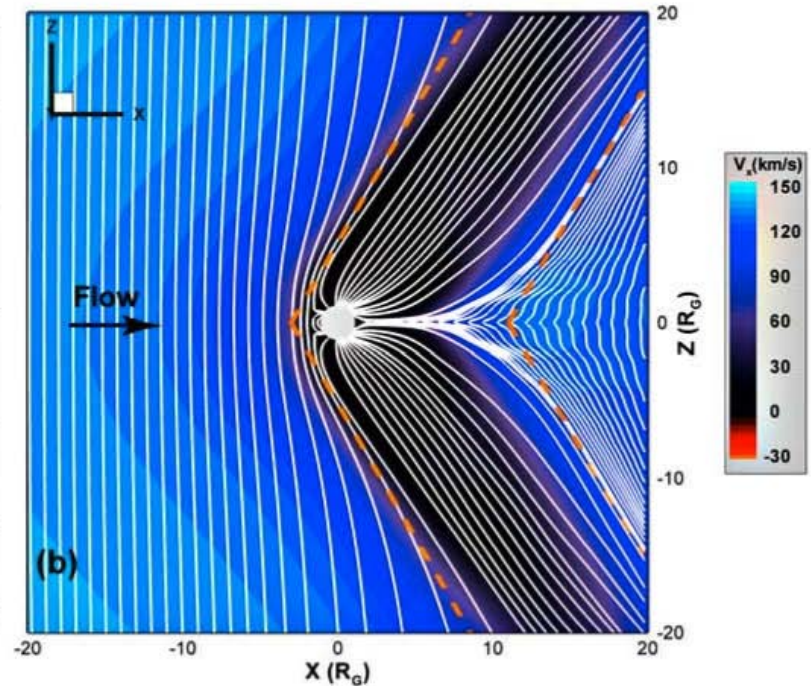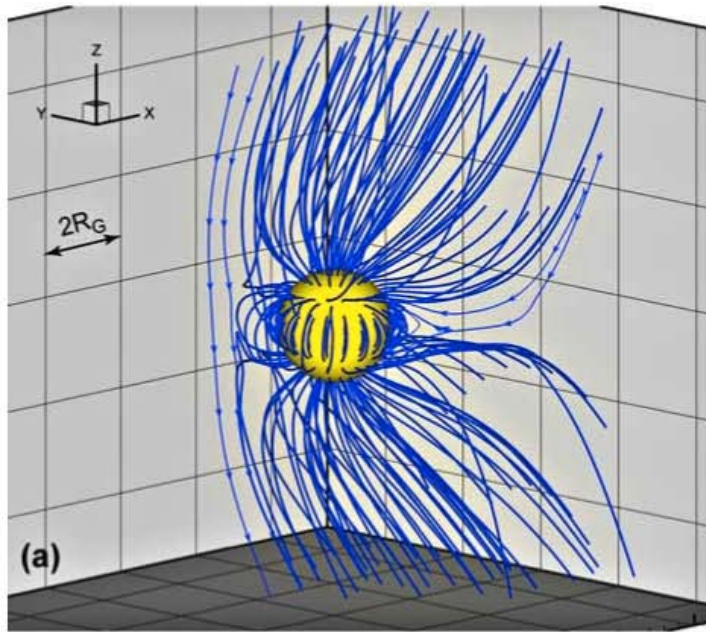
Some modeling that has been done for the Saturnian satellites involves assuming they are inert bodies

