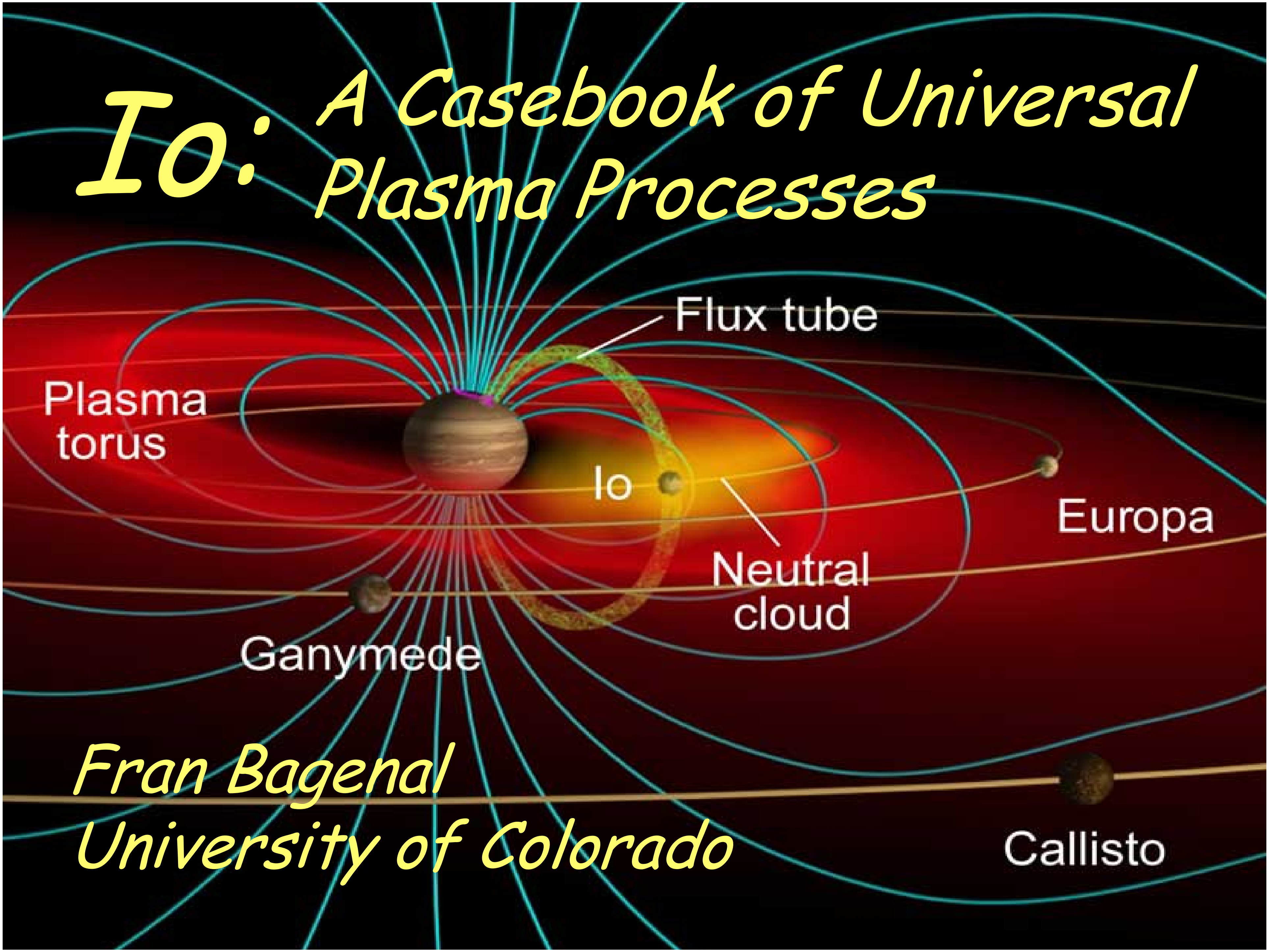
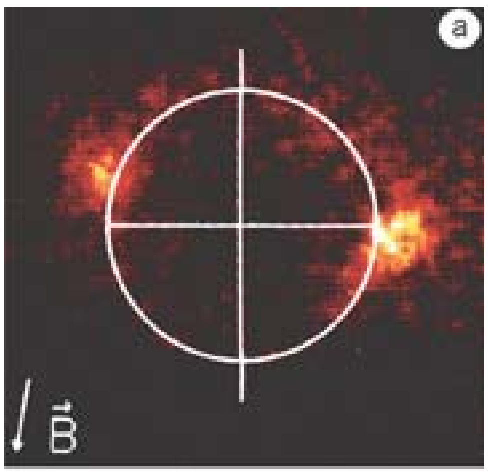
Io: A Casebook of Universal Plasma Processes

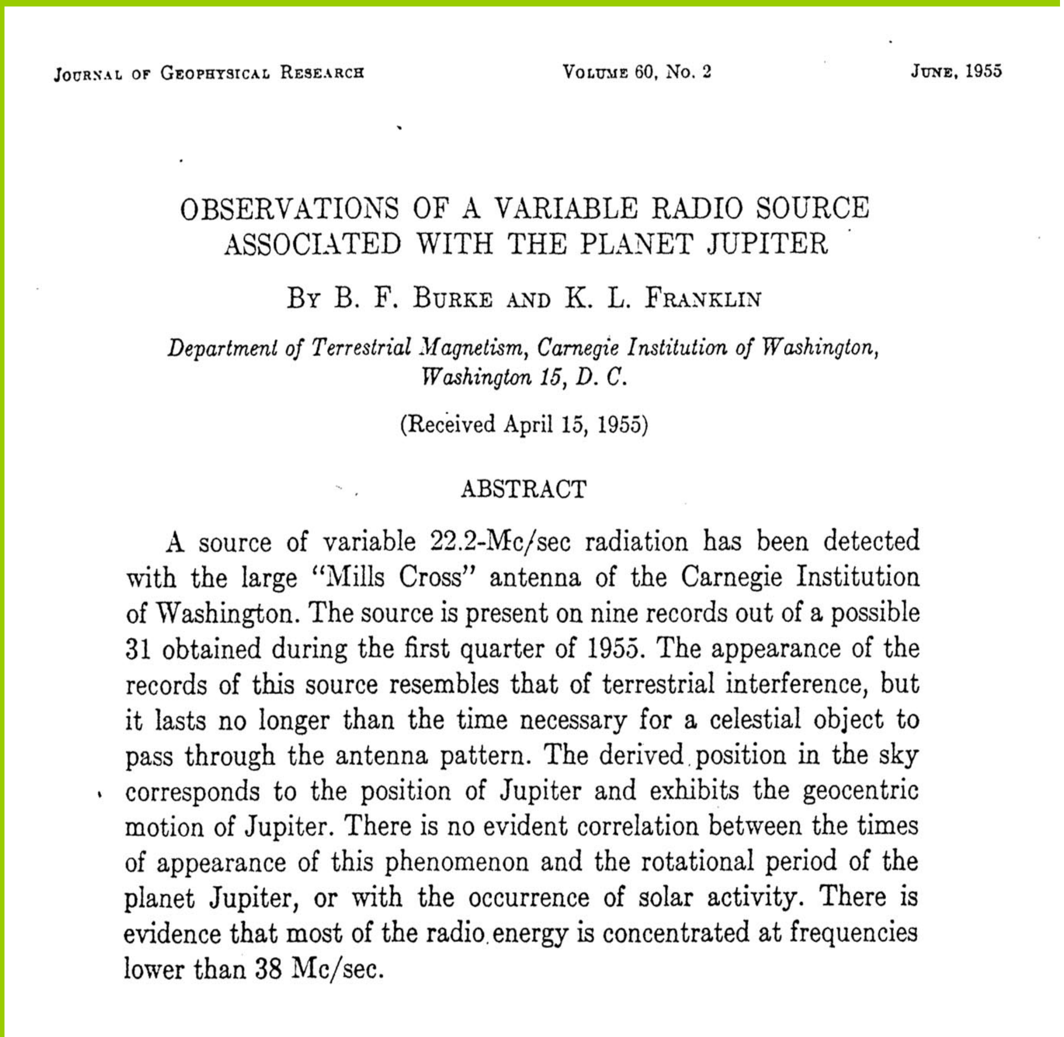


Fran Bagenal
University of Colorado

For example………

Io Story	*Process*	*Universality*
	Auroral emissions $e^- + N$ $\rightarrow N^* + e^-$ $N^* \rightarrow N + h\nu$	

Jupiter Radio Emission Discovered in 1955



JOURNAL OF GEOPHYSICAL RESEARCH VOLUME 60, NO. 2 JUNE, 1955

OBSERVATIONS OF A VARIABLE RADIO SOURCE ASSOCIATED WITH THE PLANET JUPITER

BY B. F. BURKE AND K. L. FRANKLIN

Department of Terrestrial Magnetism, Carnegie Institution of Washington, Washington 15, D. C.

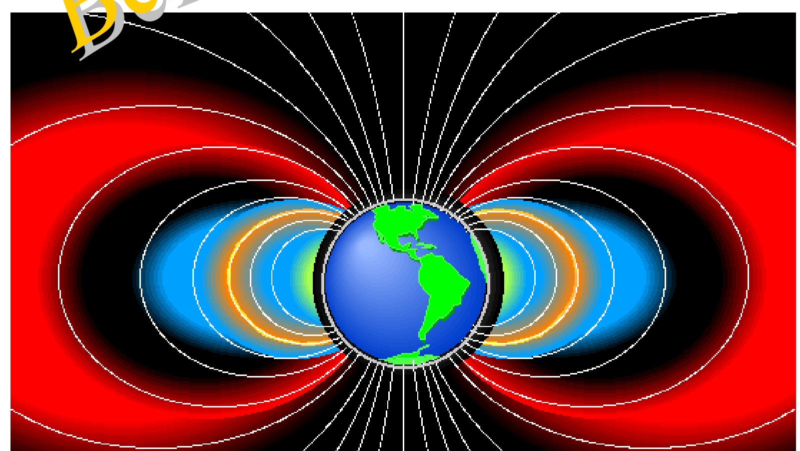
(Received April 15, 1955)

ABSTRACT

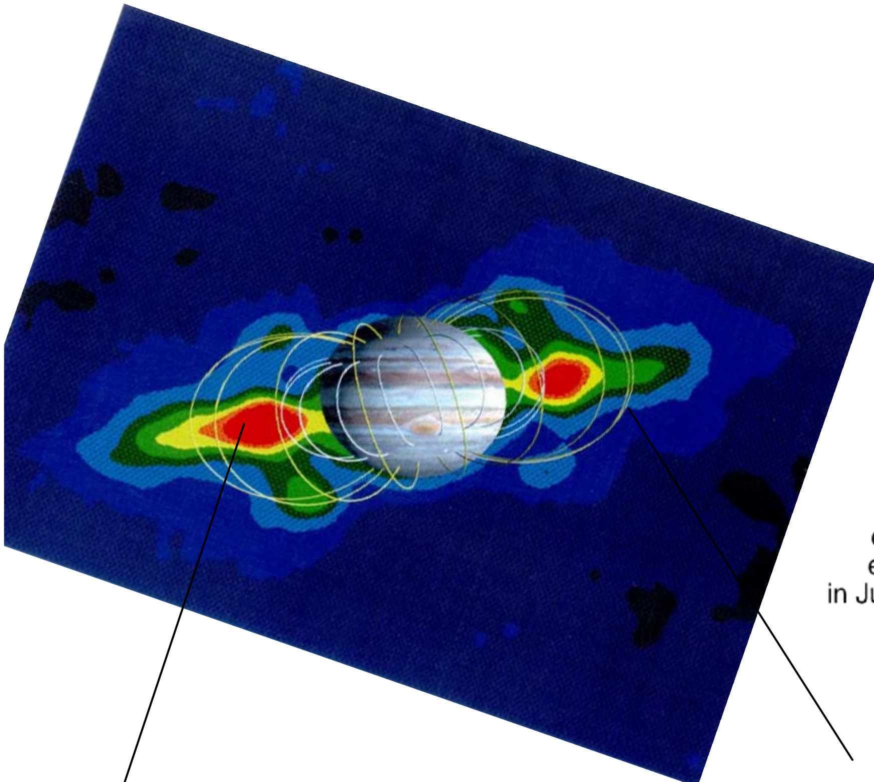
A source of variable 22.2-Mc/sec radiation has been detected with the large "Mills Cross" antenna of the Carnegie Institution of Washington. The source is present on nine records out of a possible 31 obtained during the first quarter of 1955. The appearance of the records of this source resembles that of terrestrial interference, but it lasts no longer than the time necessary for a celestial object to pass through the antenna pattern. The derived position in the sky corresponds to the position of Jupiter and exhibits the geocentric motion of Jupiter. There is no evident correlation between the times of appearance of this phenomenon and the rotational period of the planet Jupiter, or with the occurrence of solar activity. There is evidence that most of the radio energy is concentrated at frequencies lower than 38 Mc/sec.

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Before Explorer 1!

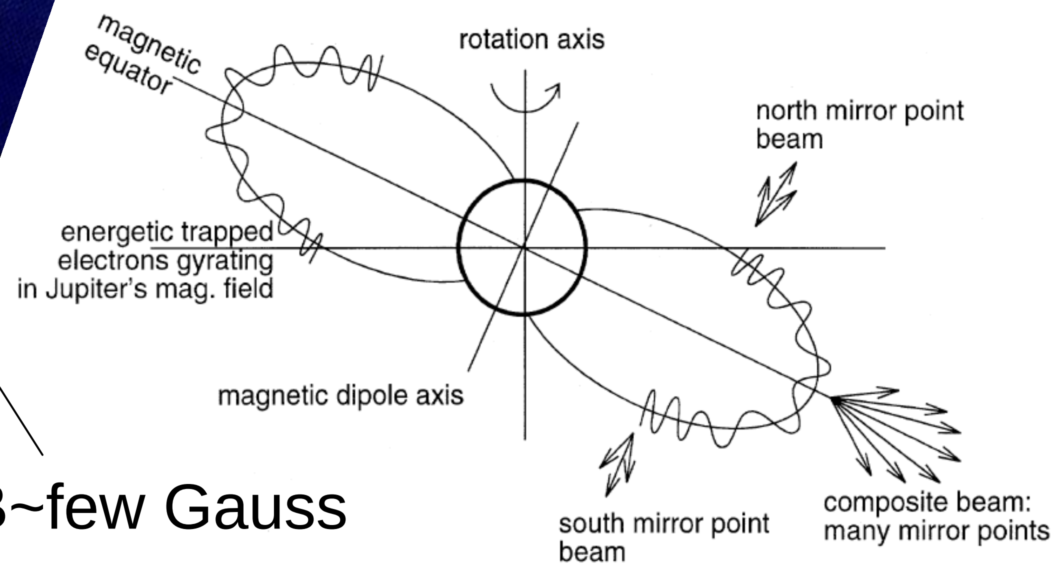


High Frequency f~few GHz Synchrotron Emission



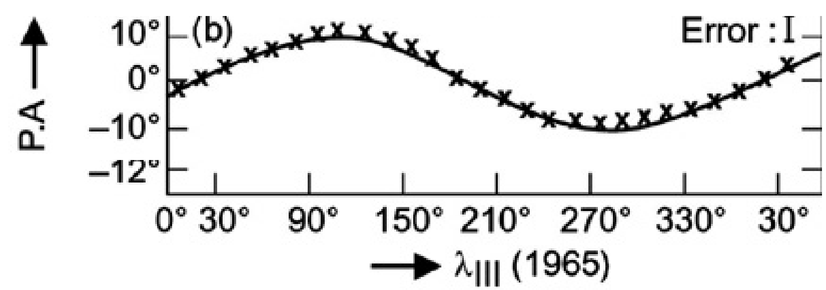
~10s MeV electrons

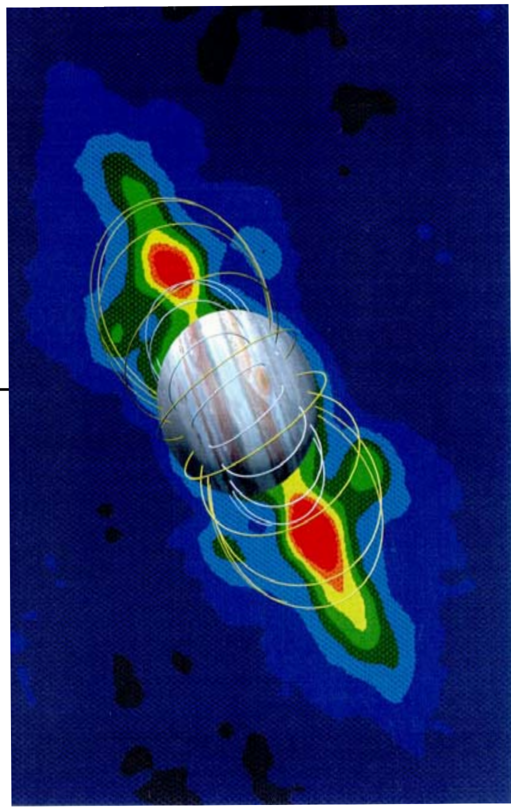
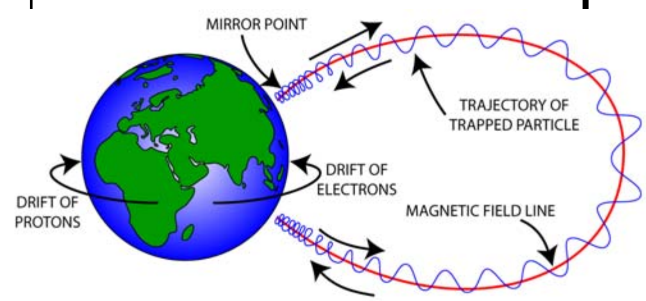
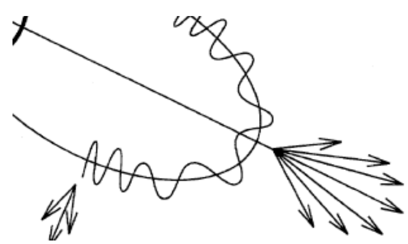
B~few Gauss



~10° tilt of dipole

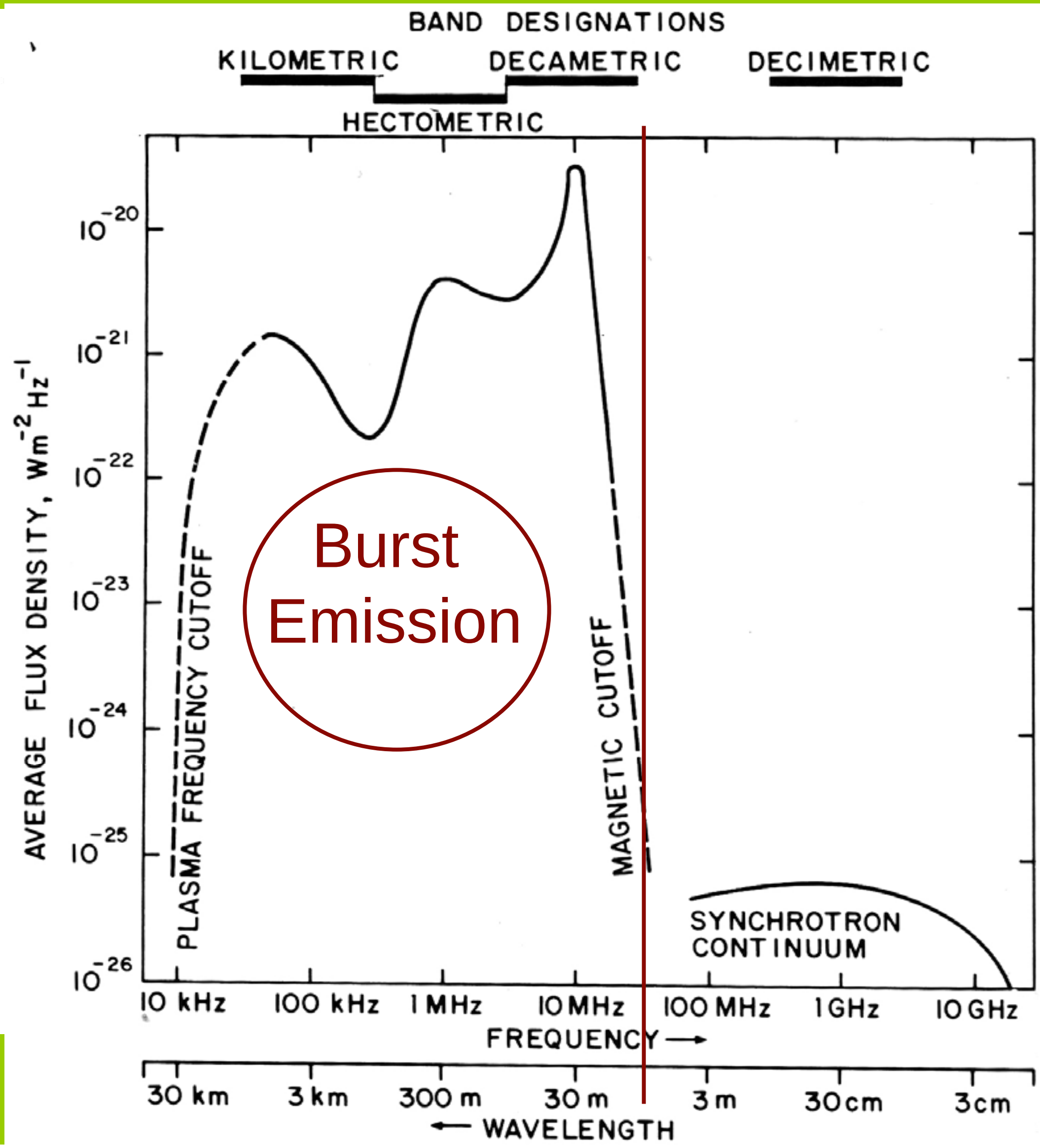
~10 hour rotation rate



Jupiter Story	*Process*	*Universality*
	Radiation Belts	
	Synchrotron Emission 	Astrophysics: Pulsars Magnetars

Come to Next Heliophysics Summ

Jupiter Radio Emission Discovered in 1955



- Jupiter has a magnetic field

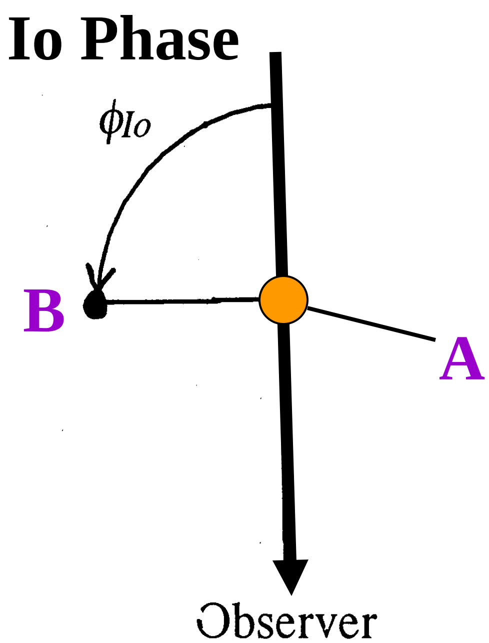
- Trapped electrons

  f_{max} ~ 40 Mhz

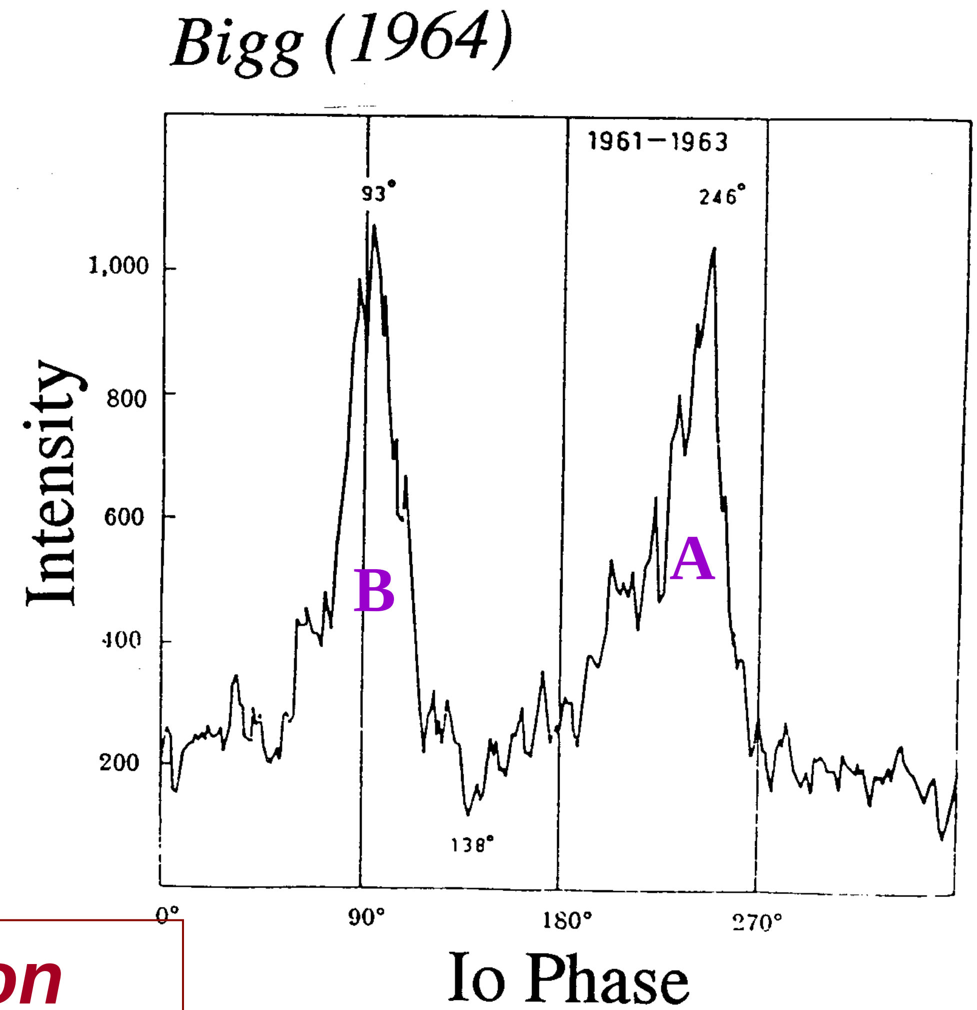
  $f = f_c = qB/2\pi m$

  -> $\boxed{B_{max} \sim 14\ G}$

Early Discoveries

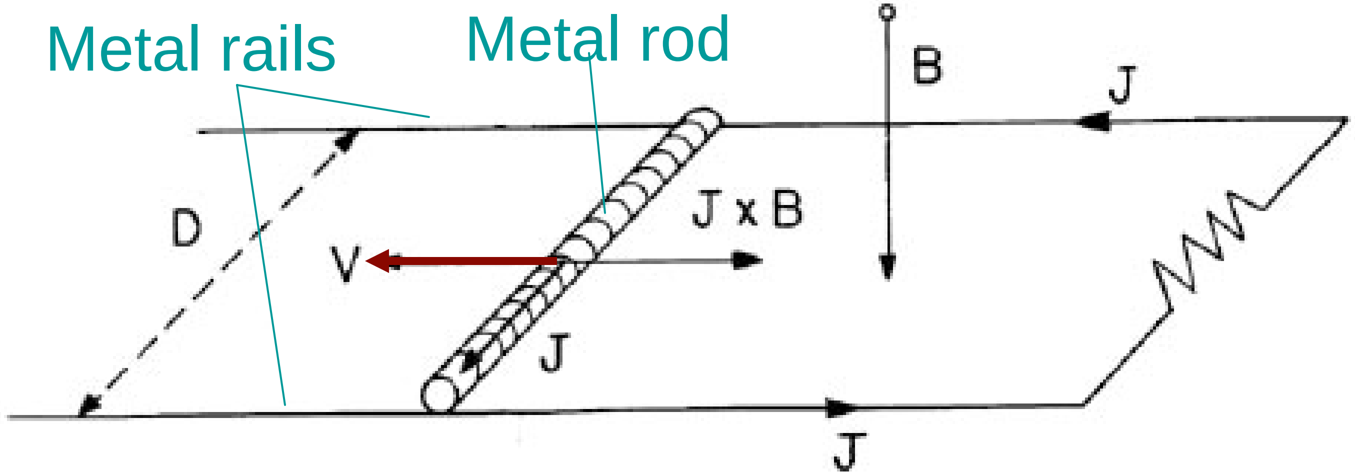


Io's Orbital Period = 42 hours



Jupiter's Radio Emission Controlled by Location of Io

Early Explanations



Goldreich & Lyndon-Bell (1969)

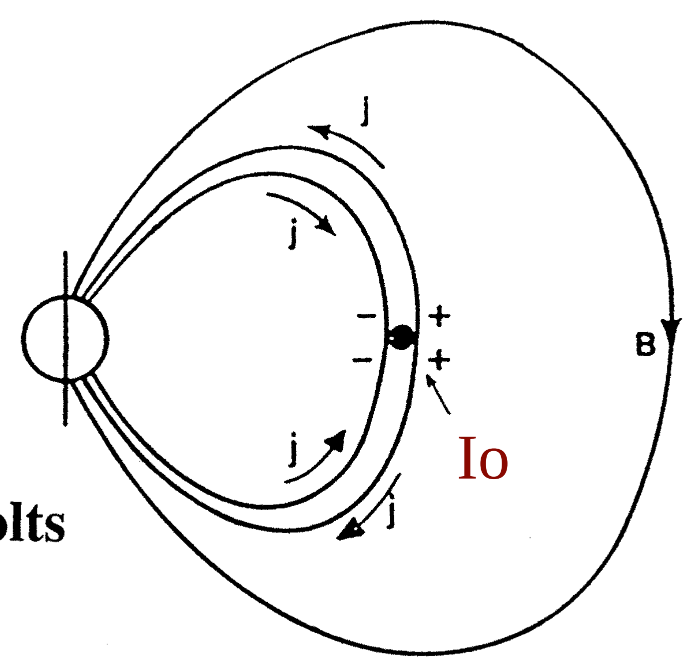
Conductor moving in magnetic field

Piddington & Drake (1968)

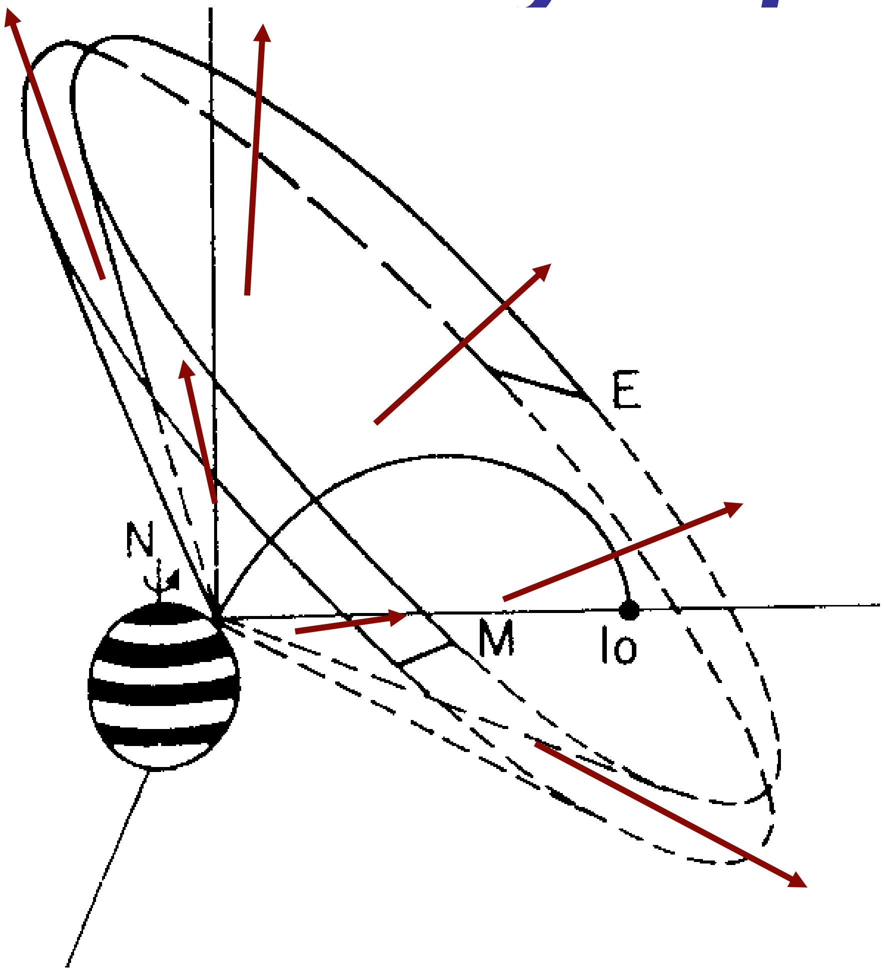
$$\underline{\mathbf{E}} = -\underline{\mathbf{V}} \times \underline{\mathbf{B}}$$

$$\mathbf{V = 57\ km\ s^{-1}}$$

$$\phi = 2\, R_{Io}\, E = 400\ \text{kVolts}$$

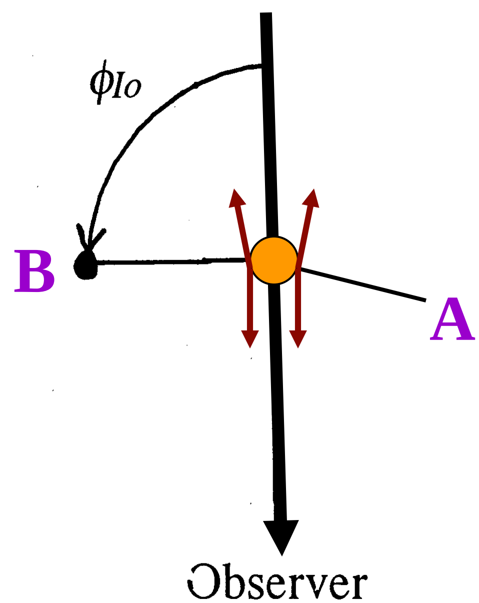


Early Explanations

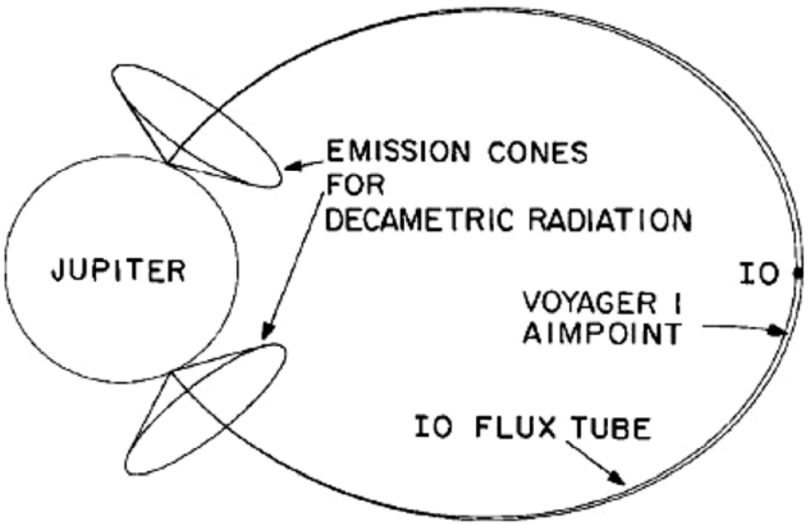


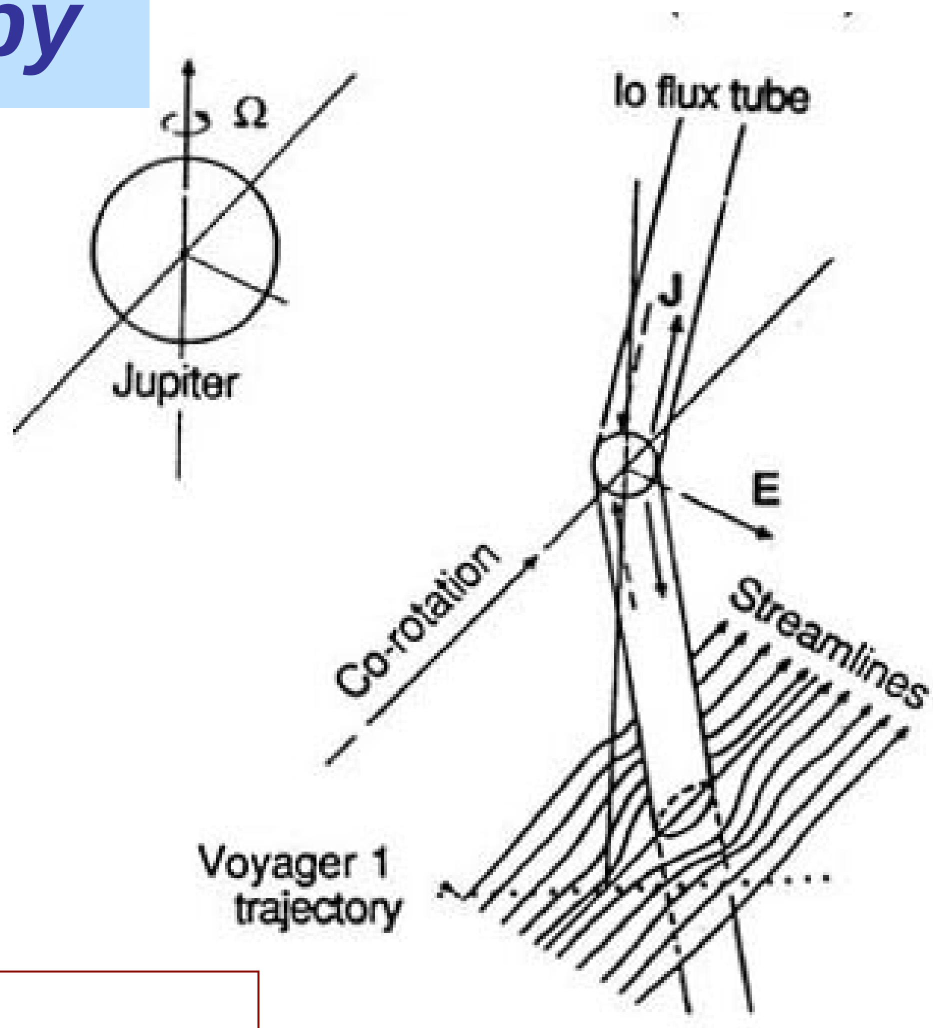
Dulk (1965)

Radio emission beamed in a wide hollow cone on field line connected to Io by a current loop



