Exploration of the Saturn System by the Cassini Mission: Observations with the Cassini Infrared Spectrometer

Mian Abbas
NASA – Marshall Space Flight Center
Collaborators

- Andre LeClair: NASA-MSFC
- Elizabeth Woodard: UAH
- CIRS - Science Team
- (NASA/GSFC; JPL; OXFORD UNIV;
- Meudon Obs. & Univ. of Paris, France)
OUTLINE

• Introduction to the **Cassini mission**, and **Cassini mission objectives**

• **Cassini spacecraft, instruments, launch, and orbit insertion**

• **Saturn, Rings, & Satellites, Titan**

• **Composite Infrared Spectrometer (CIRS)**

• **Infrared observations of Saturn and Titan**
The Cassini mission, named after the 17th century Italian/French astronomer, Giovanni Domenico Cassini, is a joint NASA-ESA mission, launched on October 17, 1997 for exploration of the Saturn system.

- Successful insertion in Saturn’s orbit for a four year orbital tour occurred on July 1, 2004.

- The French Huygens-Probe with six instruments, was programmed for a soft landing on Titan. Successful landing on Titan’s surface occurred in January 2005.
Exploration of the Saturn system for investigations of the origin, formation, & evolution of the solar system.

The solar system is believed to be formed in a gravitationally collapsing giant interstellar cloud of gas and dust, or proto-solar nebula, with the proto-sun formed at the core and the planets in the surrounding disc.

Two current models of formation are:

(a) Core accretion model: agglomeration of dust grains into pebbles, to rocks, to planetesimals, and to the formation of planets in a gaseous disc.

(b) Gravitational instability model where the planets are formed directly at various distances from the sun in a proto-stellar disc.

None of the two models provide satisfactory explanation of the observations.
The Cassini Mission Specific Objectives

- Measure atmospheric thermal structure, gas abundances & isotopic ratios for Saturn system.
- Measure wind speeds and cloud structure.
- Obtain data for better understanding of the structure and formation of the interior.
- Investigations Saturn’s rings and its satellites.
- Study Saturn’s Magnetosphere & ionosphere, and interactions with the magnetic field.
The Cassini spacecraft orbiter carries 12 instruments.
The Huygens Probe contained 6 instruments.
The spacecraft weights about 5000 kg, about the size of an empty school bus, and is 6.8 m (~22 ft) high.
Three Radioisotope Thermoelectric Generators (RTGs) provide the electric power.
Sequence commands received via 4-m diameter high gain antenna on the Orbiter’s central computer.
Attitude control maintained by a dedicated computer which continually propagates up to 50 vectors to a variety of objects (e.g., Sun, Earth, Saturn and its satellites). The computer commands the reaction wheels to point Cassini to the desired direction.
Data stored on 2 solid state recorders (SSRs) during the tour.
Spacecraft Characteristics (cont’d)

• Power at Saturn: ~ 660 W
• Data Storage: 4 Gbits
• **Pointing Accuracy**: 2.0 mrad; **Pointing stability**: 0.036 mrad (~ 5 sec)
• Number of Engineering **Computers**: 26
• **Transmitter Power**: 19 W (RF); Transmitter Freq: Xband
• Data rate at Saturn: 140 KB/s
• Main Engine Thrust: 445 N

**The Huygens Probe**

• The **Probe** was designed as a fully instrumented robotic laboratory designed to enter Titan’s atmosphere using a heat shield and a series of parachutes.
• **Scientific measurements made during descent**, with 30 min at the surface of Titan.
Optical and Microwave Remote Sensing Instruments

- **Composite Infrared Spectrometer (CIRS):** Temperature & composition of surfaces & atmospheres in the Saturn system.
- **Visual and Infrared Mapping Spectrometer (VIMS):** Spectral mapping to study composition & structure or surfaces, atmospheres, & rings.
- **Imaging Science Subsystems (ISS):** Multispectral imaging of Saturn, Titan, rings, & the icy satellites to observe their properties.
- **Ultraviolet Imaging Spectrograph (UVIS):** Spectra & low resolution imaging of atmospheres, & rings for structure, chemistry and composition.
- **Cassini Radar (RADAR):** Radar imaging, altimetry, & backscatter of Titan's surface.
- **Radio Science Subsystem (RSS):** Study of atmospheric & ring structure, gravity fields, & waves.
FIELDS, PARTICLES, AND WAVES INSTRUMENTS:

**Cosmic Dust Analyzer (CDA):** In-situ study of ice & dust grains in the Saturn system.

**Ion and Neutral Mass Spectrometer (INMS):** In-situ compositions of neutral & charged particles in the Saturn magnetosphere.

