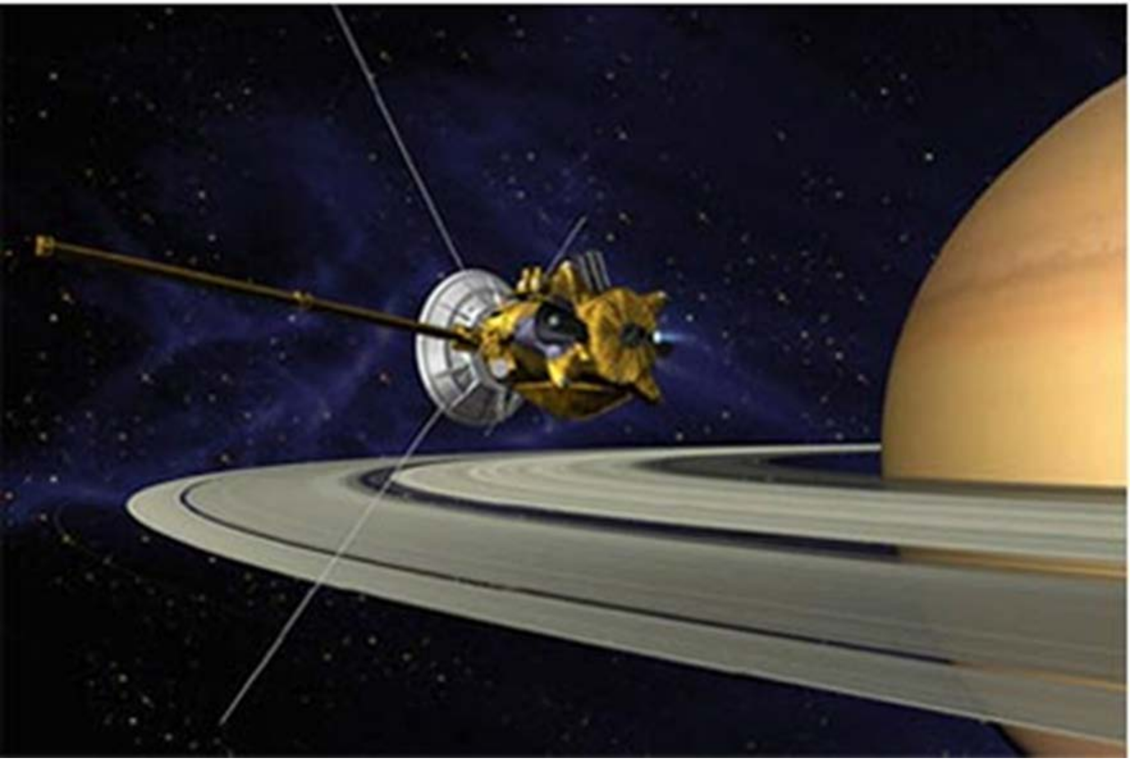
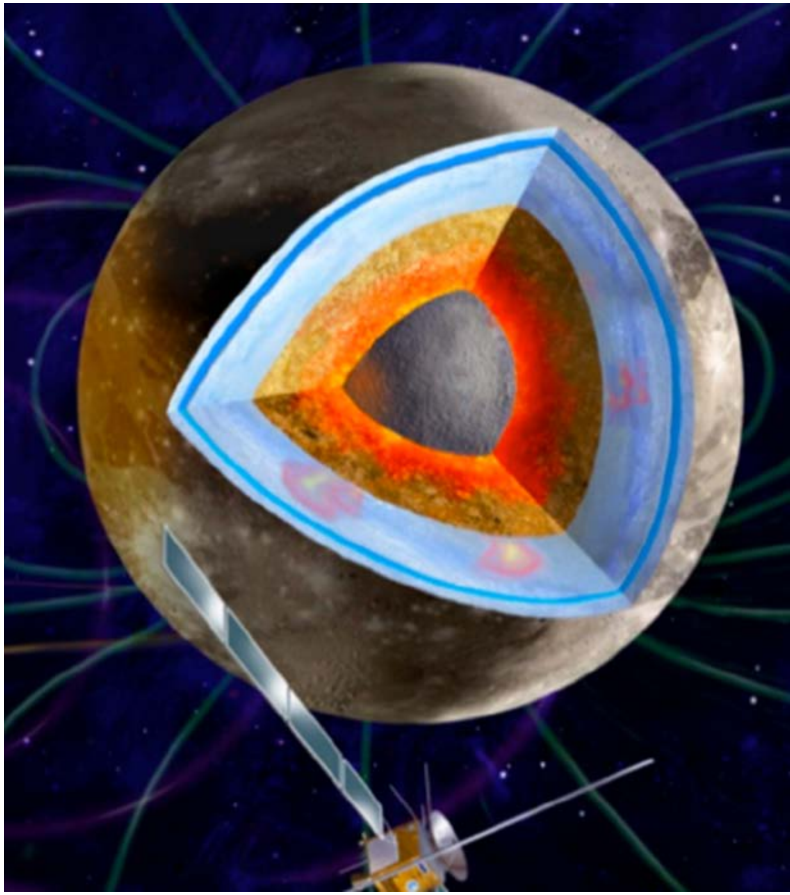
Magnetometers for Planetary Science (with a focus on Planetary Interiors)





Michele K. Dougherty

Outline

- magnetometer sensors we build:
  - Fluxgates
  - AMRs
  - their differences
- science we do from magnetic field data, focus on areas linked to interior of planetary bodies
- Cassini mission:
  - Saturn's surprising internal planetary field and what end of mission will do for us
  - discovery of Enceladus plume, driven by magnetic field observations
- JUICE mission to Jupiter's moons:
  - induced field signatures from Galilean moons
  - implications for interior structure
  - how science requirements are driving instrument design and accommodation

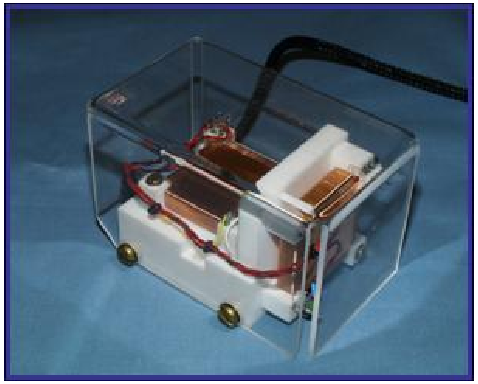
What do we mean by space magnetometer?

- Three magnetic field components in range 0 - 30Hz
- Wide measurement range 0.01nT – 50,000nT
- Robust, reliable, high performance (low noise – stable offsets)
- Optimised for power, mass, radiation etc.
- Sensors fitted to a boom away from S/C magnetic disturbance

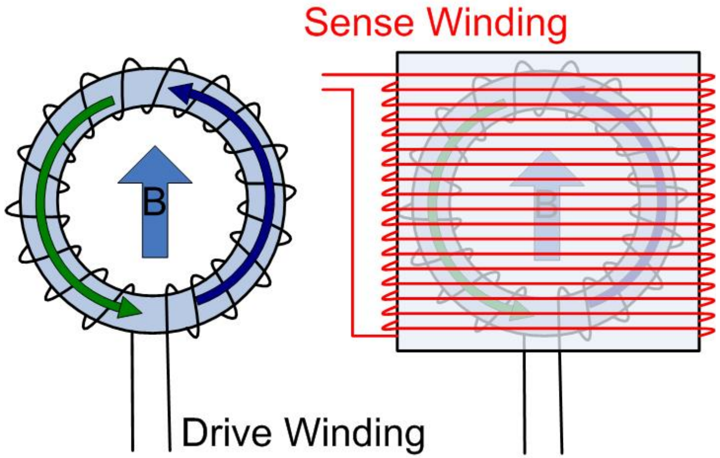
- Whilst in space, instrument offsets drift
- So need to calibrate:
  - on ground (by measurement)
  - in space (dual gradiometer technique, solar wind technique, spinning s/c, rolling s/c, absolute and vector sensors)
  - s/c magnetic cleanliness program

Anatomy of a Fluxgate

- **Operating Principle**
  - Soft permeable core driven around hysterisis loop
  - $\mathbf{H}_{\mathbf{EXT}}$ results in a net changing flux
  - Field proportional voltage induced in sense winding
  - Closed loop improves linearity



- **Advantages**
  - Low noise ~ 20pT/ √Hz @1Hz
  - Wide dynamic range
  - Mature technology
  - Relatively inexpensive

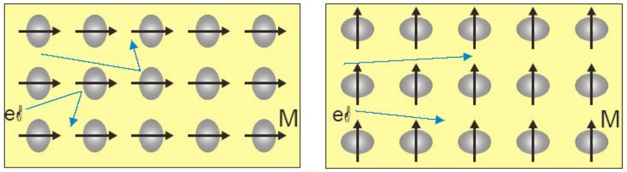


- **Disadvantages**
  - Sensor mass
  - Sensor offset
  - Power ~ 1W
  - In-flight calibration overhead