1979 Voyager flyby





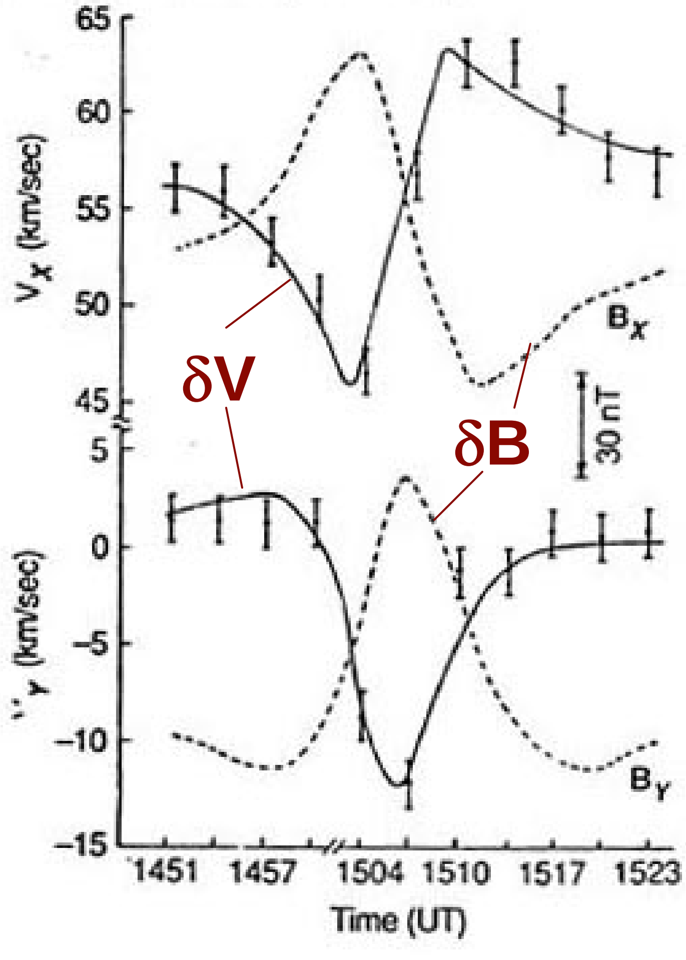
- ~3 x 10^6 Amp current
- δ**B**, δ**V** consistent with Alfven wave

1979 Voyager flyby - The Io Alfven Wave

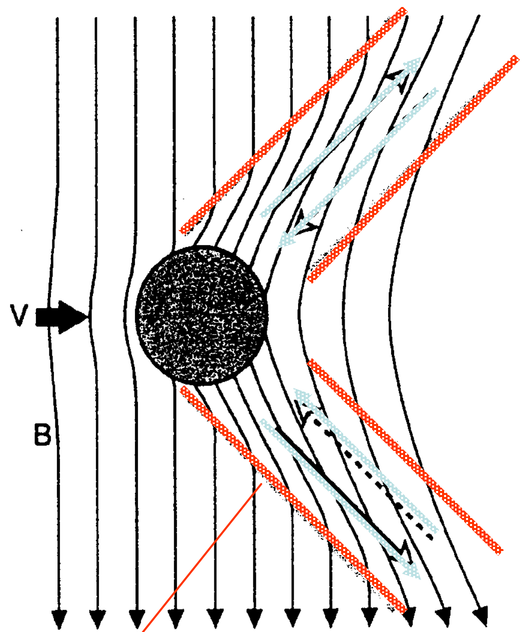
Belcher et al. (1981) *Acuna et al. (1981)*

$$\delta \mathbf{B}/B = -\,\delta \mathbf{V}/V_A$$

$$V_A = B/(\mu_o \rho)^{1/2}$$

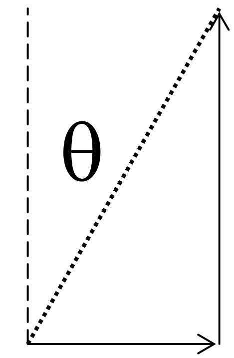


Looking From Side

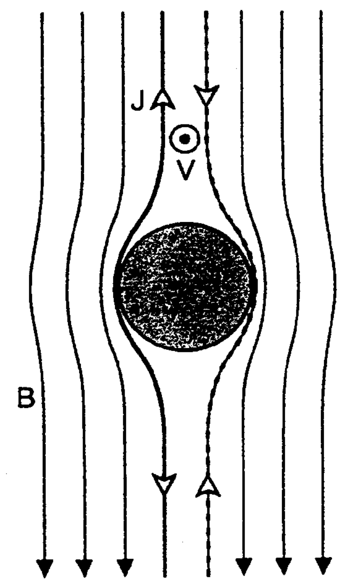


$\theta \sim V_{flow}/V_A$

$\sim 10°$

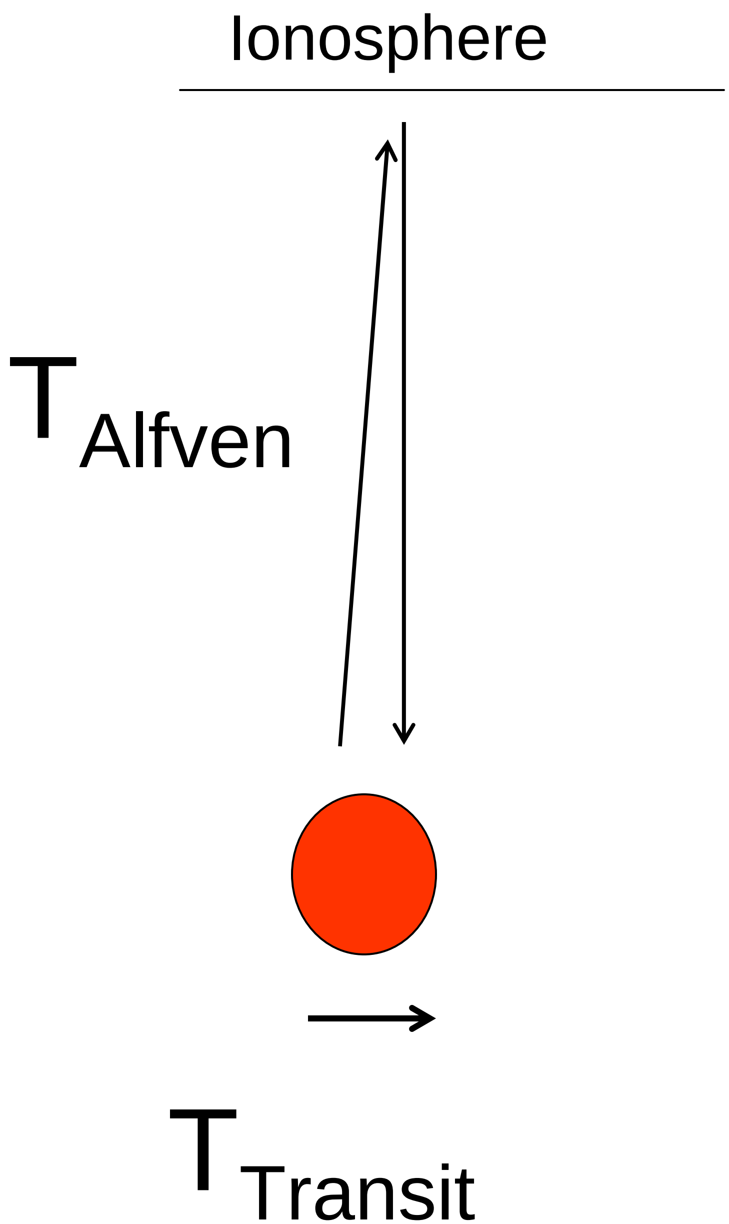


Alfven wing / wave front / characteristic



Looking Upstream

Goertz 1980; Neubauer 1980
Southwood & Kivelson
Belcher 1987



Alfvenic Interaction

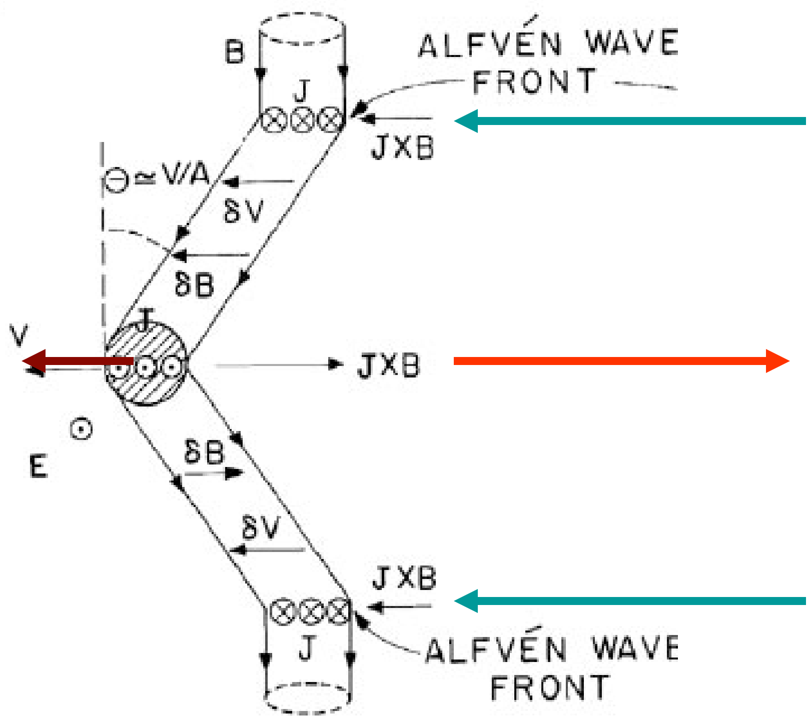
$T_{alfven} > T_{Transit}$

DC Current Loop

$T_{alfven} < T_{Transit}$

Momentum Coupling by Alfven Wave

Motion of Io relative to plasma



Slowing of ambient plasma

Acceleration of Io
Relative to Io orbital motion

Slowing of ambient plasma

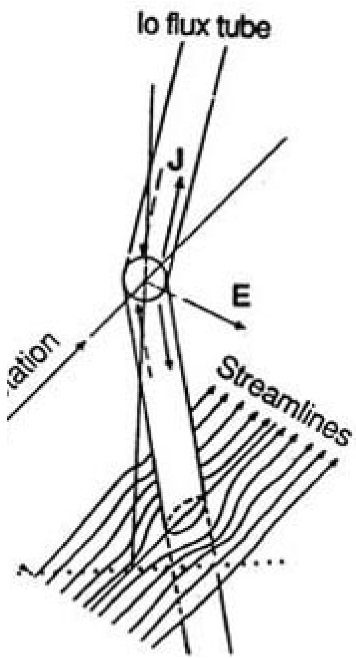
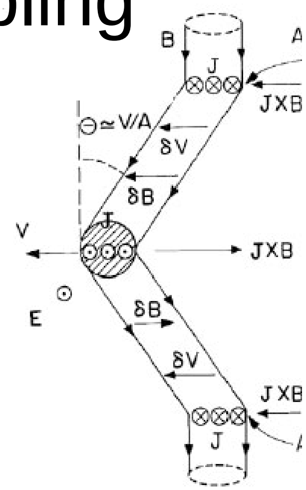
- $F \sim 10^6$ N
- ~ thrust of a Saturn V booster
- Only moves Io few km outwards in age of solar system

Drell, Foley & Ruderman 1965

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Explained drag on Echo 1 as Alfven wave drag

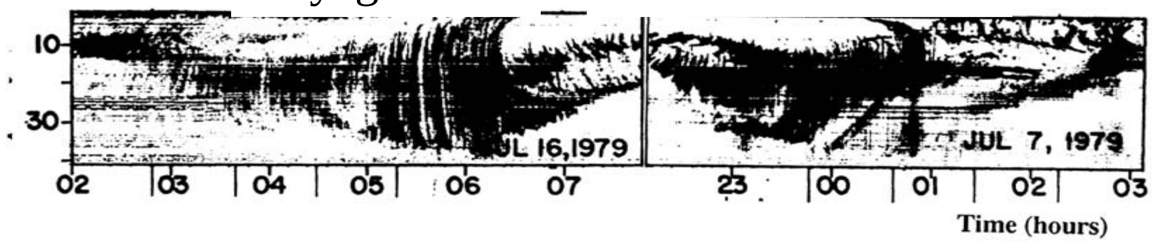
Echo 1 sits fully inflated at a Navy hangar in Weeksville, North Carolina. The spacecraft measured 100 feet across when deployed, and was nicknamed a 'satelloon' by those involved in the project.Echo 1 was launched August 12, 1960, into an orbit with an Apogee of 1684 km, a Perigee of 1523 km and an Inclination of 47.2 degrees. The mylar film balloon acted as a passive communications reflector for transcontinental and intercontinental telephone (voice), radio and television signals. Echo 1 re-entered the atmosphere May 24, 1968

<table>
<tr><th>Io Story</th><th>Process</th><th>Universality</th></tr>
<tr>
<td>
</td>
<td>Momentum Coupling

</td>
<td>Anywhere the field is kinked or plucked
™ and a
l) decompressor
this picture.</td>
</tr>
</table>

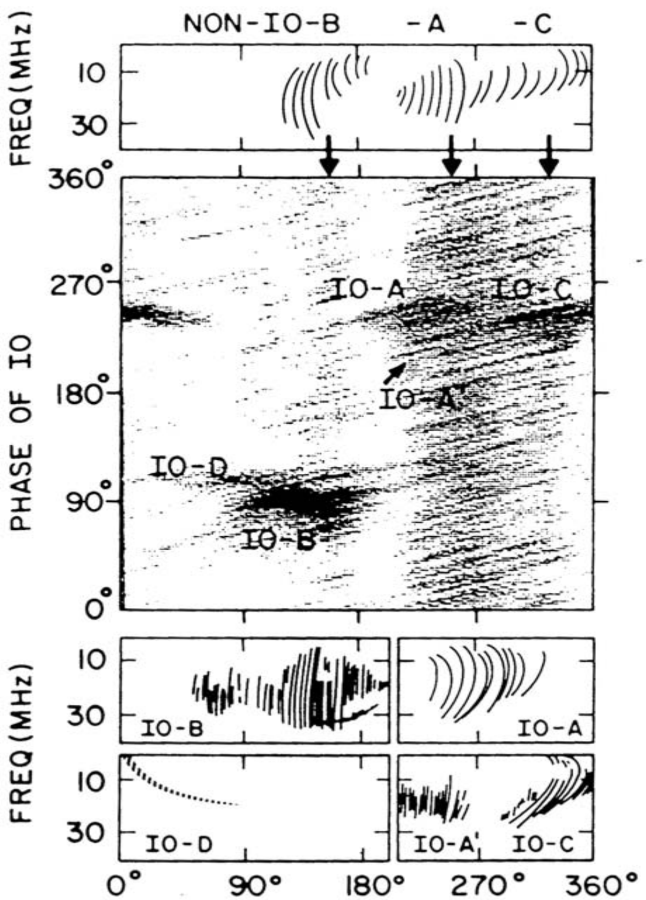
Examples of sorts of places this might happen?

Voyager Radio Discoveries

Voyager PRA *Warwick et al. 1979*

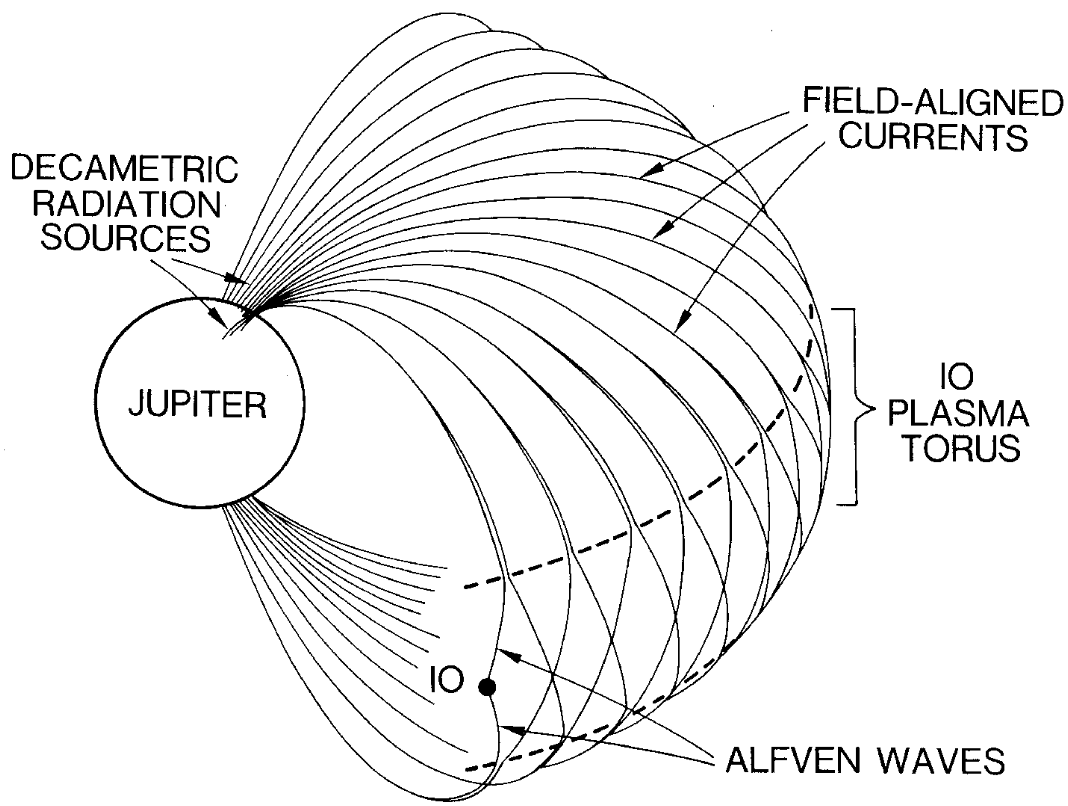


Carr et al. 1983



- ***Repeated patterns of arcs in frequency-time spectrographs***
- ***Indicates systematic beaming pattern, controlled by the geometry of Jupiter's magnetic field***
- ***And location of Io…***

Alfven Wave Theory

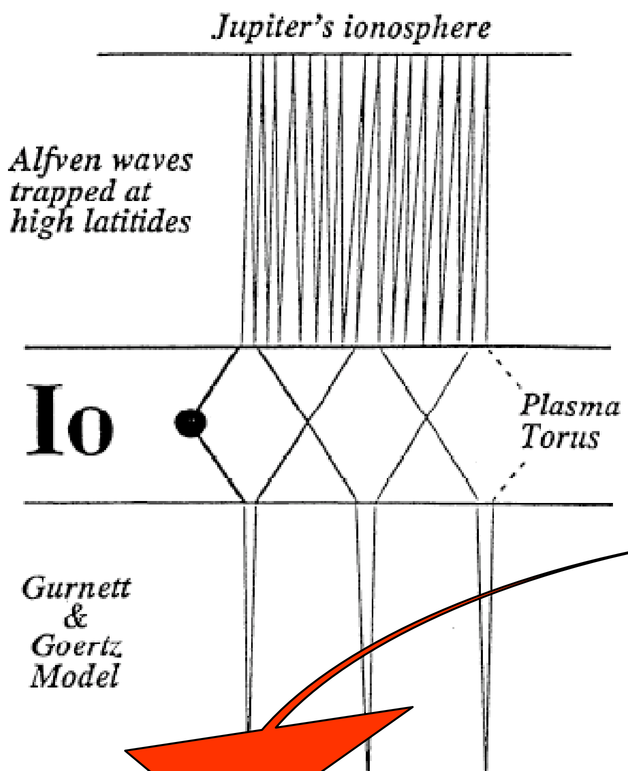


Gurnett & Geortz 1982

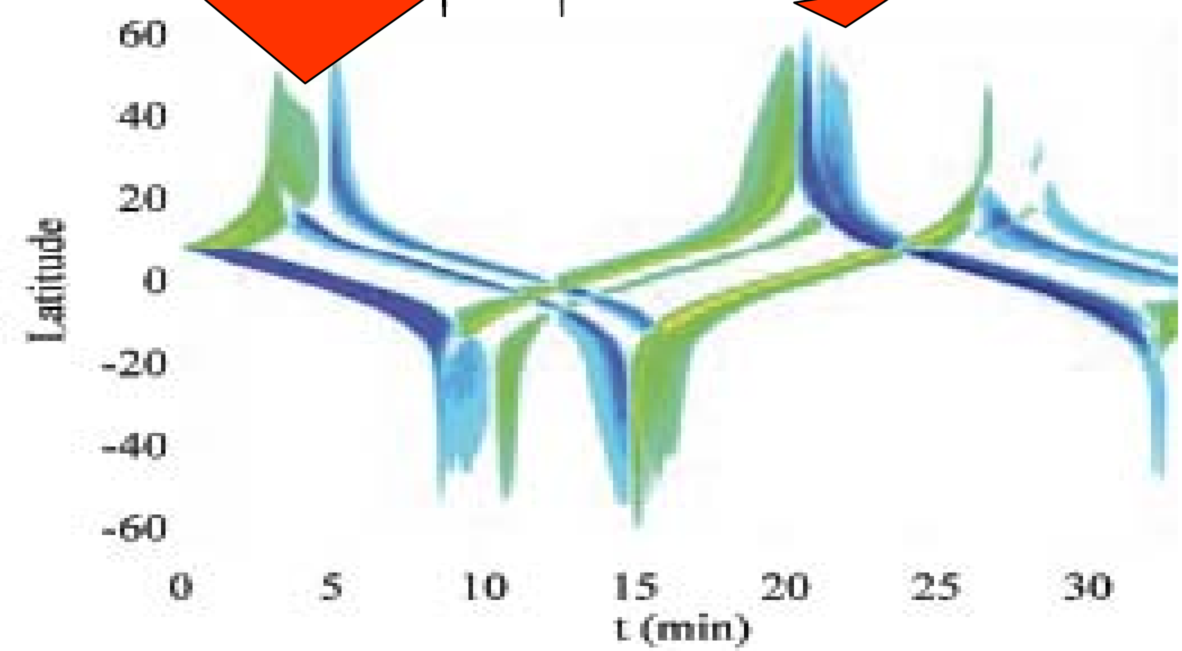
- ***Io generates Alfven waves***
- ***Pattern of reflected waves carried downstream by corotating magnetospheric plasma***
- ***Each Alfven wave excites an arc of radio emission.***
- ***Nice idea—but predicted spacing is ~5 times too big***

Crary & Bagenal 1997

Multiple bounces between torus and Jupiter's ionosphere would explain close space of radio arcs



This is what 1-D modeling of kinetic alfven waves is beginning to produce…



Lysak et al. 2006

Model Equations

Lysak et al. 2006

- Wave modeling based on Maxwell's equations:

$$\varepsilon \frac{\partial \mathbf{E}_\perp}{\partial t} = \frac{1}{\mu_0}(\nabla \times \mathbf{B})_\perp - \mathbf{j}_\perp \qquad \frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E}$$

- Current represents source due to Io, dielectric constant is:

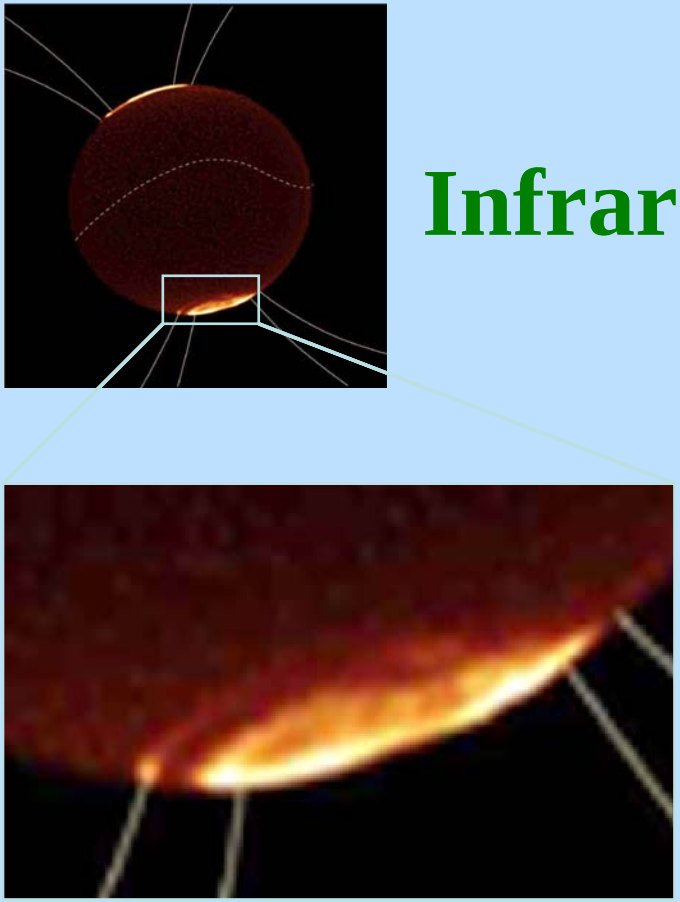
$$\varepsilon = \varepsilon_0 \left(1 + \frac{c^2}{V_A^2}\right)$$

- where the Alfvén speed profile is given by the models above.
- These equations are cast in dipole coordinates, and the Green's function for this system is found using Sturm-Liouville theory, assuming Io is essentially a point source.
- The Poynting flux delivered to the ionosphere can then be calculated as a function of frequency and the location of Io on the flux tube.

The Io Aurora

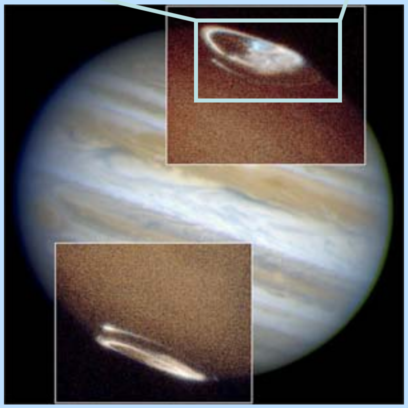
Connerney et al.

Infrared

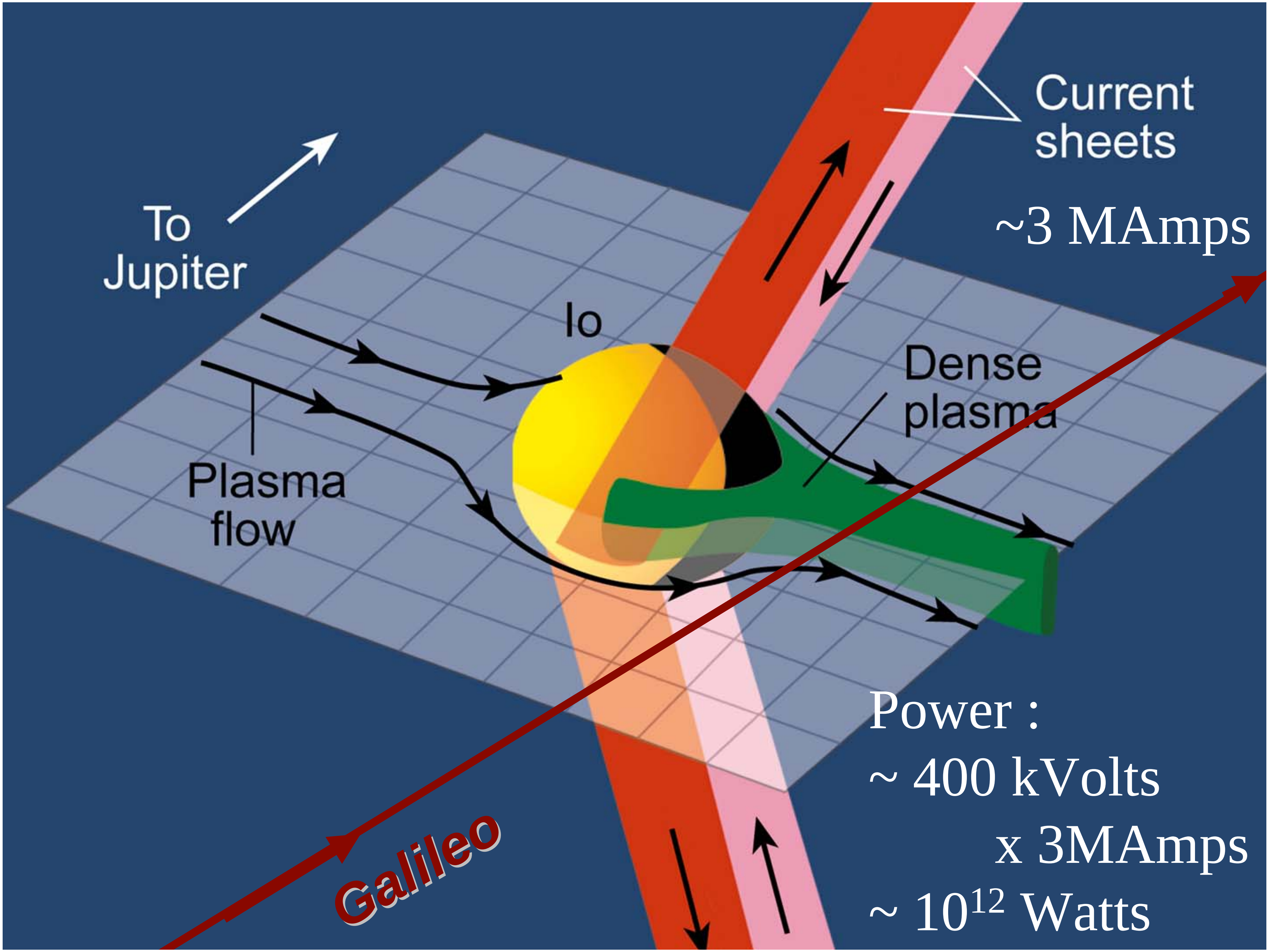


Clarke et al.

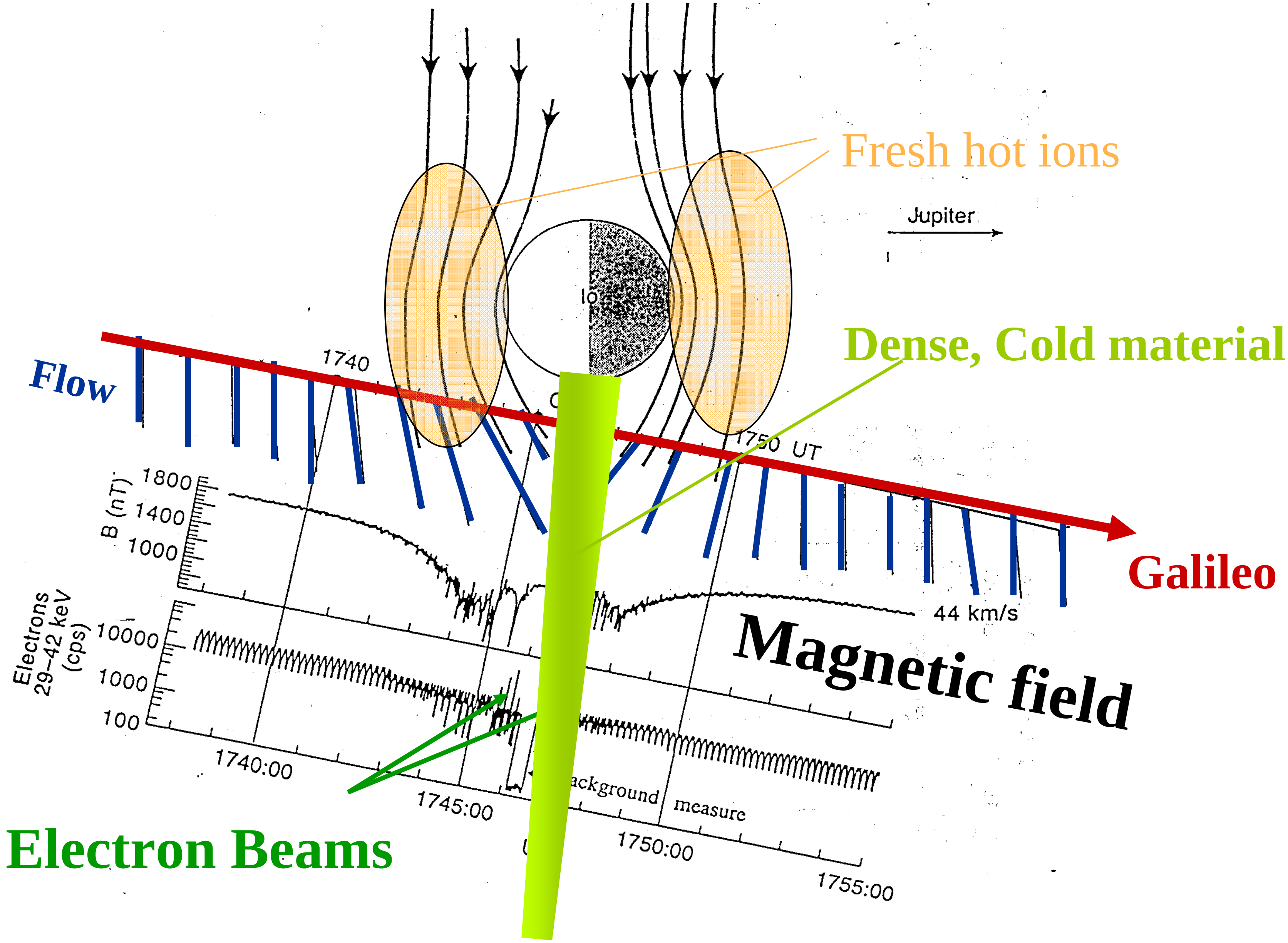
Ultraviolet

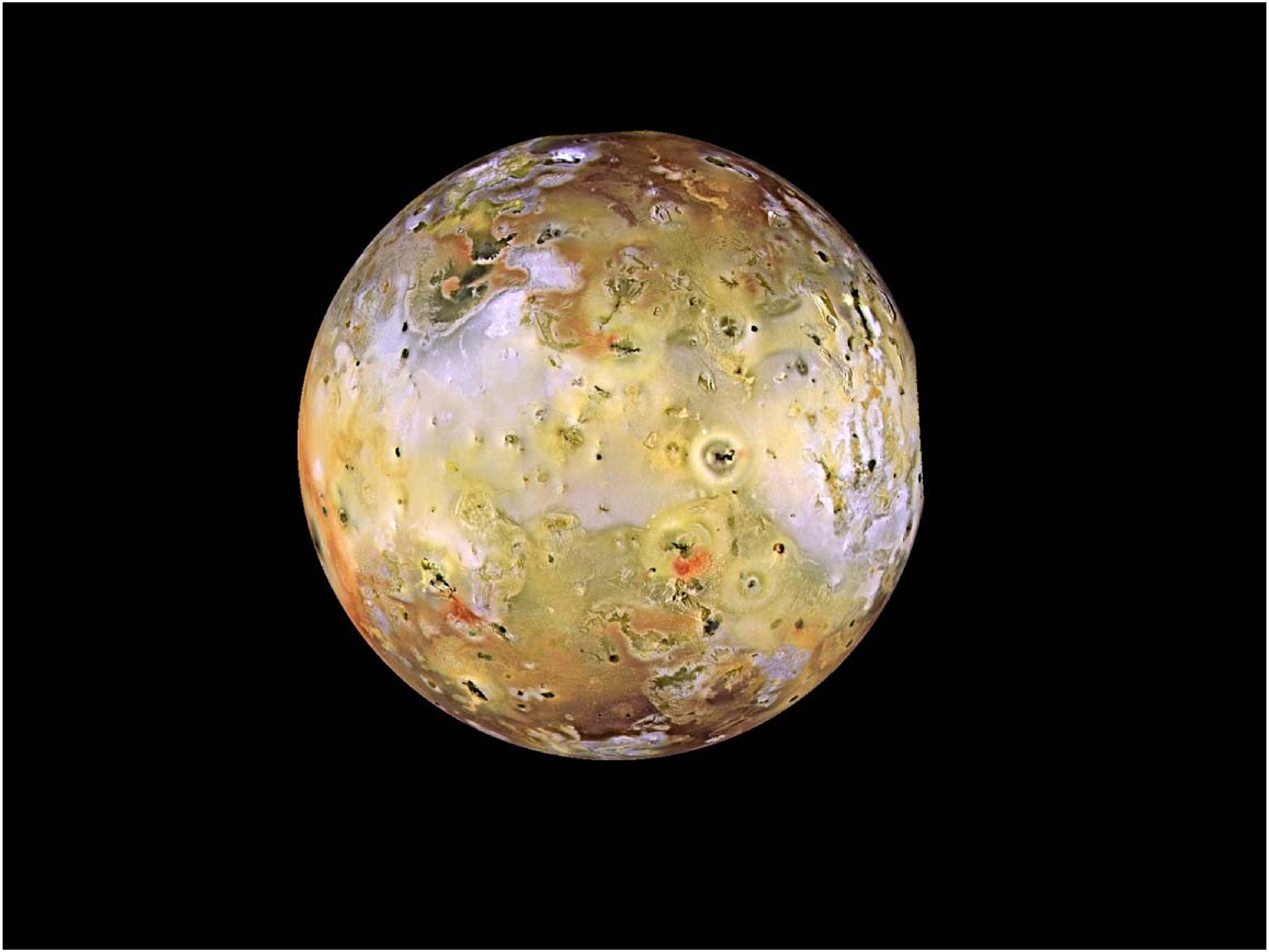


- ***energetic particles - electrons - bombard atmosphere***
- ***'wake' emission extends halfway around Jupiter***

