Cassini Proposed Extended-Extended Mission (XXM)

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Cassini Program

Cassini XXM Science: Introduction

- XXM Mission Overview
- XXM Goal and Objectives
  - Seasonal-temporal change
  - New Questions
- Discipline science XXM Priority 1 objectives
  - Titan
  - Icy Satellites
  - MAPS
  - Saturn
  - Rings
- End-of-mission science
- Summary

Each discipline is like a mission in its own right!
**Cassini Mission Overview**

<table>
<thead>
<tr>
<th>Year of Tour</th>
<th>Prime Mission</th>
<th>Equinox Mission</th>
<th>Solstice Mission</th>
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<td>'16-'17</td>
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**Orbits**
- Titan
- Enceladus
- Other icy moons (orbit<15,000 km)

**Saturn**

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**End of Mission Option with orbits inside D ring**

- Saturn impact from short period orbits
- Juno-like mission with Cassini instruments

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March 15, 2009

Cassini JUM
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Proposed Cassini XXM Goal and Objectives

- Proposed XXM Goal:
  - Observe seasonal and temporal change in the Saturn system to understand underlying processes and prepare for future missions.

- Objectives Categories:
  - Seasonal-temporal change
  - New Questions

Saturn Multi-probes

Titan Saturn System Mission

Enceladus Flagship

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Seasonal-Temporal Change in the Saturn System

- **Saturn**: Seasonal change.
- **Rings**: Opening angle and temporal variability.
- **MAPS**: Seasonal and solar cycle effects.
- **Icy Satellites**: Potential temporal variability of Enceladus activity.
- **Titan**: Seasonal change.

*Cassini XXM offers an unparalleled opportunity to study seasonal and temporal change in a giant planet system.*

March 9, 2009  Cassini XXM
**Cassini Program**

**New Questions**

- **Saturn**: Rotation rate; polar storms; trace gases; lightning.
- **Rings**: Age and mass; clearing gaps; compositional variations; microstructure; propellers.
- **MAPS**: Magnetotail dynamics; inner radiation belts; magnetospheric periodicities; coupling to Saturn’s ionosphere and rings.
- **Icy Satellites**: Enceladus ocean and interior structure; Iapetus’ magnetic signature and heterogeneity; Dione activity; Rhea rings; Tethys MAPS interactions; Rhea differentiation; Hyperion’s surface; Mimas.
- **Titan**: Surface lakes and other materials; internal structure; aerosols and heavy molecules; upper atmospheric density; surface topography; surface temperature and clouds; winds.

March 8, 2009

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**Titan: Need for follow-up**

- **Seasonal changes**: Spring equinox begins in the north this year
  - Cassini S. Hemisphere observations → strong polar seasonality
  - North is different from south: large-scale coverage by lakes; weaker summer solstice flux in north vs south.
  - If lakes are not connected to an aquifer smaller ones should shrink.
  - Expect to observe convection/rainfall in north as in south. But more areas covered in liquids → different behavior?
  - Onset of spring in the north → sunlight → opportunity to map lake composition.
  - Seasonal asymmetry at high altitude → new chemistry to be explored.

- **Future Titan missions**
  - Completion of the map of Kraken mare is essential to its potential as a splashdown site for future probes.

- **Internal structure**
  - Detecting presence of an ocean requires many RSS flybys

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XXM Titan Priority 1 Objectives and Observations

Seasonal Changes

Methane/Hydrocarbon hydrological cycle:
- Lakes (RADAR, VIMS, ISS)
- Clouds (VIMS, ISS)
- Aerosols (NIMS, CAPS, CIRS, ISS, VIMS, UVIS)

High latitude atmosphere
(temperature structure, formation and breakup of the winter polar vortex)
- Limb and nadir mapping of temperatures, aerosols, condensates, gas, with progression of the season (CIRS)
- Polar imaging (ISS, VIMS)
- Solar and stellar occultations for composition (UVIS)
- Radio occultation for temperature, moist convection (RSS)

