Solar Wind Interaction with Planetary Bodies

Michele Dougherty, 1st November 2010

Recommended Reading:

Physics of Solar System Plasmas. T. E. Cravens.

Chapter 7

Introduction to Space Physics, Ed. M. G. Kivelson & C. T. Russell.

Chapters 8 and 15

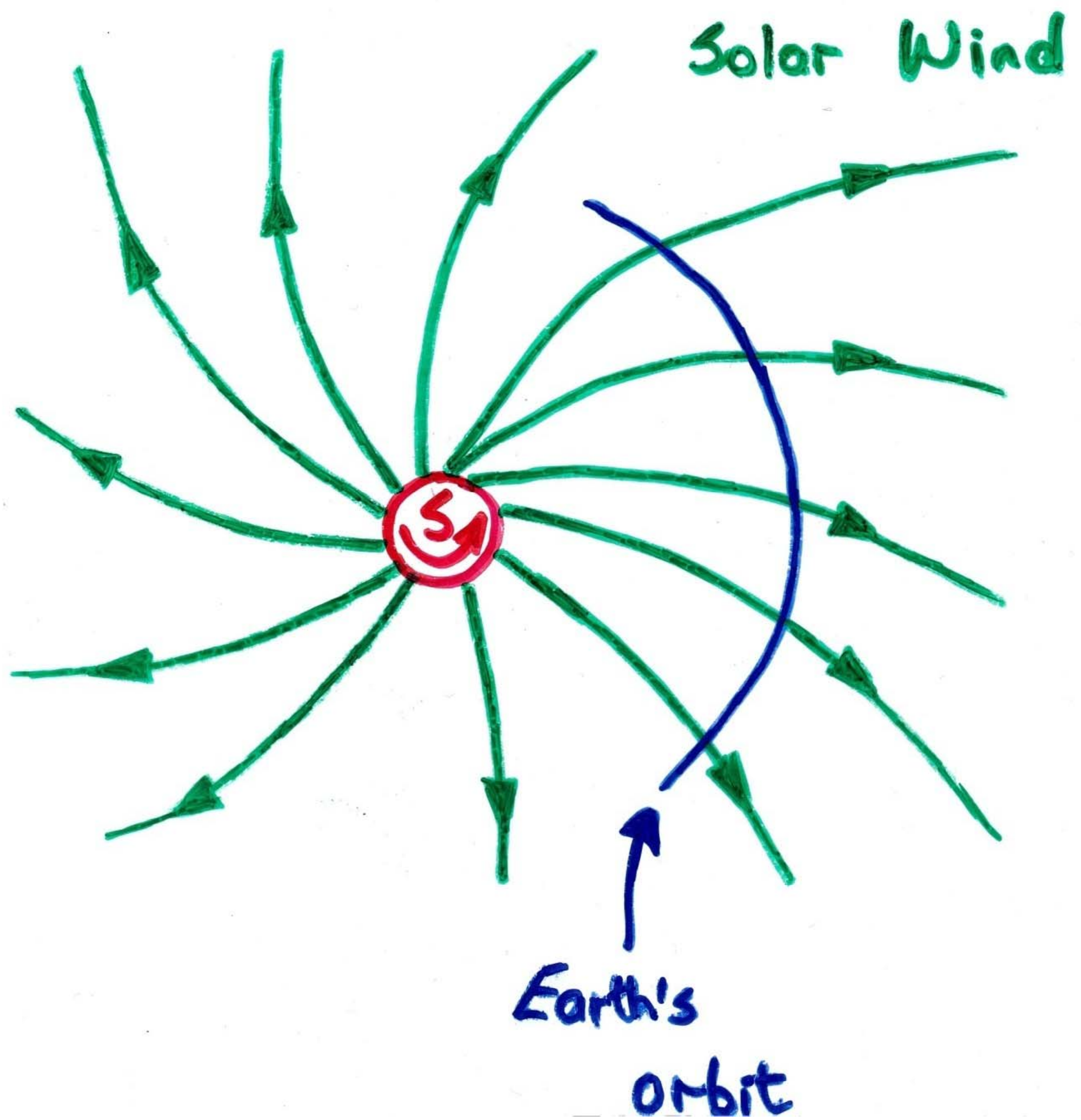
Problem Sheet, solution at end of week

The solar wind and its interaction

- Flow of plasma from Sun - solar wind (SW), supersonic, hundreds kms/sec
- IMF is carried out into solar system by solar wind
- Planets & other solar system bodies act as obstacles to flow
- These bodies have varying characteristics, nature of interaction varies great deal
- 1st we knew about such interaction at Earth, Chapman and Ferraro, 1930 predicted Earth's magnetic field act as obstacle to SW flow

The Solar Wind

- Ionised gas spirals out in steady stream
- What drives it?
- Base of SW is rotating; wind sweeps out in curve
- Cometary tails were a clue



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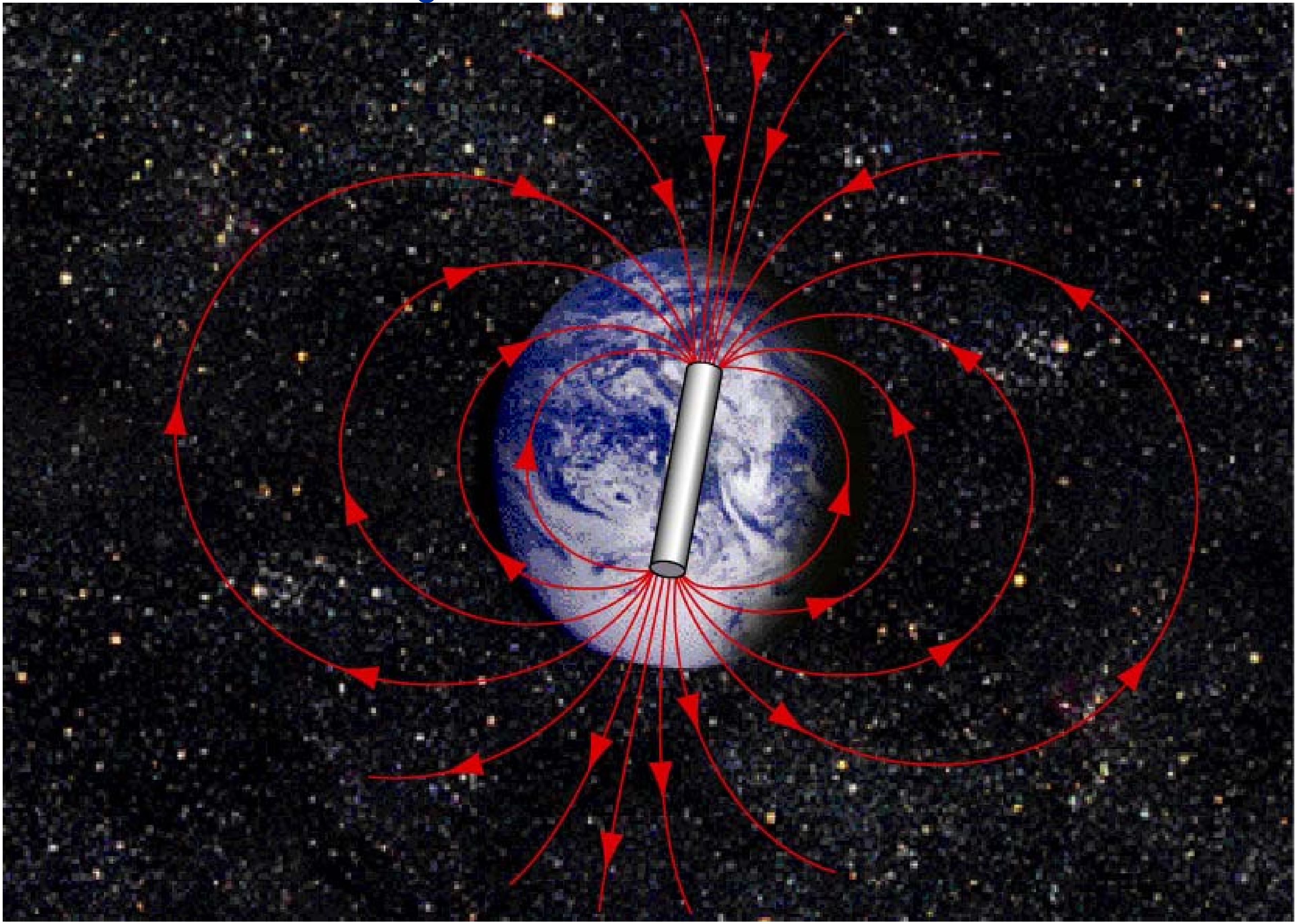
Nature of interaction

- Depends on characteristics of body, such as:
  - Distance from Sun (SW density decreases as $1/r^2$)
  - Size of body
  - Does it have atmosphere/ionosphere?
  - Does it have intrinsic magnetic field & what is it's strength (characterised via magnetic dipole moment)

Magnetic Field at Planets



Four types of interaction

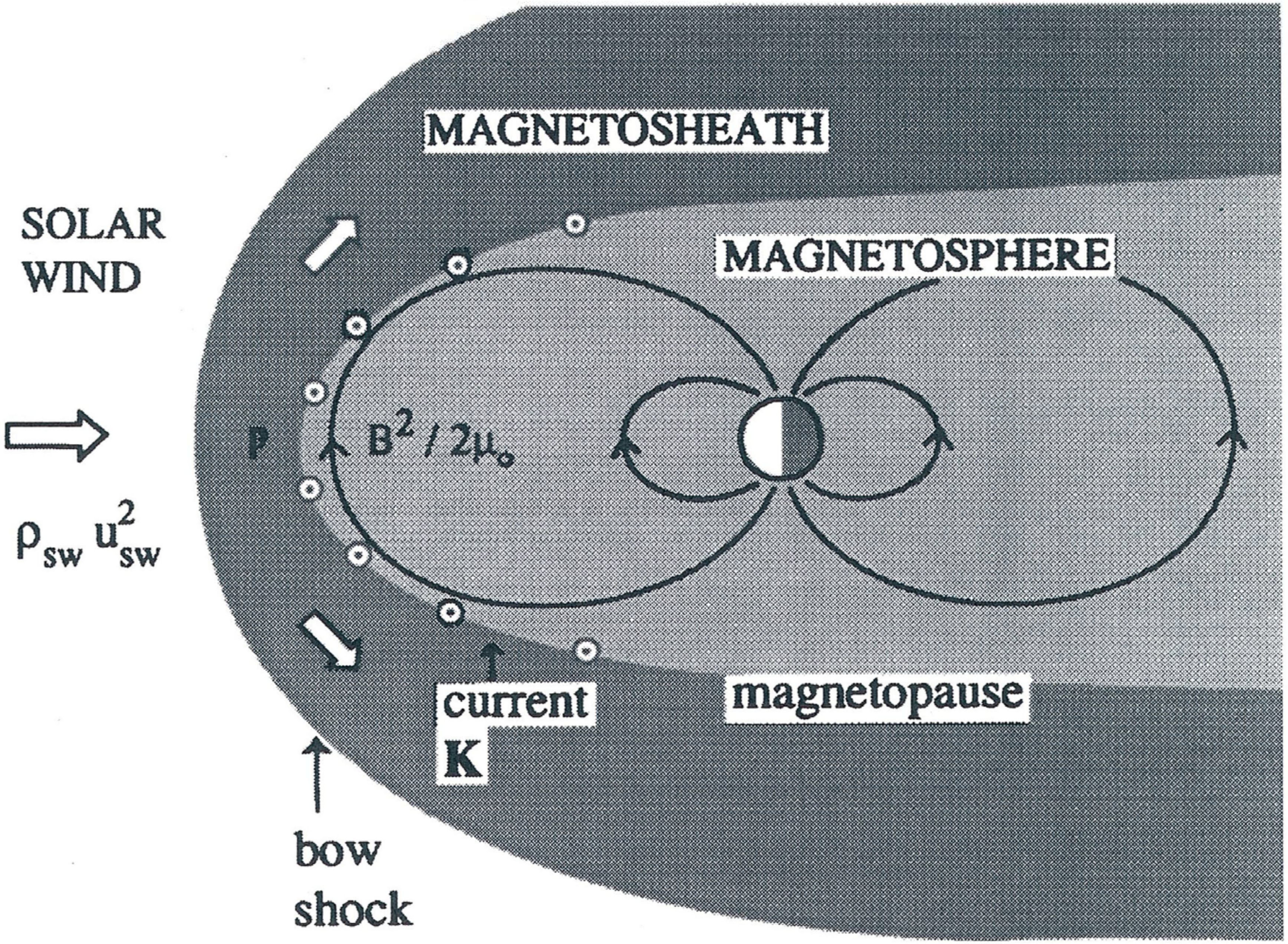
1. **Lunar/Moon type**
   - Body with no atmosphere or magnetic field, e.g. our Moon
   - SW impacts directly on surface, plasma wake downstream
   - Other egs., asteroids, inactive cometary nuclei, certain moons at other planets

2. **Earth type**
   - Magnetised body
   - SW can't penetrate magnetic field, diverts around it, forms cavity - magnetosphere (MS)
   - Other egs, Mercury, Jupiter, Saturn, Uranus, Neptune, Ganymede
   - Major differences in internal dynamics of various MS's (solar wind driven versus rotation dominated)
   - Plasma flow at Mercury & Earth dominated by SW Electric field, whereas outer planets dominated rotational flow
   - Signature of this interaction is Bow Shock (BS) and Magnetopause (MP) boundaries upstream

3. **Venus type**
   - Unmagnetised body with significant atmosphere and ionosphere
   - Venus rotates very slowly (every 243 days) – lack of significant magnetic field
   - Has significant ionosphere & dense atmosphere
   - Ionospheric plasma very good electrical conductor, acts as obstacle to SW flow with its embedded IMF, shock wave results
   - Other egs. Mars, Titan (complicated eg can be in MS, magnetosheath, SW)

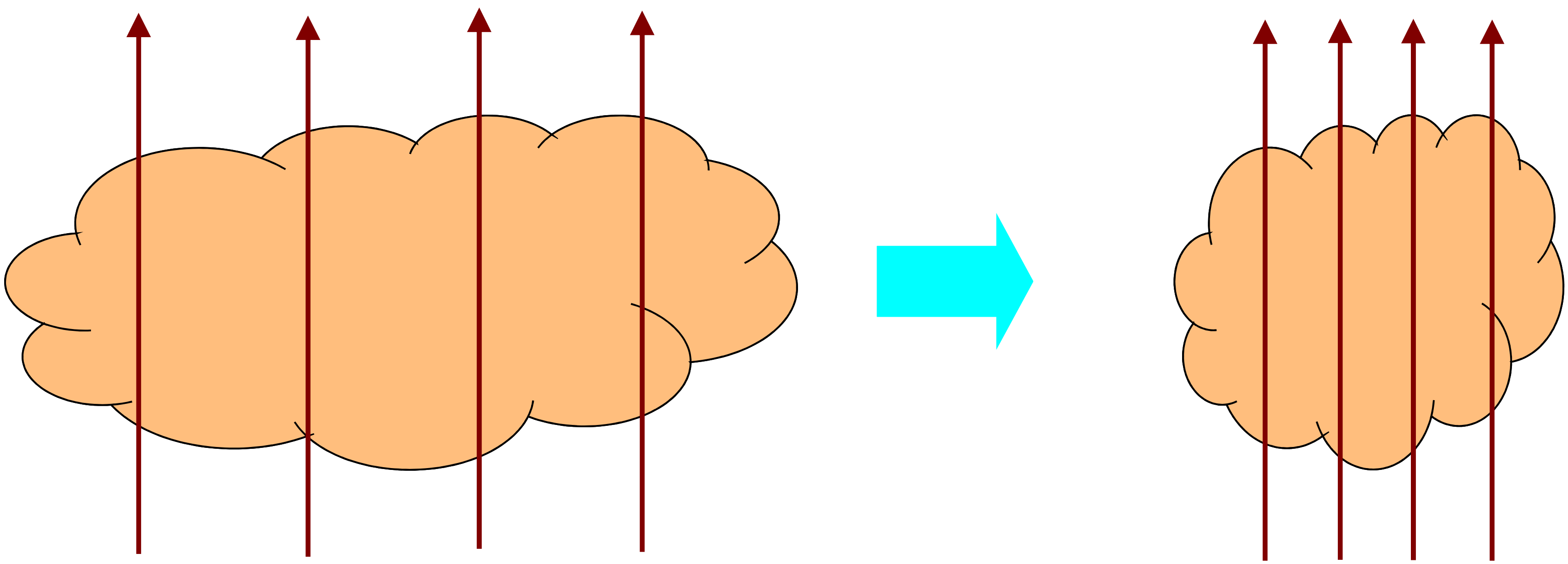
4. **Comet type**
   - Combination of:
     - Venus-like (close to Sun)
     - Lunar-like (far from Sun)
   - Cometary nuclei chunks ice & dust, radii few kms, negligible magnetic fields
   - Two states:
     - Inactive state, most of orbital period, when far from Sun
     - Active state, when nucleus approaches Sun, surface heated solar radiation, ice sublimates & produces water vapour & other volatiles
     - Produces extensive coma, millions kms extent, IS forms close to nucleus
     - ENCKE_042507.mpg
     - Stereo

Earth's Magnetosphere



Space Plasmas

- Plasma – gas of charged/ionised particles (ions & electrons)
- Most space plasmas are collisonless – assume magnetic field is frozen into the plasma