Anisotropic Magnetoresistance

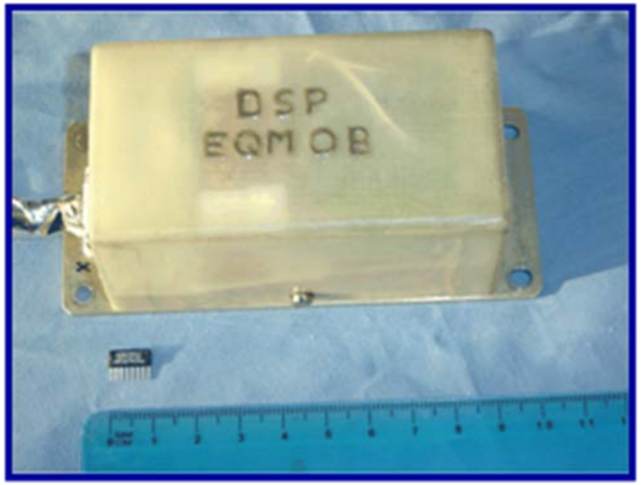
- **Magneto Resistance Effect**
  - Change of resistance in magnetic field
  - AMR single layer permalloy,
  - AMR ΔR/Rmin of order 1- 2%
  - AMR has lowest noise floor
  - Johnson noise limited - no shot noise

$$R = R_0 + \Delta R_0 \cos^2(\theta(H))$$



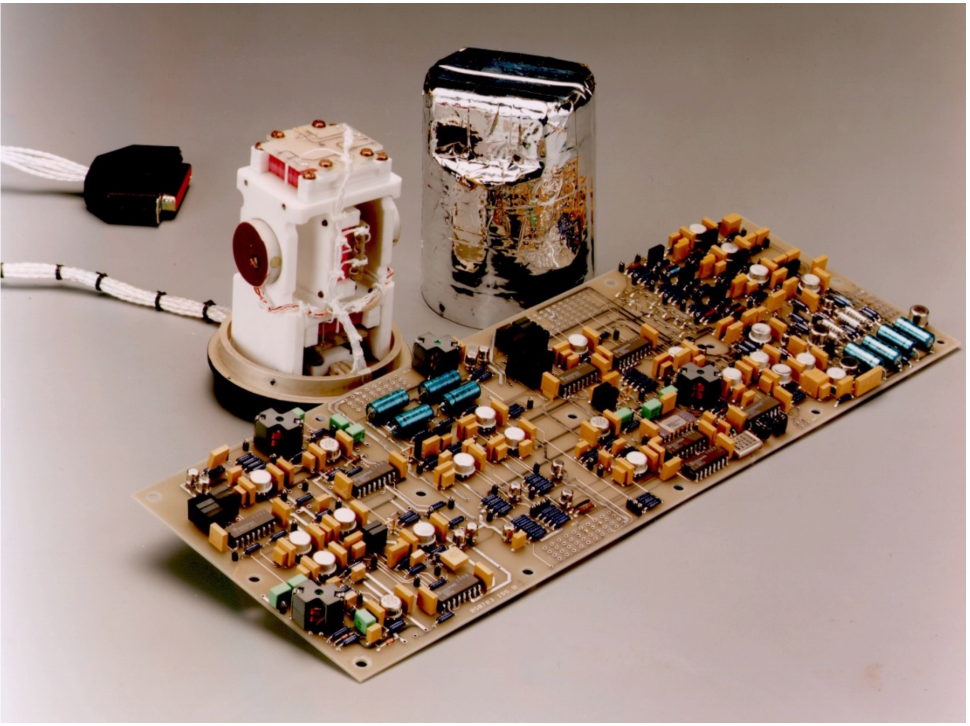
- **Barber Poles**
  - Max, sensitivity & linearity at **M** v **H** 45°
  - Conductive strips for linear operation

- **AMR Sensors**
  - Thin film solid state devices
  - Implemented as Wheatstone bridge
  - Mass <1g, Ceramic package
  - Sensitivity increases with increasing bridge voltage, V_B



MAG instrument comparison

Parameter	Fluxgate	Magneto-resistance	Comment
Composition	2 fluxgate sensors, harness, electronics box	2 hybrid AMR sensors, harness, electronics box	Multiple sensors needed for calibration, boom-mounting may also be required.
Mass	Fluxgate Sensors: 2x300g Electronics: 2500g Harness 100g Total: 3200g	AMR Sensors: 2x10g Electronics: 1000g Harness 50g Total: 1070g	Assuming stand alone MAG electronics box, could both be reduced if sensors connect to a common DPU.
Power	4.0 W	1.3 W	Sensor heaters not included.
Volume (cm^3)	Each sensor: 11 x 7 x 5 Electronics (3/4 boards): 8 x 8 x 3	Sensor: 1 x 1 x 3 Electronics: (1/2 boards) 5 x 7 x 3	Assuming stand alone MAG electronics box, could both be reduced if sensors connect to a common DPU
Operating temperature	-150degC to 90degC	-150degC to 90degC	Heaters needed if interface temp below -150degC
Radiation	>300kRad heritage	>100kRad (without shielding)	Radiation a bigger issue for MAG electronics
Accuracy	0.1nT	Between 1~2nT	
Calibration Drift	<0.1nT/degC	1nT/degC	MR drift expected to improve with further technical development

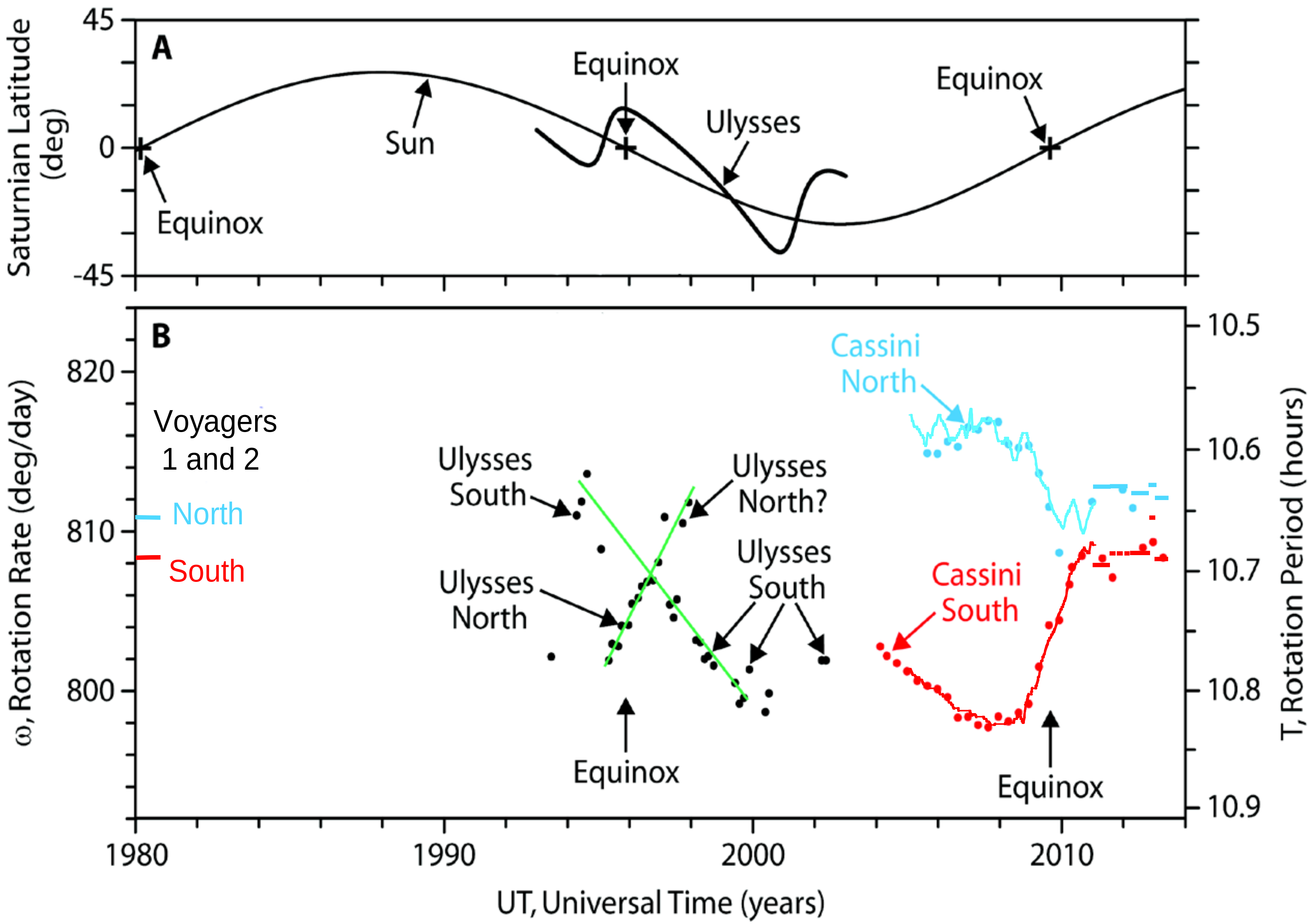


FluxGate Magnetometer (FGM)

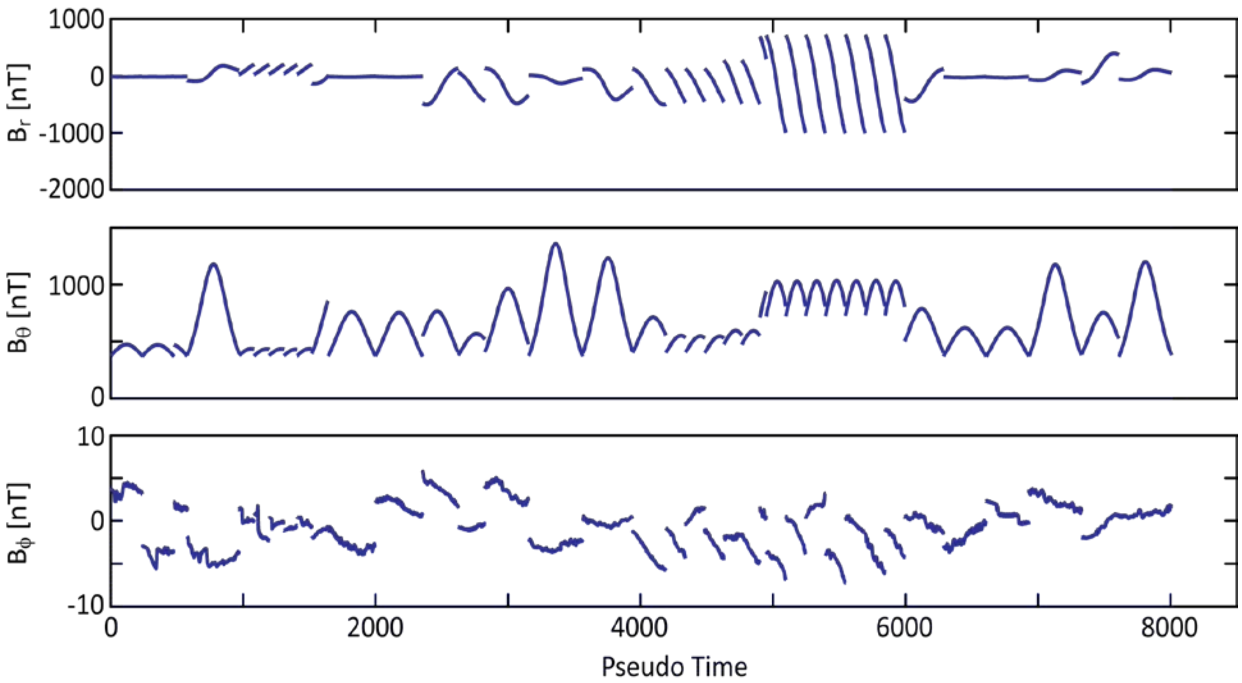
Vector Helium/Scalar Magnetometer (V/SHM)

