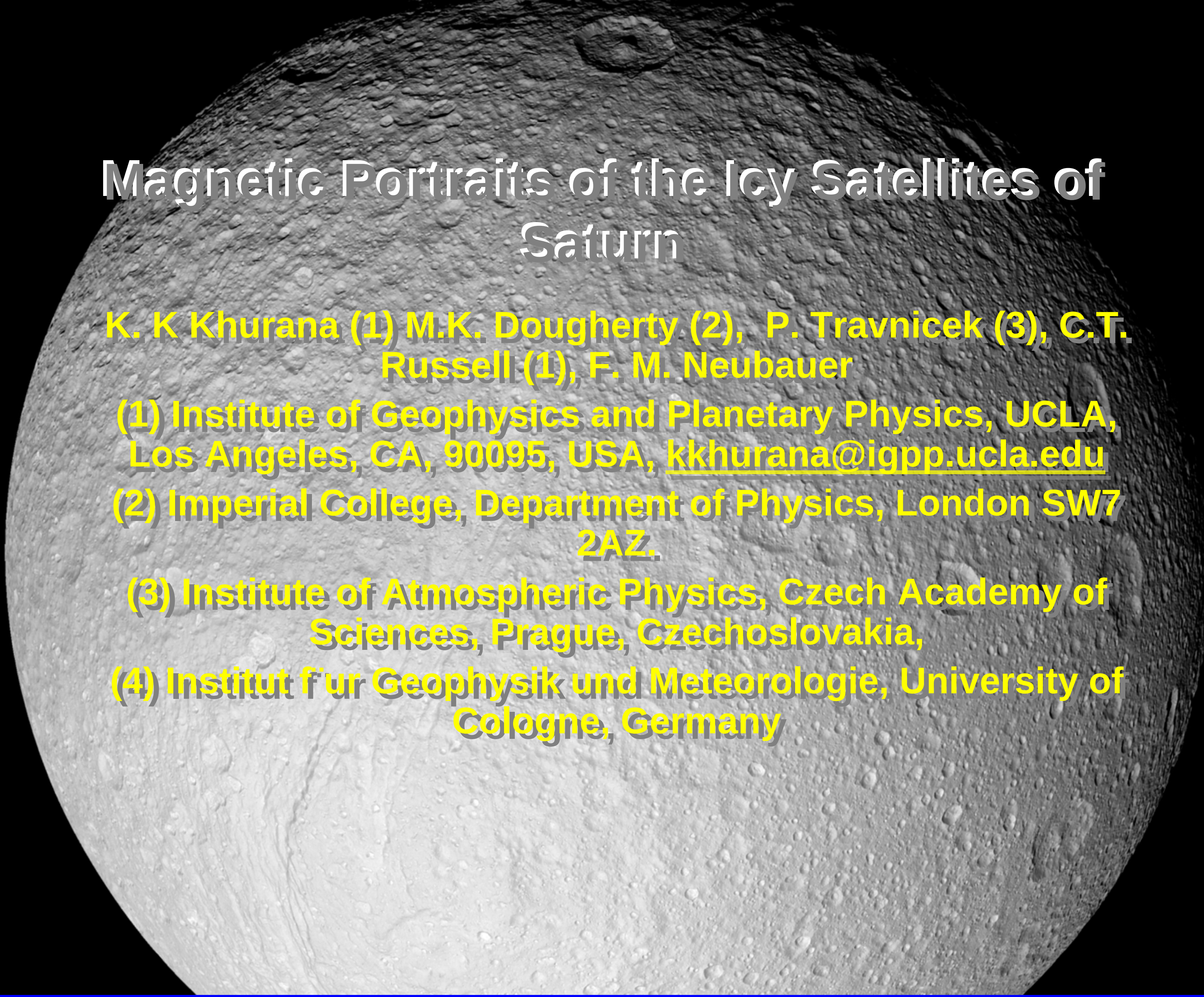

Magnetic Portraits of the Icy Satellites of Saturn

K. K Khurana (1) M.K. Dougherty (2), P. Travnicek (3), C.T. Russell (1), F. M. Neubauer

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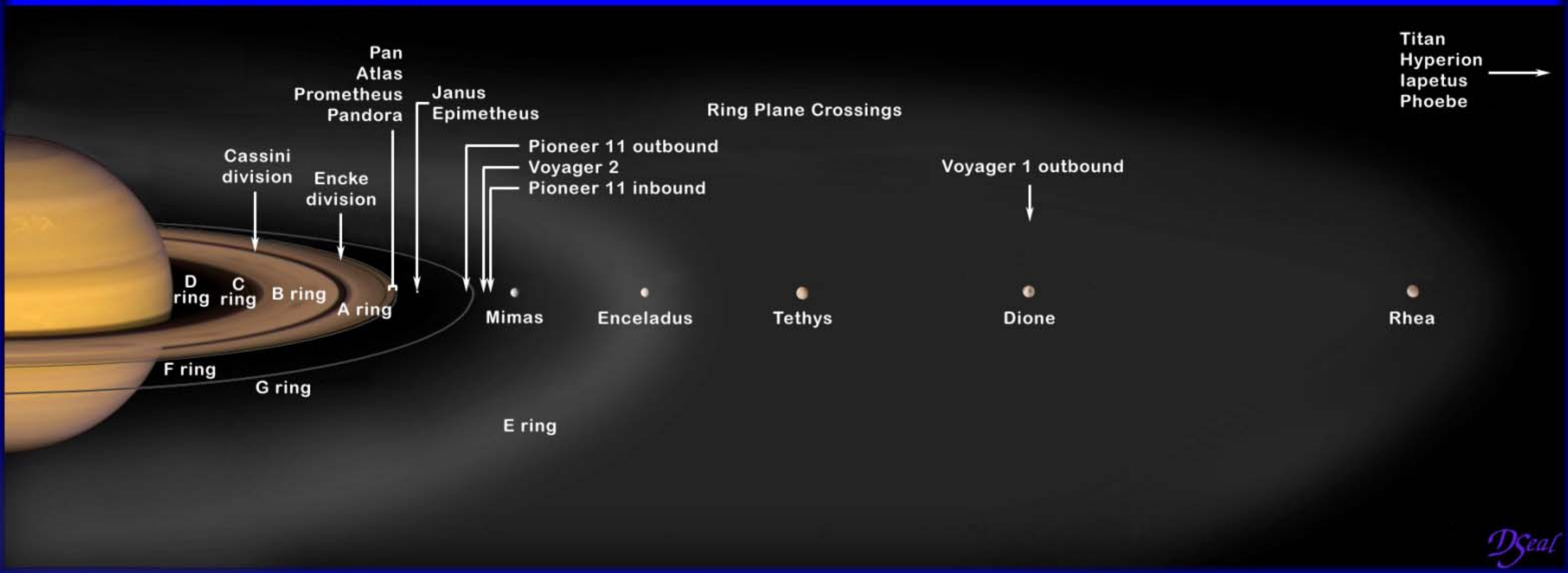
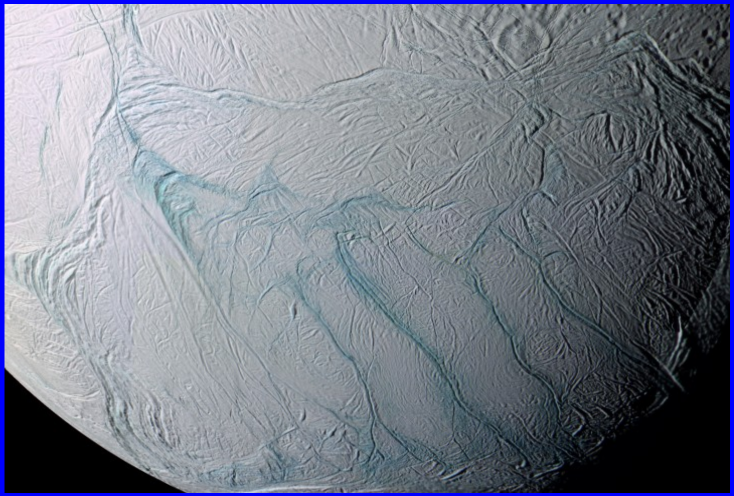
(3) Institute of Atmospheric Physics, Czech Academy of Sciences, Prague, Czechoslovakia,

(4) Institut f¨ur Geophysik und Meteorologie, University of Cologne, Germany

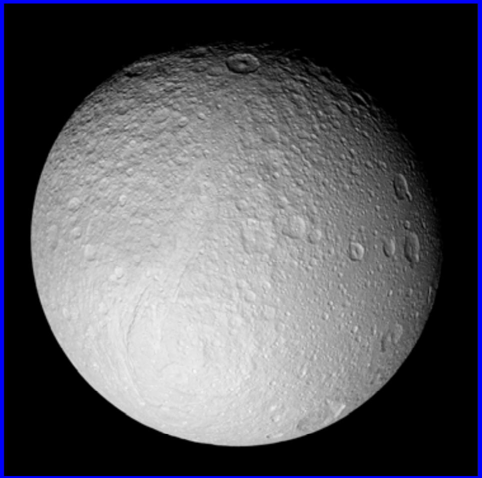
Saturn's Satellites and Ring Structure



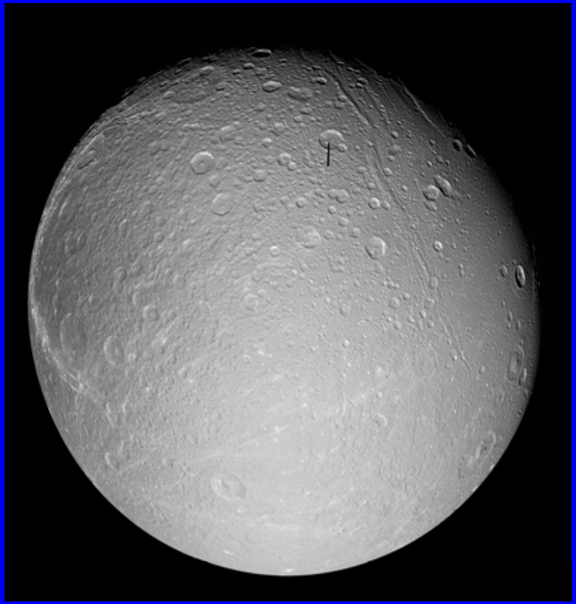
The regular portraits of the icy satellites I will discuss today (not to scale)



Enceladus



Tethys



Dione

Rhea

Hyperion

Physical Properties of Saturn's icy satellites

Satellite	Mean Radius (km)	Saturn distance (R_S)	Orbital Eccentricity	Orbital Inclination	Density gm/cm^3	Visual Albedo	Mean Surface Temp. (°K)
Mimas	198.5	3.08	0.02	1.53	1.17	0.5	64
Enceladus	**249.4**	**3.95**	**0.0045**	**0.02**	**1.61**	**~ 1.0**	**75**
Tethys	**529.9**	**4.89**	**0**	**1.86**	**1.26**	**0.9**	**86**
Dione	**560.0**	**6.26**	**0.0022**	**0.02**	**1.44**	**0.7**	**87**
Rhea	**764**	**8.74**	**0.0010**	**0.35**	**1.24**	**0.7**	**76**
Hyperion	**143**	**24.575**	**0.1042**	**0.43**	**0.6**	**0.3**	**??**

Source: http://nssdc.gsfc.nasa.gov/planetary/factsheet/saturniansatfact.html

Field and Plasma conditions near icy satellites

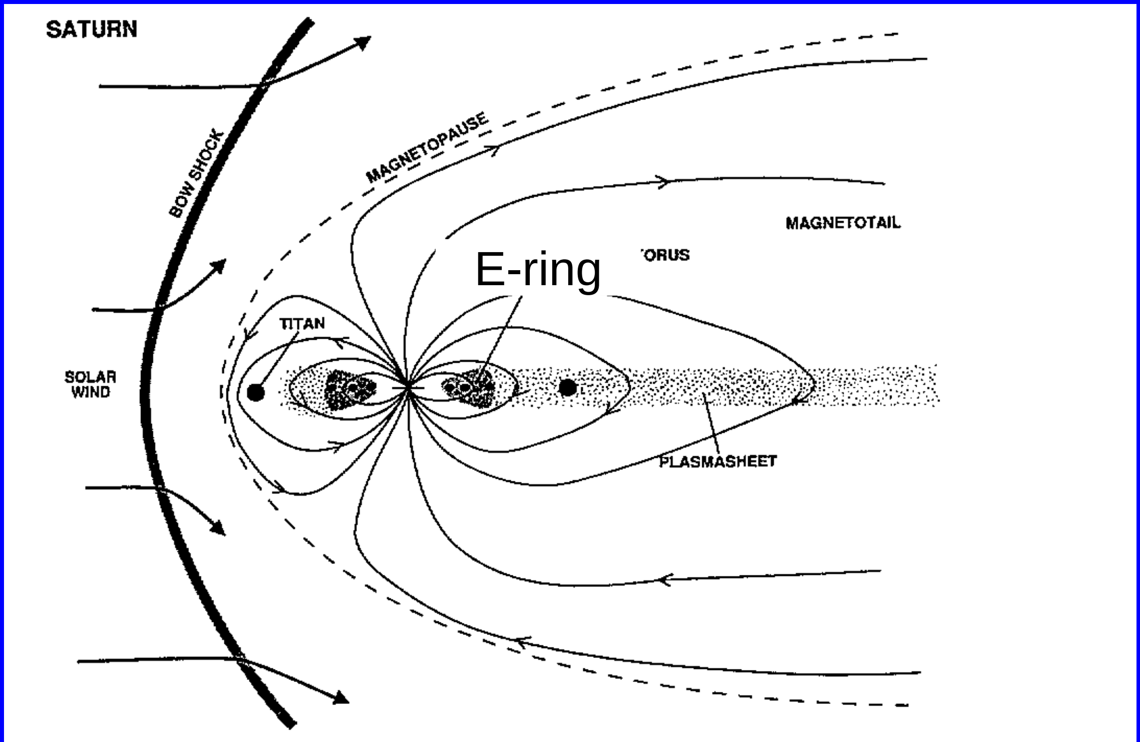


Figure 6 The magnetosphere of Saturn.

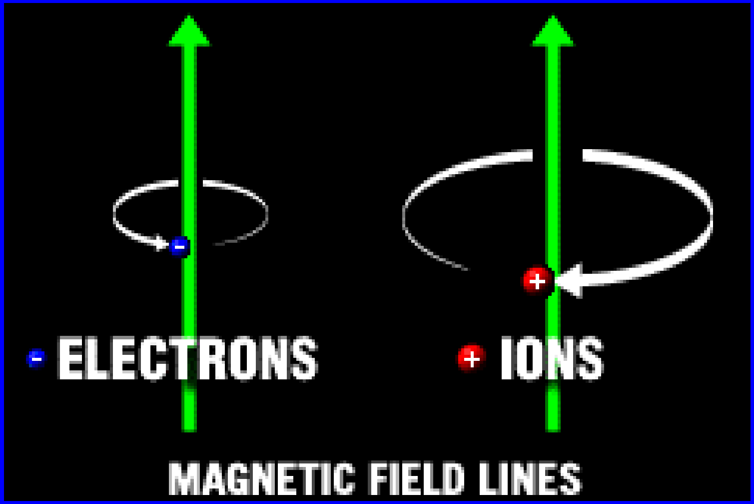
Source: Bagenal, 1994

- **Saturn has a strong magnetic field (surface equatorial strength = 0.2 Gauss) which is surprisingly axis-symmetric but tilted in the opposite sense to the Earth's magnetic field.**
- **All of the major satellites of Saturn with the exception of Iapetus are located inside the magnetosphere of Saturn.**
- **The corotating plasma of Saturn's magnetosphere overtakes the moons and preferentially sputters neutrals from their lagging sides.**

Single Particle Motion in a Dipole Field

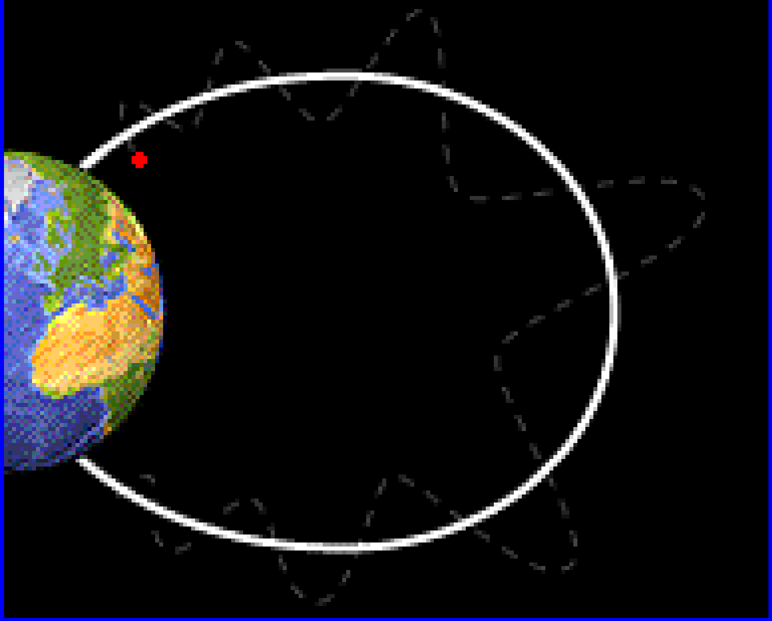
Image courtesy:
Windows to the universe
http://www.windows.ucar.edu/

$m\, d\mathbf{v}/dt = q\mathbf{v} \times \mathbf{B}$



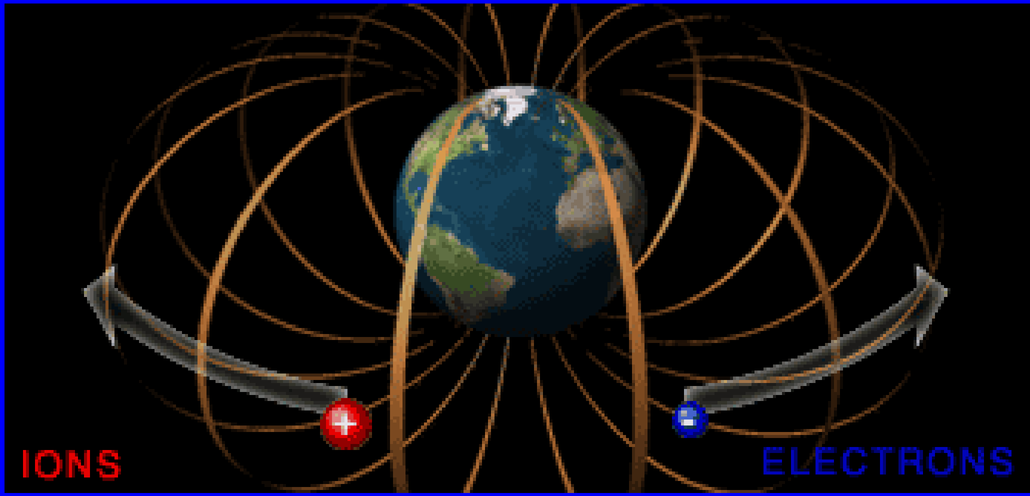
Particle Gyration

$\mathbf{r_L = m v_\perp}/q\, B$ = A few km to tens of km for a 1 keV O^+ near the icy satellites.