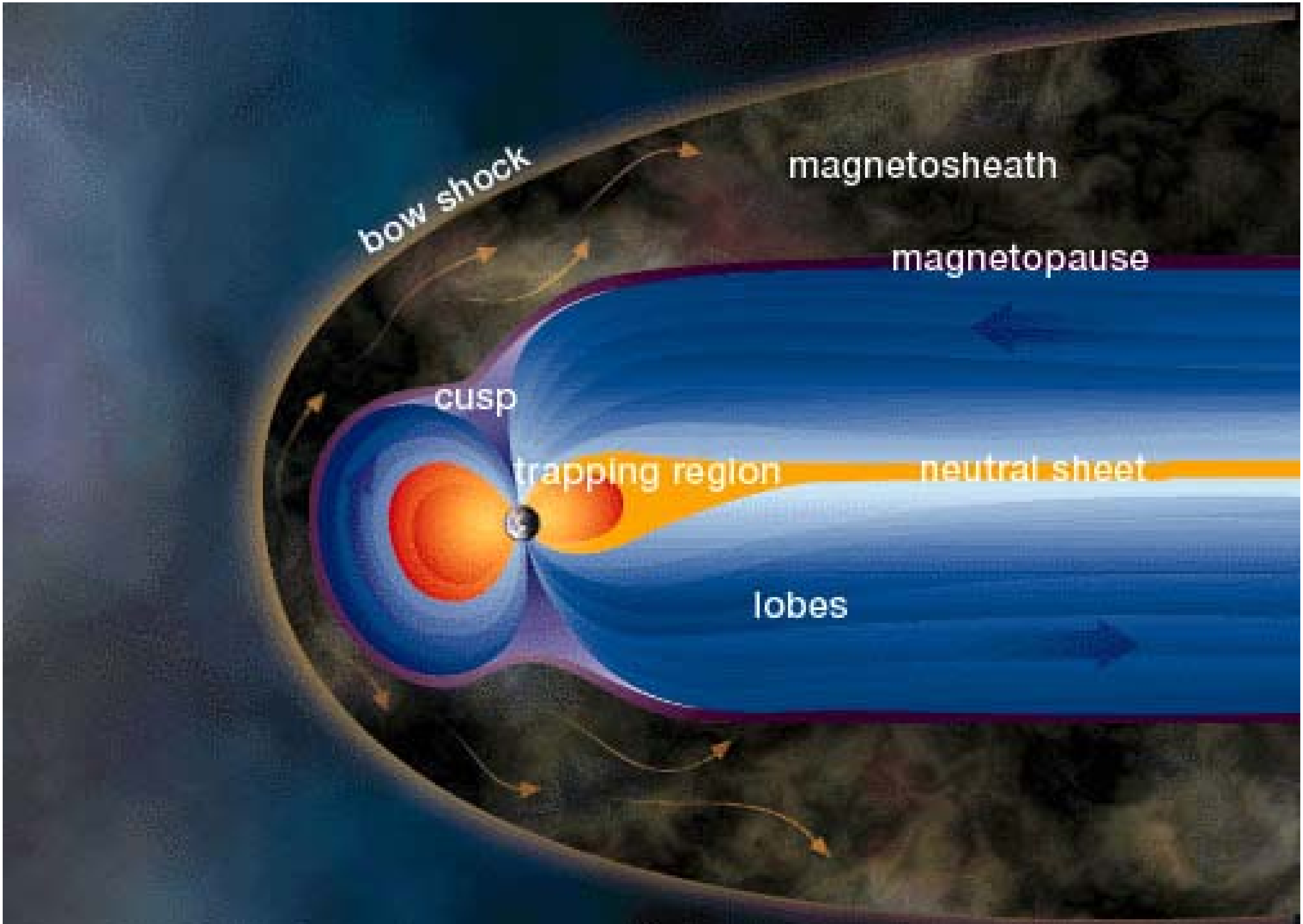


- Main pressure component in upstream SW is dynamic pressure
- Thermal pressure dominates dynamics downstream
- Inside MS magnetic pressure most important

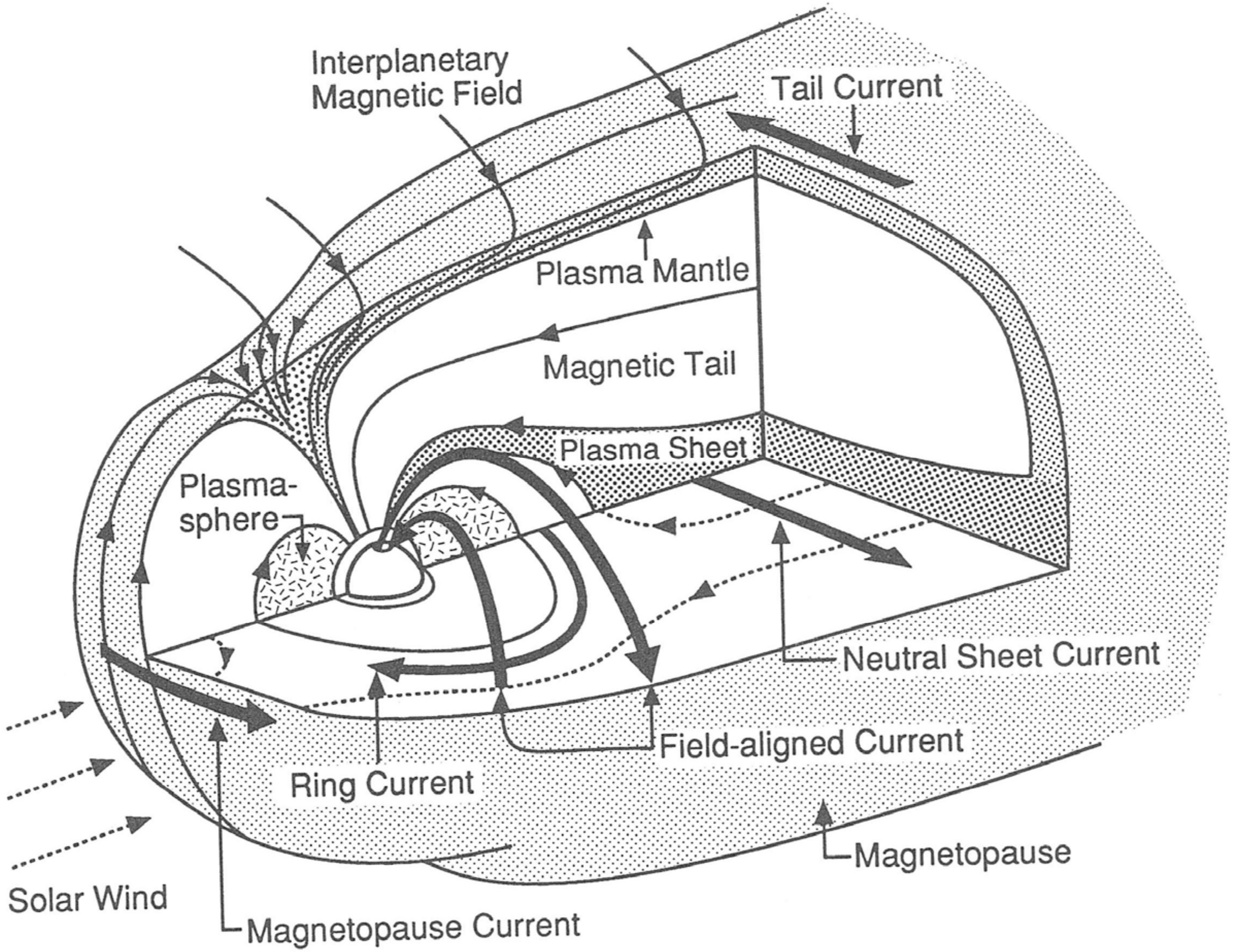
- Why does intrinsic magnetic field act as obstacle to SW flow?

- Usually in space plasmas assume plasma & magnetic field are frozen together (MHD approx)
- External SW plasma flow with embedded IMF can’t easily penetrate another magnetised plasma region

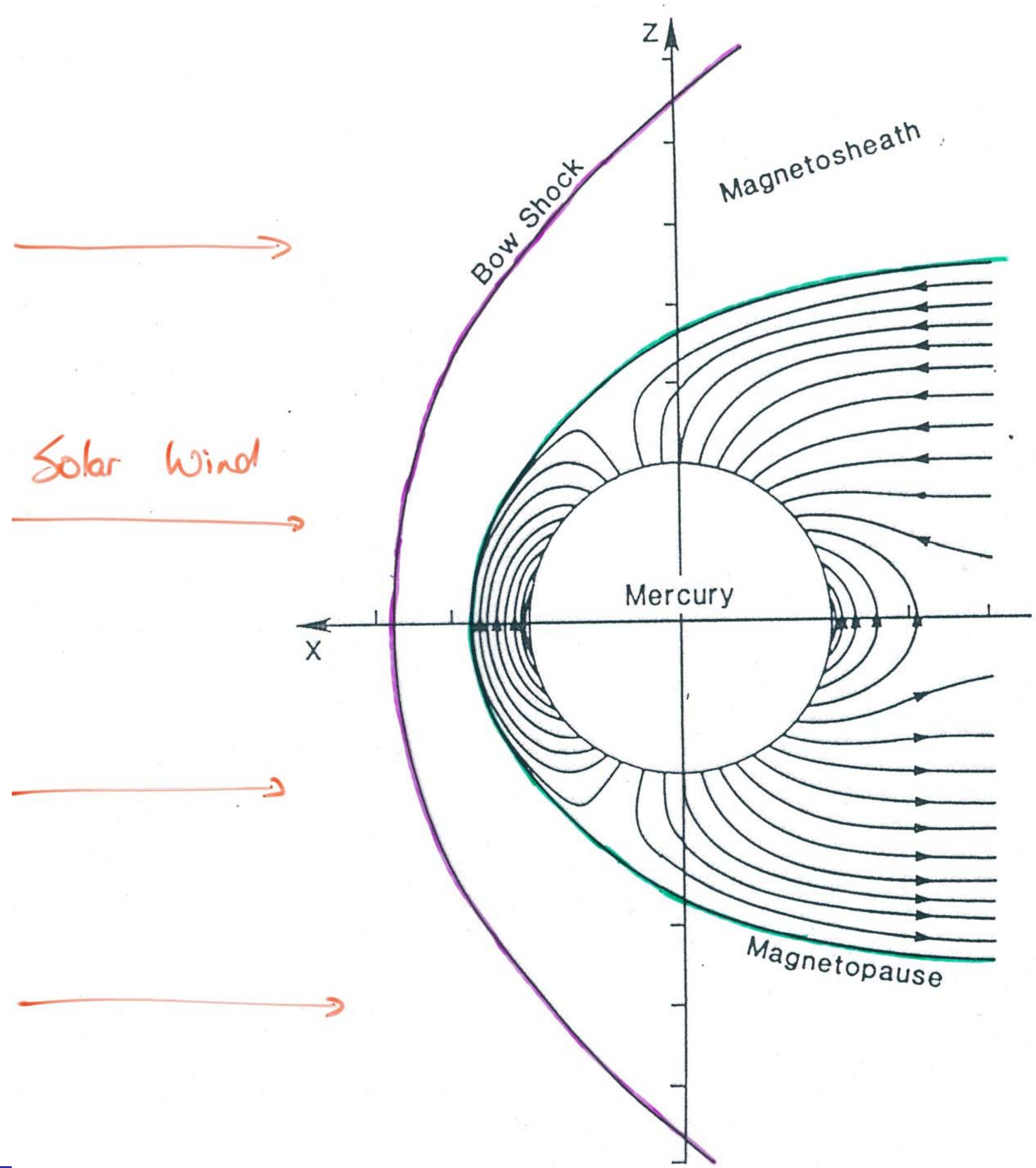
- Examine in more detail…………

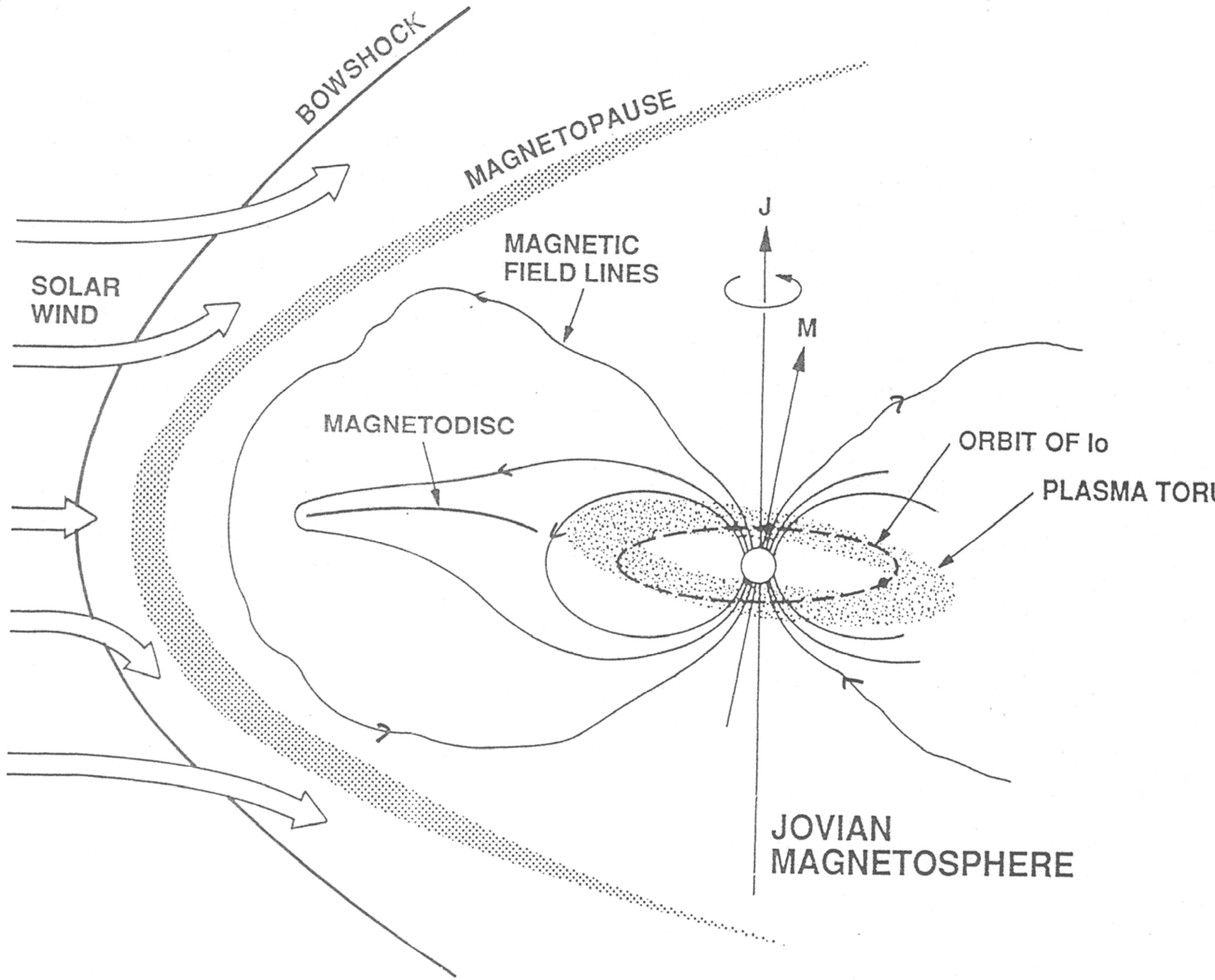

bow shock
magnetosheath
magnetopause
cusp
trapping region
neutral sheet
lobes

London


Interplanetary
Magnetic Field
Tail Current
Plasma Mantle
Magnetic Tail
Plasma Sheet
Plasma-
sphere
Neutral Sheet Current
Field-aligned Current
Ring Current
Magnetopause
Solar Wind
Magnetopause Current

- Mercury has small magnetic dipole
- Information from Mariner 10
- NASA – Messenger
- ESA – Bepi Colombo

