Recent Discoveries from the Analysis of Cassini Spacecraft Data in Saturn's Orbit

Part 1 : The Saturn system, its exploration by Voyager, and the Cassini mission

Philippe Zarka
LESIA, CNRS-Observatoire de Paris
France
philippe.zarka@obspm.fr

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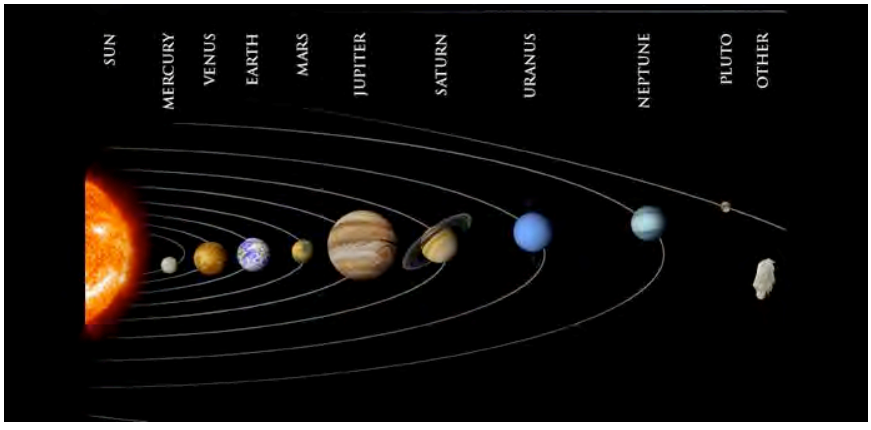
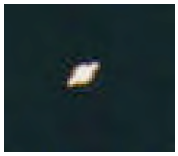
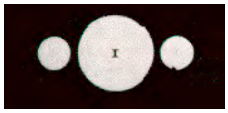
- Saturn known from ancients
- 6th planet in solar system, farthest visible with naked eye



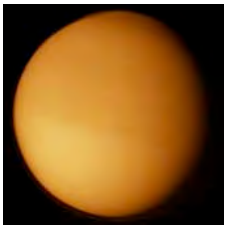
- Scientific exploration started in 17th century, with first telescopic observations



• 1610 Galileo notes the “triple planet Saturn with his telescope (1612 single, 1616 ansae)



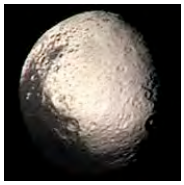
• 1655 Huygens discovers Saturn’s largest satellite, Titan



• 1659 Huygens proposes the concept of planetary rings → solid or particles ?

• 1671–84 Cassini discovers a division in the ring (→A&B)

• He also discovers the satellites Iapetus, Rhea, Dione and Tethys



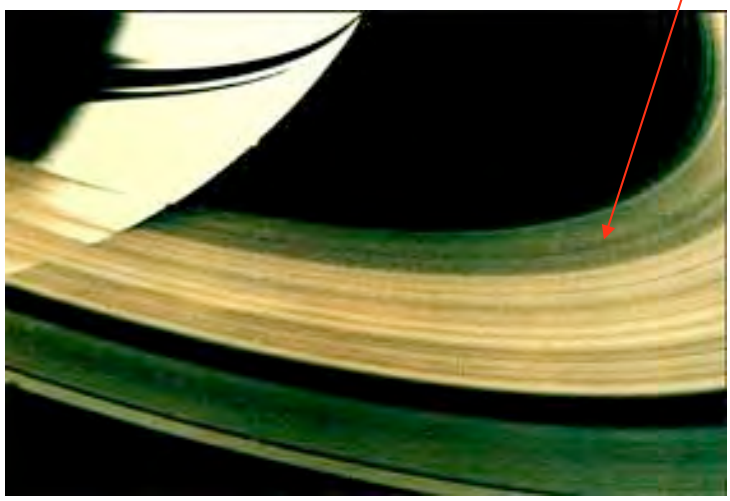
Iapetus

Rhea

Dione

Tethys

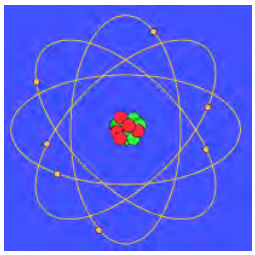
• 1789 Herschel discovers satellites Mimas and Enceladus — and notes thinness of rings
• 1848 Bond and Lassel discover the satellite Hyperion
• 1850 Bond, Bond and Daws discover inner ring C

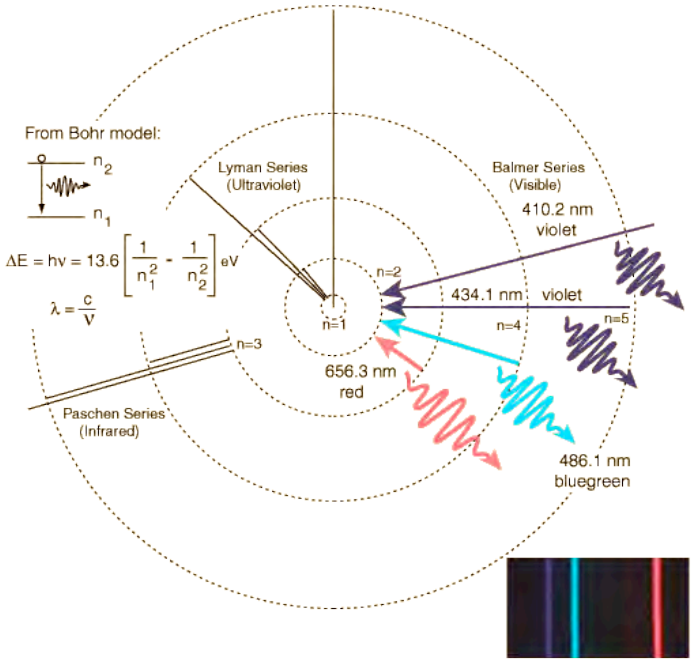


• 1857 Maxwell proves that rings are not solid
(stability relative to Keplerian motion)

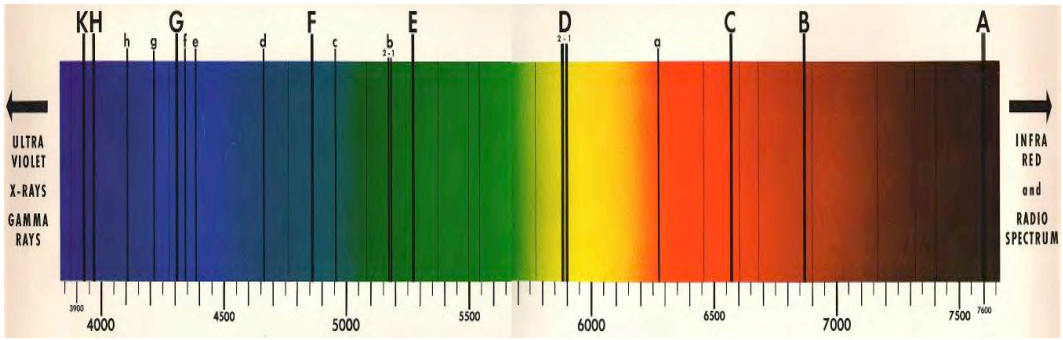
[SPECTROSCOPY]

Atoms and molecules change electrons' energy in absorbing or emitting light



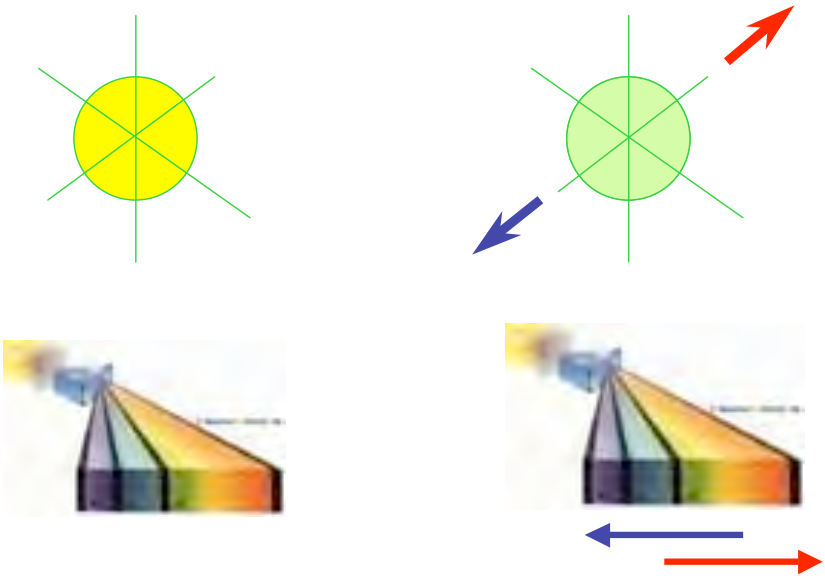


A series of lines is the fingerprint of a particular atom or molecule



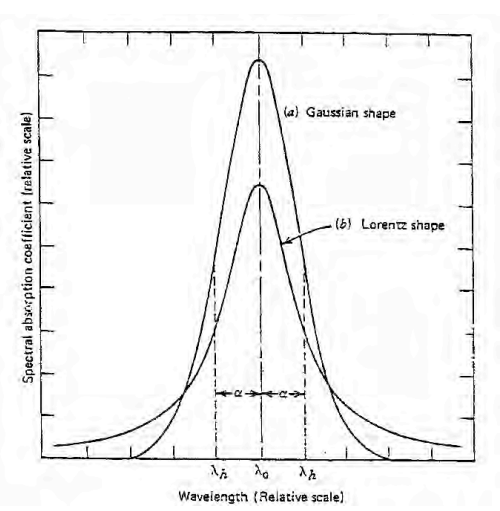
→ *SPECTROSCOPY reveals chemical composition*

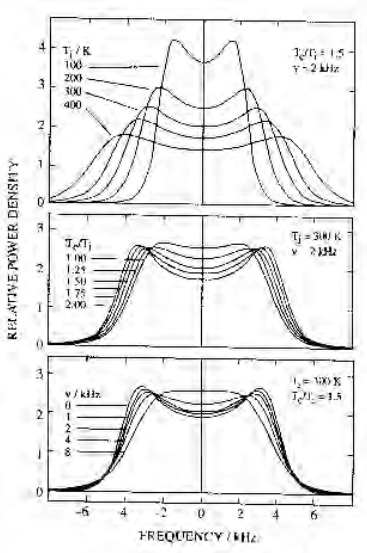
Relative motion source-observer shift the frequency of light …



… or sound : DOPPLER effect

Shape of spectral line reveals temperature or rotation of source

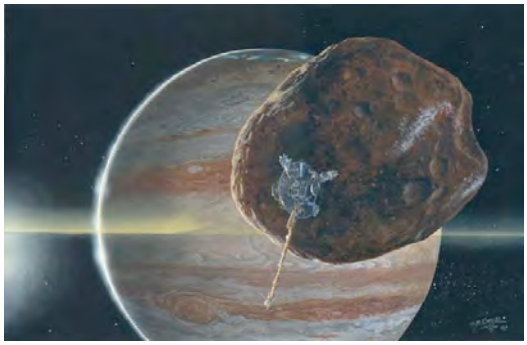


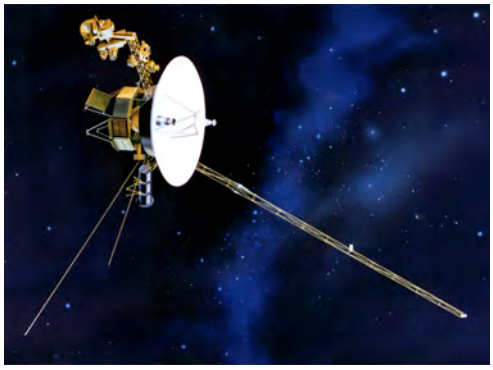


- 1872-95 Keeler measures ring velocities by spectroscopy
  → observational proof of ring particles
  He discovers Keeler/Encke gap in A ring
- 1898 Pickering discovers satellite Phoebe
- 1932 Wildt discovers methane (CH_4) and ammonia (NH_3) on Saturn
- 1943–44 Kuiper discovers methane and ammonia on Titan

- 1957 Space exploration starts with Spoutnik satellite
- 1960's Satellites orbiting Earth
- 1970-80's Planetary exploration : Mars, Venus, Mercury…

• 1979 Pioneer 11 flies past Saturn
• 1980 Voyager 1 encounters Saturn
• 1981 Voyager 2 encounters Saturn





→ Next steps

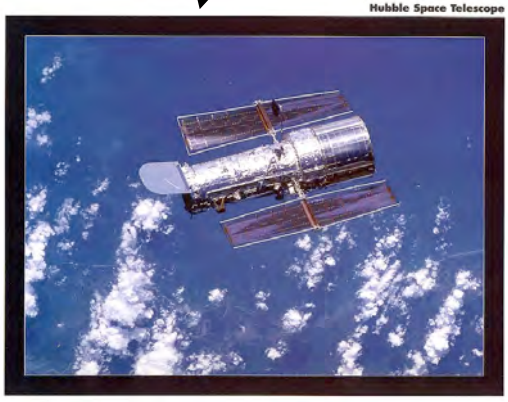
• Jupiter : Galileo orbital tour + probe (1995-2002)

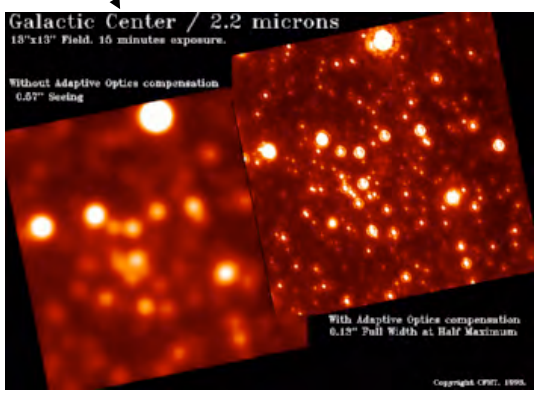
• Saturn : Cassini orbital tour
+ Huygens Titan descent probe (2004-2008)

+ Remote observations :

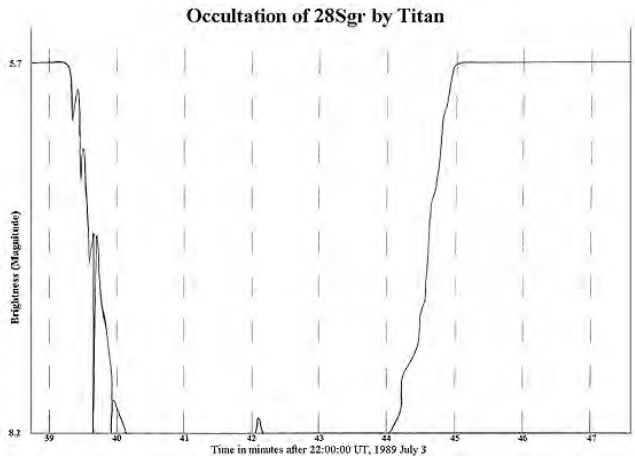
• ≥ 1989 Hubble Space Telescope's
Wide Field and Planetary Camera