**Cassini Plasma Spectrometer (CAPS):** In-situ study of plasma within & near Saturn's magnetic field of atmospheres, & rings for structure, composition.

**Radio & Plasma Wave Science (RPWS):** Study of plasma waves, radio emissions, and dust in the Saturn system.

**Dual Technique Magnetometer (MAG):** Study of Saturn's magnetic field & interactions in the solar wind.

**Magnetospheric Imaging Instrument (MIMI):** Global magnetospheric imaging & in-situ measurements of Saturn’s magnetosphere & solar wind interaction.
Huygens Probe Instruments

Probe Science Payload Instrumentation:

**Huygens Atmospheric Structure Instrument (HASI)**
A suite of sensors to measure the physical and electrical properties of Titan's atmosphere.

**Doppler Wind Experiment (DWE)**
Radio signals to deduce wind speeds on Titan

**Descent Imager/Spectral Radiometer (DISR)**
Imaging and spectral observations of Titan's surface and atmospheric hazes.

**Aerosol Collector and Pyrolyser (ACP)**
Chemical composition of Titan's aerosols. composition analysis.

**Surface-Science Package (SSP)**
A number of sensors designed to determine the physical properties of Titan's surface.

**Gas Chromatograph & Mass Spectrometer (GCMS)**
The Cassini Launch on Oct. 17, 1997, Cape Canaveral
The Cassini Launch on Oct. 17, 1997, Cape Canaveral
Cassini Interplanetary Trajectory

- Venus Swingby: 26 Apr 1998
- Venus Swingby: 24 Jun 1999
- Earth Swingby: 18 Aug 1999
- Launch: 15 Oct 1997
- Jupiter Swingby: 30 Dec 2000
- Saturn Arrival: 1 Jul 2004

Venus-Venus-Earth-Jupiter: Gravity Assist

Perihelia:
- 27 Mar 1998: 0.67 AU
- 29 Jun 1999: 0.72 AU

Ganymede
• Global Temperature Maps
  – Observations of dynamical processes on Jupiter

• Global distribution of gas abundances
  – $^{14}$NH$_3$, $^{15}$NH$_3$, PH$_3$, C$_2$H$_6$, C$_2$H$_2$
  – Complex hydrocarbons
Saturn's Satellites and Ring Structure

Saturn

Not shown: Pan 2.22 Rs
Atlas 2.28 Rs
Prometheus 2.31 Rs
Pandora 2.35 Rs
Titan 20.3 Rs
Hyperion 24.6 Rs
Iapetus 59.1 Rs
Phoebe 214.9 Rs

The diagram is not to scale except for Pan, Atlas, Telesto, Calypso, and Helene, whose sizes have been exaggerated by a factor of 5 to show rough topography.
Saturn’s Orbit Insertion

Spacecraft turns away from Earth for SOI activities June 30 6:11pm PDT

Ascending ring-plane crossing 7:11pm PDT

SOI burn 7:36 - 9:12pm PDT

Spacecraft passes behind rings, planet 9:54 - 10:44pm PDT

Descending ring-plane crossing 10:58pm PDT

Spacecraft returns to Earth-point Playback of SOI data begins July 1 12:00am PDT

Cassini Saturn Orbit Insertion View from Earth
Saturn’s Rings
Some Physical Parameters of Saturn

- **Mean Distance from Sun**: 9.6 AU
  - 1.4 billion km (~ 0.9 billion miles)
- **Diameter**:
  - Equator: 120,660 km
  - Polar: 107,629 km
- **Mass (Earth = 1)**: 95.2
- **Gravity (Earth = 1)**: 1.06
- **Density (Earth = 5.52)**: 0.69 g/cm³ (Water = 1.0)
- **Orbital Period**: 29.4 years
- **Rotation Period**: 10 h 40 m
- **Orbital Inclination**: 2.5°
Saturn’s Atmospheric Thermal Structure and Composition