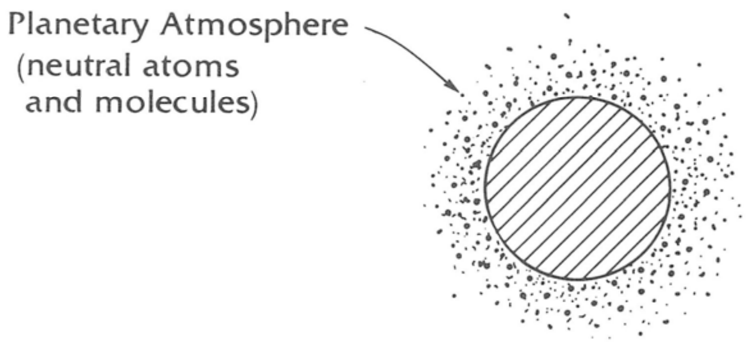


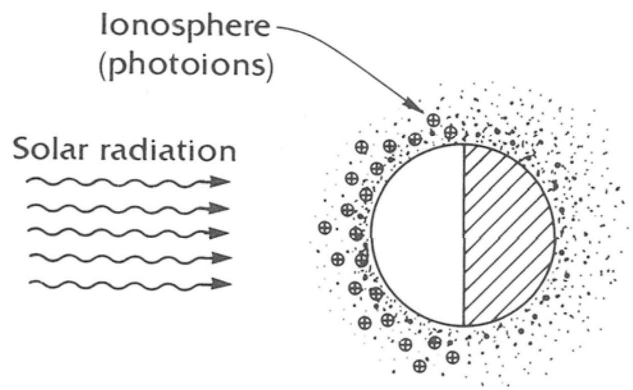

BOWSHOCK
MAGNETOPAUSE
SOLAR WIND
MAGNETIC FIELD LINES
J
M
MAGNETODISC
ORBIT OF Io
PLASMA TORU
JOVIAN MAGNETOSPHERE

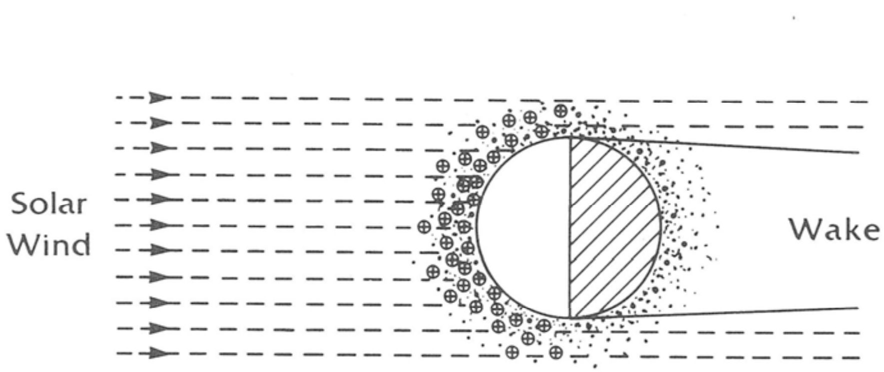
Ir
L

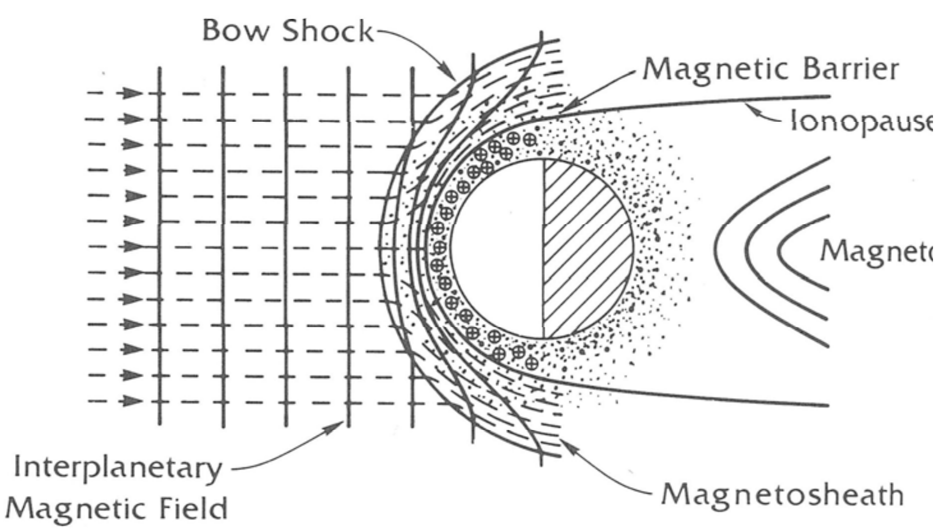
Solar wind interaction with Venus

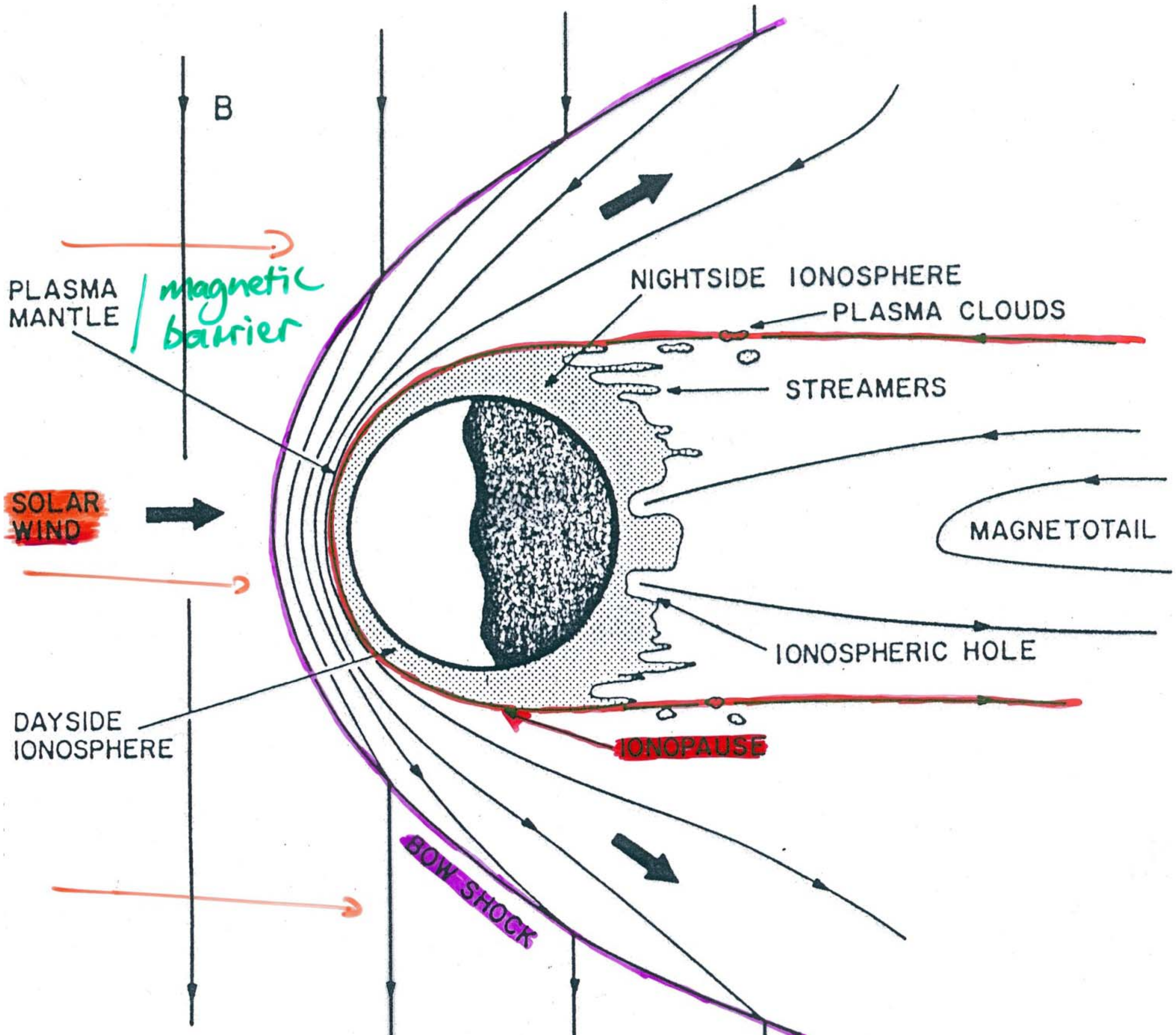
- Gases of atmosphere become ionised
- Also have B field in SW
- Formation of ionospheric (IS) planetary obstacle







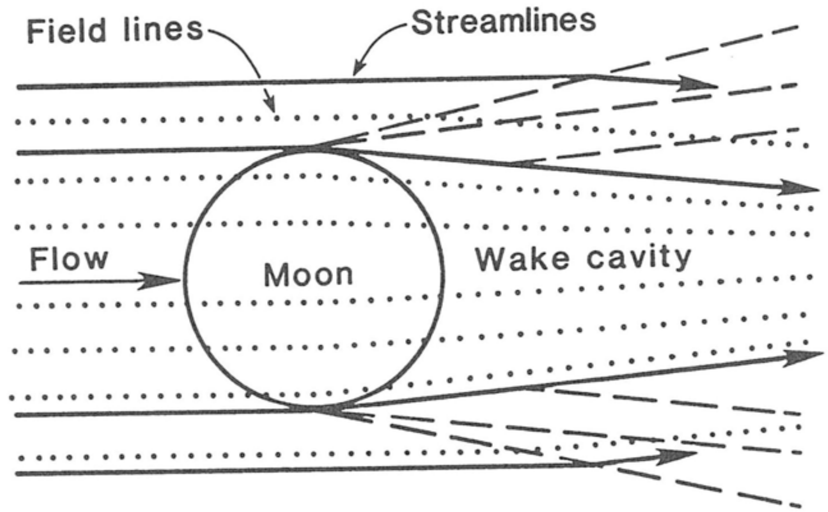




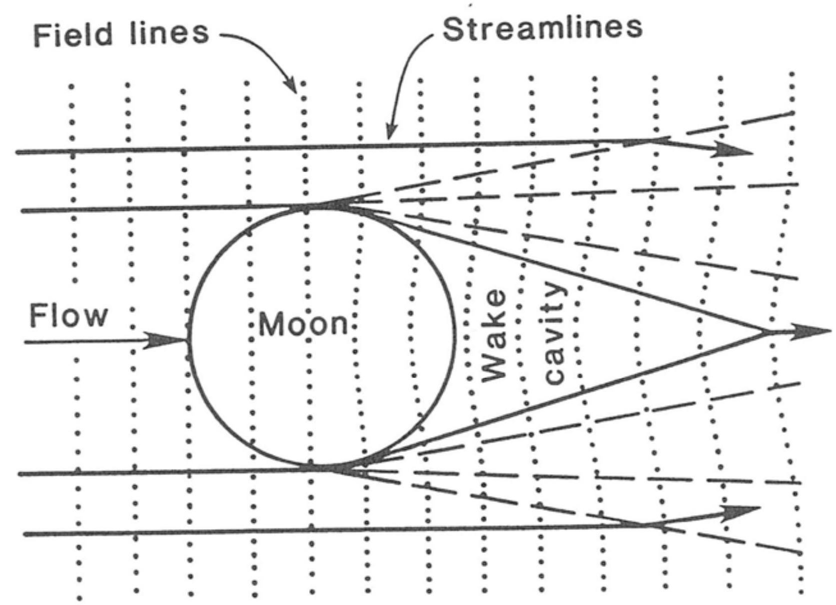
VENUS PLASMA ENVIRONMENT

Lunar Interaction

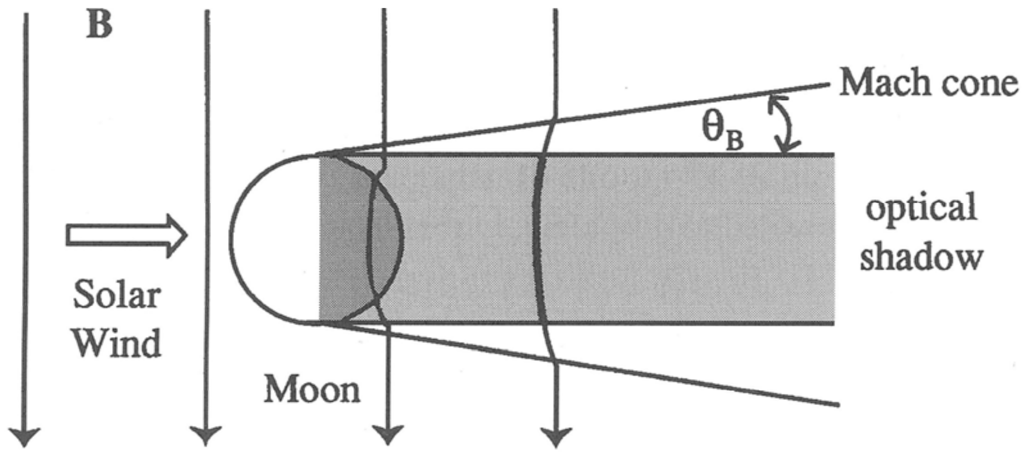
- Body like our Moon, composed of insulating material & submerged in flowing plasma
- Simply absorbs SW particles incident on it
- No Bow Shock forms, SW plasma stopped at surface, IMF passes through body (so no field line pile-up)
- B field perturbation forms downstream
- Propagates away at Alfven speed
- SW absorbed on ram side – flows back into plasma wake region



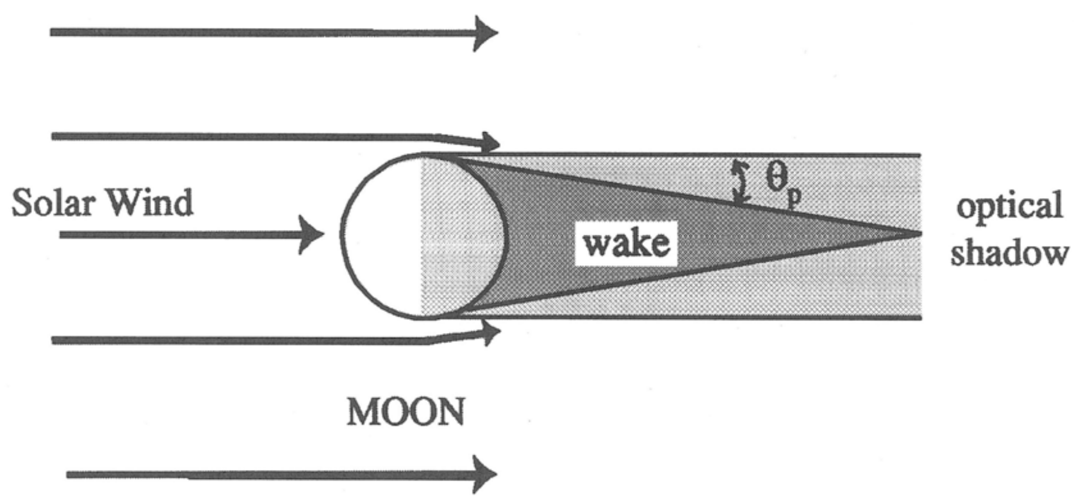
Aligned Field



Nonaligned Field

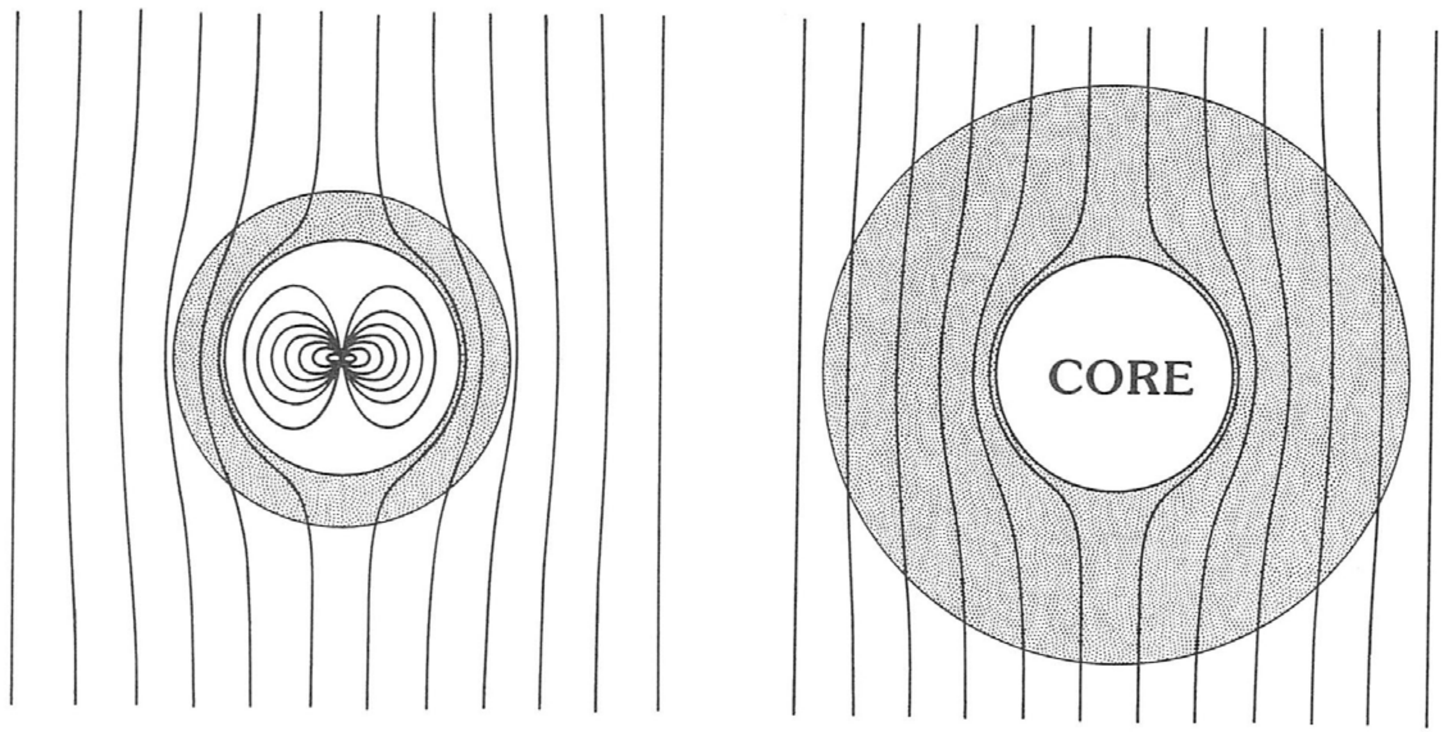


B
Mach cone
θ_B
optical
shadow
Solar
Wind
Moon



Solar Wind
θ_p
wake
optical
shadow
MOON

- Some additional effects if body has conducting core:
  - (a) insulating mantle is thin
  - (b) insulating mantle is thick
- Perturbation persists as long as external field varies on short time scales



(a) (b)

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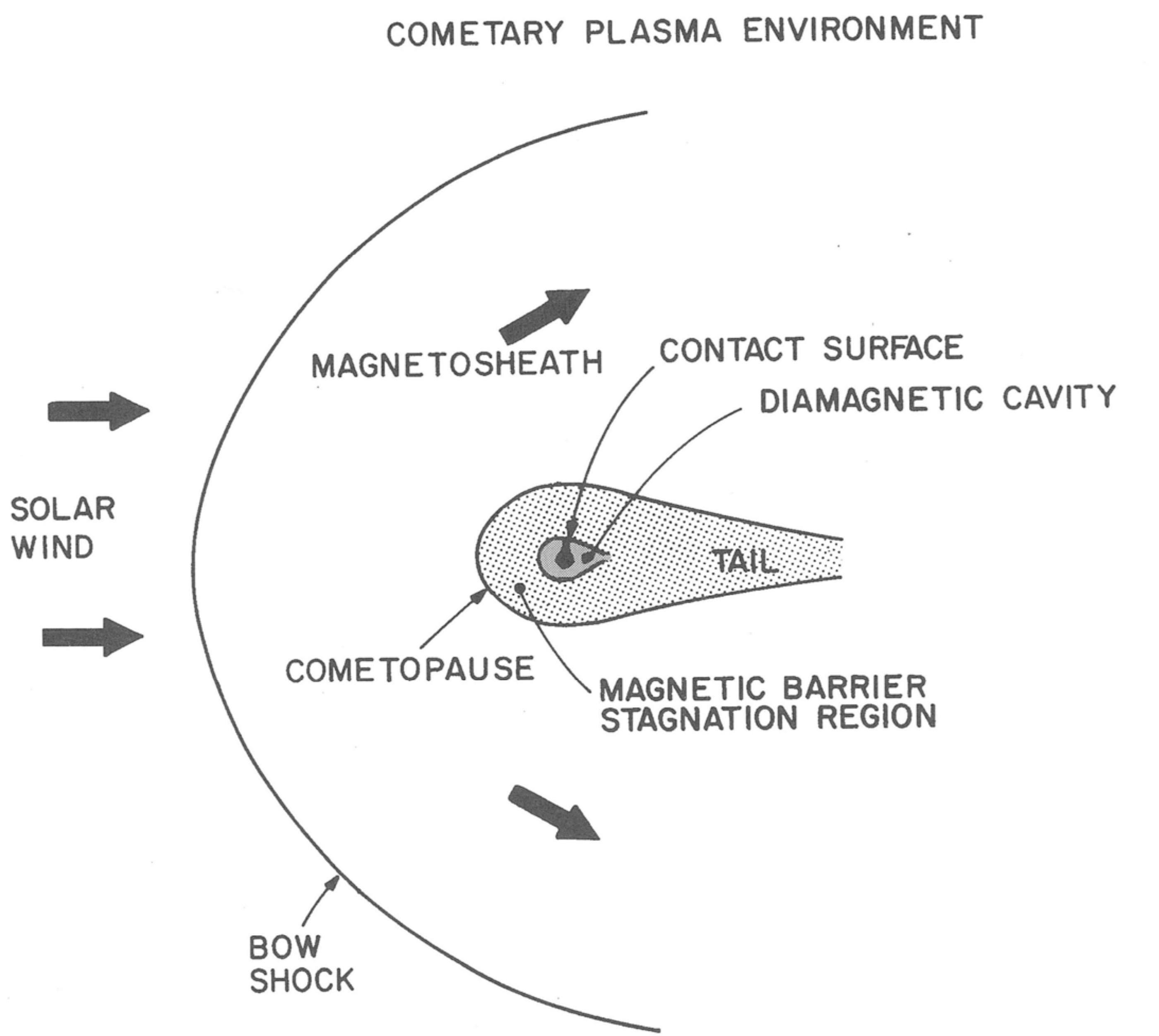
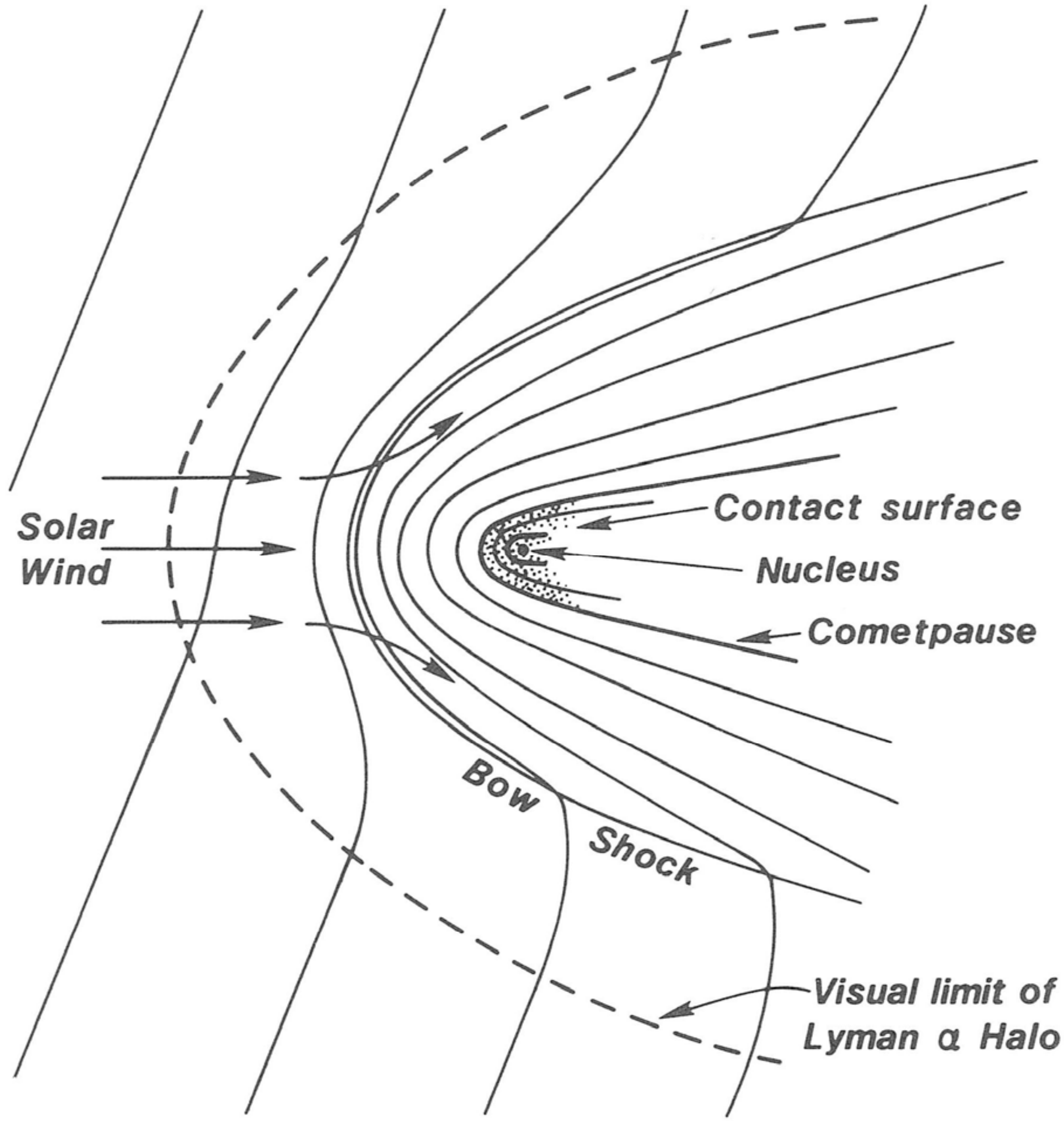
Cometary Interaction