Particle Bounce

$\mathbf{F}_{||} = -\mu \nabla_{||} B \qquad \mu = \frac{1}{2} m v_\perp^2 / B$



Particle ∇B drift

Field and Plasma Properties near the Icy moons

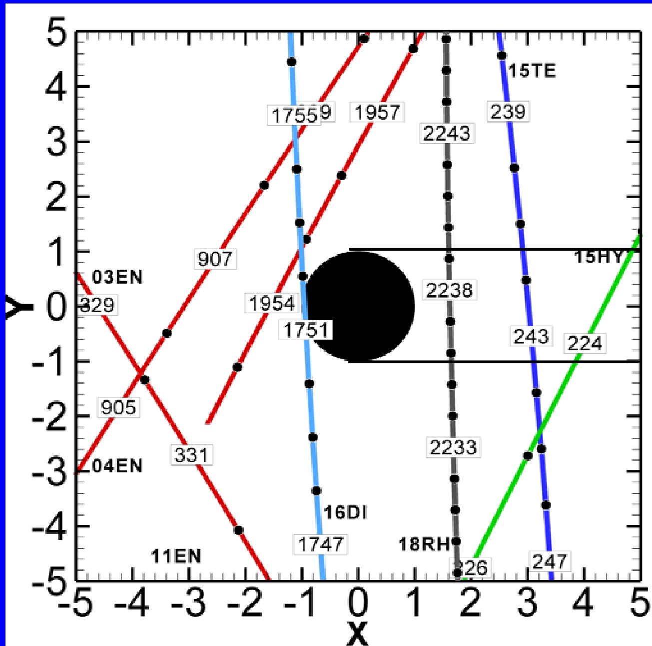
Saur and Strobel, 2005

TABLE 1

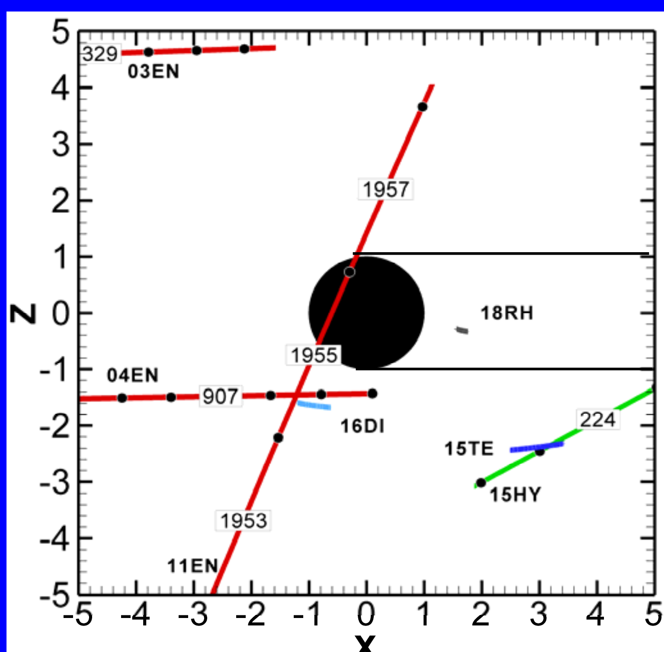
Properties at Icy Satellites

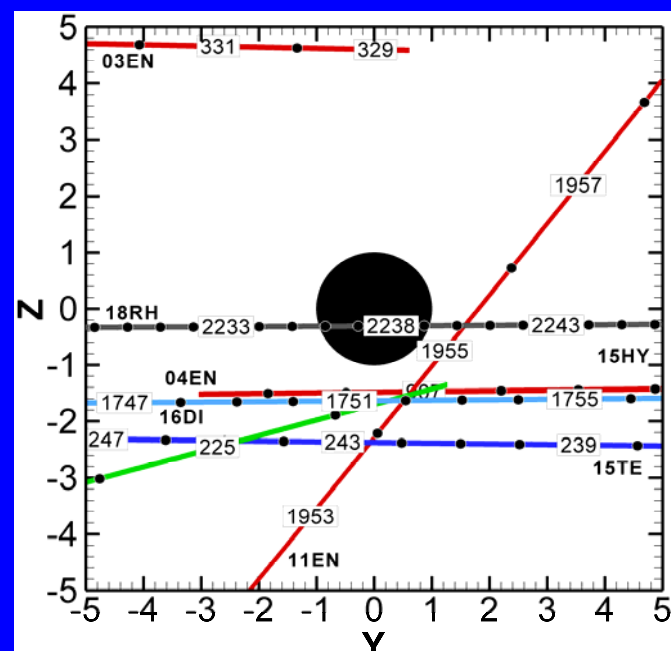
Parameter	Mimas	Enceladus	Tethys	Dione	Rhea
Distance (R_{Saturn})[a]	3.1	3.9	4.9	6.3	8.7
Period (h)[a]	22.6	32.9	45.3	65.7	108.4
Diameter (km)[a]	390	500	1060	1120	1530
Mass (10^{20} kg)[b]	0.46	0.8	7.6	10.5	24.9
v relative (km s^{-1})[c]	15.6	25.5	33.6	39.9	56.6
B_0 (nT)[d]	722	362	183	86	32
$n_{i,\,thermal}$ (cm^{-3})[e]	90	70	40	20	3.5
$n_{e,\,supra}/n_{e,\,thermal}$[f]	0.03	0.03	0.02	0.12	0.13
$T_{e,\,thermal}$ (eV)[e]	5[f]	5[f]	8	15	30
$p_{e,\,supra}/p_{e,\,therm}$[f]	0.05	0.1	0.4	0.6	0.7
$p_{e,\,total}$ ($10^{-12}P$)[c]	75	61	72	77	29
T_i heavy (eV)[e]	50[f]	50[f]	90	200	200
v_A (km s^{-1})[c]	237	158	105	96	88
M_A[c]	0.04	0.11	0.21	0.38	0.59
β[c]	0.003	0.01	0.04	0.2	0.26
M_s[c]	0.69	1.14	1.1	0.89	1.3
M_f[c]	0.04	0.1	0.2	0.53	0.79
ω_i (s^{-1})[c]	4.3	2.2	1.1	0.52	0.20
$v_{therm,\,i}$ (km s^{-1})[c]	30.0	30.0	40.2	60.0	60.0
r_g (km)[c]	6.9	13.8	37	116	306
S-sputter (10^{26} s^{-1})[g]	0.12	0.09	0.41	0.4	0.32
$T_{surface}$ (K)[b]	69	50	69	87	85
Jeans λ[c]	1.2	1.6	5.3	5.5	9.8

Trajectories and coordinate system

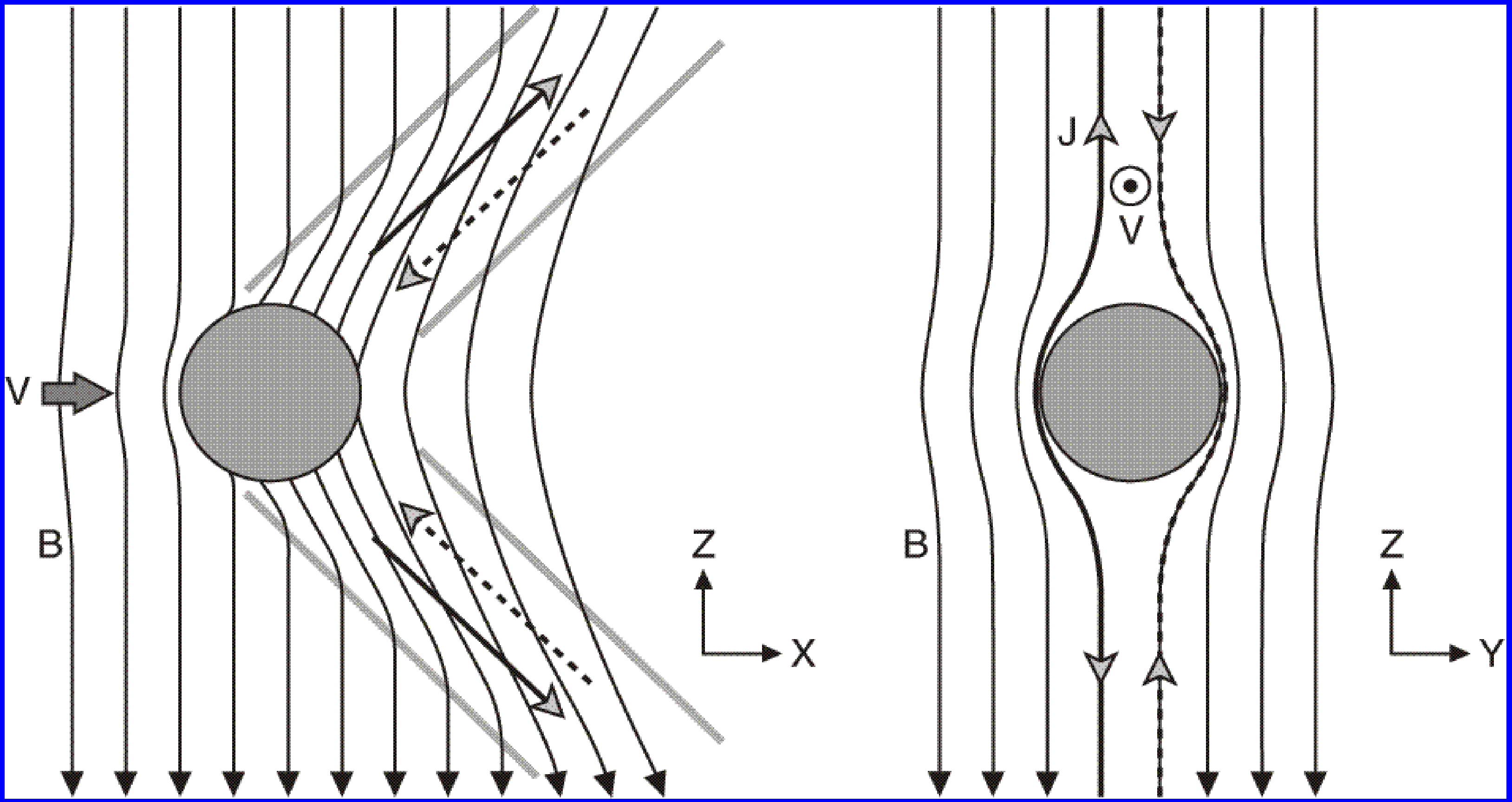


X along the plasma flow direction.
Y positive towards Saturn
Z axis oriented along the rotation axis of Saturn



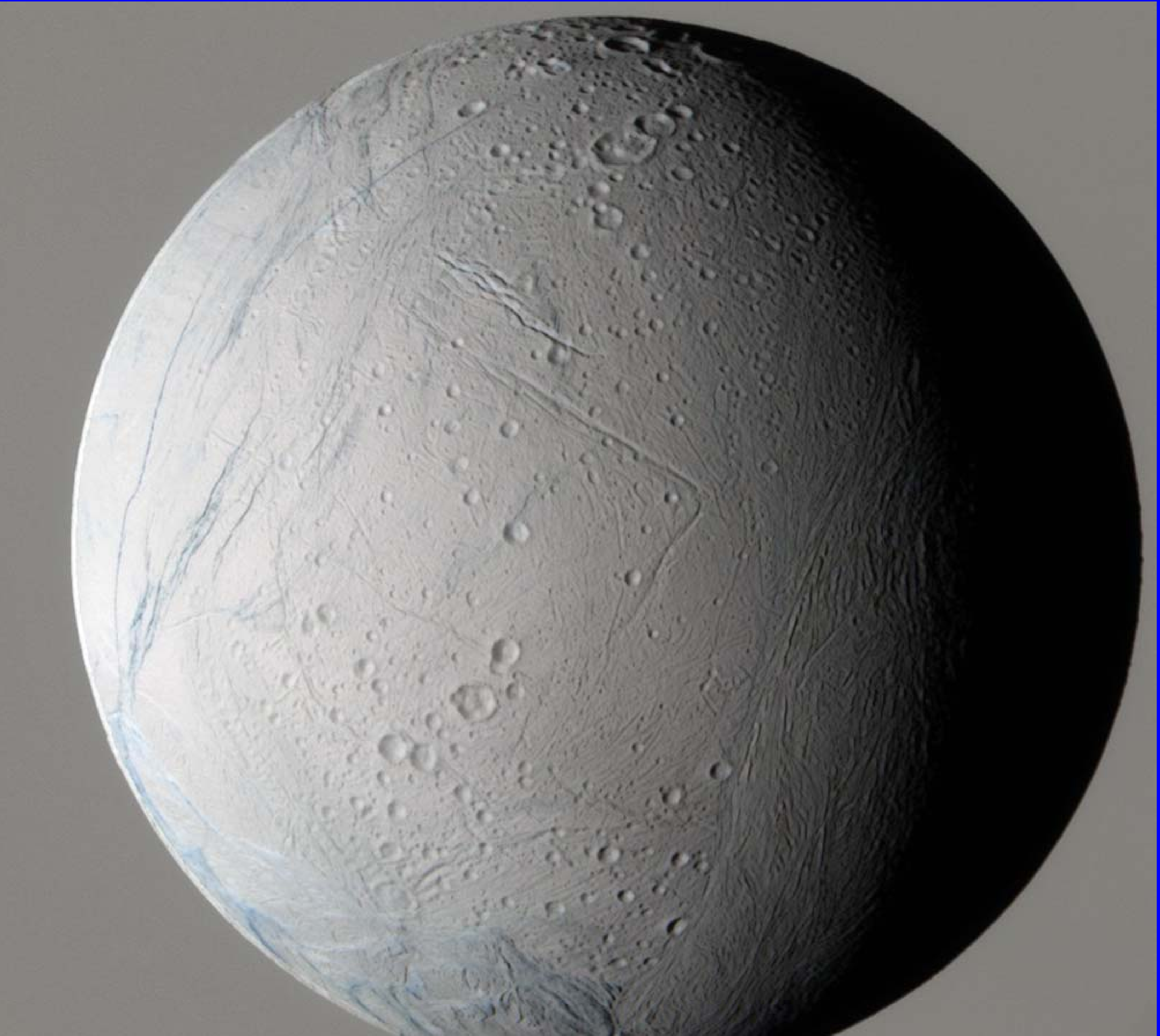


MHD interaction of a mass loading/conducting moon with flowing plasma



Enceladus

- Discovered by William Herschel on August 28, 1789.
- Mean radius of 252.1 km and density 1.61 g/cm^3.
- May be fully differentiated with an icy crust and rocky core.
- Currently in a 2:1 orbital resonance with Dione.
- Wide range of surface types, from heavily cratered old to relatively crater-free young regions near the south pole.
- Enceladus is tectonically active today where eruptions have been observed
  - (Other such moons are Jupiter's Io and Neptune's Triton.)
- Analysis of outgassing material is consistent with a subsurface source of liquid water.
- Particles from Enceladus populate the E-ring (~4 - 10 R_S) and are the main population source for the magnetosphere of Saturn.