• 1990's Adaptive Optics
on ground-based IR telescopes





• Use of Star Occultations
(e.g. 28 Sgr observed from Earth in 1989)



+ Theory, Laboratory experiments, Numerical simulations

• Spacecraft instrumentation : Pioneer 11

Imaging Photopolarimeter (→ low-res images)

[MAG] Flux Gate Magnetometer

[PLS] Plasma Analyzer
Charged Particle Instrument
Trapped Radiation Detector

[UV] Ultraviolet Photometer

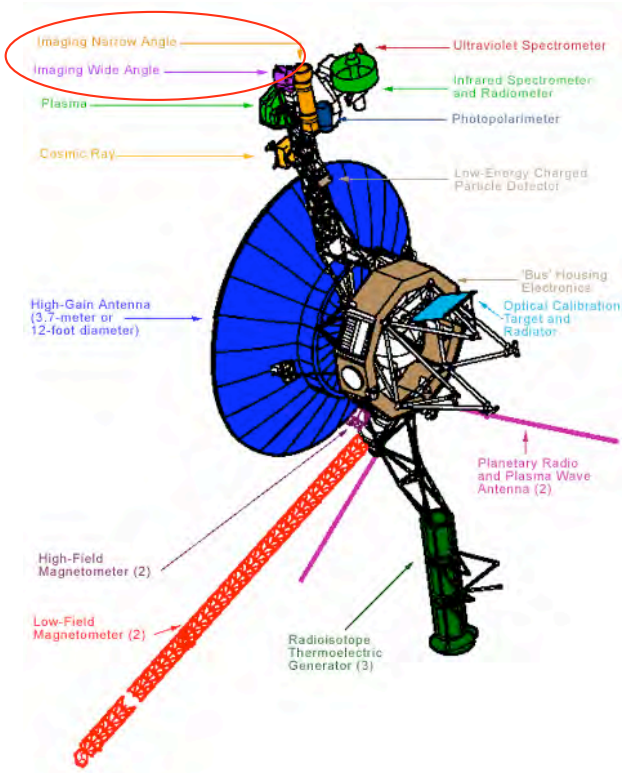
Cosmic Ray Telescope
Geiger Tube Telescope

(4 other experiments failed)

• Voyager 1-2 :

12 experiments

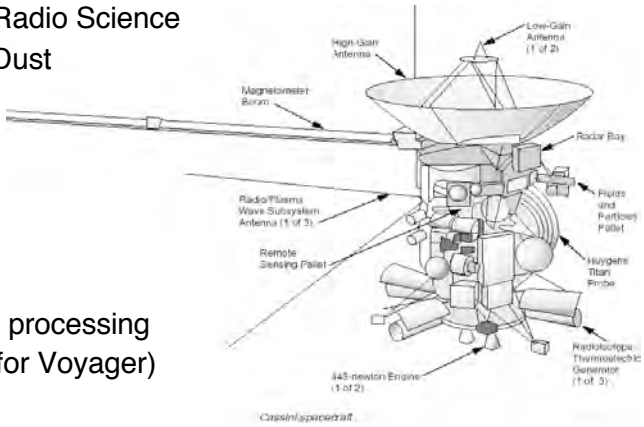
(0 failed)



Cassini instrumentation :

12 experiments on Orbiter :

[ISS]	Imaging
[UVIS, VIMS, CIRS]	Spectroscopy
[MAG]	Magnetometer
[CAPS, INMS, MIMI, RPWS]	Waves & Particles
[RSS]	Radio Science
[CDA]	Dust
[RADAR]	



+ 6 experiments on Huygens probe

Extensive onboard signal processing (400 microprocessors, 1 for Voyager)

SUMMARY OF
PRE-CASSINI KNOWLEDGE ABOUT SATURN
&
QUESTIONS TO BE ADDRESSED BY CASSINI

(1) Saturn's interior

(2) Saturn's atmosphere

(3) Rings

(4) Titan

(5) Icy satellites

(6) Magnetosphere

SATURN'S DATA

Orbital period :	29.4 years
Semi-major axis :	9.54 AU
Mass :	95 x Earth's mass
Radius :	9.4 x Earth's radius
Density :	687 kg/m3
Composition :	Mostly H, He

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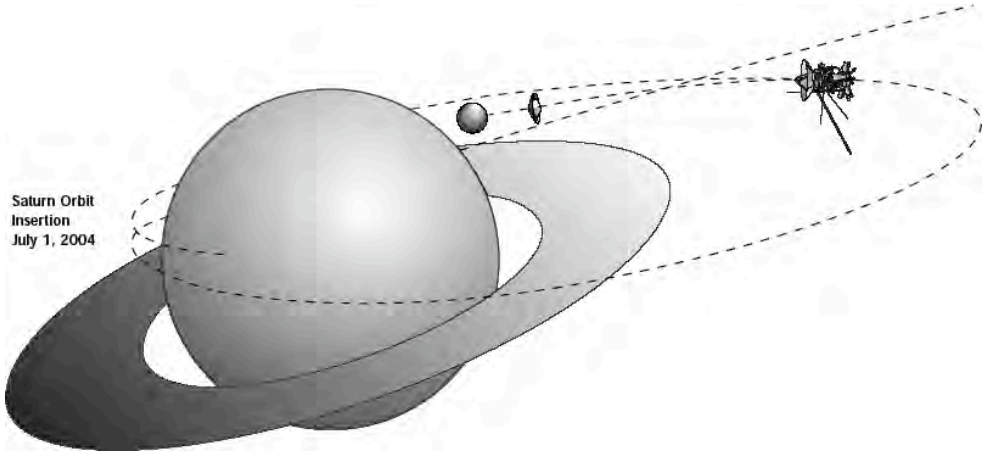
• Density (0.7), Gravity & mass distribution (J_2…) *[S/C trajectories]*



• Composition : ~94% H, 6% He *[Voyager-UV Spectroscopy]*

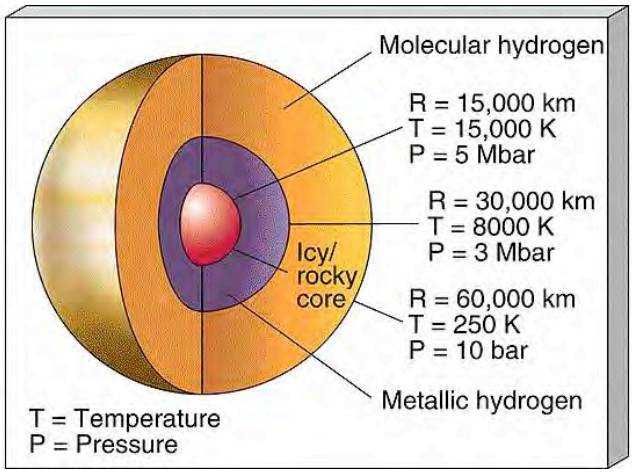
• Gaseous / liquid / metallic H,He (hot and high pressure) *[Theory]*

• Transition liquid / gas supercritical → no surface → z_o = 1 bar level

• Emitted energy ~2 x received from Sun

→ primordial condensation terminated (≠ Jupiter)

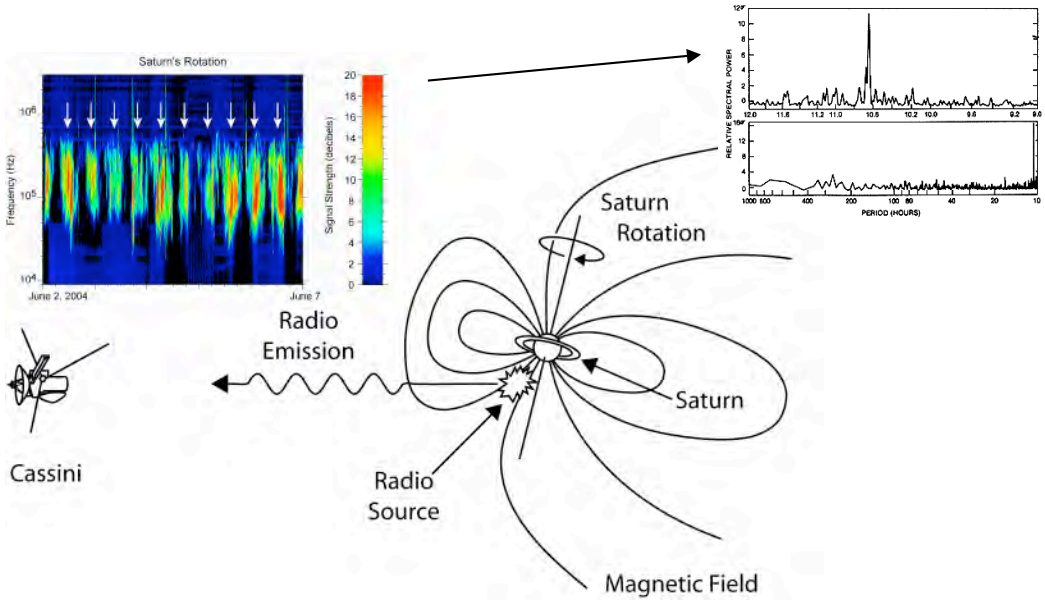
→ He rain/condensation ? (6% He compared to 13% at Jupiter)



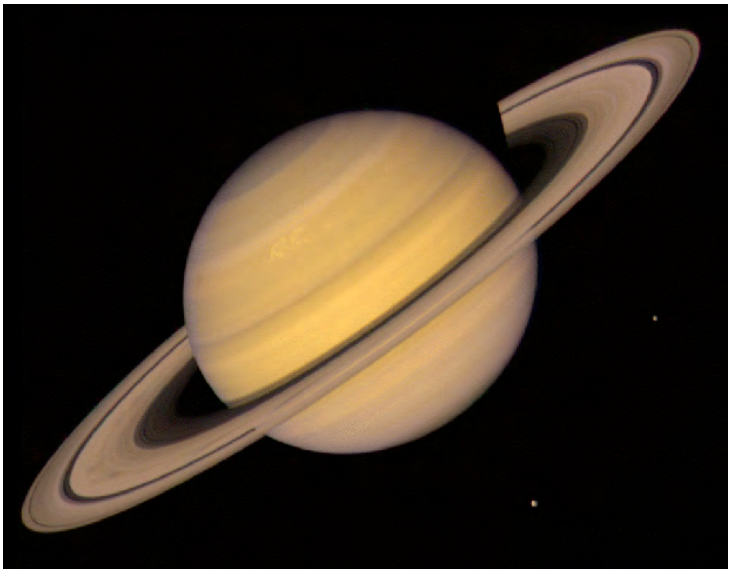
• Magnetic field ~axial → dynamo theory ? Source in metallic H ? *[MAG]*

• Magnetic field rotation period = 10h39.4 min *[Voyager-PRA]*

(from magnetospheric radio emissions modulation → reference for wind speeds)



• Radio rotation → polar flattening 9% (of fluid ball)



SOME QUESTIONS FOR CASSINI

- Internal structure *[Trajectory along many orbits]*
- Compare internal / external energy sources *[Temperature maps]*
- Magnetic anomalies ? *[MAG + Radio emissions]*

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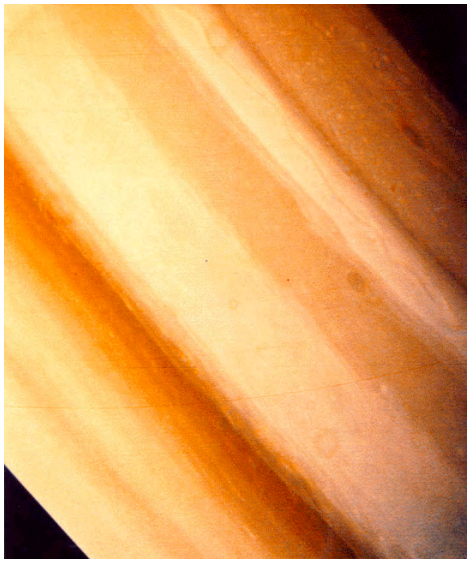
• H, He, minor constituents (10^{-6}) → chemistry, colors, rain ?

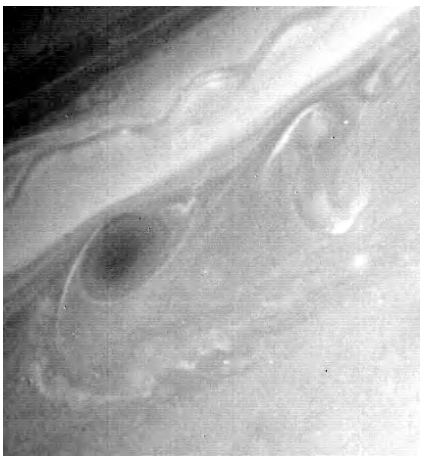
[Spectroscopy]

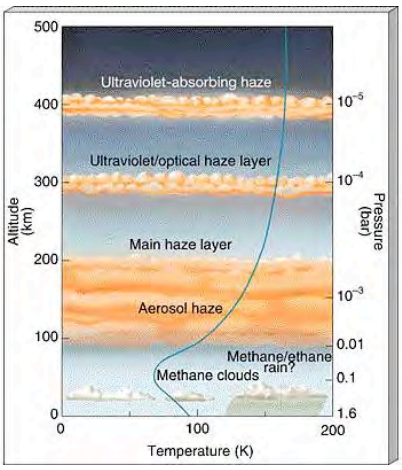


• Clouds & bands, cyclonic storms → convection + rotation

[Voyager ISS + P11 photopolarimeter]