- Most extreme example of atmosphere interacting with flowing plasma
- When near Sun – have huge atmospheres & small solid body
- Need to introduce term – mass loading
- Where background flowing plasma becomes laden with heavy ions of atmospheric origin – slows down
- Our understanding greatly increased s/c missions



COMETARY PLASMA ENVIRONMENT
MAGNETOSHEATH
CONTACT SURFACE
DIAMAGNETIC CAVITY
SOLAR WIND
TAIL
COMETOPAUSE
MAGNETIC BARRIER STAGNATION REGION
BOW SHOCK

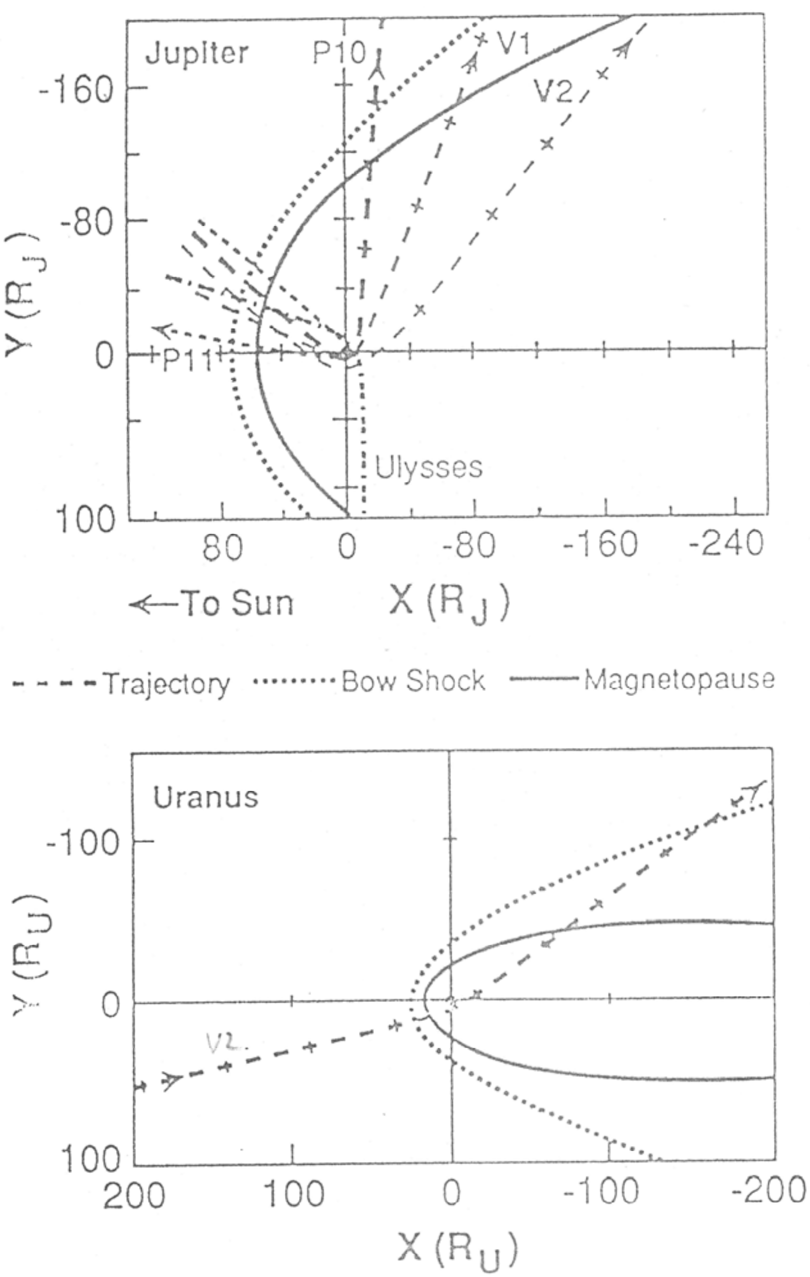


Comet MHD Model

Outer Planets

- Revisit Earth-type of interaction
- Knowledge of outer planets arisen from s/c flybys, orbiters
- Pioneer 10 & 11, Voyager 1 & 2, Ulysses, Galileo & Cassini
- All outer planets have large magnetic fields
- Use simple theory estimate MP locations at Saturn, Neptune & Uranus, reasonably consistent
- At Jupiter – MS plasma very important, interaction not entirely Earth-like

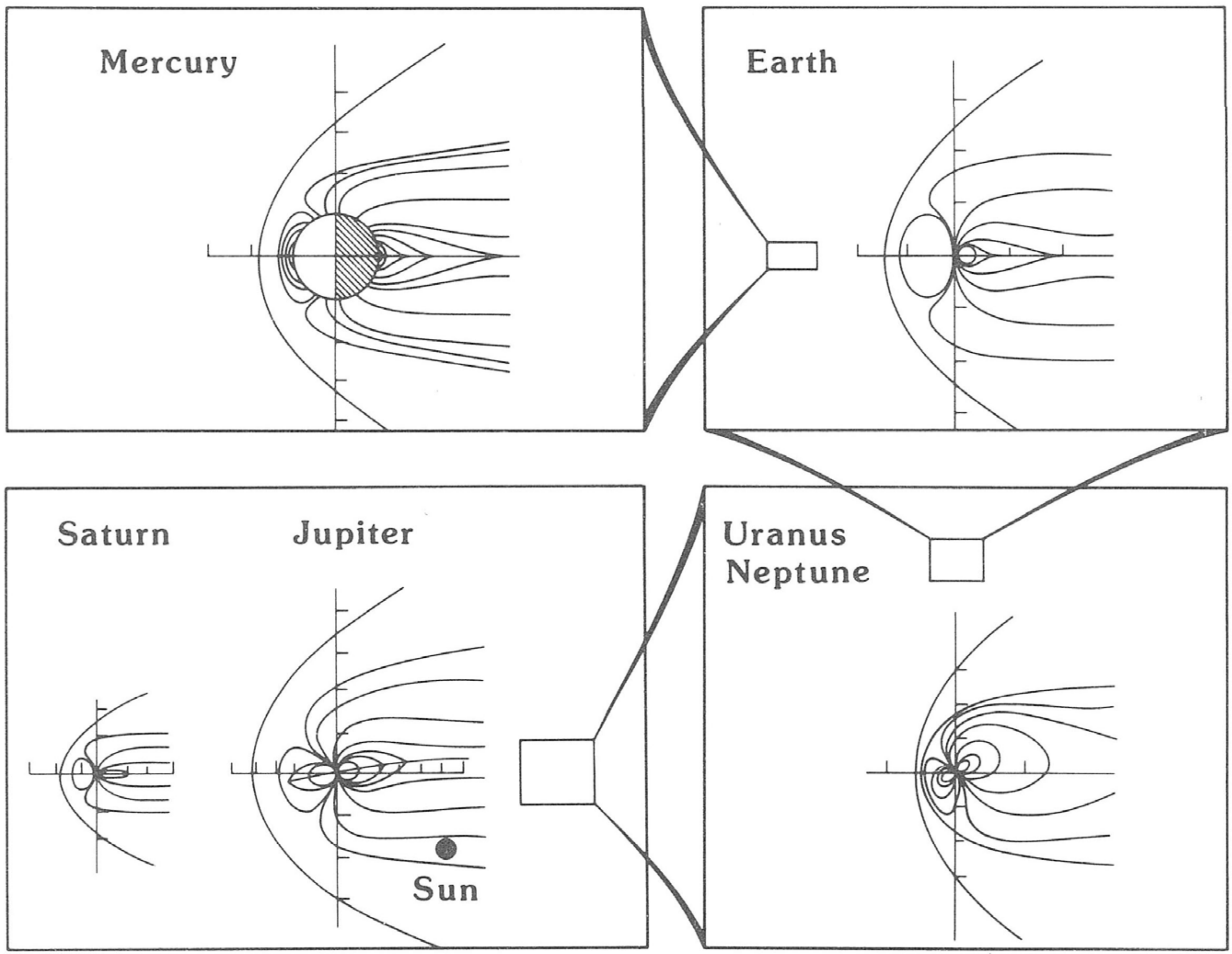
Outer planet
s/c flybys

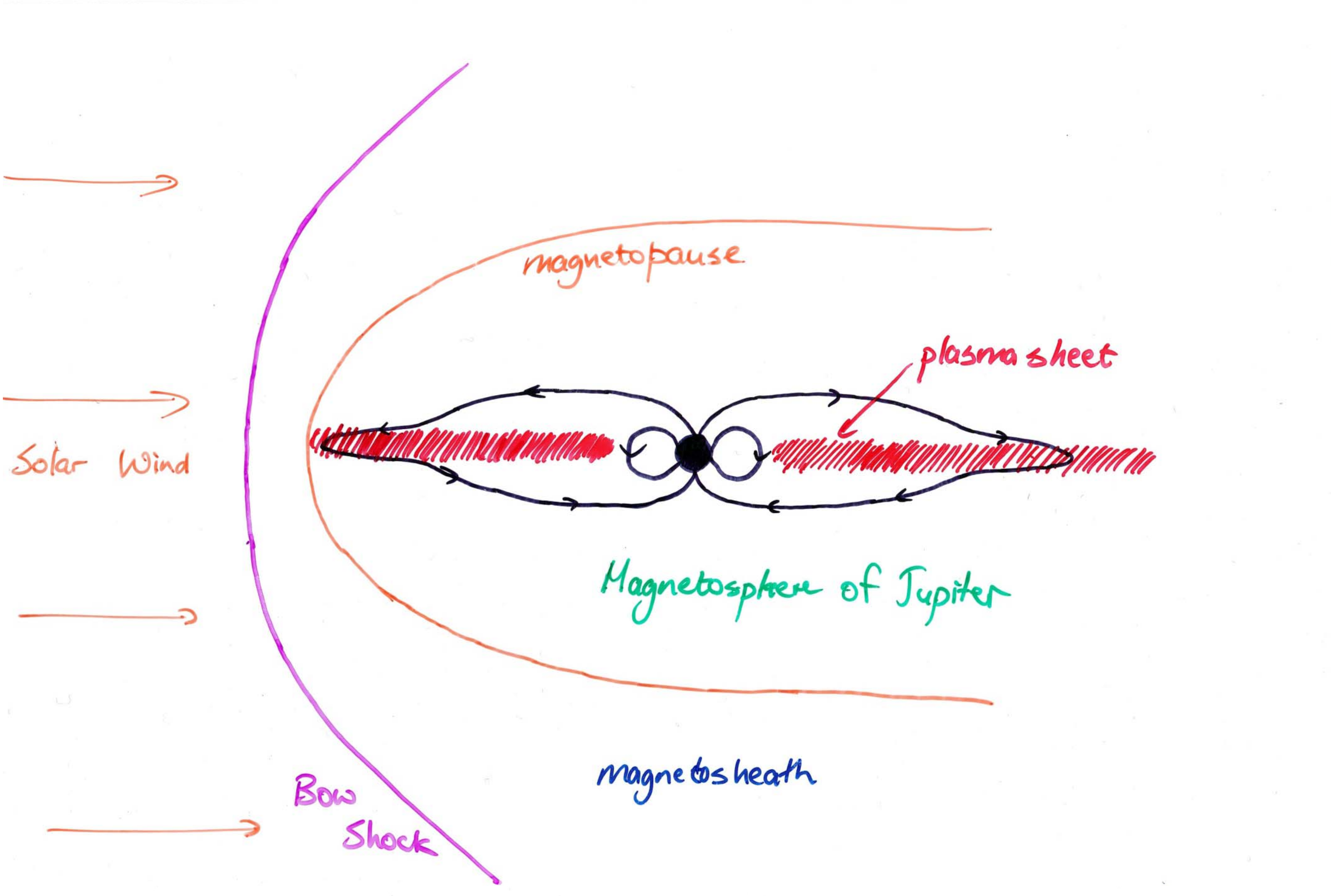


size of magnetic cavity $\propto \left(\frac{M_p^2}{\text{dyn. press}} \right)^{1/6}$

$M_E = 8 \times 10^{15}$ Tm^3

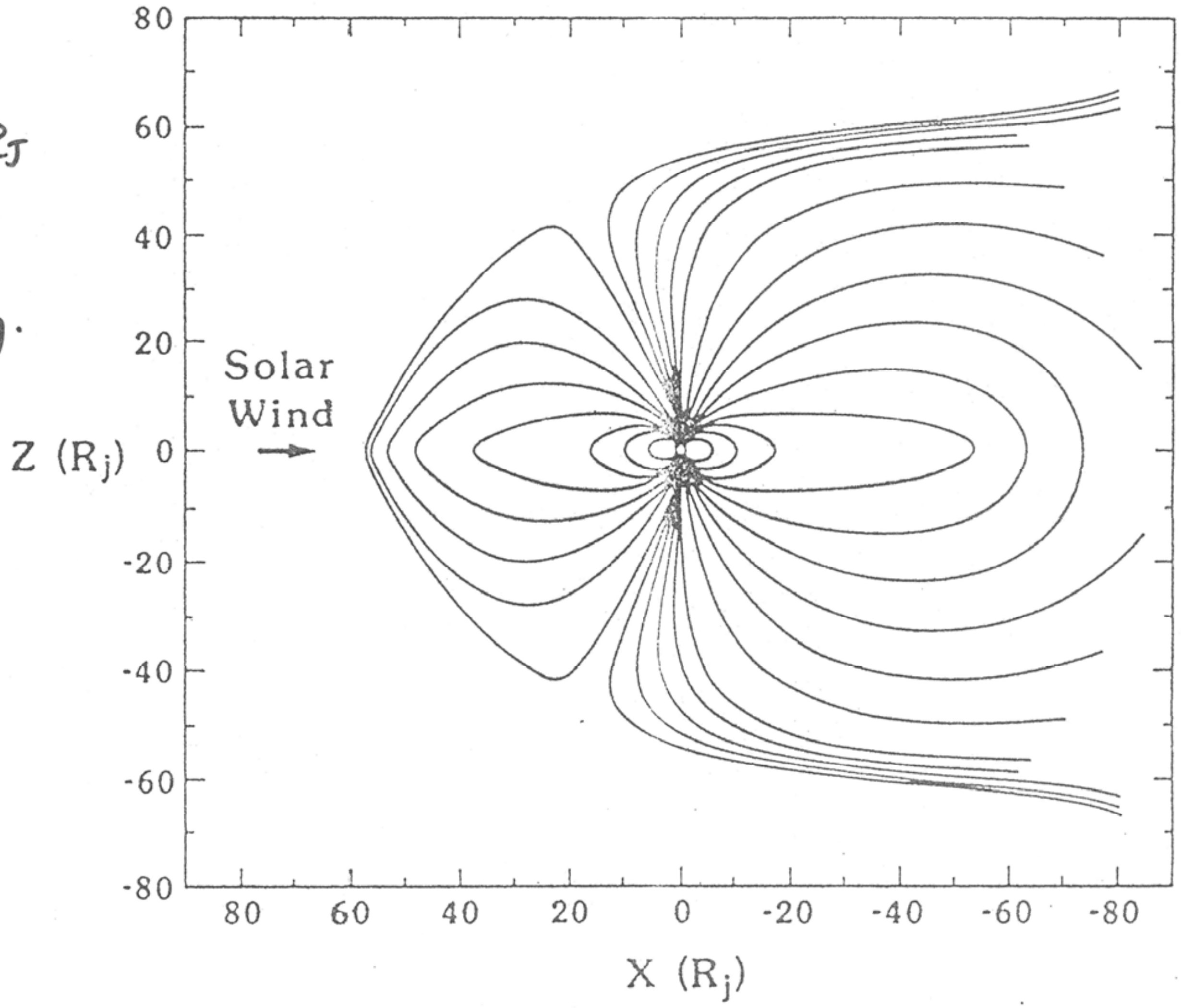
Planet	Heliocentric Distance (AU)	Magnetic Moment (M_E)	Tilt Angle	Expected Magnetopause Distance: Kilometers	Expected Magnetopause Distance: Planetary Radii
Earth	1.0	1	10.8°	0.7×10^5	$11 R_E$
Jupiter	5.2	20,000	9.7°	30×10^5	$45 R_J$
Saturn	9.5	580	<1°	12×10^5	$21 R_S$
Uranus	19.2	49	59°	6.9×10^5	$27 R_U$
Neptune	30.1	27	47°	6.3×10^5	$26 R_N$