New Questions

Types, composition, distribution, ages of surface units (most notably lakes)
- Composition of liquids and solids (VIMS)
- Depth of lakes (RADAR)
- Surface modification due to geologic activity (VIMS, RADAR)
  (Origin of depressions, Xanadu, fluvial features, crypto-circles, cryovolcanism)

Internal and Crustal Structure
(liquid mantle, crustal mass distribution, rotational state of surface with time, intrinsic and/or internal induced magnetic field)
- Gravity of Titan (RSS)
- Shape, topography (RADAR)
- Rotational state (RADAR, VIMS)
- Magnetic field (MAG)

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**New Questions**

Aerosol and heavy molecule layers and properties

- Aerosol properties:
  - Limb, nadir mapping vs. time (ISS, VIMS, CIRS)
  - Stellar and solar occultations (UVIS)

- Properties of complex molecules
  - Direct sampling vs. latitude/time (INMS)
  - Stellar and solar occultations (UVIS)
  - Limb, nadir mapping (CIRS)

- Properties of complex ions
  - Direct sampling (INMS, CAPS)

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**Titan Surface Coverage**

Altitude

[Map of Titan surface coverage with altitude and latitude]
Saturn-Titan Year Scaled to an Earth Calendar Year

- Saturn year = 29.66 Earth years.
- Nearly 1/2 Saturn year will be sampled by Cassini Prime + Equinox + XXM.

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XXM Icy Satellite Priority 1 Objectives:
Temporal Change at Enceladus

- Multiple plume penetrations, 2010 - 2015, to study changes in morphology and chemistry
- Multiple distant views of the south pole to study changes in heat output and distribution, 2010 - 2017
- Many distant high-phase views of the plumes to monitor dust output, including Saturn eclipses to study the "tendrils" seen in 2006
- UV stellar occultations in 2011 and 2016
- South polar imaging in Saturn-shine to look for morphological changes
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XXM icy satellite priority 1 objectives: Exploration of Enceladus and Dione

- Enceladus
  - High-resolution imaging of plume sources. 2010
  - Increase high-resolution imaging coverage of south pole in sunlight and Saturn-sunshine. 2010, 2015
  - High-resolution mapping of endogenic thermal emission. 2010, 2016
  - Gravity mapping to constrain interior structure (up to 3 passes total).
  - Search for magnetic induction signature.
  - High-resolution imaging of the northern hemisphere. 2016

- Dione
  - High-resolution imaging and thermal mapping of features and other endogenic features to look for recent and ongoing activity.
  - Close encounters to look for mass loading.
  - Gravity passes to probe interior structure, degree of differentiation.

Enceladus Close Encounters

[Graphs showing encounter data]
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MAPS XXM Priority 1 Objectives

Enceladus
Determine the temporal variability of Enceladus' plumes.
Tour offers close plume flybys

CAPS-ELS and IMS detection of ~ Sizes particles within the Enceladus plume and fine structure of plume observable in CAPS-ELS. Grains may be charged in the vent. Jets split into positive and negatively-charged components.

March 5, 2009
Cassini XMM

Saturn's Magnetosphere
Observe Saturn's magnetosphere over a solar cycle, from one solar minimum to the next.
Good LT coverage of the inner magnetosphere (<15 R_S)
Determine the dynamics of Saturn's magnetotail
~ 2 month in the tail
In situ studies of Saturn's ionosphere and inner radiation belt
D ring/Juno-like EGM orbit
Investigate magnetospheric periodicities, their coupling to the ionosphere, and how the SKR period is imposed from close to the planet (3-5 R_S) out to the deep tail
Low perihelion (3-5 R_S) with good local time coverage, tail excursions

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Rings: Objectives for the XXM

Campaigns based on new discoveries
- Ring Age: measure meteoroid flux and ring mass to constrain formation age
- F Ring campaign: closely monitor chaotic F ring region for interactions between ring and nearby (mostly unseen) moonlets
- Moonlet search: intensive searches of still-empty gaps to detect or rule out moonlets
- Ring composition: zero in with VIMS on selected regions where known color differences have been seen
- Microstructure: penetrate dense B ring to ascertain role of wakes and overstabilities
- Propellers: track giant propellers to understand apparent radial drifts

Proximal orbits

Ring XXM Objectives:
Ring Structure - spatial and temporal variations

Global structure probed by radio & stellar occultations

Embedded objects: Primordial shards or locally grown?