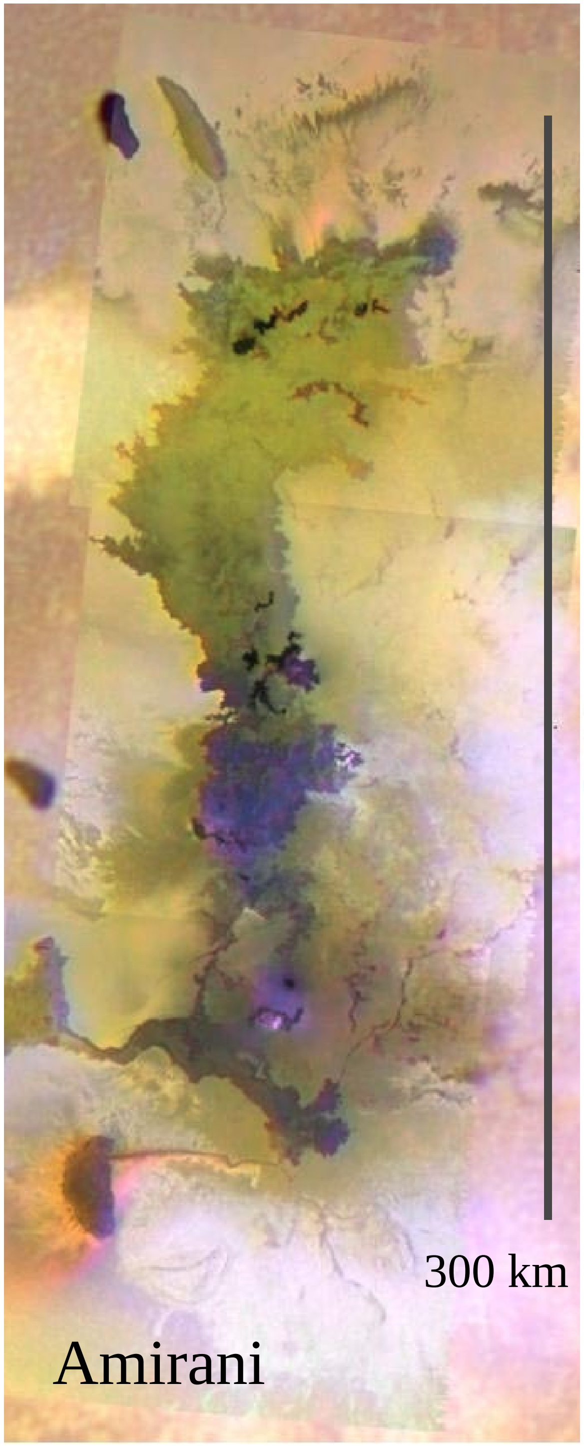

Current
sheets
~3 MAmps
To
Jupiter
Io
Dense
plasma
Plasma
flow
Galileo
Power :
~ 400 kVolts
x 3MAmps
~ 10^12 Watts

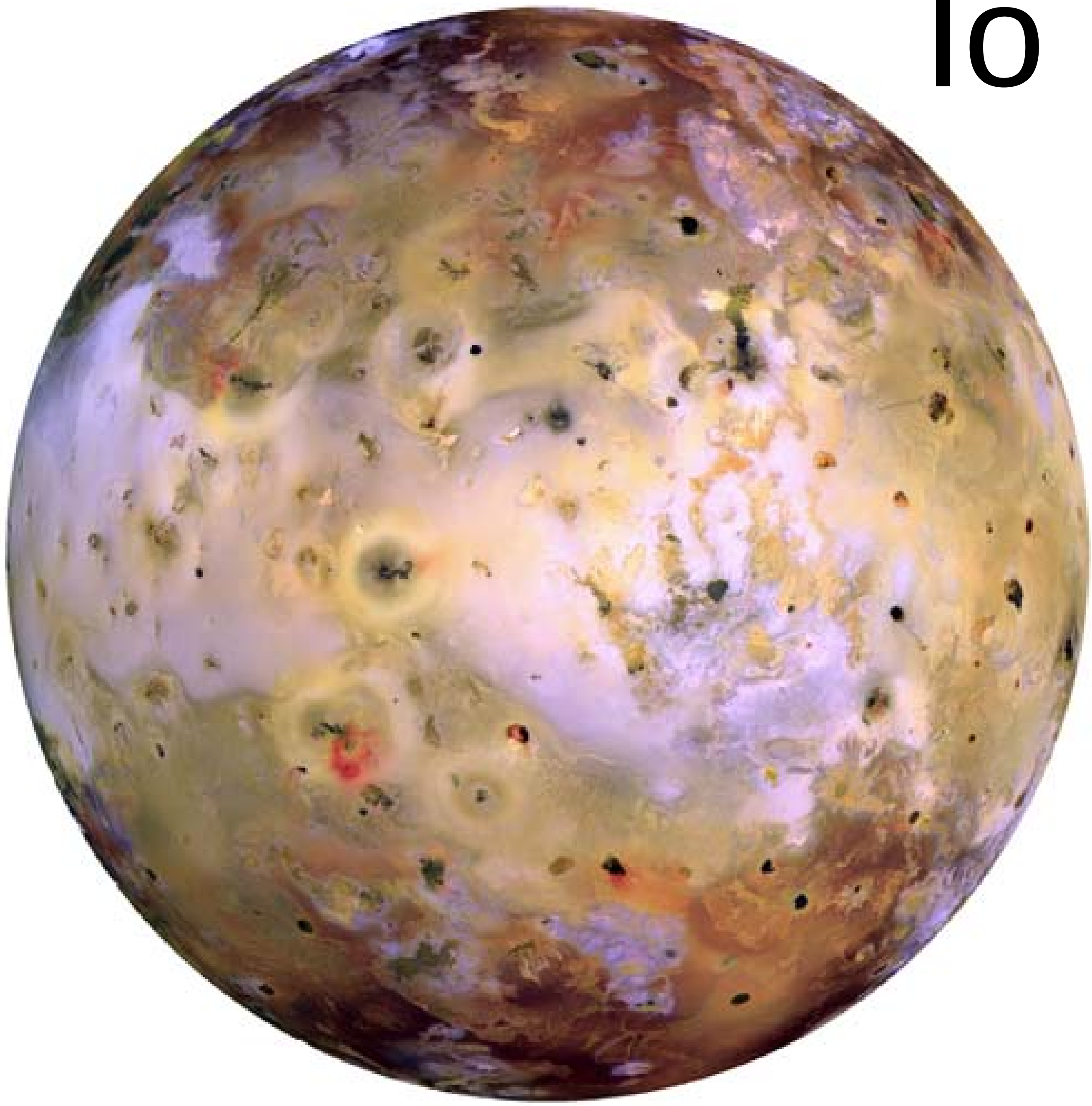
Galileo Io Flyby - 1995



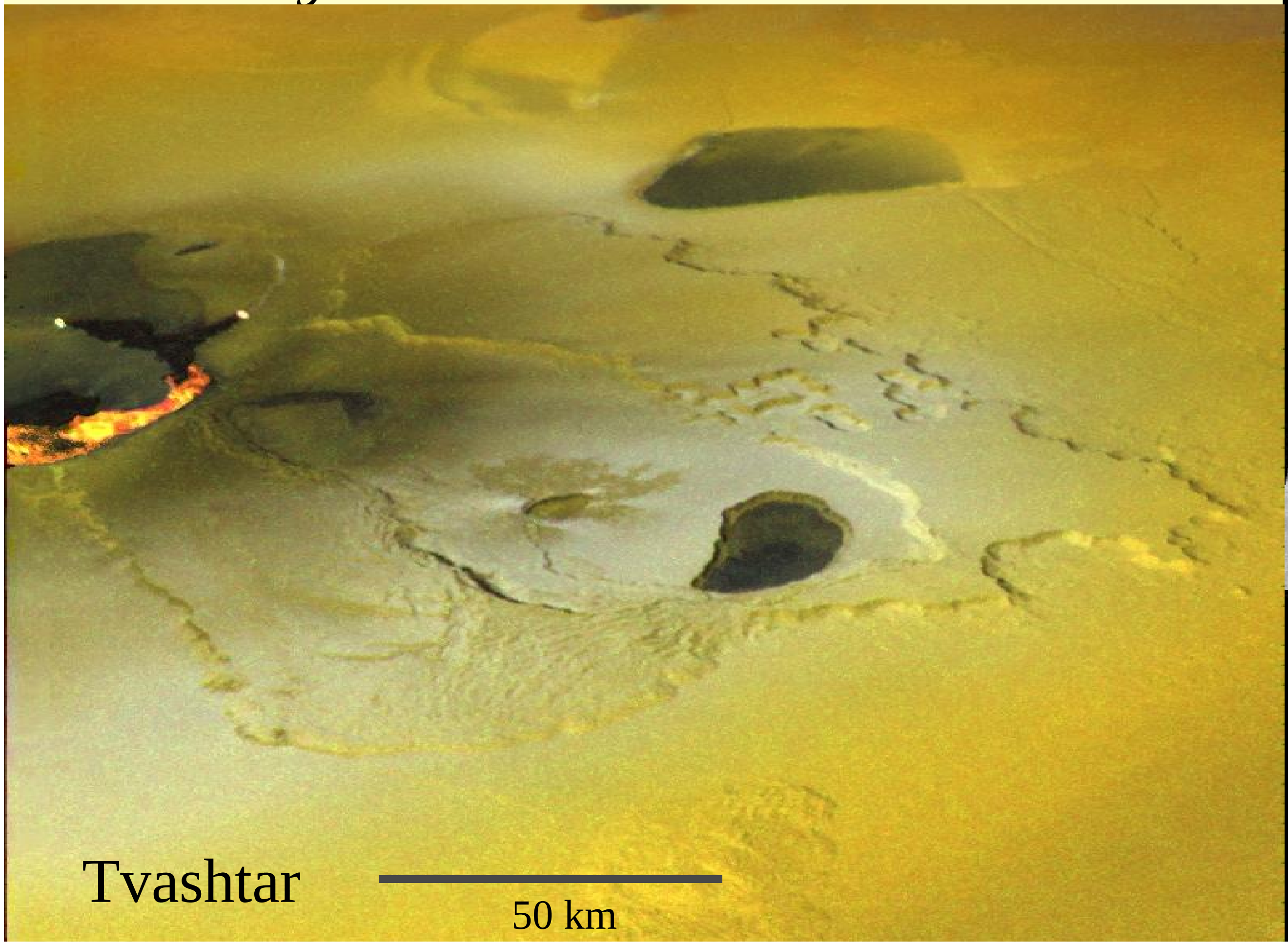


Io

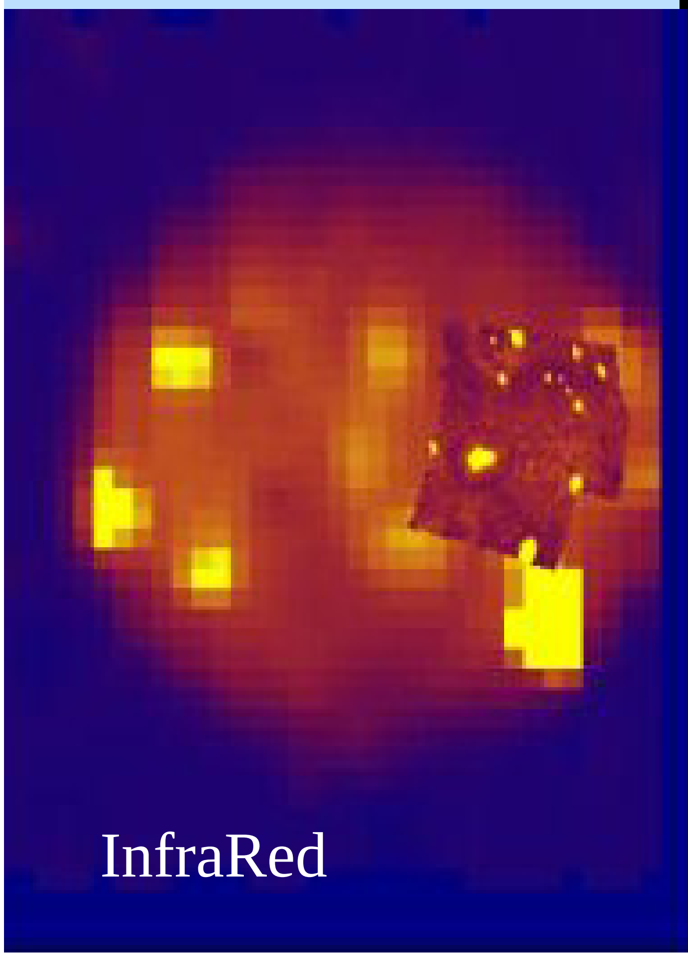


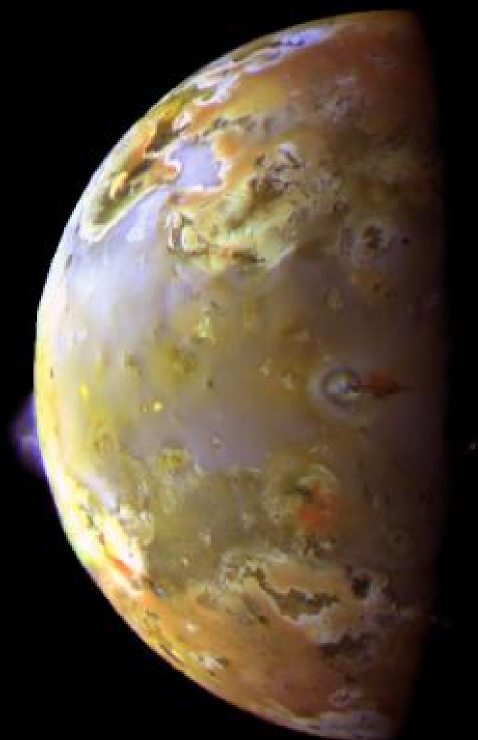


After quantities of lava are removed from below, the crust cracks and tilts, making tall, blocky mountains.

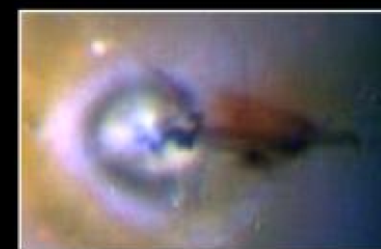


Volcanoe
s
&

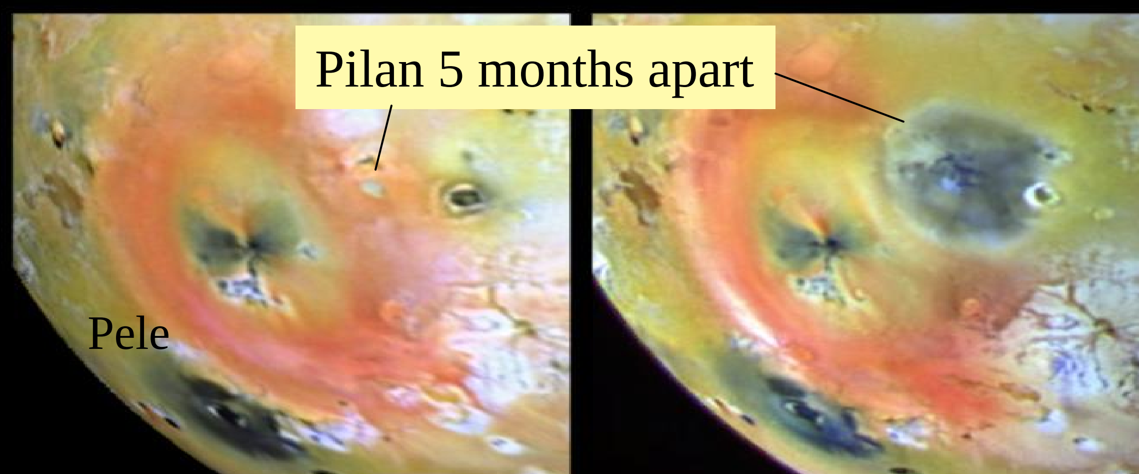


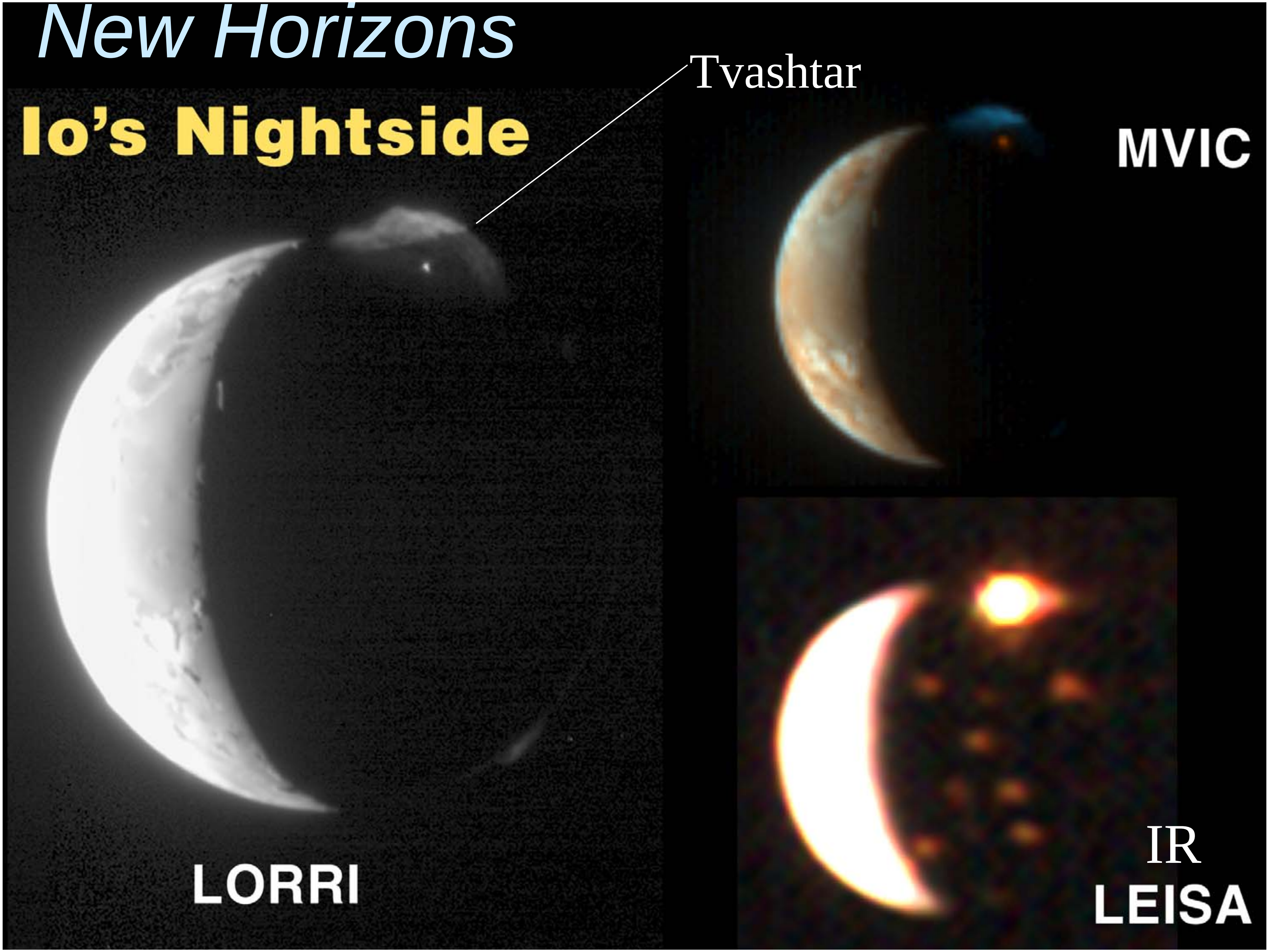


Pilan Plume



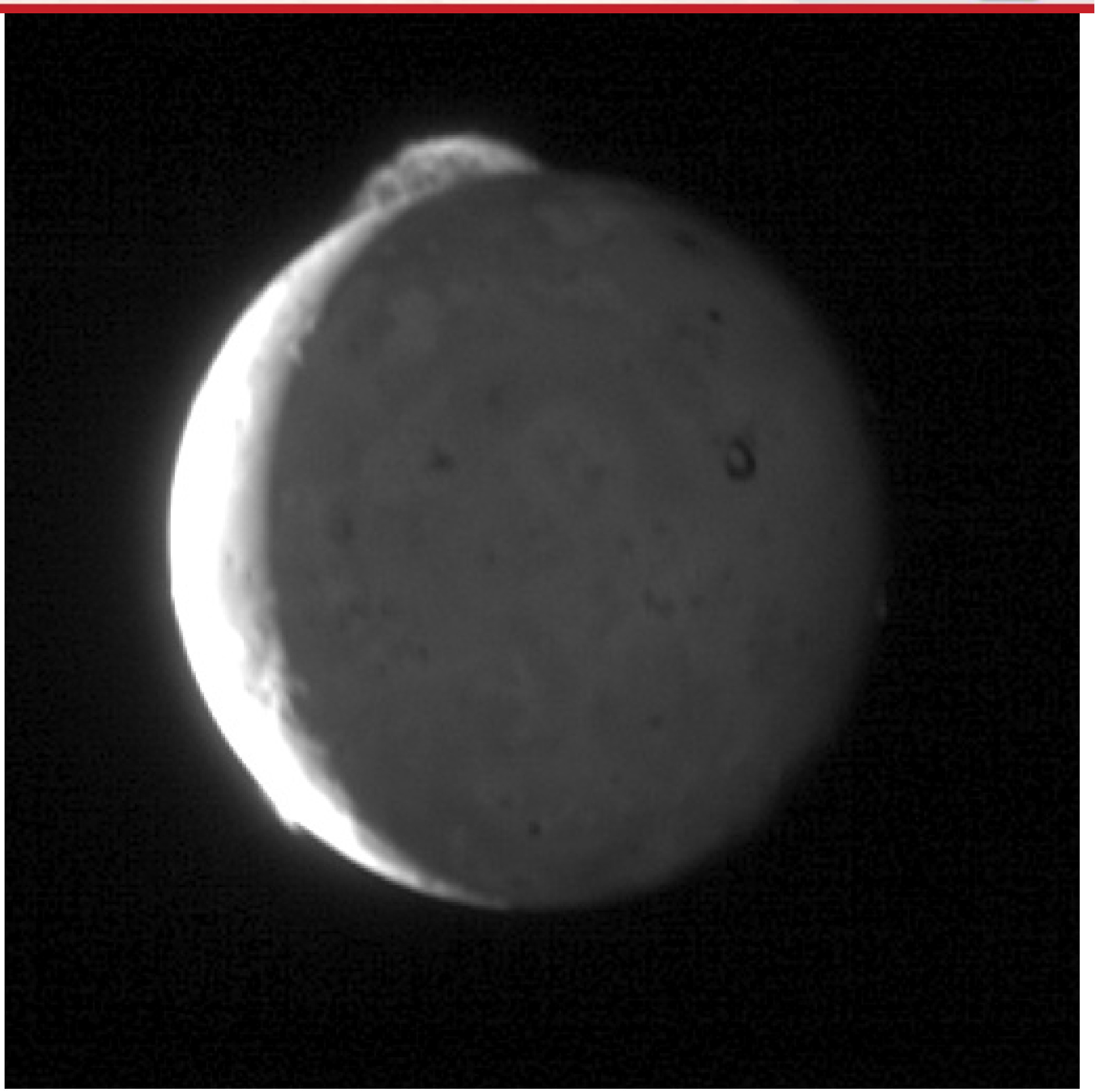
Prometheus




New Horizons
Tvashtar
Io's Nightside
MVIC
LORRI
IR
LEISA

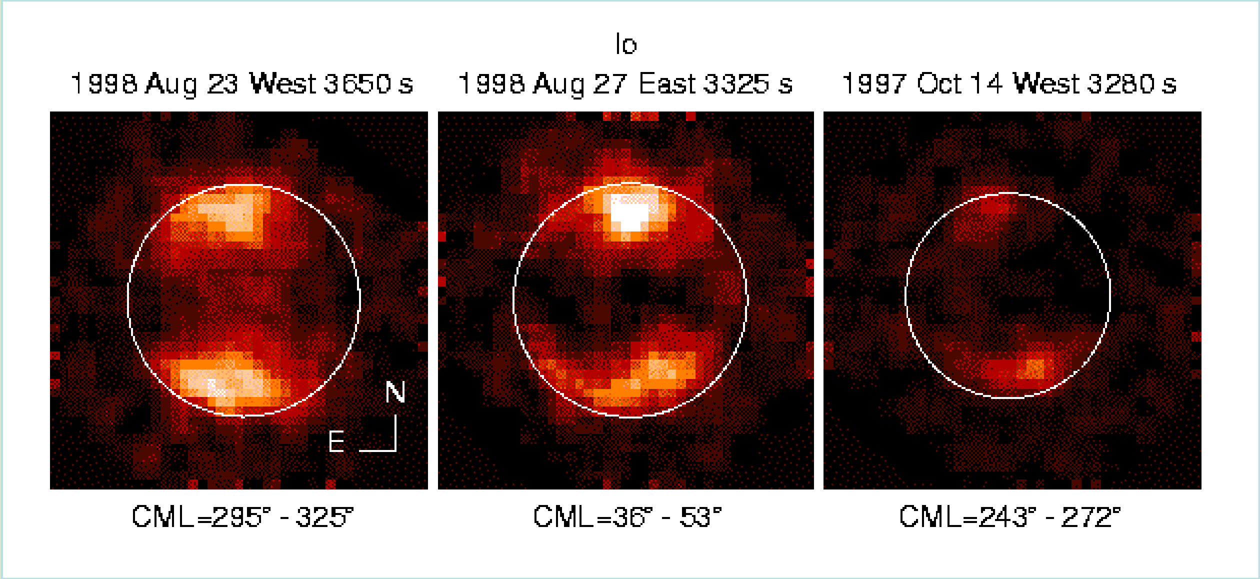
Io Plume Movie

- 5 frames
- 2 mins between frames
- Ballistic trajectories with fallout time of ~30 mins



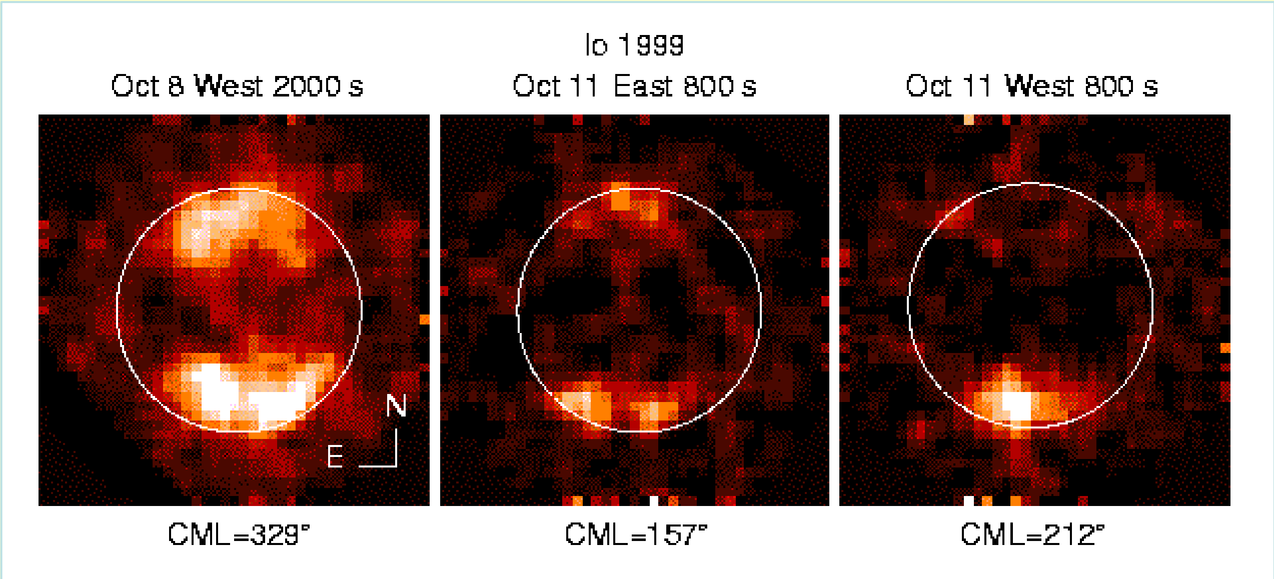
1998 observations

Because SO_2 gas absorbs strongly at 1215A, Lyman-α images provide a map of the SO_2 atmosphere on Io. Dark=more SO_2 gas.

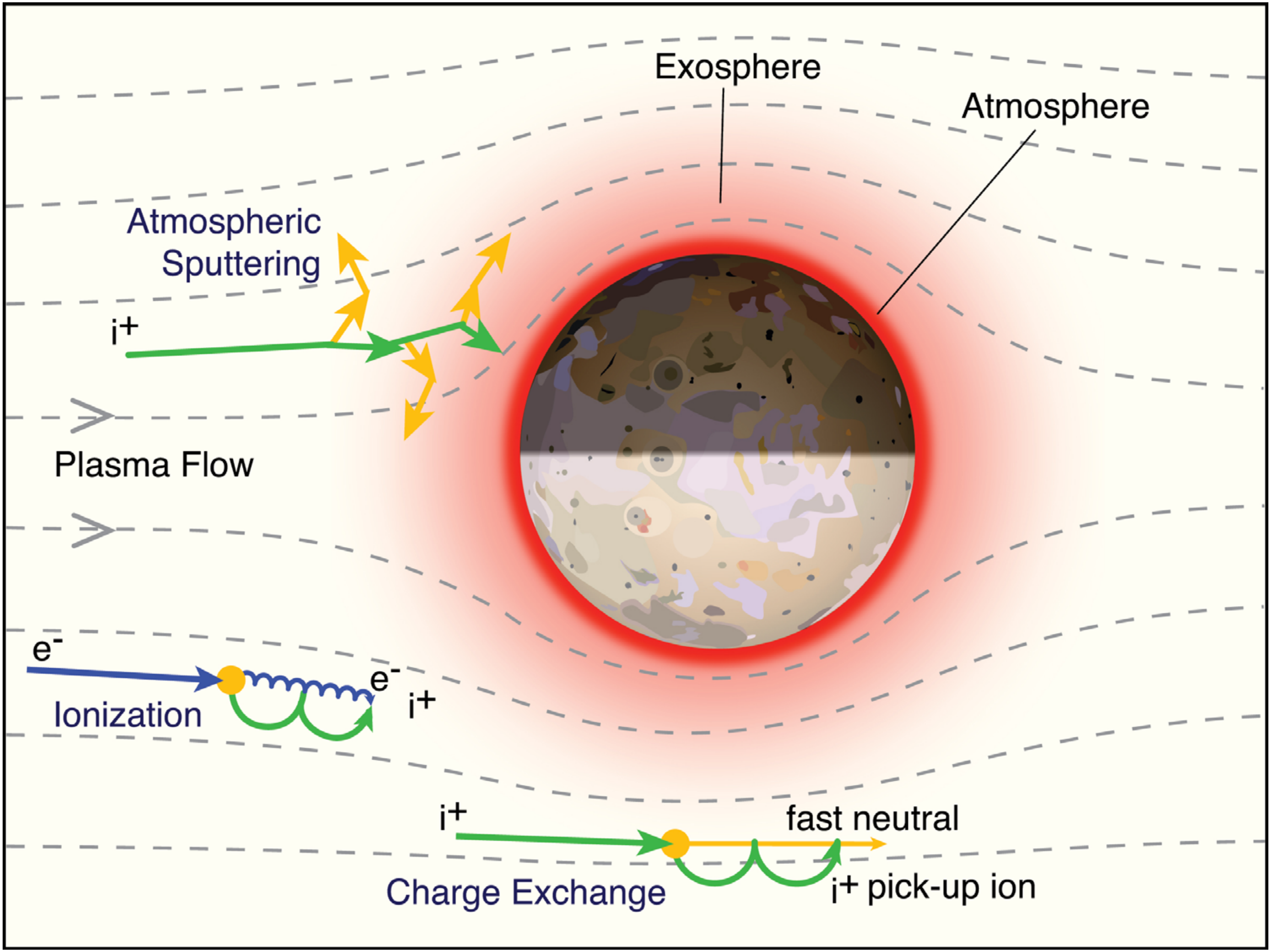


Lyman-α Images → $\mathcal{N}_{SO2} \sim$ few x 10^{16} cm $^{-2}$

Note the pronounced variability in the inferred abundance and distribution of the gas between 1998 & 1999. It is unclear at present whether this variability is temporal or longitudinal.

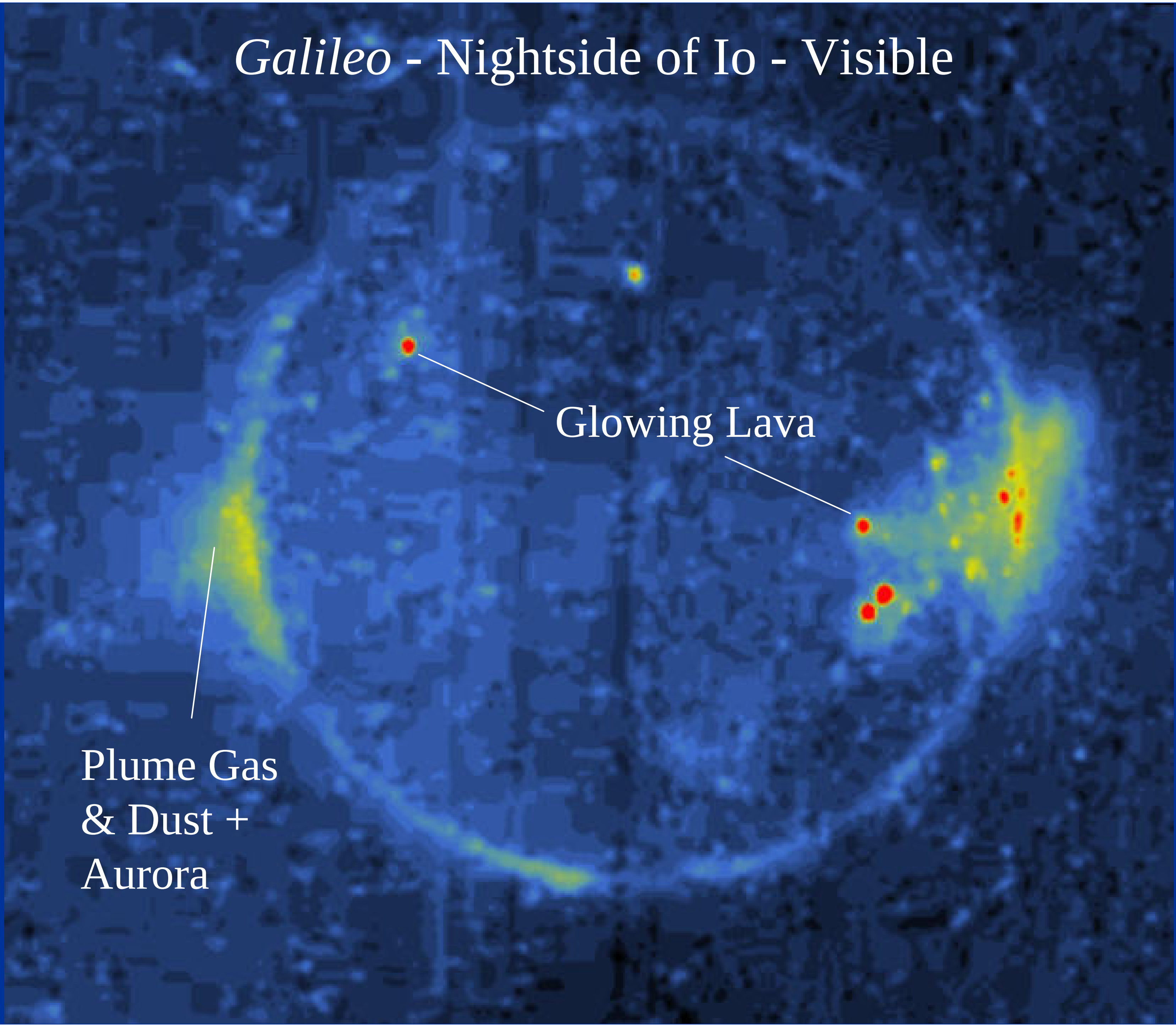


Io campaign observations, 1999



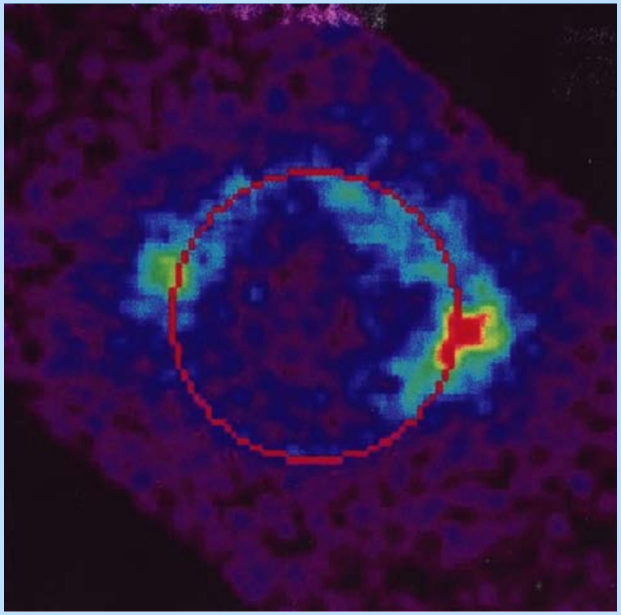
Exosphere
Atmosphere
Atmospheric Sputtering
i+
Plasma Flow
e-
Ionization
e-
i+
i+
fast neutral
Charge Exchange
i+ pick-up ion