Mercury
Earth
Saturn
Jupiter
Sun
Uranus
Neptune

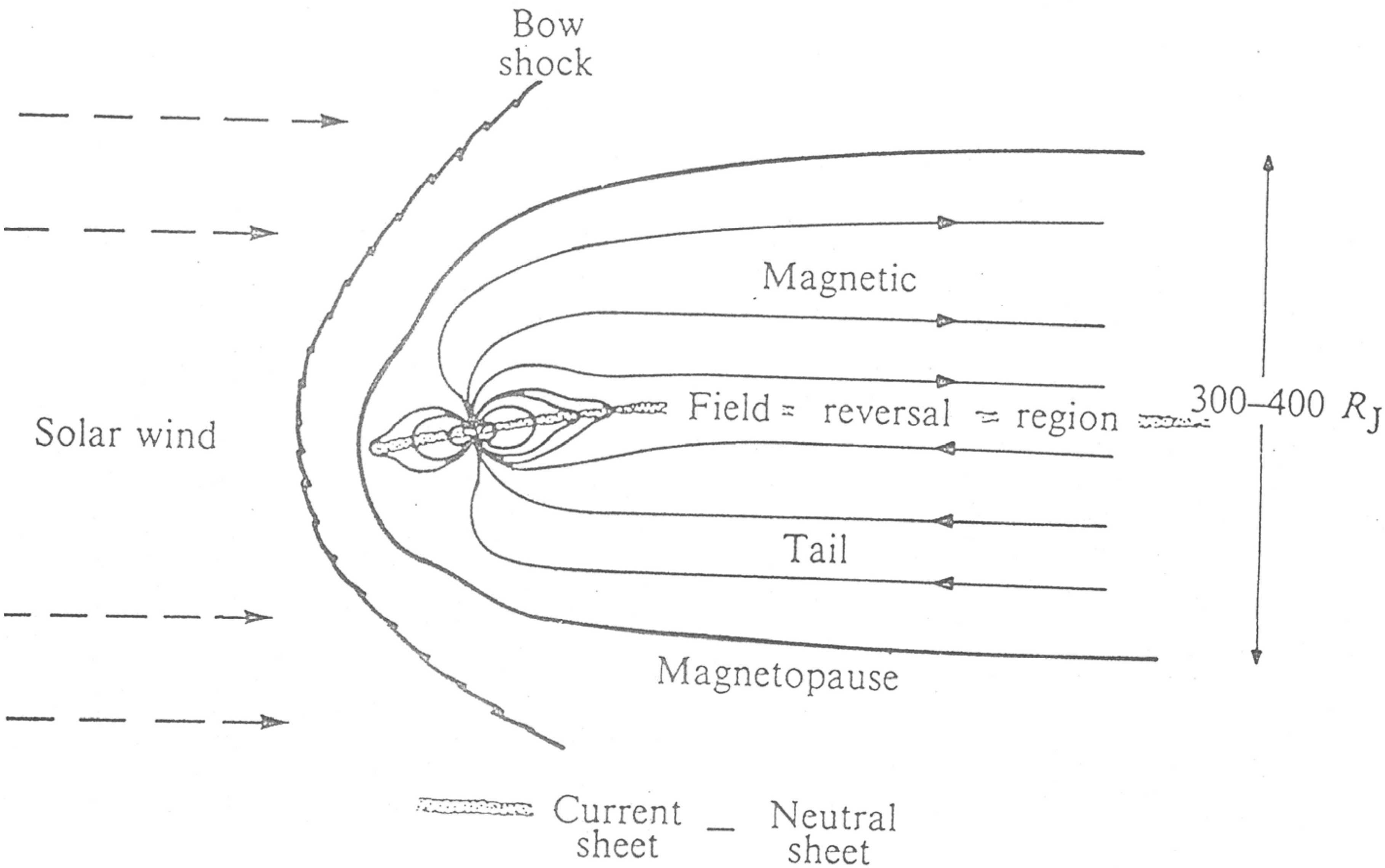

magnetopause
plasma sheet
Solar Wind
Magnetosphere of Jupiter
magnetosheath
Bow Shock

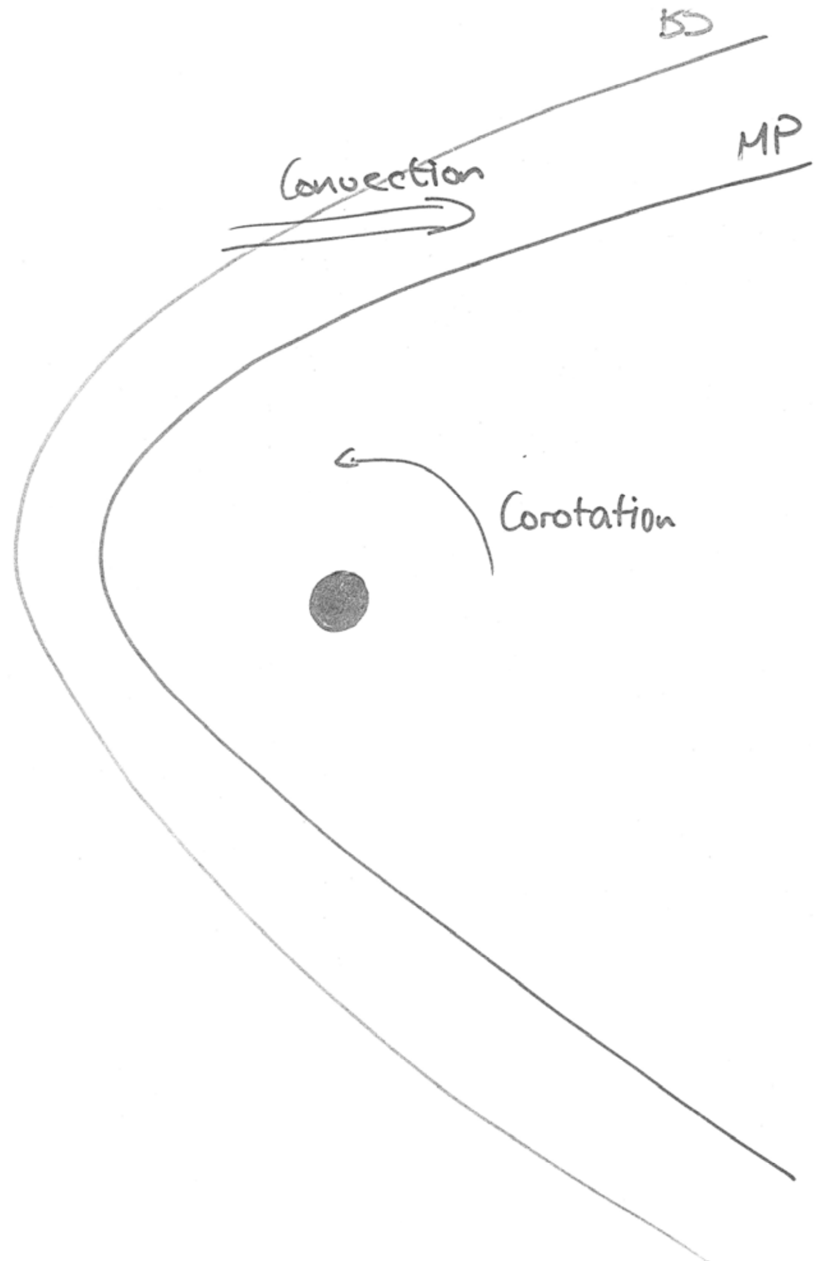
Jupiter

- MP 45 – 113 R_J
- Io produces sig. mass



noon – midnight meridian


Bow shock
Magnetic
Field reversal region
300–400 R_J
Solar wind
Tail
Magnetopause
Current sheet
Neutral sheet



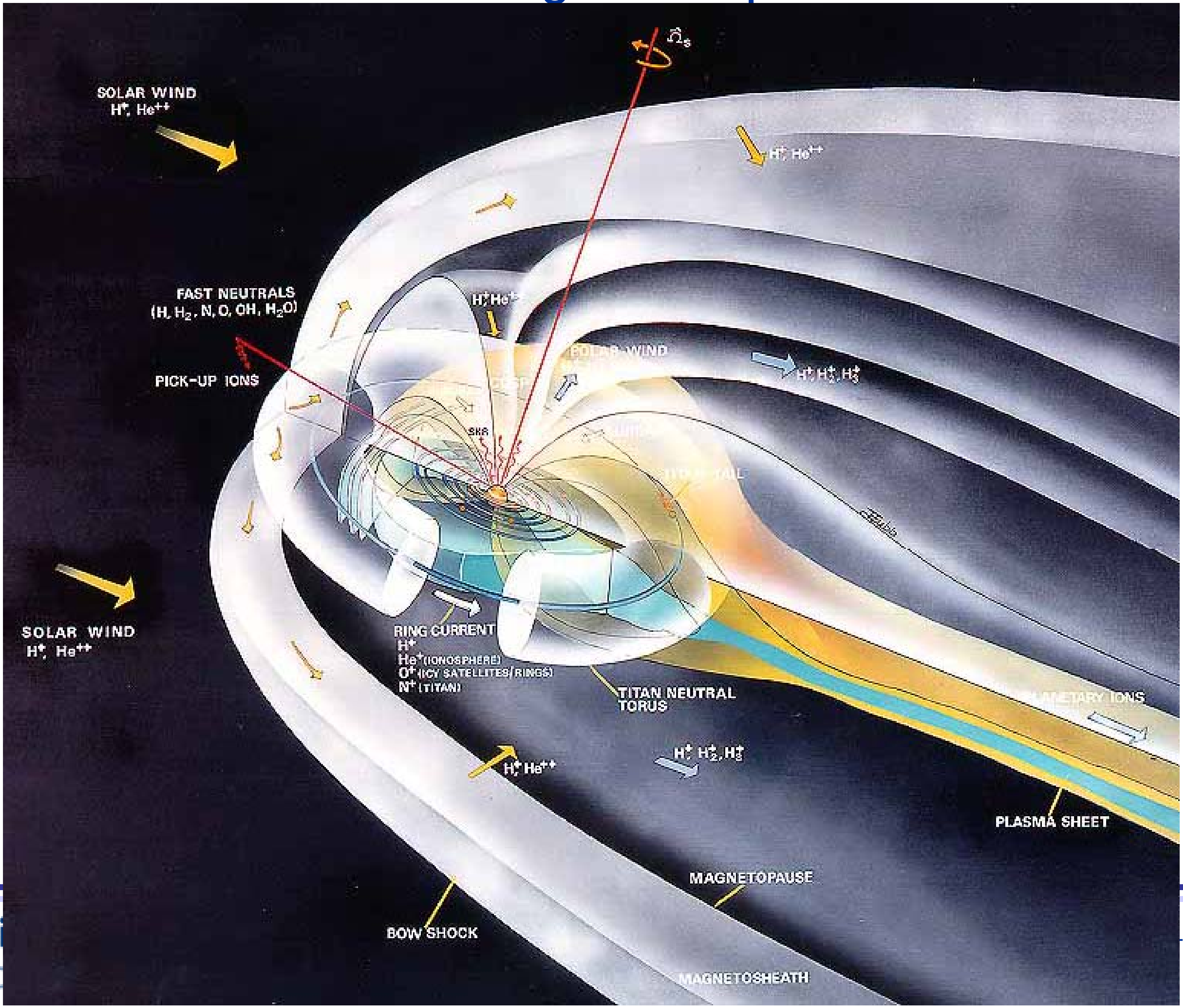
Earth – dominated sw processes

Jupiter – planetary rotation

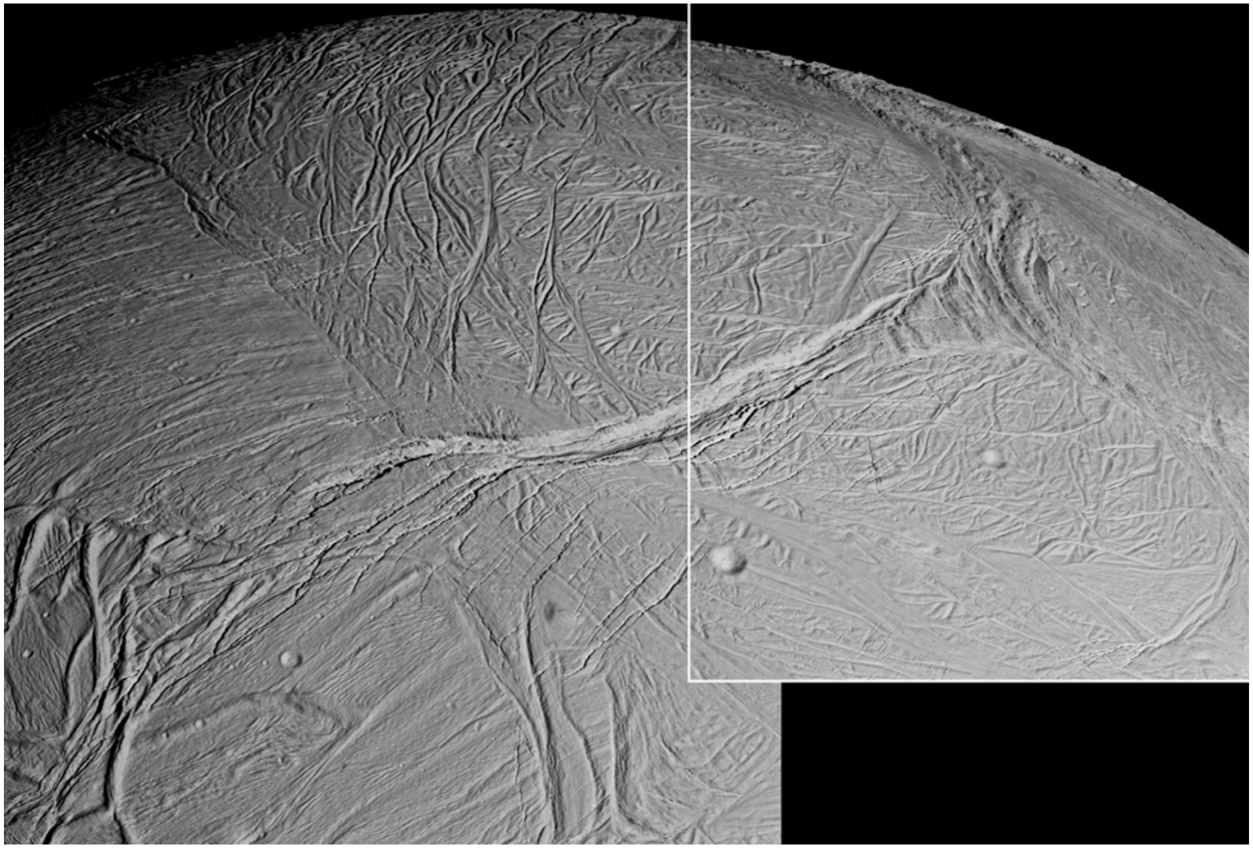
Saturn – combination

Figure 7

Saturn's Magnetosphere



Enceladus



Three Cassini flybys
(1265km, 500km, 173km)

In inner magnetosphere

Source of Saturn's E ring?