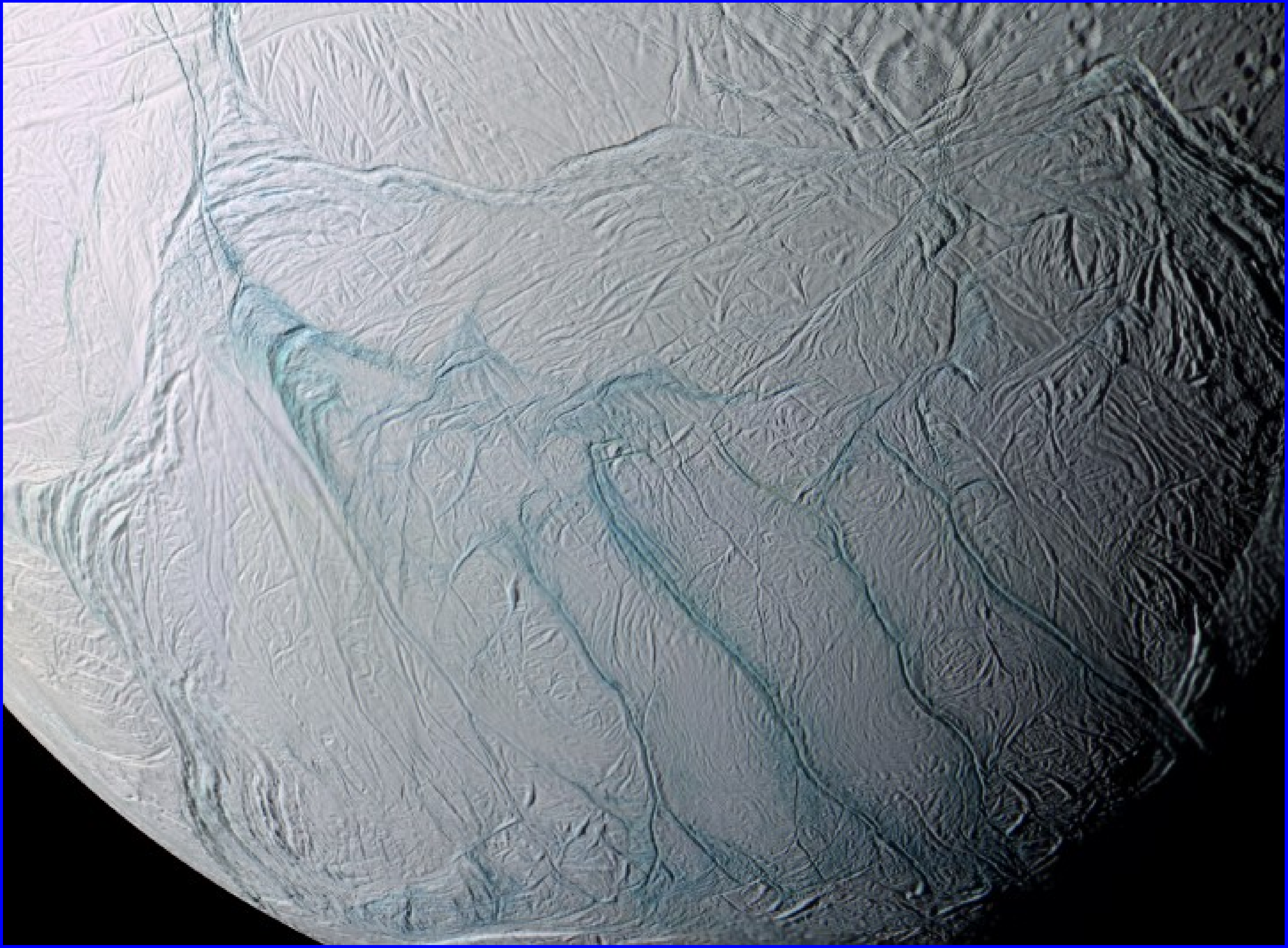


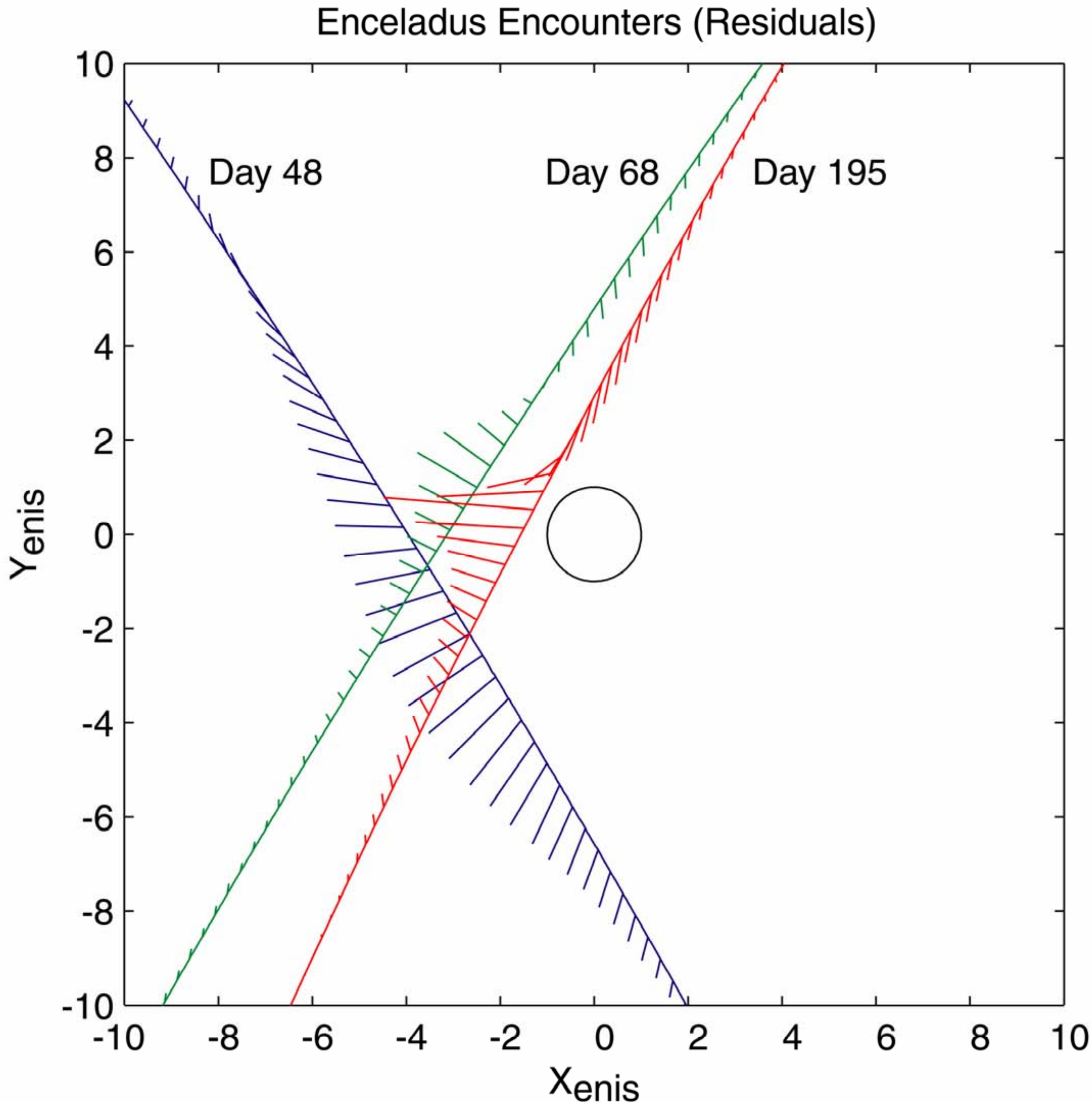
Enceladus

Enceladus deep color view of transitional terrain between smooth plains and cratered terrain

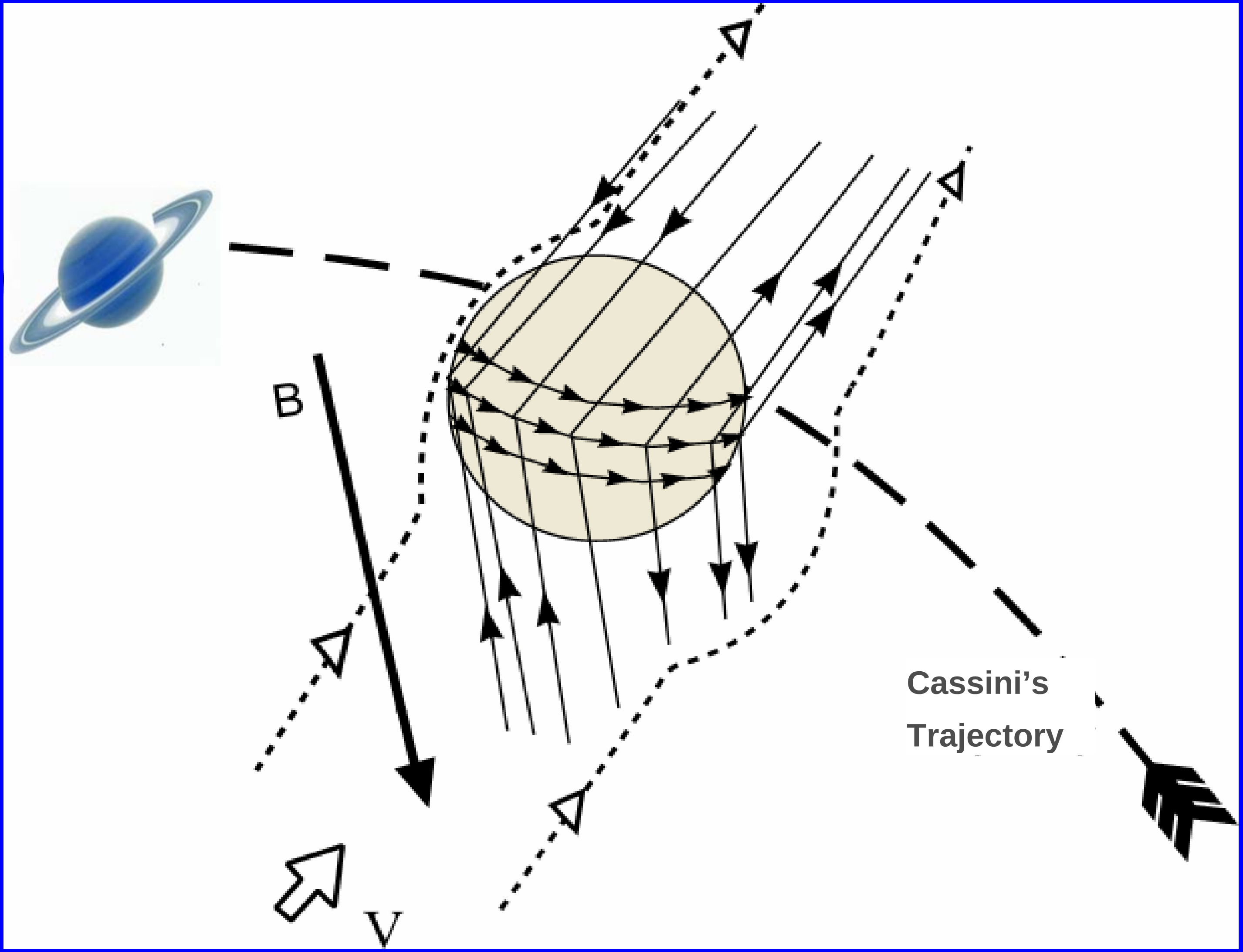
150 meters/pixel

Tiger Stripes

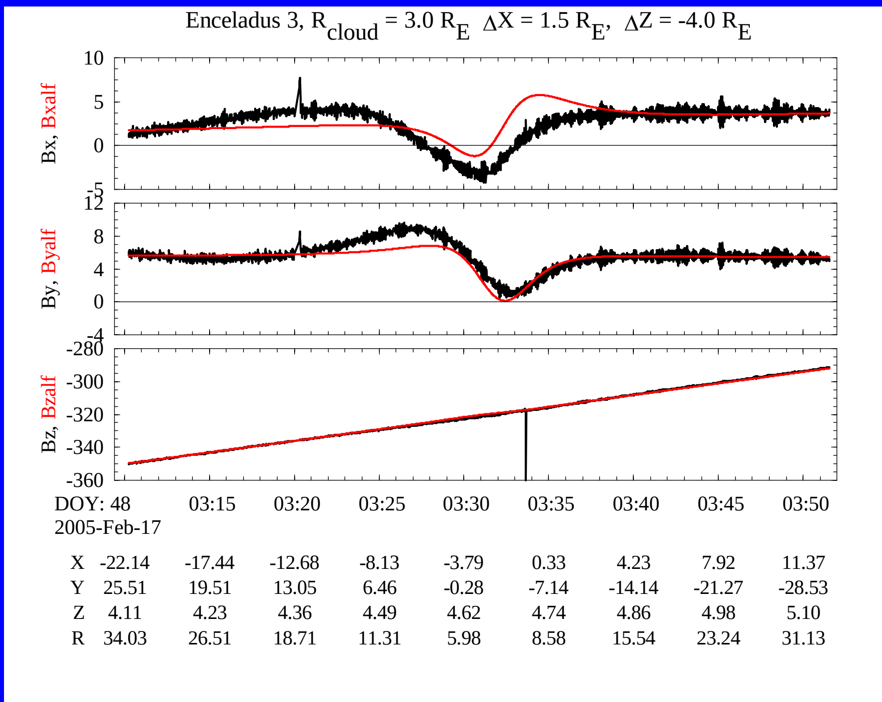


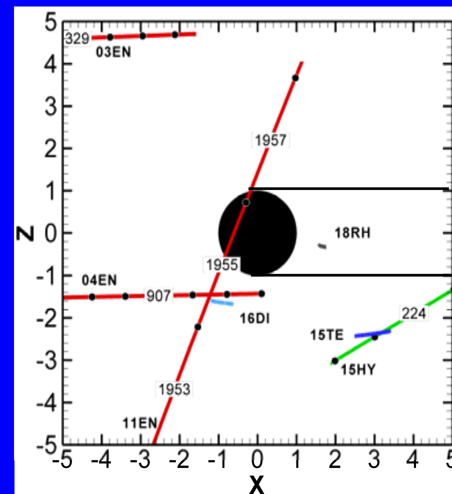

Enceladus Encounters (Residuals)
Day 48
Day 68
Day 195
10
8
6
4
2
0
-2
-4
-6
-8
-10
-10 -8 -6 -4 -2 0 2 4 6 8 10
Yenis
Xenis