- Temperature: 135 K at 1 bar; 82 K at tropopause (60 mbar)
- Composition: $\text{H}_2$ (\~{}88\%), $\text{He}$ (\~{}12\%), $\text{CH}_4$, $\text{NH}_3$, $\text{PH}_3$, $\text{C}_2\text{H}_2$, $\text{C}_2\text{H}_6$, $\text{CO}$, $\text{CO}_2$, $\text{H}_2\text{O}$, plus other trace gases.
- Cloud layers of: Water cloud at the bottom, Ammonia at the top, and $\text{NH}_4\text{SH}$ in the middle troposphere, theorized.
<table>
<thead>
<tr>
<th>Name</th>
<th>Inner Radius (Rs)</th>
<th>Width (km)</th>
<th>Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D-Ring</td>
<td>1.1</td>
<td>7500</td>
<td>?</td>
</tr>
<tr>
<td>C-Ring (inner)</td>
<td>1.235</td>
<td>17,500</td>
<td>1x10^{18}</td>
</tr>
<tr>
<td>B-Ring</td>
<td>1.524-1.947</td>
<td>25,500</td>
<td>3x10^{19}</td>
</tr>
<tr>
<td>Cassini Division</td>
<td>1.985 (center)</td>
<td>4800</td>
<td></td>
</tr>
<tr>
<td>A-Ring</td>
<td>2.023-2.267</td>
<td>14,600</td>
<td>6x10^{18}</td>
</tr>
<tr>
<td>F-Ring</td>
<td>2.3267</td>
<td>30-500</td>
<td>?</td>
</tr>
<tr>
<td>G-Ring</td>
<td>2.8</td>
<td>8000</td>
<td>1x10^{7} (?)</td>
</tr>
<tr>
<td>E-Ring</td>
<td>3.0 - 8.0</td>
<td>300,000</td>
<td>?</td>
</tr>
</tbody>
</table>
Ring Science Objectives

• Study the **shape and structure of the rings and the processes responsible for the ring structure** (gravitational, viscous, erosional, and electromagnetic).

• Map the **chemical makeup and the size distribution of ring material**.

• Investigate the **relationship between the rings and the moons of Saturn**, including moons contained within the ring system.

• Determine the **distribution of dust and meteoroids in the vicinity of the rings**.

• Study **interactions between the rings and Saturn's magnetosphere, ionosphere, and atmosphere**.
Saturn Science Objectives

- Global mapping of atmospheric thermal structure, gas abundances, and isotopic ratios to provide observational constraints for the formation and evolution of Saturn and Titan.
- Measure wind speeds and directions across the planet.
- Observe long-term variations in the cloud features and processes.
- Collect data for better understanding of the interior of the planet.
- Study the day-to-night variations of Saturn's ionosphere and determine its degree of interaction with the magnetic field.
<table>
<thead>
<tr>
<th>Name</th>
<th>Diameter (km)</th>
<th>Distance (Rₖ)</th>
<th>Discoverer</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pan</td>
<td>20</td>
<td>2.2</td>
<td>Showalter</td>
<td>1980</td>
</tr>
<tr>
<td>Atlas</td>
<td>28</td>
<td>2.3</td>
<td>Terrile</td>
<td>1980</td>
</tr>
<tr>
<td>Prometheus</td>
<td>92</td>
<td>2.3</td>
<td>Collins</td>
<td>1980</td>
</tr>
<tr>
<td>Pandora</td>
<td>92</td>
<td>2.4</td>
<td>Collins</td>
<td>1980</td>
</tr>
<tr>
<td>Epimetheus</td>
<td>114</td>
<td>2.5</td>
<td>Walker</td>
<td>1980</td>
</tr>
<tr>
<td>Janus</td>
<td>178</td>
<td>2.5</td>
<td>Dollfus</td>
<td>1966</td>
</tr>
<tr>
<td>Mimas</td>
<td>392</td>
<td>3.1</td>
<td>Herschel</td>
<td>1789</td>
</tr>
<tr>
<td>Enceladus</td>
<td>520</td>
<td>4.0</td>
<td>Herschel</td>
<td>1789</td>
</tr>
<tr>
<td>Tethys</td>
<td>1060</td>
<td>4.9</td>
<td>Cassini</td>
<td>1684</td>
</tr>
<tr>
<td>Name</td>
<td>Diameter (km)</td>
<td>Distance (Rₚ)</td>
<td>Discoverer</td>
<td>Date</td>
</tr>
<tr>
<td>---------</td>
<td>---------------</td>
<td>---------------</td>
<td>--------------</td>
<td>-------</td>
</tr>
<tr>
<td>Telesto</td>
<td>30</td>
<td>4.9</td>
<td>Reitsema</td>
<td>1980</td>
</tr>
<tr>
<td>Calypso</td>
<td>26</td>
<td>4.9</td>
<td>Pascu</td>
<td>1980</td>
</tr>
<tr>
<td>Dione</td>
<td>1120</td>
<td>6.3</td>
<td>Cassini</td>
<td>1684</td>
</tr>
<tr>
<td>Helene</td>
<td>32</td>
<td>6.3</td>
<td>Laques</td>
<td>1980</td>
</tr>
<tr>
<td>Rhea</td>
<td>1530</td>
<td>8.8</td>
<td>Cassini</td>
<td>1672</td>
</tr>
<tr>
<td>Titan</td>
<td>5146</td>
<td>20.4</td>
<td>Huygens</td>
<td>1655</td>
</tr>
<tr>
<td>Hyperion</td>
<td>286</td>
<td>24.7</td>
<td>Bond</td>
<td>1848</td>
</tr>
<tr>
<td>Iapetus</td>
<td>1460</td>
<td>59.4</td>
<td>Cassini</td>
<td>1671</td>
</tr>
<tr>
<td>Phoebe</td>
<td>220</td>
<td>216</td>
<td>Pickering</td>
<td>1898</td>
</tr>
</tbody>
</table>
Saturn’s Moon – IAPETUS