Relatively young surface

Cracks on surface

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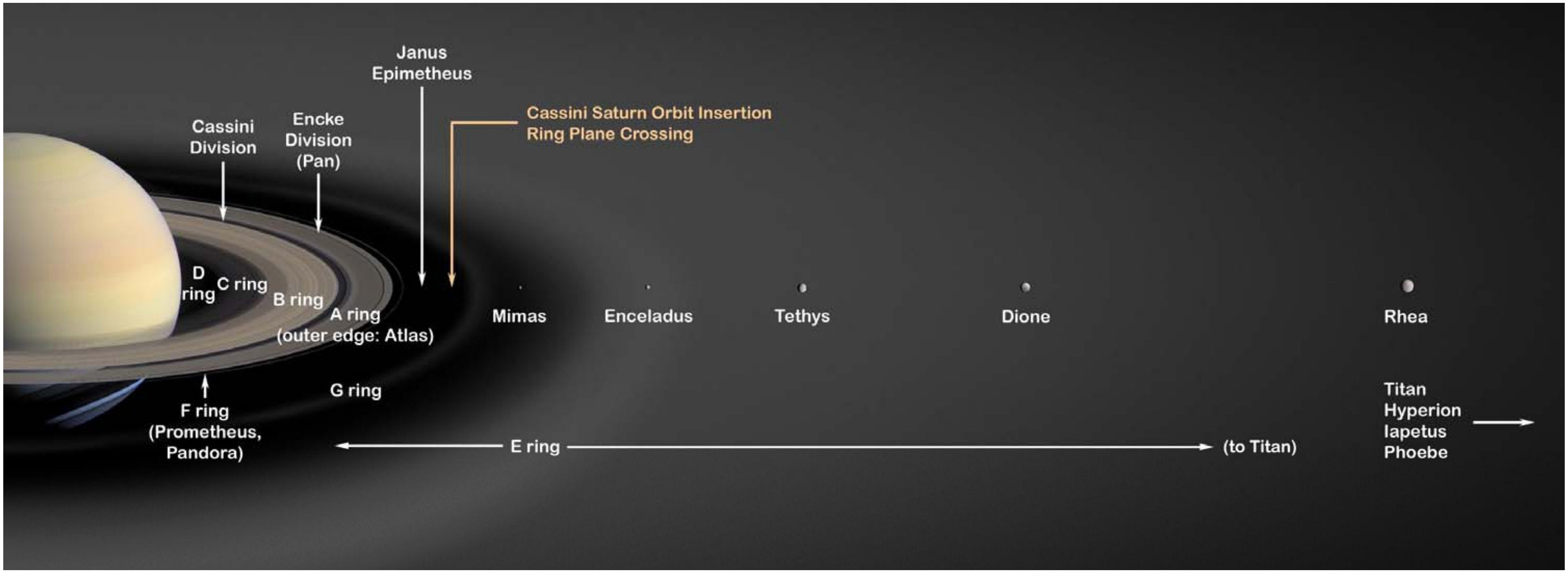
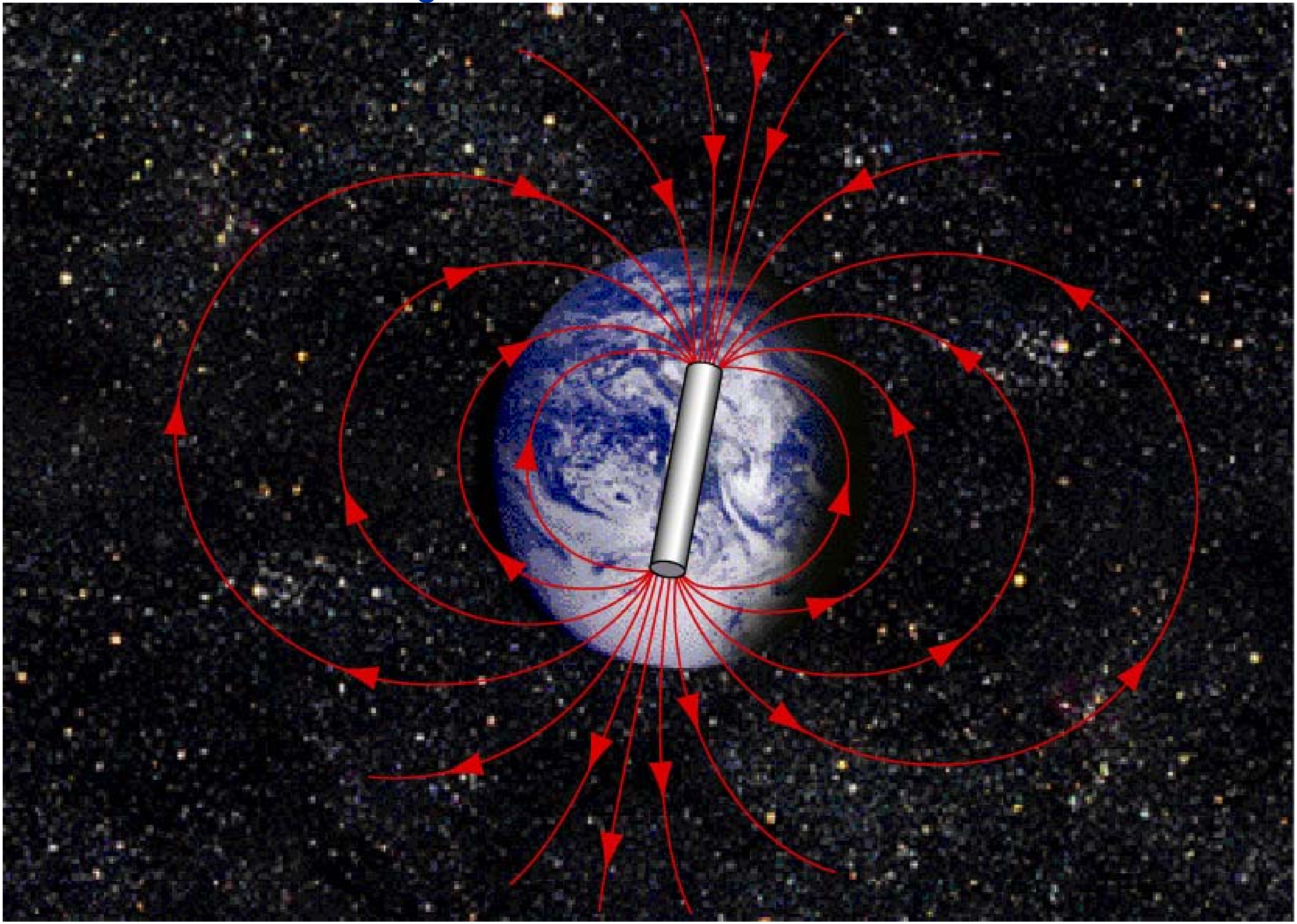
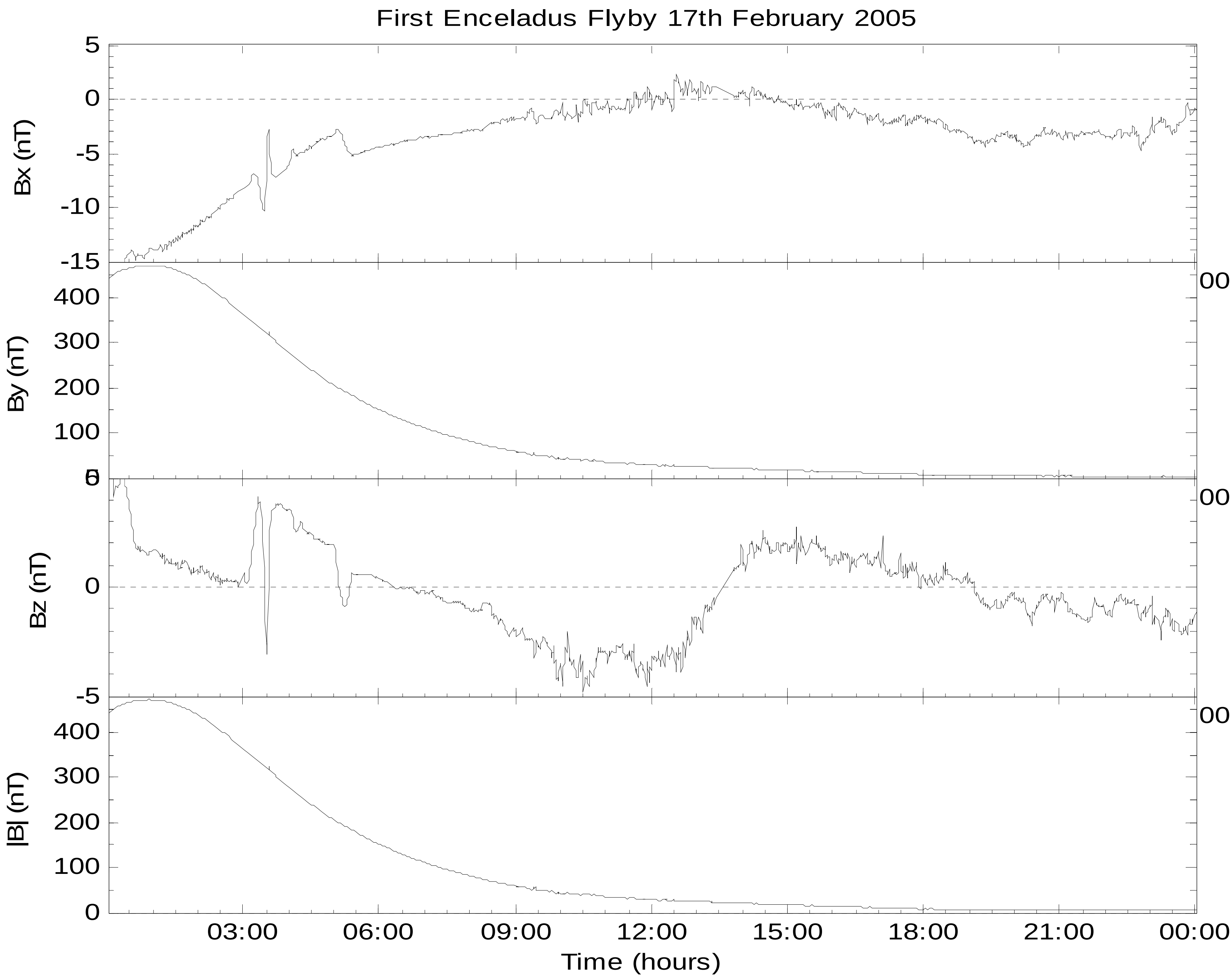


- Rings are an enormous, complex structure
- E ring largest planetary ring in solar system (from orbit of Mimas to Titan)
- Particle's in rings mainly water ice

Magnetic Field at Planets

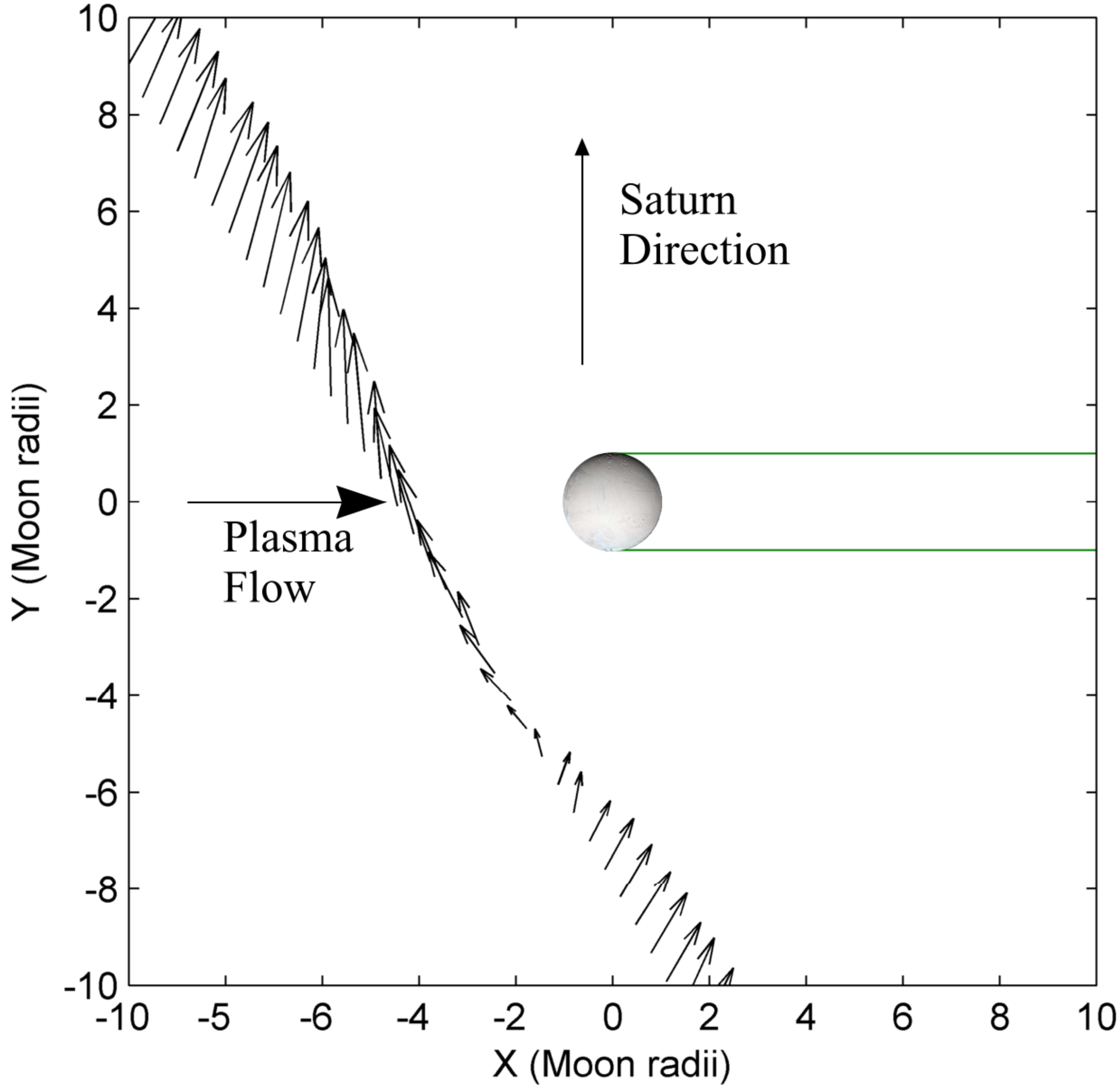




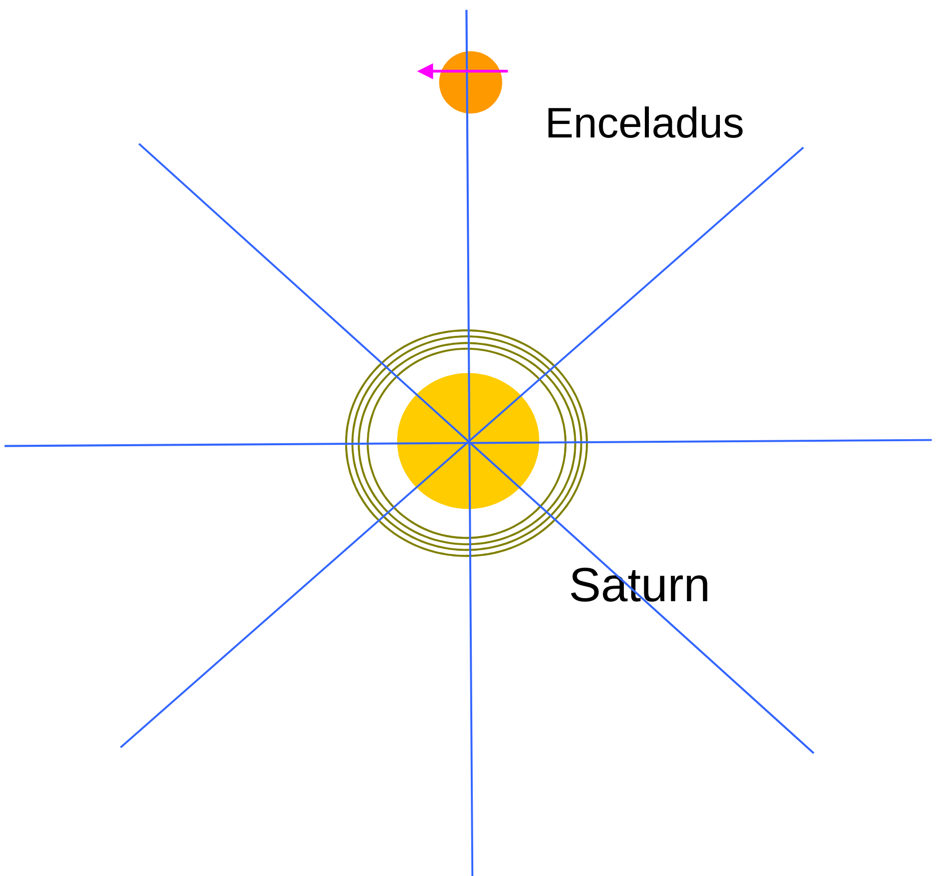
First Enceladus Flyby 17th February 2005
Bx (nT)
By (nT)
Bz (nT)
|B| (nT)
Time (hours)
03:00
06:00
09:00
12:00
15:00
18:00
21:00
00:00