Self-gravity wakes discovered & described throughout

F ring region: chaotic moonlet dynamics
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End of Mission Option with orbits inside D ring

- Saturn impact from short period orbits
- Planetary Protection approval pending
- EOM geometry reachable from any point in XIXM tour
  - 2-10 months set up
  - Delta v: 5 - 30 m/s
- Unique Saturn science possible

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Key Orbital Characteristics of EOM phase

- 42 short period orbits from November 2016 to September 2017
- 20 F ring orbits with periapses just outside Saturn's F ring
  - Set up for final jump to orbits inside D ring
  - Rich scientifically
    - High resolution F and A ring observations
    - Ring occultations (Earth and Solar)
    - Auroral field line crossings at r = 3.4 - 4 Rs
- 22 Proximal orbits between D ring and Saturn atmosphere prior to ballistic impact
  - Periapses in 3,000 km "clear" region between inner edge of D ring and Saturn's upper atmosphere
  - Critical inclination of 63.4° to prevent orbit rotation from J₂
  - If delta v is available, could execute maneuver to delay spacecraft atmospheric entry a few more orbits
  - Current impact date: 15 September 2017

March 9, 2009 Cassini XIXM

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Key science objectives during End of Mission Phase

- High priority, unique science enabled by these orbits
- Saturn internal structure
  - Higher order moments for gravity field and magnetic field
  - Internal rotation rate for Saturn
- Ring mass
  - Ring mass currently uncertain by order of magnitude
  - Ring mass will be used to address age of main rings
- Saturn’s ionosphere, innermost radiation belts & D ring
- Highest resolution main ring studies
- High resolution Saturn atmospheric studies

Saturn Internal Structure: Magnetic field

- Condition number is a measure of the accuracy with which a magnetic field model can be determined based on spacecraft trajectory.
- Significant improvement possible with periapse inside D ring.
- May be possible to determine depth of Saturn’s conducting, metallic core.
Saturn Internal Structure: Gravity Harmonics

- Saturn gravity harmonics (zonal) up to degree 10 can be estimated with an accuracy < 10⁻⁵ (with multiranc solution using 6 proximal orbits for gravity passes)

Ring Mass: Constrain age of rings

- Without proximal orbits, a-priori ring mass uncertainty is 100% of nominal values
- 6 orbital arcs for ring mass (and Saturn gravity) provide estimation accuracy for total ring $\delta CM = 0.34 \text{ km}^{3}/\text{a}^2$ (–5%)
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Proximal Orbit Hazard Studies

- Inner D ring opacity
  - Inside 65,000 km identified for “safe” passage

- Saturn upper atmosphere
  - Extrapolated tumble densities 1500 km above 1 bar (62,000 km) are acceptable

- Energetic particles
  - Low energy particles are not a risk to spacecraft
  - High energy particles still under study

March 6, 2009

Cassini DCM

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Compare F ring/Proximal orbits to Juno

- Comparable orbits and scientific goals
    - 33 science orbits
  - Cassini’s F ring/Proximal orbits: Nov. 2016 to Sept. 2017
    - 42 science orbits,
    - 22 orbits with Juno-like periapses
  - Different inclinations (Cassini: 63.4° vs. Juno: 90°)
  - Common science goals:
    - Interior structure of giant planets: Gravity and magnetic field mapping
    - Dynamics of polar magnetosphere
    - High resolution measurements of giant planet atmospheres
  - Differences in science goals:
    - Juno: Deep interior composition/water abundance
    - Cassini: Saturn rotation rate (well known for Jupiter)
    - Cassini: Saturn’s ring mass and detailed ring structure

March 9, 2009

Cassini JCM
**Cassini Program**

Mapping of Cassini XXM Potential to Decadal Survey*

<table>
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<tr>
<th>Fundamental Scientific Question</th>
<th>Saturn</th>
<th>Rings</th>
<th>MAPS</th>
<th>IcyS</th>
<th>Titan</th>
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*Decadal Survey relevance is indicated; achieving such requires prudent funding of Cassini XXM science.