D = 1460 km; R = 59.4 Rs
Saturn’s Moon - Tethys
Saturn’s Moon - ENCELADUS
Objectives for the Icy Satellites

- Determine the **general characteristics and geological histories** of the icy satellites.

- Determine the processes that change the **surface and near-surface of the icy satellites**, and determine the **makeup and distribution of surface materials**, especially the **dark material**.

- Provide observational constraints on the **internal structure and makeup of the moons**.

- Investigate **interaction of the icy satellites with the magnetosphere** and the **ring system**.
Near IR image of Titan, with the dark and the bright reds representing the presence of pure water ice, simple hydrocarbons, respectively.
Near IR view of Titan by VIMS with the yellow, blue and white colors indicating presence of hydrocarbons, ice, and methane clouds, respectively.
Titan’s Atmospheric Thermal Structure and Composition

- **Temperature:** 92 K at surface (1.5 bar)
  72 K at tropopause (150 mbar)
- **Gases:** N\textsubscript{2} (~ 95%), H\textsubscript{2}, Ar, CH\textsubscript{4}, C\textsubscript{2}H\textsubscript{2}, C\textsubscript{2}H\textsubscript{4}, C\textsubscript{2}H\textsubscript{6}, C\textsubscript{3}H\textsubscript{4}, C\textsubscript{3}H\textsubscript{8}, C\textsubscript{4}H\textsubscript{2}, HCN, HC\textsubscript{3}N, CO, CO\textsubscript{2}, H\textsubscript{2}O, complex hydrocarbons
- **Haze, Clouds:** CH\textsubscript{4}, Hydrocarbons
Titan Science Objectives

- Global distribution of atmospheric gas abundances and isotopic ratios, Provide information for better understanding of the formation and evolution of Titan’s atmosphere.

- Search for more complex organic molecules. Study photochemical models, the formation and composition of aerosols, and clouds.

- Measure winds and global temperatures and the seasonal effects.

- Determine whether the surface is liquid or solid, and determine the shape and composition of the surface.

- Collect data to determine the internal structure of Titan.

- Investigate the upper atmosphere and ionosphere of Titan and their roles as sources of neutral and ionized material in the magnetosphere of Saturn.
Cassini Infrared Observations with the Composite Infrared Spectrometer (CIRS)
## CIRS Instrument Characteristics