Large increase in ion cyclotron wave activity

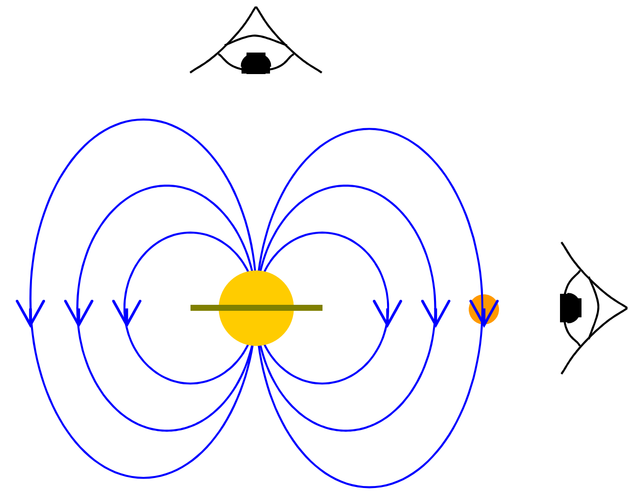
Water group ions

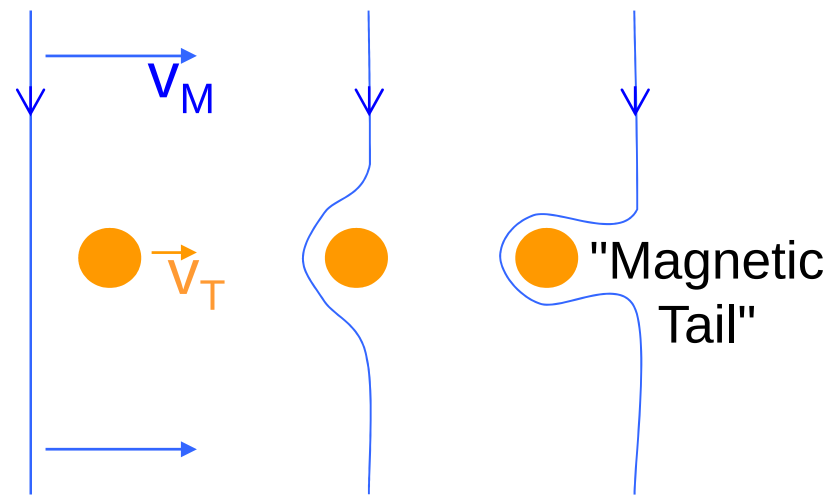


Field Line Draping



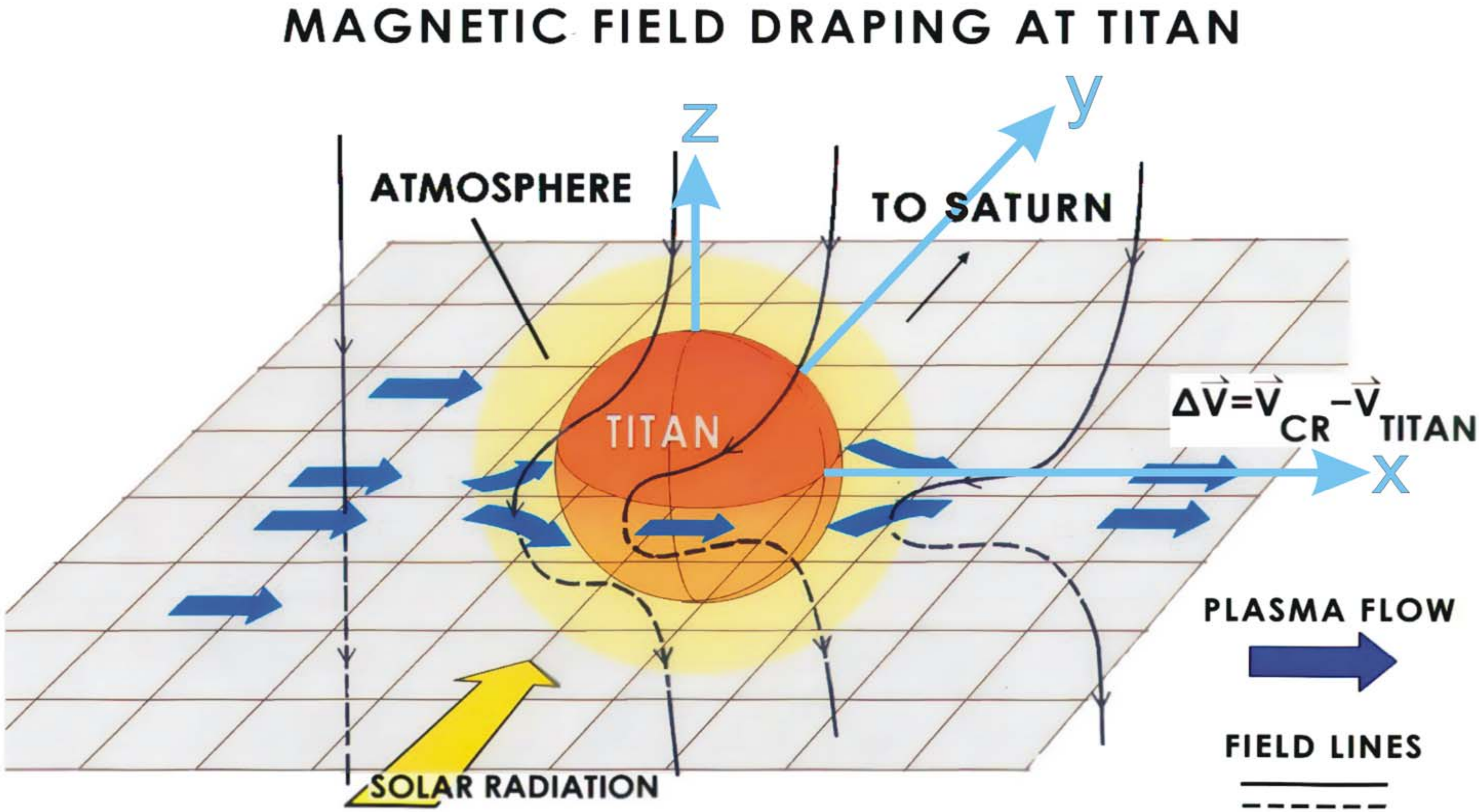
"Co-rotating" plasma





$V_M > V_T$

Draping geometry schematic,formation of an induced magnetosphere



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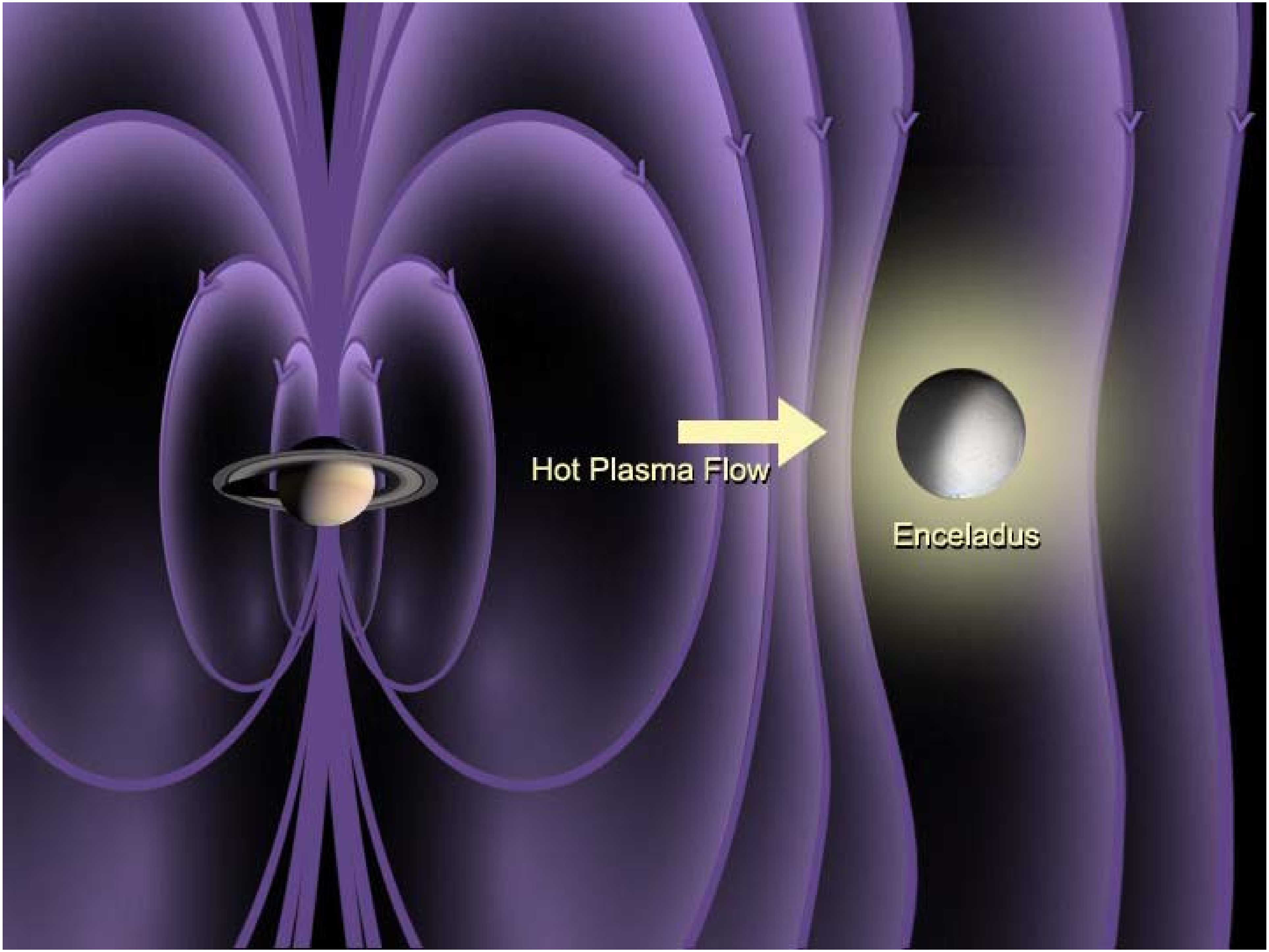

Hot Plasma Flow
Enceladus

Initial ideas after 2 flybys

- Diffuse atmosphere around Enceladus, strong source to maintain?
- Strong ion cyclotron wave activity – water group ions
- Seems to be additional signature around CA of March flyby – in addition to the atmospheric type signature
- Field is being pulled towards Enceladus – almost as if Enceladus is acting as an amplifier of the Saturn field
- Cassini Project moved 3rd flyby much closer

Looking down on XY plane

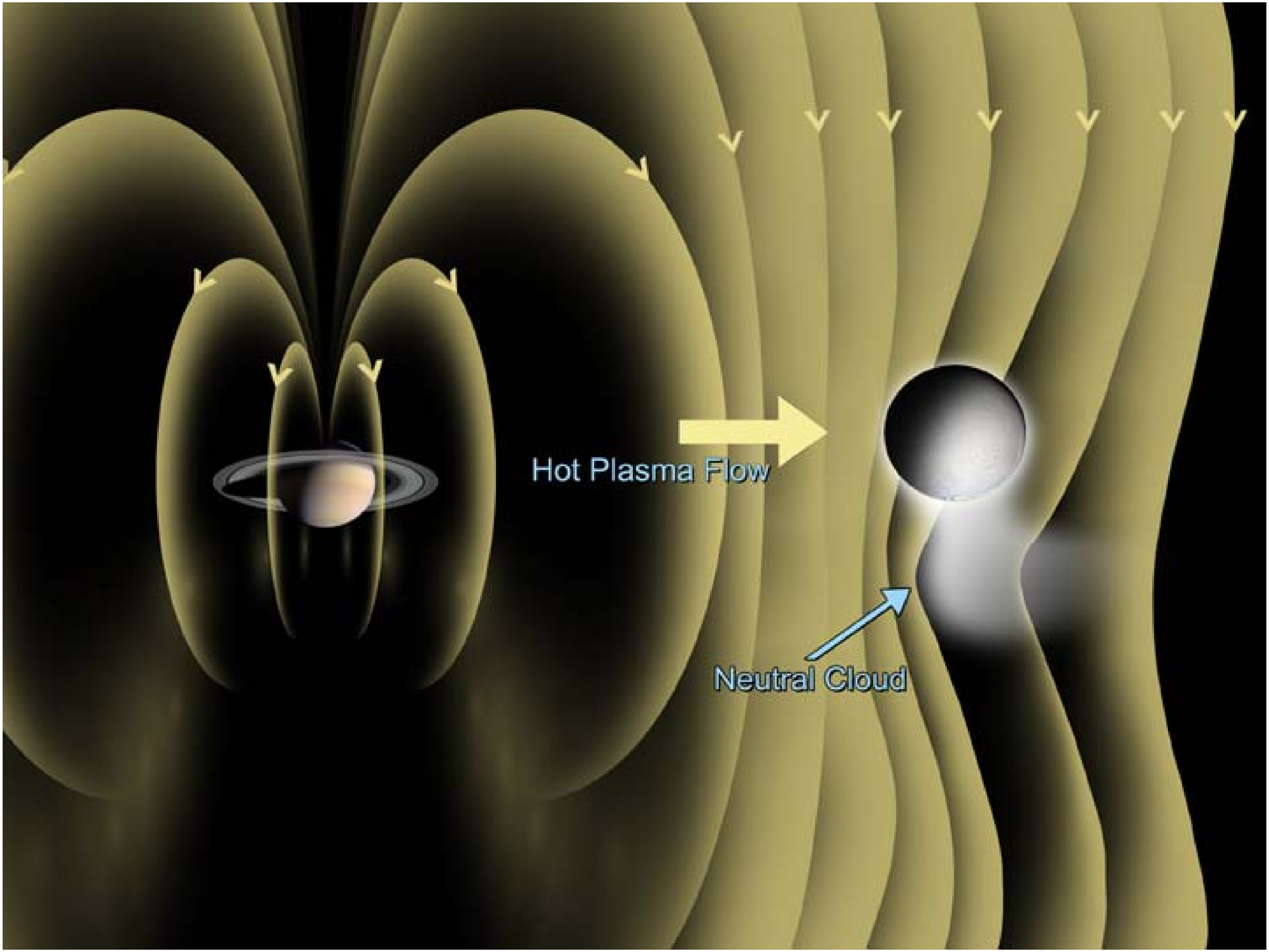
0 8 6 0 6 8 0

Corotation Axis (R_S)

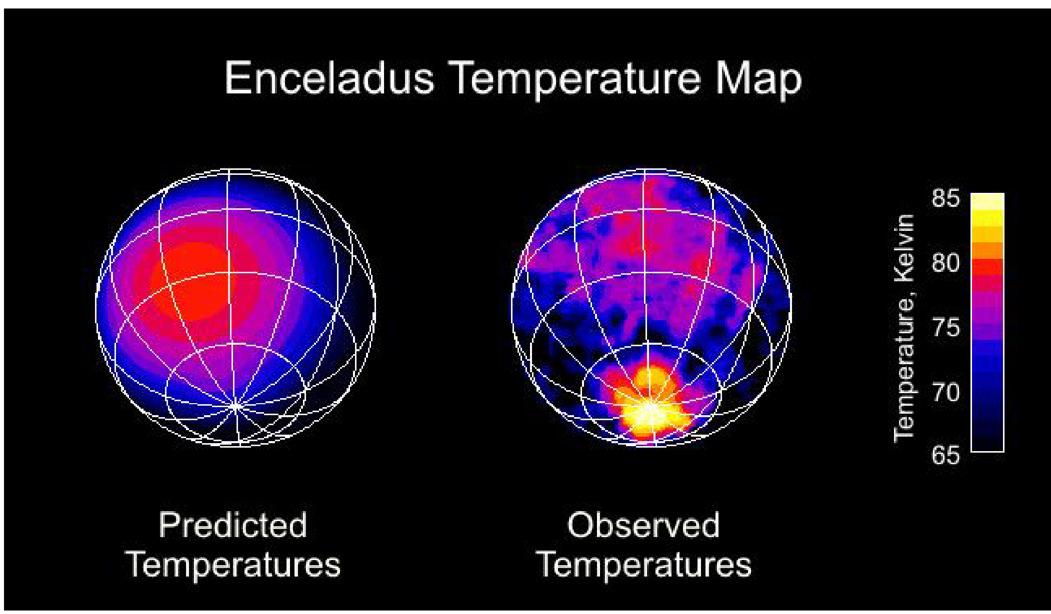
YZ plane with Saturn to right

10 8 6 4 2 0 2 4 6 8 10

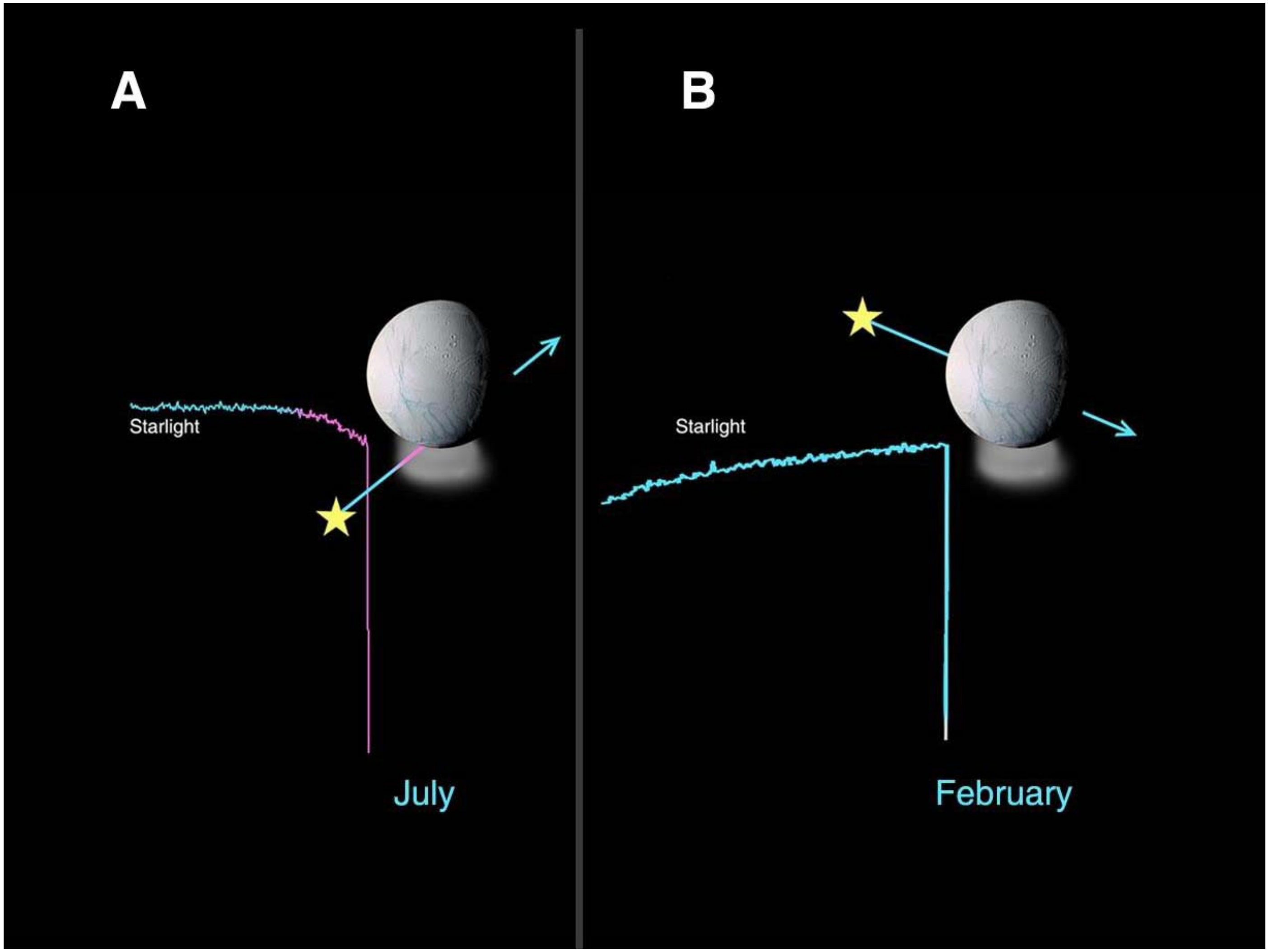
Moon-Saturn Axis (R_S)

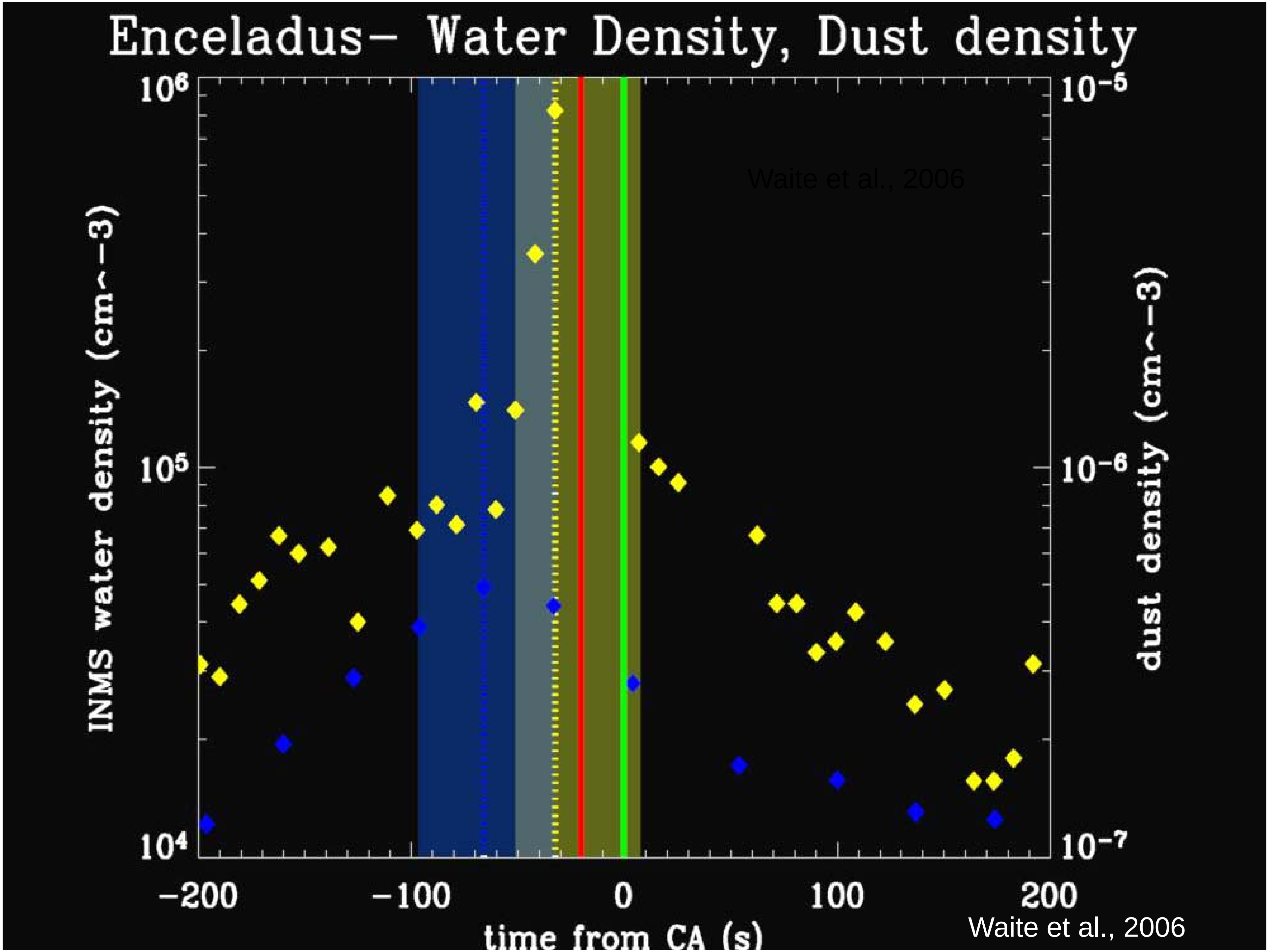

Hot Plasma Flow
Neutral Cloud

- Fractures/ Tiger Stripes near south pole
- Warm Spot near south pole
- Internal heat leaking out?
- Warmest temperature over one of fractures
- ISS & CIRS data (Porco et al., Spencer et al, 2006)