- Mounted on 11m boom
- Use SCAS system to help with understanding of orientation of boom
- V/SHM stopped working in 2005
- Now we need to roll s/c to calibrate

Planetary Period Oscillations



Gurnett et al., 2010, Provan et al., 2014

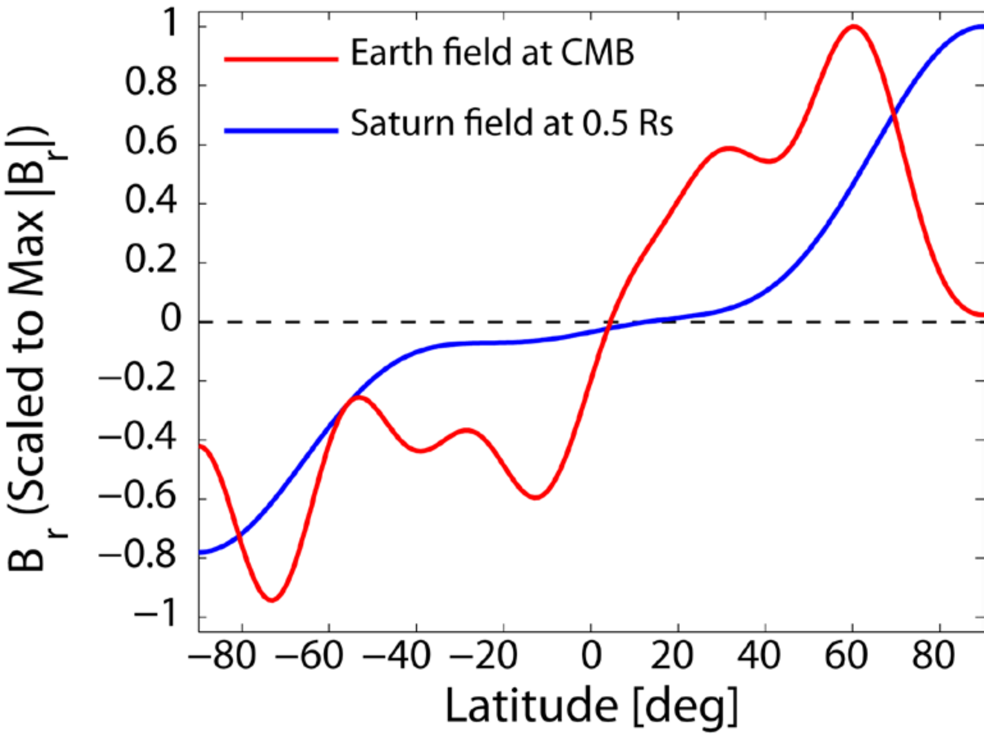


Axisymmetric Planetary Field

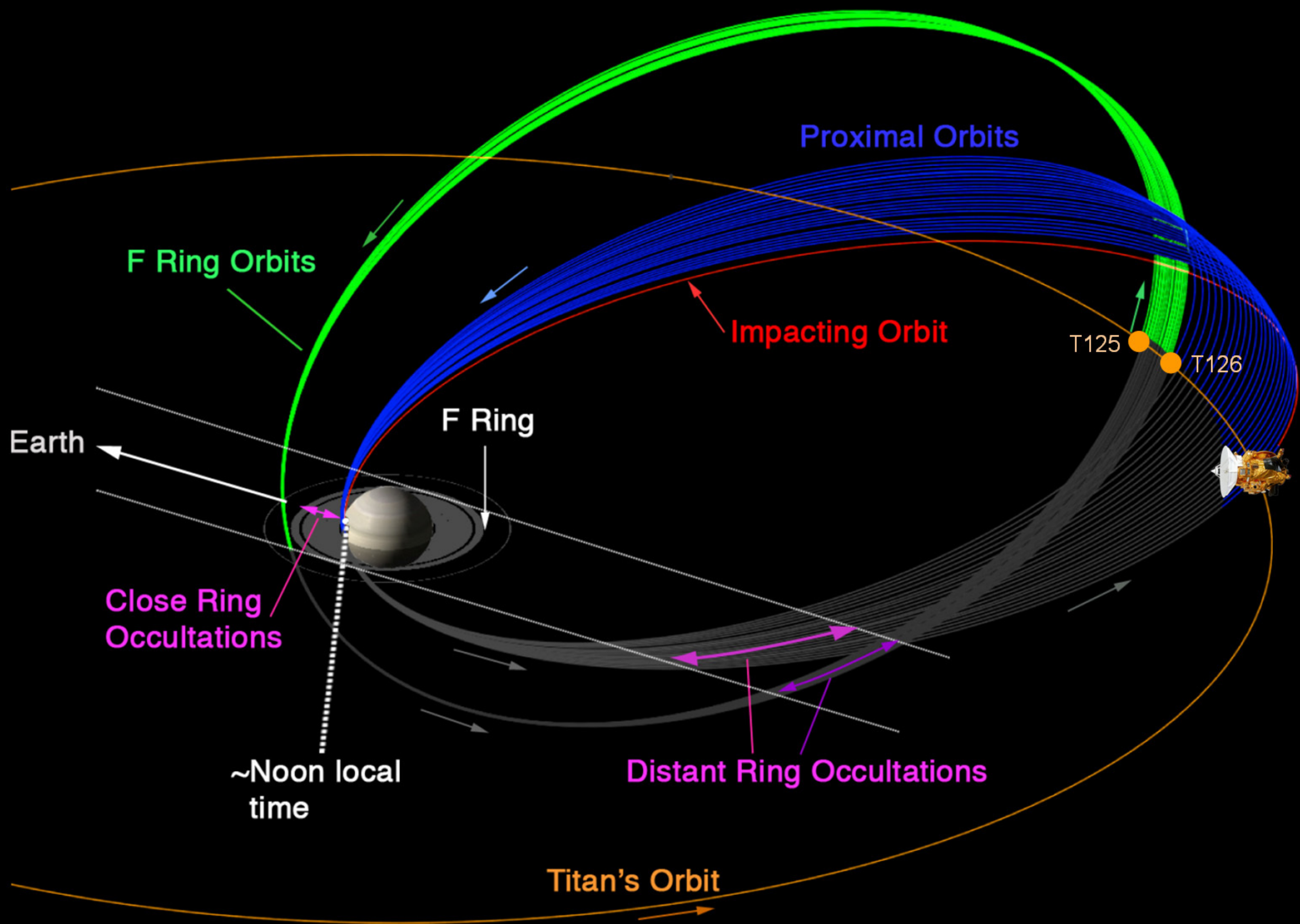
Dougherty et al., 2005
Burton et al., 2009
Hao et al., 2011