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Far-IR</th>
<th>Mid-IR</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Telescope diameter (cm)</strong></td>
<td>50 8</td>
<td></td>
</tr>
<tr>
<td><strong>Interferometers</strong></td>
<td>Polarizing</td>
<td>Michelson</td>
</tr>
<tr>
<td><strong>Type</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Spectral range (cm⁻¹)</strong></td>
<td>10—600</td>
<td>600—1400</td>
</tr>
<tr>
<td><strong>Spectral range (µm)</strong></td>
<td>17—1000</td>
<td>7—17</td>
</tr>
<tr>
<td><strong>Spectral resolution (cm⁻¹)</strong></td>
<td>0.5—15.5</td>
<td>0.5—15.5</td>
</tr>
<tr>
<td><strong>Integration time (s)</strong></td>
<td>2—50</td>
<td>2—50</td>
</tr>
<tr>
<td><strong>Focal planes</strong></td>
<td>FP1</td>
<td>FP3</td>
</tr>
<tr>
<td><strong>Spectral range (cm⁻¹)</strong></td>
<td>10—600</td>
<td>600—1100</td>
</tr>
<tr>
<td><strong>Detectors</strong></td>
<td>Thermopile</td>
<td>PC HgCdTe</td>
</tr>
<tr>
<td><strong>Pixels</strong></td>
<td>2ᵃ</td>
<td>1 × 10</td>
</tr>
<tr>
<td><strong>Pixel FOV (mrad)</strong></td>
<td>3.9</td>
<td>0.273</td>
</tr>
<tr>
<td><em><em>Peak D</em> (cm Hz¹/² W⁻¹)</em>*</td>
<td>4 × 10⁹</td>
<td>2 × 10¹⁰</td>
</tr>
<tr>
<td><strong>Data telemetry rate (kbs)</strong></td>
<td>2 and 4</td>
<td></td>
</tr>
<tr>
<td><strong>Instrument temperature (K)</strong></td>
<td></td>
<td>170</td>
</tr>
<tr>
<td><strong>Focal planes 3 and 4 Temperature (K)</strong></td>
<td></td>
<td>75—90</td>
</tr>
</tbody>
</table>

ᵃSingle FOV, two polarizations.
CIRS Infrared Spectrum of Saturn
CIRS Infrared Spectrum Titan
FIR Spectrum of Titan
Titan’s Composition Retrievals from Infrared Spectra
Analytical Techniques for Retrieval of Atmospheric Thermal Structure & Composition

• **Radiative Transfer Models (Forward solutions of the Radiative Transfer Equation (RTE))**
  – Provide synthetic spectra for known values of: model atmosphere with known parameters (thermal structure, gas distributions, cloud opacity etc.), instrument characteristics, and modes of observation.

• **Retrieval Programs (Inverse solutions of the RTE)**
  – Calculate the atmospheric parameters (temperatures, gas distributions, isotopic ratios, cloud opacity, pointing directions, etc.) by comparison with the synthetic spectra and employing non-linear least-squares iterative techniques.
Radiative Transfer Model

Observed radiance:
\[ I_v(\theta) = \varepsilon_{vs} \tau_{vs} B_v(T_s) - \int_{ps}^{pt} B_v(T) C_v(\theta, p, T, n_i) d\ln p \]

Transmittance:
\[ t_n = \exp \left( \hat{e}_i \hat{\alpha}_i k_n^i (p, T) \right) du_i \]

Contribution Functions:
\[ C_v = B_v(T) \frac{\partial \tau_v}{\partial \ln p} \]
\[ C_v = \frac{\partial B_v}{\partial T} \cdot \frac{\partial \tau_v}{\partial \ln p} \]
\[ C_v = \frac{\partial \tau_v}{\partial \ln u_i} \cdot \frac{\partial B_v}{\partial \ln p} \]
Relaxation Equations:

- Assuming an initial guess model atmosphere, radiances are calculated for the selected frequencies and compared with the observed values.
- The atmospheric parameters (T, gas mixing ratios) are corrected at the peaks of the contributions functions (CFs) till the rms differences approach the noise level.
- The regions above and below the CFs are scaled appropriately.

\[
I_i^n = I(q^n)
\]

\[
r_i^n = I_i^o - I_i^n
\]

\[
\sigma^n = \sqrt{\frac{1}{m} \sum_{i=1}^{m} (r_i^n)^2}
\]

\[
q^n = q^{n-1} + \frac{\sum_{i=1}^{m} (r_i^{n-1} a_i^{n-1})}{\sum_{i=1}^{m} (a_i^{n-1})^2}
\]

\[
a_i^n = \left( \frac{\partial I(q; \nu_i)}{\partial q} \right)_{q=q^n}
\]
Titan Temperature Retrieval

**Titan View from 100,000 km**

- CH$_4$ Limb View
  - 1305 cm$^{-1}$
  - 340 km
  - 310 km
  - 280 km
  - 250 km
  - 220 km
  - 1305 cm$^{-1}$
  - 1295 cm$^{-1}$
  - 1276 cm$^{-1}$

**Titan**

- Pressures (mbar)
  - Model Profile
  - T0: Lat. -84°
  - T0: Lat. -16°

**Temperature (K)**

- 60 to 200
Combined limb and nadir temperature retrieval of Titan Tb observations at −13° latitude.
Titan Model Atmosphere