Galileo - Nightside of Io - Visible

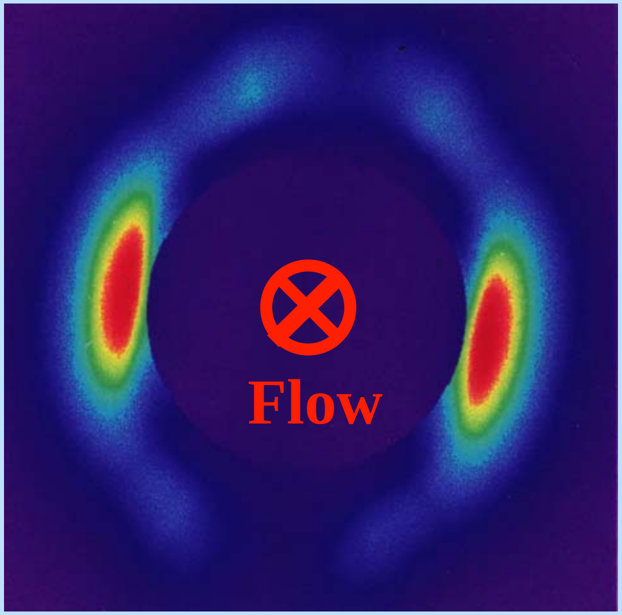


Io-plasma interaction: HST data vs. model

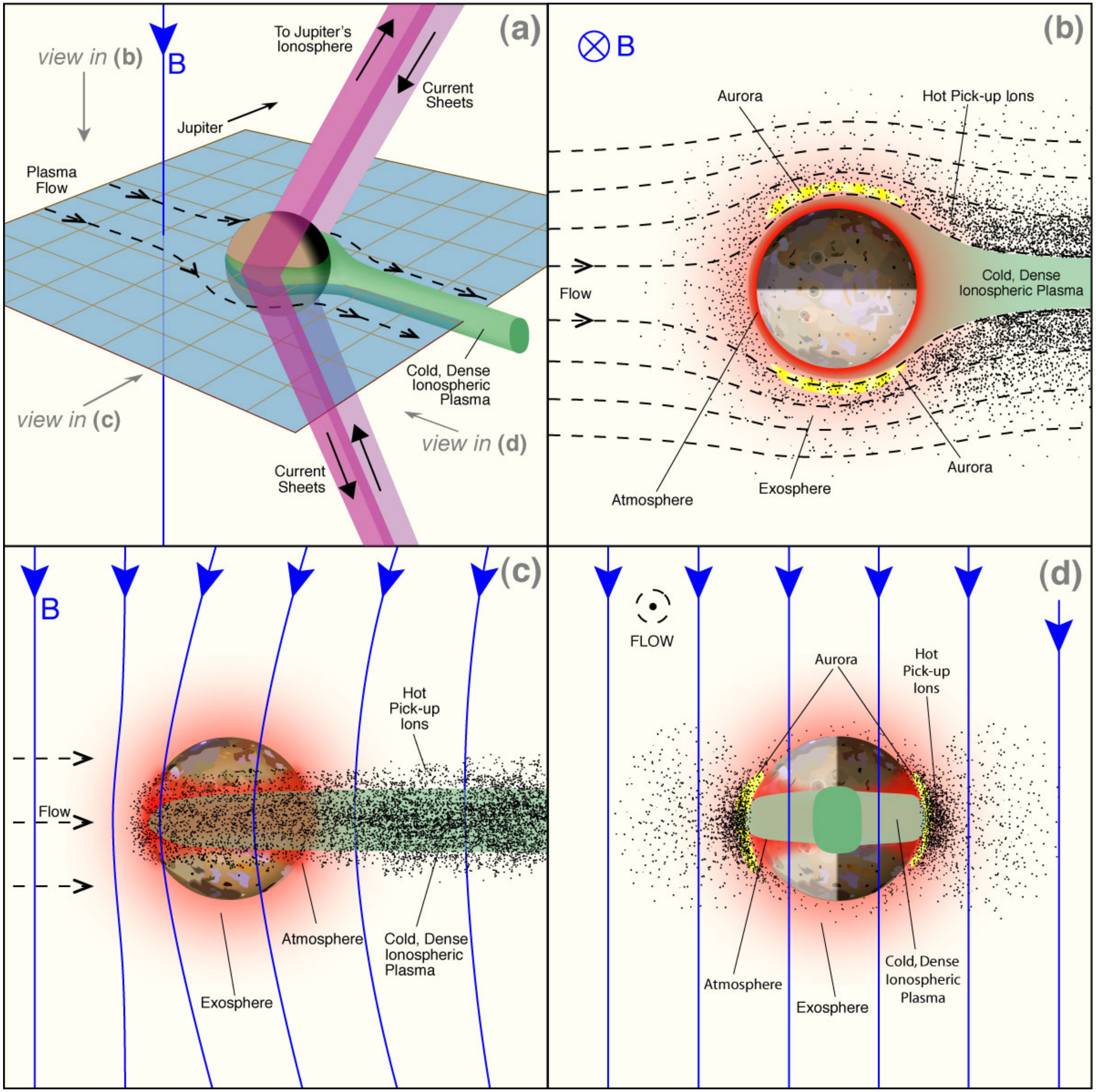
Jupiter



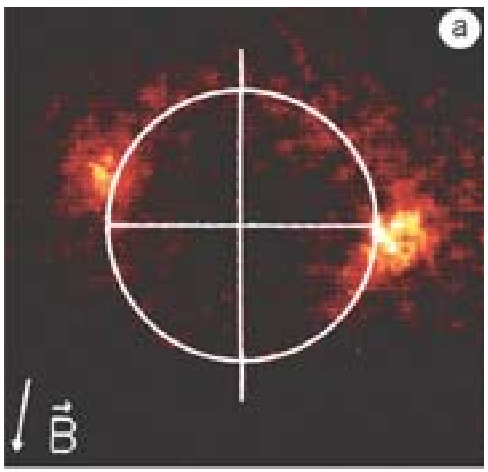
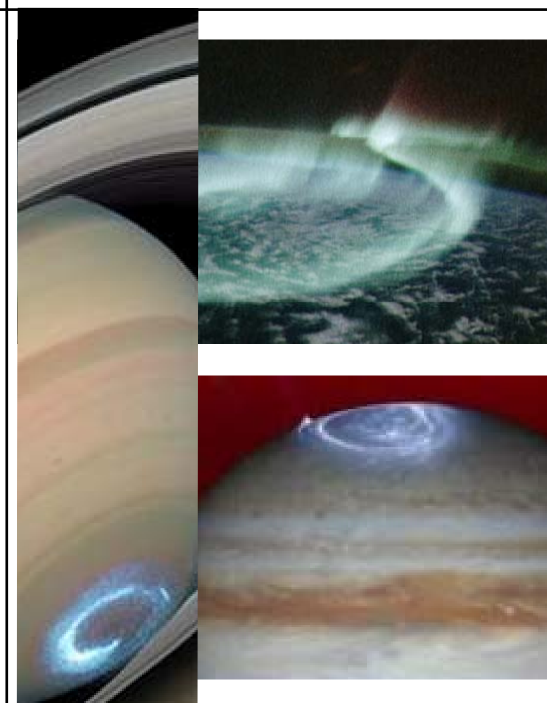
Hubble Space Telescope image of O+ emission - *Roessler et al. 1997*



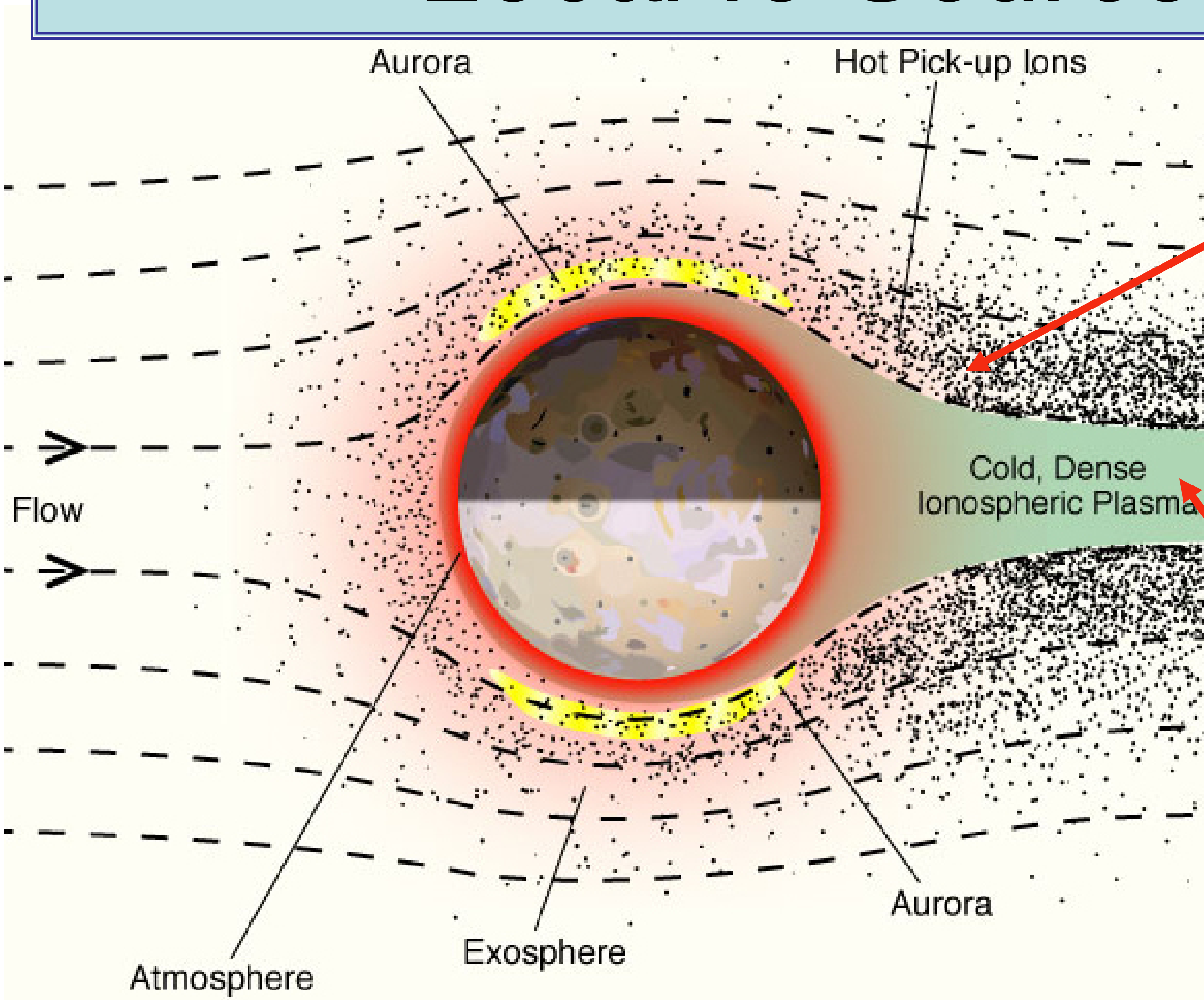
MHD model of Io interaction - prediction of O+ emission excited by electron impact - *Linker & McGrath 1998*



(a)
view in (b)
B
To Jupiter's Ionosphere
Current Sheets
Jupiter
Plasma Flow
Cold, Dense Ionospheric Plasma
view in (c)
view in (d)
Current Sheets
(b)
B
Aurora
Hot Pick-up Ions
Flow
Cold, Dense Ionospheric Plasma
Atmosphere
Exosphere
Aurora
(c)
B
Hot Pick-up Ions
Flow
Atmosphere
Cold, Dense Ionospheric Plasma
Exosphere
(d)
FLOW
Aurora
Hot Pick-up Ions
Atmosphere
Exosphere
Cold, Dense Ionospheric Plasma

Io Story	*Process*	*Universality*
	Auroral emissions $e^- + N$ $\rightarrow N^* + e^-$ $N^* \rightarrow N + h\nu$	

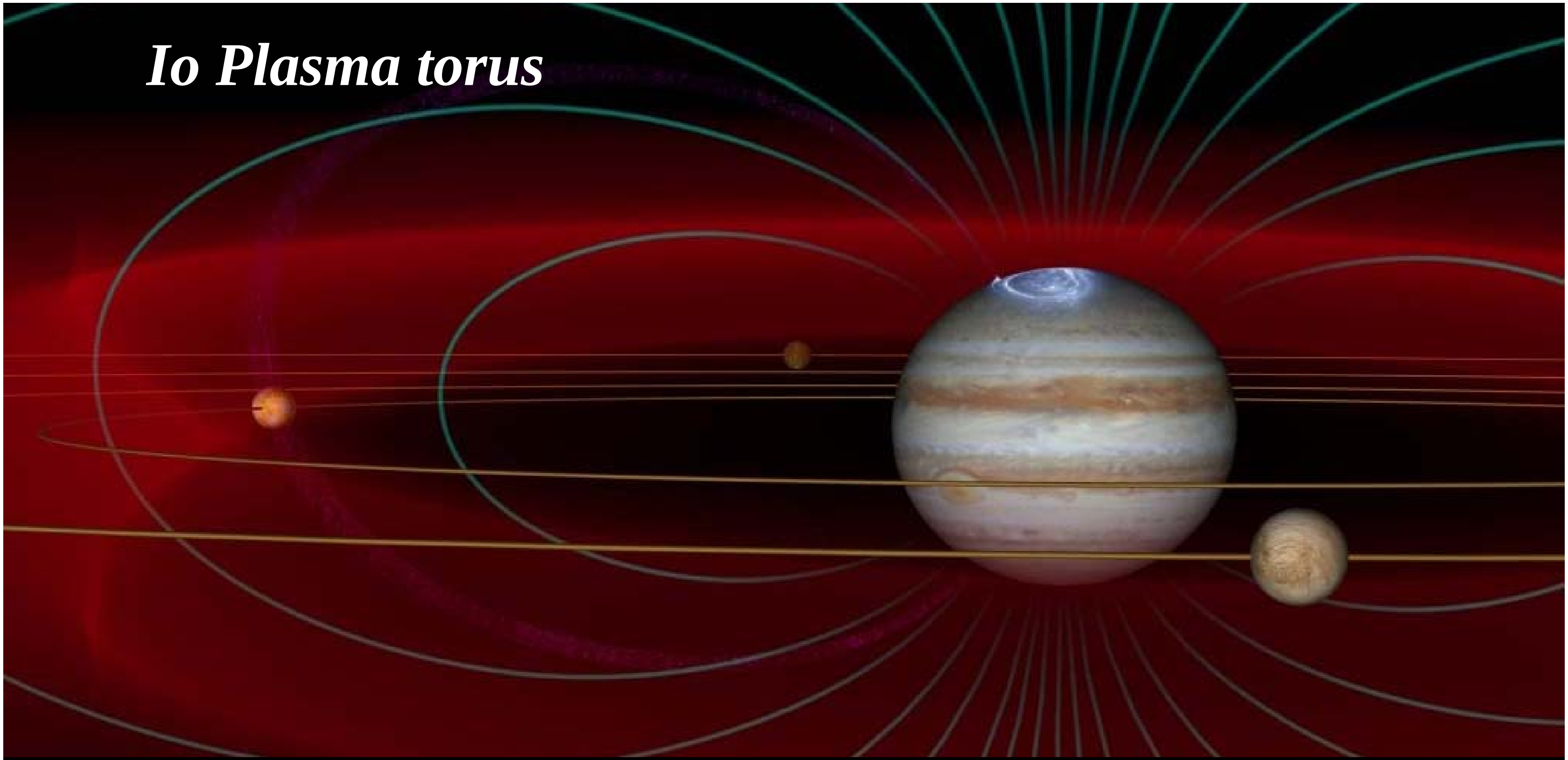
Local Io Source



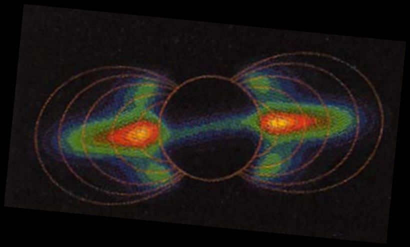
Local hot pick-up source:
3-20 x 10^{27} s^{-1}
<100 kg s^{-1}

“cold slug”:
3-20 x 10^{26} s^{-1}
~ 10-70 kg s^{-1}

Total ion source 200-900 kg s^{-1} - Mostly far from Io



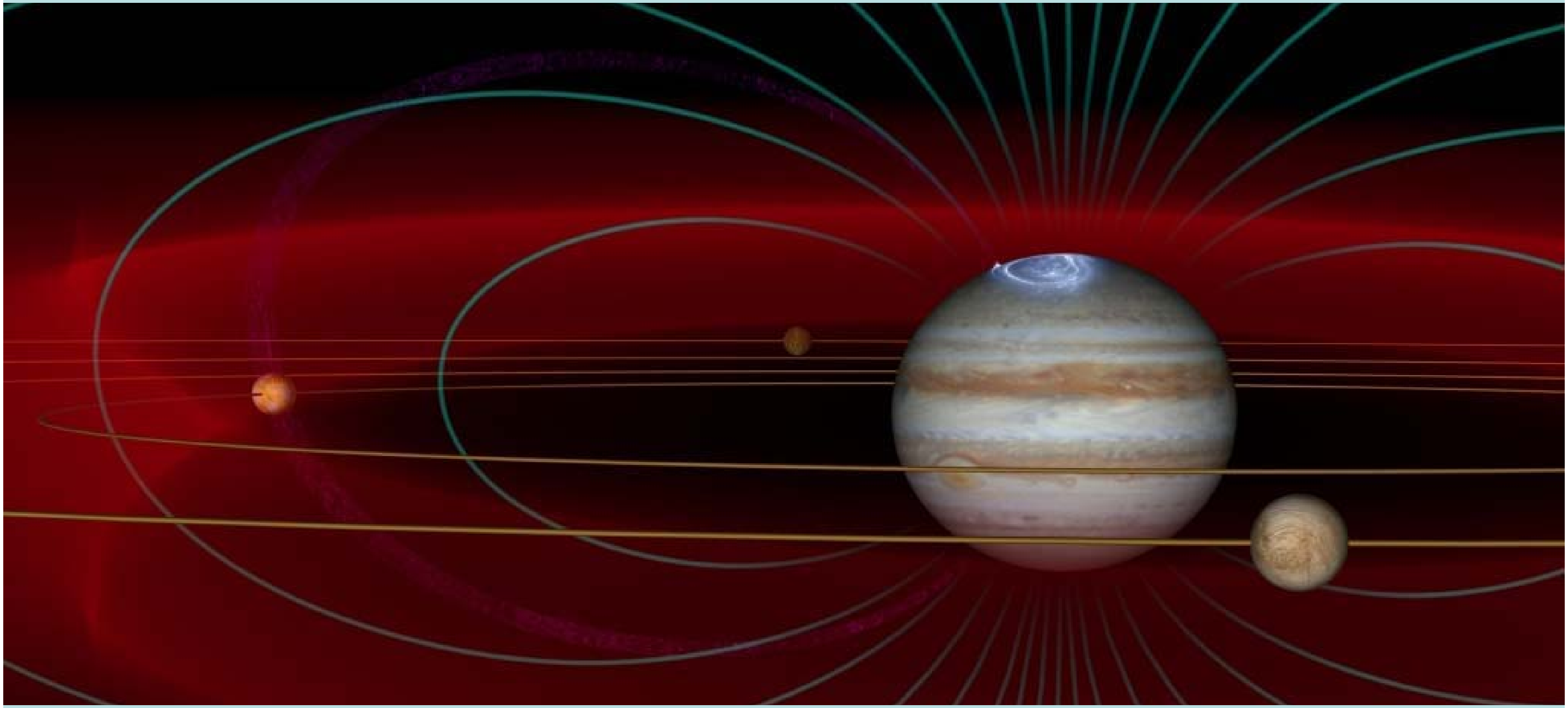
Total mass ~ 2 Mton
Source @ ~1 ton/s
~3 x 10^{28} ions/s
replaced in 23 days



Io Plasma torus:

Total mass ~ 2 Mton

Source @ 1 ton/s replaced in 23 days



Total thermal energy ~6 x 10^{17} J

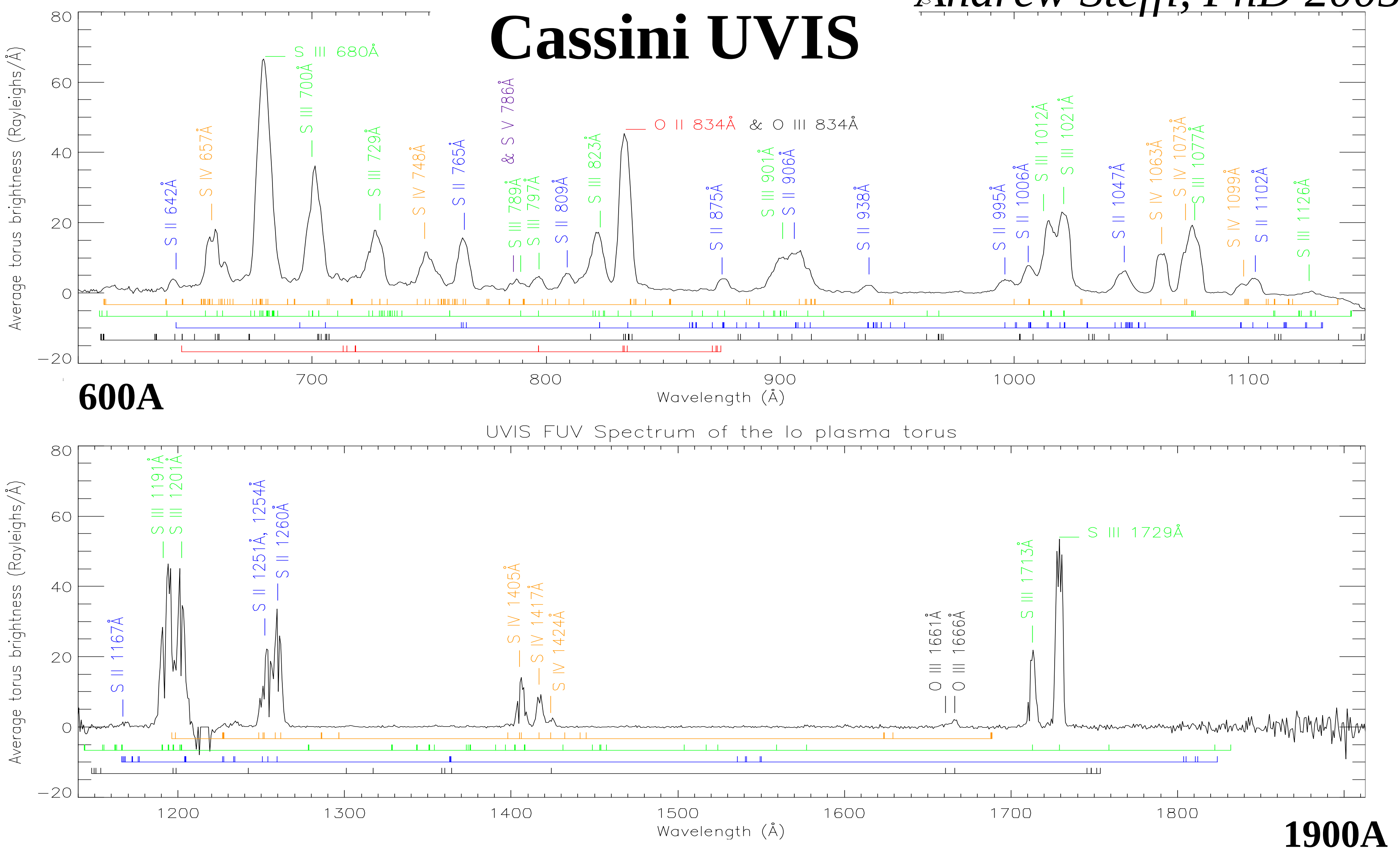
UV power @ 1.5 terawatt cools electrons in ~7 hours

Ion pick-up @ 2 terawatt generates total energy in 4 days

How do composition, temperatures & UV power vary?

Andrew Steffl, PhD 2005

Cassini UVIS



Torus Chemistry Models

Neutral Cloud Theory:

Source = atomic O, S

Ionization, Charge Exchange, Recombination

Radiative Cooling

Ion-Electron coupling - Coulomb collisions

Electron heating:

Necessary to provide UV emitted power

Usually specified as $F_{hot}=Ne_{hot}/Ne_{cold}$ and T_{hot}

Homogeneous Volume Five Parameters:

Transport Timescale - $\tau_{transport}$

Source of Neutrals - $S_{neutrals}$

Oxygen to Sulfur Ratio - $O/S_{neutrals}$

Hot Electron Fraction - $F_{hot} = Ne_{hot}/Ne_{cold}$

Hot Electron Temperature - T_{hot}

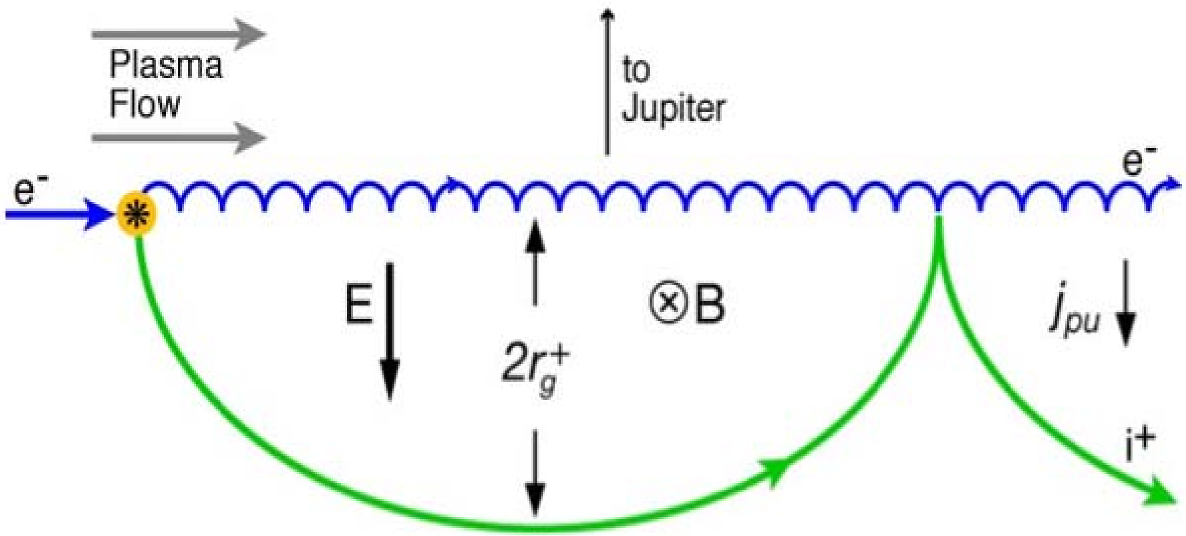
Output:

Neutral, Ion, Electron Densities

Ion Temperatures

Thermal Electron temperatures

Mass, Energy Flows



$\mathbf{E} = -\mathbf{V} \times \mathbf{B}$

Pick-up Energy

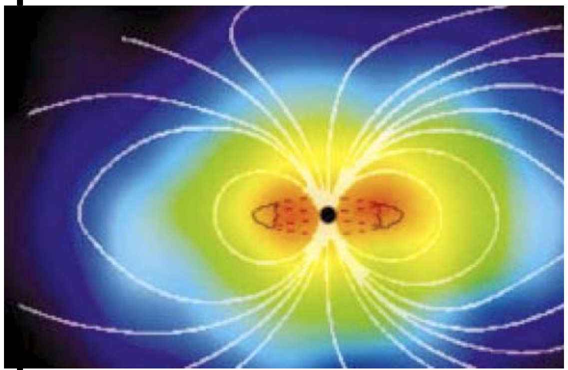
$$\varepsilon = {}^1/_2 m_{ion} V^2$$

Pick-up Current

$$J_{pu} = \dot{N}\, e\, 2r_g^{+}$$

Add Charge exchange reactions

Add ring-beam distribution function

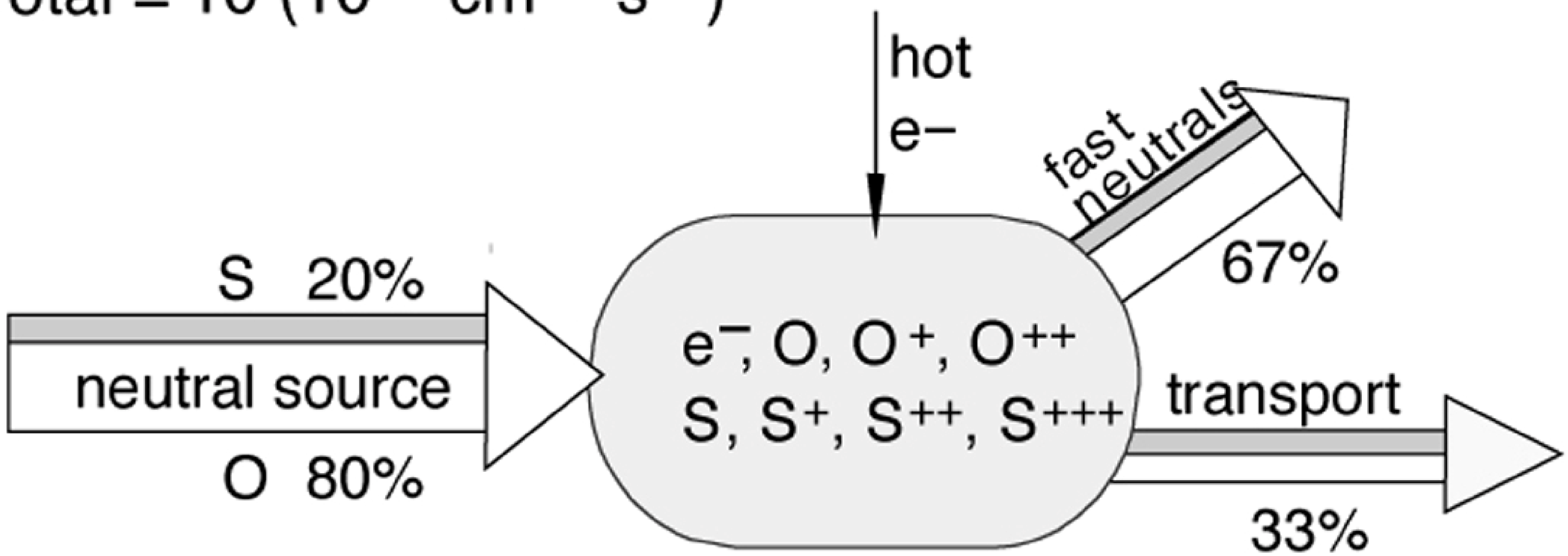
Io Story	*Process*	*Universality*
	Charge Exchange $X^+ + Y$ $\rightarrow Y^+ + X_{fast}$	Solar wind + Interstellar pick-ions

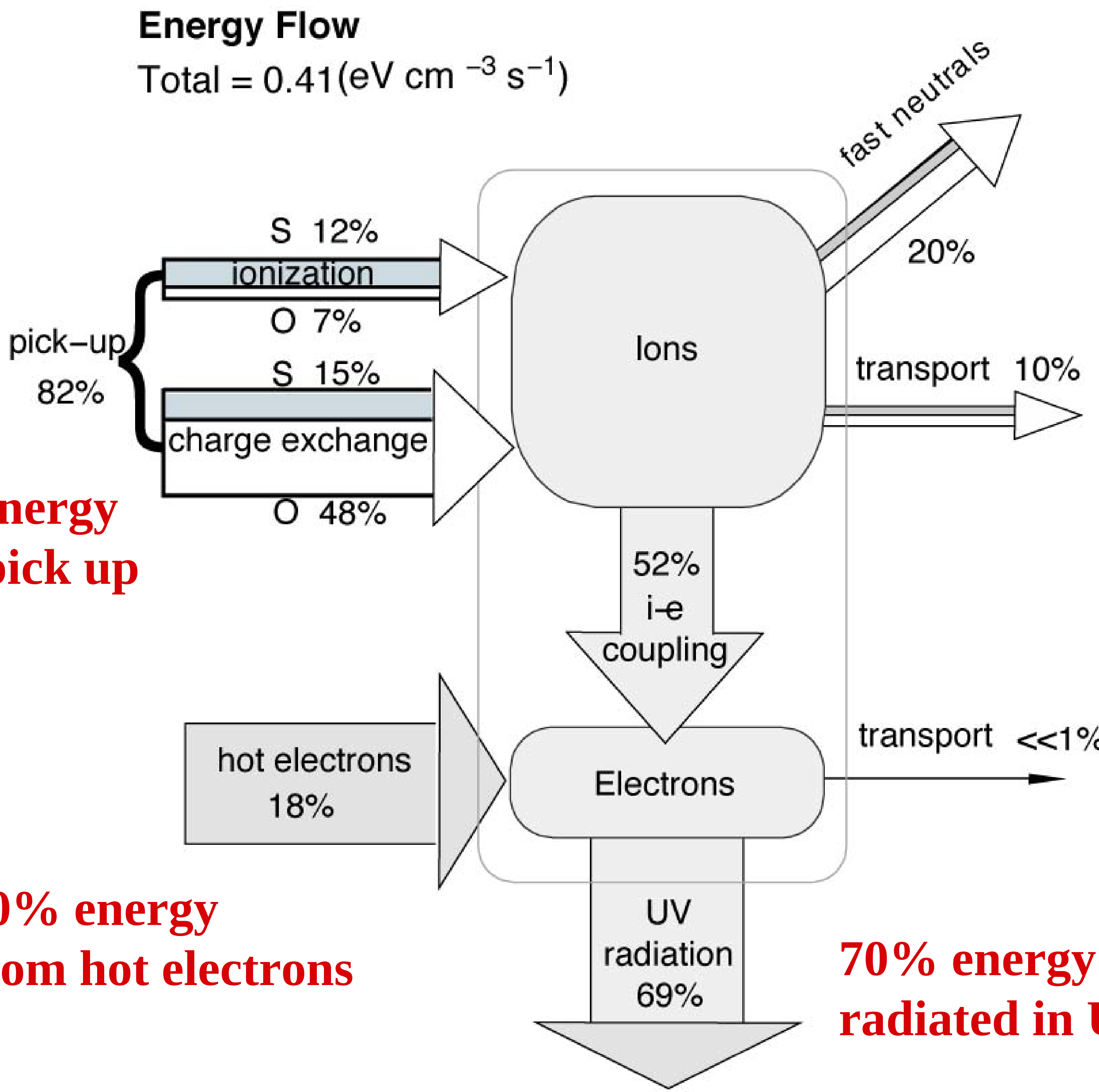
Charge Exchange Reactions @ L=6

Reaction	k, $cm^3 s^{-1}$	
$S^+ + S^{++} \rightarrow S^{++} + S^+$	$k0 = 8:1\ 10^{-9}$	Smith & Strobel 1985
$S + S^+ \rightarrow S^+ + S$	$k1 = 2.4\ 10^{-8}$	
$S + S^{++} \rightarrow S^+ + S^+$	$k2 = 3\ 10^{-10}$	
$S + S^{++} \rightarrow S^{++} + S$	$k3 = 7.8\ 10^{-9}$	
$S + S^{+++} \rightarrow S^+ + S^{++}$	$k4 = 1.32\ 10^{-8}$	
$O + O^+ \rightarrow O^+ + O$	$k5 = 1.32\ 10^{-8}$	
$O + O^{++} \rightarrow O^+ + O^+$	$k6 = 5.2\ 10^{-10}$	
$O + O^{++} \rightarrow O^{++} + O$	$k7 = 5.4\ 10^{-9}$	
$O + S^+ \rightarrow O^+ + S$	$k8 = 6\ 10^{-11}$	McGrath & Johnson 1989
$S + O^+ \rightarrow S^+ + O$	$k9 = 3.1\ 10^{-9}$	
$S + O^{++} \rightarrow S^+ + O^+$	$k10 = 2.34\ 10^{-8}$	
$S + O^{++} \rightarrow S^{++} + O^+ + e^-$	$k11 = 1.62\ 10^{-8}$	
$O + S^{++} \rightarrow O^+ + S^+$	$k12 = 2.3\ 10^{-9}$	
$O^{++} + S^+ \rightarrow O^+ + S^{++}$	$k13 = 1.4\ 10^{-9}$	
$O + S^{+++} \rightarrow O^+ + S^{++}$	$k14 = 1.92\ 10^{-8}$	
$O^{++} + S^{++} \rightarrow O^+ + S^{+++}$	$k15 = 9\ 10^{-10}$	
$S^{+++} + S^+ \rightarrow S^{++} + S^{++}$	$k16 = 3.6\ 10^{-10}$	

Particle Flow

Total = 10 (10^{-4} cm^{-3} s^{-1})