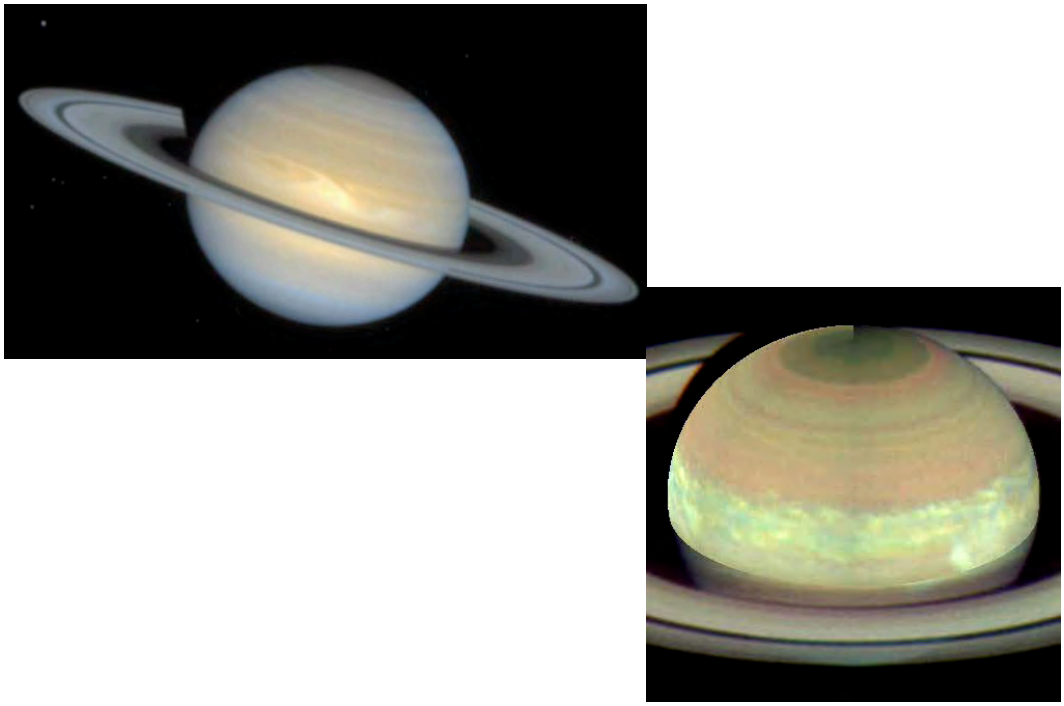
• T(z) profile, minimum ~1 bar level *[IR spectroscopy of ≠ components]*



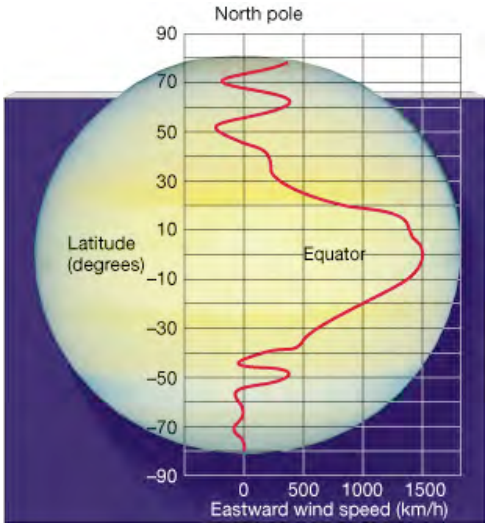


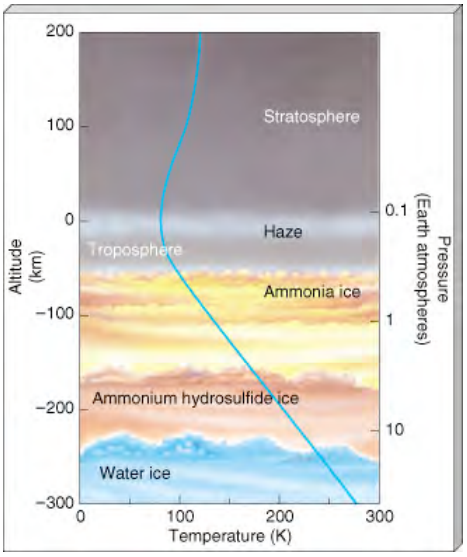
Convection : hot gas rises, cool, form clouds, sink/rain
+ Rotation/zonal winds → generates bands, cyclones
Primary engines = ΔT (latitude, z), strong internal energy source

• HST imaged a large storm in 1994



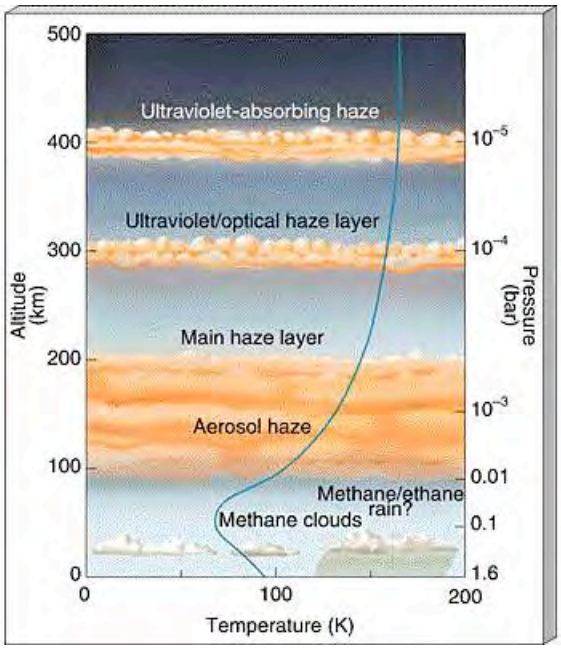
• Rotation period of clouds = 10h15 (equator) to 10h38 (poles)
→ winds up to 1800 km/h (= 5 × Jupiter) *[Imaging]*



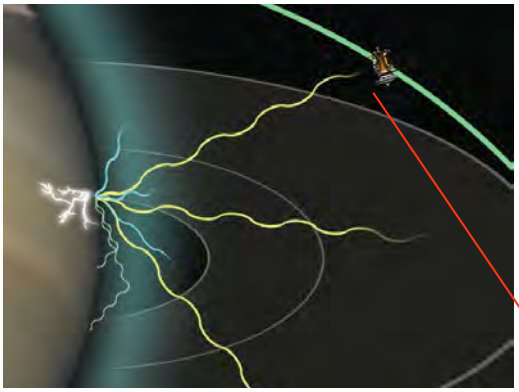


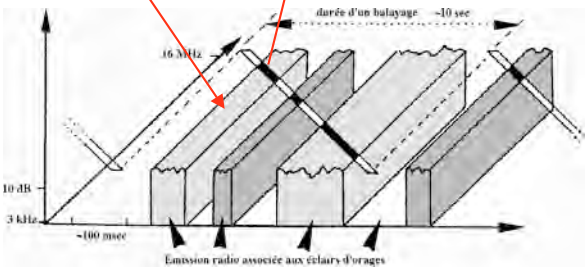
• Clouds of NH_3, NH_4SH, H_2O ? *[Voyager RSS + Theory]*

• Haze between 0.1 & 0.01 bar (cold planet) → dim colors
[Imaging, Spectroscopy, RSS]



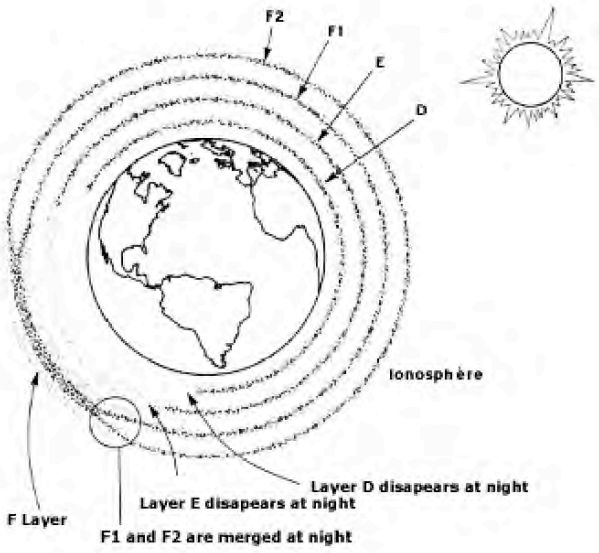
• Strong Lightning *[Radio Emissions]*





• Ionosphere density and temperature *[Lightning + Radio Science]*

• Hot thin exosphere up to 20 R_S, T=400-800 K



SOME QUESTIONS FOR CASSINI

- Maps of atmospheric T(L,λ,z), clouds, composition, winds
  [3 spectrographs : CIRS (molecules), VIMS, UVIS (atoms) + imaging ISS]
- Seasonal variations (white spot = NH_3 crystals ?…) *[ISS]*
- Opacity of haze & clouds *[UVIS, VIMS, RSS]*
  (absorption/emission lines, scattering at sunrise/sunset)
- Map lightning *[RPWS k vector]*
- Measure He/H & D/H ratios (→ solar system origin) *[UVIS, RSS]*
- Ne, T, P, winds in ionosphere, diurnal variations *[RPWS, RSS]*

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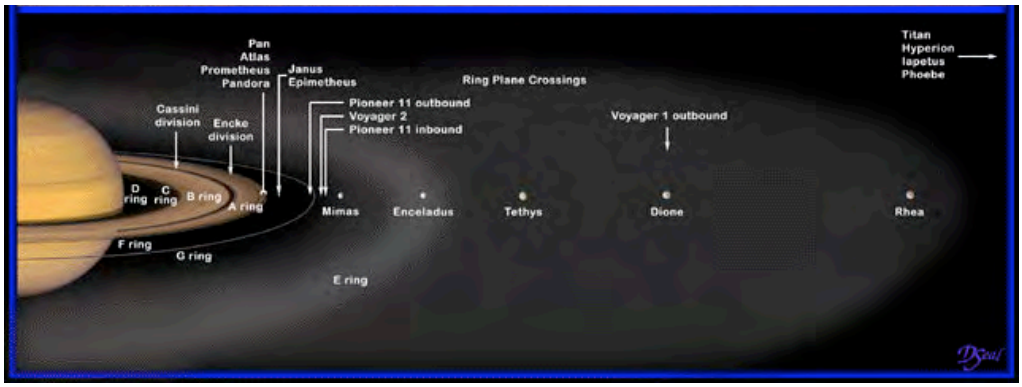
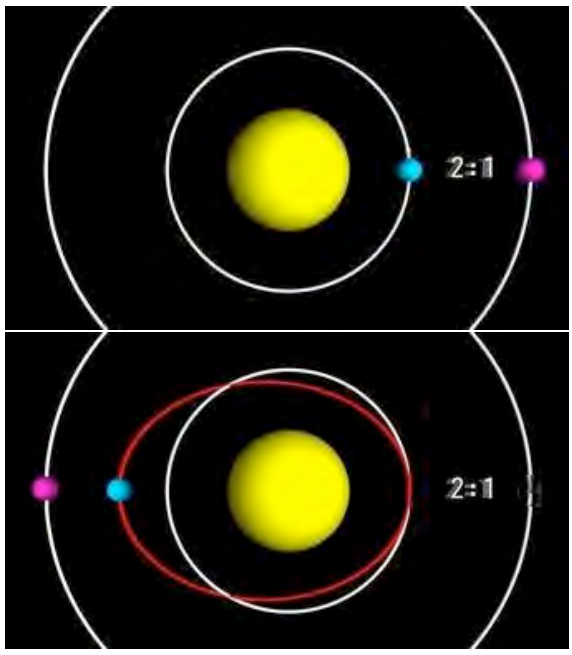
• 1866 Kirkwood finds Cassini gap resonant with Mimas

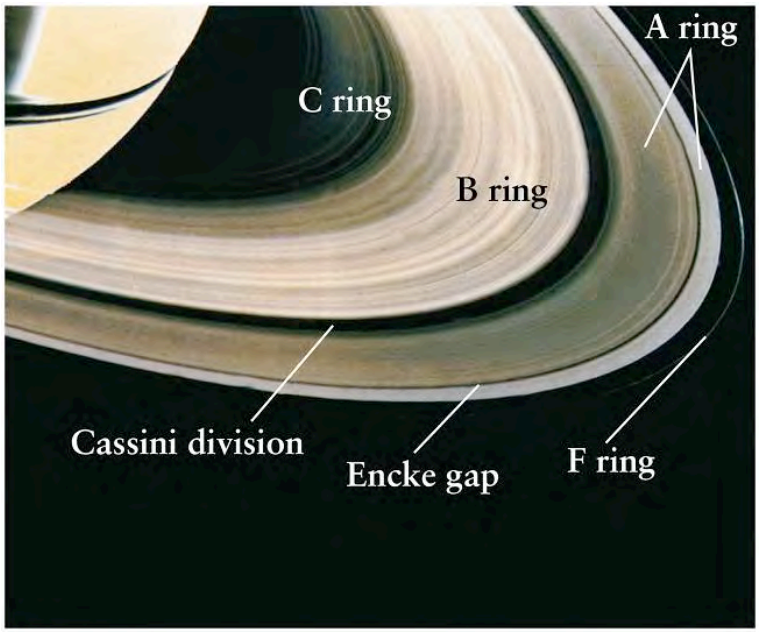
also true for Keeler/Encke gap



Resonances n :m → cumulative gravitational influence

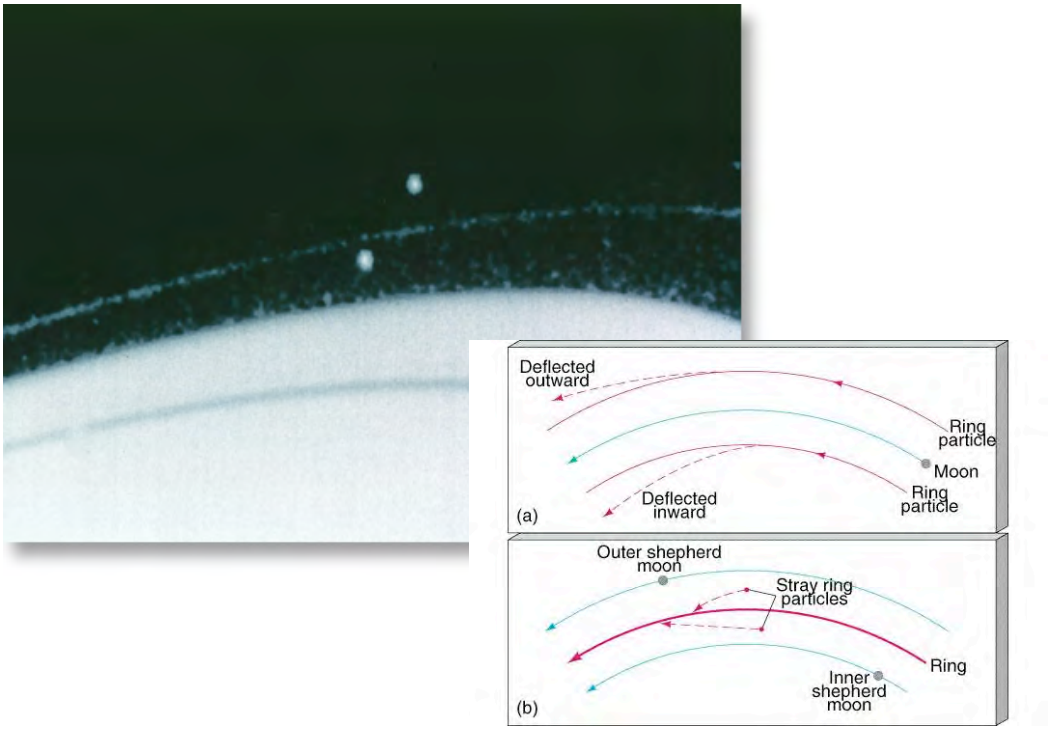


• Occultation of Iapetus by C ring → semi-transparent
• Cassini division not empty (Barnard, 1889-1908)