- Extreme axisymmetry
- Dipole tilt < 0.06°
- Rotation period is uncertain

- Equatorial flux expulsion up to degree 5



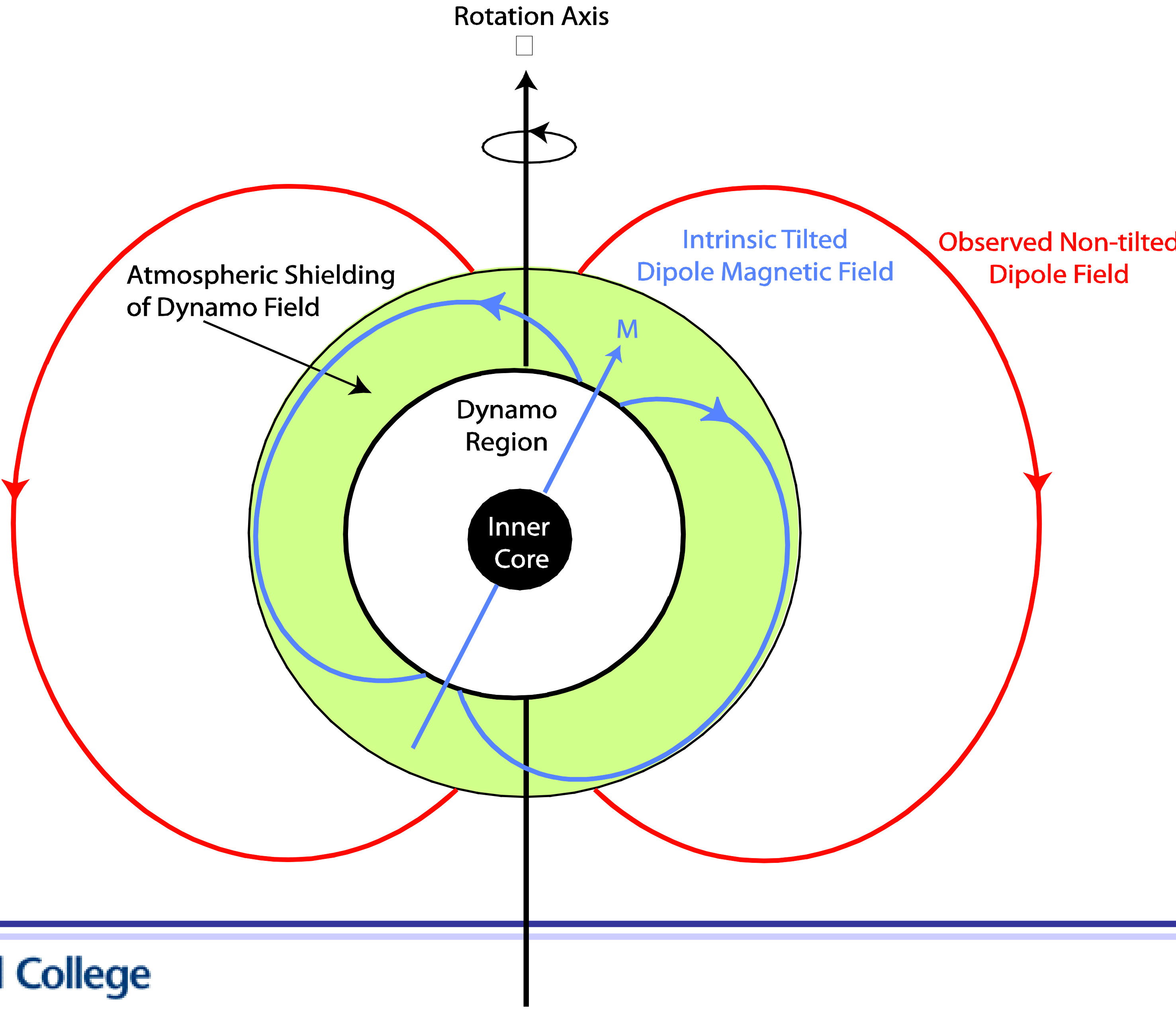
Imperial College
London



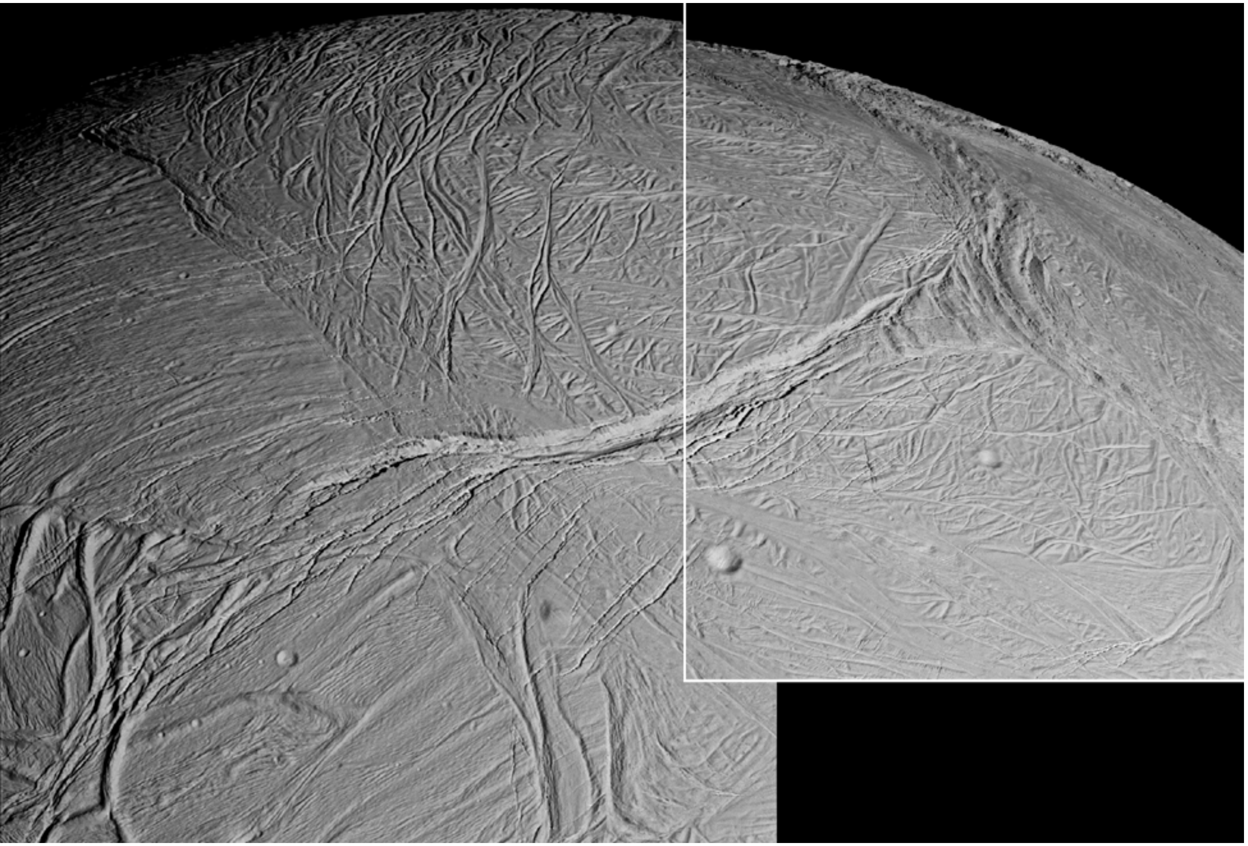
Proximal Orbits
F Ring Orbits
Impacting Orbit
T125
T126
F Ring
Earth
Close Ring
Occultations
~Noon local
time
Distant Ring Occultations
Titan's Orbit

Prior to Proximal Orbits

- Characterisation of external periodic magnetic fields
- Unify different elements of external magnetic fields (periodic, current sheet, field aligned currents)
- Is there a current system linked to rings of Saturn?
- Ensure MAG team has strategy in place:
  - Instrument requirements are met
  - Necessary calibration is carried out
  - Data analysis tools in place
  - Science return


Rotation Axis
Intrinsic Tilted
Dipole Magnetic Field
Observed Non-tilted
Dipole Field
Atmospheric Shielding
of Dynamo Field
M
Dynamo
Region
Inner
Core

Enceladus



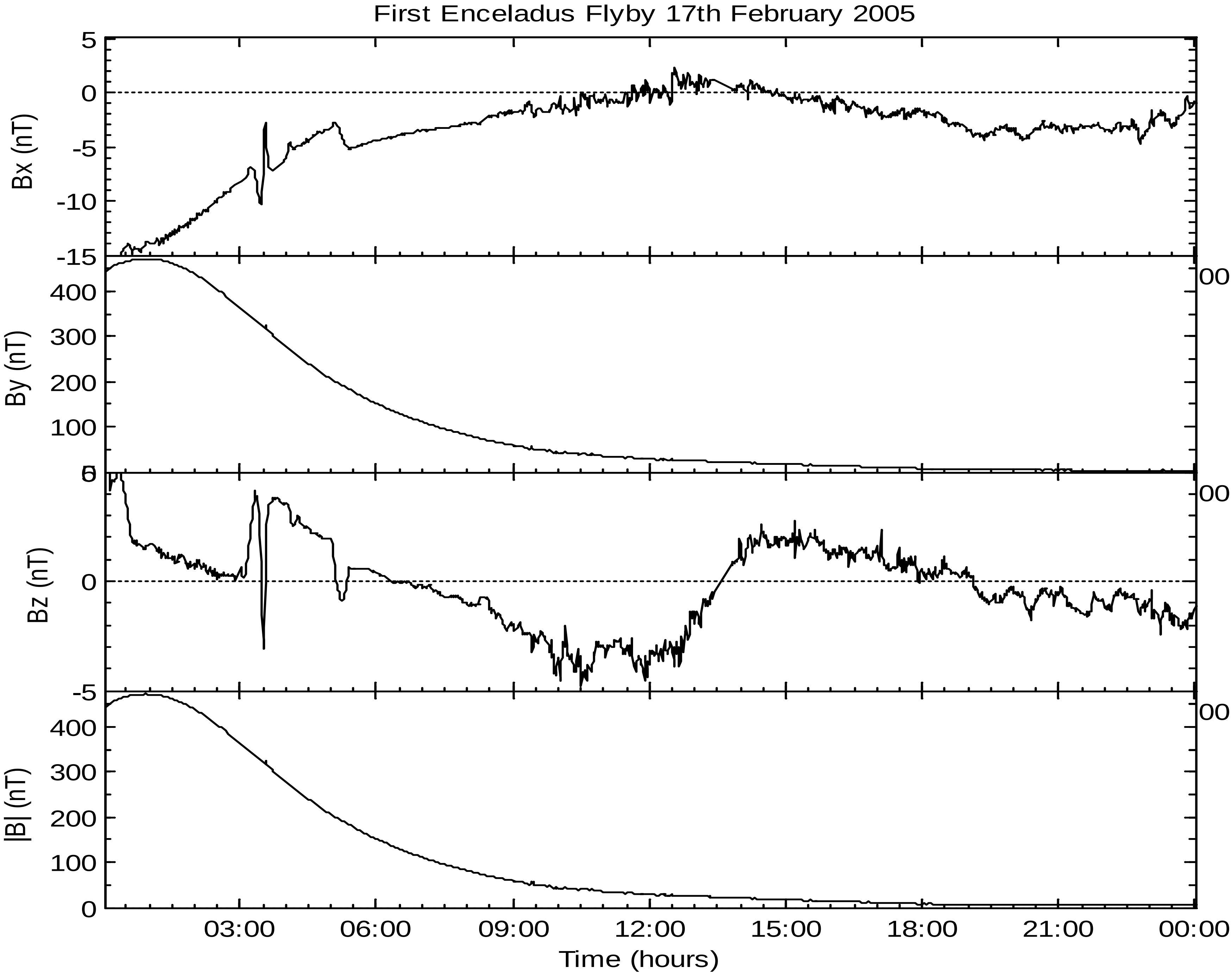
In inner magnetosphere

Source of Saturn’s E ring?