For the Jovian satellites, this is often not the case

For instance, the moon Ganymede produces a magnetic field of its own

This model of Ganymede's interaction shows how the plasma flow is slowed down by the moon's presence (right). From Jia et al. (2008)
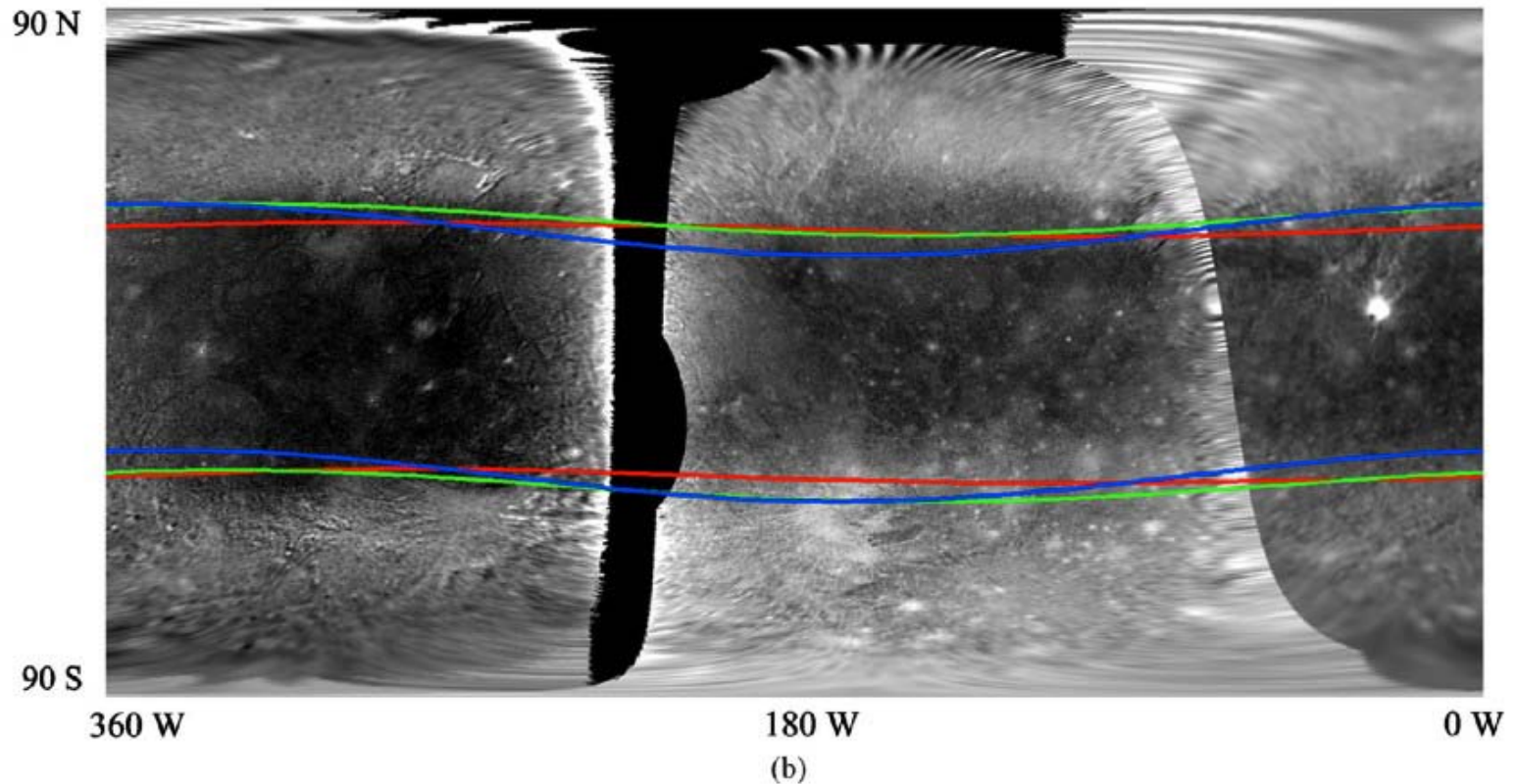
# Impact of magnetospheres on satellite surfaces