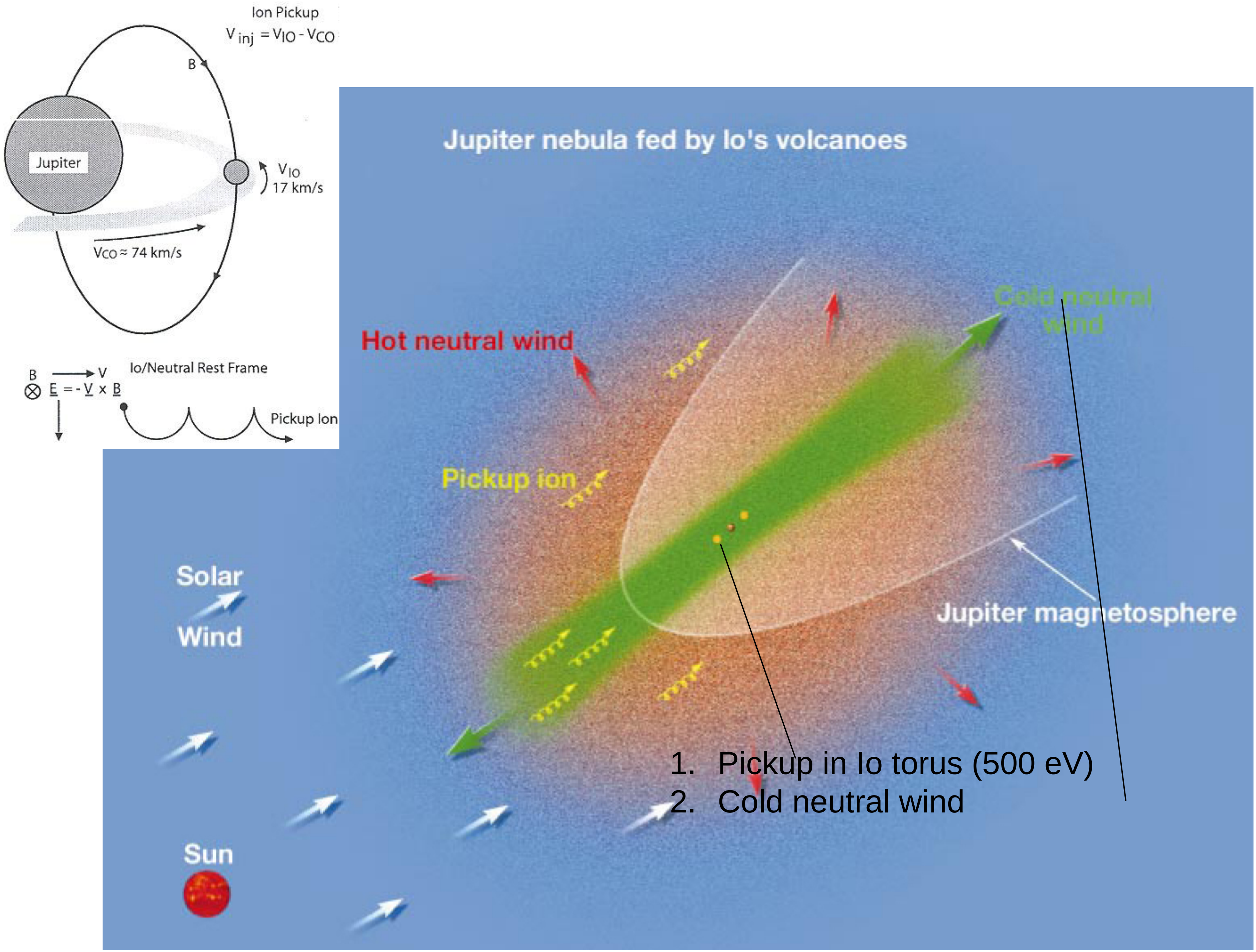




80% energy from pick up

20% energy from hot electrons

70% energy radiated in UV

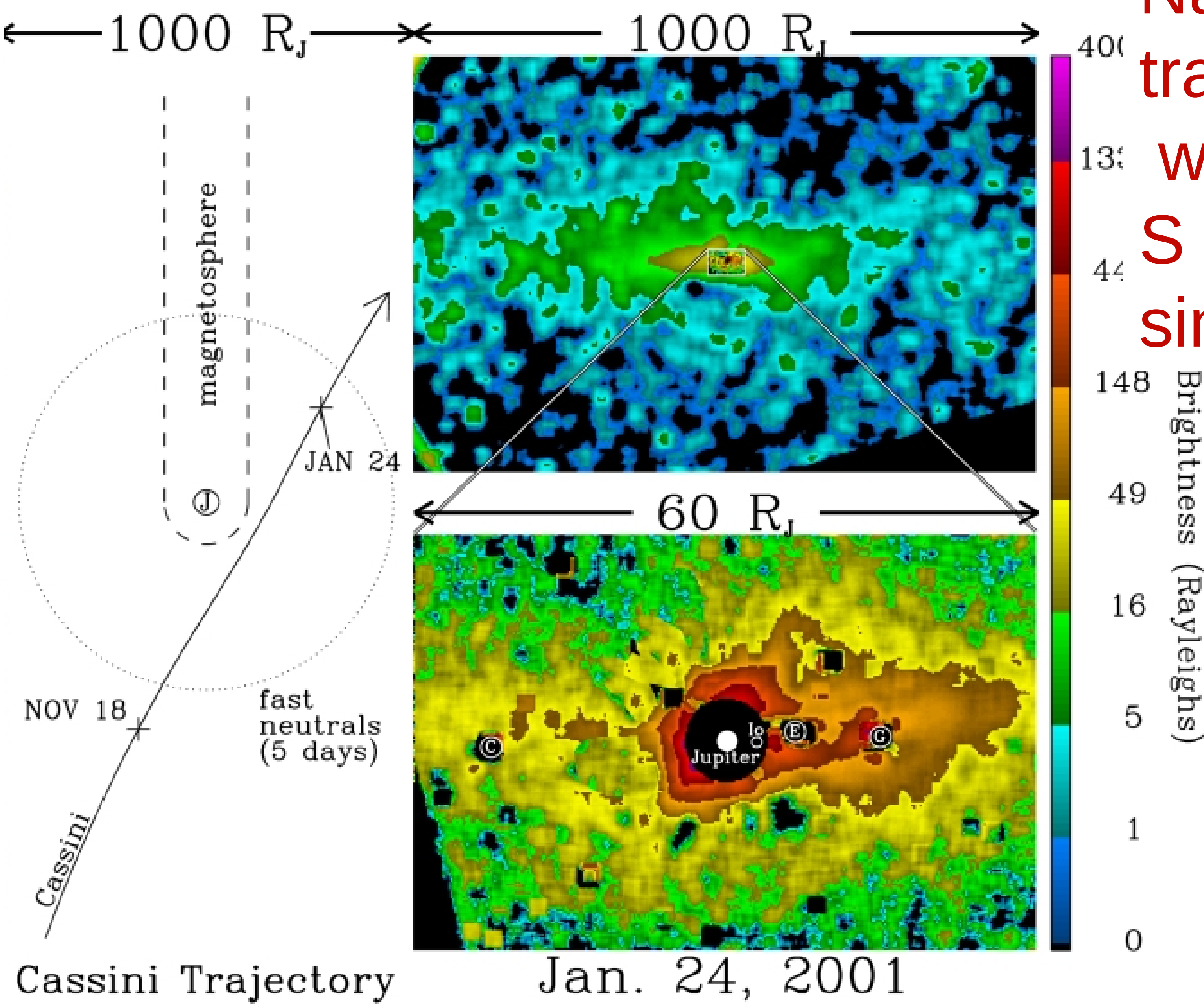


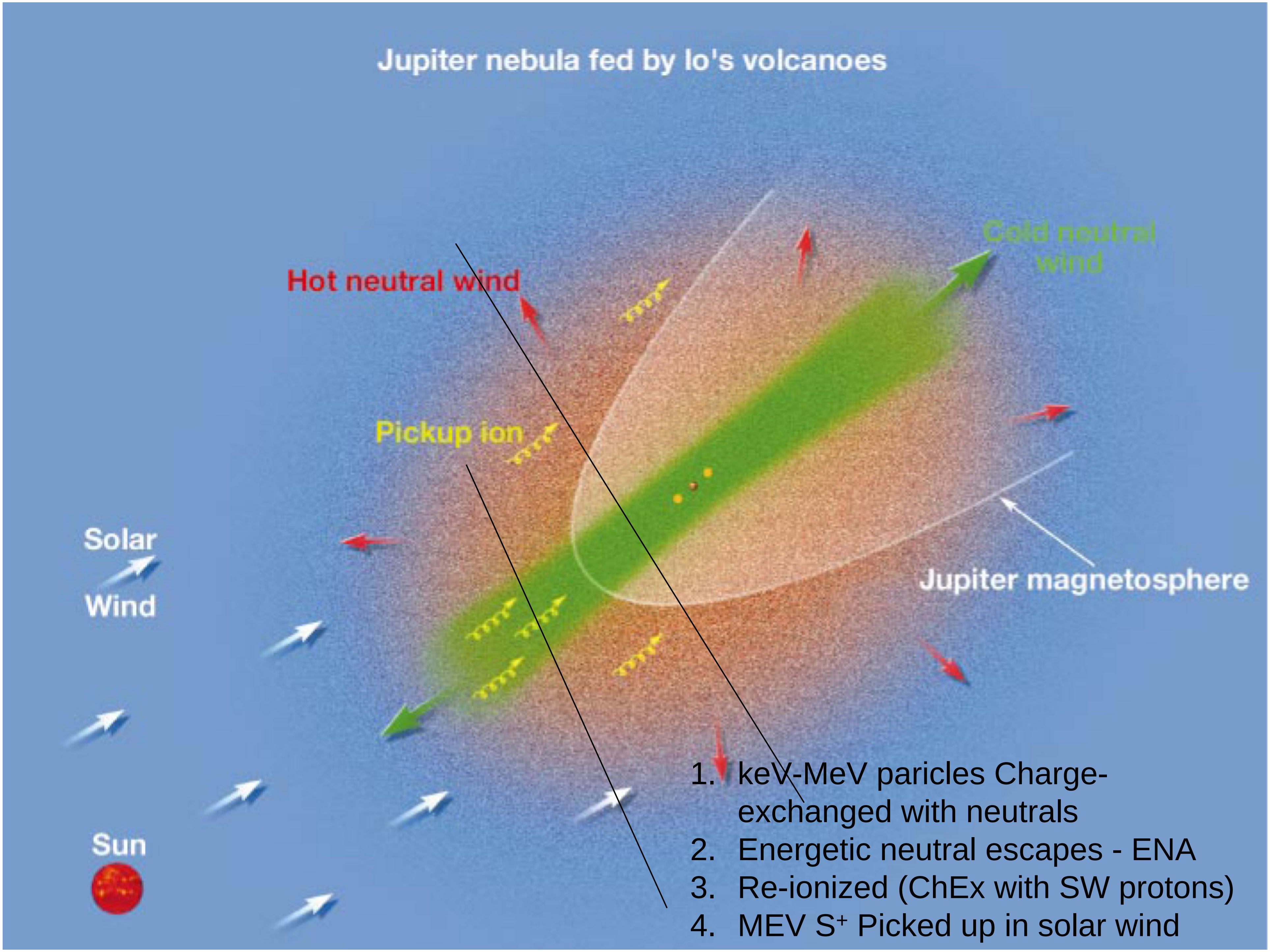
1. Pickup in Io torus (500 eV)
2. Cold neutral wind

1000 Rj ~0.5 AU!

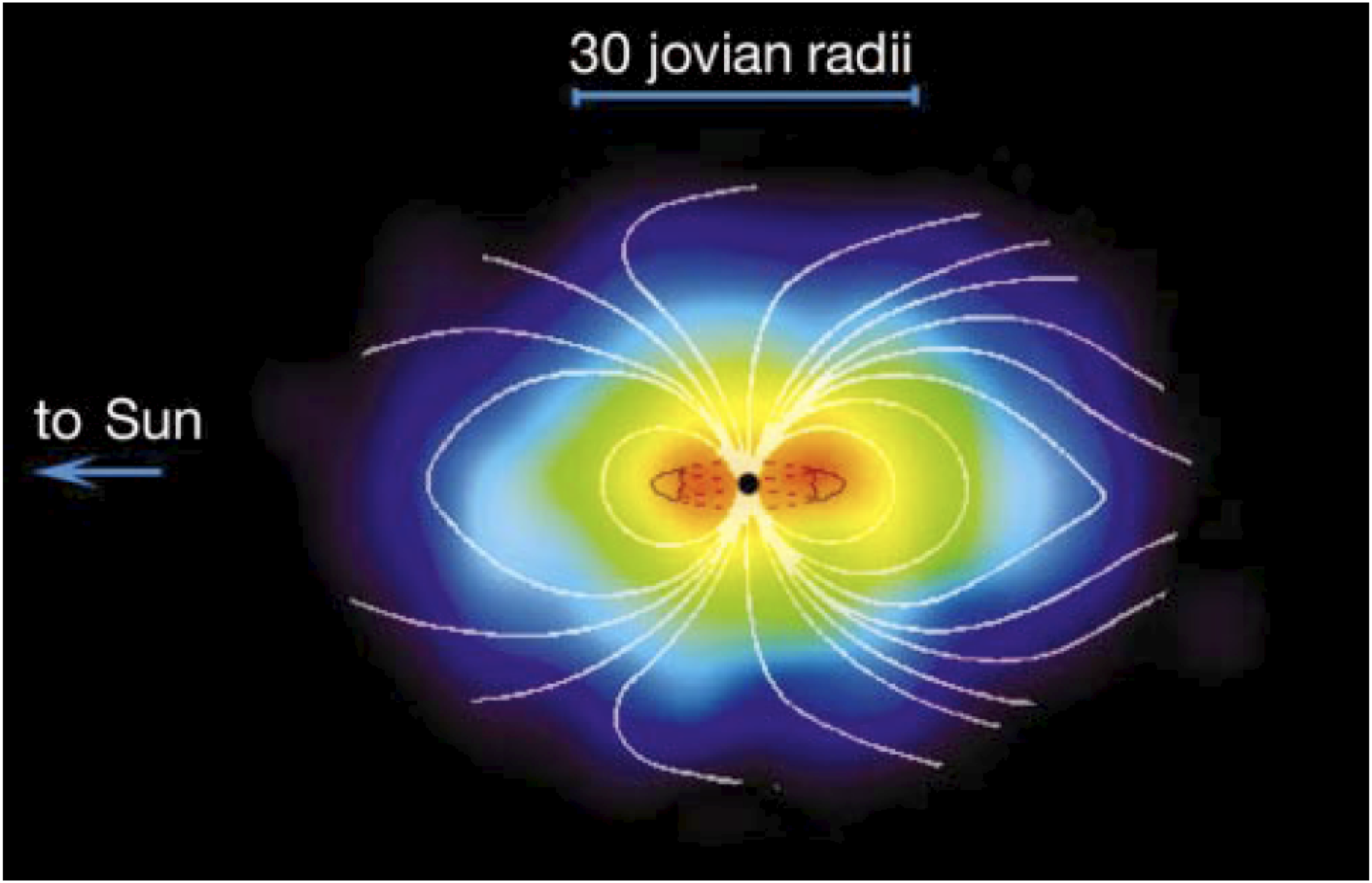
Wilson & Mendillo

Na = good tracer - we expect S & O to do similar





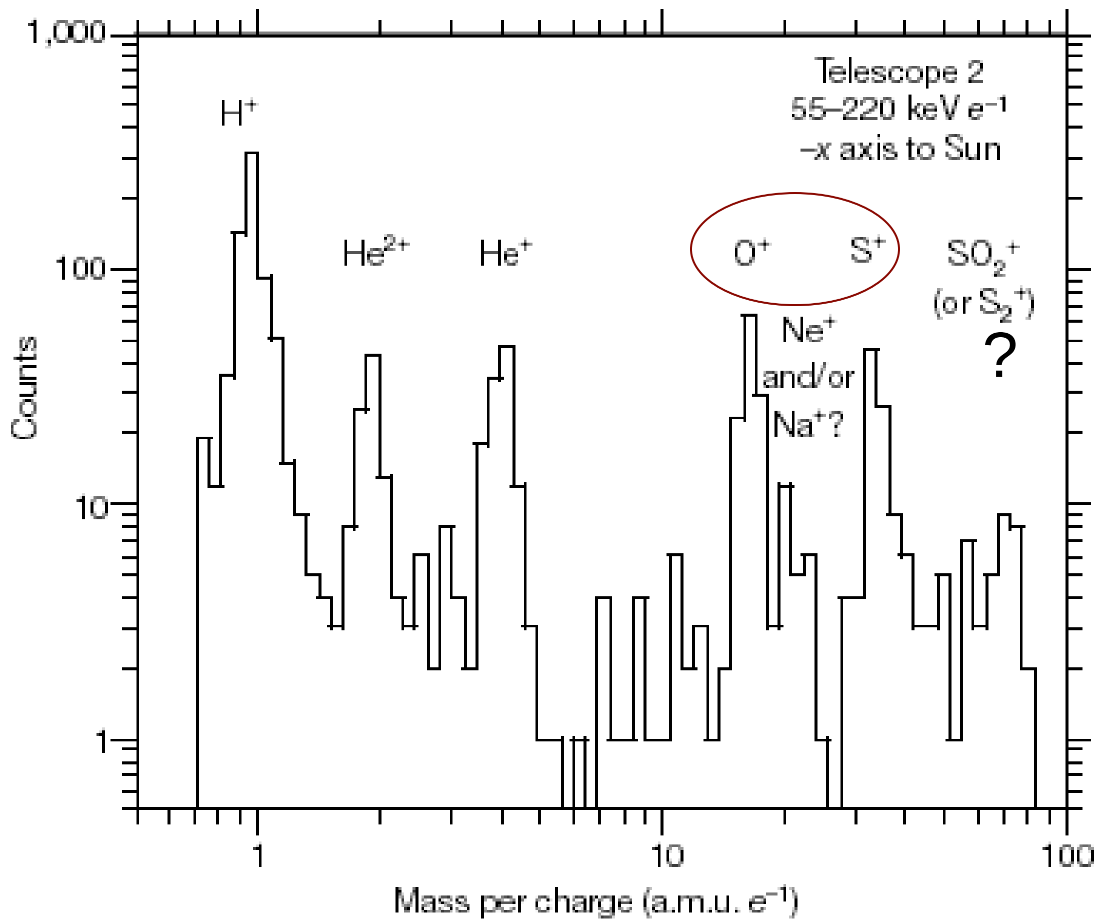
1. keV-MeV paricles Charge-exchanged with neutrals
2. Energetic neutral escapes - ENA
3. Re-ionized (ChEx with SW protons)
4. MEV S^+ Picked up in solar wind

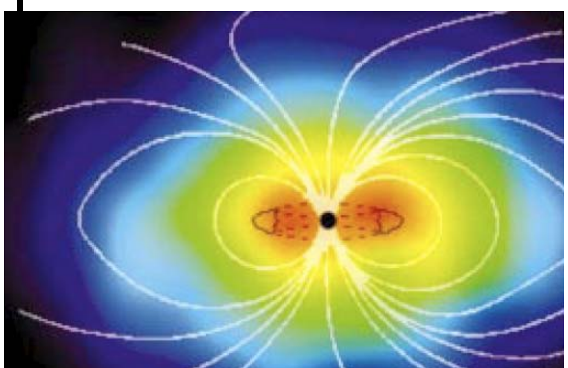


Energetic Neutral Atoms - produced by charge exchange

Cassini Energetic Ions - 55-220 keV

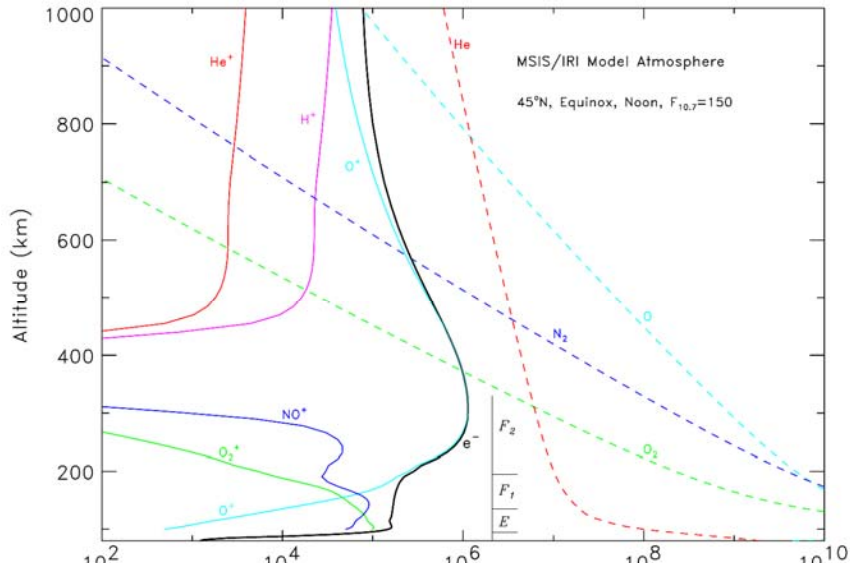
Upstream of Jupiter

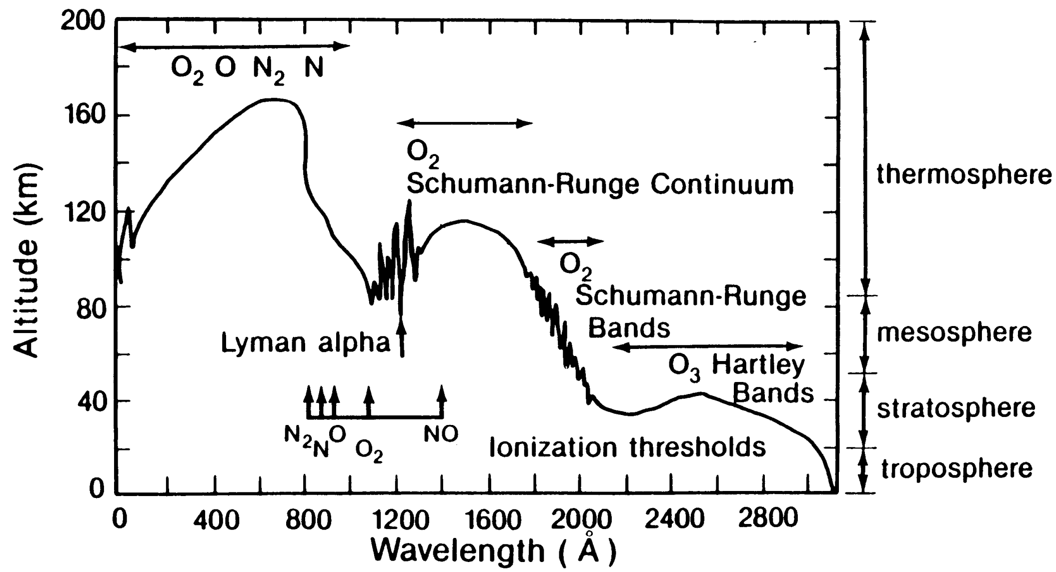


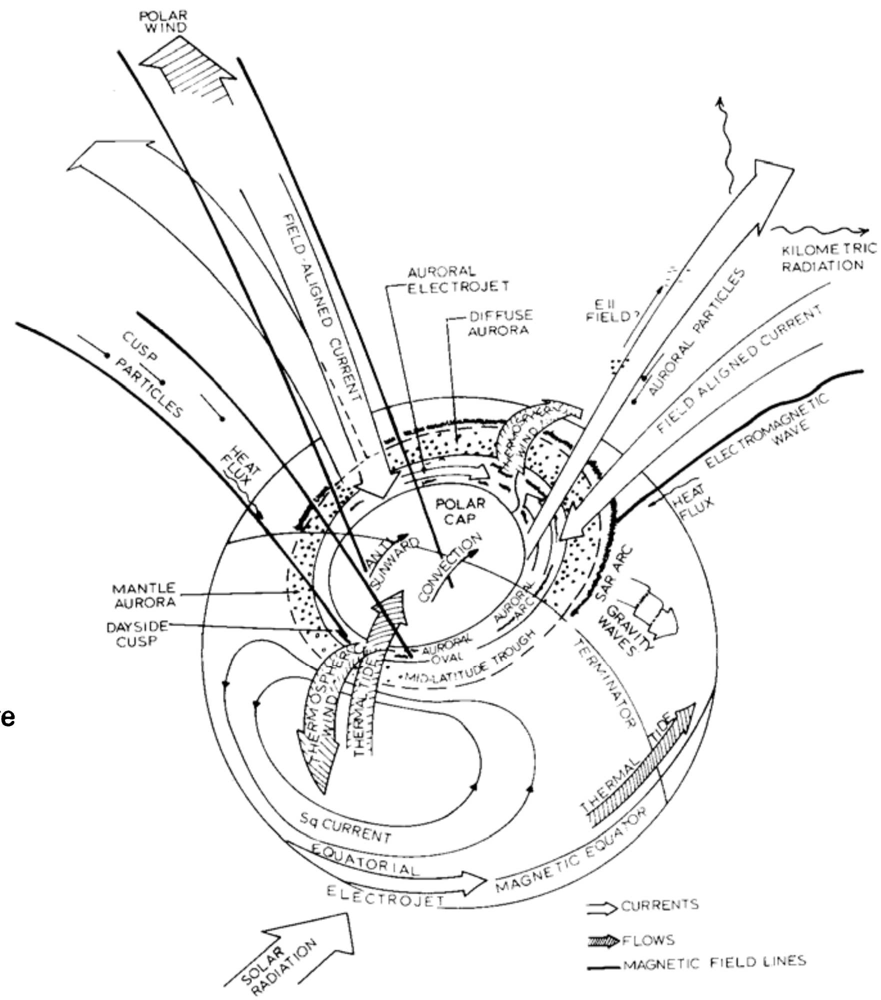
Io Story	*Process*	*Universality*
	Charge Exchange $X^+ + Y$ $\rightarrow Y^+ + X_{fast}$	Solar wind + Interstellar pick-ions

2 - electrical conductivity of a plasma

Ionospheres - Sets boundary conditions for magnetospheric dynamics

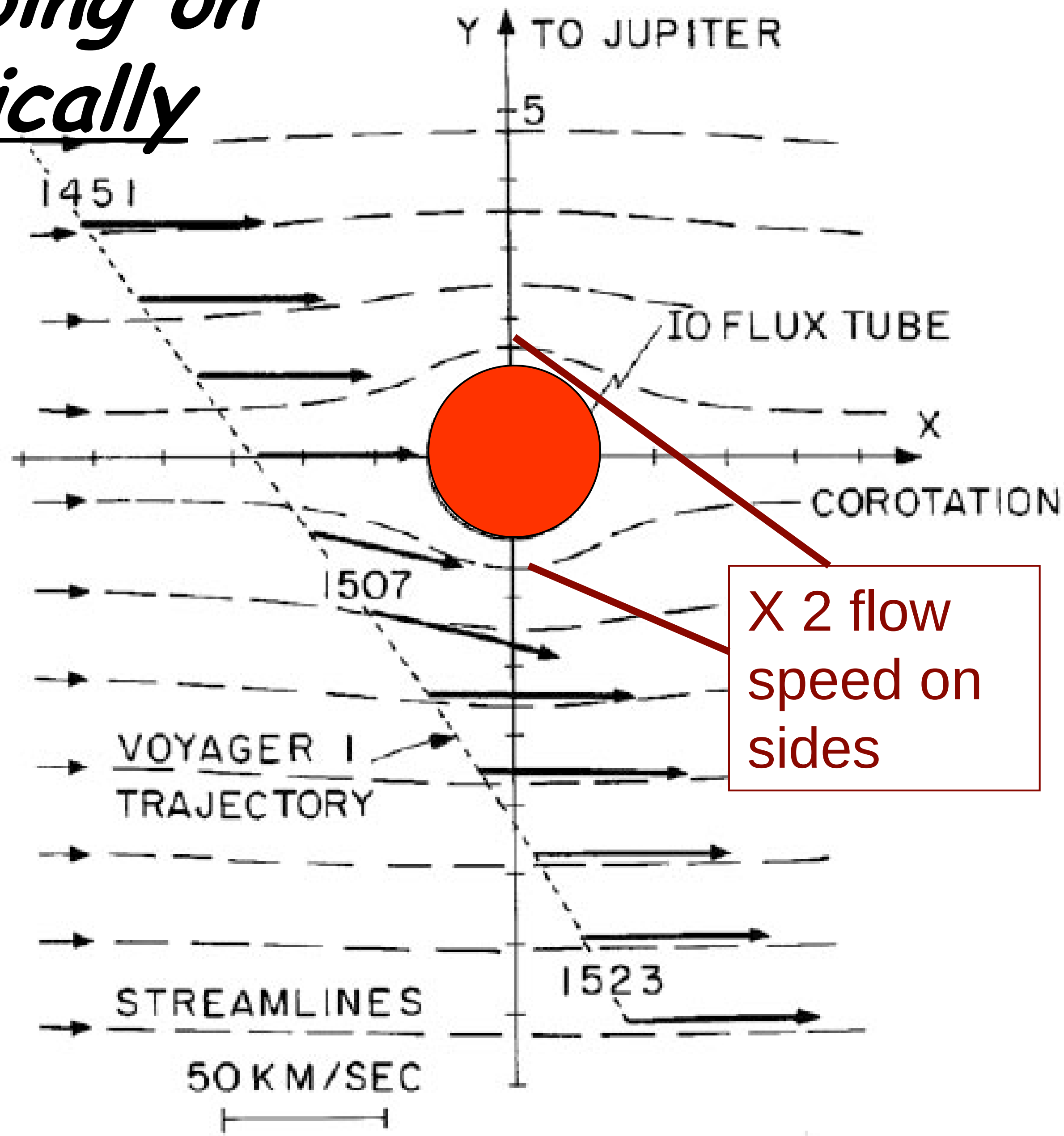




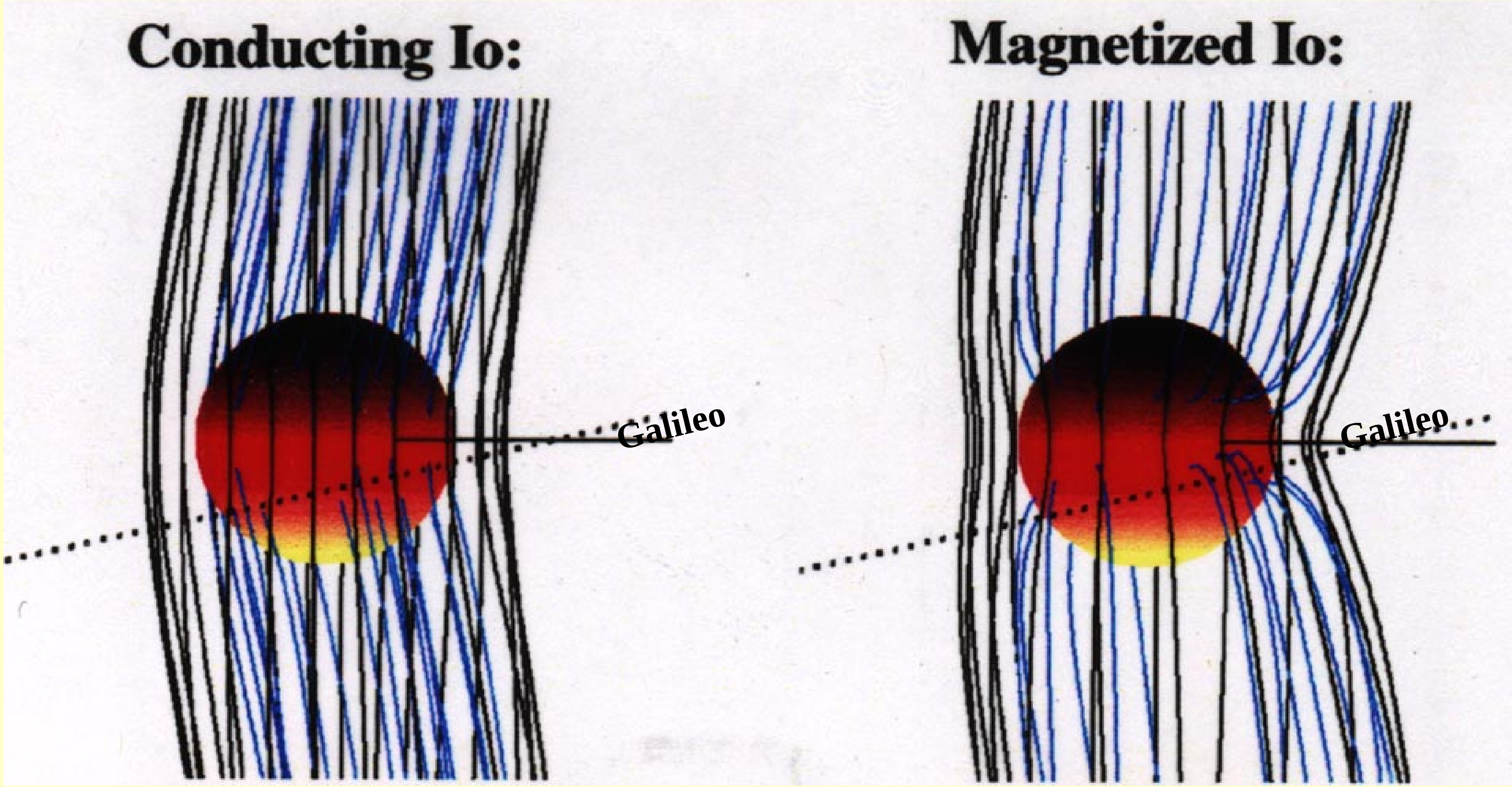


So, what's going on <u>electrodynamically</u> near Io?

Flow around a perfectly conducting sphere - or cylinder



Does Io Have a Magnetic Dynamo?

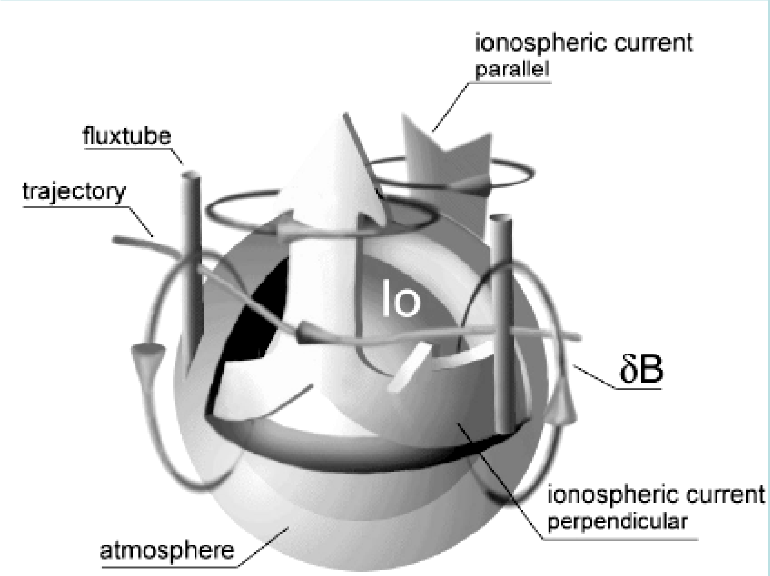


- *Magnetic field geometries look very similar*
- *To distinguish between the two models we need to fly over the pole*
- *Answer? Probably NO.*

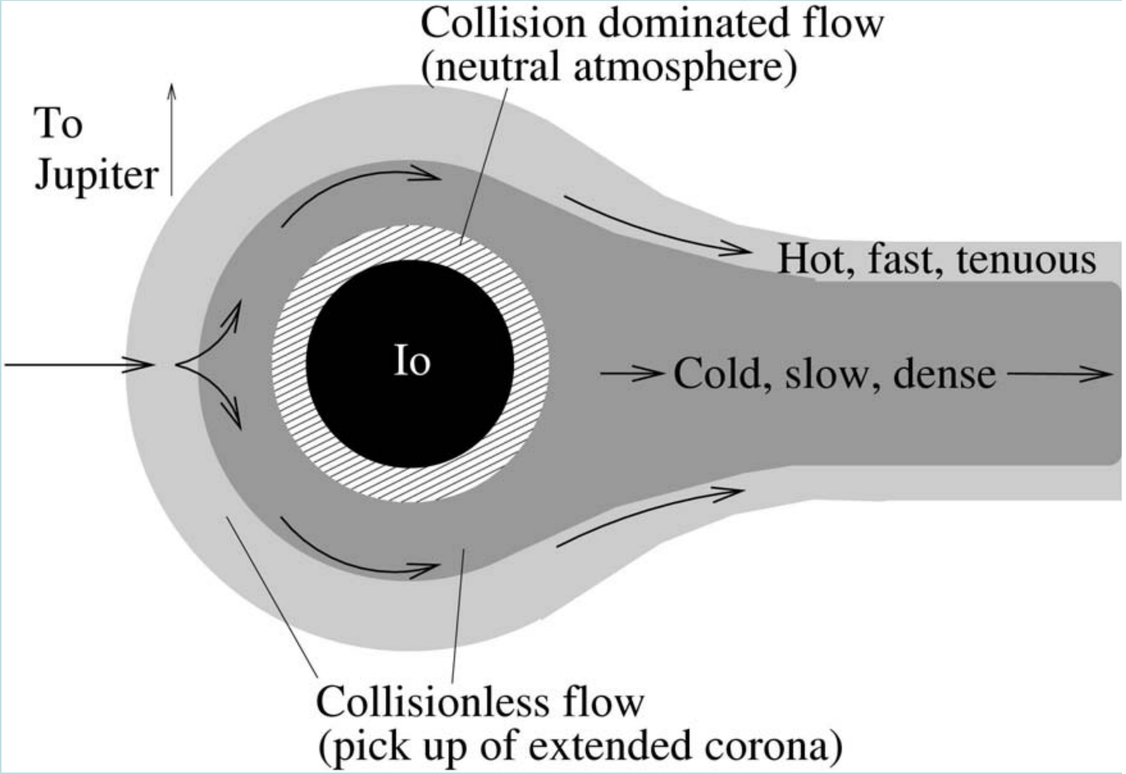
MHD model Linker et al. 1996

Io Plasma-Atmosphere electrodynamics

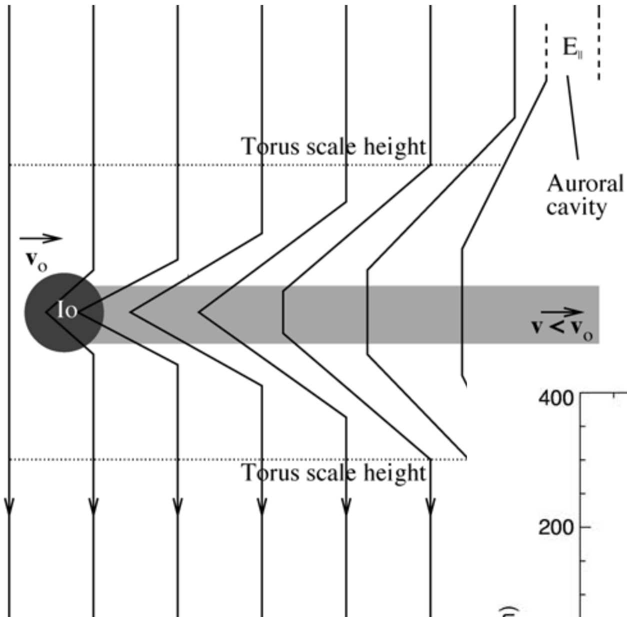
- Electrodynamics: Induction and Pick-up currents deflect flow
- Heating, ionization and charge-exchange in atmosphere
- Cooling, deceleration of upstream plasma
- Acceleration of downstream plasma
- Messy!