Relatively young surface

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

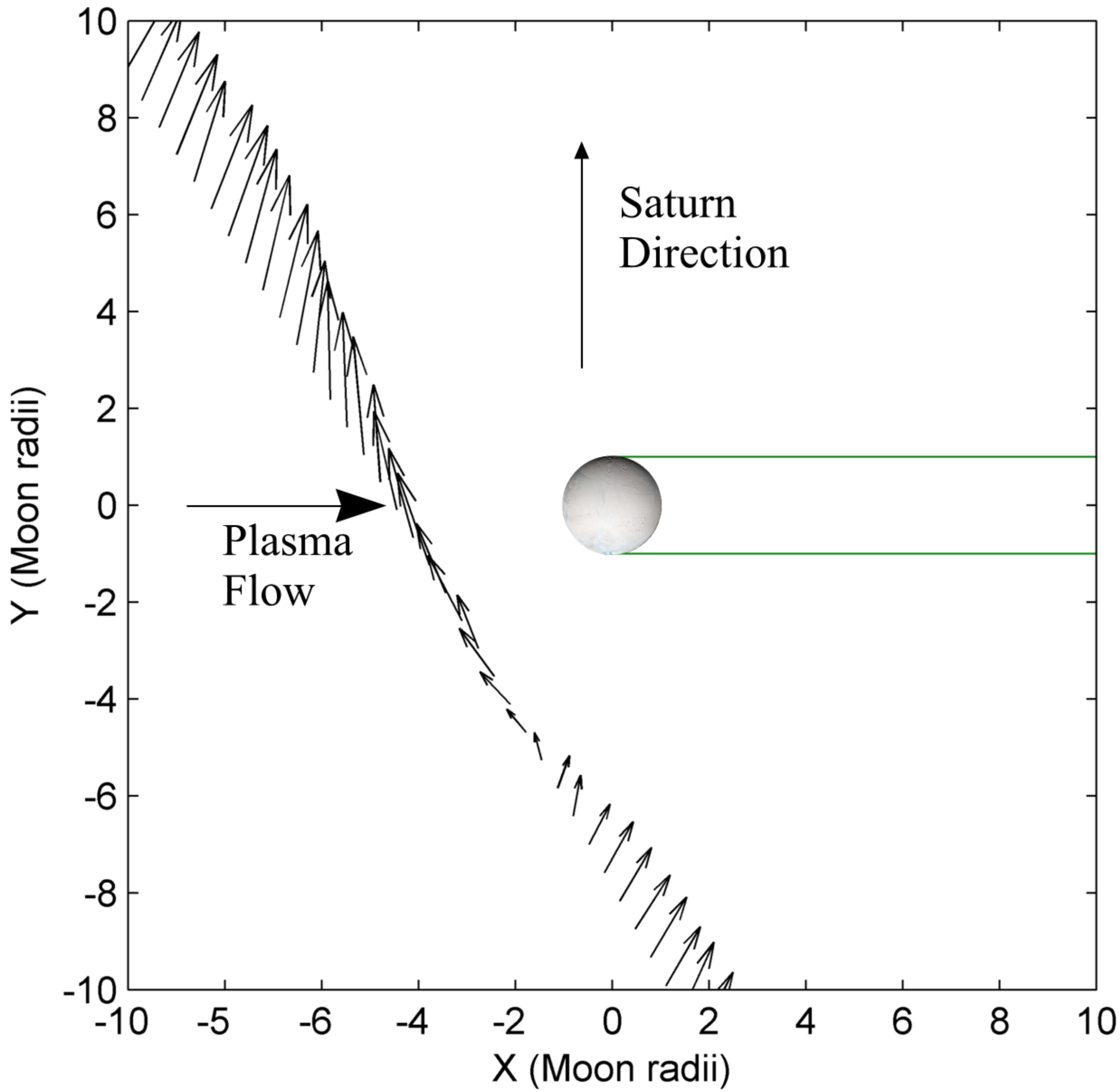
Cracks on surface



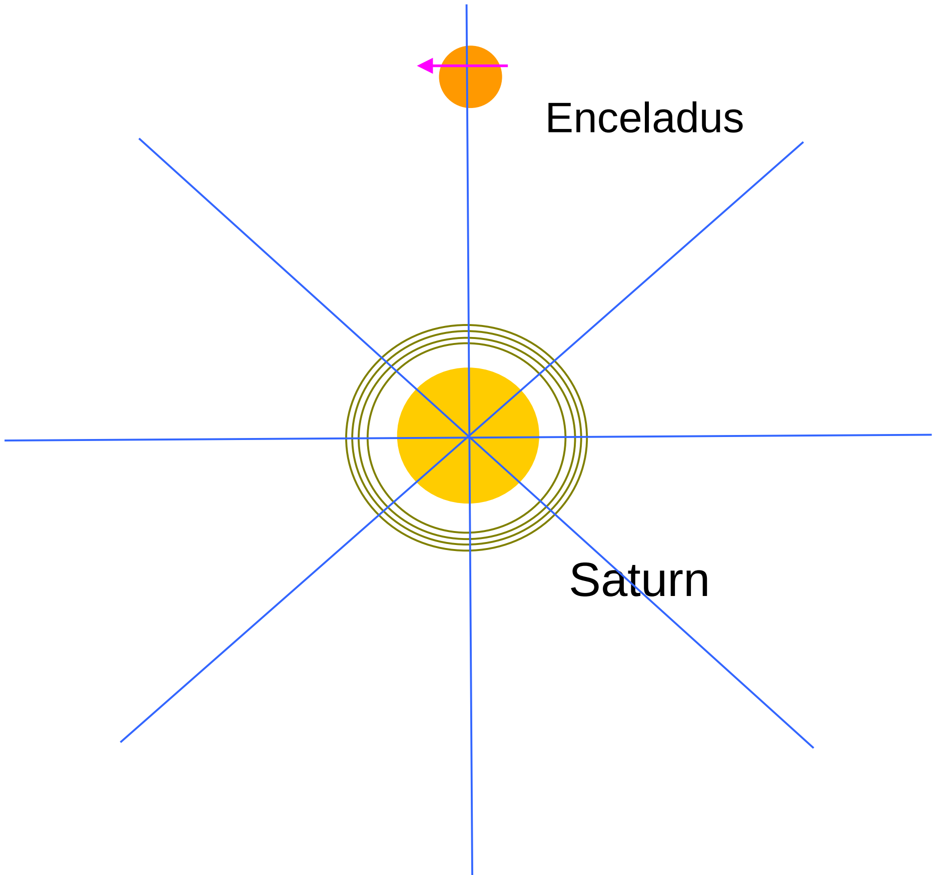
First Enceladus Flyby 17th February 2005
Bx (nT)
By (nT)
Bz (nT)
|B| (nT)
5
0
-5
-10
-15
400
300
200
100
0
00
03:00
06:00
09:00
12:00
15:00
18:00
21:00
00:00
Time (hours)

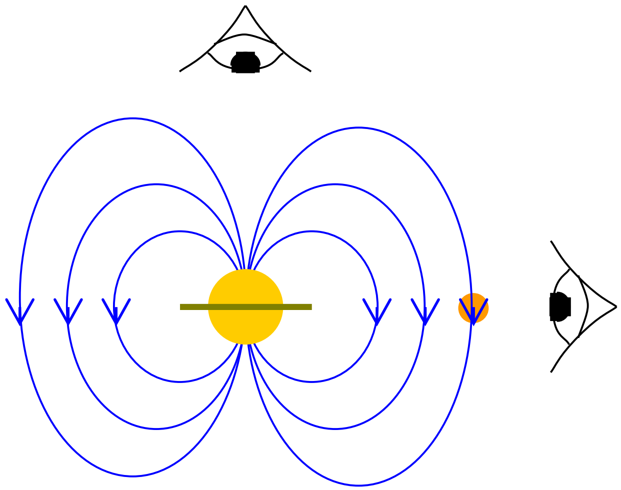
Large increase in ion cyclotron wave activity