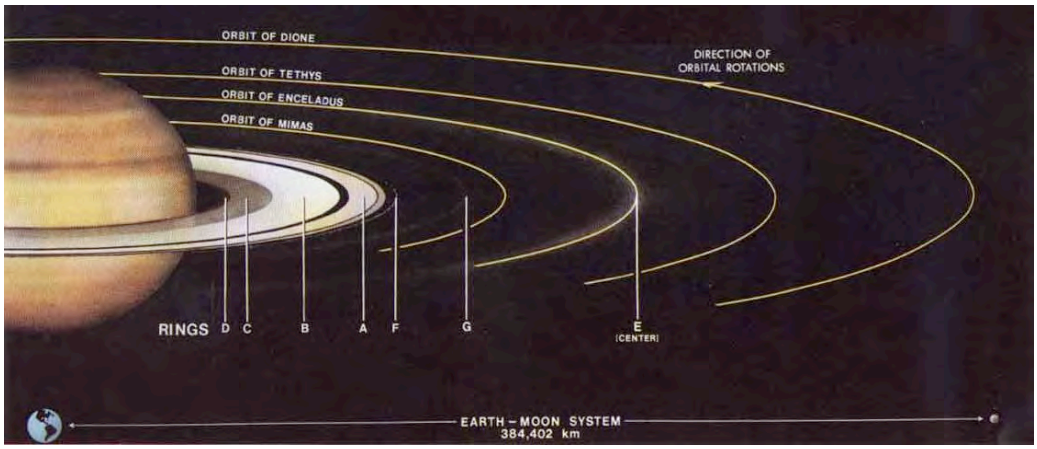


• 1979 Pioneer 11 discovers thin F ring *[Photopolarimeter]*
→ seen braided & kinked by Voyager

• Voyager discovered shepherds satellites



• 1980 Voyager 1 discovers D & G rings *[ISS, PPS]*

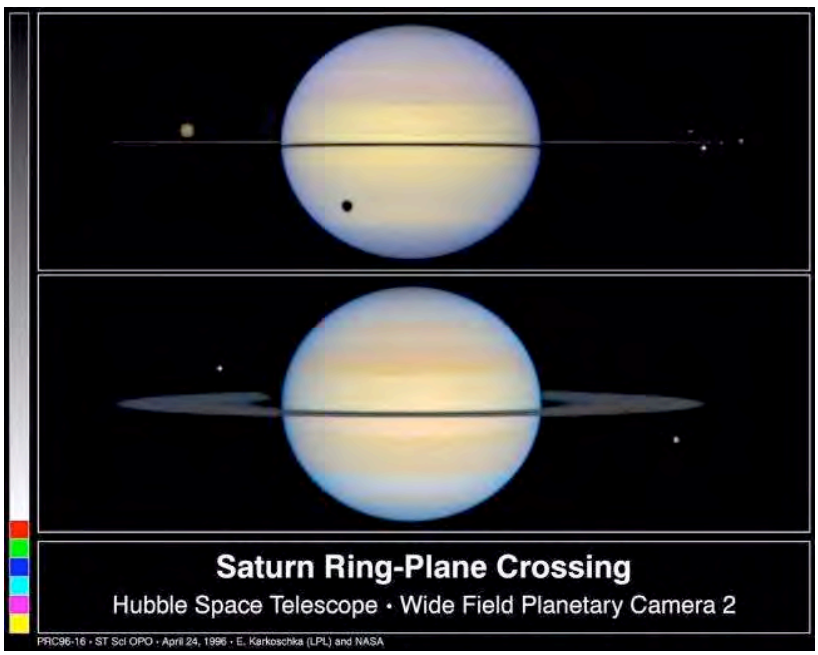


THE RINGS OF SATURN

Ring	Distance, kilometers*	Width, kilometers
D	66,970	7,500
C	74,500	17,500
B	92,000	25,400
A	122,170	14,610
F	140,180	50
G	170,180	8,000
E	180,000	300,000

* *Distance from Saturn to closest edge of ring.*

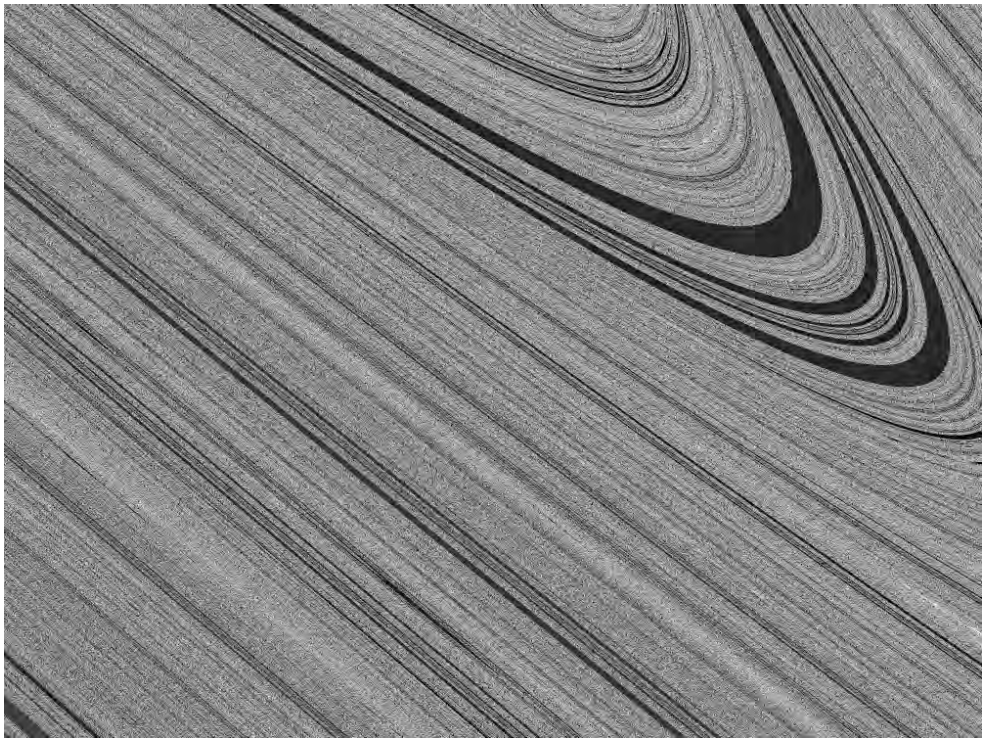
• Thickness of rings ~100 m *[ISS, RSS]*



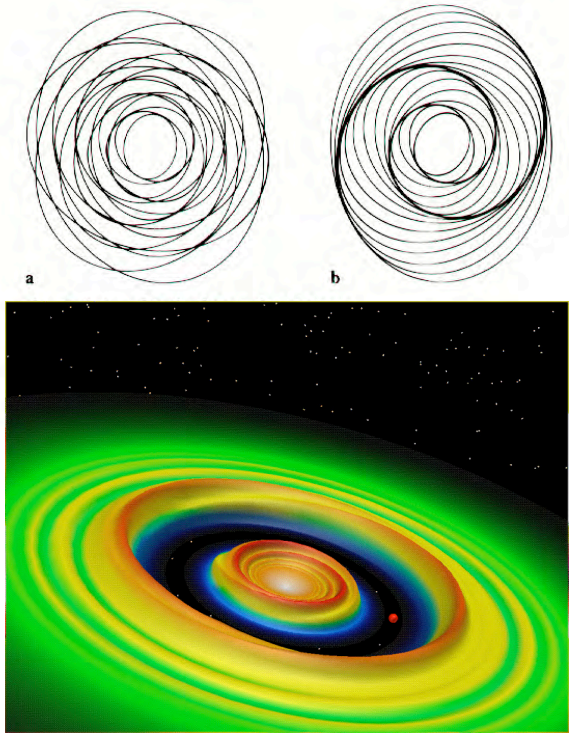
• 500-1000 ringlets → resonances ?

[Star occultation observed by Voyager 2, PPS, UVS]

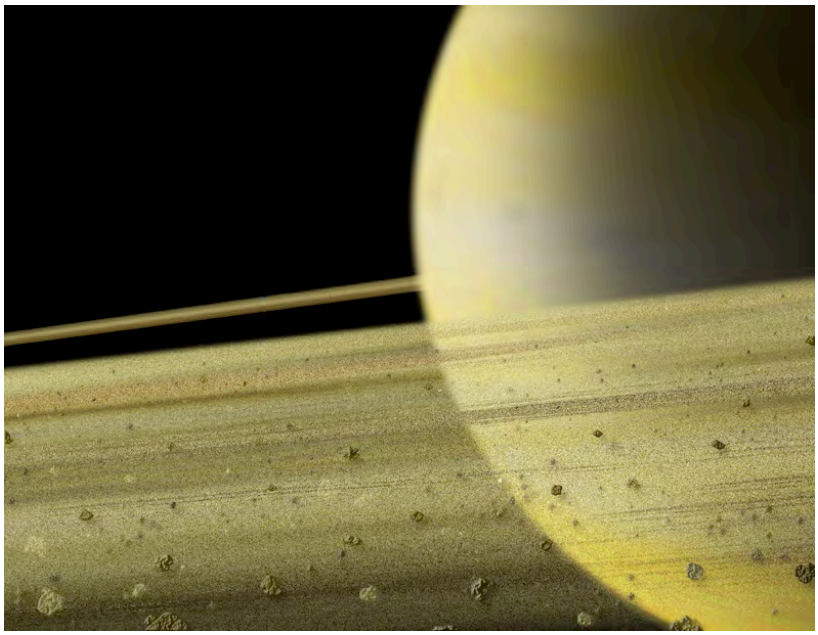
• Eccentric & azimuthally asymetric ringlets



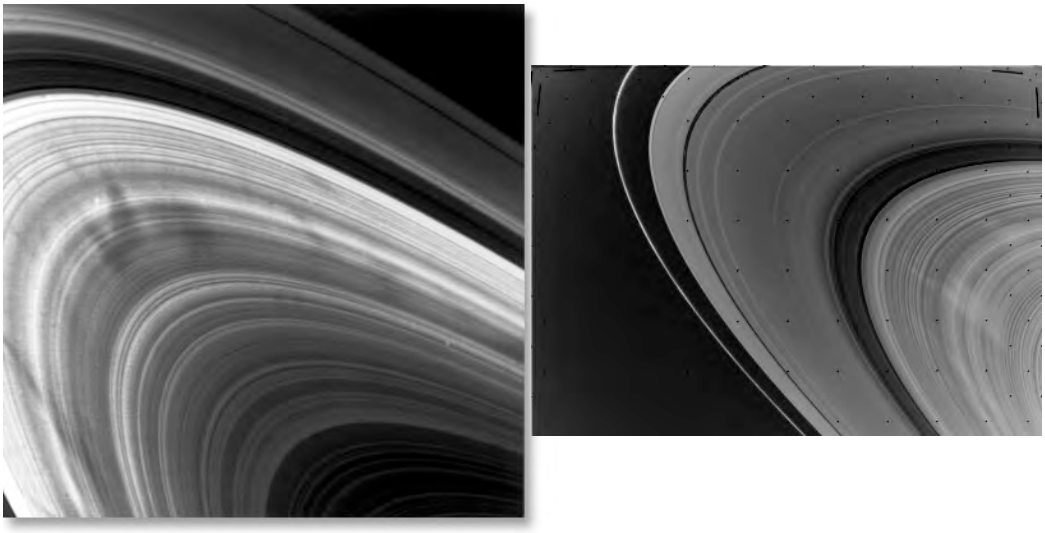
• Density waves (~spiral) → resonances



• Particle size distribution (most of the mass in cm-m range)
& measure of collision-viscosity *[RSS]*



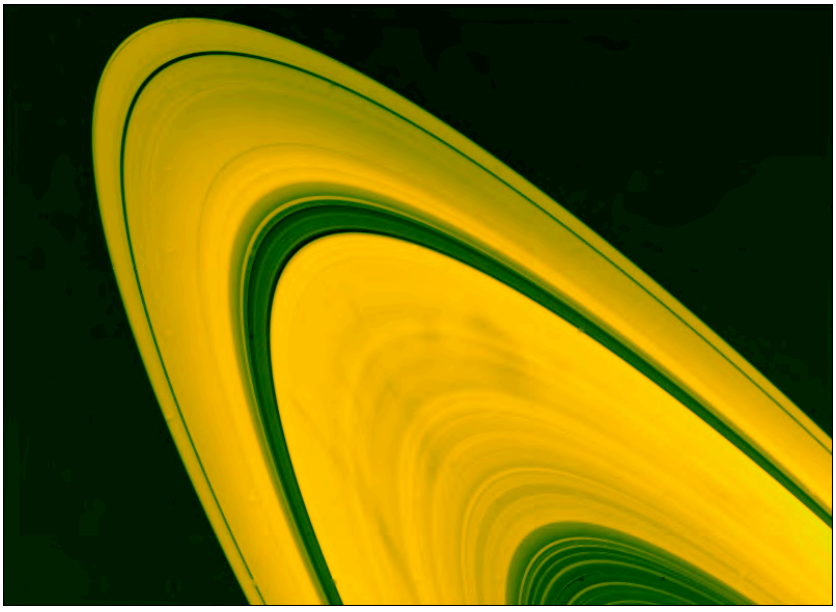
• Spokes (~radial, dark/bright features in back/forward scattered light, rapid apparition) → micron sized particles in e.s. levitation ? *[ISS, PPS]*



Scattering probability of a photon λ (fraction of incident light deviated) by a particle of size r : $P(\lambda) \propto 1/\lambda^2$ *(r ~ λ) mostly forward*
$P(\lambda) \propto 1/\lambda^4$ *(r << λ) ~isotropic*

• Colors → composition ~ pure H_2O ice + impurities

• Differences between rings *[ISS, Spectroscopy]*



SOME QUESTIONS FOR CASSINI

- Why several morphologically distinct rings ?
- Complex structure (more than resonances can explain)
  → many embedded moonlets to discover ?
  → extensive monitoring for moonlets and/or density waves at ring edges
- Formation : satellite broken / not formed, or comets captured ?
- Stability ? theory predicts 40-400 Myears lifetime
  → short-lived, with recurrent formation/dissipation ?
- Why almost pure ice in spite of particle bombardment ?
- Spoke formation ? Relation to Magnetosphere & Radio emission ?
- Relation between ring composition and satellite composition (e.g. is Enceladus the source of E-ring ?)