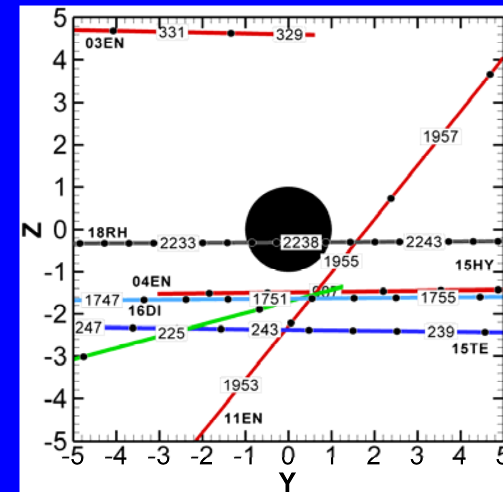
Modeling of Alfven wing current system

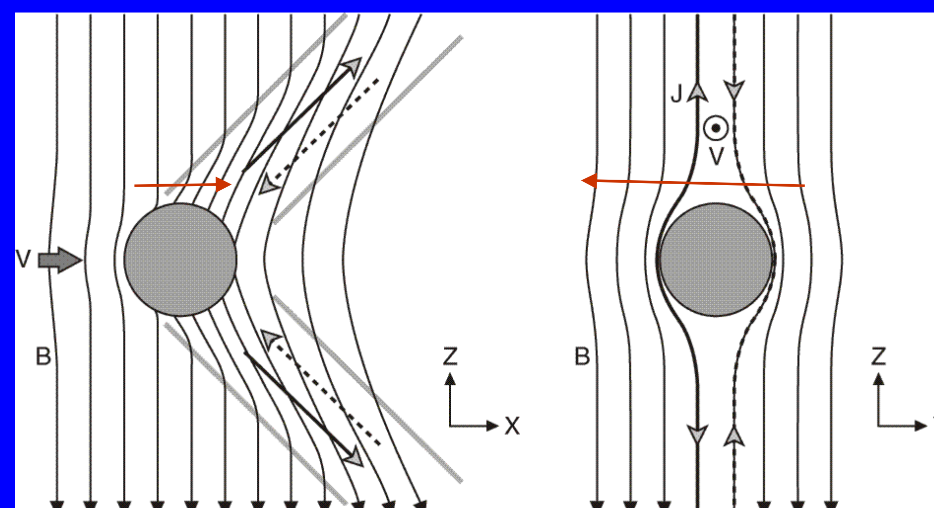


Shifted mass-loading region: E3



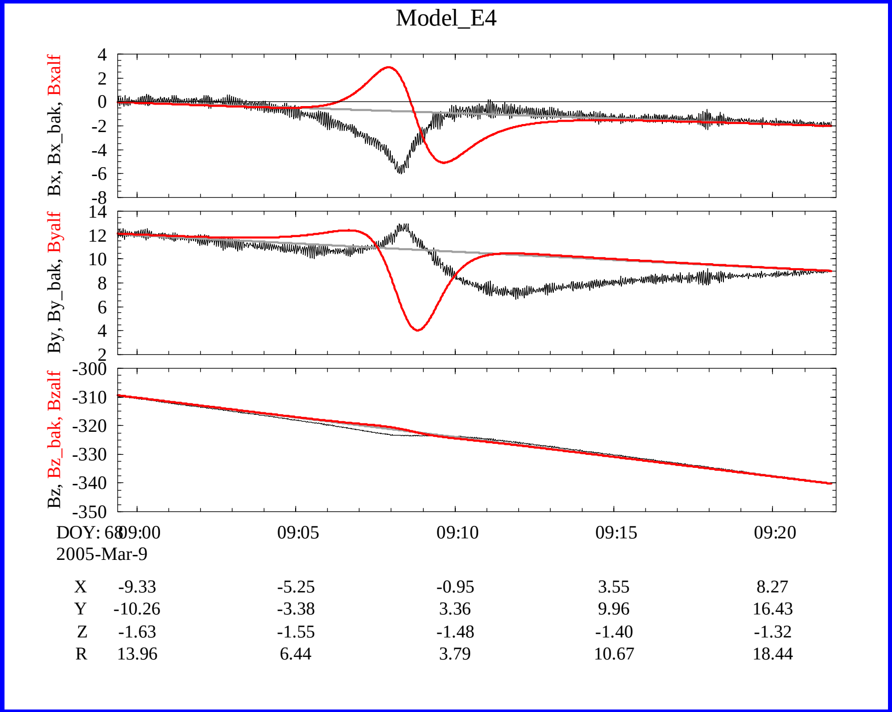


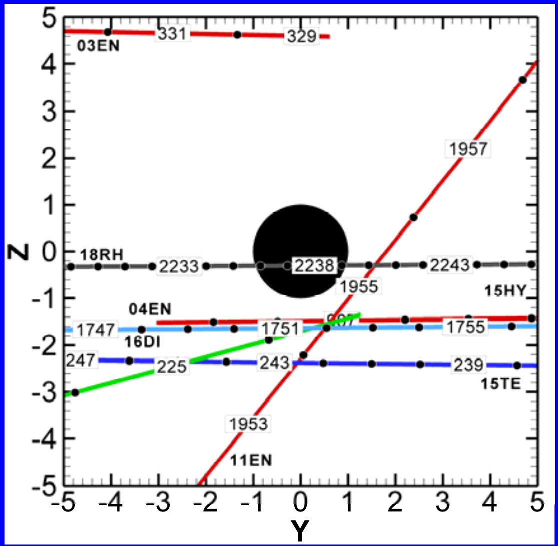


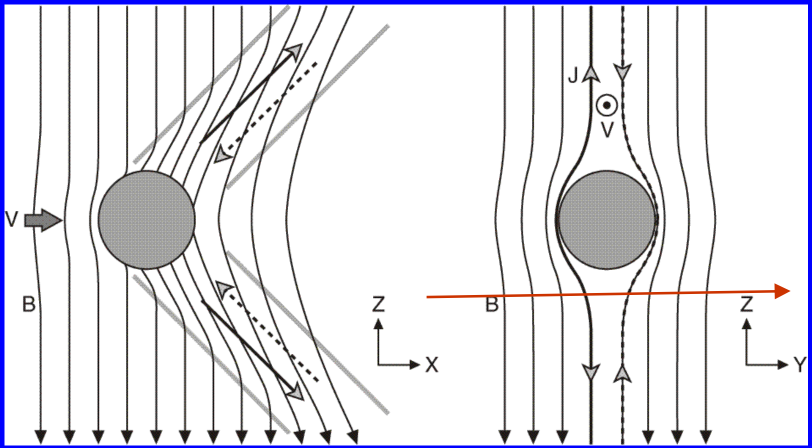


I = 10^5 Amp, Mass pick-up rate = ~ 2kg/s

Modeling of E4 as a cloud centered at Enceladus fails

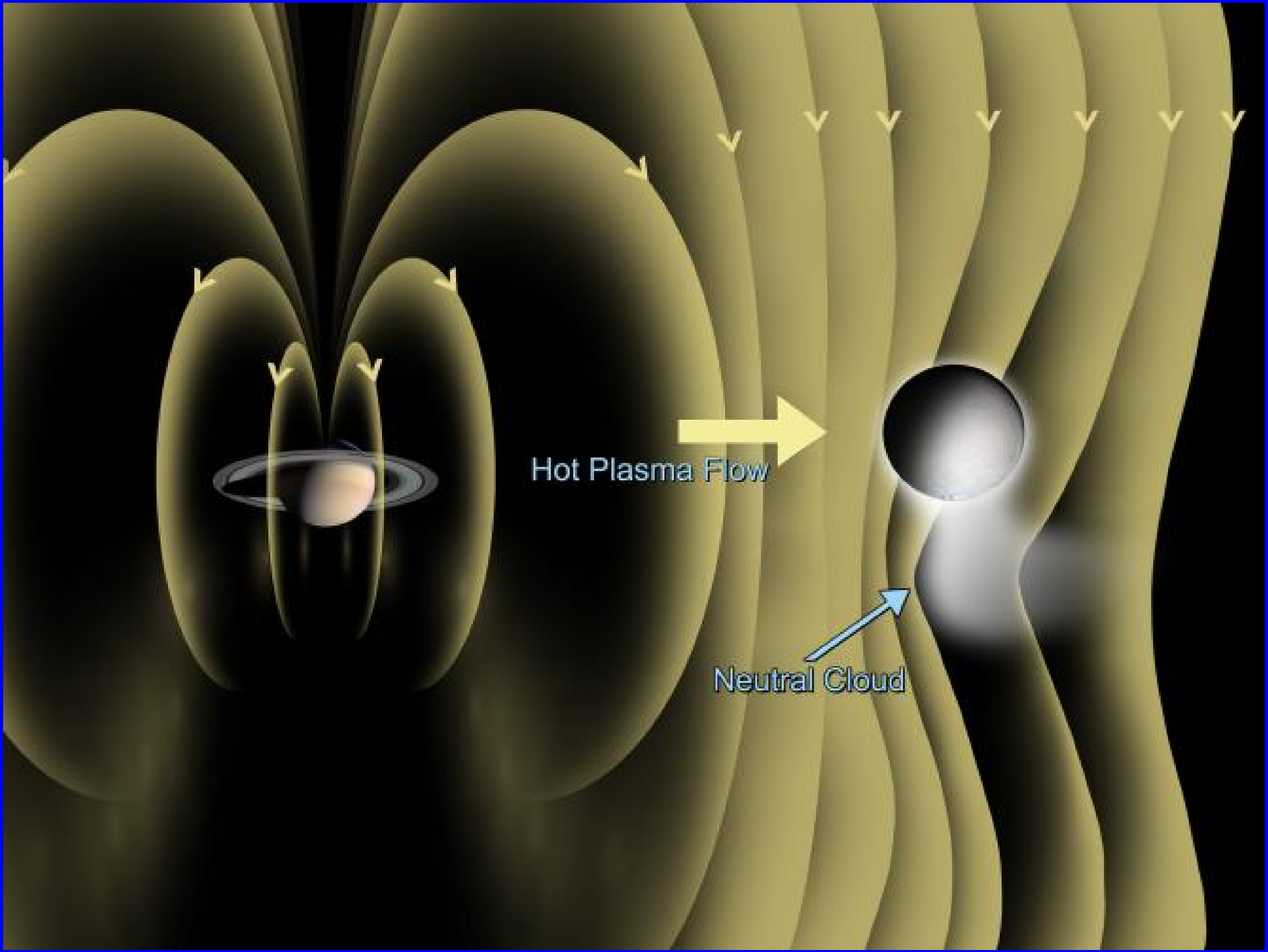




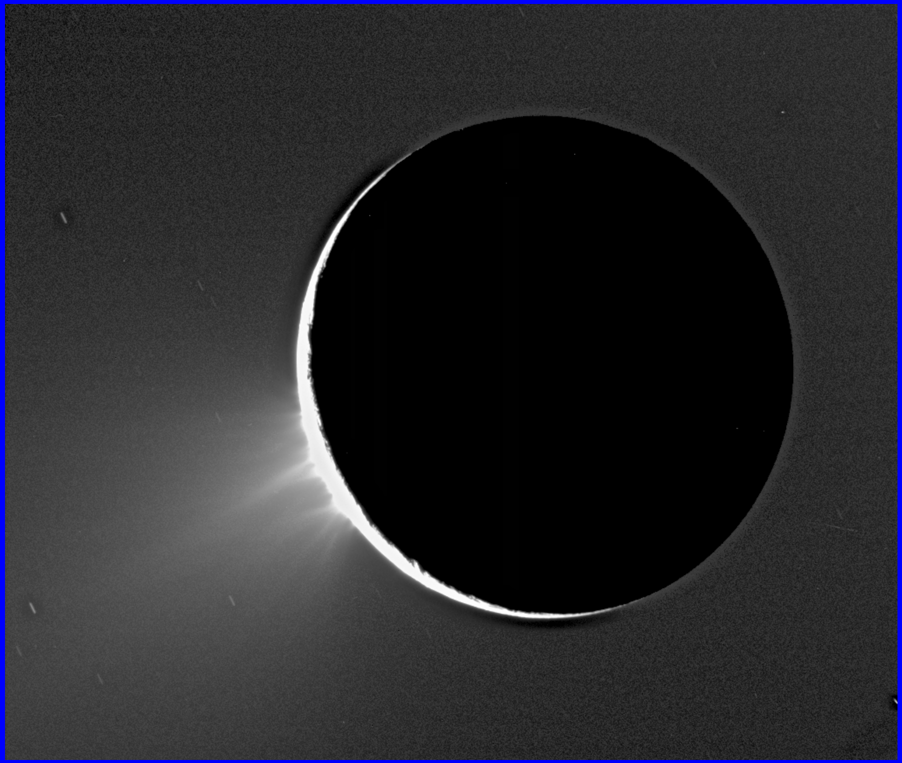


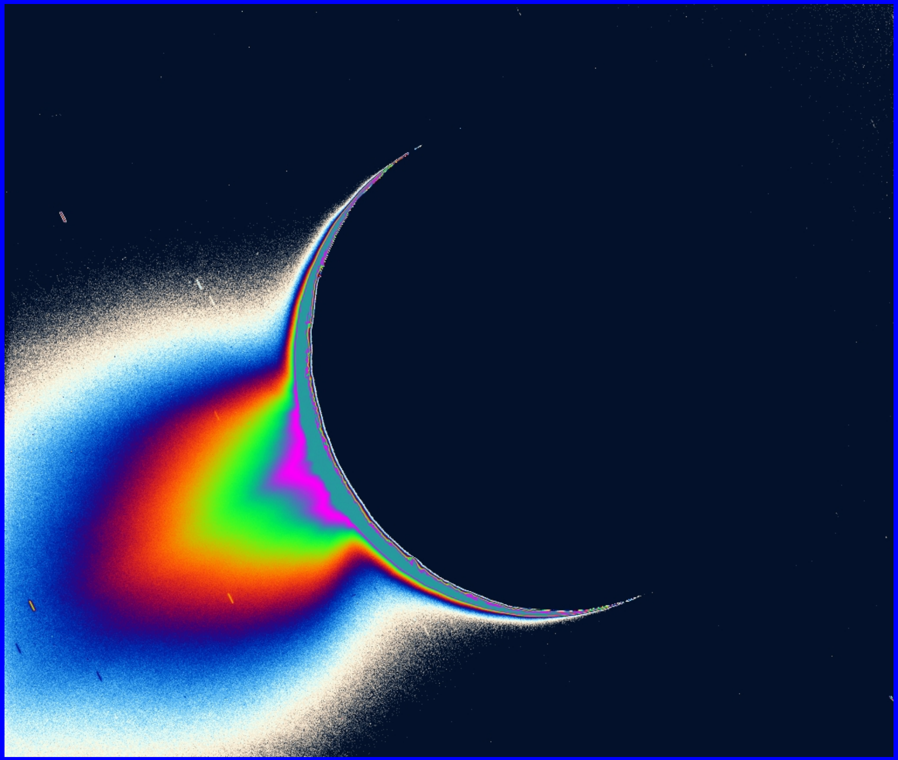
Notice that even though the spacecraft was below Enceladus nearest the closest approach (Z is negative), the observed Bx component was negative.

Enceladus's plume interacts with plasma

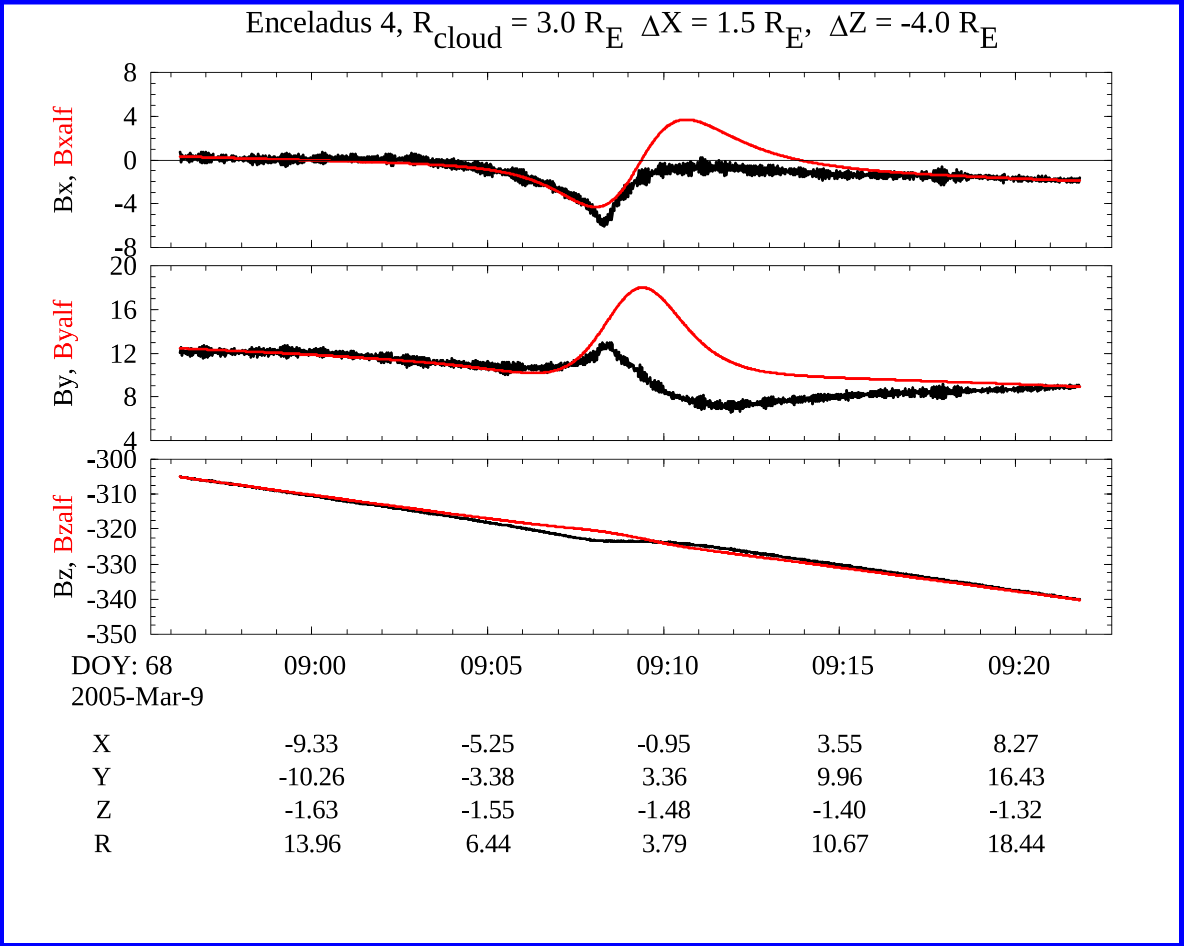


Fountains of Enceladus



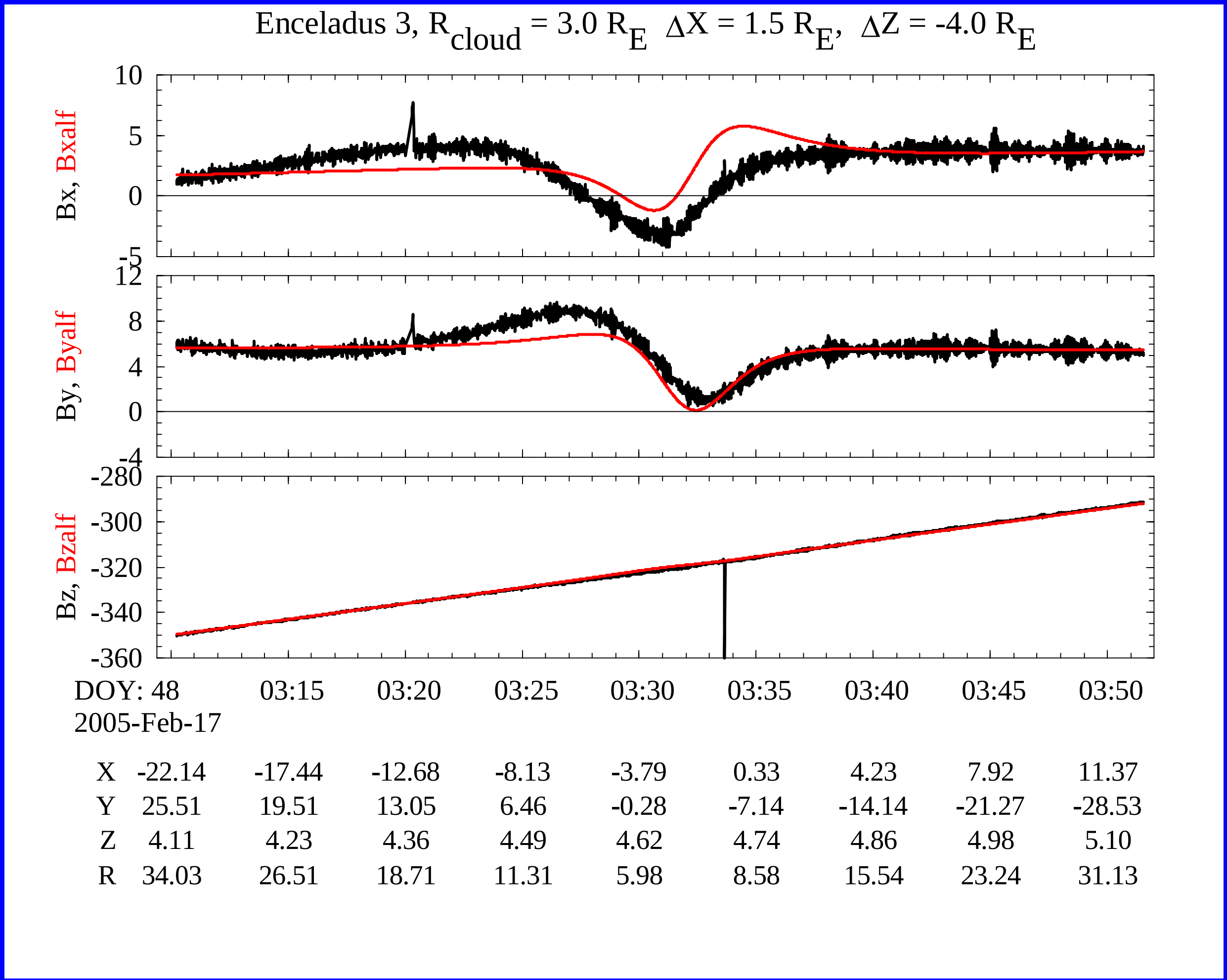


Shifted mass-loading region: E4



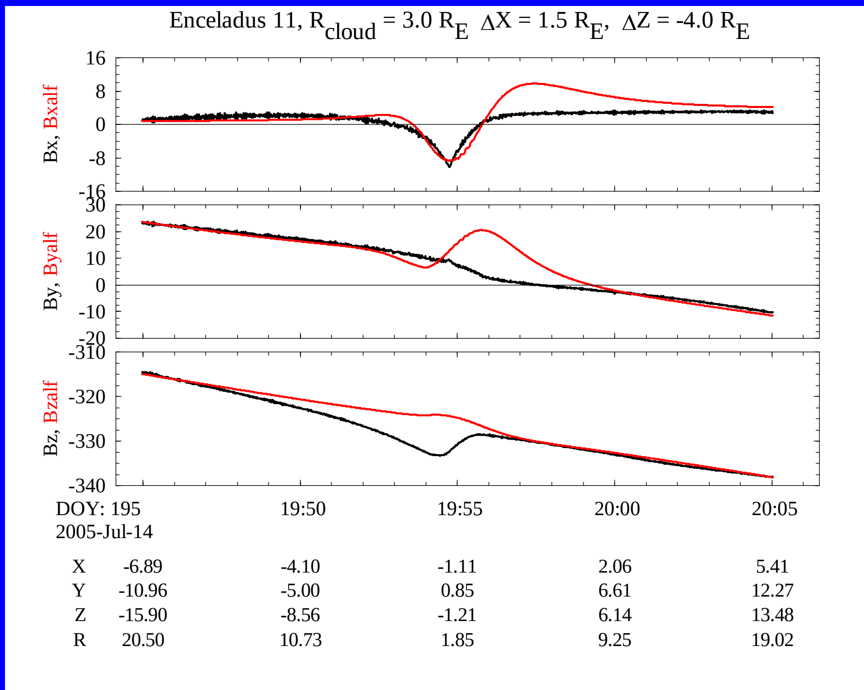
Imaging Observations have shown that a plume near the south pole spouts dust and gas into space. Thus the mass-loading region would be expected to be shifted below Enceladus. Here we model the E4 signature with a mass-loading region located 4 R_E below Enceladus.

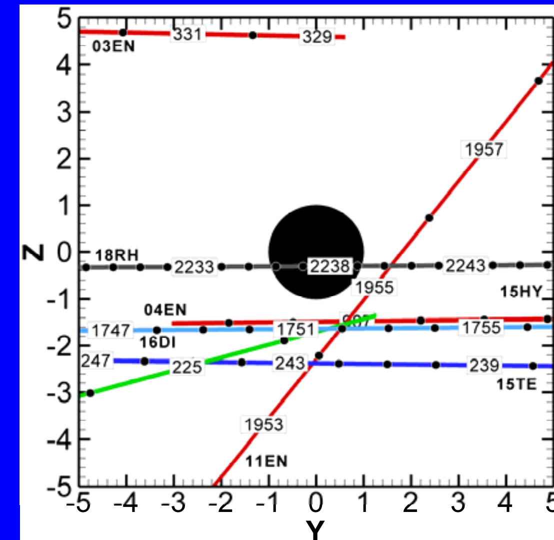
Shifted mass-loading region: E3

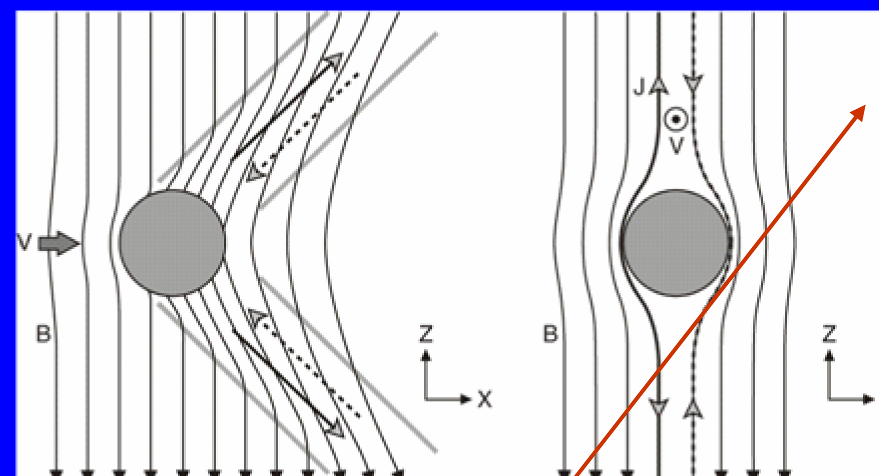


And here is a fit to the E3 data with the same southward shift of the mass-loading region. The reasonable nature of the fit suggests that our conjecture that the plume is the source of mass-loading is correct.

Shifted mass-loading region: E11







And here are the fits to the E11 data. The phasing of the signature is correct but the poor fit suggests that we need to improve upon the specifics of the mass-loading region.