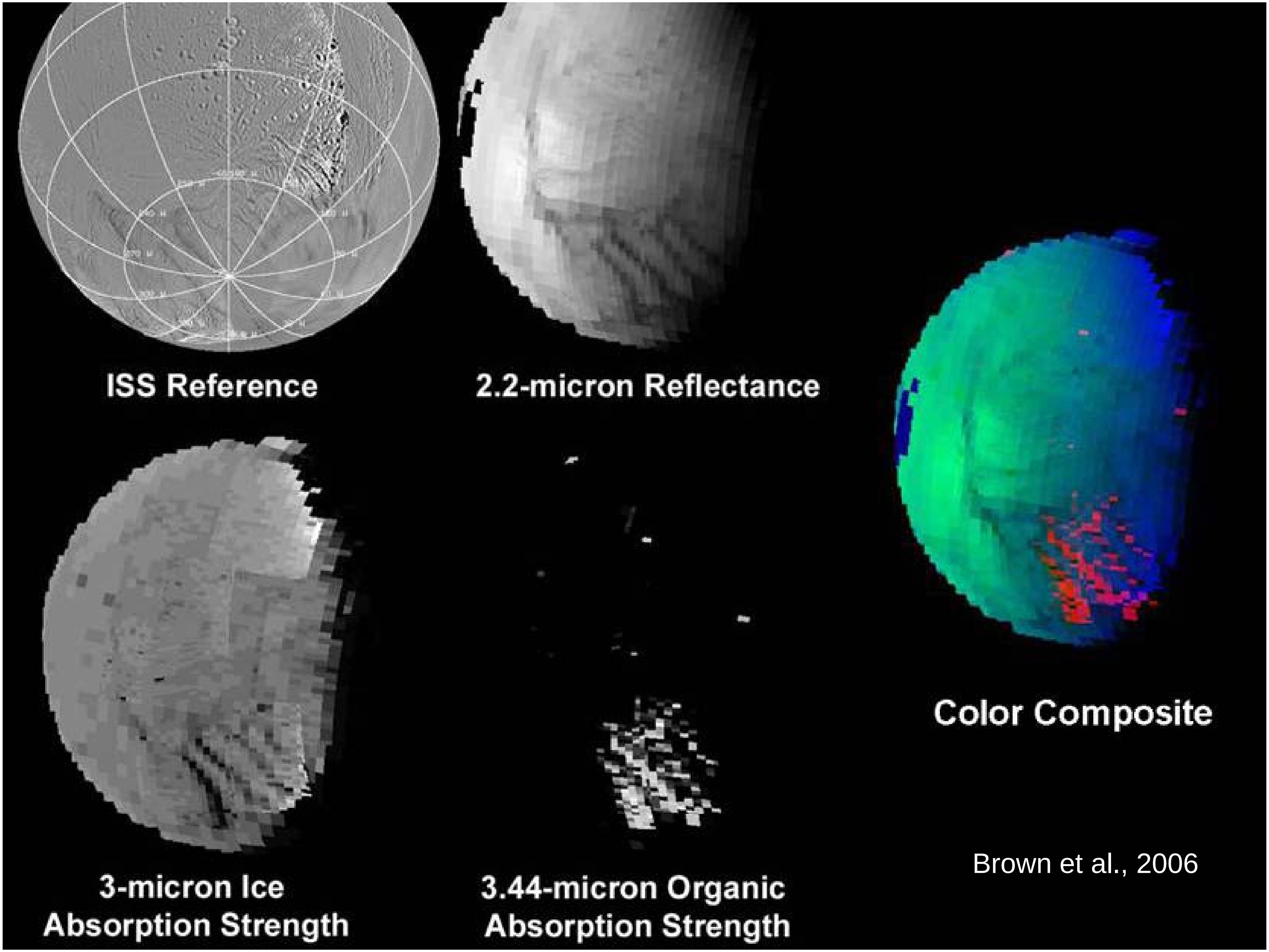


UVIS occultation data
(Hansen et al., 2006)



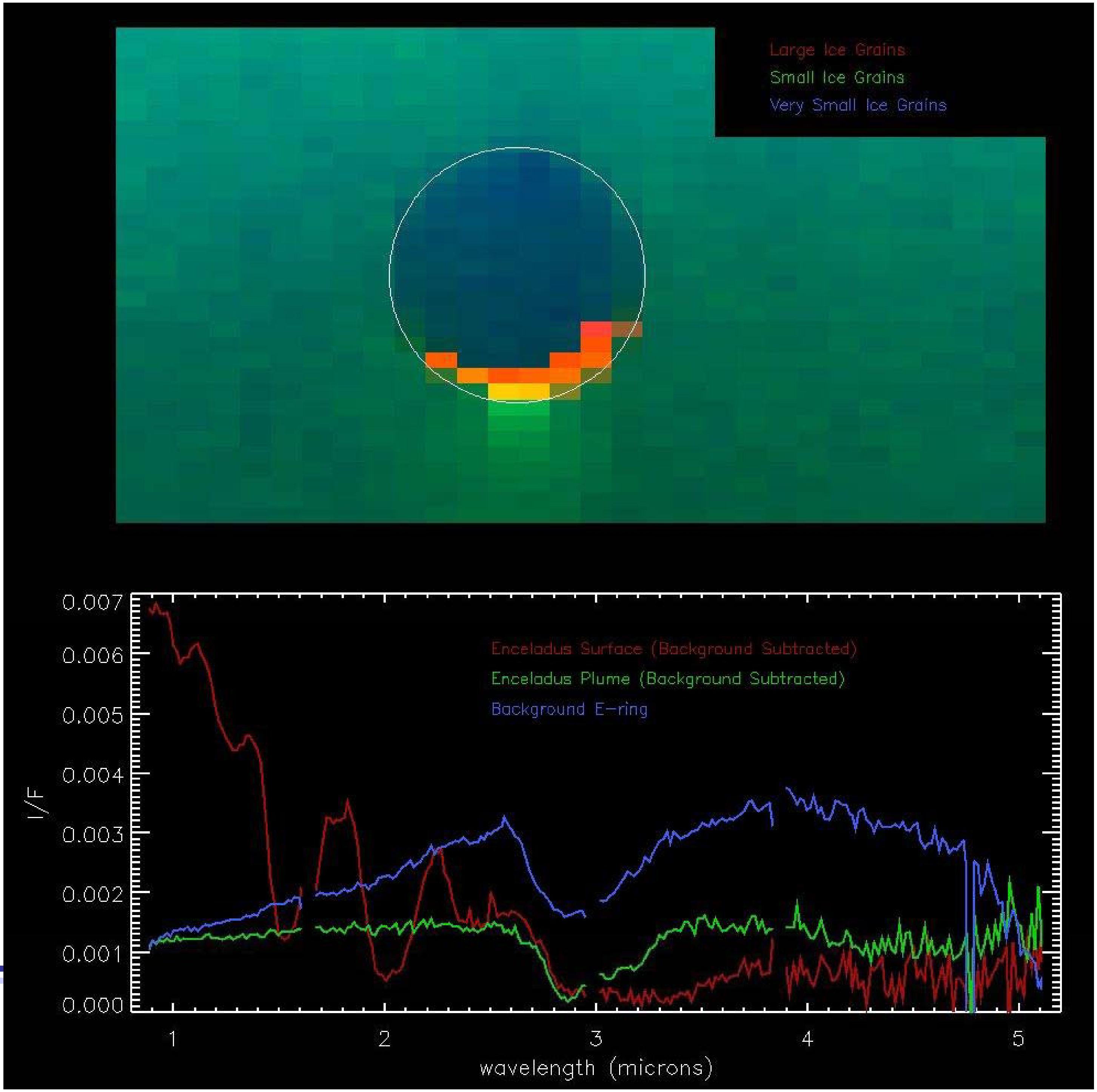


Waite et al., 2006


ISS Reference
2.2-micron Reflectance
Color Composite
3-micron Ice
Absorption Strength
3.44-micron Organic
Absorption Strength
Brown et al., 2006

Polar Plume
VIMS data

- November 2005
- Enceladus is source of E ring



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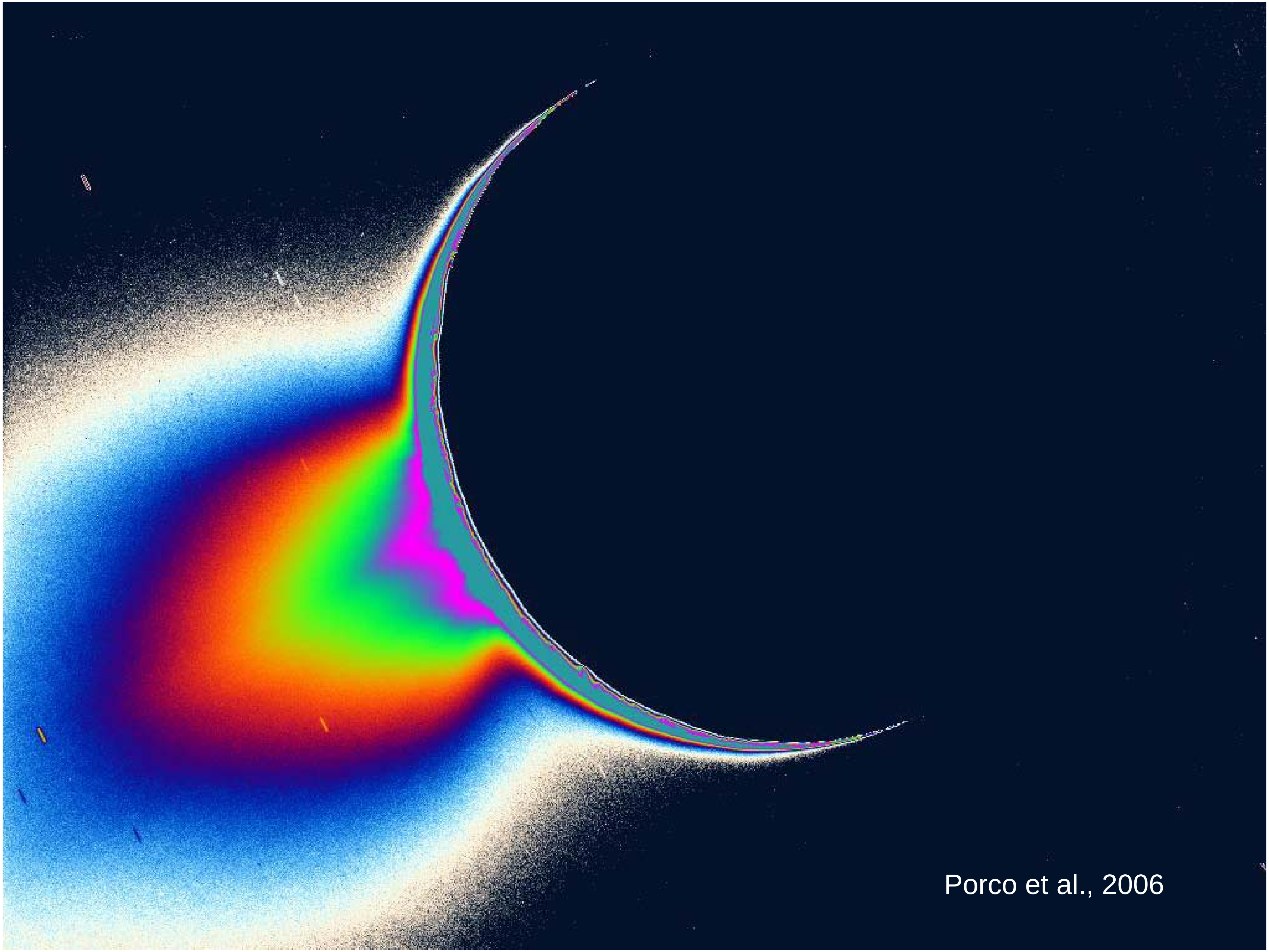
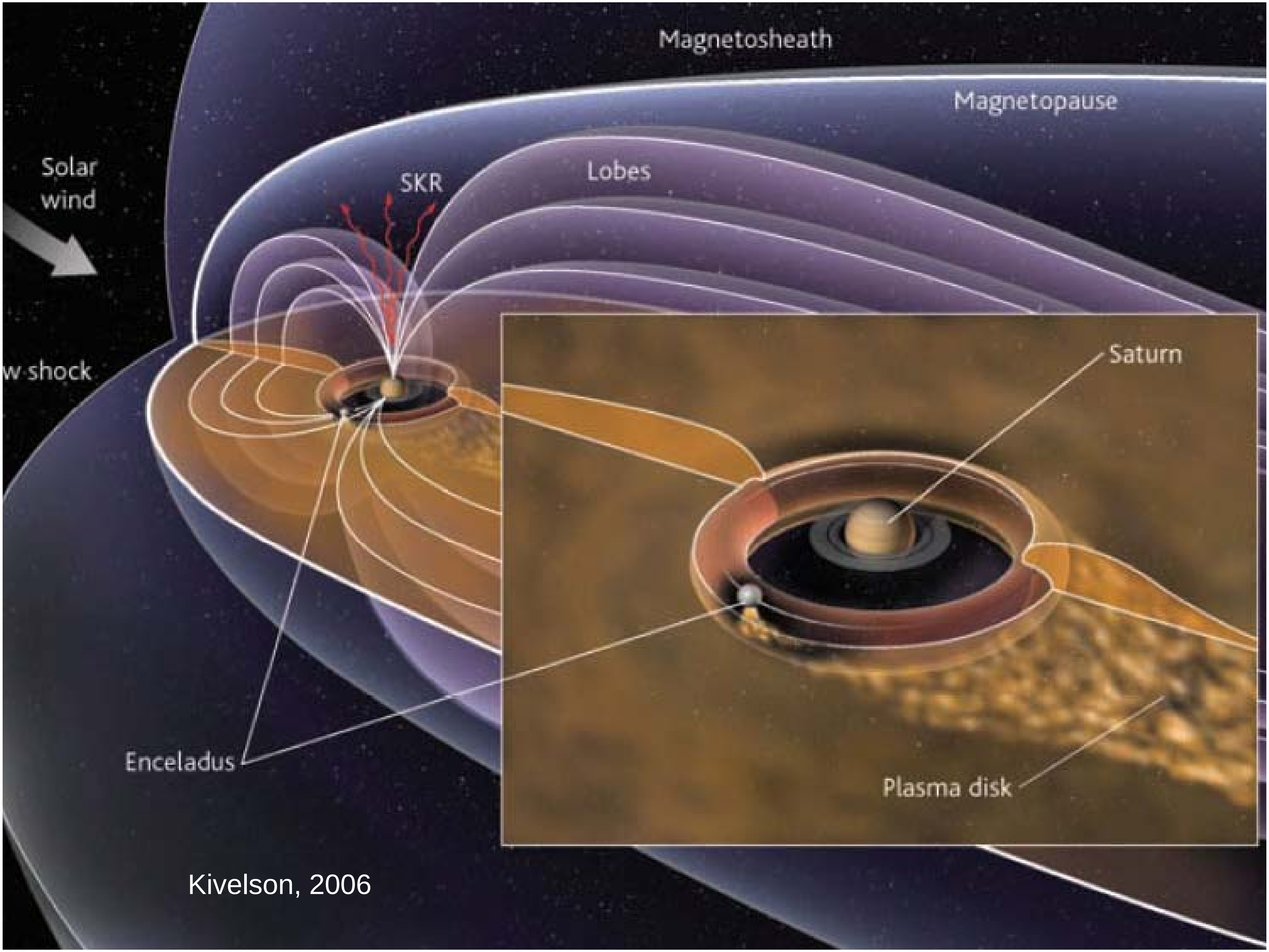
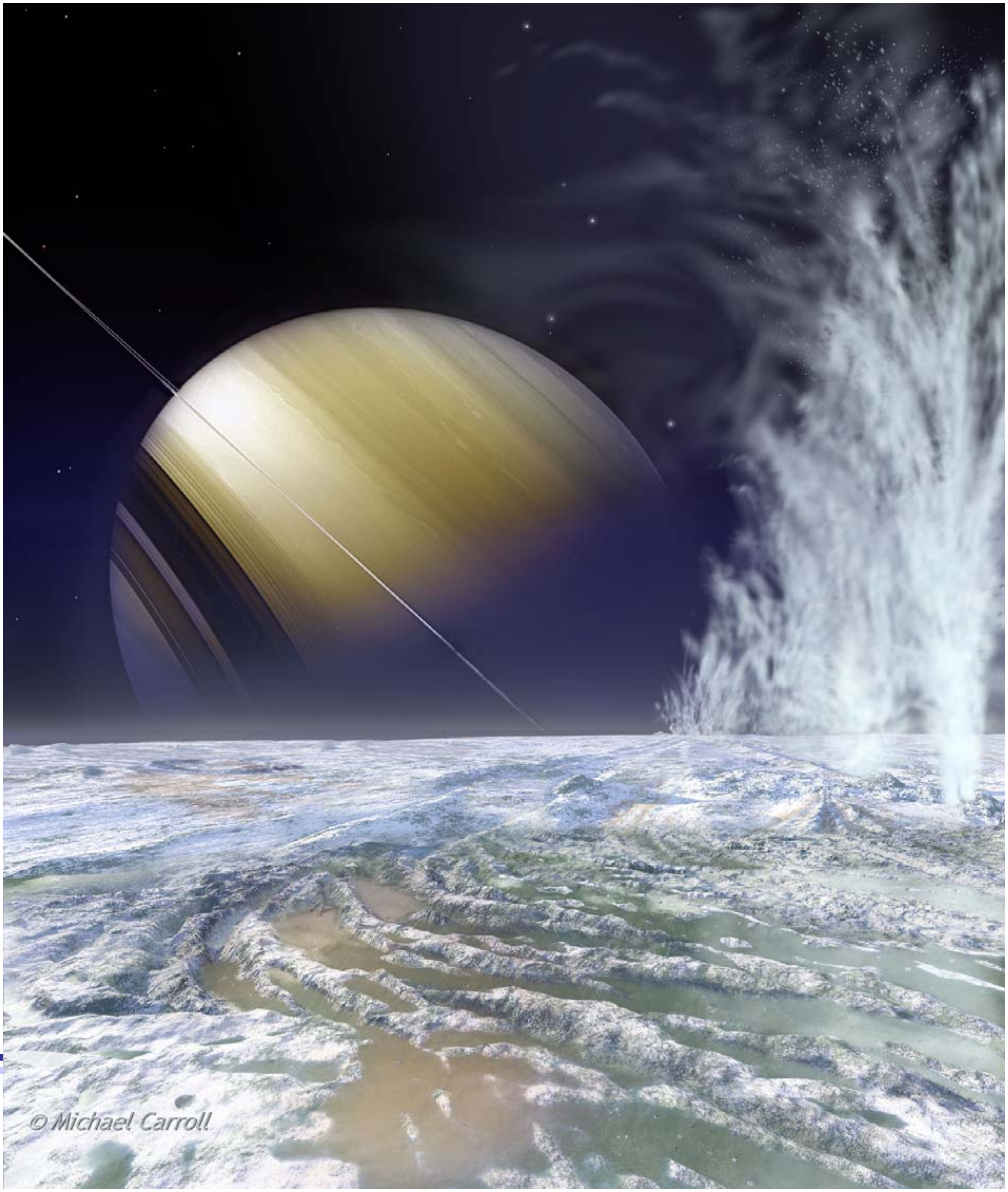

Porco et al., 2006



Kivelson, 2006

- Close flyby in 2008
- Numerous flybys in extended mission
- Discussions about future missions to Enceladus
- Marvellous example of inter-disciplinary science



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