Saur et al. 2002



Delamere et al. 2003

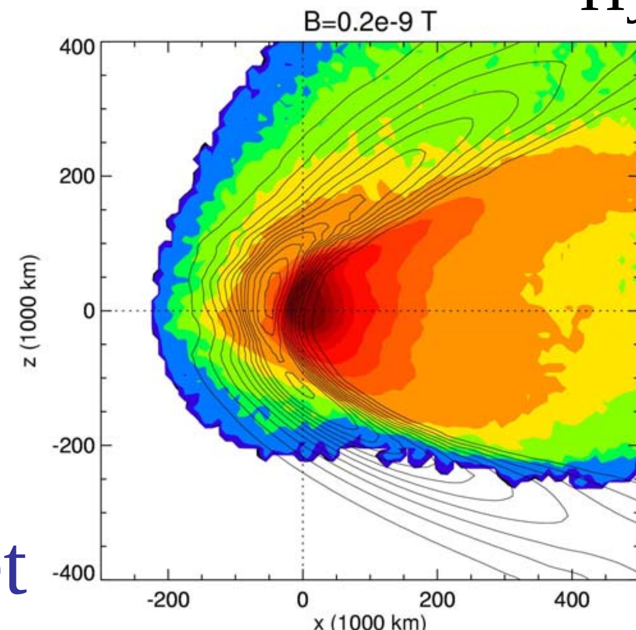


MHD/electrodynamic

Io

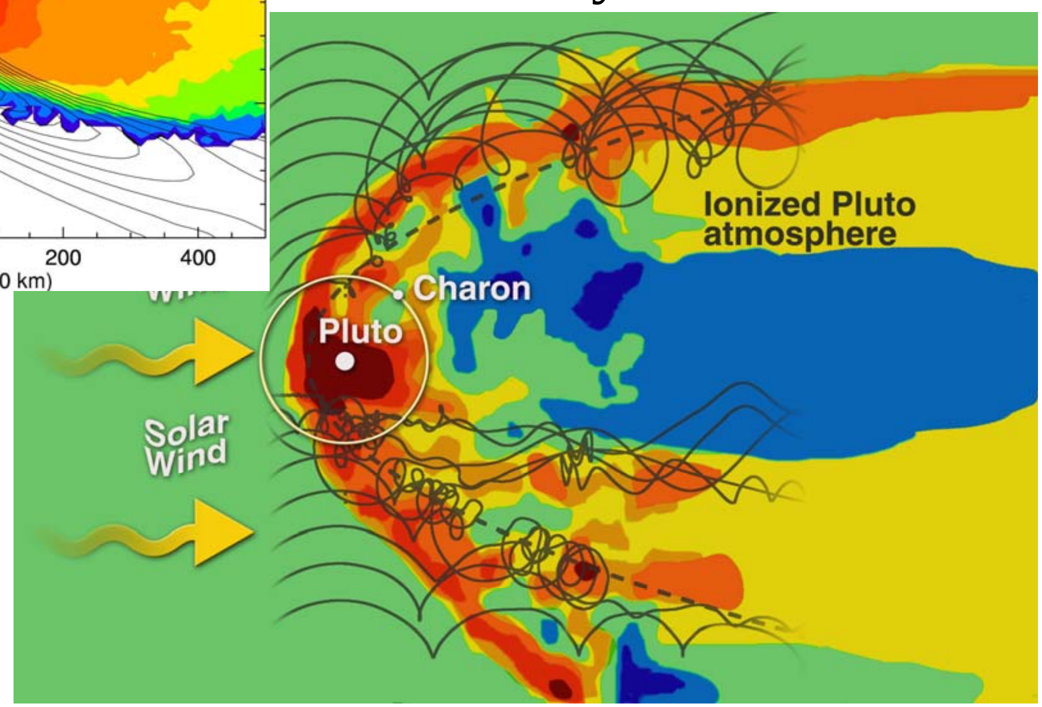
Hybrid

(fluid electons,
particle ions)



Comet
Borrelly

Hybrid / Kinetic



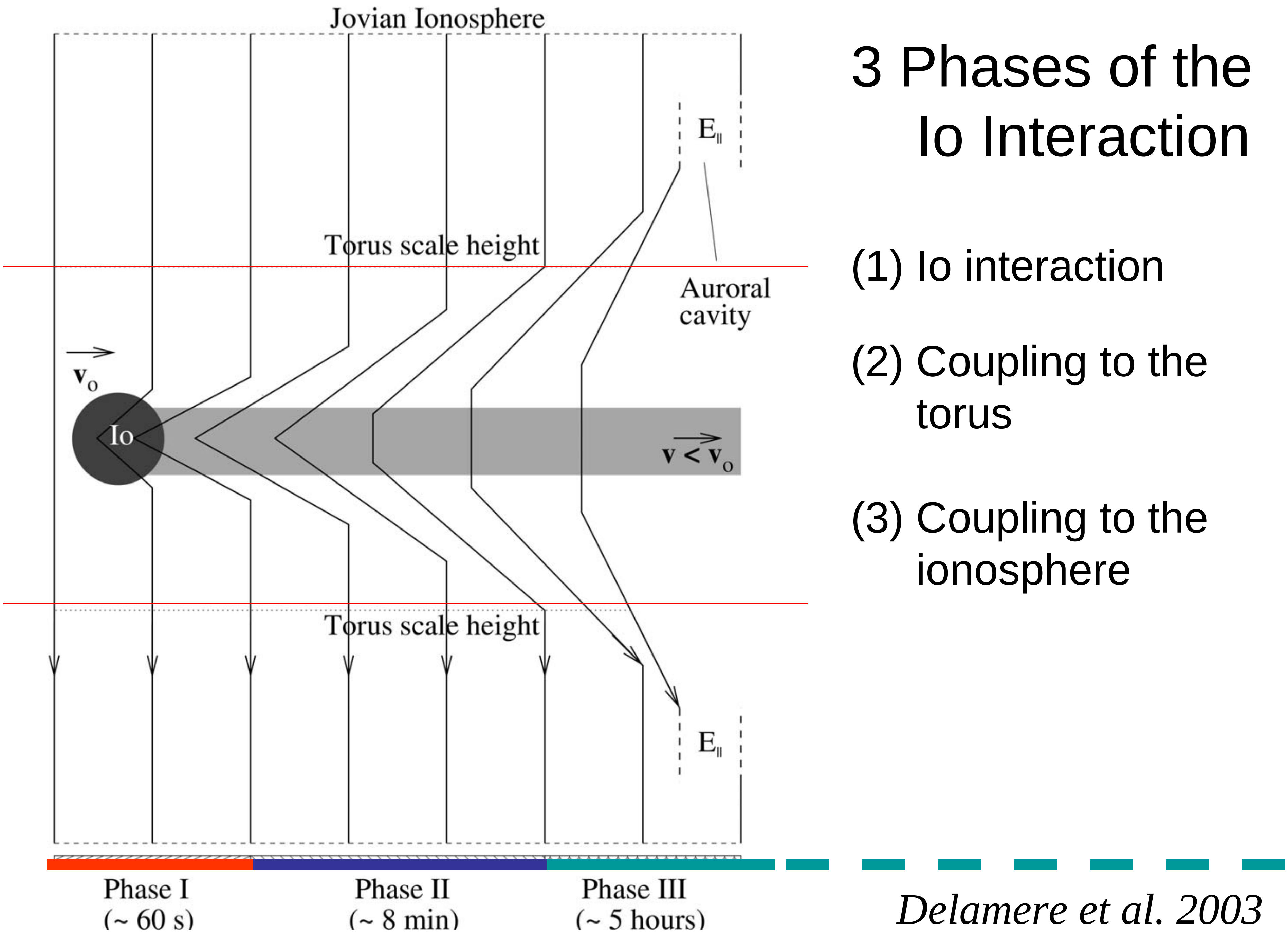
Pluto

3 Phases of the Io Interaction

(1) Io interaction

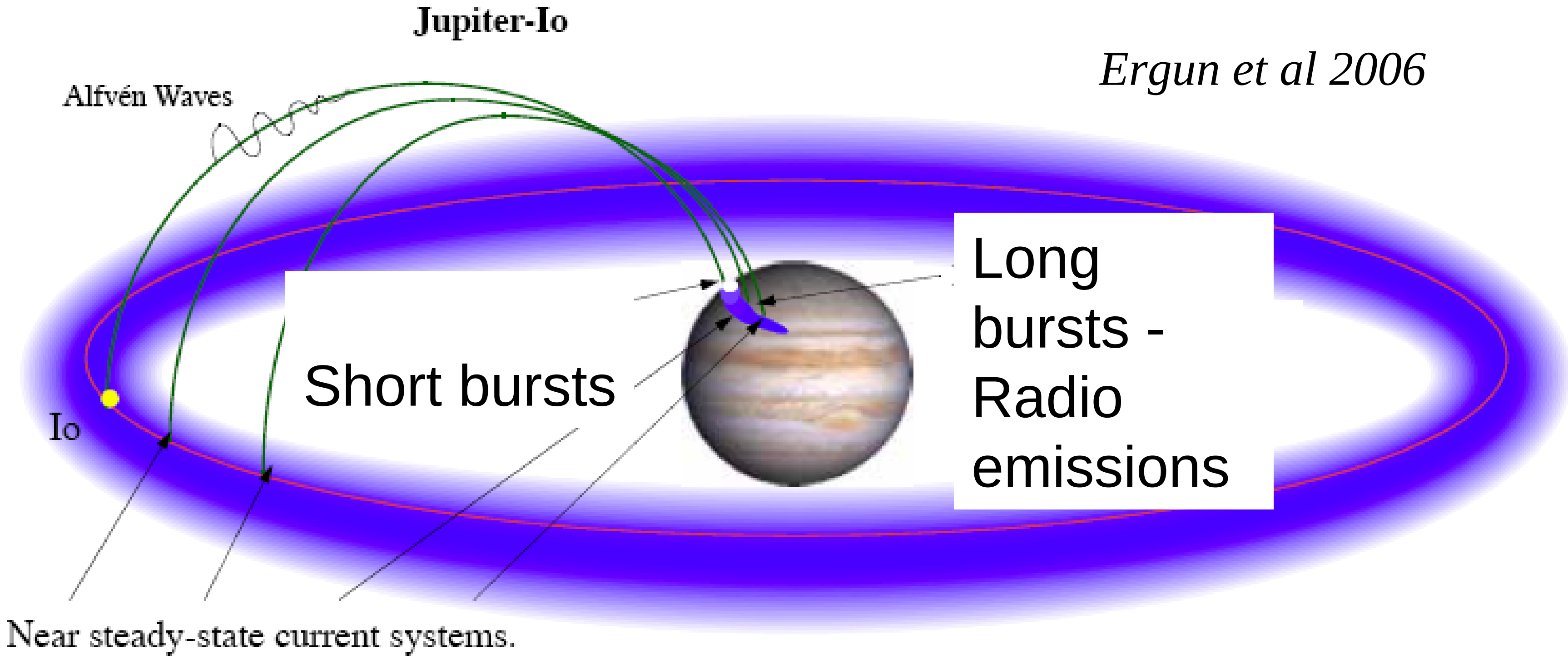
(2) Coupling to the torus

(3) Coupling to the ionosphere

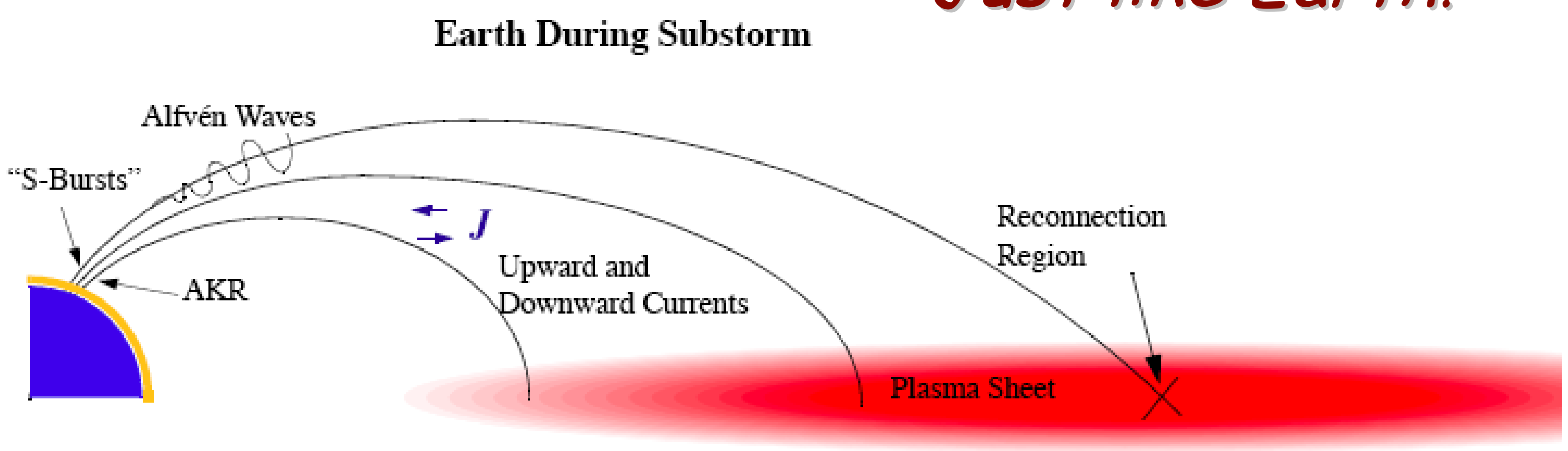


Delamere et al. 2003

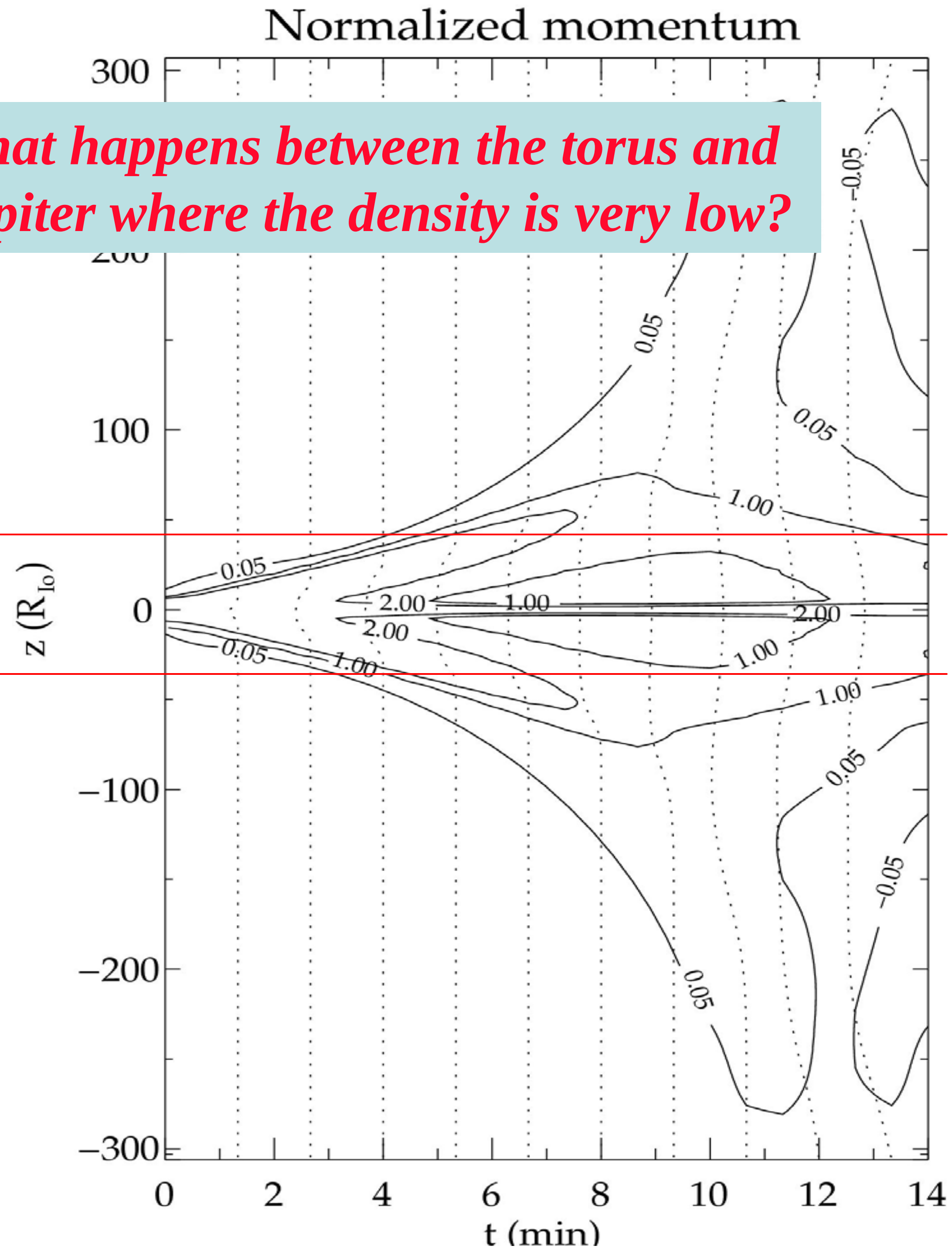
Ergun et al 2006



Just like Earth!



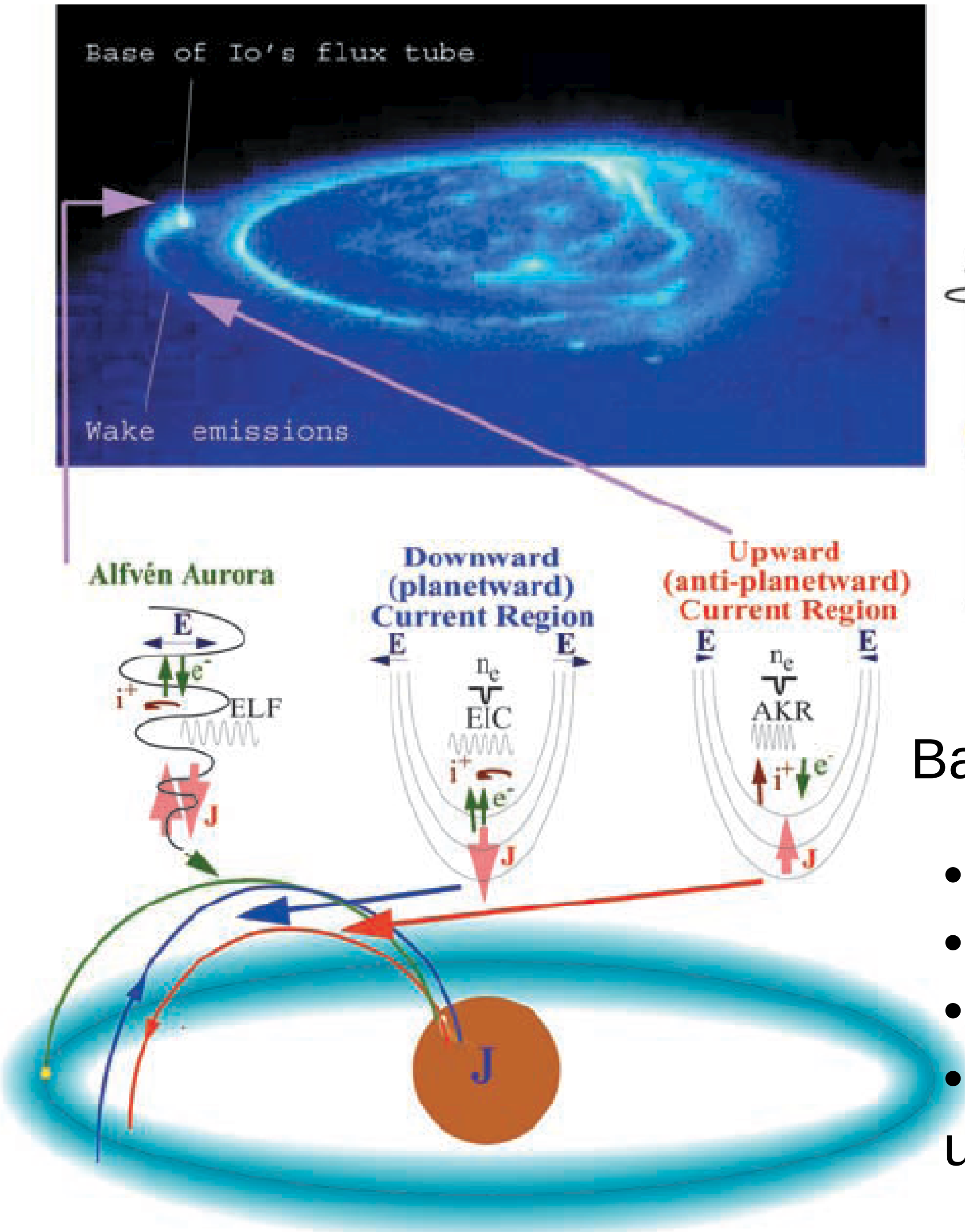
What happens between the torus and Jupiter where the density is very low?



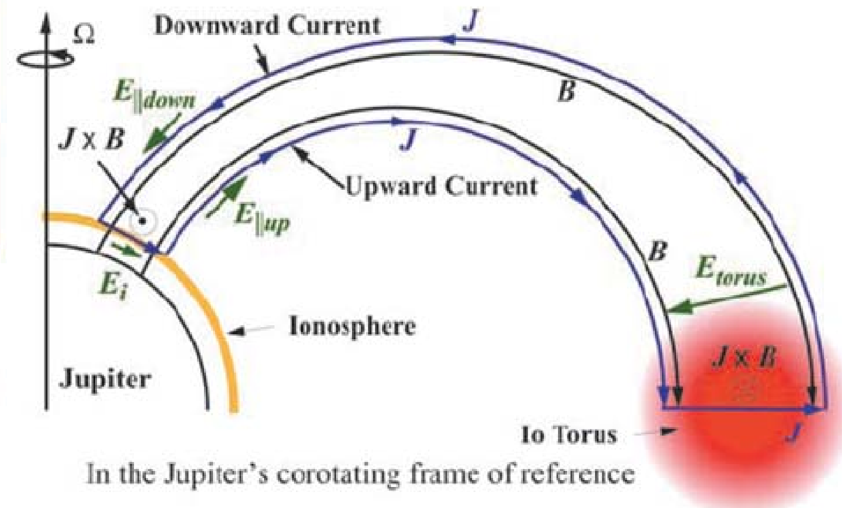
Phase II: Pick-up of New Plasma in Io's Wake

- Coupling to torus plasma
- Alfven travel-time to "edge" of torus
- Acceleration to few% of corotation
- 2-D MHD in non-uniform background plasma

Delamere et al. 2003

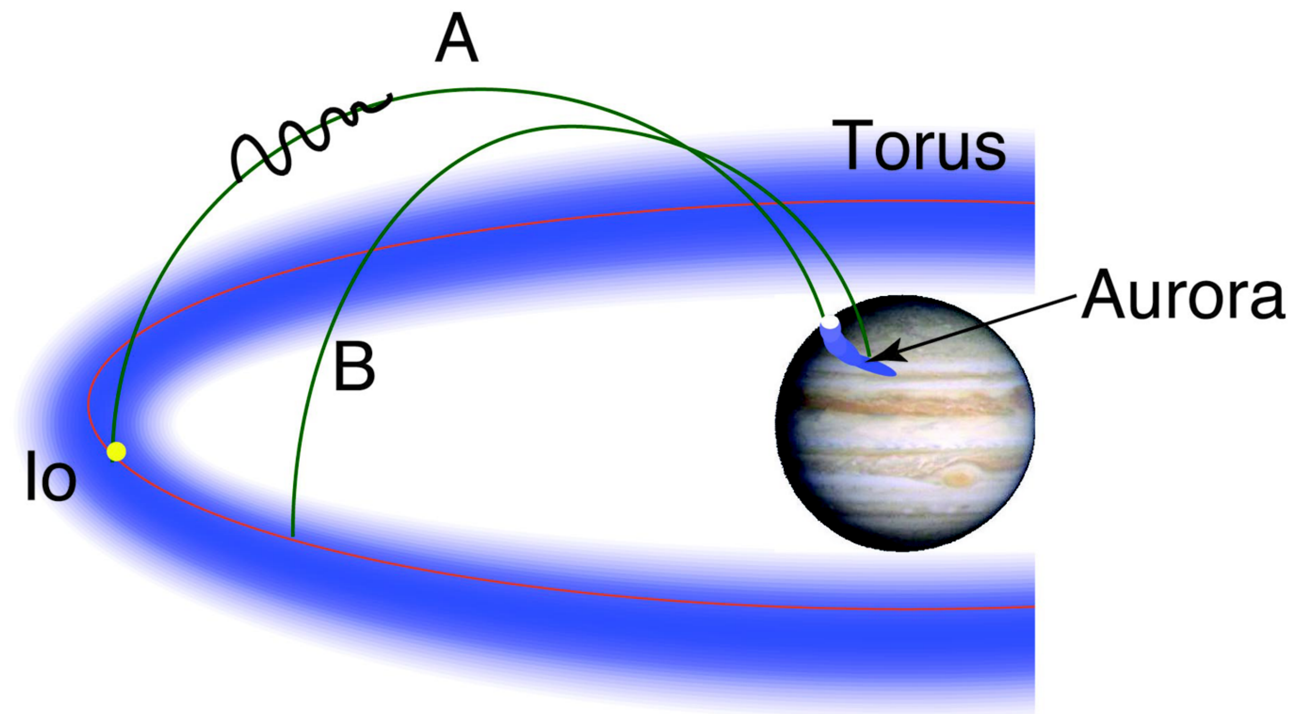


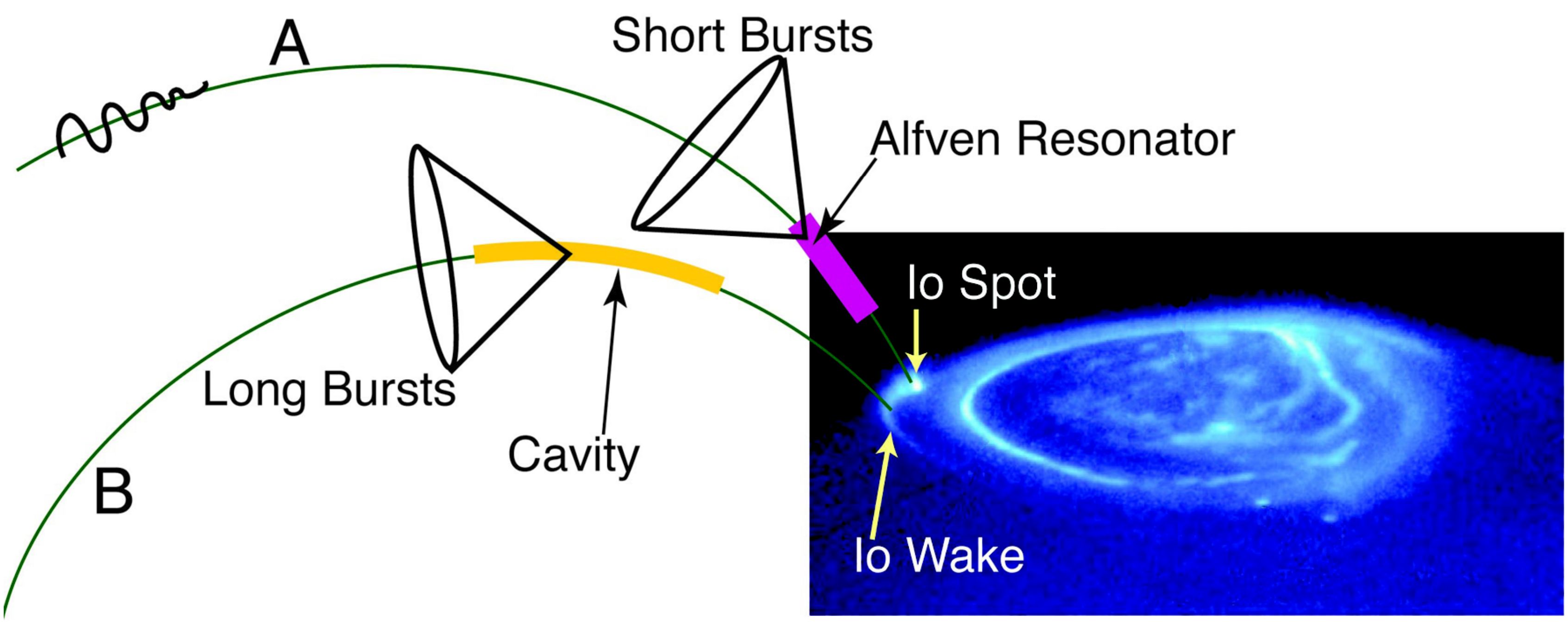
Su et al. 2003



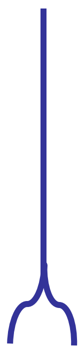
Based on Earth Experience:

- 3 current types
- Alfven: alternating
- Upward: e^- ->atmosphere
- Downward: moves upwards, transient


A
Torus
Aurora
B
Io

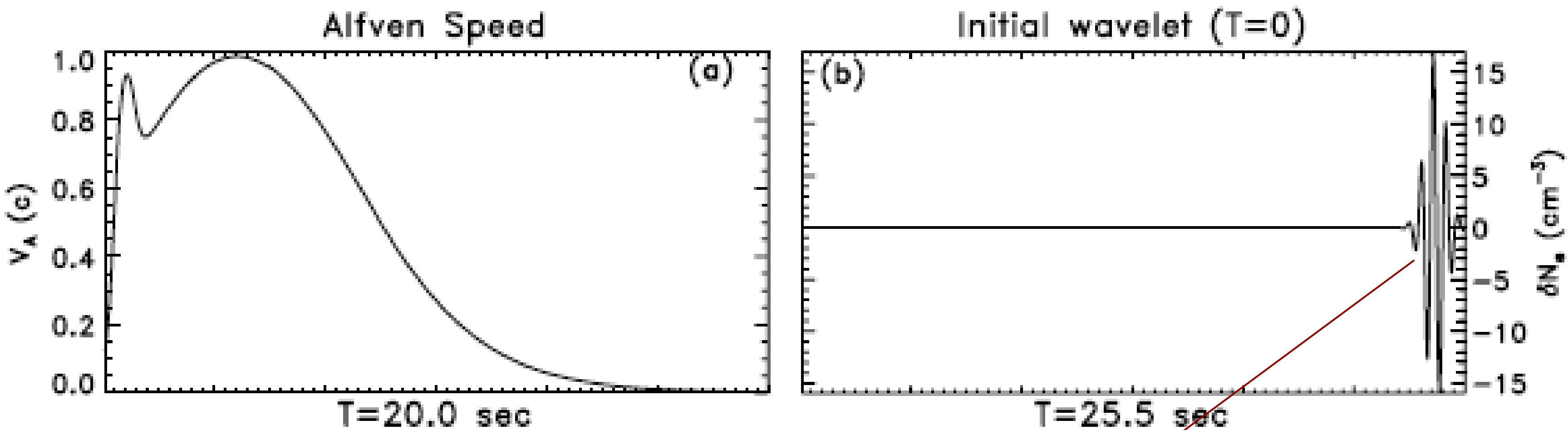

A
Short Bursts
Alfven Resonator
Io Spot
Long Bursts
Cavity
B
Io Wake

Alfven Resonator



- Accelerates outward electron beams

-> Short-Bursts of radio emission



Launch a wavepacket

Kinetic Alfven wave in dipole field with Prescribed V_A profile

Su et al. 2006

QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

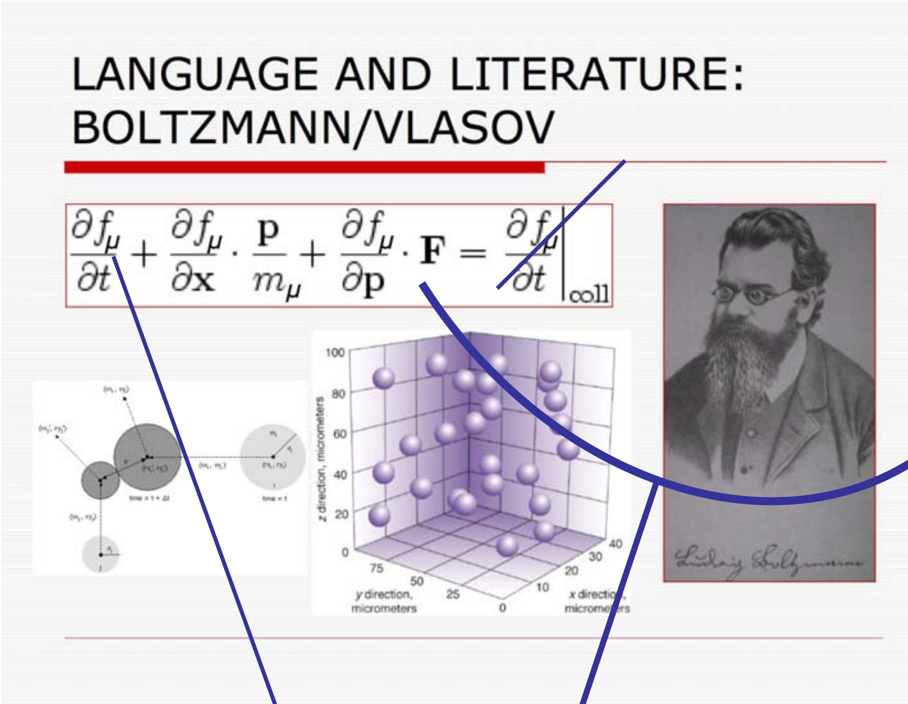
Unstable electron distribution function

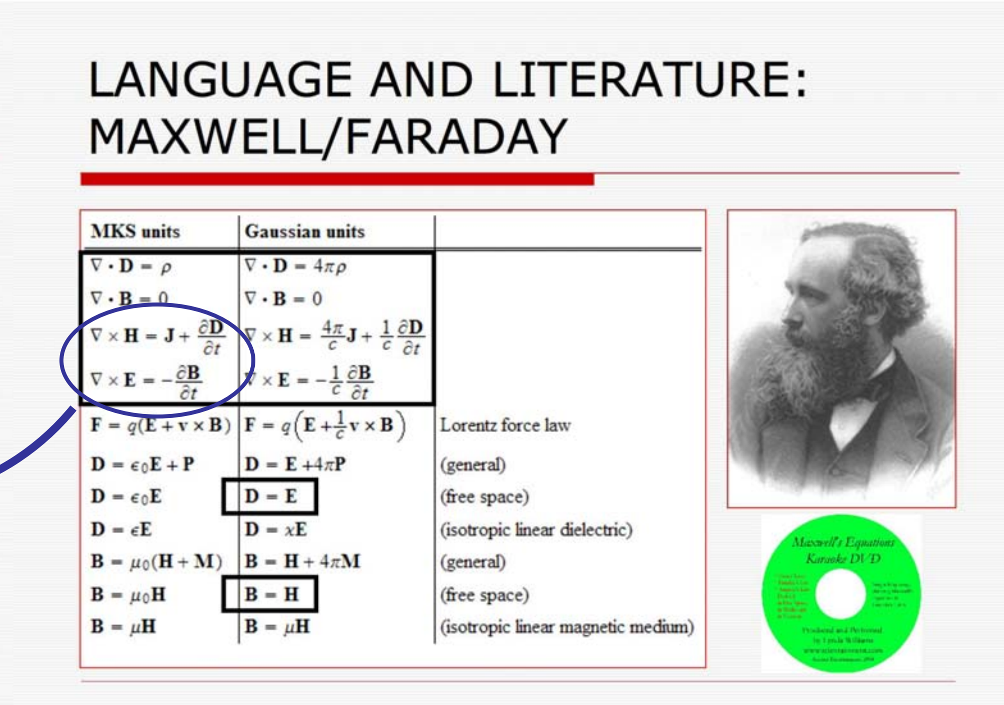
-> Cyclotron Maser Instability

-> EM radiation at F_{ce}

Beamed in hollow cone

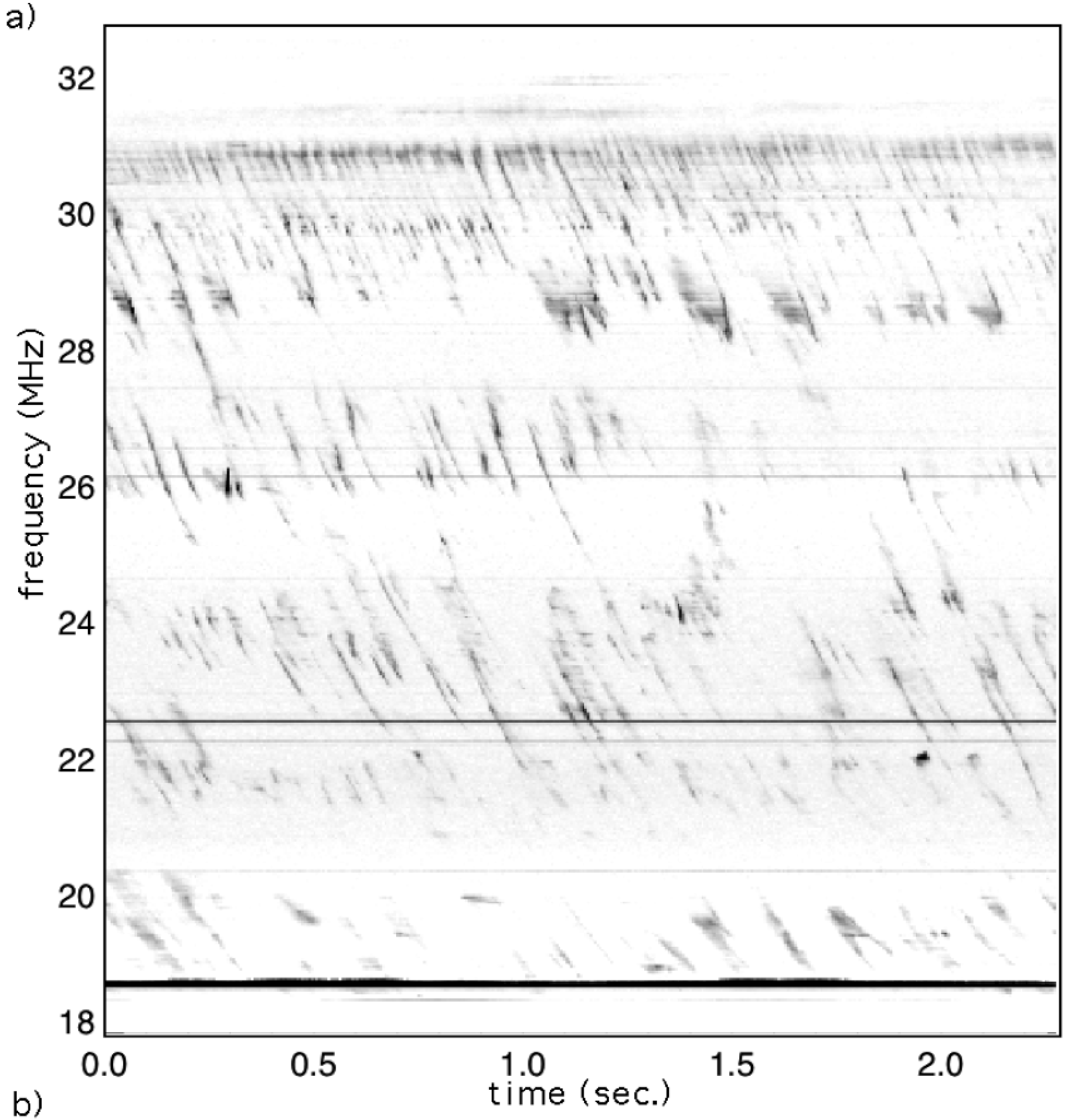
QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.





$$\mathbf{F} = (\nabla \times \mathbf{b}) \times \mathbf{b}$$

Kinetic Code: Calculate change in particle distribution function due to wave fields