Rate of Mass loading

$$J_y = q\dot{n}\rho_L = \dot{n}mv_\perp / B$$

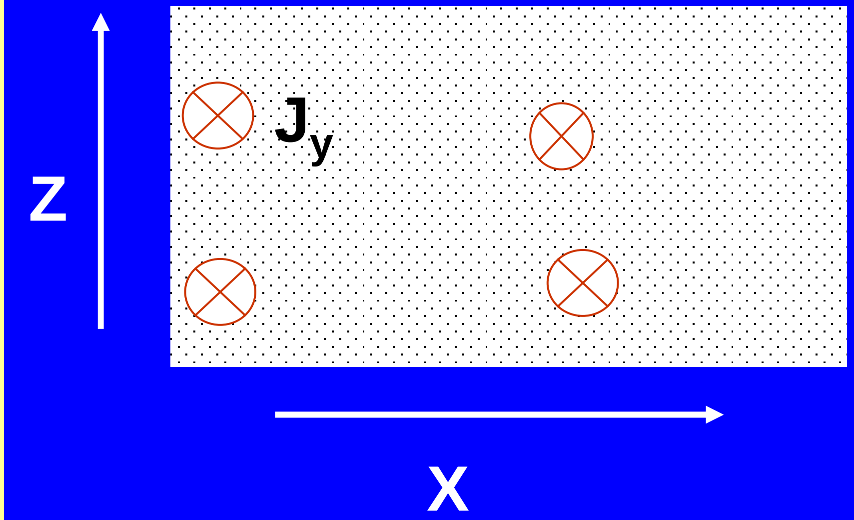
$$I_y = \int\int J_y dX\, dZ = \frac{\dot{M}v_\perp}{Bl_y}$$

$$\text{where } \dot{M} = \iiint \dot{n}m\, dX\, dY\, dZ$$

$$\text{or } \dot{M} = \frac{Bl_y I_y}{v_\perp} =$$

$$\frac{320\text{x}10^{-9}\,\text{x}1500\text{x}10^{3}\,\text{x}1.0\text{x}10^{5}}{26x10^{3}}$$

$$\dot{M} = 1.8\text{kg/s}$$

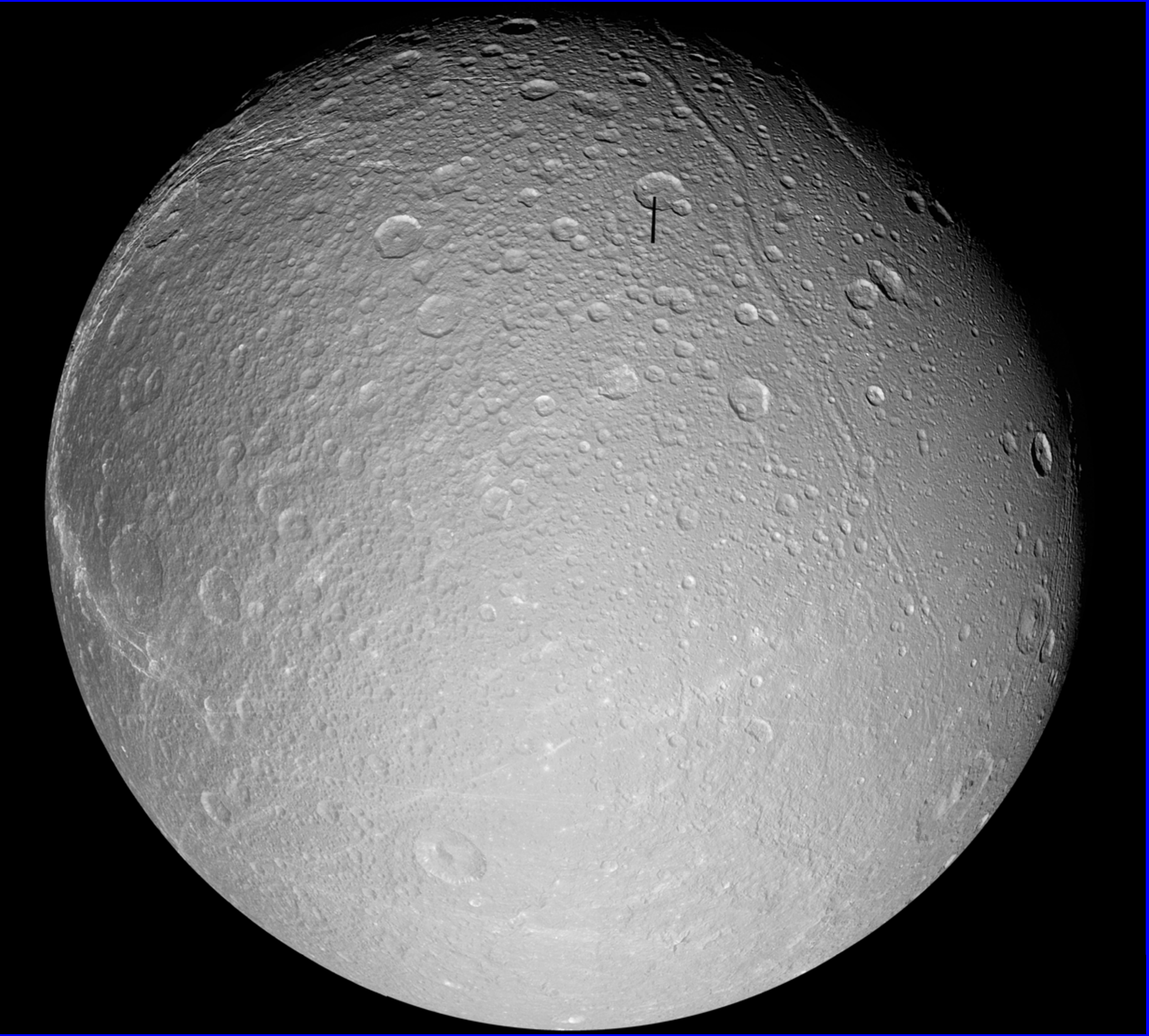


The rate of mass-loading can be related to the current passing through the mass-loading region. Surprisingly, the total amount of mass loading implied is quite low.

After Chris Goertz

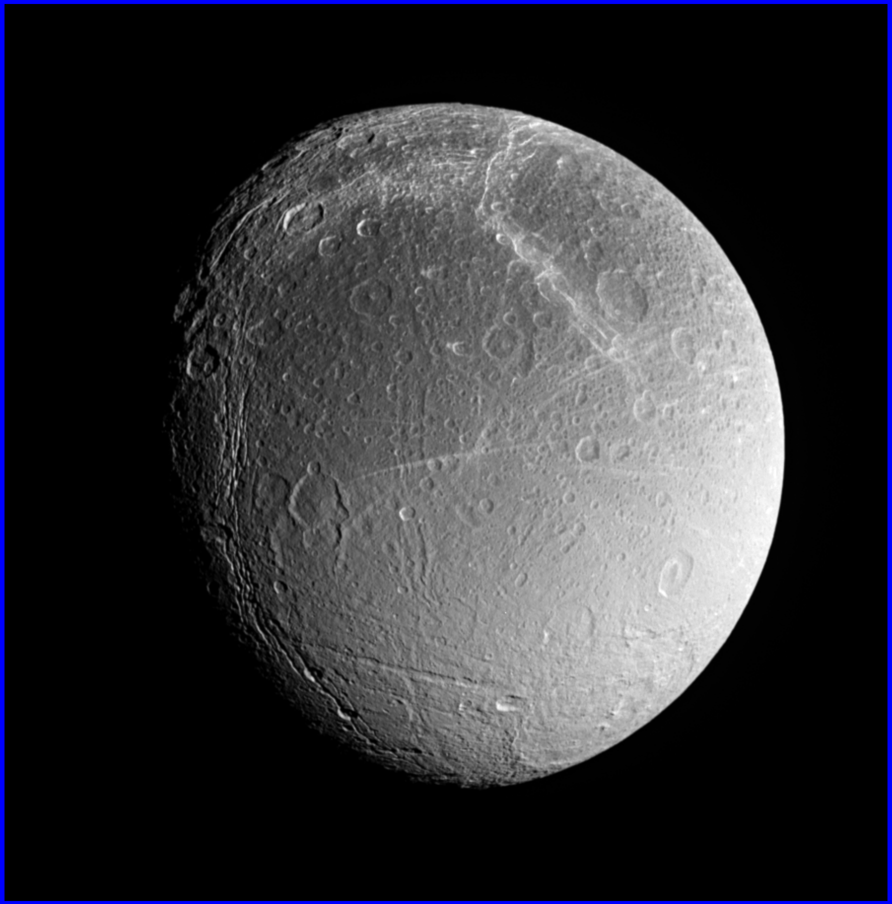
Dione

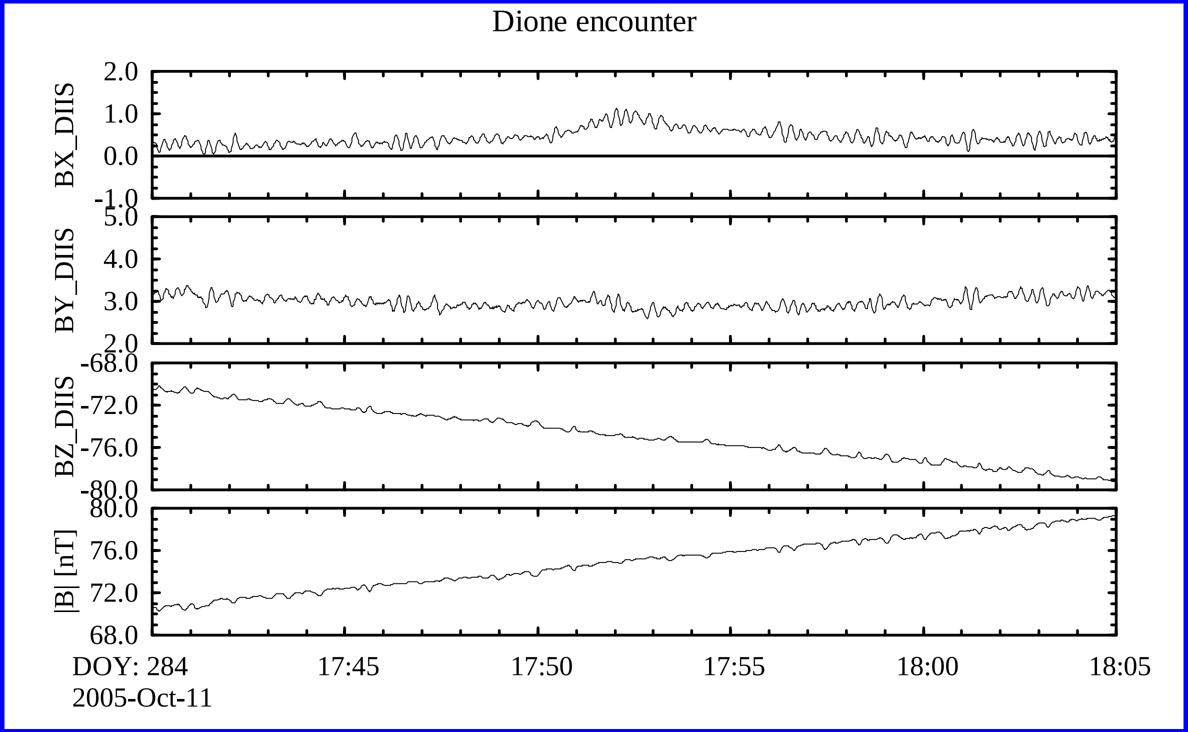
- Discovered by Giovanni Cassini on March 21, 1684.
- Mean radius of 560 km and surprisingly high density of 1.5 g/cm^3.
- Probably differentiated with rocky core making 1/3rd of the moon's mass.
- Currently in a 2:1 orbital resonance with Enceladus.
- Terrain types consist of heavily cratered terrain, moderately cratered plains, lightly cratered plains, and wispy material.
- Several regions show evidence of past tectonic activity.
- The wispy material may have arisen from eruptions along cracks and then deposited on the surface.



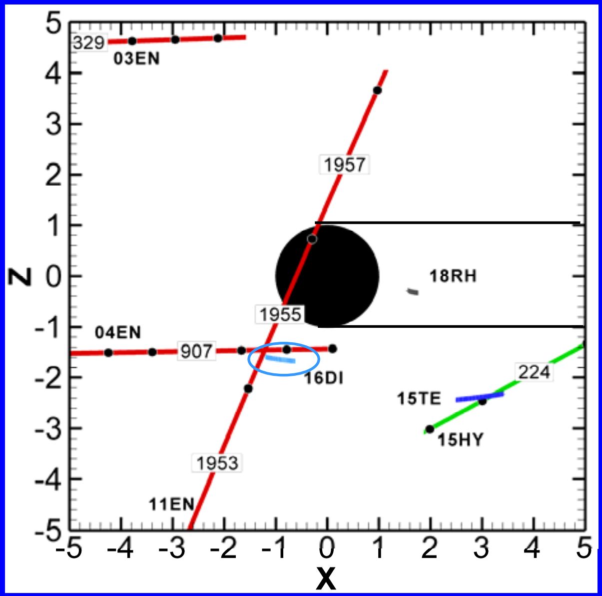
Dione

Dione Fractures and wispy terrain

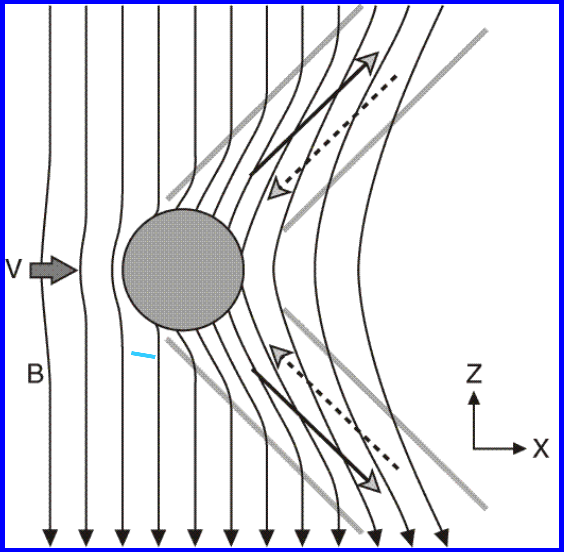




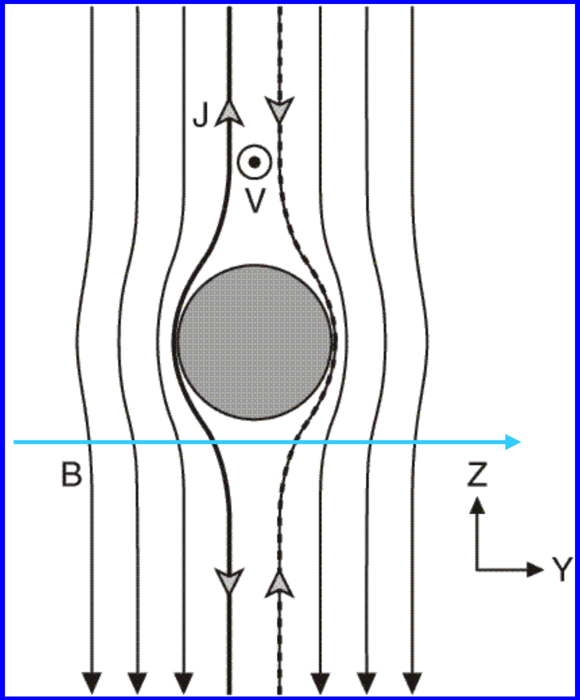
Dione

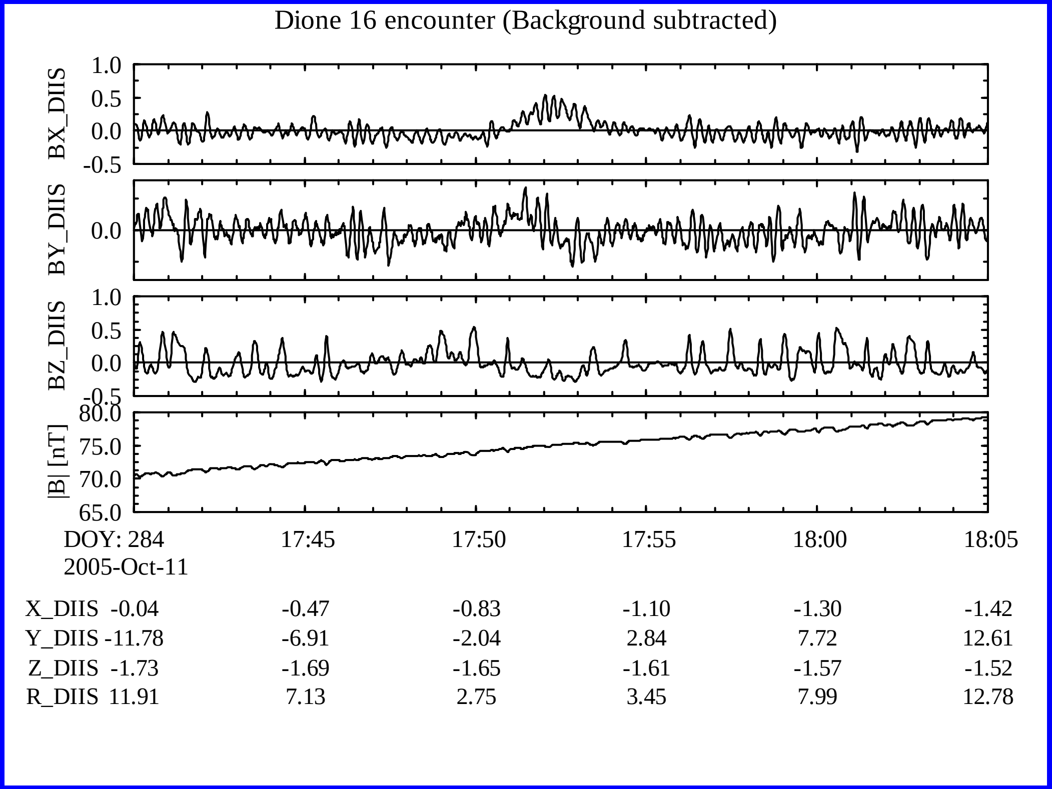


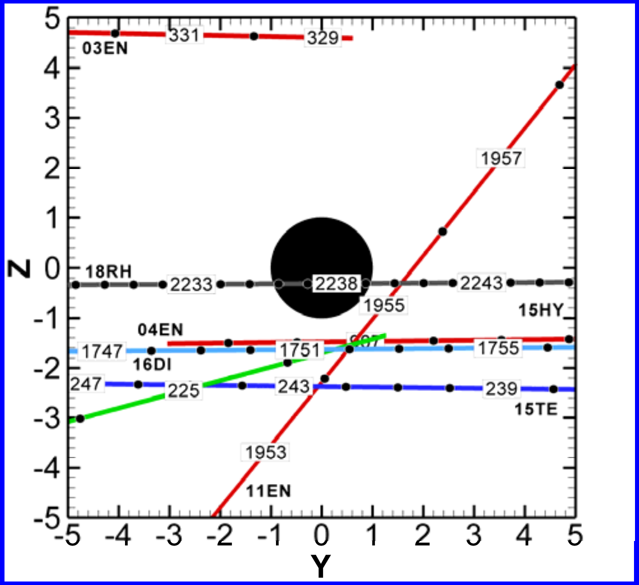
- A close upstream flyby.
- CA distance 1.89 R_{DI}
- A mass-loading type interaction.
- Field is draped around the mass loading region.
- X, Y and Z? signatures are consistent with a mass-loading interaction.
- Mirror modes have counterparts in plasma wave data.



