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

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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

• 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
• Saturn : Cassini orbital tour

+ 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)

![Occultation of 28Sgr by Titan](image)

+ 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

+ 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 $\rightarrow$ 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 NH₃, NH₂SH, H₂O ? [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 $T(L,\lambda,z)$, 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 $n:m \rightarrow$ 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]
• Thickness of rings ~100 m

[ISS, RSS]
• 500-1000 ringlets → resonances?
  [Star occultation observed by Voyager 2, PPS, UVS]
• Eccentric & azimuthally asymmetric 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) $\rightarrow$ micron sized particles in e.s. levitation?  

Scattering probability of a photon $\lambda$ (fraction of incident light deviated) by a particle of size $r$:

\[ P(\lambda) \propto \frac{1}{\lambda^2} \quad (r \sim \lambda) \text{ mostly forward} \]

\[ P(\lambda) \propto \frac{1}{\lambda^4} \quad (r \ll \lambda) \text{ isotropic} \]

• Colors $\rightarrow$ composition $\sim$ pure $\text{H}_2\text{O}$ 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]

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• Orbit at 20.3 R₃ from Saturn

→ Voyager 1 flyby at 4000 km

• Density 1.88 \( \rightarrow \) 50% rock, 50% H₂O ice
• Atmosphere: \( \text{N}_2 + \) a few \% \( \text{CH}_4 \) \[[\text{Spectroscopy}]\]

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Common Name</th>
<th>Atmospheric Concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{N}_2 )</td>
<td>Nitrogen</td>
<td>99–97 percent</td>
</tr>
<tr>
<td>Hydrocarbons</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \text{CH}_4 )</td>
<td>Methane</td>
<td>2–10 percent</td>
</tr>
<tr>
<td>( \text{C}_2\text{H}_2 )</td>
<td>Acetylene</td>
<td>2.2 parts per million</td>
</tr>
<tr>
<td>( \text{C}_2\text{H}_4 )</td>
<td>Ethylene</td>
<td>0.1 parts per million</td>
</tr>
<tr>
<td>( \text{C}_2\text{H}_6 )</td>
<td>Ethane</td>
<td>13 parts per million</td>
</tr>
<tr>
<td>( \text{C}_3\text{H}_8 )</td>
<td>Propane</td>
<td>0.7 parts per million</td>
</tr>
<tr>
<td>Nitrites</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \text{HCN} )</td>
<td>Hydrogen cyanide</td>
<td>190 parts per billion</td>
</tr>
<tr>
<td>( \text{HCN} )</td>
<td>Cyanacetylene</td>
<td>1.5 parts per billion</td>
</tr>
</tbody>
</table>

• Thick atmosphere (\( P_{\text{surface}} = 1.5 \text{ bar} \)) \( \rightarrow \) Greenhouse effect, \( T_{\text{surface}} = 94 \text{ K} \) \[[\text{Star occultation, 1989}]\]
Greenhouse effect:
Thick atmosphere lets Visible light in, prevents IR to exit
→ heats surface → reradiates
→ $T_{\text{max}}$ at low & high z, $T_{\text{min}}$ 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 sputtered regolith) reservoirs of CH₄, C₂H₆ … ?

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

[Earth based RADAR + NIR/OO + HST/WFPC2]
- Ice tectonics? $\text{H}_2\text{O} + \text{NH}_3$ magma, possibly erupting?

15% more $\text{NH}_3$ at 10 AU than at 5 AU; $\text{NH}_3$ = antifreeze → liquid below $\text{H}_2\text{O}$ ice surface → favours cold tectonics?

- $\Delta T$ equator-poles = 15K → winds, jet streams at high altitude? [IR spectroscopy]
- No lightning? [Voyager-PRA]

- No magnetic field? ($B_{\text{equator}} < 4$ 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 $\rightarrow$ if $N_2$ 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 $\rightarrow$ irreversible $\rightarrow$ lost in $10^7$ years $\rightarrow$ source of $C_nH_n$ cycle? ocean?

• Clouds, rain? (Voyager $\rightarrow$ 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 $\rightarrow$ 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

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

[Voyager trajectories, Imaging, Crater counts + Spectroscopy]
• 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 $\geq 10^9$ years (differentiation, eruptions, resurfacing)
  → Engines = primordial gravitational energy, tidal/resonant interactions, cratering, or radioactive decay
  → Presence of hydrated NH$_3$, CH$_4$ in H$_2$O 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

- 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
  \[S/C\text{ path along many close flybys}\]
- Morphology, geology, crater counts, relation to composition
  \(\rightarrow\) structure, differentiation? \[ISS\]
- Surface compositions (volatiles, hydrates, clathrates, impurities)
  \[VIMS, UVIS, CIRS\]
- Origin of dark material on Iapetus, Hyperion, Phoebe
  \(\rightarrow\) unprocessed primordial or organic?
- Comparison of rings, dust, satellite composition \(\rightarrow\) 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? \[RPWS, MAG\]
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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

motion ⊥ B forbidden
Solar Wind cannot penetrate planetary field → formation of magnetospheric cavity
• 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 (meridian)**
- 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 …

KHI ?
… but tight control of solar wind on magnetospheric activity and aurora (radio extinctions when Saturn in Jovian magnetotail)

![Graph showing Saturn radio emission vs. Solar wind pressure at Saturn.](image)

**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*
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