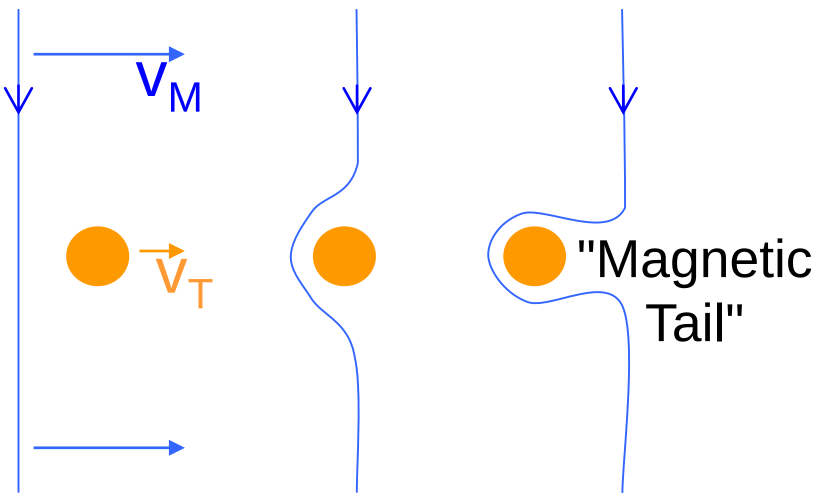
Water group ions



Field Line Draping



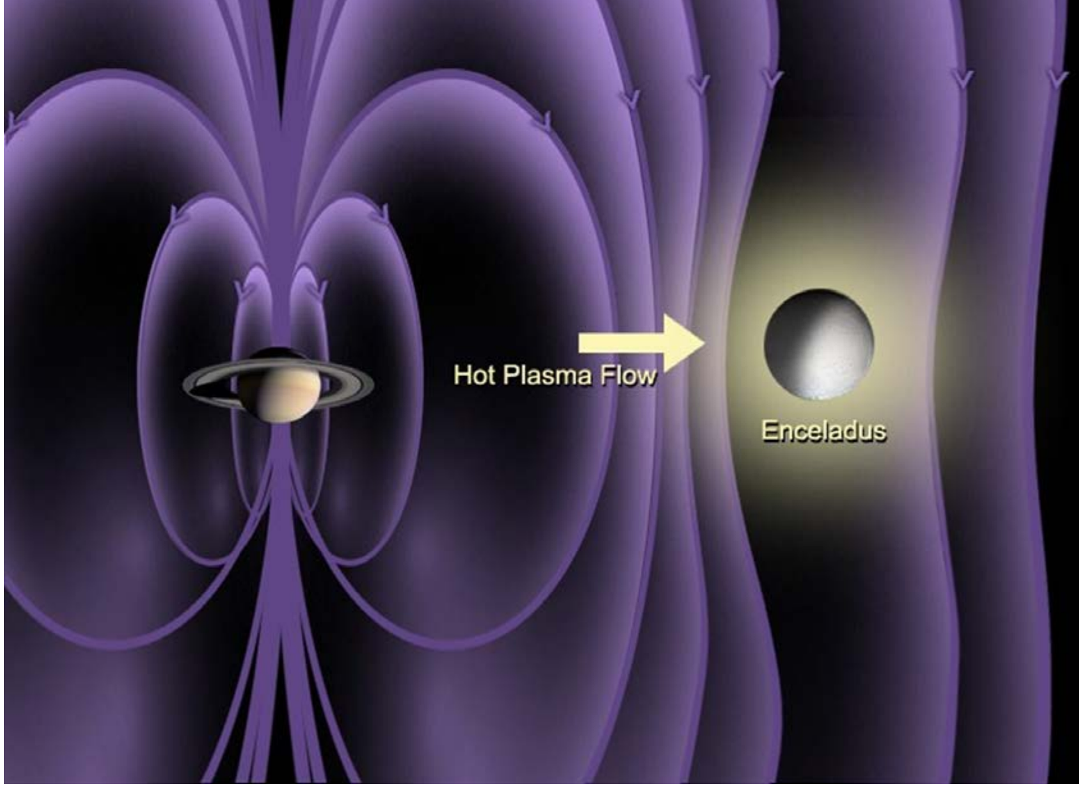




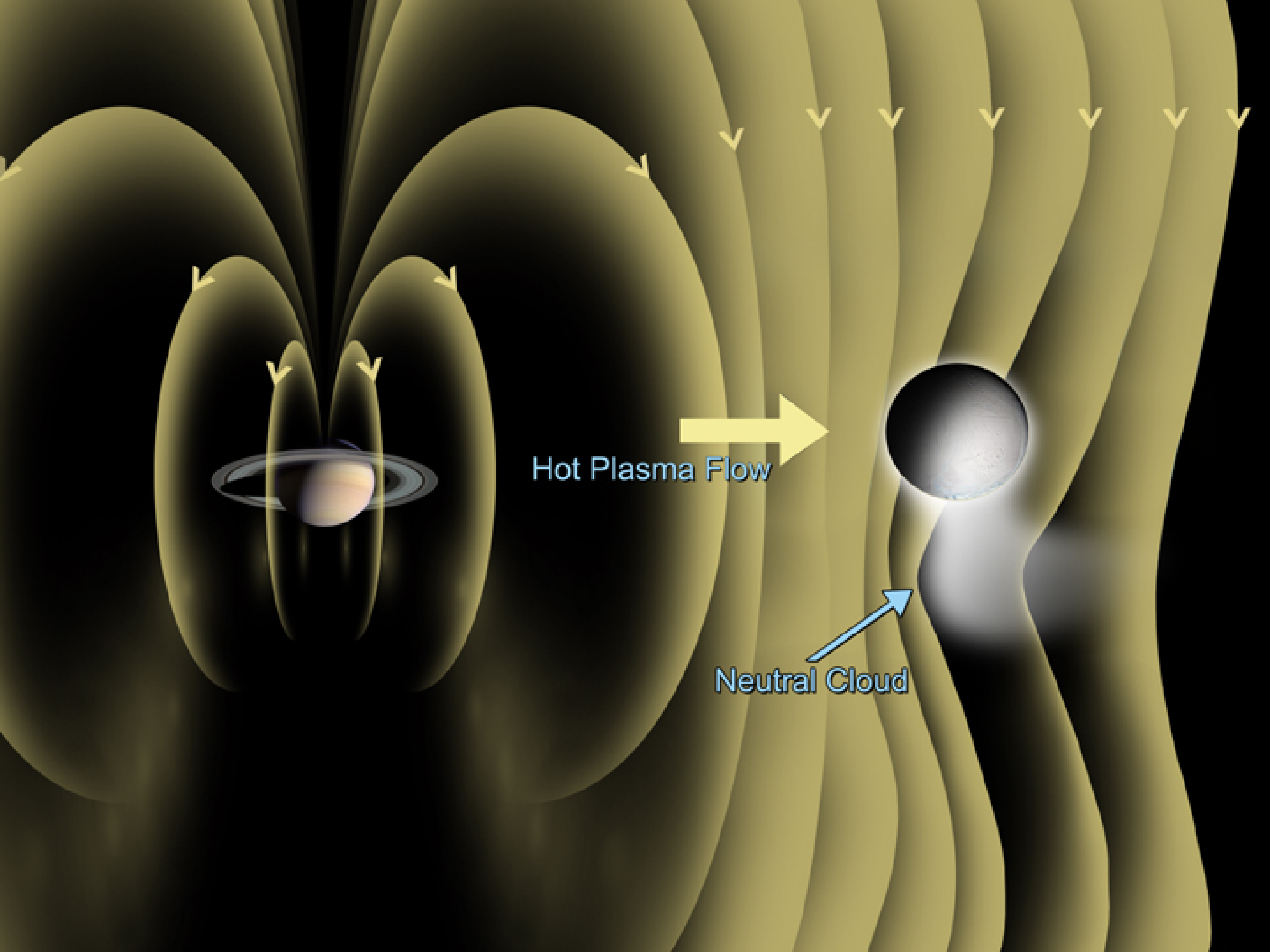
"Co-rotating" plasma

$v_M > v_T$

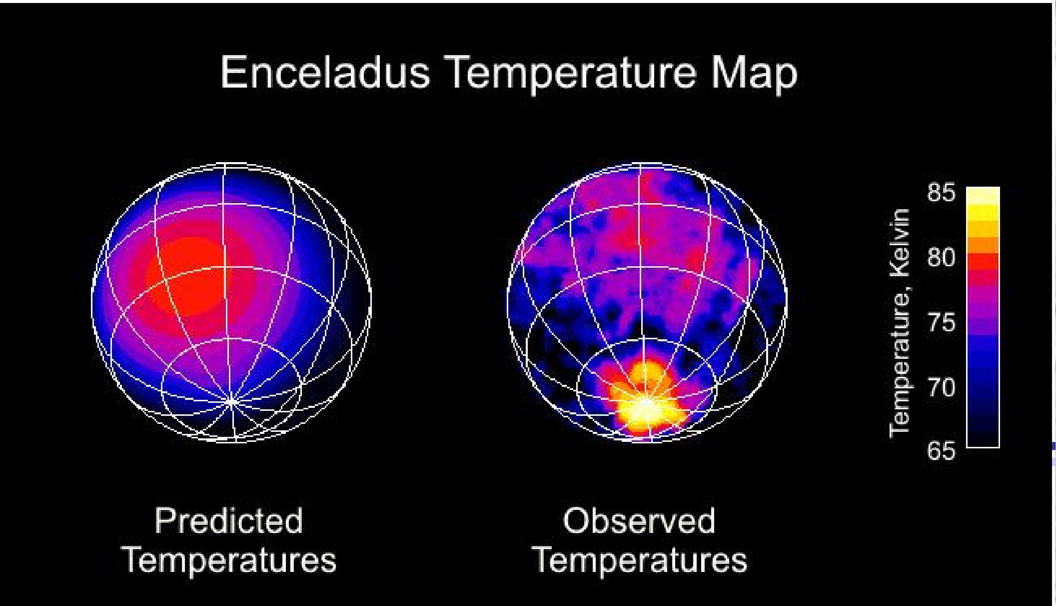
Initial ideas after 2 flybys



- Diffuse atmosphere around Enceladus, strong source to maintain?
- Strong ion cyclotron wave activity – water group ions
- Seemed 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


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)



Exploration of the habitable zone

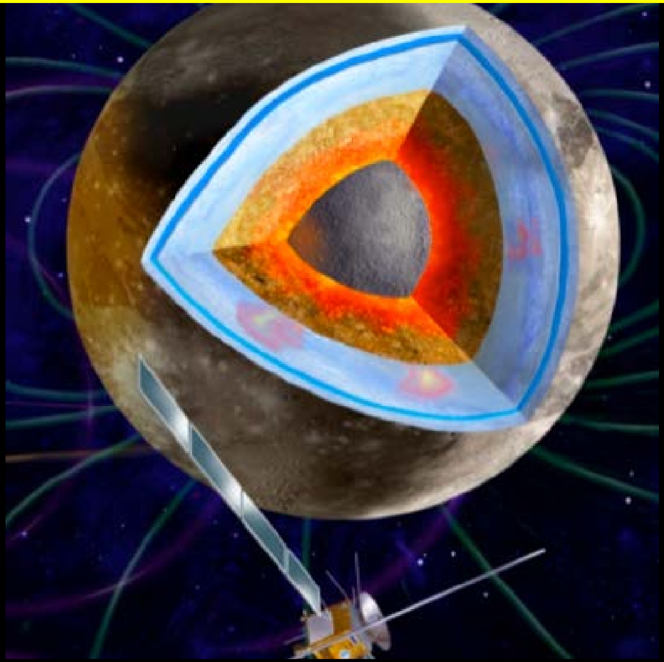
JUICE

Three large icy moons to explore

Ganymede

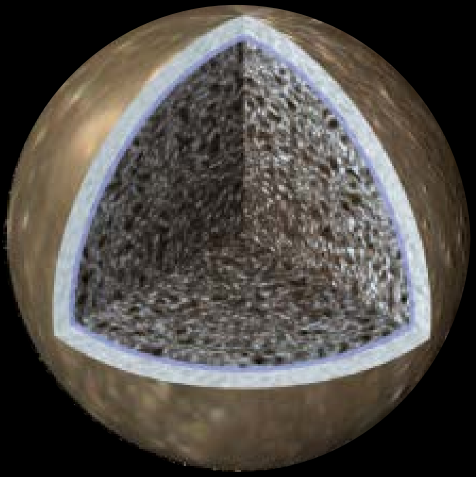
- Largest satellite in the solar system
- A deep ocean
- Internal dynamo and an induced magnetic field – unique
- Richest crater morphologies

- Archetype of waterworlds
- Best example of liquid environment trapped between icy layers



Callisto

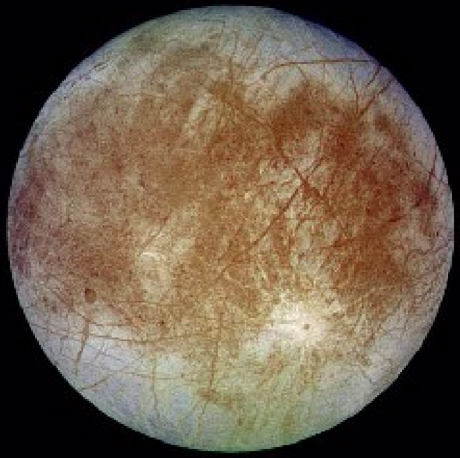
- Best place to study the impactor history
- Differentiation – still an enigma
- Only known example of non active but ocean-bearing world
- The witness of early ages



Europa

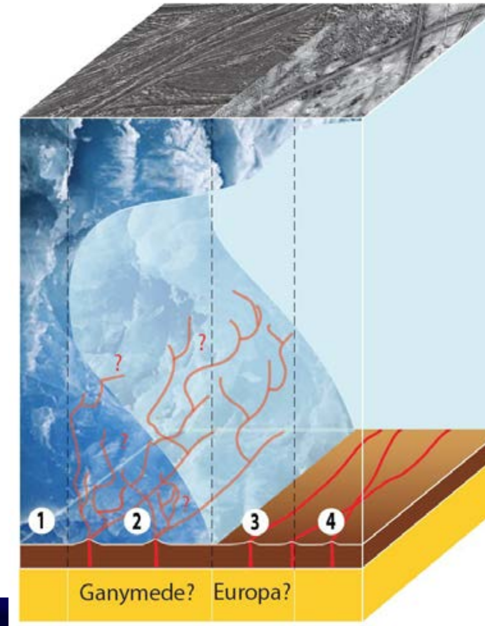
- A deep ocean
- An active world?