Dione perturbation consistent with mass-loading







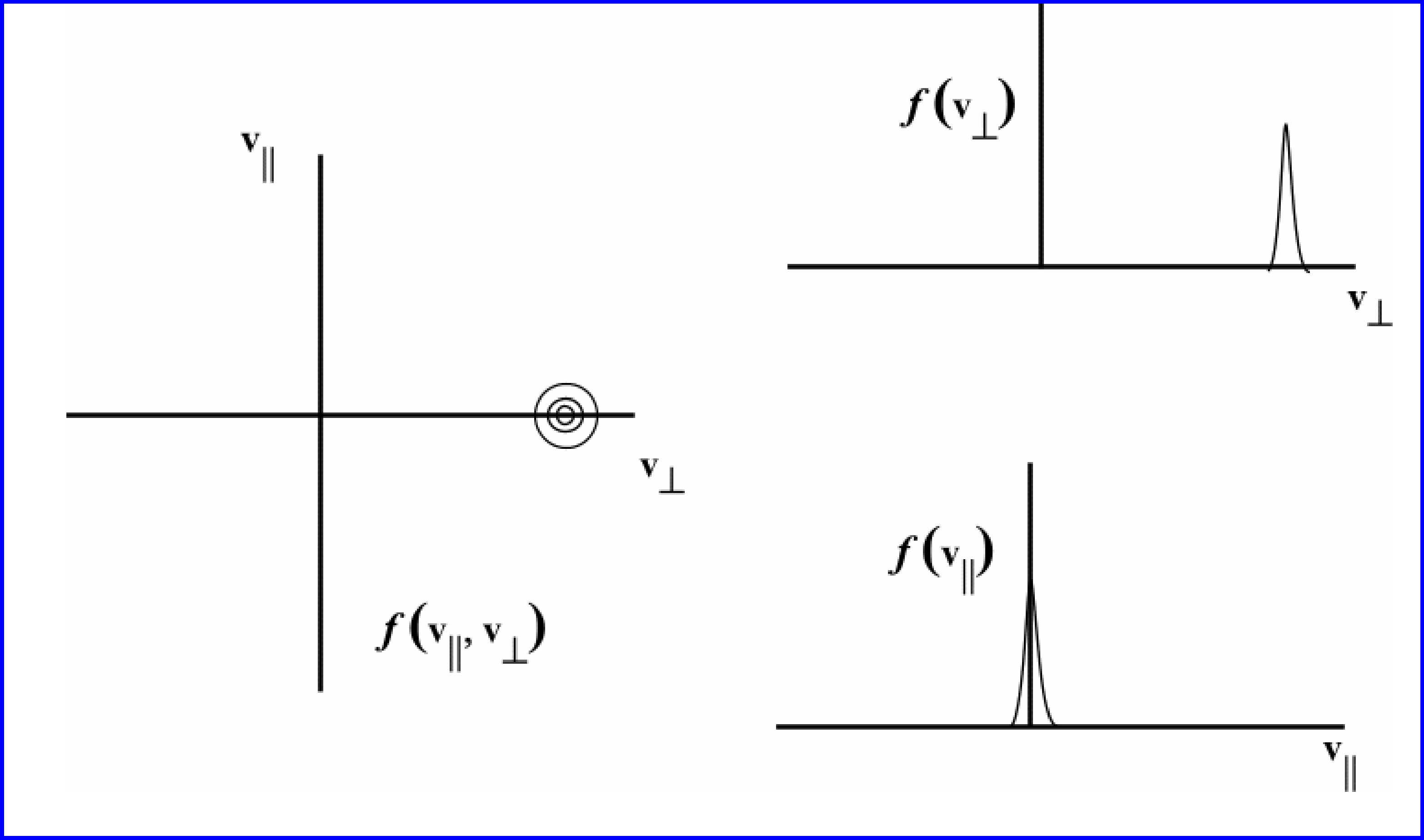
- Cassini trajectory from left to right.
- Both x and y perturbations consistent with mass-loading.

Mass absorbing super-magnetosonic interaction

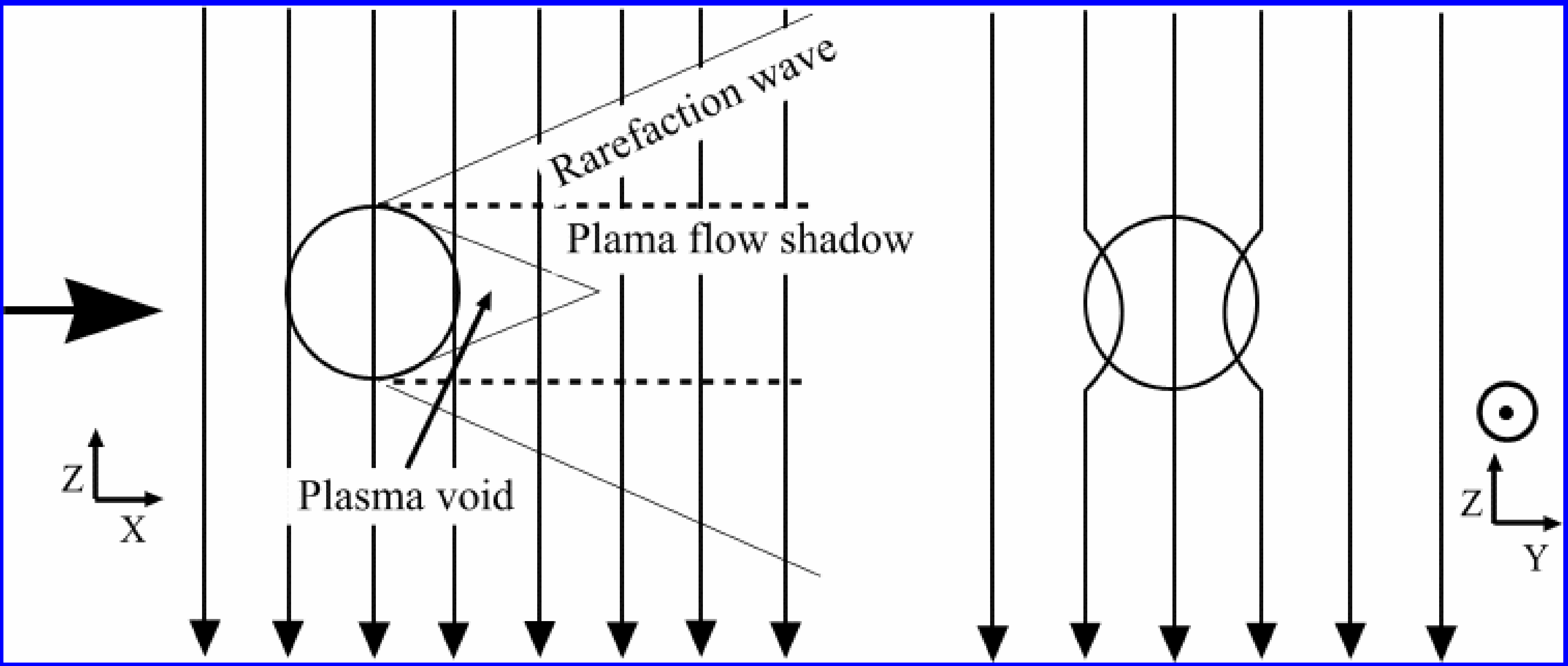
Phase space density in a supersonic plasma

|| and $\perp$ refer to directions w.r.t. field

Assume $\mathbf{v}_{\mathbf{flow}} \perp \mathbf{B}$



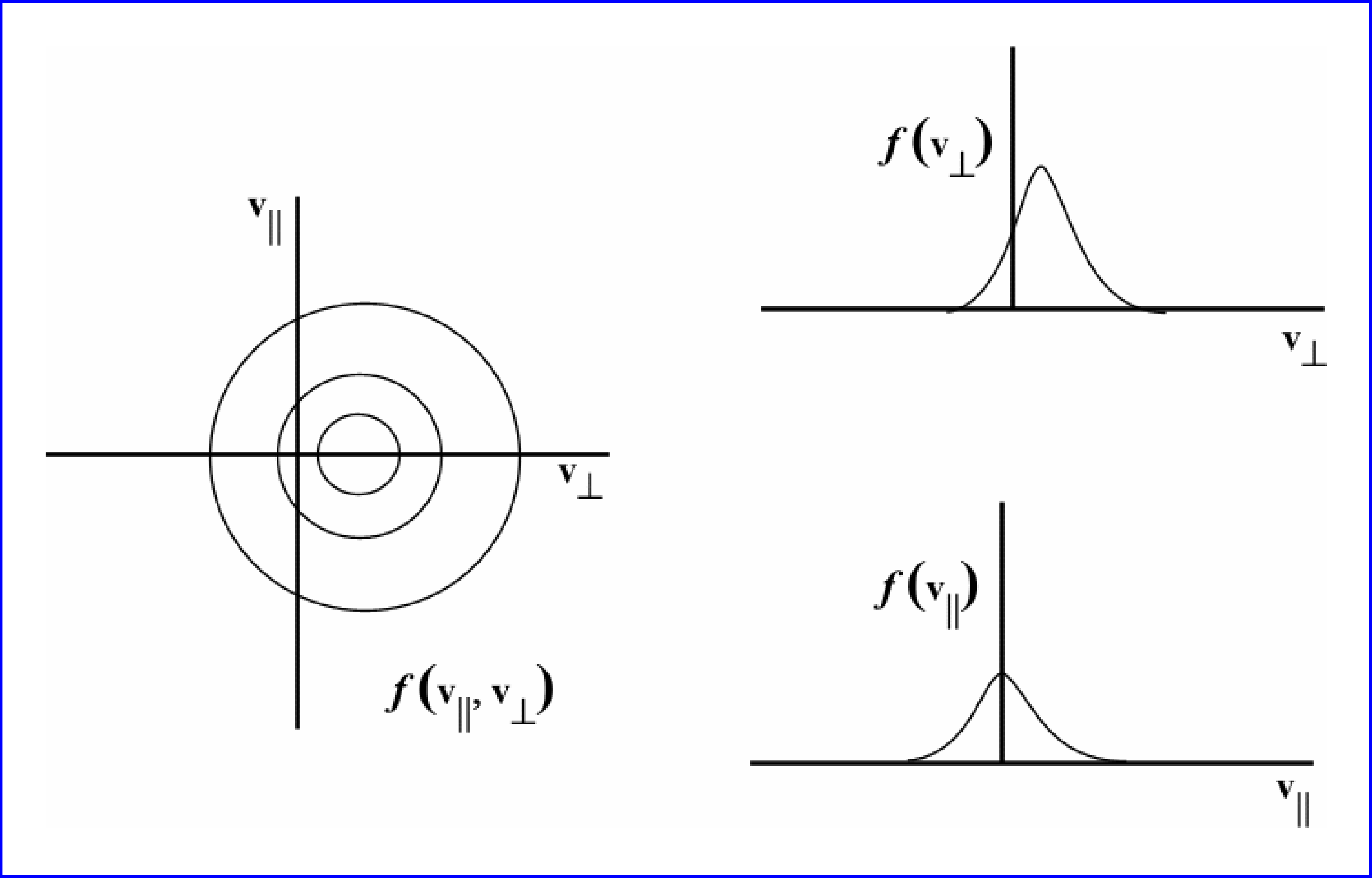
Mass absorbing super-magnetosonic interaction



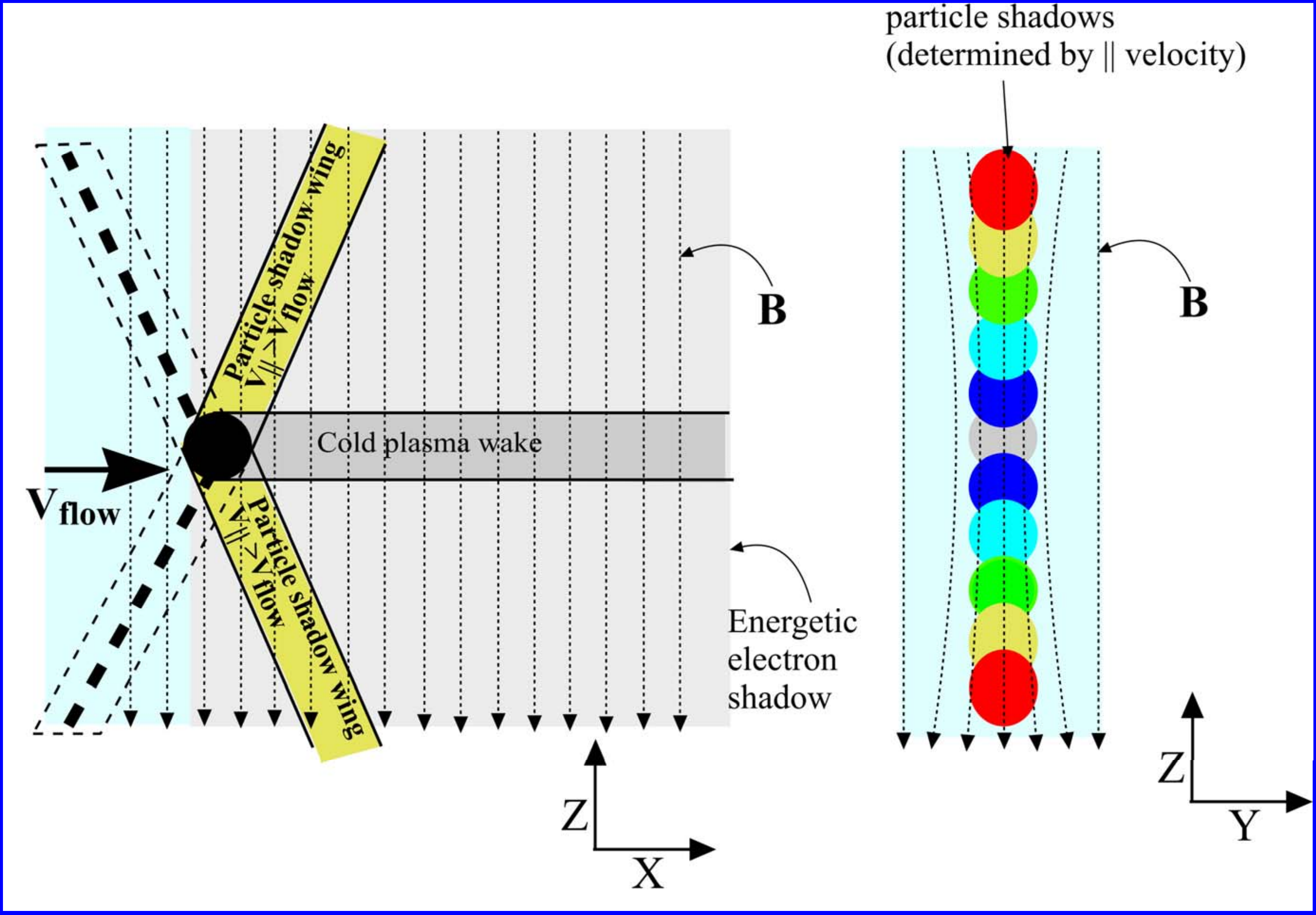
Phase space density in a subsonic plasma