Sketch from Johnson et al. (2004) showing how charged particles impacting a surface can be involved in chemical processes
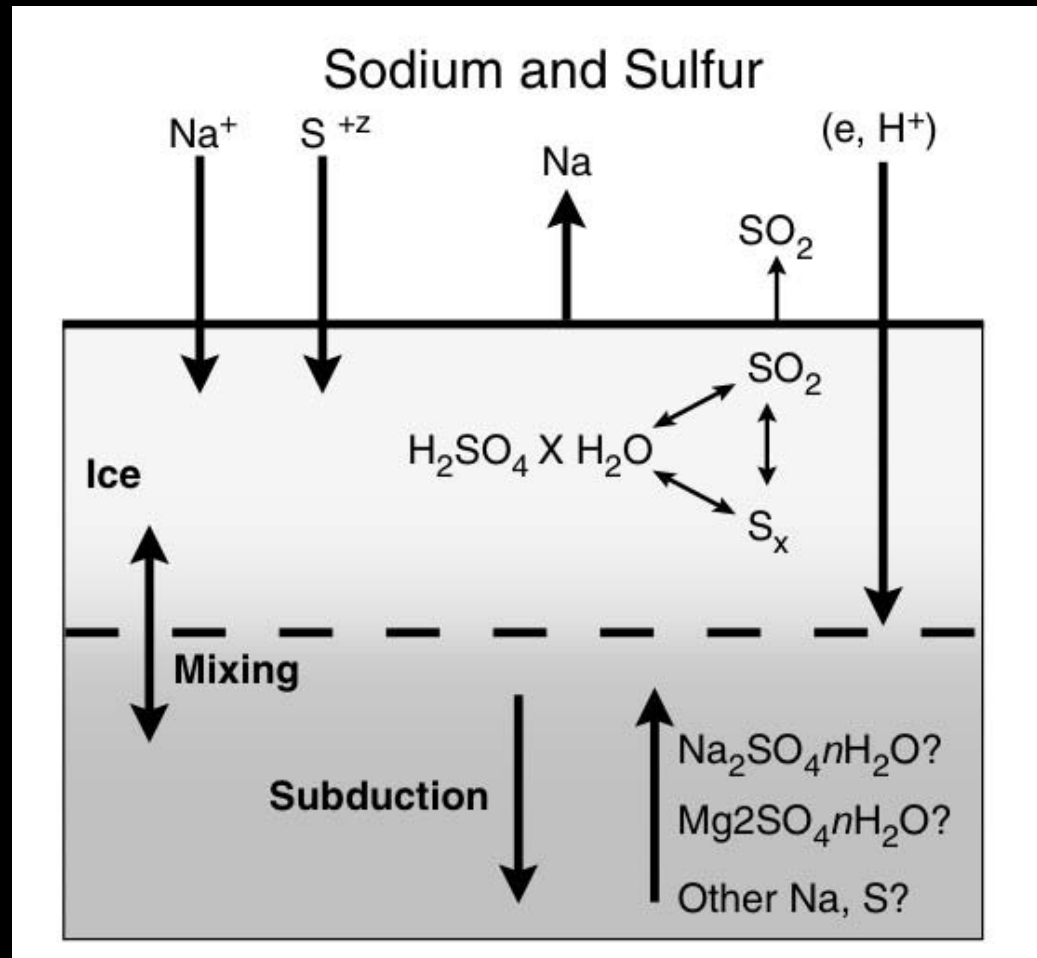
The surface of Ganymede in color ratio illustrating that the portion of the surface with magnetic field lines connecting to Jovian ones is brighter (Khurana et al. 2007)

(b)