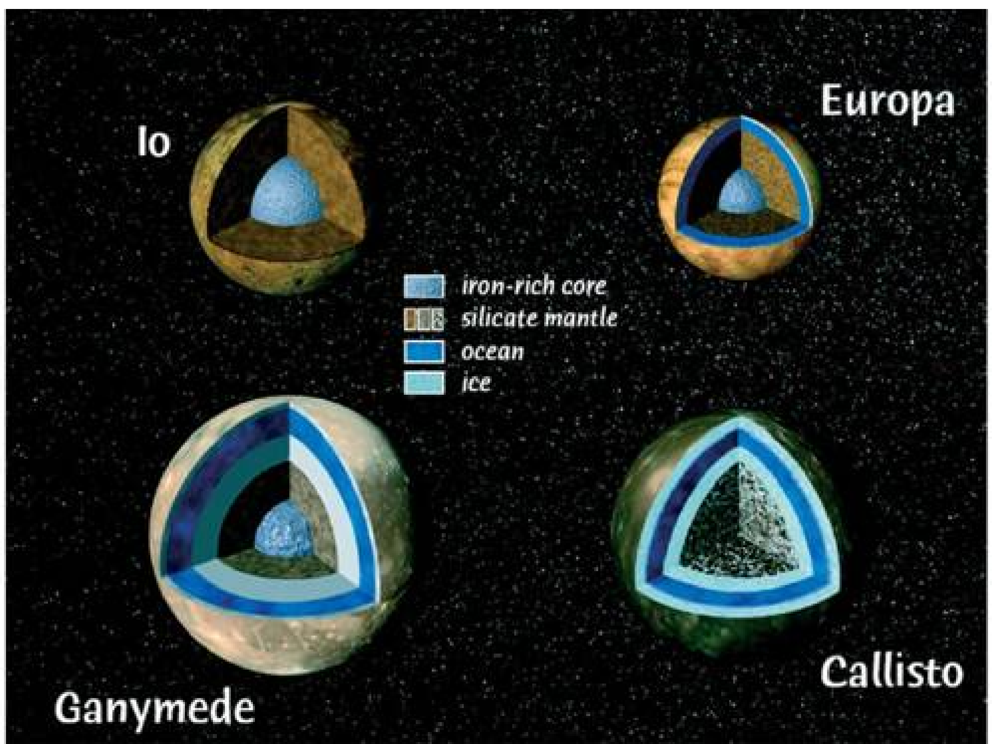
- Best example of liquid environment in contact with silicates

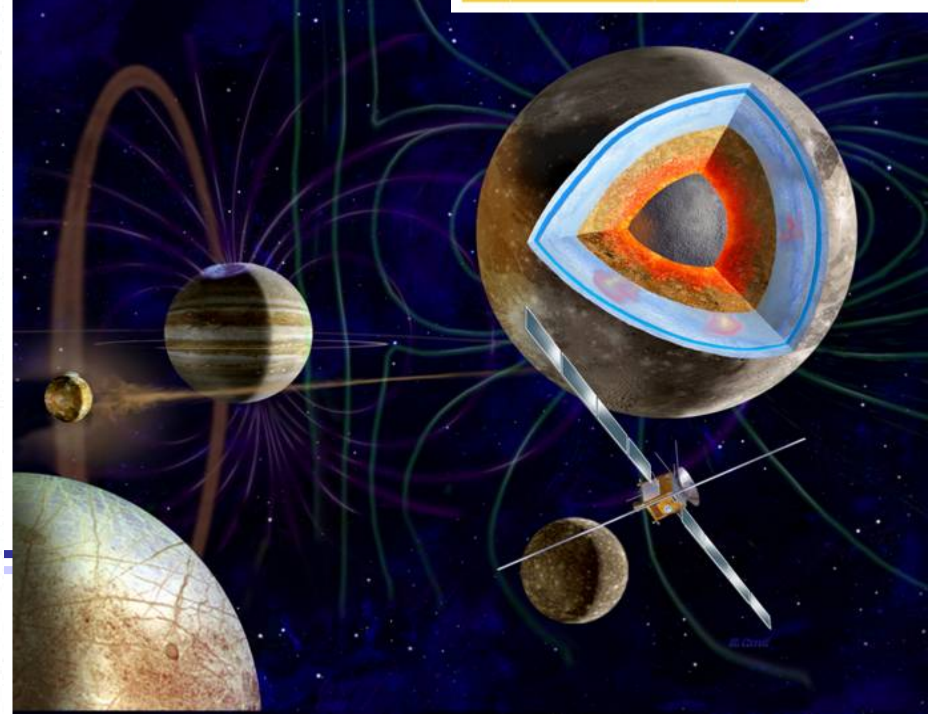


Science Case I : Resolve interior structure of icy moons

- Resolve strength of induced magnetic fields
- What are depth of the liquid oceans beneath icy surfaces
- What is the conductivity of the water?
- Resolve strength of Ganymede internal magnetic field
- Implications for the deep interior structure of Ganymede
- Compare differentiated with undifferentiated body

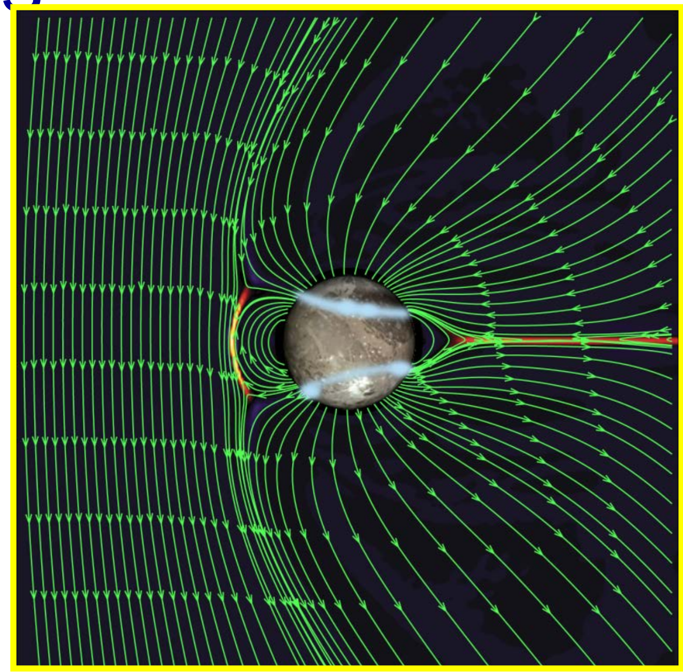


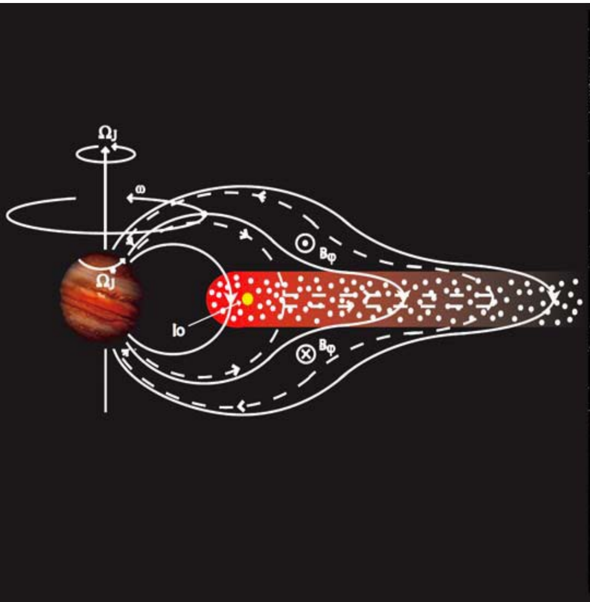


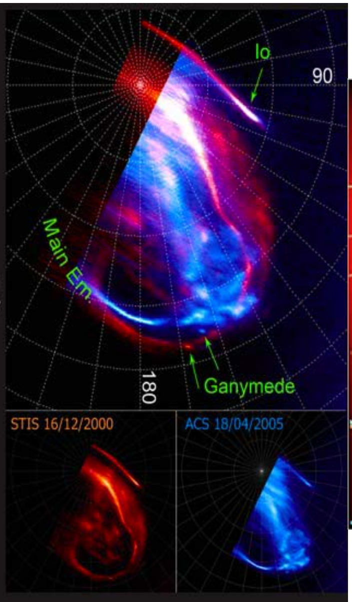


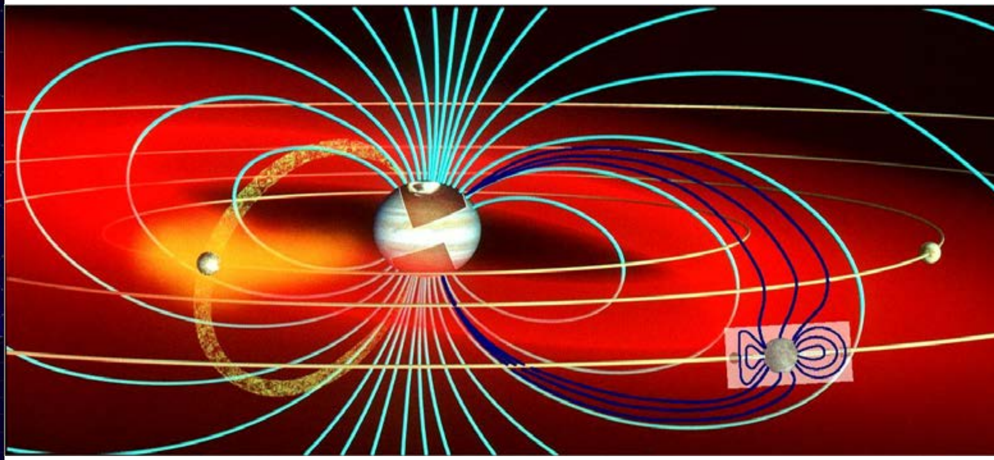
Science Case II : Dynamical plasma processes

- Magnetic field measurements are vital to allow a better understanding of dynamical plasma processes
- Interactions of the magnetosphere of Ganymede within the Jovian magnetosphere
- Dynamics of Jovian magnetodisk
- Generation of aurora and of the various current systems which arise