|| and $\perp$ refer to directions w.r.t. field

Assume $\mathbf{v}_{\mathbf{flow}} \perp \mathbf{B}$

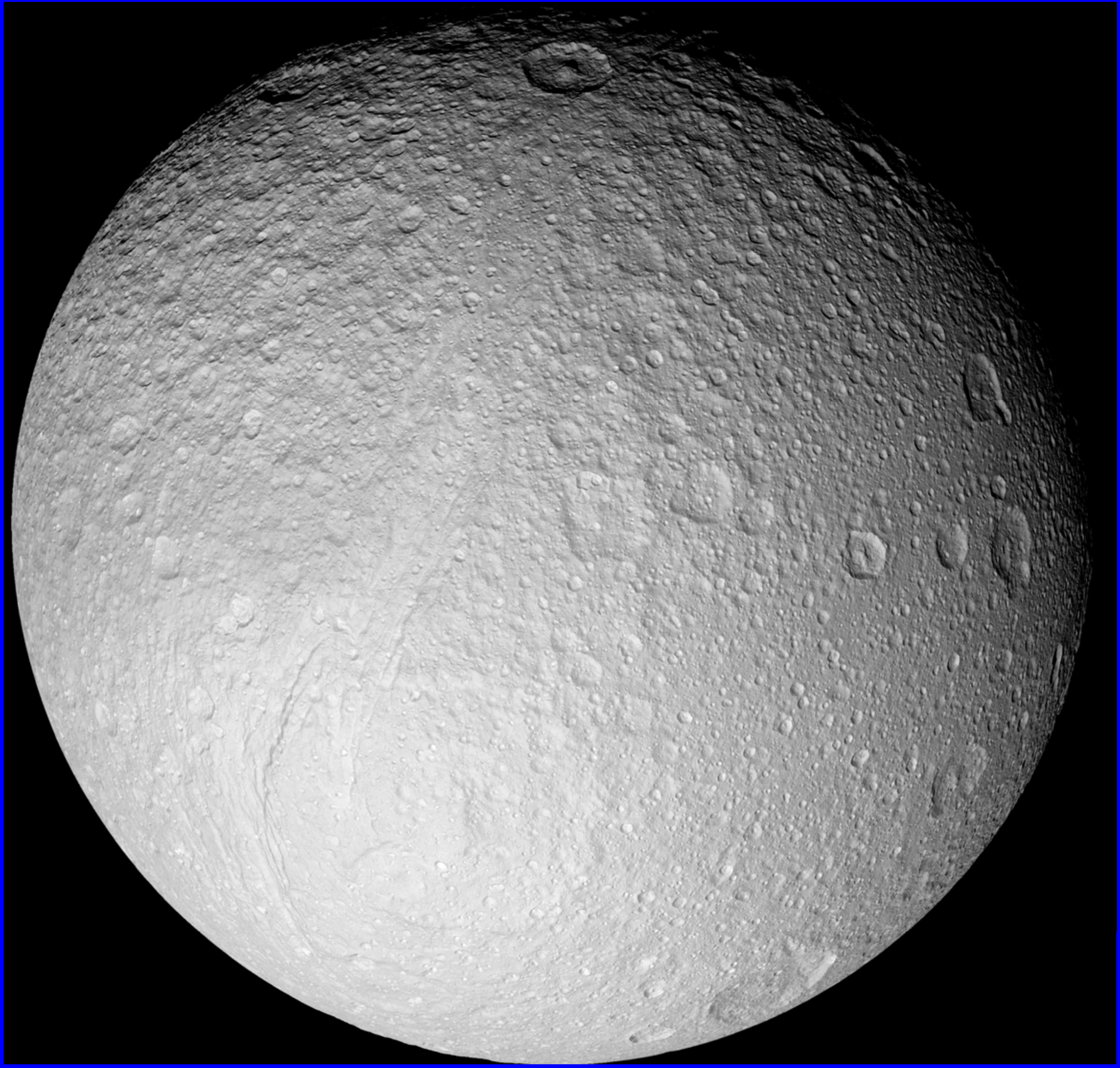


Mass absorbing sub-magnetosonic interaction



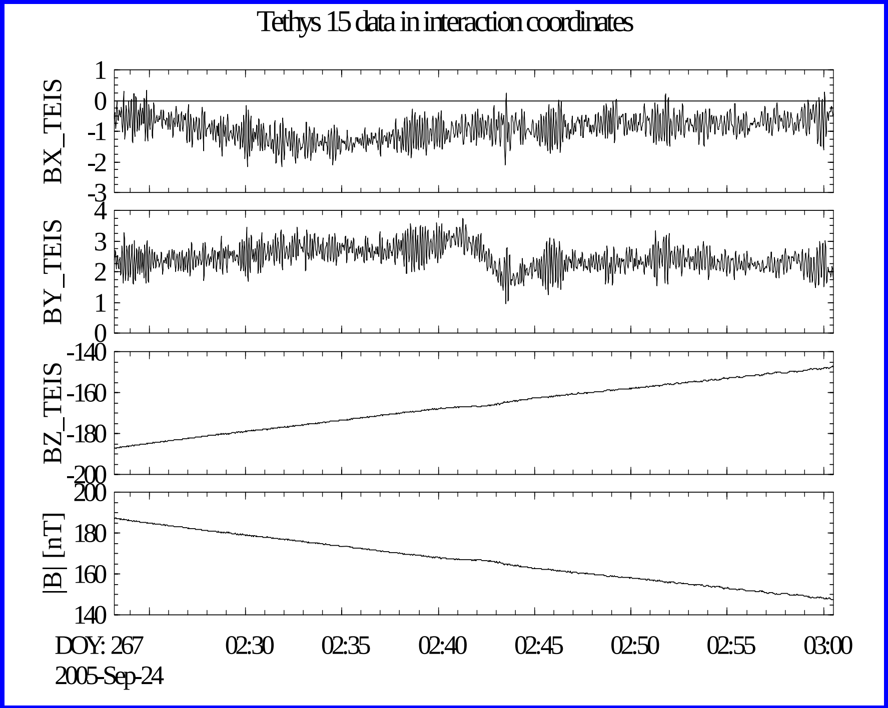
Tethys

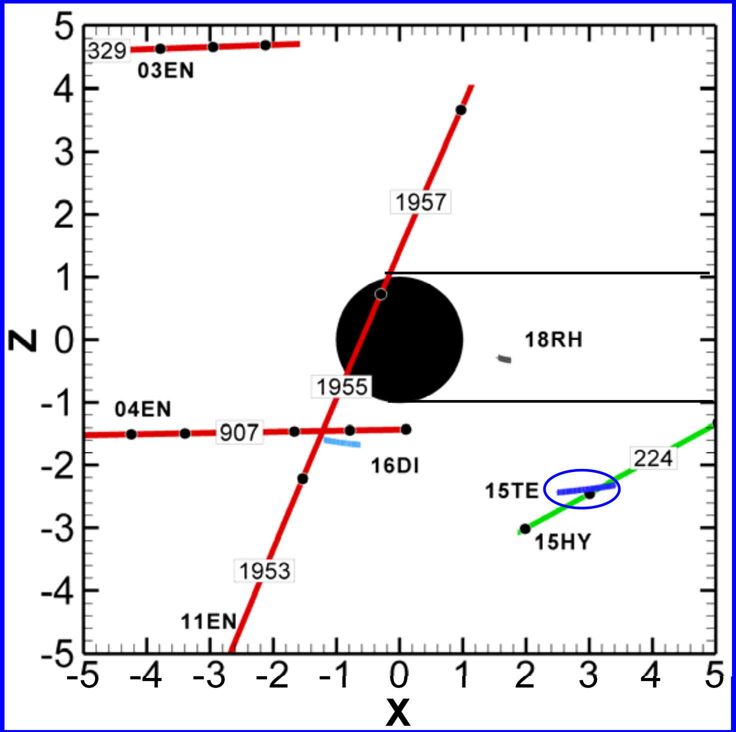
- Discovered by Giovanni Cassini on March 21, 1684.
- Mean radius of 530 km and density of 1.21 g/cm^3.
- Internal structure unknown but mostly pure ice.
- Currently in a 4:2 orbital resonance with Mimas.
- Terrain mostly heavily cratered. Surface age several billion years.
- Two minor moons Telesto and Calypso inhabit the same orbit and are located within Tethys' Lagrangian points L4 and L5, 60 degrees ahead and behind Tethys in its orbit respectively.

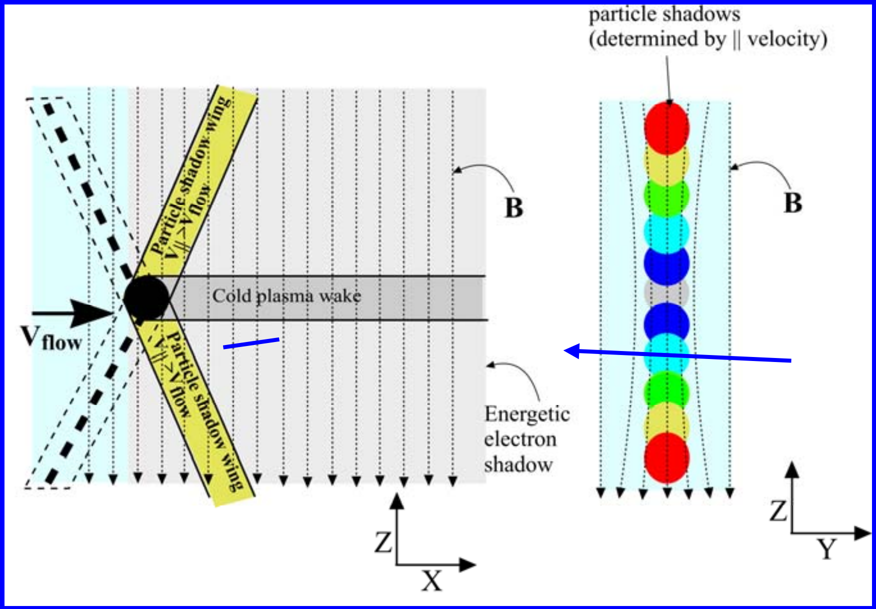


Tethys

Tethys

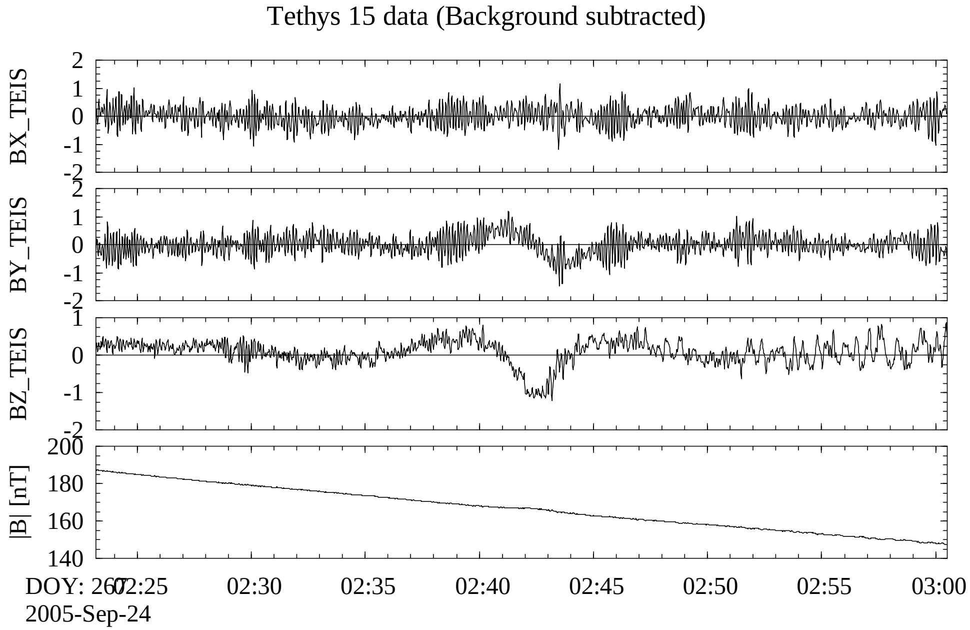




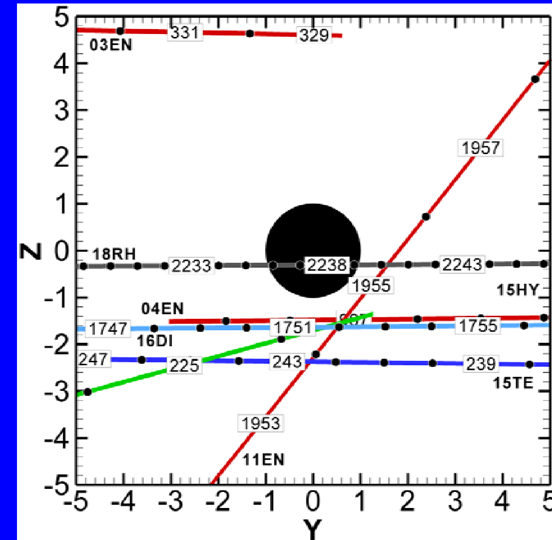


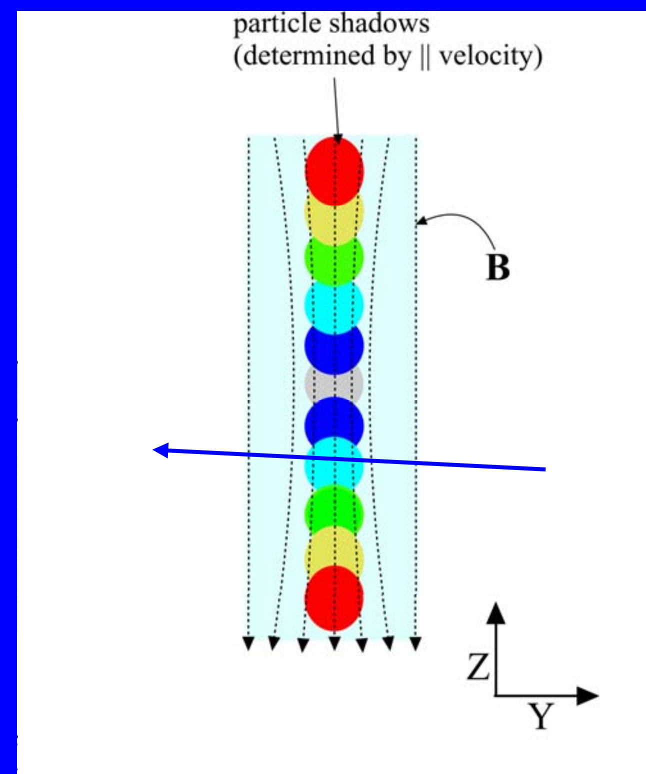
- No internal field.
- A close downstream flyby.
- CA distance 3.83 R_{Te}
- Shows an inert moon type “empty” wake which extends to high latitudes where some plasma has been absorbed upstream.
- Both Y and Z signatures are consistent with an absorbing moon model.

Tethys



X_TEIS	0.61	1.45	2.16	2.76	3.23	3.59	3.83	3.95
Y_TEIS	17.88	12.80	7.71	2.61	-2.51	-7.63	-12.77	-17.91
Z_TEIS	-2.58	-2.52	-2.47	-2.41	-2.35	-2.28	-2.22	-2.15
R_TEIS	18.07	13.13	8.38	4.49	4.72	8.74	13.51	18.47

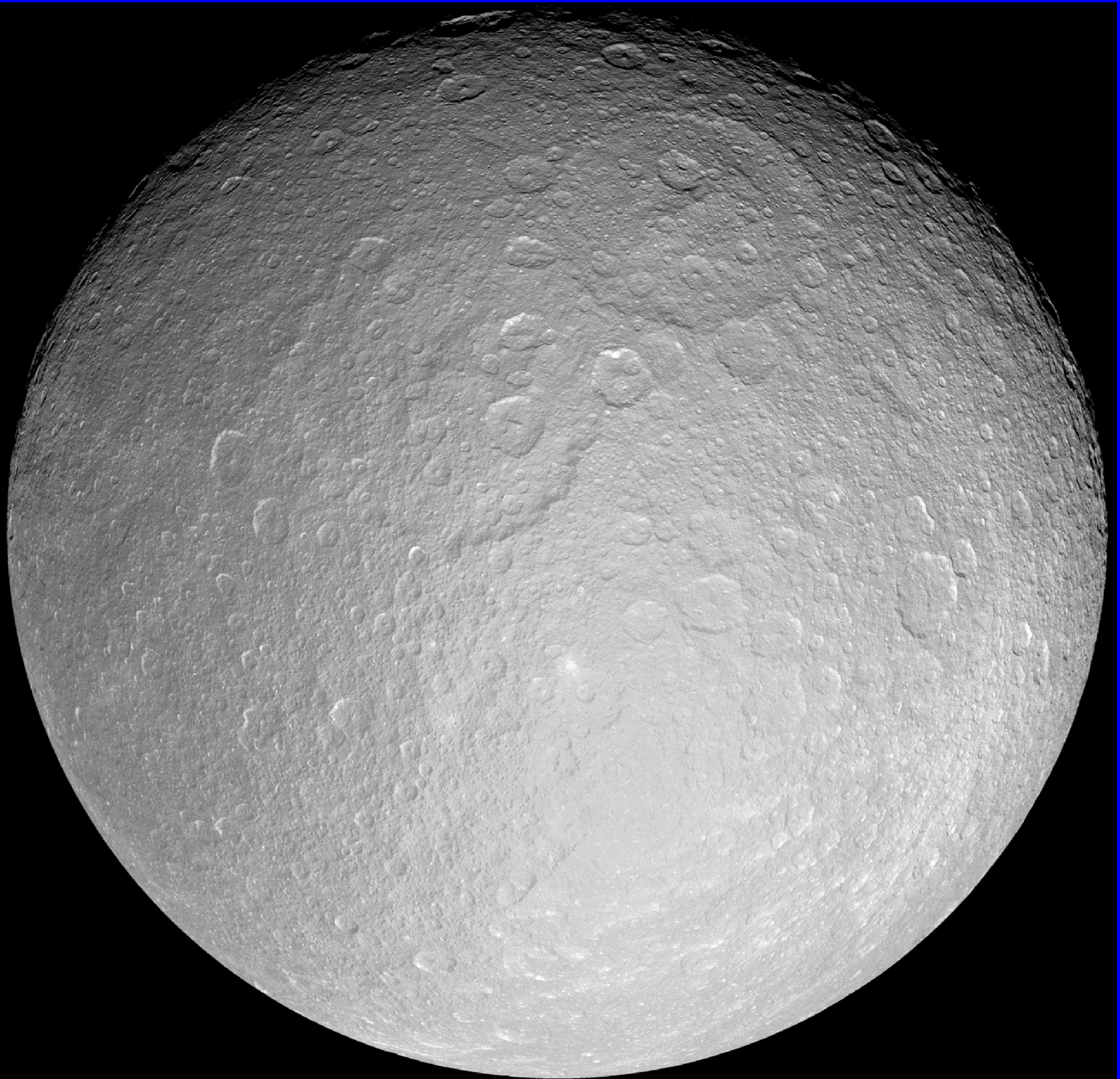




- Cassini trajectory from right to left.
- Both Y and Z signatures are consistent with an absorbing moon model.
- Field enhances in the wake to maintain pressure balance.
- IC waves are present in the wake.

Rhea

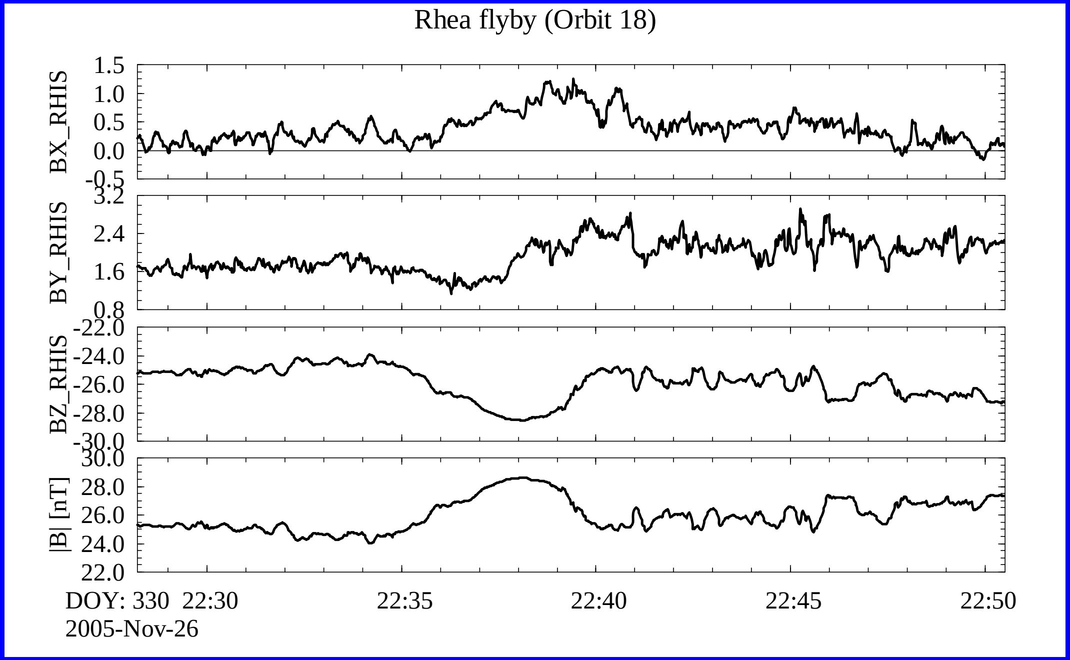
- Discovered by Giovanni Cassini on December 23, 1672.
- Mean radius of 764 km and density of 1.24 g/cm^3.
- Internal structure unknown but mostly pure ice.
- Currently in a 5:3 **near** orbital resonance with Dione.
- Terrain mostly heavily cratered. Like Dione shows leading/trailing hemisphere differences in cratering.
- A major resurfacing event occurred during its formation.
- Also shows wispy features like Dione but not associated with cracks.