Short Radio Emissions

aka S-Bursts

frequency~20 Mhz

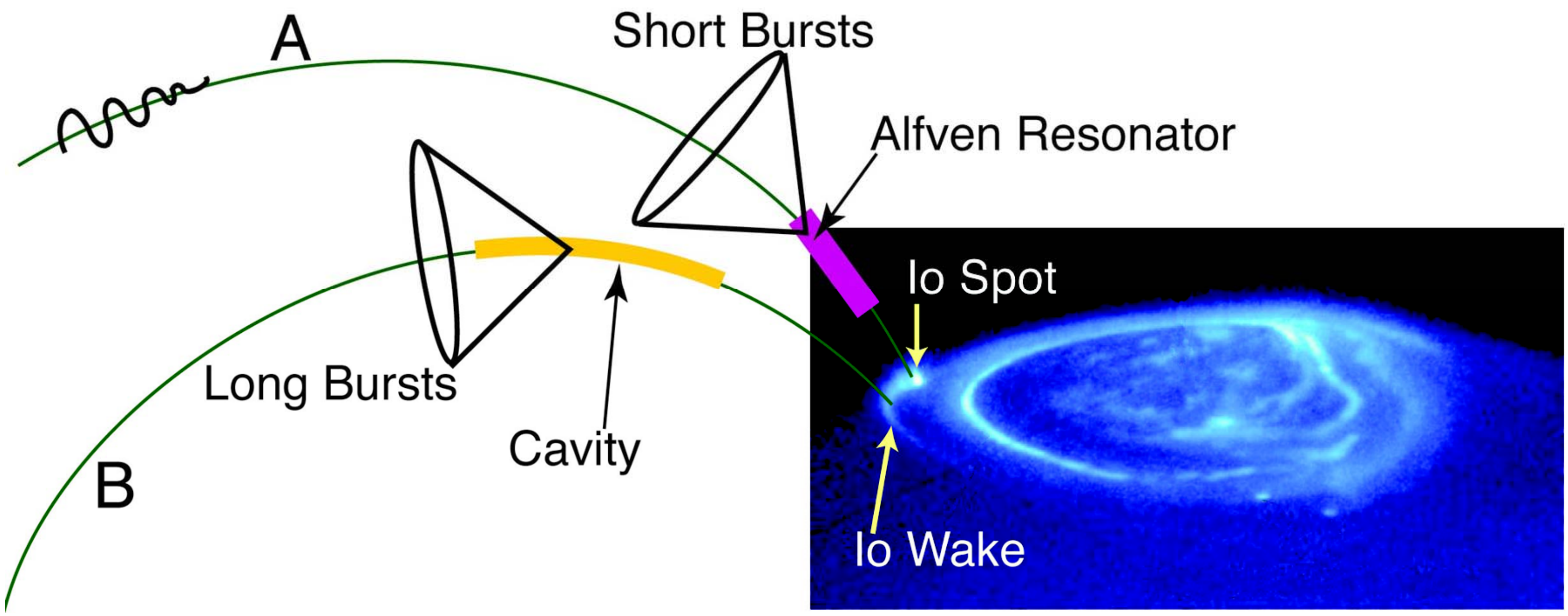
Duration ~10s milliseconds

Drift ~ 10 MHz/s

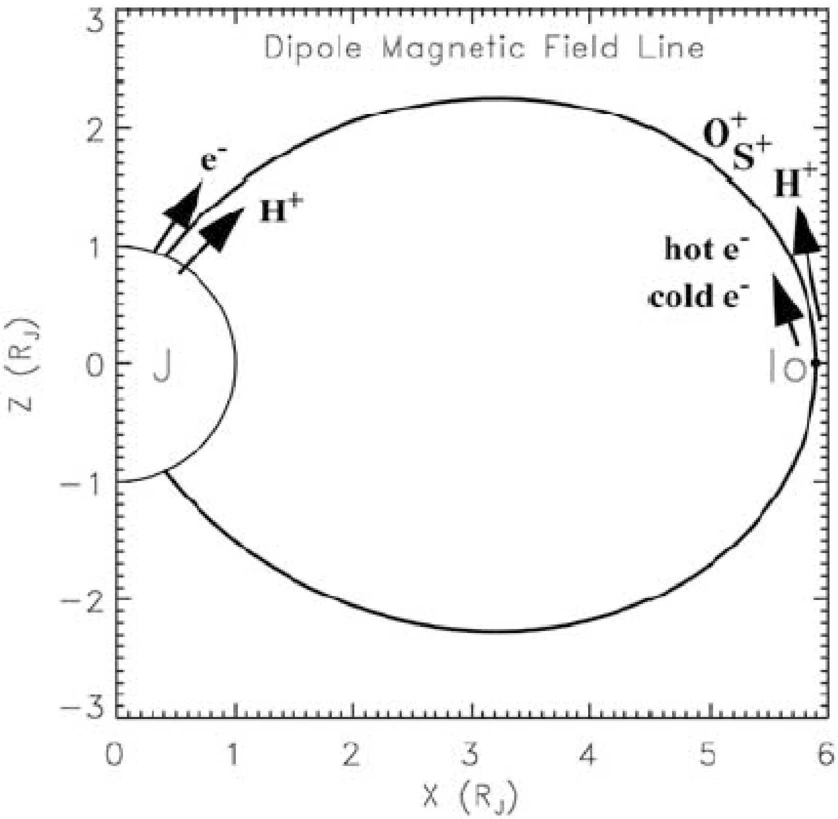
e- moving 10^4-10^5 km/s
Several keV

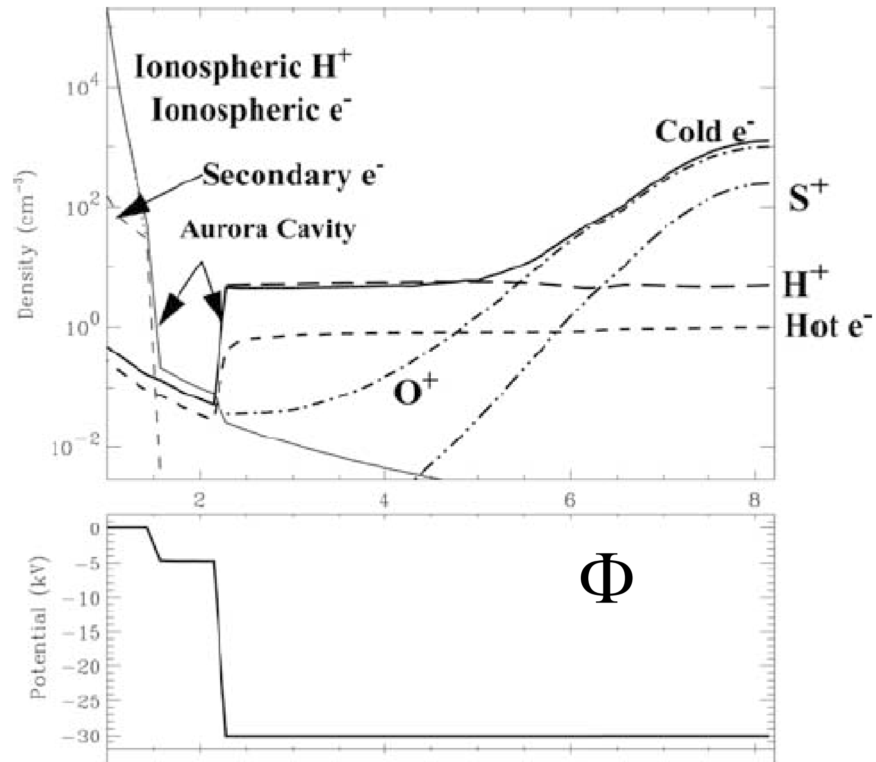
Lowering f -> away from Jupiter

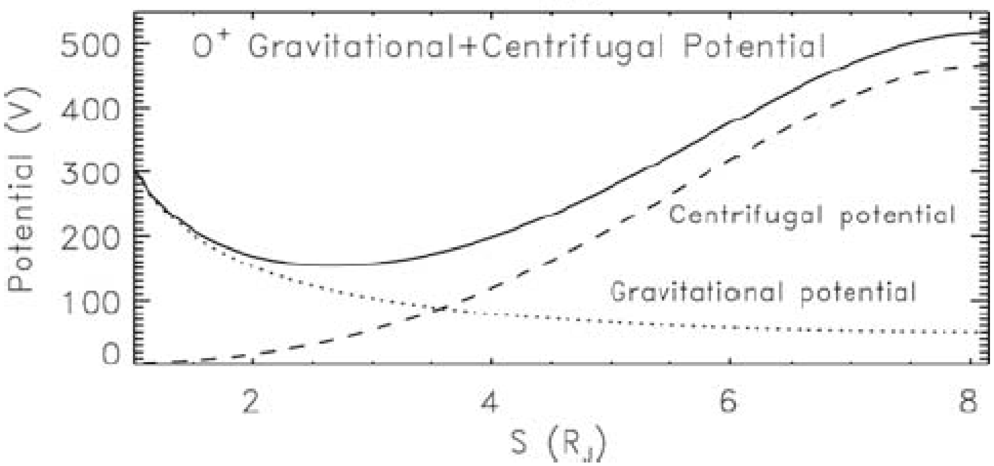
e.g. Hess et al. 2007



What about the wake?







Steady-state

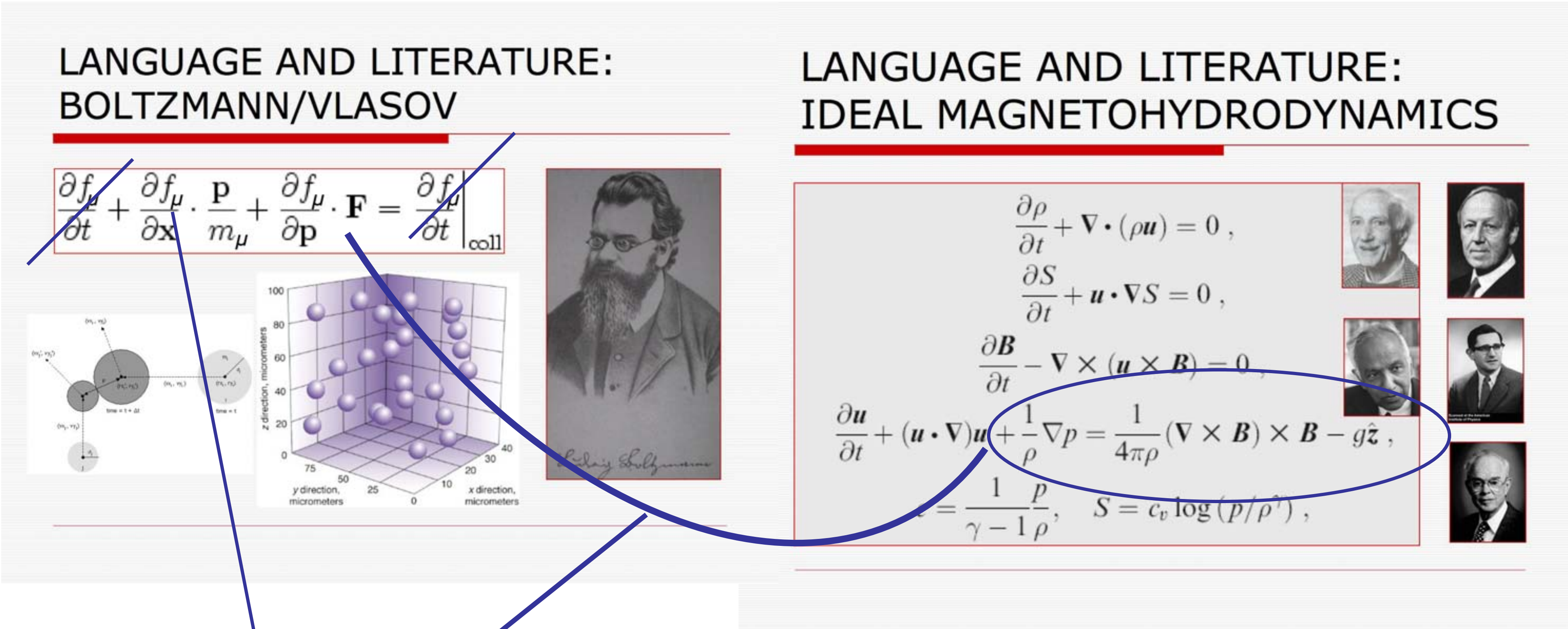
Boundary conditions set

ionosphere

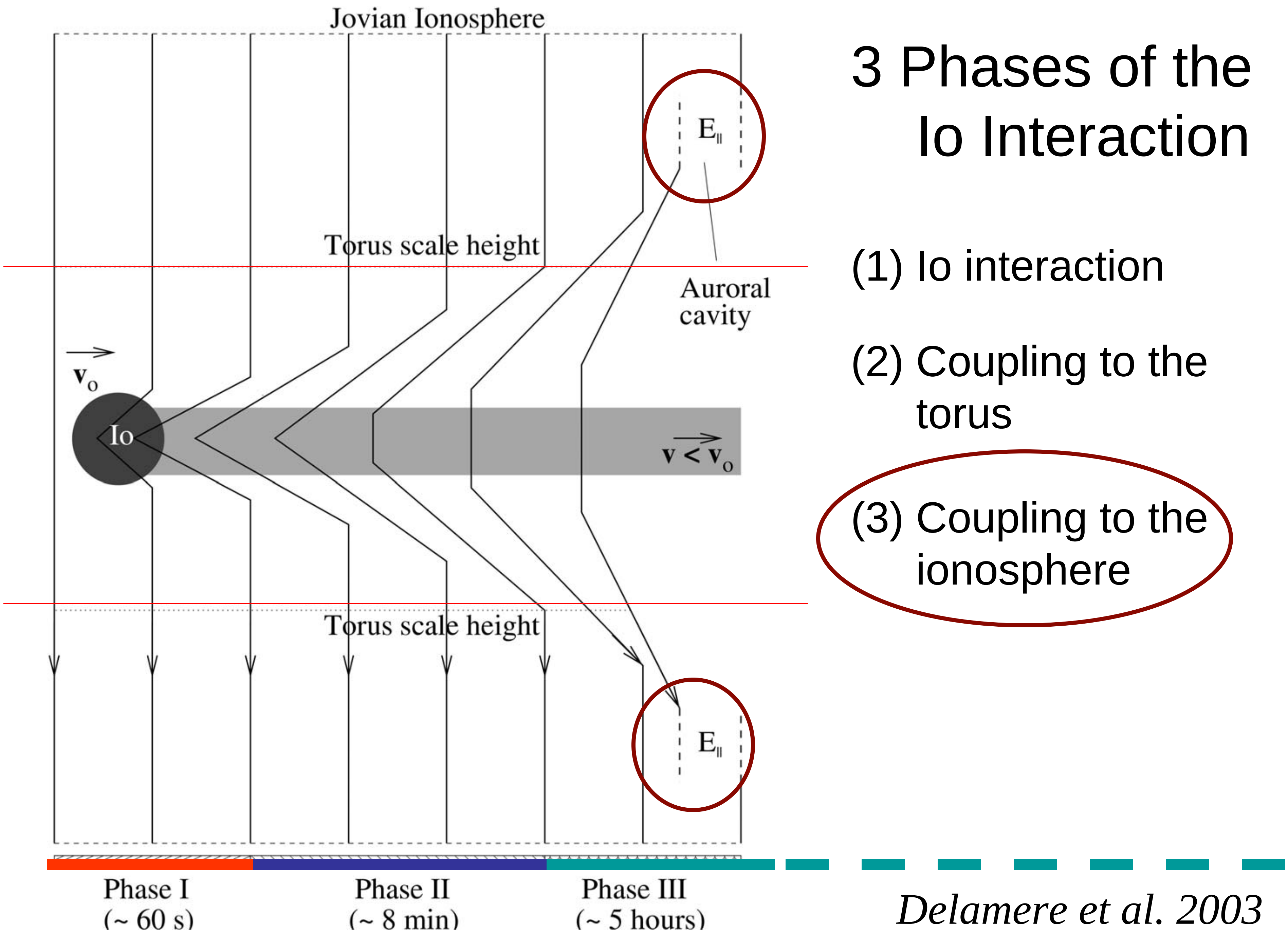
torus

10s kV Potential drops

Su et al. 2003



Vlasov Code: Calculate steady-state particle distribution function due to imposed gravitational, centrifugal and electrostatic potentials



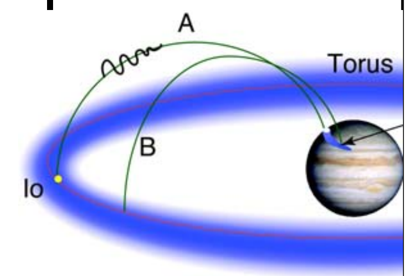
3 Phases of the Io Interaction

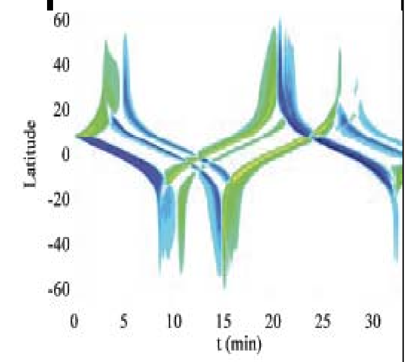
(1) Io interaction

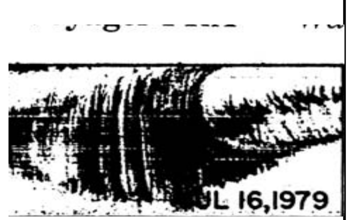
(2) Coupling to the torus

(3) Coupling to the ionosphere

Delamere et al. 2003

<table>
<tr><th>Io Story</th><th>Process</th><th>Universality</th></tr>
<tr>
<td>


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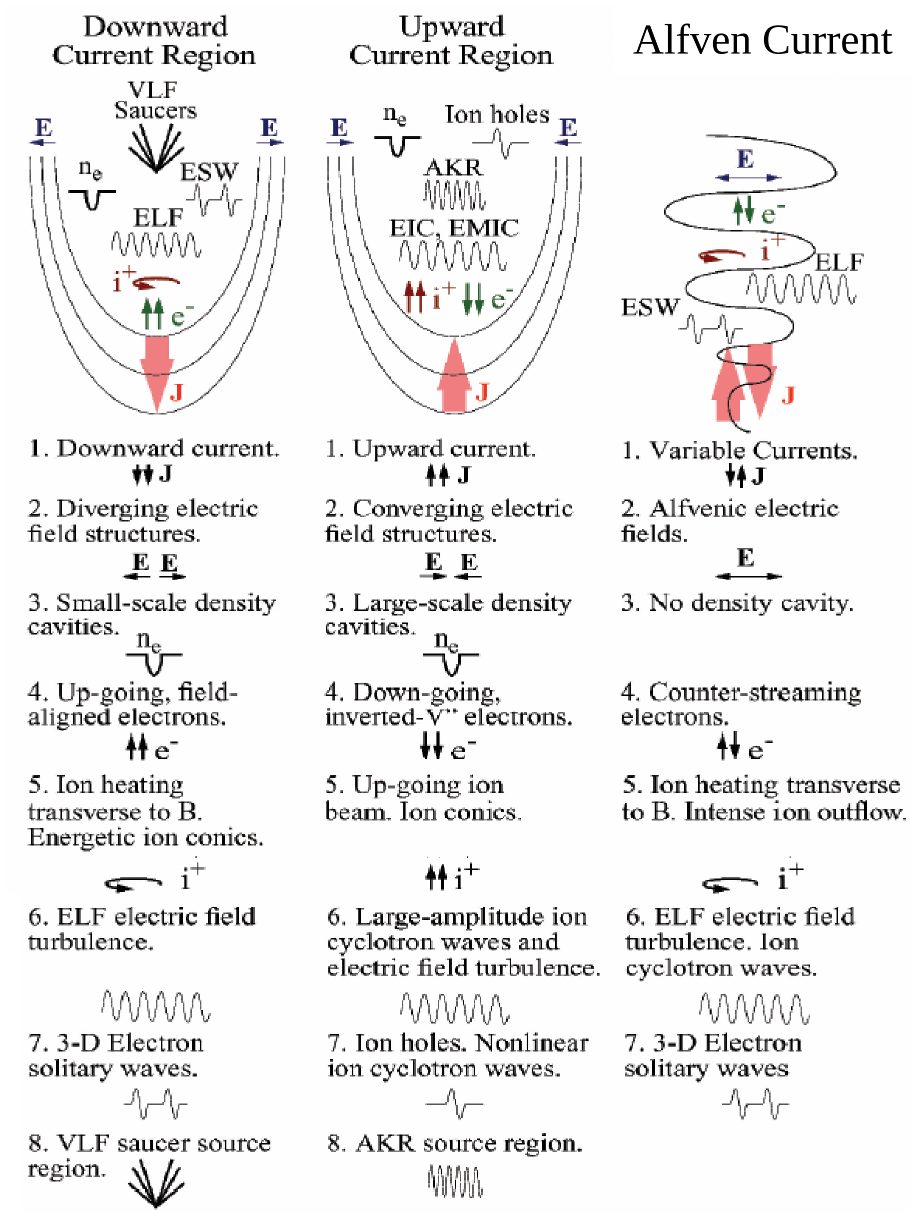
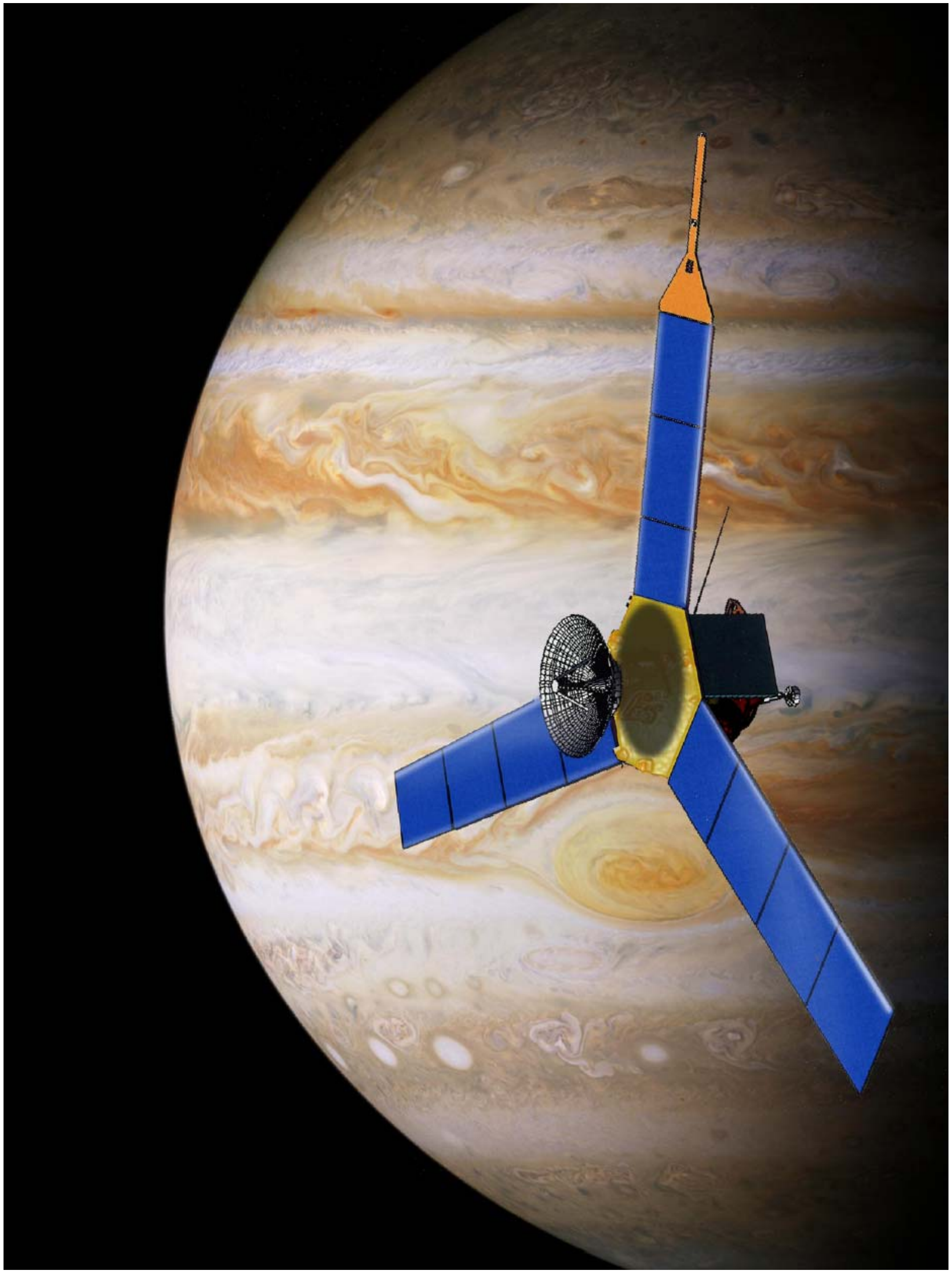
<td>


</td>
<td>ALL magnetospheres?