**Data-derived model of the distribution of energetic electron flux impacting Europa's surface. The apex of the trailing hemisphere receives the highest dose. Figure created by C. Monaco, APL.**
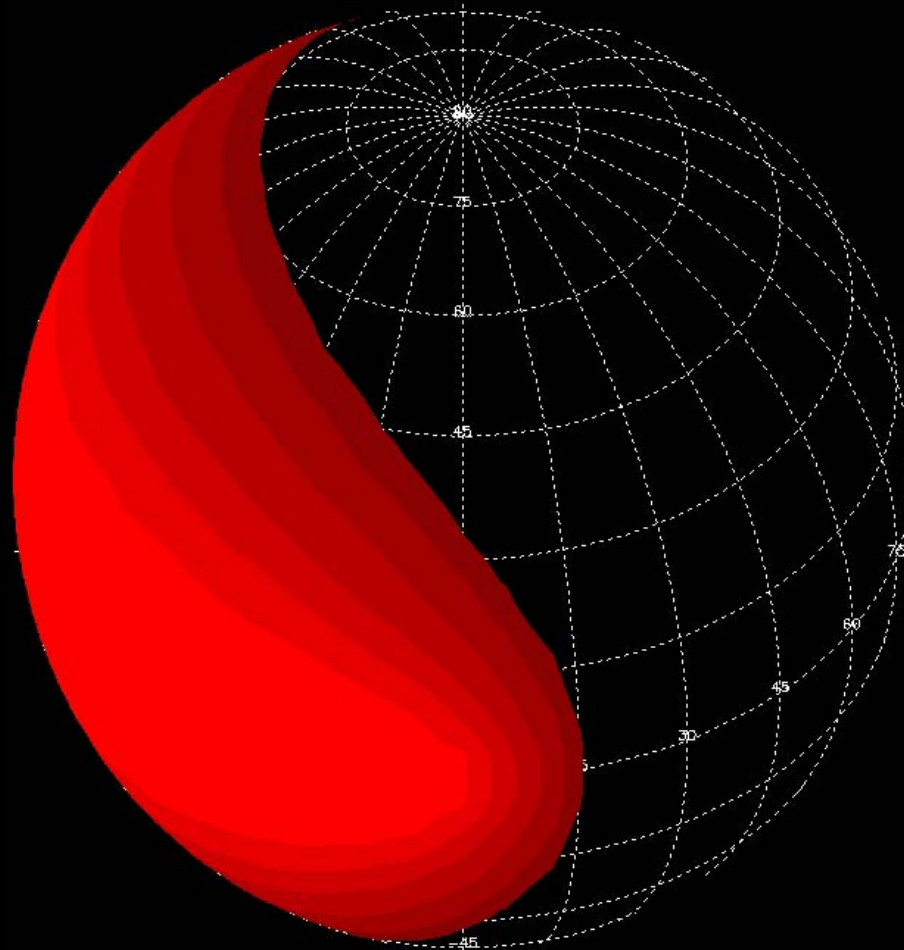
Galileo NIMS images of Europa's surface