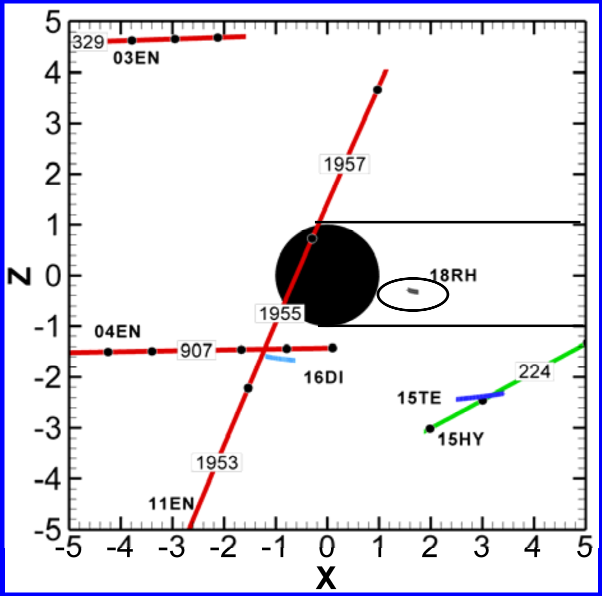


Rhea

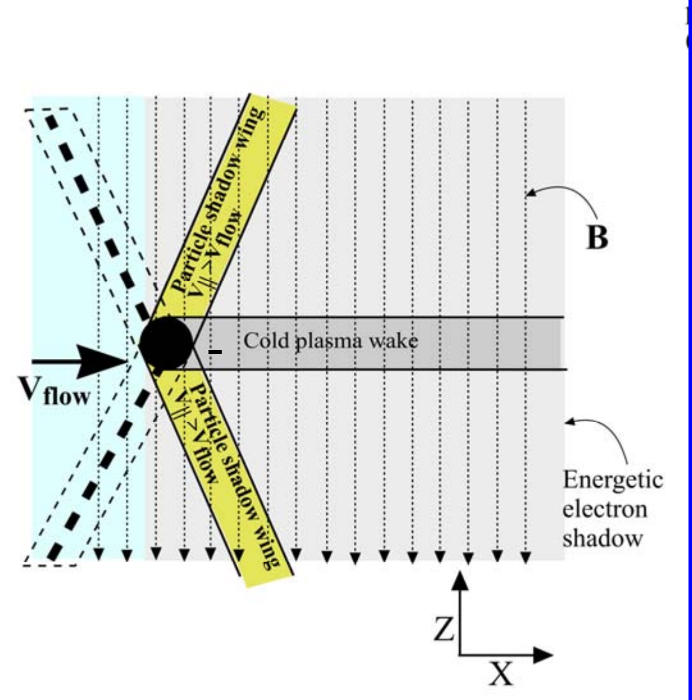
Rhea wispy features on the trailing side

Rhea

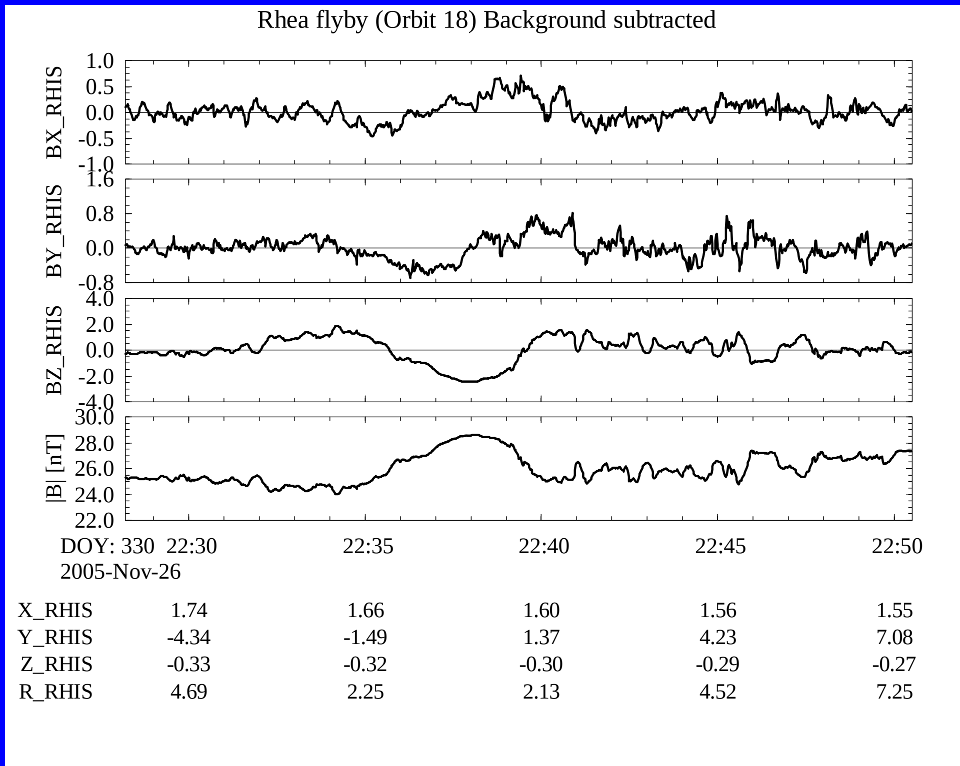


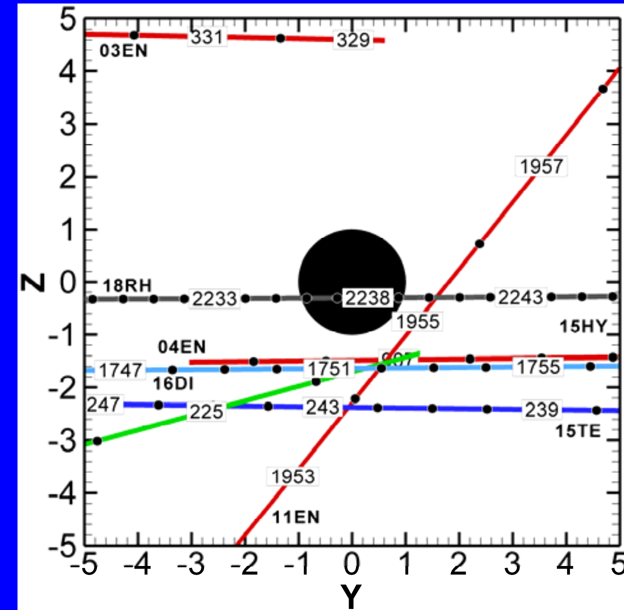


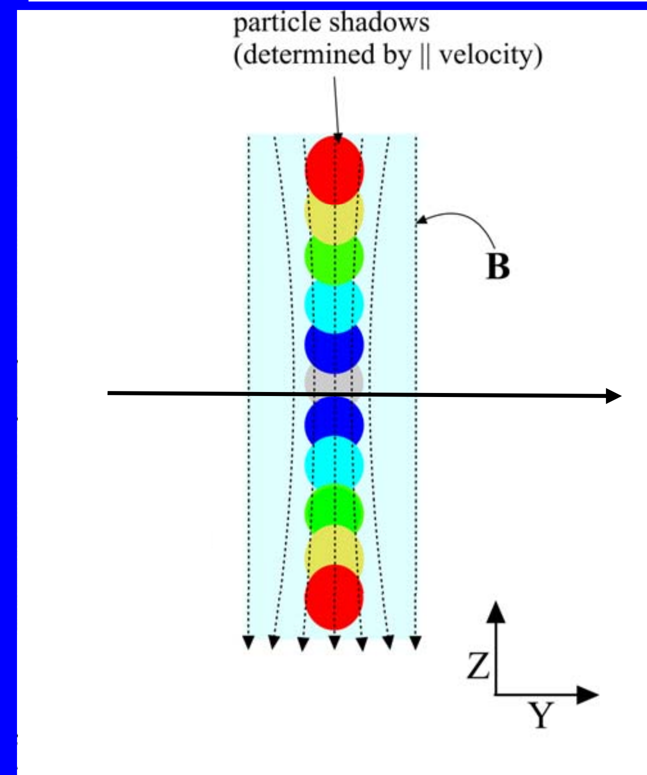
- No internal field.
- A close downstream flyby at 1.65 R_{RH}.
- Shows a classical Lunar type wake where plasma has been absorbed upstream.
- Field enhances in the wake to maintain pressure balance.



Rhea



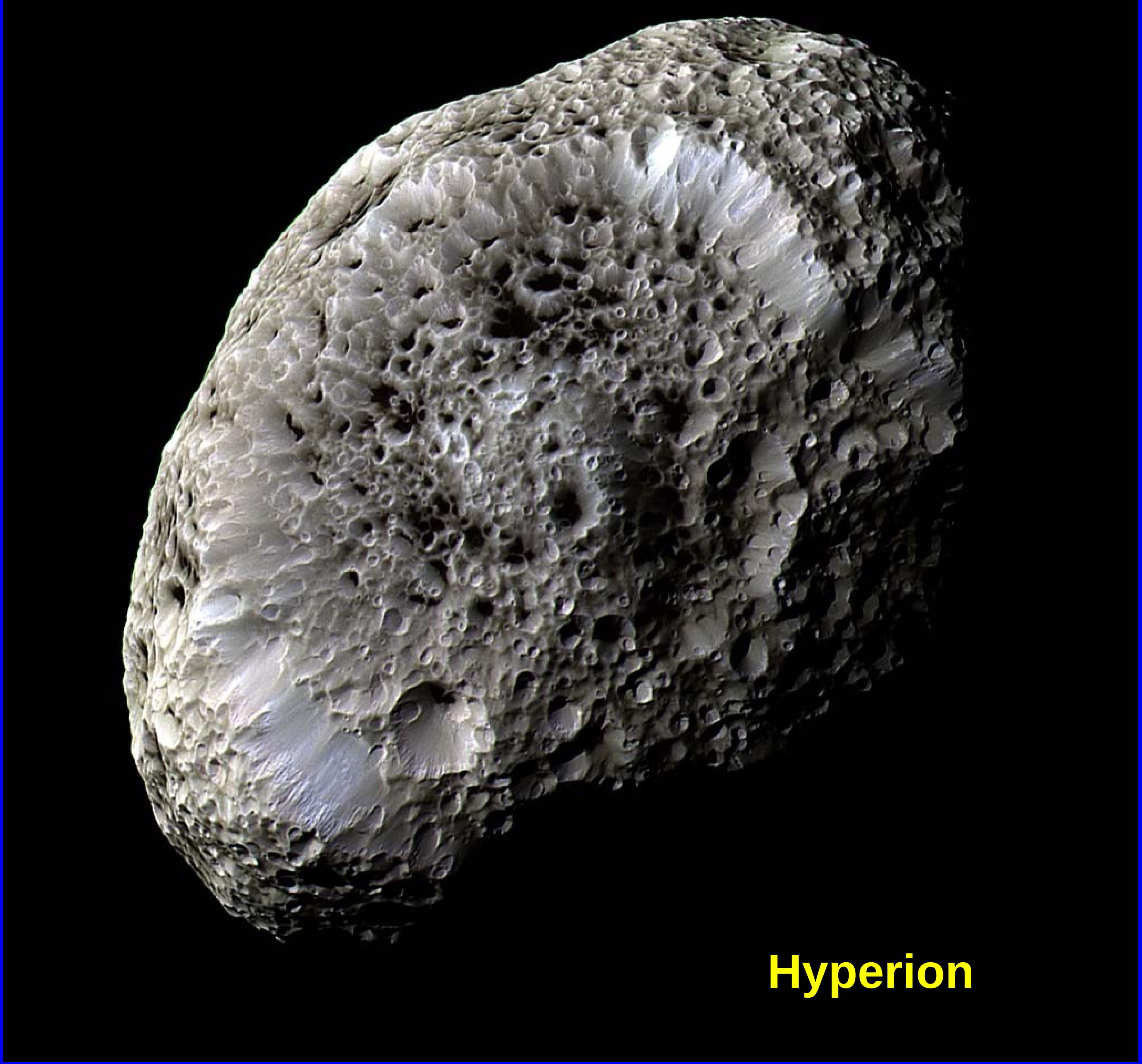




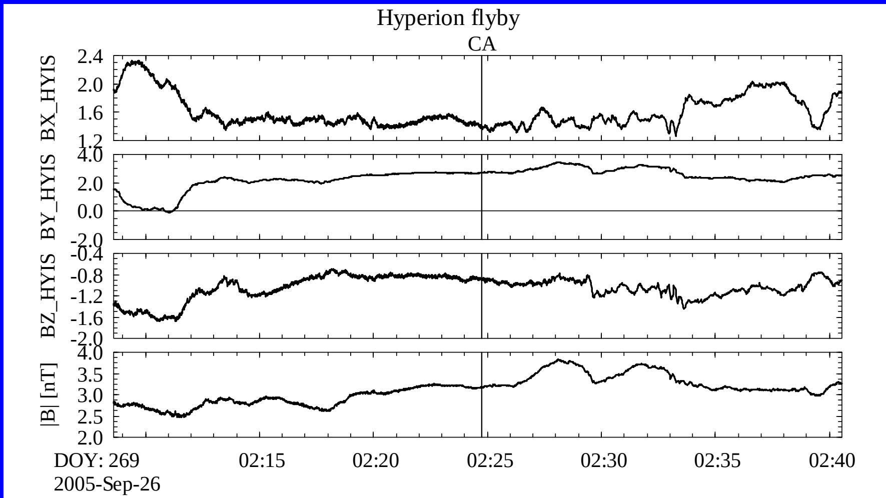
- Spacecraft trajectory from left to right.
- Field enhances in the wake to maintain pressure balance.
- Both Y and Z signatures are consistent with an absorbing moon model.
- X signature may be due to subsonic regime interaction.

Hyperion

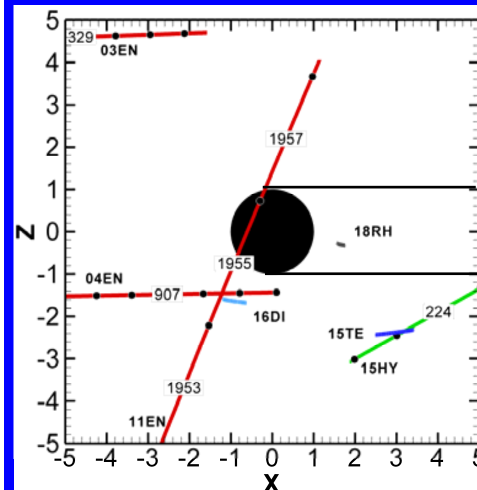
- Discovered by William Cranch Bond, George Phillips Bond, and William Lassell in September 1848.
- Diameter of 360×280×225 km and density of 0.6 g/cm^3.
- Internal structure unknown but mostly pure ice.
- Currently in a 4:3 orbital resonance with Titan.
- Terrain mostly heavily cratered. Surface age > 4 billion years.
- Has one of the lowest albedos in the solar system suggesting it is covered by at least a thin layer of dark material.
- Because of the large eccentricity and resonance with Titan does not have a fixed rotation period or axis (it tumbles chaotically).

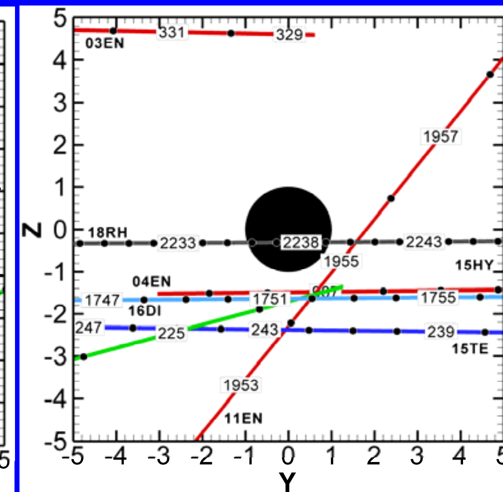

Hyperion

Hyperion

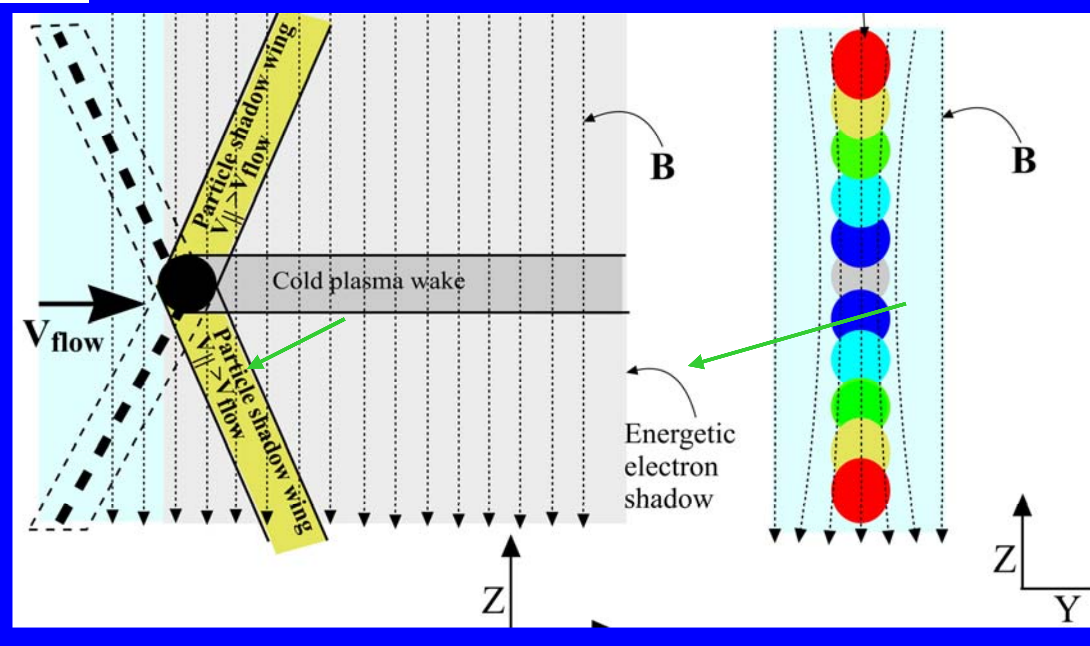


X_HYIS	18.60	13.59	8.56	3.49	-1.60	-6.72	-11.87
Y_HYIS	28.96	18.72	8.49	-1.73	-11.93	-22.13	-32.30
Z_HYIS	6.28	3.46	0.64	-2.18	-5.00	-7.81	-10.61
R_HYIS	34.99	23.39	12.07	4.47	13.04	24.41	36.01





- Not a very close downstream flyby.
- CA distance 4.44 R_{Hy}
- No discernible features associated with Hyperion.



Conclusions

- No internal magnetic fields in any of the satellites visited.
- Enceladus interacts with the corotating plasma of Saturn’s magnetosphere over an extended region (~ 6 R_E).
- The plasma pick-up region is below Enceladus (~ 4 R_E) and the total mass pick-up rate ~ 2 kg/s.
- Dione also mass-loads the corotating plasma. A hidden plume? We should look for it.
- The pick-up rates at Dione are at least an order of magnitude lower than those observed at Enceladus.
- Tethys and Rhea absorb the incoming plasma and form a plasma depleted wake.
- So far upstream trajectories showed evidence of plasma pick-up and downstream trajectories showed evidence of plasma depleted wakes. Coincidence? Feature of interaction? Need more flybys.