[INMS, CDA, CAPS measurements in many geometries, illuminations, phase angles]

SUMMARY OF PRE-CASSINI KNOWLEDGE ABOUT SATURN & QUESTIONS TO BE ADDRESSED BY CASSINI

(1) Saturn's interior

(2) Saturn's atmosphere

(3) Rings

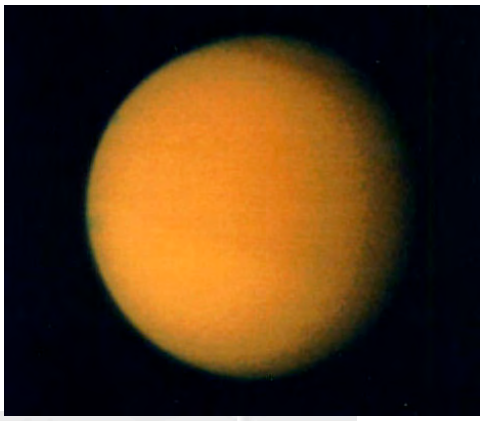
(4) Titan

(5) Icy satellites

(6) Magnetosphere

• Orbit at 20.3 R_S from Saturn

→ *Voyager 1 flyby at 4000 km*

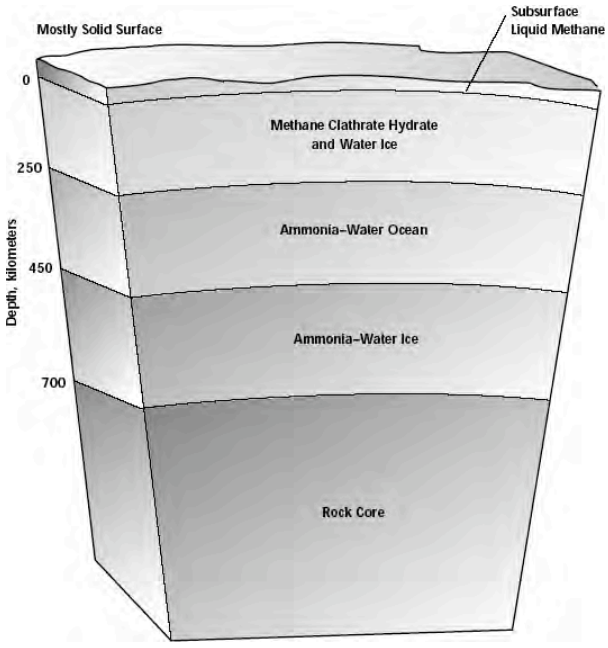


SIX GIANT SATELLITES

Satellite (Planet)	Titan (Saturn)	Moon (Earth)	Io (Jupiter)	Europa (Jupiter)	Ganymede (Jupiter)	Callisto (Jupiter)
Distance from Parent, kilometers	1,221,850	384,400	421,600	670,900	1,070,000	1,883,000
Rotation Period, days	15.945	27.322	1.769	3.551	7.155	16.689
Radius, kilometers	2575	1738	1815	1569	2631	2400
Average Density, grams per cubic centimeter	1.88	3.34	3.57	2.97	1.94	1.86

• Density 1.88 → 50% rock, 50% H_2O ice

[S/C trajectory]

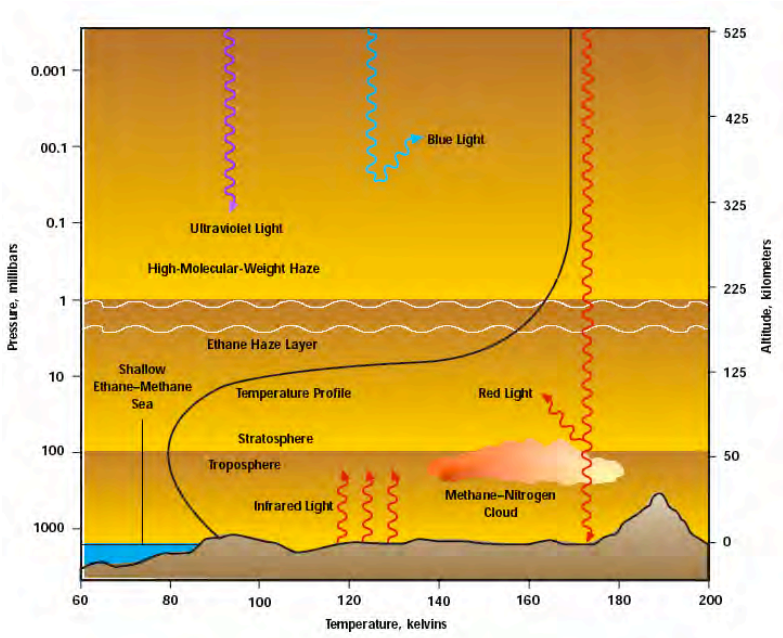


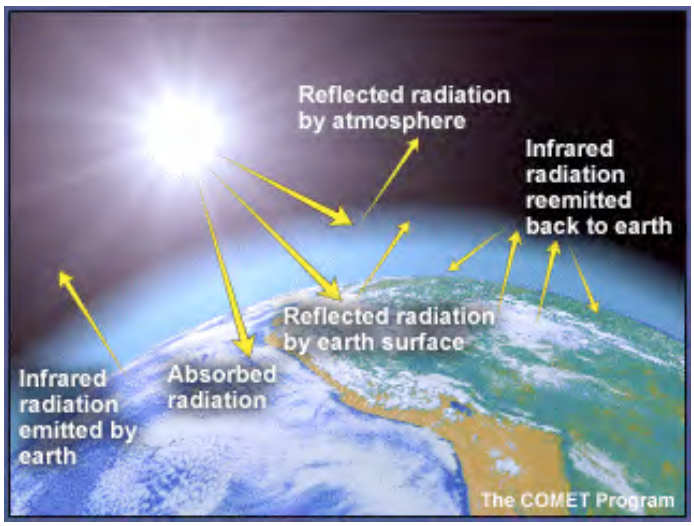
• Atmosphere : N2 + a few % CH_4 *[Spectroscopy]*

CONSTITUENTS OF THE TITAN ATMOSPHERE

Chemical Constituent	Common Name	Atmospheric Concentration
N_2	Nitrogen	90–97 percent
Hydrocarbons		
CH_4	Methane	2–10 percent
C_2H_2	Acetylene	2.2 parts per million
C_2H_4	Ethylene	0.1 parts per million
C_2H_6	Ethane	13 parts per million
C_3H_8	Propane	0.7 parts per million
Nitriles		
HCN	Hydrogen cyanide	160 parts per billion
HC_3N	Cyanoacetylene	1.5 parts per billion

• Thick atmosphere ($P_{surface}$ = 1.5 bar) → Greenhouse effect, $T_{surface}$=94 K
[Star occultation, 1989]

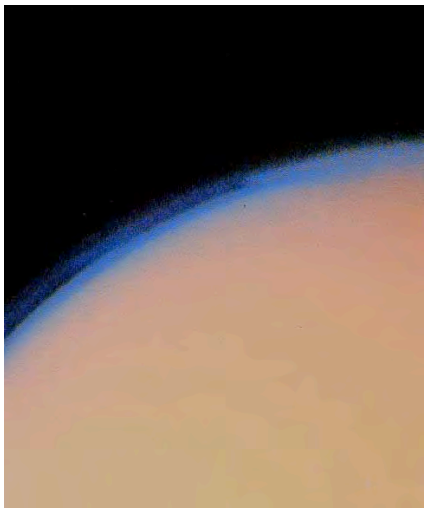


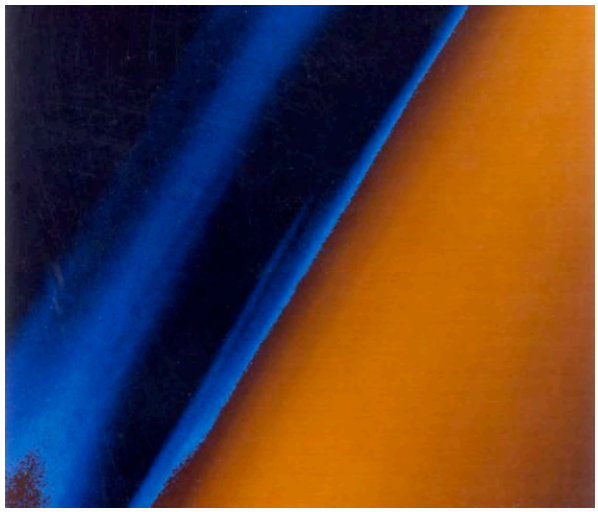


Greenhouse effect :
Thick atmosphere lets Visible light In, prevents IR to exit
→ heats surface → reradiates
→ T_{max} at low & high z, T_{min} at mid z

- Photochemistry (+ bombardment by magnetospheric electrons)
  → C_nH_n smog & haze (500 km > clouds)
  → condense/polymerize + rain ? → organic compounds on soil ?

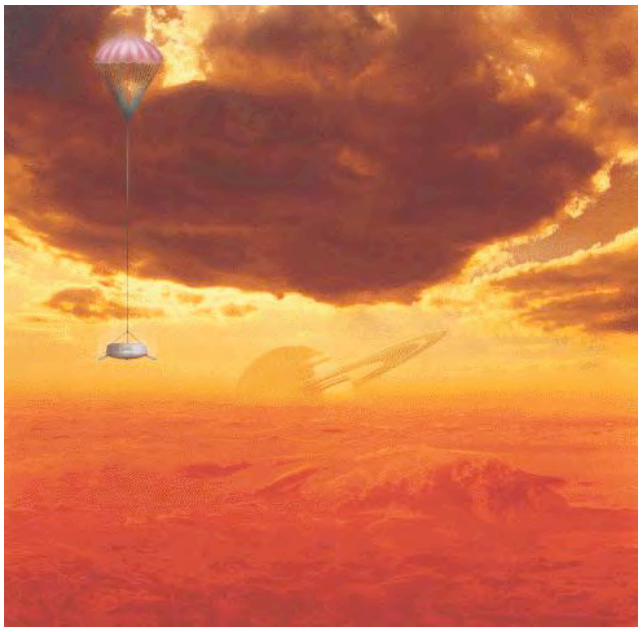
[Imaging, Spectroscopy + Theory, Modelisation, Lab. Experiments]





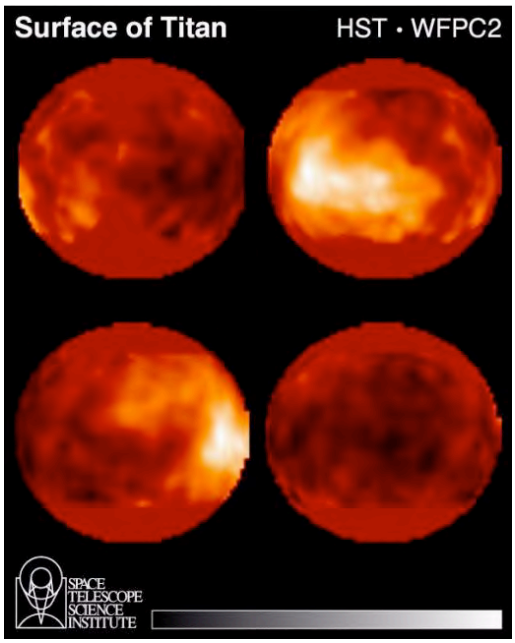
Smoggiest world in solar system, 1/1000 solar luminosity / Earth !

• Solid surface ? Ocean (up to 1 km deep) ? Lakes or subsurface (in sputttered regolith) reservoirs of CH_4, C_2H_6 … ?



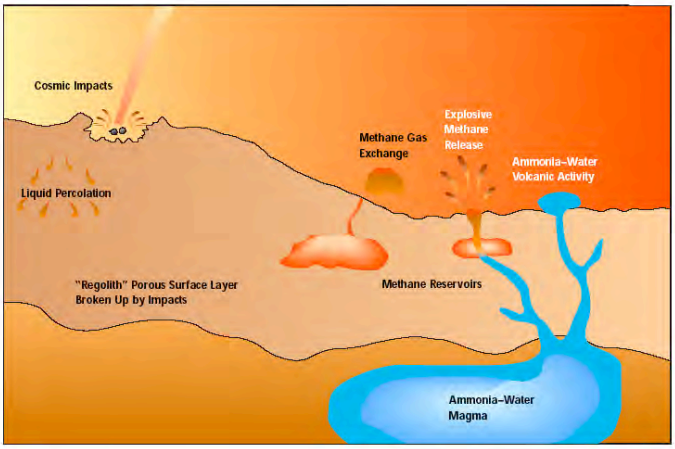
• Ground-based observations → no global ocean, bright spot

[Earth based RADAR + NIR/AO + HST/WFPC2]



• Ice tectonics ? H_2O + NH_3 magma, possibly erupting ?

15% more NH_3 at 10 AU than at 5 AU ; NH_3 ~antifreeze
→ liquid below H_2O ice surface → favours cold tectonics ?