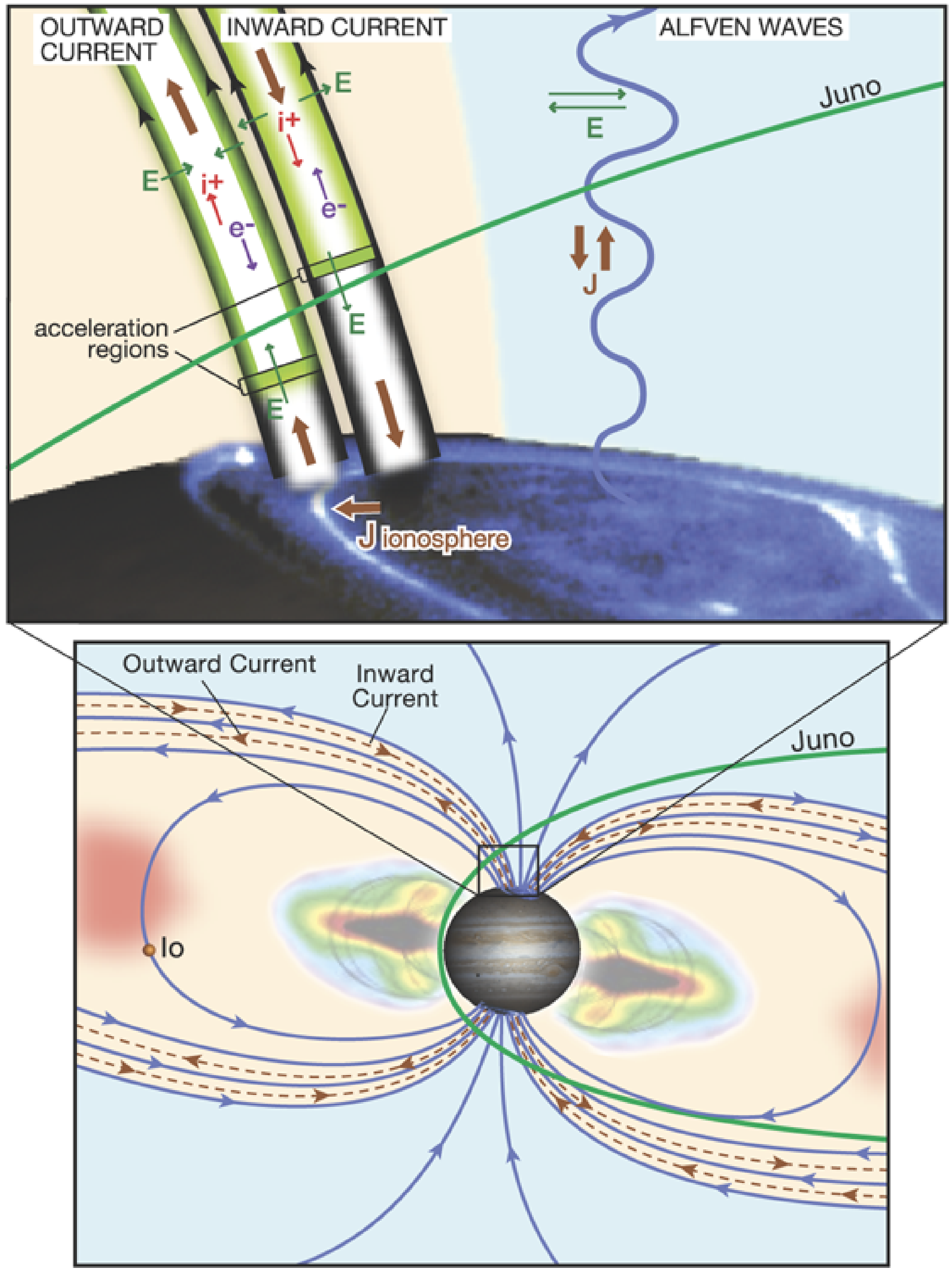
Momentum Coupling</td>
</tr>
</table>

Juno

Jupiter Polar Orbiter

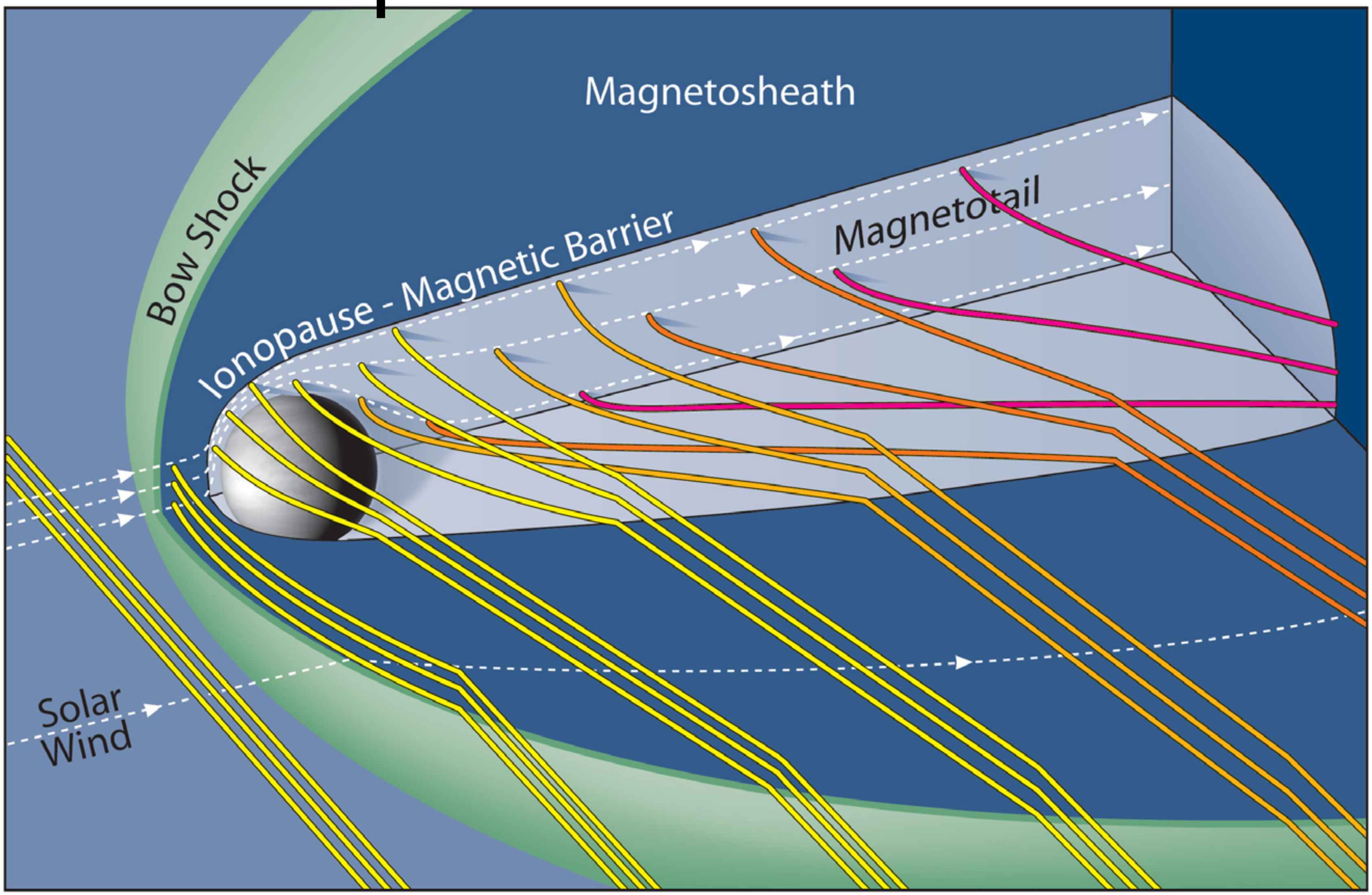


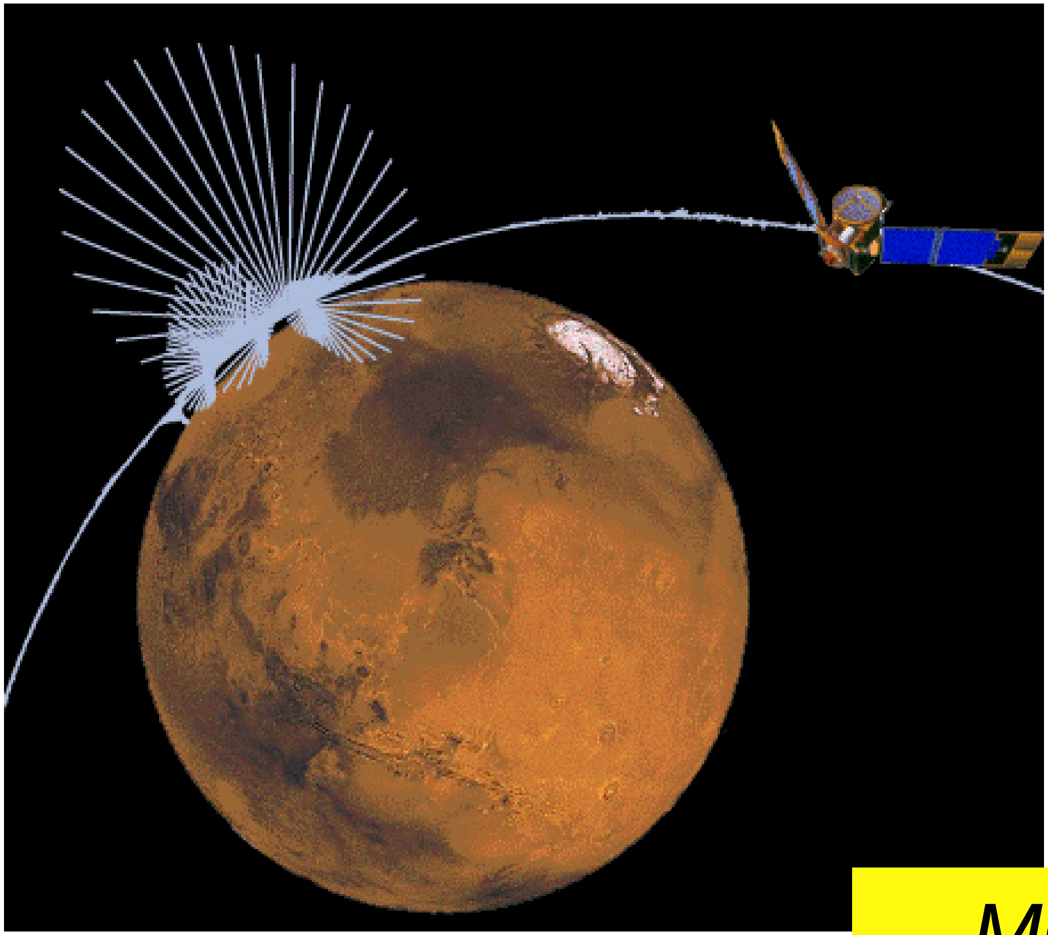
Juno arrives
At Jupiter
In 2016

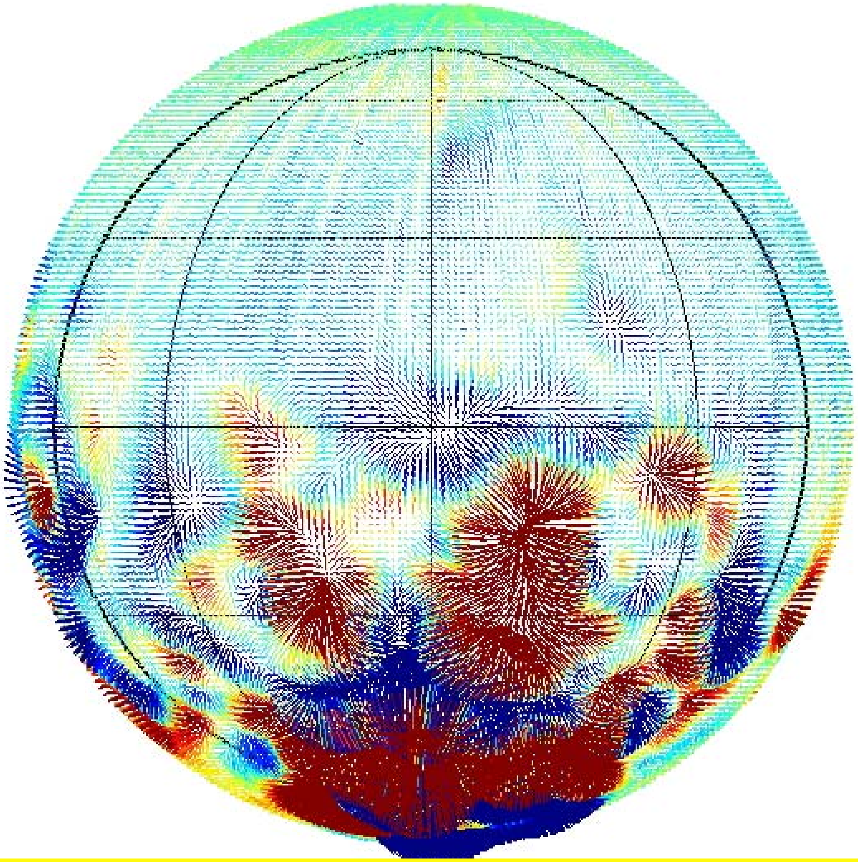


Other Plasma-Atmosphere Interactions

Venus, Mars, Titan - Ionospheres + Bow Shocks







MGS Measurements - Implications for Mars' Atmosphere

- Ancient dynamo

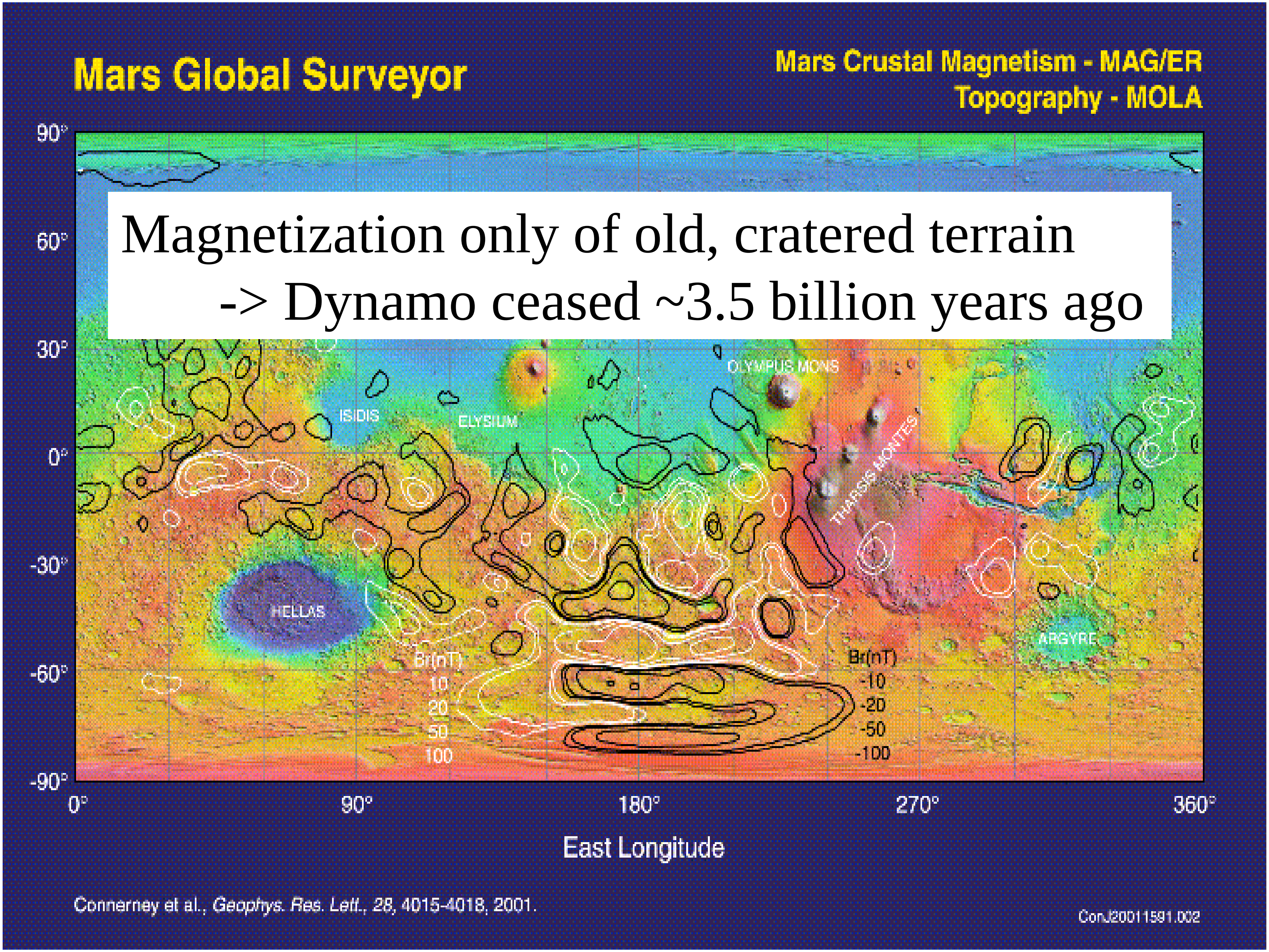
-> early protection for atmosphere

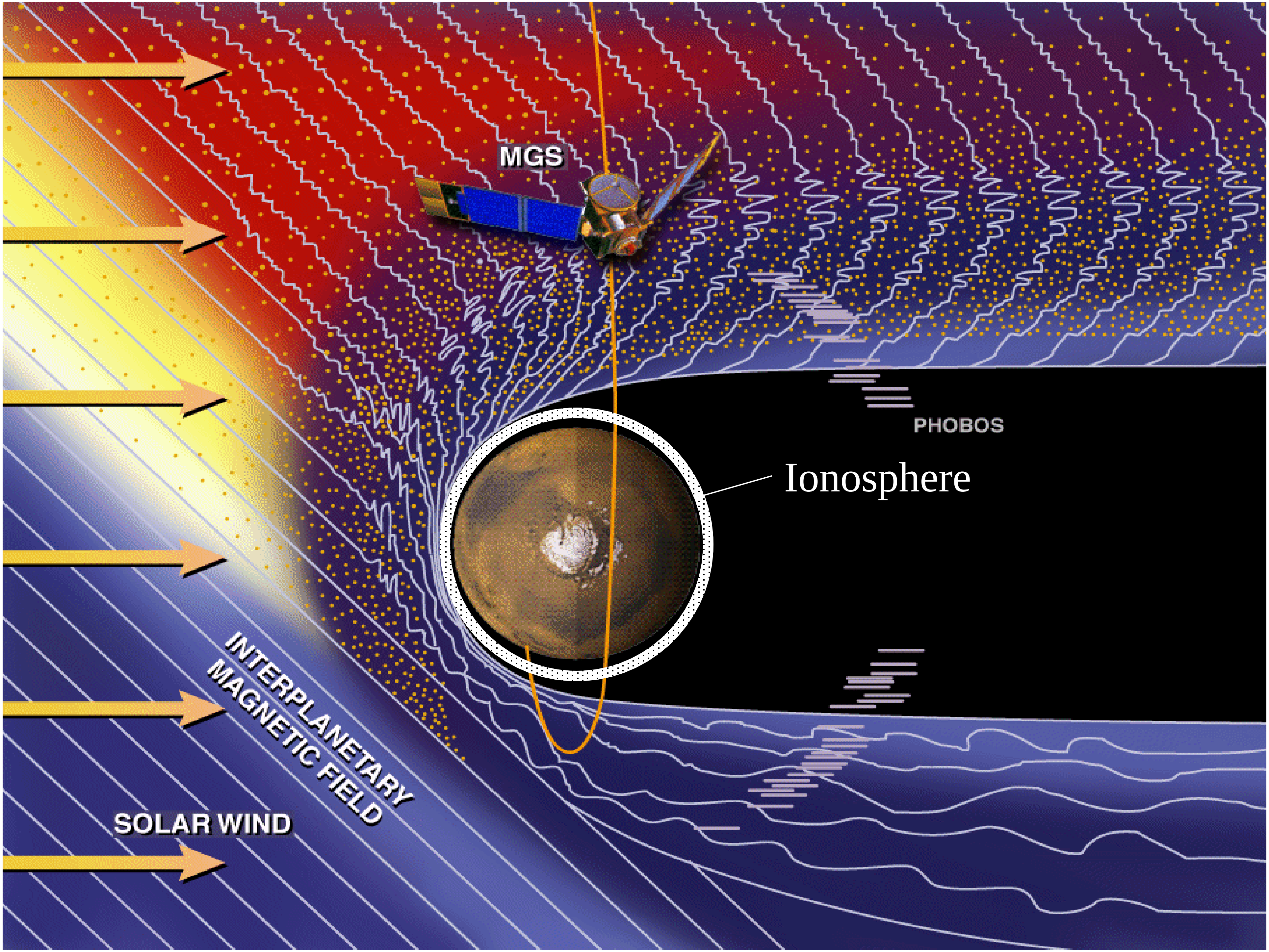
- **<u>Strong</u>** crustal magnetization

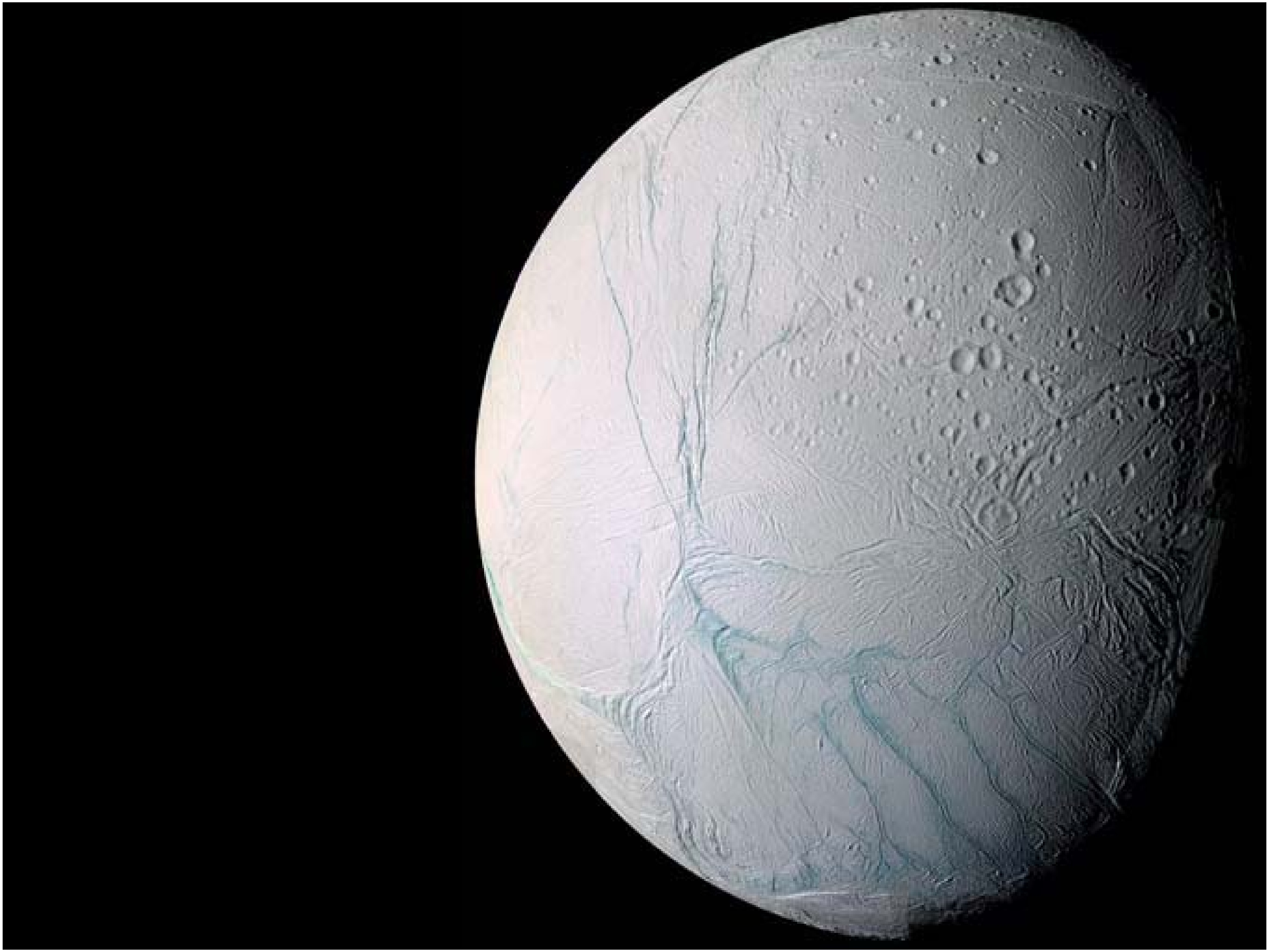
-> affect atmospheric loss after dynamo turn-off

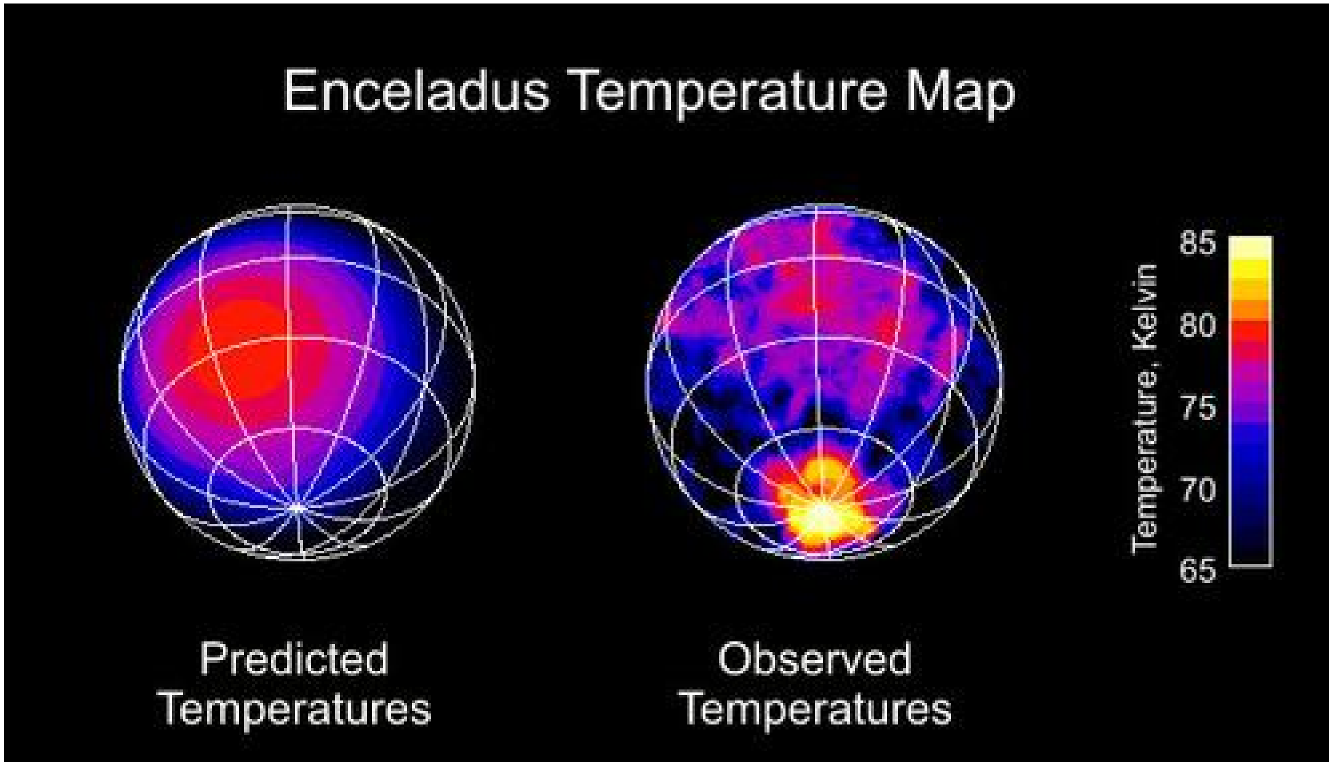
Magnetization only of old, cratered terrain

-> Dynamo ceased ~3.5 billion years ago




MGS
PHOBOS
Ionosphere
INTERPLANETARY MAGNETIC FIELD
SOLAR WIND

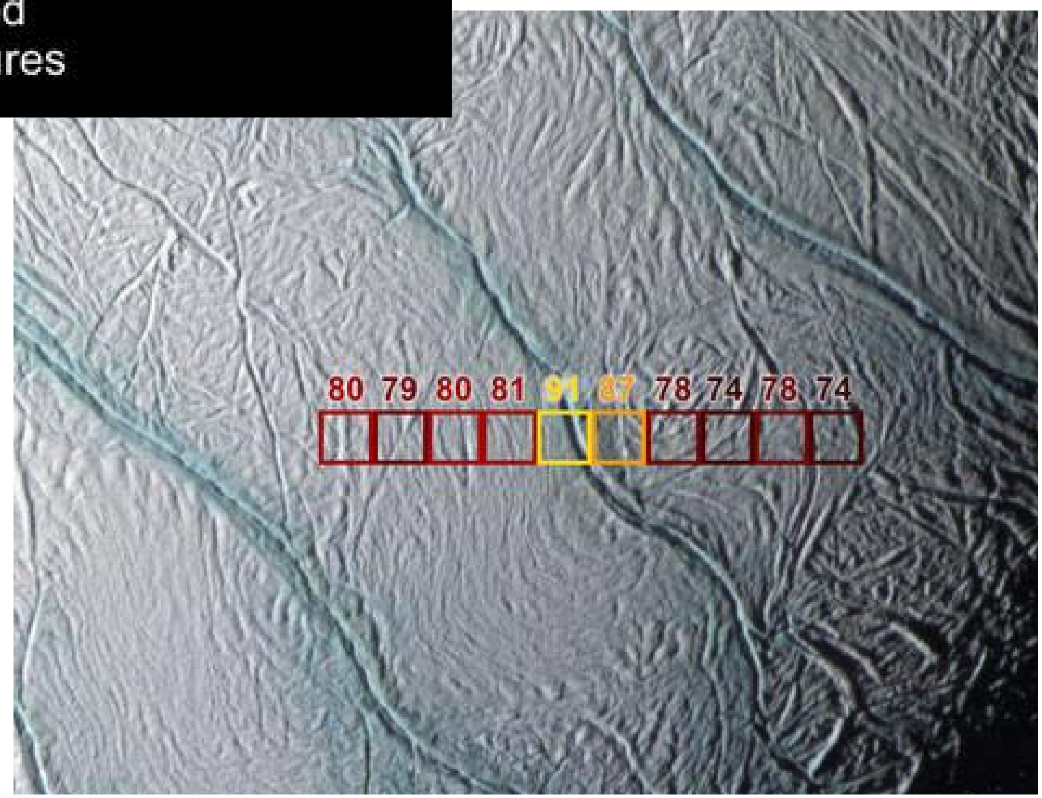


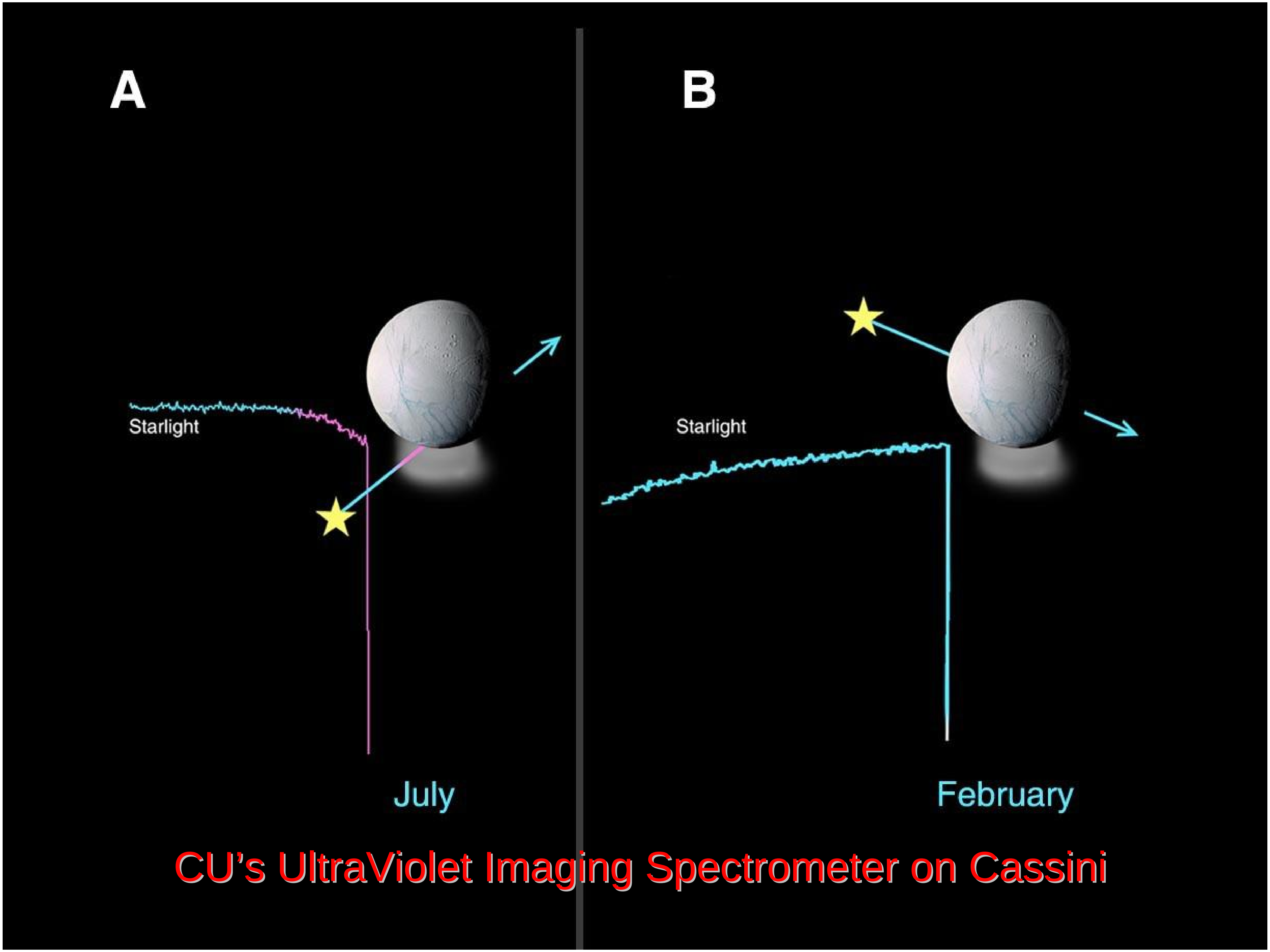


Wow! It's hot!

Heat Flux ~10^{10} W

Water vapor escaping - but is there a substantial reservoir of liquid water?

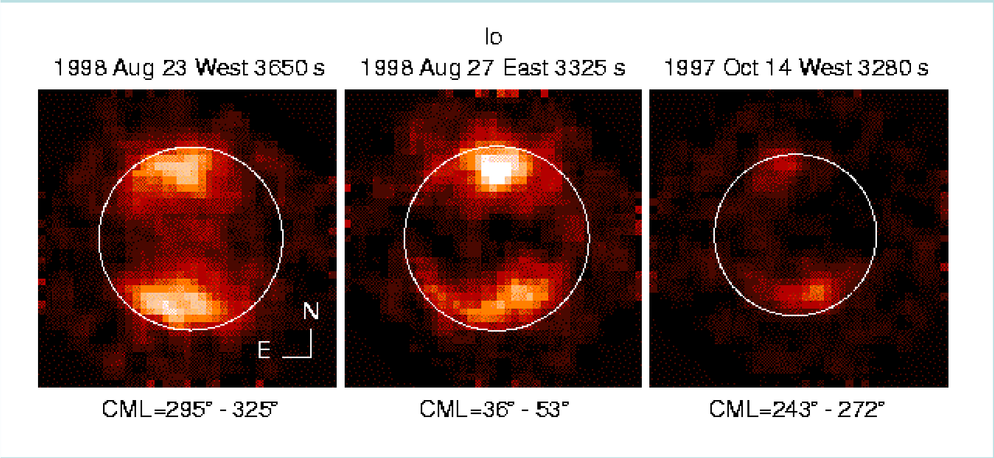


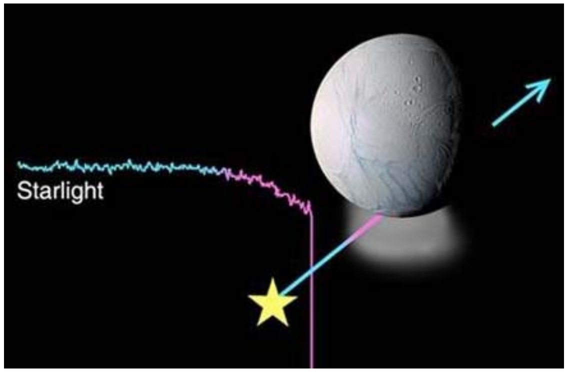


CU's UltraViolet Imaging Spectrometer on Cassini

Atmospheres

McGrath et al. 2004





- SO_2, S_2
- $1\text{-}10 \times 10^{16}$ cm^{-2}
- x 10? over plumes

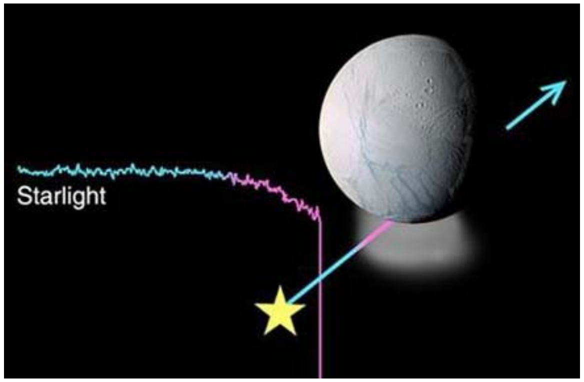
- H_2O
- 1.5×10^{16} cm^{-2}

UVIS

Area of Io = $(3630/500)^2$ = 53 times Enceladus

Atmospheric Loss

QuickTime™ and a
GIF decompressor
are needed to see this picture.



Mol/atom loss

$3 \times 10^{28}\ s^{-1}$

Mass loss

$3000\ kg\ s^{-1}$

Ionization

$1000\ kg\ s^{-1}$

Molecular loss

$5 \times 10^{27}\ s^{-1}$

Mass loss

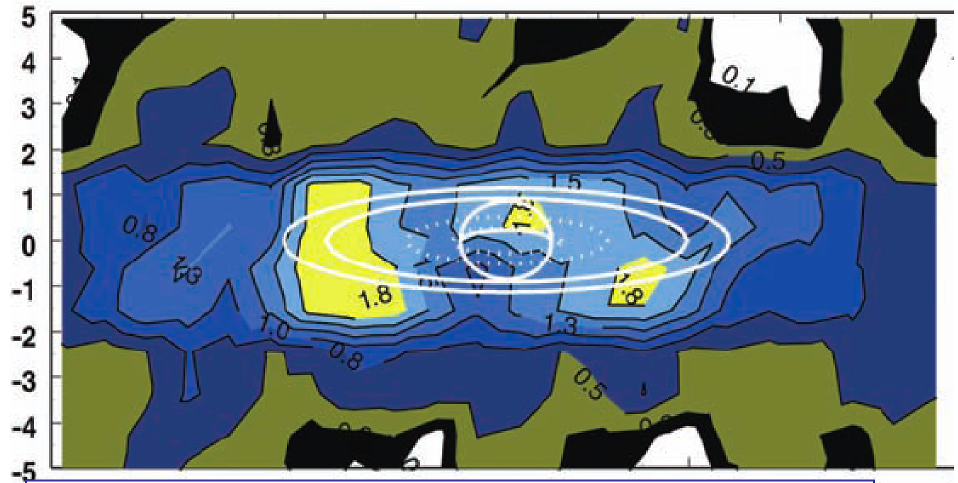
$150\ kg\ s^{-1}$

Ionization

$10\ kg\ s^{-1}$

Plasma & Neutral Tori *Esposito*

QuickTime™ and a
GIF decompressor
are needed to see this picture.



5×10^{34} ions O^+, S^{++}

$N_{neutral}$ ~ 50-100 cm^{-3}

N_{ions} ~ 2000 cm^{-3}

Pick-up energy

$1.5\text{-}2 \times 10^{12}$ W

UV power~3×10^{12} W

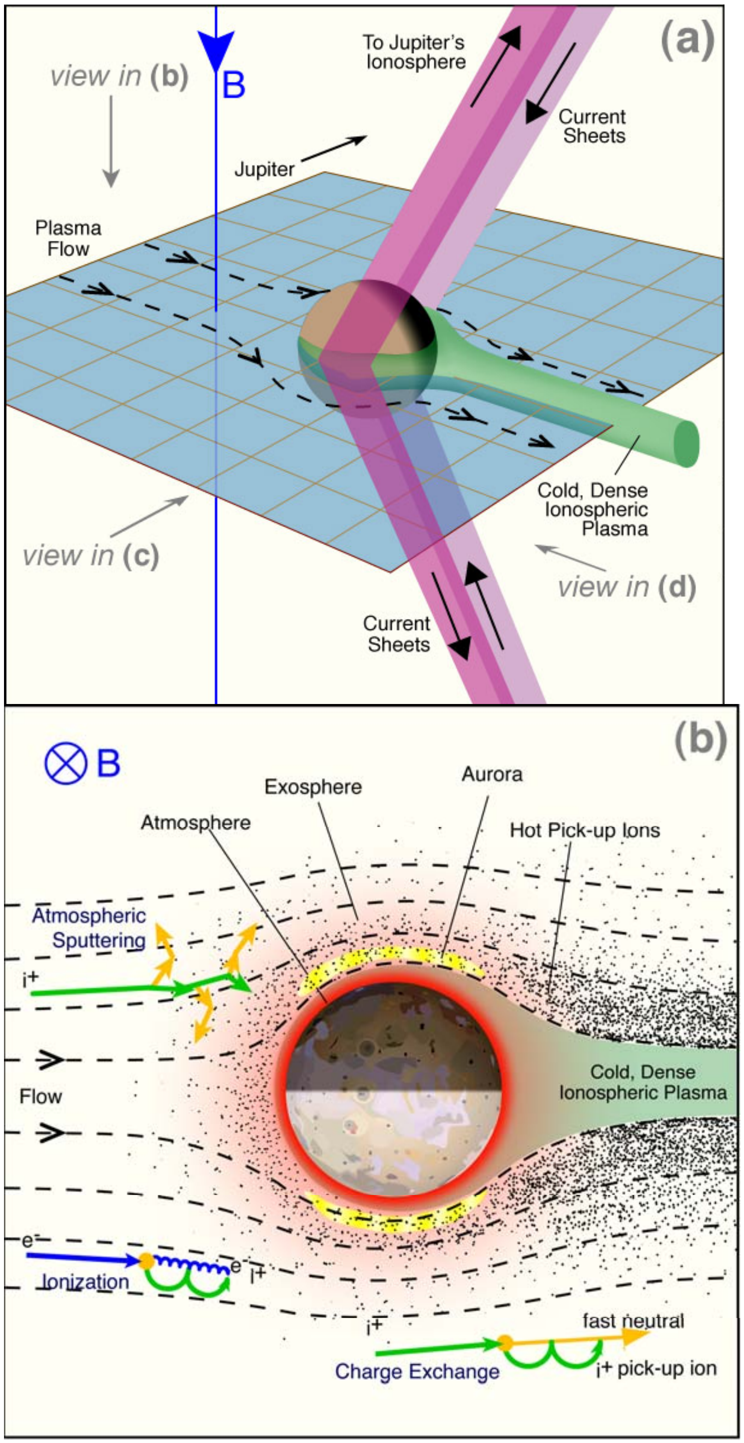
4×10^{34} O atoms

$N_{neutral}$ ~ 750 cm^{-3}

N_{ions} ~ 100 cm^{-3}

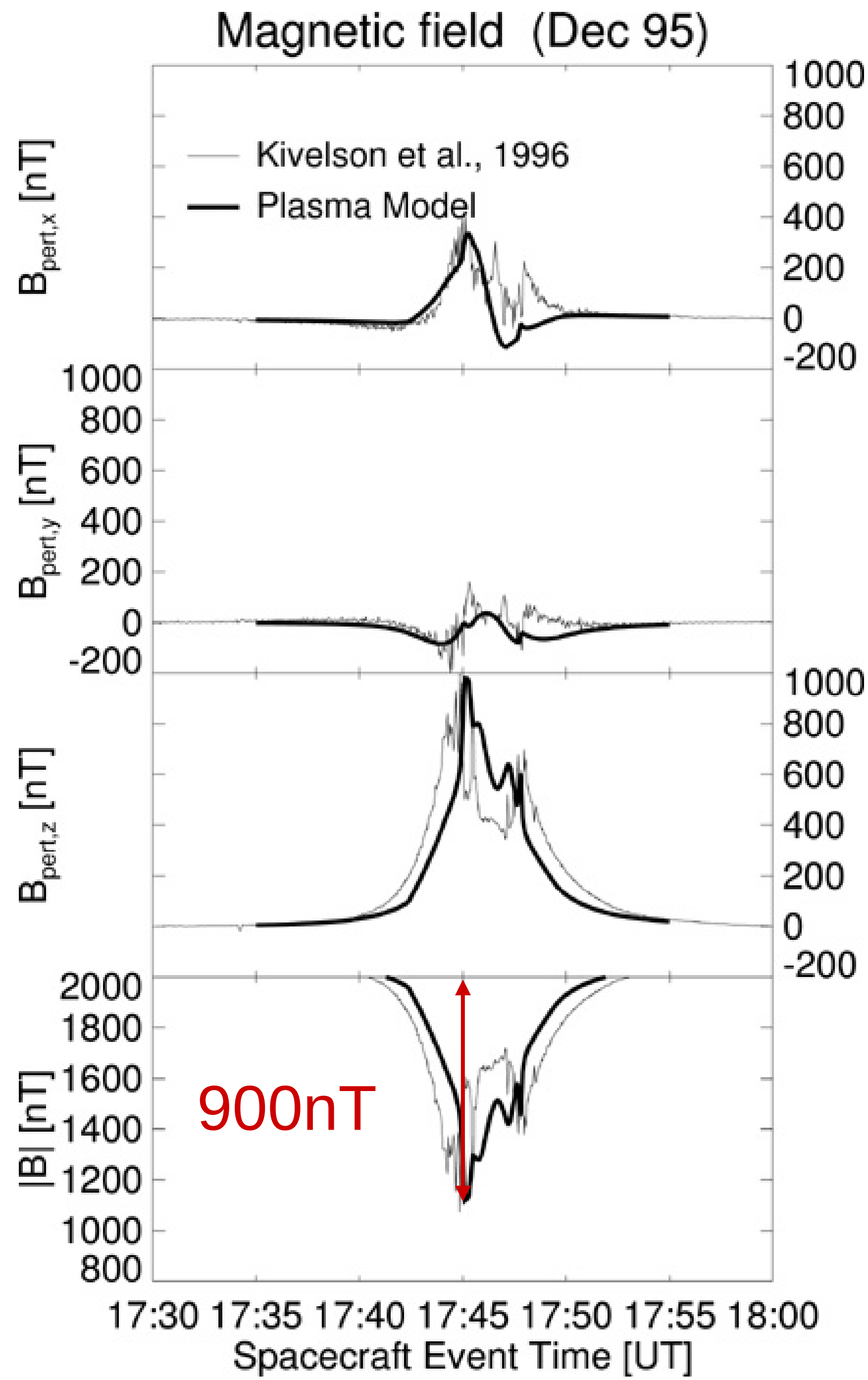
Pick-up energy

1.4×10^{10} W



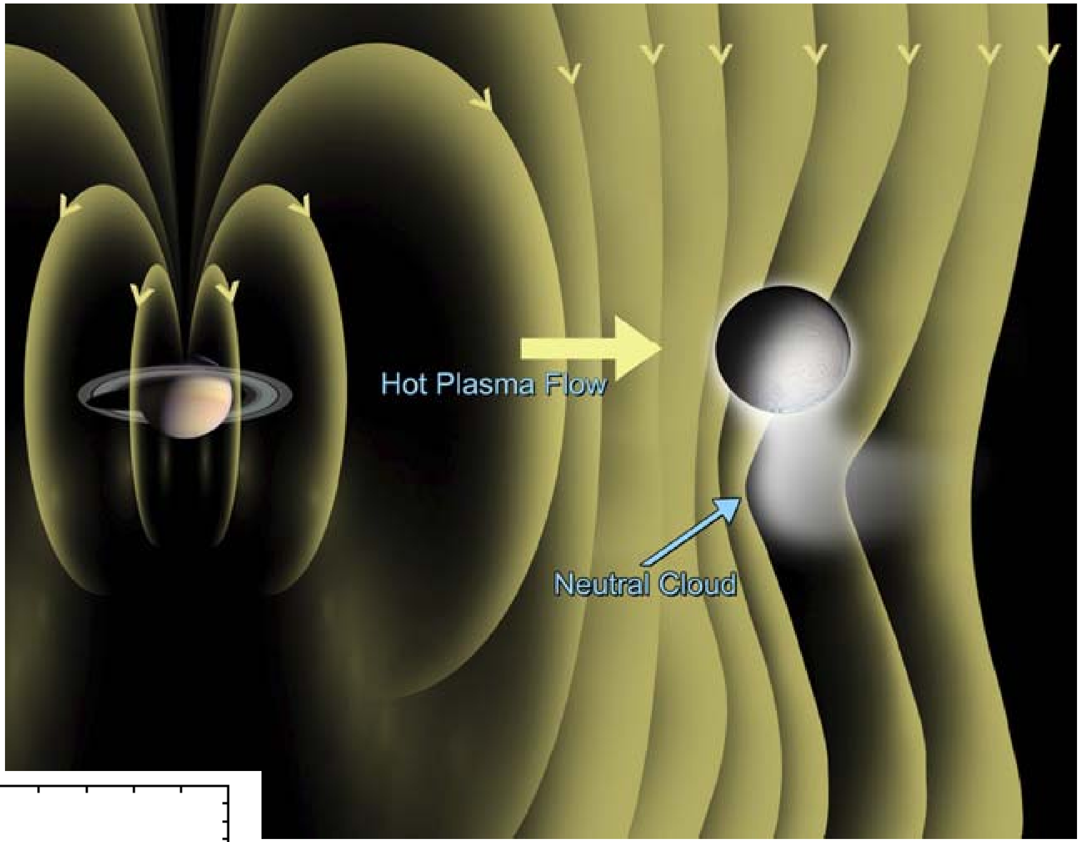
I=3 MA

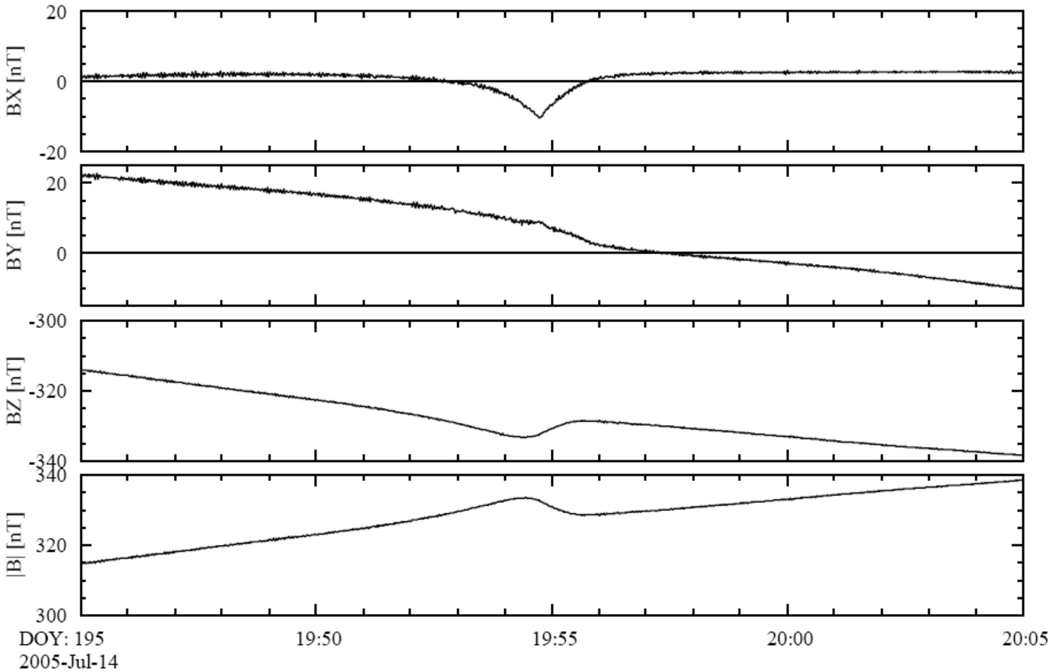
$\Delta B/B = 0.45$



$\Delta B = 20$ nT

$\Delta B/B = 0.07$





Dougherty