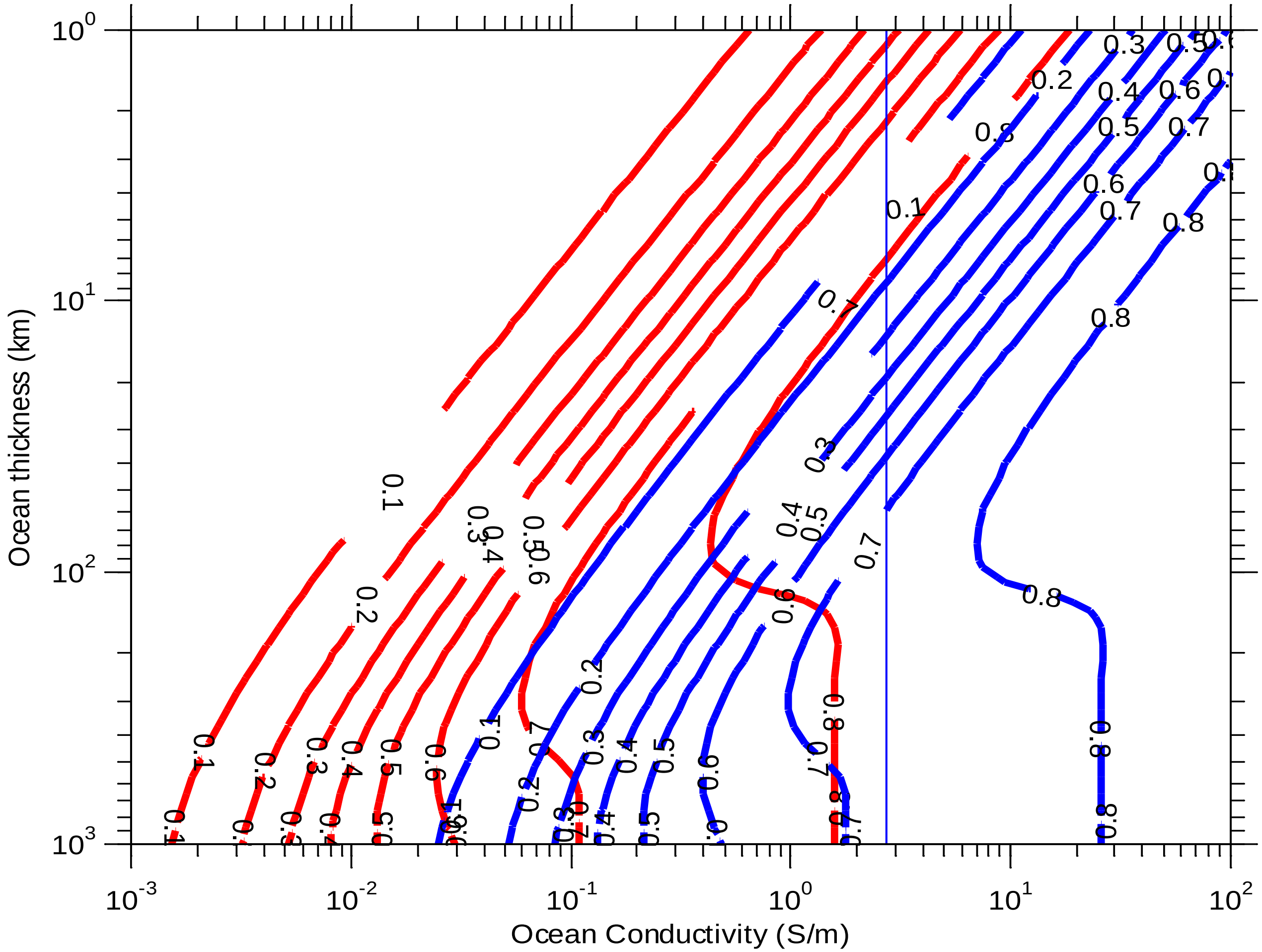






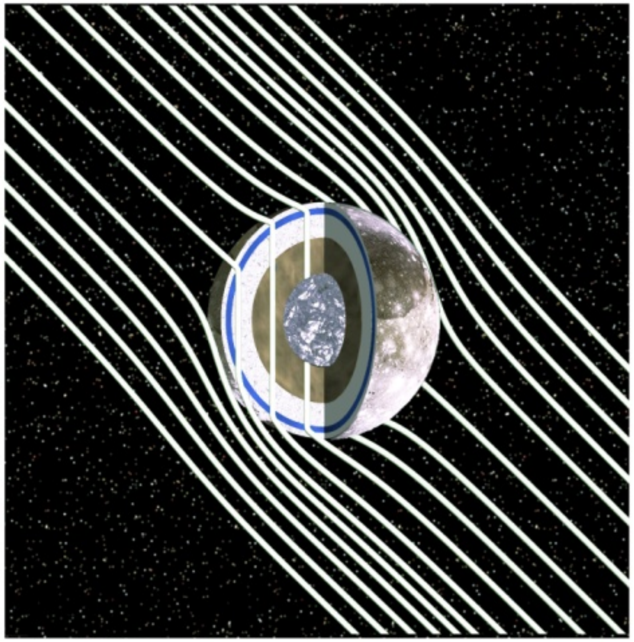


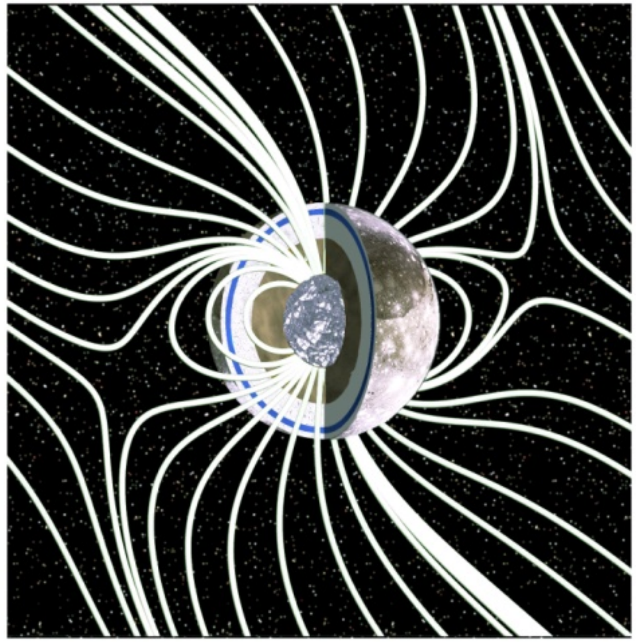
Use of inducing frequencies

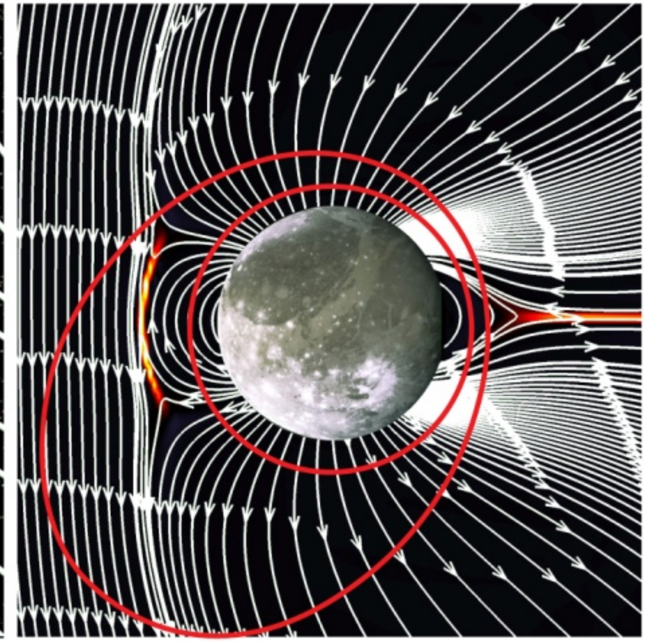


Normalised response (induction/primary field ratio) as a function of the conductivity and thickness of the ocean for two primary frequencies [synodic period (red) and orbital period, 171.72hr (blue)]. The assumed ice thickness is 150km and the mantle conductivity is 10^{-4} S/m).

Magnetic Fields to be resolved at Ganymede







Variable (10h, 171h, 27days)

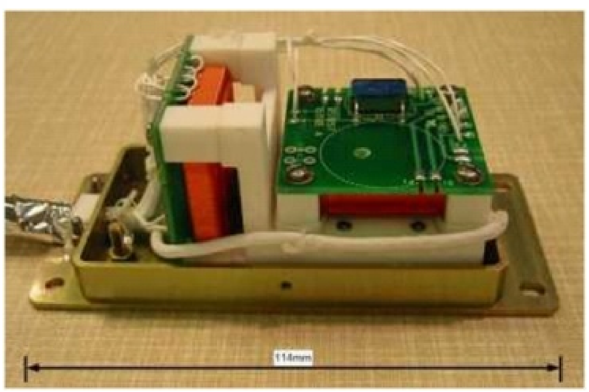
Static

Variable (< 10min, 10h)

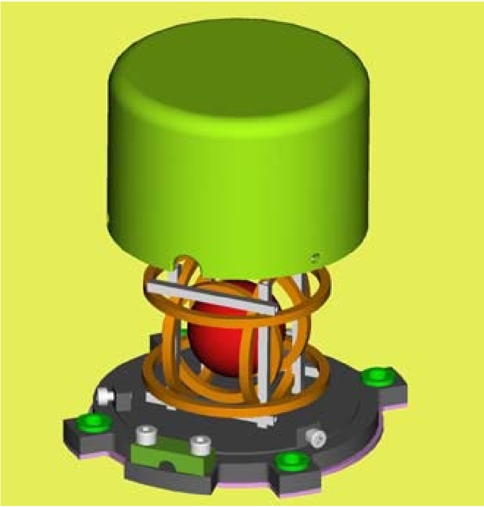
Left: Jupiter's background field plus Ganymede's induced magnetic field
Middle: combined with internally generated magnetic field
Right: interacts with Jupiter's magnetospheric field to produce mini-magnetosphere

Instrument Concept Summary

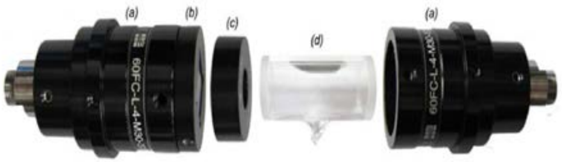
- J- MAG is DC (0-64Hz) Magnetometer featuring dual fluxgate sensors plus an absolute scalar sensor
- Sensors are mounted on S/C provided 10.5m magnetometer boom
- Fluxgate sensors are non-identical designs
- Outboard sensor built by Imperial College London
- Inboard sensor built by Technical University Braunschweig (TU-BS)
- Scalar sensor built by IWF-Graz



Imperial Fluxgate



TUBS Fluxgate



IWF-Graz Scalar

J-MAG Consortium

Imperial College London

University of Leicester

Technische Universität Braunschweig

Wigner

IWF Institut für Weltraumforschung