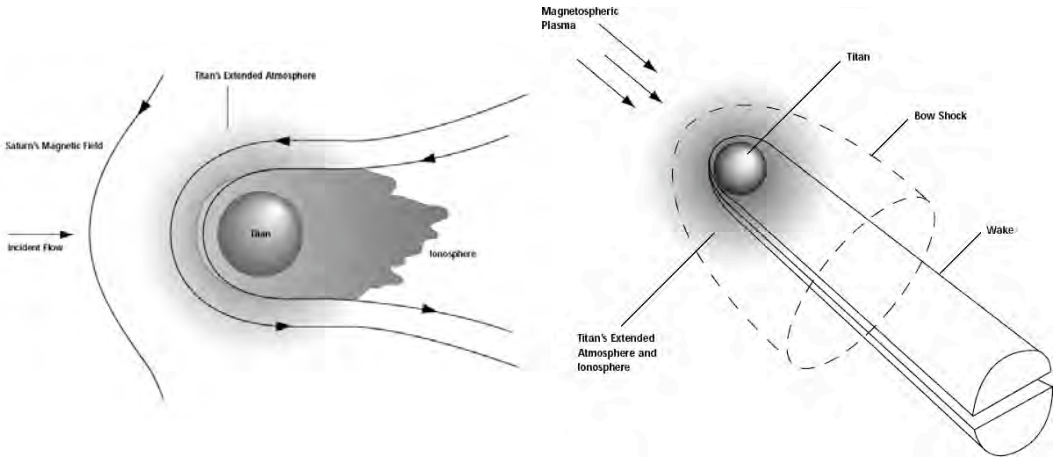


• ΔT equator-poles = 15K → winds, jet streams at high altitude ? *[IR spectroscopy]*

• No lightning ? *[Voyager-PRA]*

• No magnetic field ? ($B_{equator}$ < 4 nT) *[MAG]*

• Plasma wake (interaction with magnetosphere) *[Voyager-PLS, PWS]*



SOME QUESTIONS FOR CASSINI

- Structure of interior ? differentiated ? *[S/C path along 40 close flybys]*
- Origin / evolution of atmosphere ? *[Spectroscopy UVIS, VIMS, CIRS]*
- N_2 primordial or from cometary NH_3 ? *[Ar/N_2 concentrations]*

Ar & N_2 have same condensation Temperature → if N2 primordial, Ar/N_2 ratio should have the solar nebula value ; Voyager suggests 6× less (but poor sensitivity)

- H escapes in C_nH_n reactions → irreversible → lost in 10^7 years
  → source of C_nH_n cycle ? ocean ?
- Clouds, rain ? (Voyager → supersaturated atmosphere) *[RSS]*
- Lightning ? *[RPWS, ISS, HP instruments]*

SOME QUESTIONS FOR CASSINI (continued)

- Nature of surface ? Ocean, continent size plateau ?
  [long (IR) wavelength imaging - VIMS]
- Ice tectonics, Craters, Erosion → geological activity ?
- Prebiotic chemistry ? Titan = Primitive Earth in fridge ?
  (but no liquid water except perhaps temporarily after large impacts)
  [Spectroscopy, HP instruments]
- Interaction with dust & ring particles ? *[CDA]*
- B field ? Interaction with Magnetosphere (transsonic) or Solar Wind (supersonic) at various locations *[MAG, INMS, RPWS, UVIS]*
- Source of Magnetospheric plasma ? Nitrogen torus ? *[CAPS, INMS]*
- High energy particle environment (bombardment) *[MIMI]*

Huygens Probe instruments :

- HASI → atmospheric properties (T, density, P, electrical)
- Radar Altimeter → surface properties (Δz, roughness)
- GCMS → chemical comp. analysis
- ACP → captures/vaporizes aerosols → sends to GCMS
- DISR → opacity, clouds, surface features (solar energy deposited at each altitude, reflectance)
- Doppler Wind Experiment → trajectory, winds, turbulence, liquid waves *(+VLBI)*
- SSP → surface solid/liquid properties

SUMMARY OF
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(1) Saturn's interior

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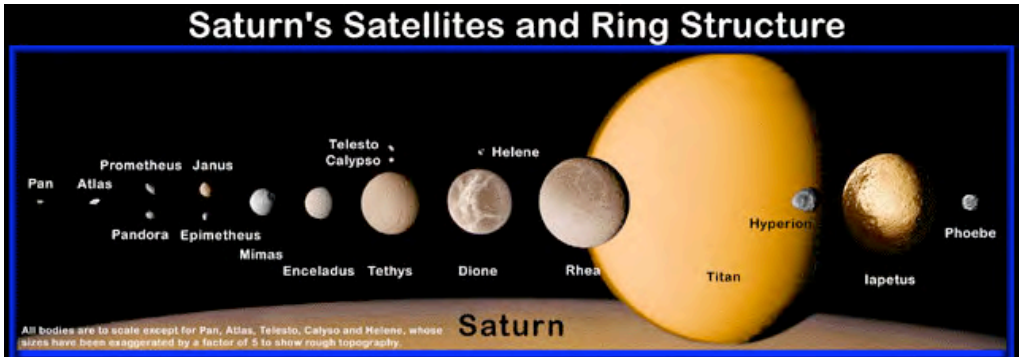


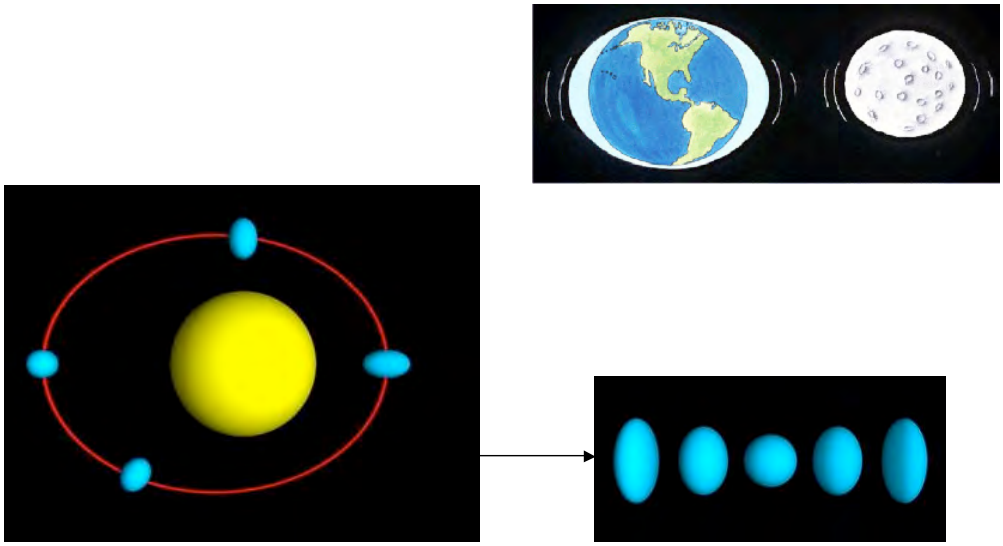
• After Voyager 17 satellites known (+1 found in 1990 using 1981 data)

[Voyager trajectories, Imaging, Crater counts + Spectroscopy]

THE KNOWN MOONS OF SATURN

Moon	Diameter, kilometers	Distance, kilometers	Orbital Period, days	Year Discovered: Discoverer
Pan	20	133,580	0.56	1990: Showalter
Atlas	30	137,670	0.60	1980: Terrile
Prometheus	100	139,350	0.61	1980: Collins
Pandora	90	141,700	0.63	1980: Collins
Epimetheus	120	151,450	0.69	1966: Walker
Janus	190	151,450	0.69	1966: Dolfus
Mimas	392	185,520	0.94	1789: Herschel
Enceladus	500	238,020	1.37	1789: Herschel
Tethys	1060	294,660	1.89	1684: Cassini
Telesto	30	294,660	1.89	1980: Smith
Calypso	26	294,660	1.89	1980: Smith
Dione	1120	377,400	2.74	1684: Cassini
Helene	32	377,400	2.74	1980: Laques and Lecacheux
Rhea	1530	527,040	4.52	1672: Cassini
Titan	5150	1,221,830	15.94	1655: Huygens
Hyperion	290	1,481,100	21.28	1848: Bond
Iapetus	1460	3,561,300	79.33	1671: Cassini
Phoebe	220	12,952,000	550.40	1898: Pickering

• All tidally locked in synchronous rotation except Hyperion & Phoebe



Tidal forces → energy dissipation → locking of smaller body in synchronous rotation (in a few 10^6 years)

• Most sustained geological activity during ≥ 10^9 years (differentiation, eruptions, resurfacing)

→ Engines = primordial gravitational energy, tidal/resonant interactions, cratering, or radioactive decay

→ Presence of hydrated NH_3, CH_4 in H_2O clathrate may increase geological activity

• Not all geologically dead : Is Enceladus still active ?

• Sputtering by micrometeorites or energetic particles
→ modify surface properties (brighter if fresh material excavated)
→ leading face of satellites often brighter *(cf. Iapetus)*

• No atmosphere (thermal escape)

• 6 medium sized satellites :

➢ Mimas : large impact crater (Herschel) + breaks
→ little viscous relaxation, episodes of resurfacing

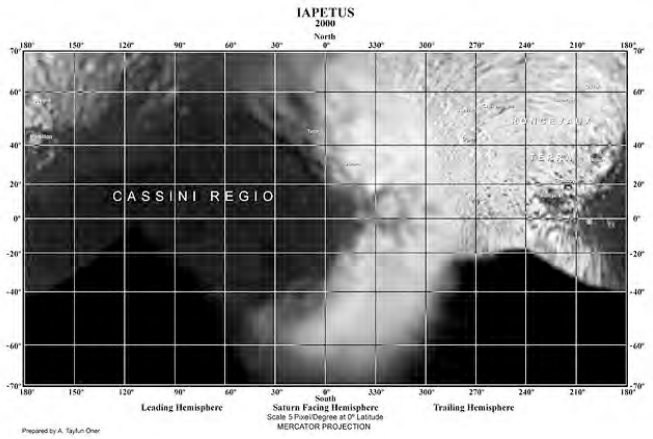
➢ Enceladus : bright with streaks (~Ganymede), pure water ice ?
extensive resurfacing through volcanism ?

➢ Tethys : largest impact crater (Odysseus), huge trench (Ithaca chasma)

➢ Dione : more dense, diverse surface morphology

→ internal activity ? Auroral radio source modulation ?

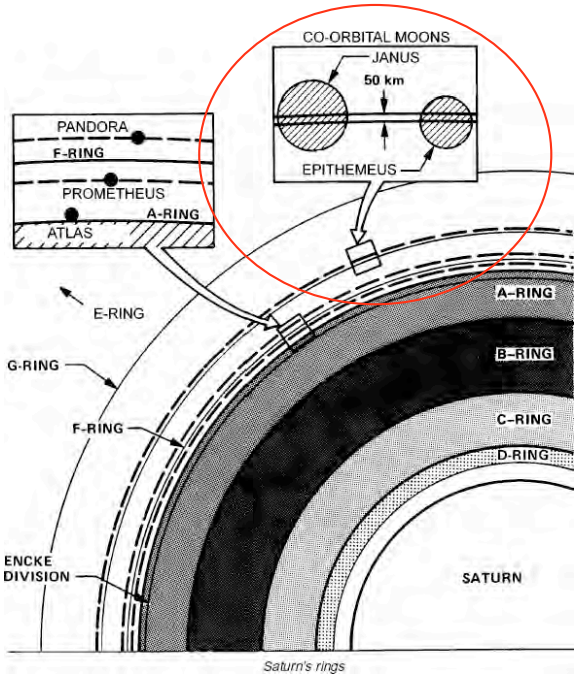
➢ Iapetus : bright/dark faces, highly inclined orbit



• Small satellites with irregular shape :

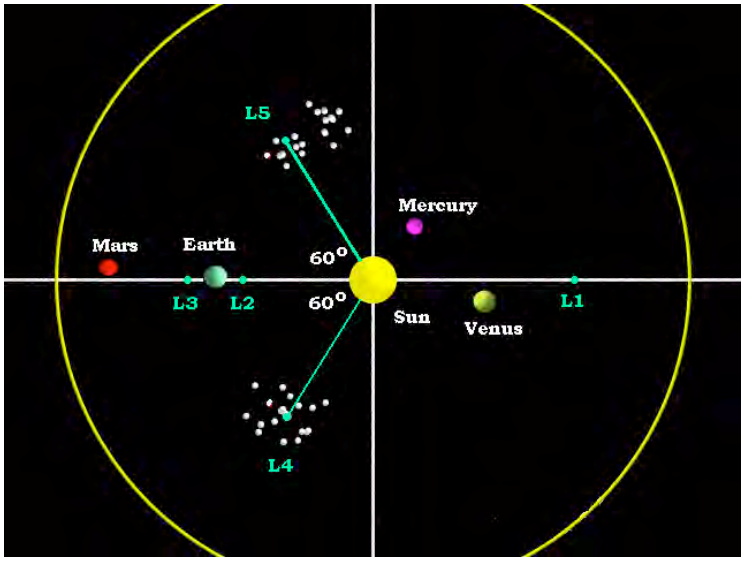
➢ 3 shepherds : Prometheus & Pandora for F ring
Atlas at outer edge of A ring

- Co-orbital Janus & Epimetheus (discovered in 1966 & 1978)
  crossing with orbit exchange every 4 years

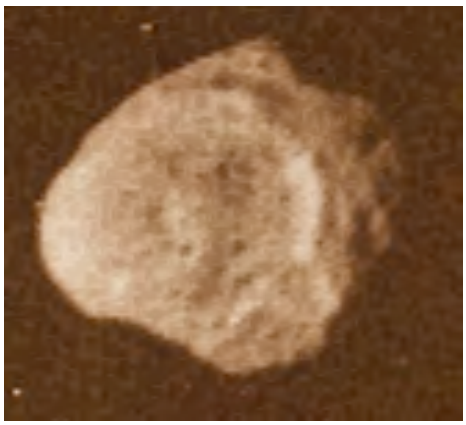


Saturn's rings

- Calypso, Helene & Telesto at Lagrangian points (60°) of larger satellites
  (~trojan asteroids / Earth or Jupiter)

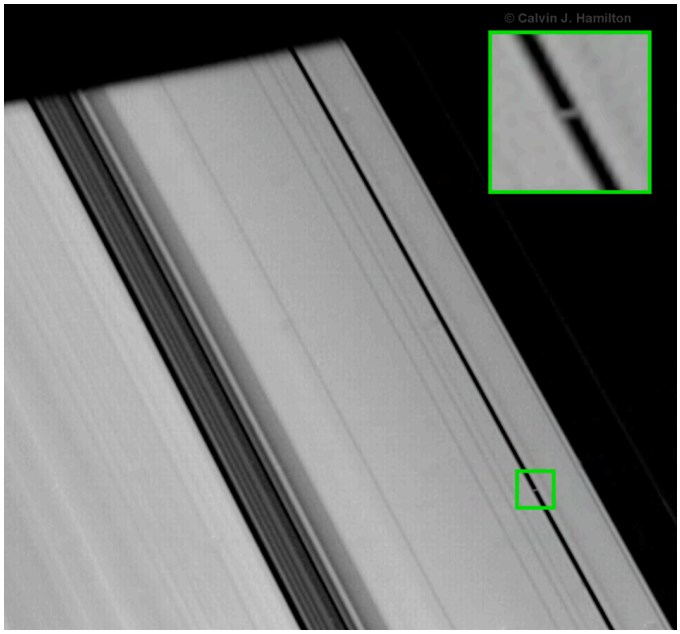


- Phoebe : outermost, dark and highly inclined retrograde orbit
  → captured asteroid ?
  simple asynchronous rotation of 9 hours



- Hyperion : larger but more irregular than Phoebe, chaotic rotation
  → bombardment / fragmentation ?
  → perhaps recently knocked out of tidal locking