illustrating a concentration of hydrated SO₂ in a "lens" or "bull's-eye" pattern (in Paranicas et al. 2001)
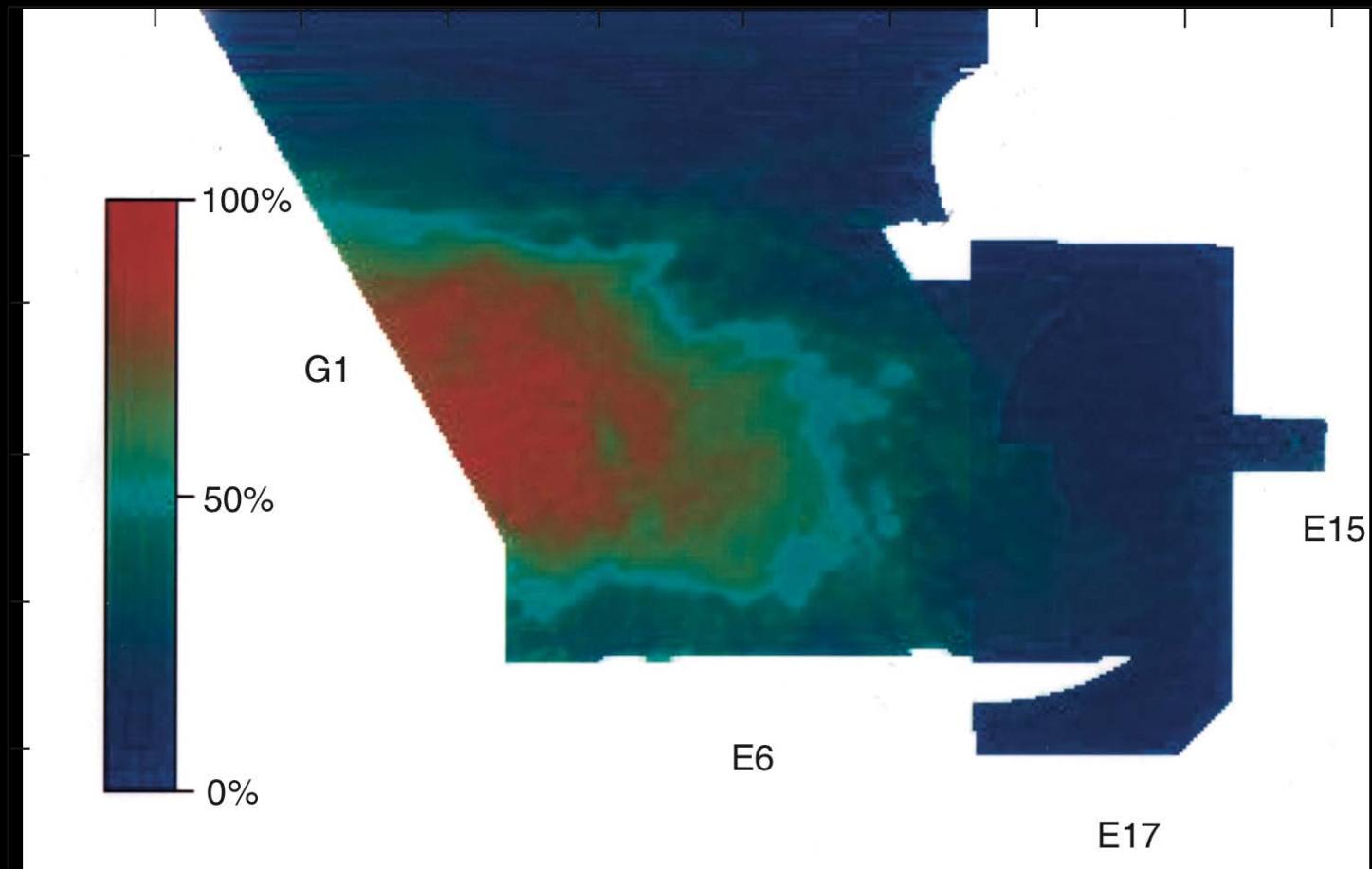
Superimposed calculation of electron input into Europa's surface and NIMS image
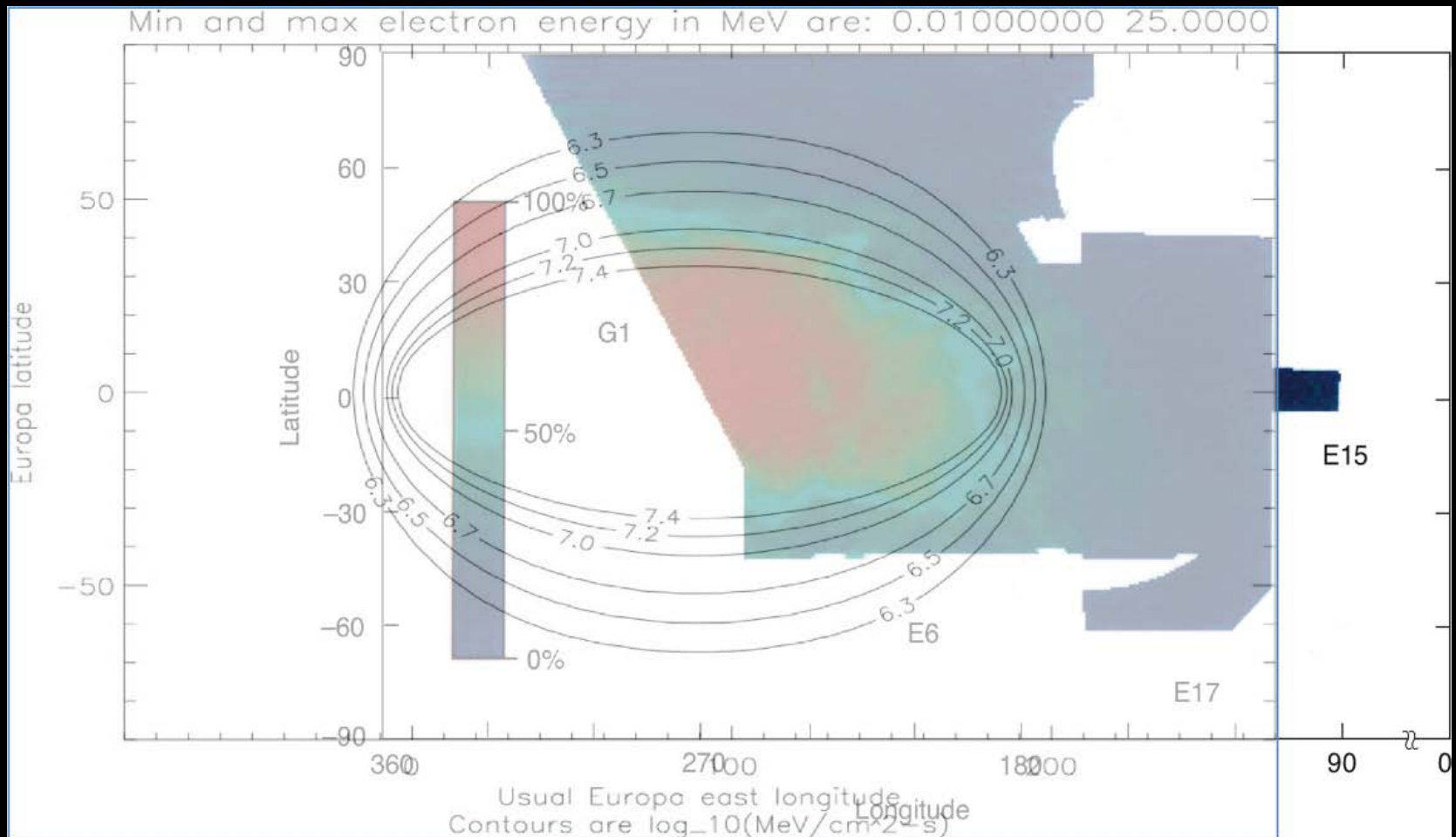
Conclusions