- **Composition:**
  - $N_2 \sim 95.6 - 98.1\%$
  - $CH_4 \sim 4.4 - 1.6\%$
  - $H_2 \sim 0.1\%$
  - $C_2H_2, C_2H_4, C_2H_6,$
    $C_3H_4, C_3H_8, C_4H_2,$
    $C_6H_6$
  - HCN, HC$_3$N
  - CO, CO$_2$, H$_2$O
Titan Composition Retrieval: C2H2

Mean C2H2 mixing ratio at 3 mbar in each latitude bin retrieved from T0, Tb, and T3 nadir observations.
Mean C2H6 uniform mixing ratio in each latitude bin retrieved from T0, Tb, and T3 nadir observations. Run with HT04 data. Test run with GS03 data retrieves 1.6e-5 in southern hemisphere.
Mean HCN uniform mixing ratio in each latitude bin retrieved from T0, Tb, and T3 nadir observations.
Mean CO2 uniform mixing ratio in each latitude bin retrieved from T0, Tb, and T3 nadir observations.
Titan Composition Retrieval: Comparison Spectra

![Graph showing Titan Composition Retrieval: Comparison Spectra](image)

- **Titan**
- **-45° Latitude**
- **Res: 2.8 cm⁻¹**

- **Observed**
- **Retrieved**

- **CO₂**
- **C₂H₂**
- **HCN**

**Graph Details:**
- **Y-axis:** Intensity (W/cm² ster cm⁻¹)
- **X-axis:** Frequency (cm⁻¹)
**CH₃D Retrievals and D/H Ratio**

- **Data:** T₀, Tₜ, T₃ nadir observations at 0.5 cm⁻¹ res, for 10° latitude bins centered at (T₀: -60.6, -58.1); (Tₜ: -3.4, 4.3, 15.3); (T₃: -23.0, -16.5)
- Spectral isolated CH₃D lines used: 1130.75, 1143.50, 1156.00 cm⁻¹
- Temperature profile retrieved from nadir observations at 2.8 cm⁻¹ res. Provides good fit with the 0.5 cm⁻¹ data in the 1300 cm⁻¹ region.
- Continuum level is fitted with aerosol next to each frequency. The CH₃D abundance is retrieved to find the best fit of the three lines together.
- Retrieved CH₃D mean mixing ratio = 1.30×10⁻⁵
  - CH₃D/CH₄ ratio = (8.14 ± 2.2)×10⁻⁴
  - Mean D/H ratio = (2.04 ± 0.55) ×10⁻⁴
- **Comparison with**
  - Athena Coustenis: D/H: (1.17 +0.16 −0.21) ×10⁻⁴
  - Huygens D/H: (2.3 ± 0.5) ×10⁻⁴
Saturn Infrared Spectra: CO2

Wave Number (cm⁻¹)
655 660 665 670 675 680

Intensity (W cm⁻² sr⁻¹/cm⁻¹)
0.0 5.0e⁻⁹ 1.0e⁻⁸ 1.5e⁻⁸ 2.0e⁻⁸ 2.5e⁻⁸ 3.0e⁻⁸

Saturn: Nadir View
s58.128SA.C001: FP3
Lat: -53.65
Res = 0.5 cm⁻¹
Saturn IR Observed and Synthetic Spectra:

Saturn
Nadir View: s18.021SA.C003
Lat = 14.69°; EA = 67.32°
Res= 0.53 cm⁻¹
Retrieved Saturn CO₂ Mixing Ratio Profile

Saturn CO₂ Retrieved & Model Distributions

Moses, Model profile

Cassini: Limb Obs.

Cassini: Mean Nadir Obs.
### Summary of Saturn’s CO$_2$ mixing ratios retrieved from Cassini/CIRS Nadir observations

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$Q_v$ (CO$_2$)</th>
<th>N (CO$_2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean Value of Atmos. Pressure @ 1 mb</td>
<td>4.74E-10</td>
<td>2.14E+14</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>1.52E-10</td>
<td>5.74E+13</td>
</tr>
<tr>
<td>Standard Deviation of Mean</td>
<td>5.10E-12</td>
<td>2.21E+12</td>
</tr>
<tr>
<td>Mean Value of Atmos. Pressure @ 10 mb</td>
<td>1.05E-10</td>
<td>6.30E+14</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>3.19E-11</td>
<td>1.56E+14</td>
</tr>
<tr>
<td>Standard Deviation of Mean</td>
<td>1.10E-12</td>
<td>5.77E+12</td>
</tr>
</tbody>
</table>
Thank You!