➢ Pan : embedded in Encke gap in A ring , last discovered



SOME QUESTIONS FOR CASSINI

- New satellites, densities, gravitational interactions with rings
  [S/C path along many close flybys]
- Morphology, geology, crater counts, relation to composition
  → structure, diffferentiation ? *[ISS]*
- Surface compositions (volatiles, hydrates, clathrates, impurities)
  [VIMS, UVIS, CIRS]
- Origin of dark material on Iapetus, Hyperion, Phoebe
  → unprocessed primordial or organic ?
- Comparison of rings, dust, satelllite composition → origin ? *[CDA]*
- Enceladus = source of E ring ? still active ? (look for geysers, plumes)
- Origin of Phoebe ? Captured from Kuiper belt ?
- Relations satellite – magnetosphere (sources ?) *[CAPS, INMS, RPWS]*
- Radio emission modulation by Dione ? *[RPWS, MAG]*

SUMMARY OF
PRE-CASSINI KNOWLEDGE ABOUT SATURN
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QUESTIONS TO BE ADDRESSED BY CASSINI

(1) Saturn's interior

(2) Saturn's atmosphere

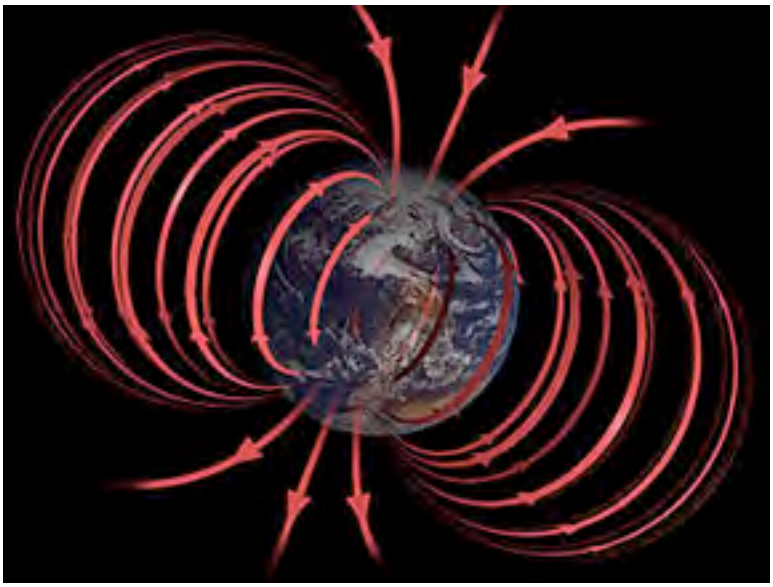
(3) Rings

(4) Titan

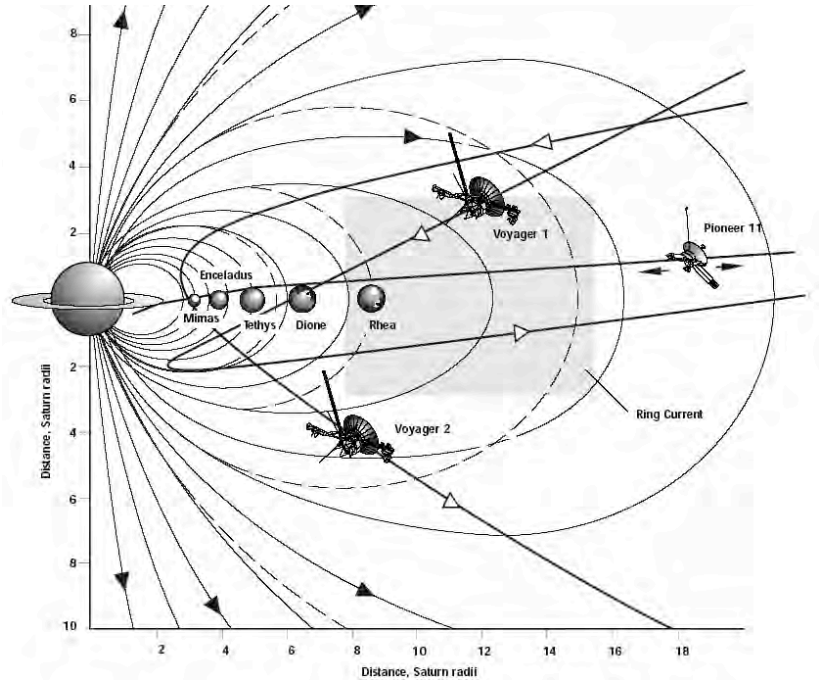
(5) Icy satellites

(6) Magnetosphere

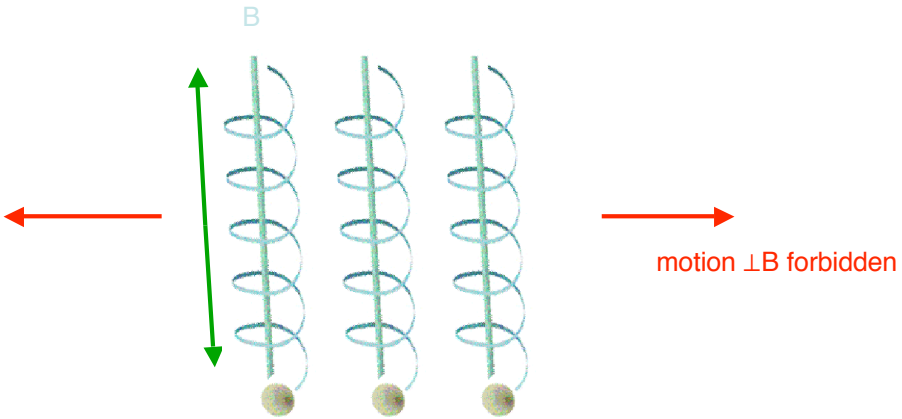
Planetary magnetic fields are dipole-like



• Saturn's field with polarity opposed to Earth (same as Jupiter), ~axial

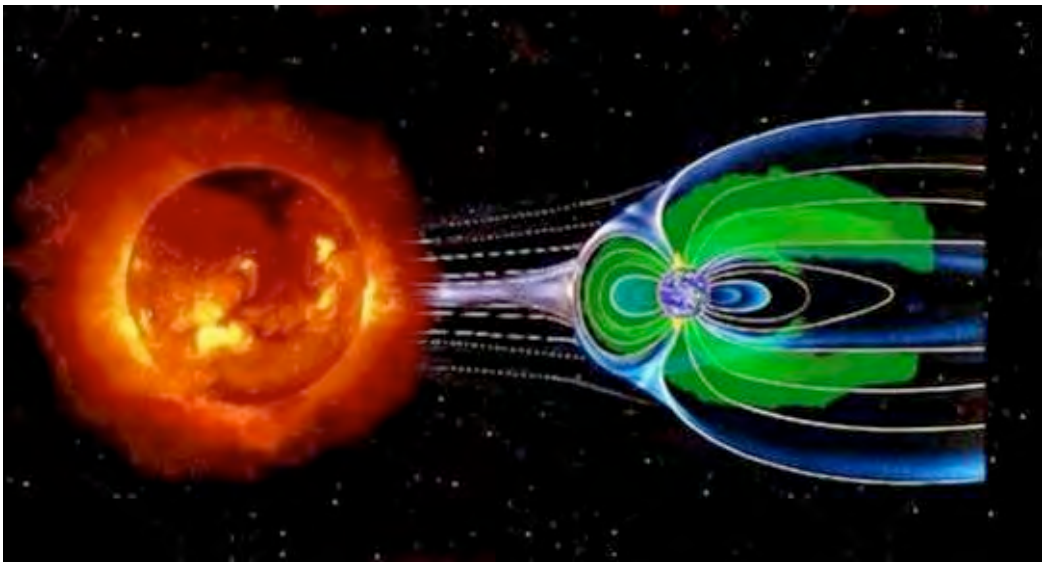


Constrains the motion of charged particles



Giration and motion // B allowed

Solar Wind cannot penetrate planetary field
→ formation of magnetospheric cavity



Solar Wind cannot penetrate planetary field
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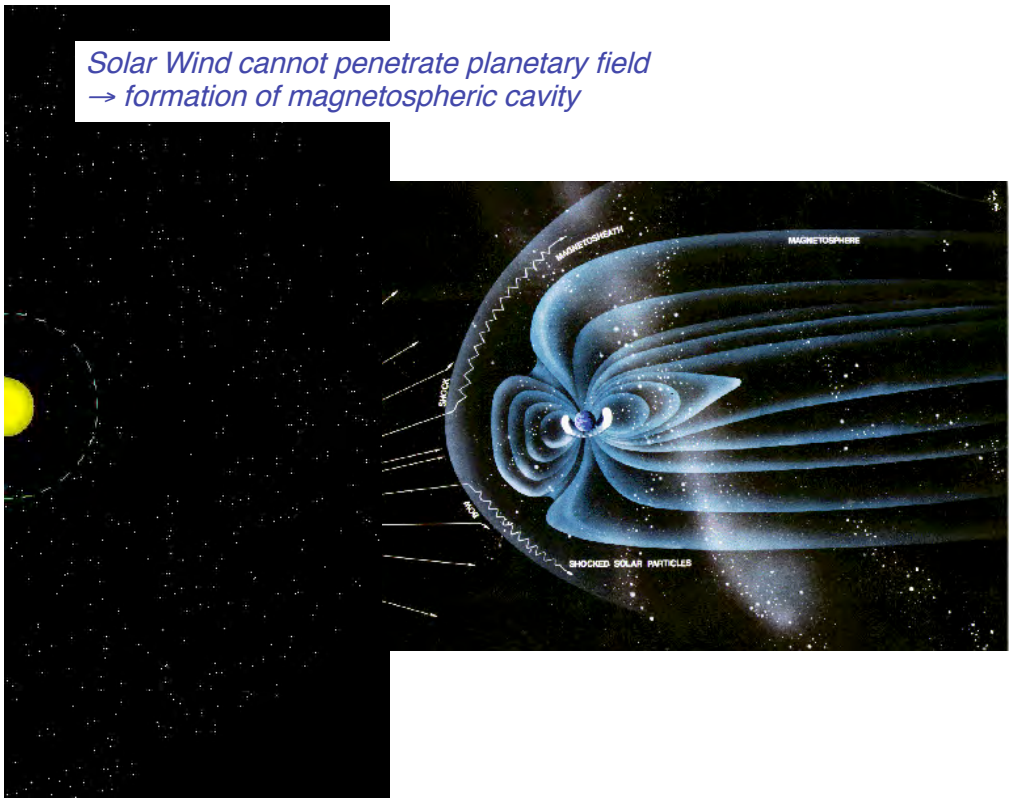
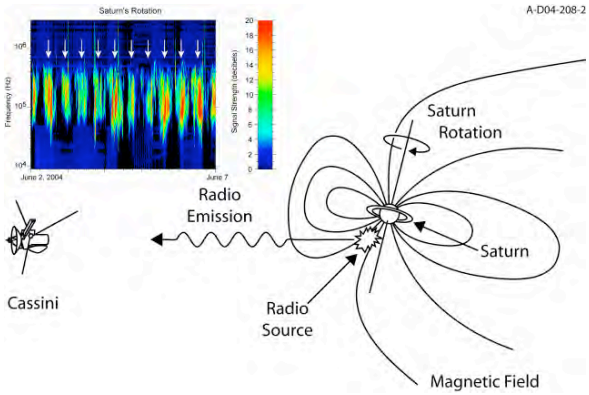
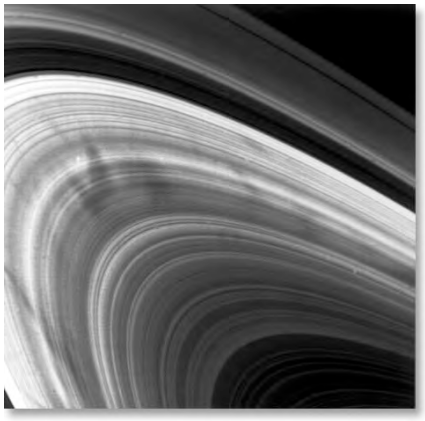


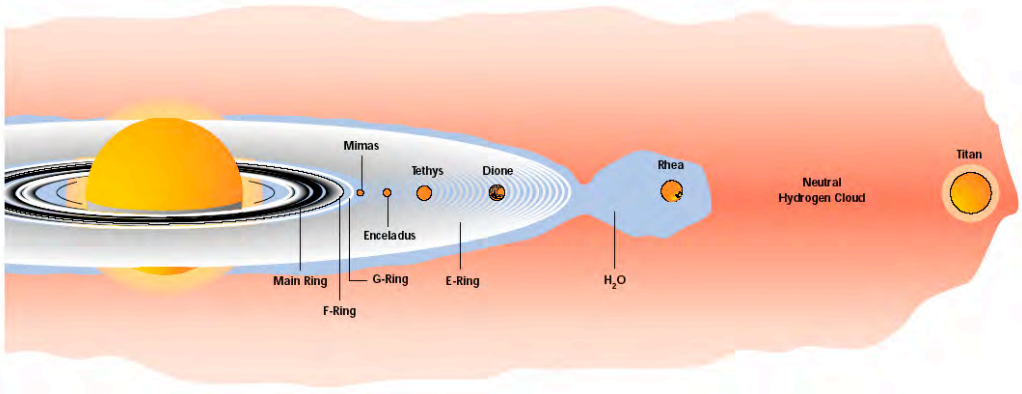
• Saturn's magnetosphere size = 20 x Earth's magnetosphere
[Waves & particles instruments + UV on Pioneer 11 and Voyager 1 & 2, + HST]
• B axial forbidden by dynamo theory
+ rotational modulation of radio emission, energetic electron spectra, spokes formation …





• 1% variations of radio period measured by Ulysses !