- **Take away message:**
  - We are using data and modeling to understand the interactions of satellites with magnetospheres
  - These influence each other and their influence gives us clues about the systems involved
  - For example…
  - The Io volcanoes add a lot of mass to the magnetosphere; as these particles are ionized and accelerated, currents influence the polar aurora
  - Some surface constituents at Europa may be the product of weathering and do not reveal properties of the deep interior
  - The polar caps of Ganymede are "brightened" by charged particles
  - The Enceladus plumes were foreshadowed by perturbations to the magnetic field….

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Dougherty, M. K., et al. (2006), Identification of a dynamic atmosphere at Enceladus with the Cassini magnetometer , *Science, 311*, 1406-1409.

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Jia, X., et al. (2008), Three-dimensional MHD simulations of Ganymede's magnetosphere, *J. Geophys. Res., 113*, A06212, doi:10.1029/2007JA012748.

Johnson, R. E., R. W. Carlson, J. F. Cooper, C. Paranicas, M. H. Moore, and M. C. Wong (2004), Radiation effects on the surfaces of the Galilean satellites, in *Jupiter: The Planet, Satellites and Magnetosphere*, F. Bagenal, T. Dowling, and W. McKinnon (Eds.), pp. 485-512, Cambridge University Press, Cambridge.

Jones, G. H., et al. (2006), Enceladus's varying imprint on the magnetosphere of Saturn, *Science, 311,* 1412-1415.

Kivelson, M. G., F. Bagenal, W. Kurth, F. M. Neubauer, C. Paranicas, and J. Saur (2004), Magnetospheric interactions with satellites, in *Jupiter: The Planet, Satellites and Magnetosphere*, F. Bagenal, T. Dowling, and W. McKinnon (Eds.), pp. 513-536, Cambridge University Press, Cambridge.

Khurana, K. K., et al. (2007), The origin of Ganymede's polar caps, *Icarus, 191*, 193-202.

References -- 2

Krupp, N., et al. (2009), Energetic particles in Saturn's magnetosphere during the Cassini nominal mission (July 2004 -- July 2008), *Planet. Space Sci,* doi10.1016/j.pss.2009.06.010.

Magnetosphere sketches: Several magnetospheric sketches can be found through Google (magnetosphere) and then by choosing the item, "images for magnetosphere." If you go to this page of pictures and click on a particular one, it will usually direct you to the author of the sketch/image and more details

Paranicas, C., J. F. Cooper, H. B. Garrett, R. E. Johnson, and S. J. Sturner (2010), Europa's radiation environment and its effects on the surface, in *Europa*, R. T. Pappalardo, W. B. McKinnon, and K. K. Khurana, (Eds.), pp. 529-544, University of Arizona Press, Tucson.

Paranicas, C., et al. (2005), Some recent research highlights from the planetary magnetospheres and the heliosphere, *The Johns Hopkins Univ. APL Technical Digest, 26,* 156-163 (see also, Clarke, J. (2002), Ultraviolet emissions from the magnetic footprints of Io, Ganymede, and Europa on Jupiter, *Nature, 415*, 997-1000).

Paranicas, C., R. W. Carlson, and R. E. Johnson (2001), Electron bombardment of Europa, *Geophys. Res. Lett., 28*, 673-676.

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Roussos, E., et al. (2008), Discovery of a transient radiation belt at Saturn, *Geophys. Res. Lett., 35*, doi:10.1029/2008GL035767.

Roussos, E., et al. (2007), Electron microdiffusion in the Saturnian radiation belts: Cassini MIMI/LEMMS observations of energetic electron absorption by the icy moons, *J. Geophys. Res., 112*, A06214, doi:10.1029/2006JA012027.

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Williams, D. J. (1999), Radiation belts and beyond, *Johns Hopkins APL Technical Digest, 20(4)*.