• Many sources of plasmas
(escape, sputtering from rings and satellites, Titan, solar wind, ionosphere)
2 at Earth, 3 at Jupiter

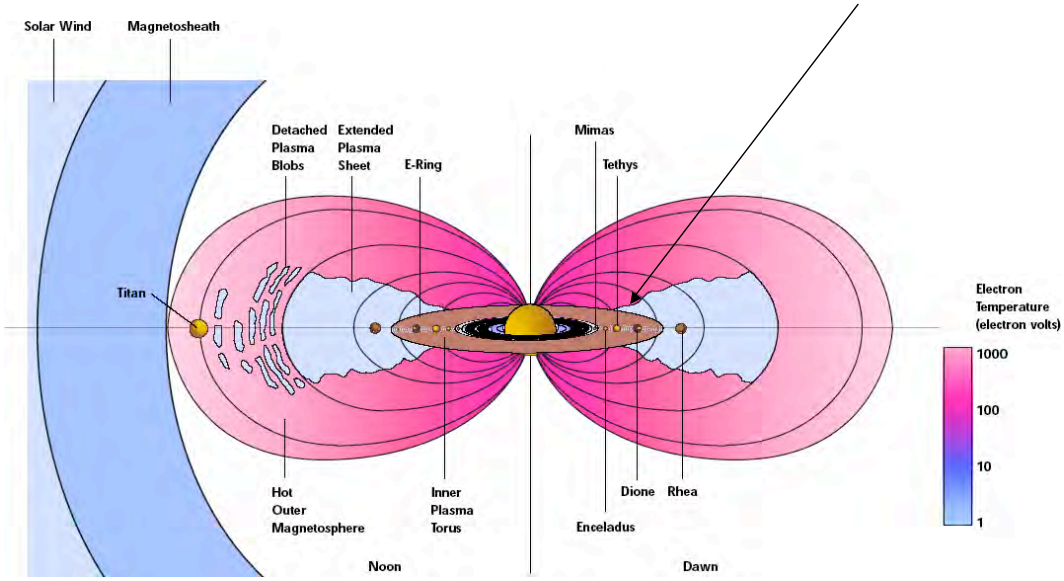


• Magnetospheric structure :

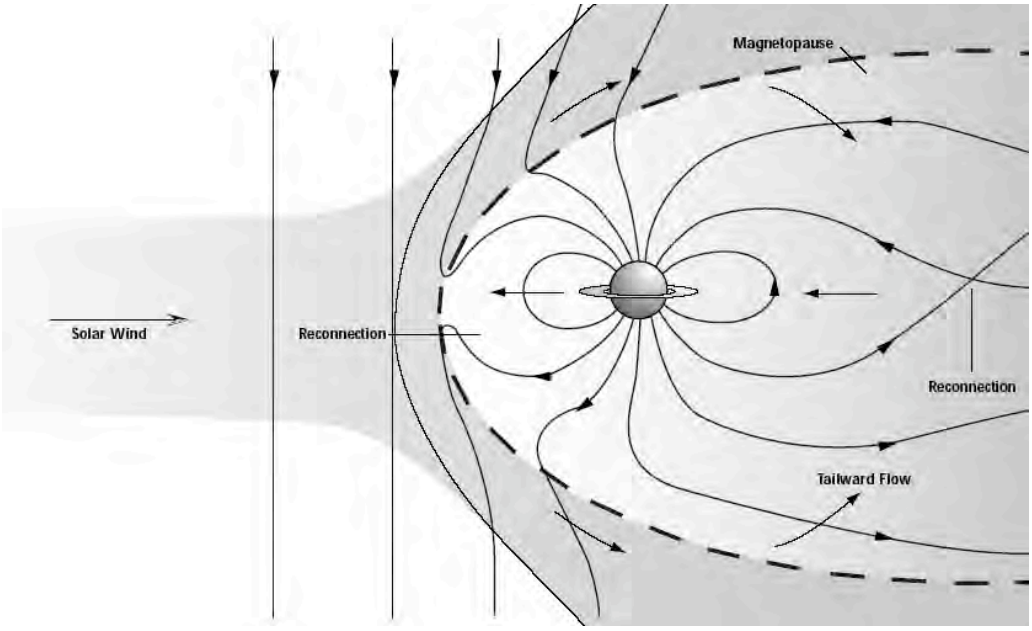
→ quiet inner MS (interaction with ring material ?), with Dione-Tethys O torus

→ hot outer variable MS (rotational energy ?)

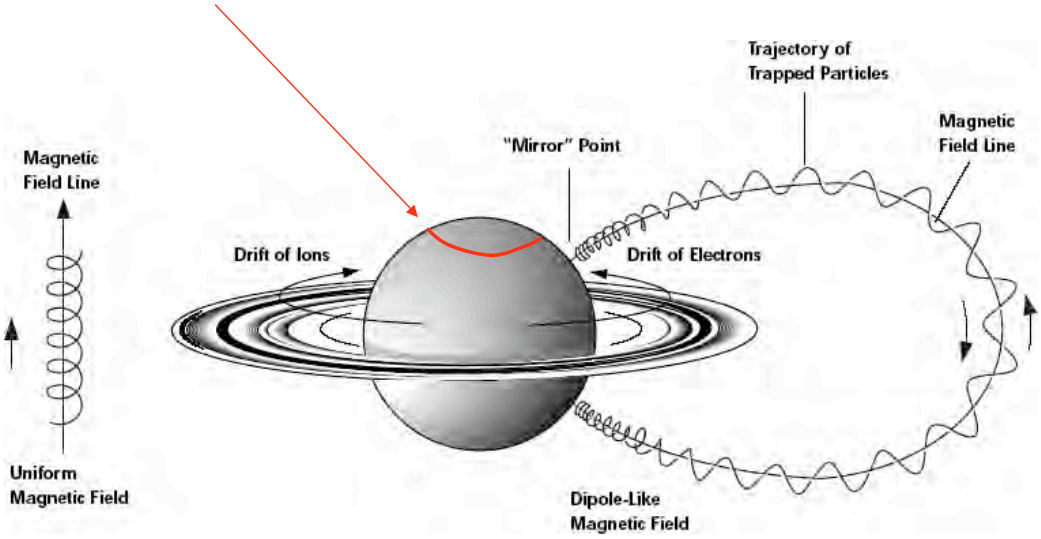
• Rings absorption → radiation belt outwards of main rings (around E,F,G rings)

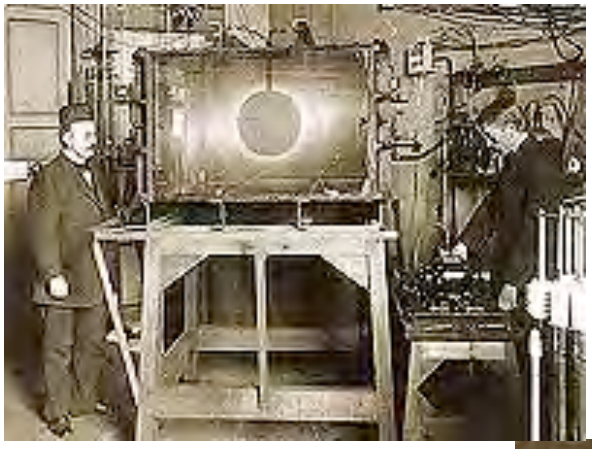


• Circulation of plasma in magnetosphere (meridan)



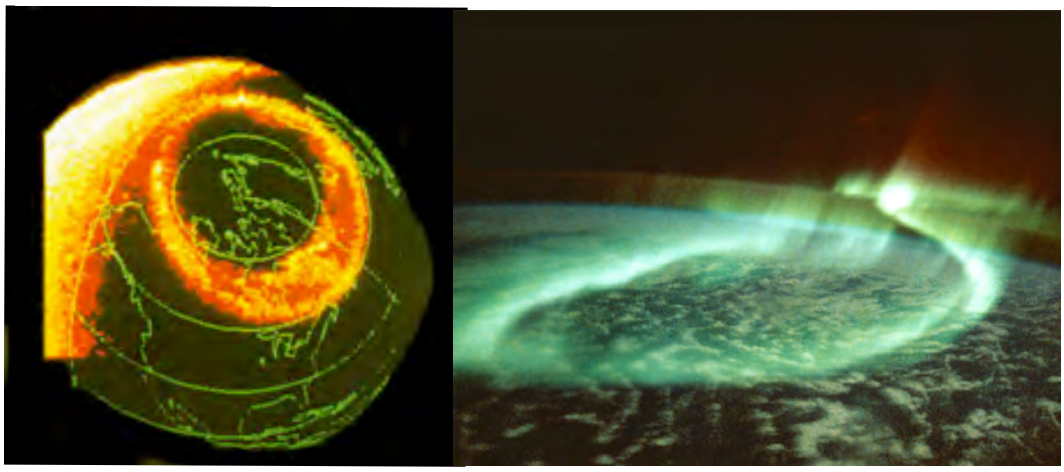
• Particle precipitation & collision at high latitudes
→ aurora (UV, IR, radio)



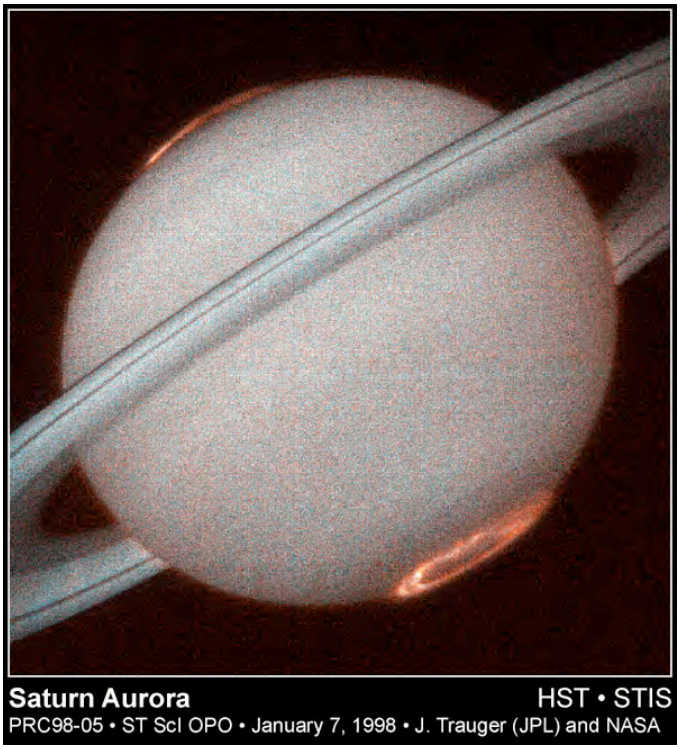


laboratory experiment by Kristian Birkeland (~1910) : « Terella »

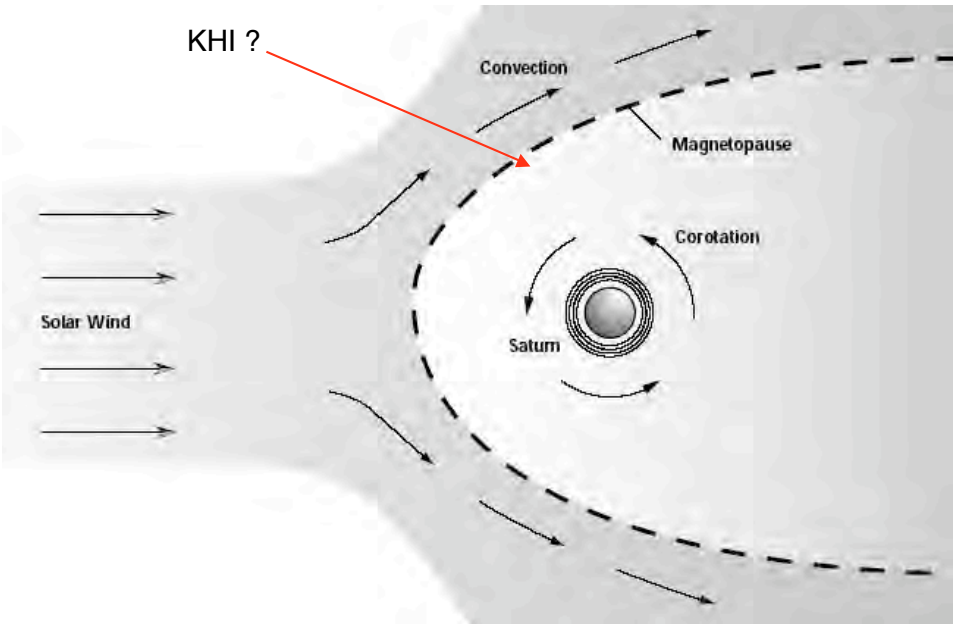
On Earth …



… and on Saturn

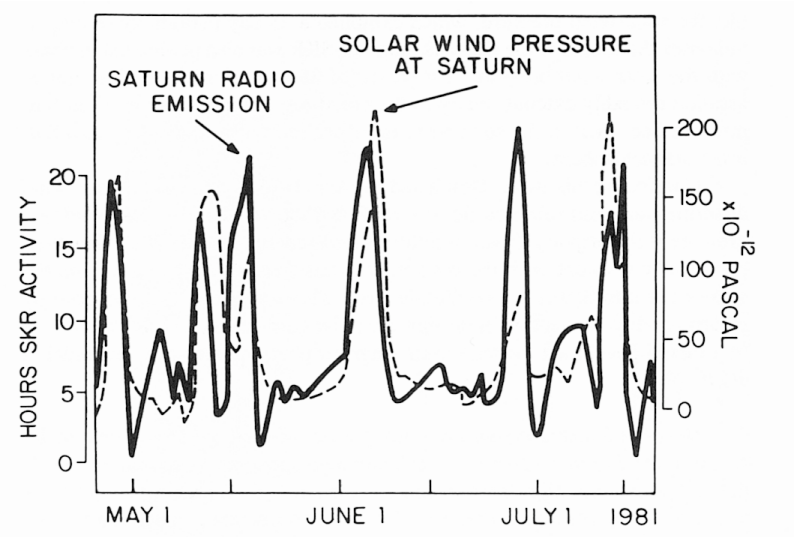


• Circulation of plasma in magnetosphere (equatorial)
→ corotation should dominate …



… but tight control of solar wind on magnetospheric activity and aurora

(radio extinctions when Saturn in Jovian magnetotail)



SOME QUESTIONS FOR CASSINI

- Relative importance of sources (LT,λ,t), … → map plasma populations (Ionosphere above Saturn's rings ?)
- Map fields, currents & waves (→ scattering of particles)
- B anomaly ? (or reexamine dynamo theory)
- Topology / Origin of radiation belts : Cosmic Rays interaction with rings ?
- Relative role of convection/corotation (intermediate between Earth and Jupiter ?)
- Dynamics of (outer) Magnetosphere (plasma blobs, plumes from Titan, Solar wind fluctuations ?)
- Direction-Finding of auroral radio source, nature of source, of rotation modulation ? Variations of radio rotation period ?
- Role of Titan ? Radio emission modulation by Dione ?

→ Complete mapping/exploration of plasma environment with MAPS package : CDA, INMS, MAG RPWS, CAPS, UVIS, MIMI (1st ENA imager embarked), +RSS

CASSINI'S MAPS INSTRUMENTS

Instrument	Objective
Cassini Plasma Spectrometer	Measures composition, density, velocity and temperature of ions and electrons
Cosmic Dust Analyzer	Measures flux, velocity, charge, mass and composition of dust and ice particles from 10^{-16}–10^{-6} grams
Dual Technique Magnetometer	Measures the direction and strength of the magnetic field
Ion and Neutral Mass Spectrometer	Measures neutral species and low-energy ions
Magnetospheric Imaging Instrument	Images Saturn's magnetosphere using energetic neutral atoms, and measures the composition, charge state and energy distribution of energetic ions and electrons
Radio and Plasma Wave Science	Measures wave emissions as well as electron density and temperature
Radio Science Instrument	Measures the density of Saturn's ionosphere
Ultraviolet Imaging Spectrograph	Measures ultraviolet emissions to determine sources of plasma in Saturn's magnetosphere

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