Cassini XXM
**Cassini Program**

**Outer Planets Missions, 2010–2020**

- Jupiter: Cassini, Juno
- Saturn: EM, XXM
- Uranus
- Neptune
- Pluto / Kuiper

**Cassini XXM will fill a critical gap in NASA’s outer solar system exploration.**

March 9, 2009

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**Cassini Program**

**Cassini XXM Science**

- Outstanding opportunities for unique, groundbreaking science.
- Direct relevance to the Planetary Decadal Survey and NASA’s exploration program.

March 9, 2009
Backup Slides

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Prime Mission and Equinox Mission Tours

- **Prime:**
  - SOL 7/1/04
  - 4 yr
  - 75 orbits
  - 45 Titan
  - 4 Enceladus
  - 9 other icy

- **Equinox:**
  - 7/1/08
  - 2-1/4 yr
  - 64 orbits
  - 28 Titan
  - 8 Enceladus
  - 4 other icy
Cassini Mission Overview

Year of Tour
1 2 3 4 5 6
Orbits 11 15 22 27 30 21 4
Titan

Enceladus
Other Icy Satellites

Saturn (as seen from Sun)

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XXM Tour Overview

- 156 orbits (20 F ring, 22 proximal)
- 54 Titan flybys
- 11 Enceladus flybys (6 plume passages)
- 4 Dione flybys (1 in wake)
- 2 Rhea flybys
- 2 Iapetus flybys
- 4 smaller moon flybys
  - Ileuste, Methone, Helene, Epimetheus
- 1 G ring arc flyby
- Many dozens of radio, Solar, stellar occultations of Saturn, its rings, and Titan
- Maximum inclination: 62° (first inclined period) / 64° (second)
- Total cost: 160 m/s
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XXM Tour Drivers

- Plume / ocean drag field, plume passages, very low alt.
- Internal structure (RSS, low altitude, no occ., SEP=30)
- Thermal mapping of S.P. (CIRS/VIMS, S.P. viewing)
- Rhea ring detection (stellar occ., high phase site), mass/grav.
- Iapetus internal ocean (low phase, sub-Saturn hemi)
- Thin ice plumes? (close flyby, wake passage), magnetically pass
- Tethys mass/grav., wake passage
- Hyperion addit., large rings (close flyby)
- Mimas (close flyby)
- Many Saturn occs observed in latitude up to pole at high inclination
- Dedicated Saturn flybys inside 5RM for multiple rotations
- Orbital with 1st/2nd passageway for non-photographic study
- High-resolution particle observations
- Saturn occultations within 2" of pole to study visors
- Many Titan flybys with mixture of geologies, mostly polar passages below north
- 2 Titan polar passages of 20-40 fb
- Distant Titan flybys to look out north polar observations
- Close flybys (40%) for NACAM, VIMS, HIRIS, medium flybys (10%) for TIRIS, str. range flybys (10%) for CIRS, CASO

Cassini XXM Objectives

Some tour "twists" are under consideration, but no XXM tour can enable all objectives.
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Discoveries of the Prime and Equinox Mission: Titan

- Active methane cycle on Titan:
  - Polar lakes
  - Clouds/precipitation
  - Erosional features (dendritic channels, rounded pebbles...)
  - Dunes
- Evidence for an internal, presumably water, ocean
- Complex organic chemistry in upper atmosphere
- Strong connections to Saturn magnetosphere
  - Imprint of Saturn magnetic field
  - Enceladus as a source of oxygen for Titan chem.

Key Questions
- What happens to methane on the surface and in the atmosphere over time? (methane hydrological cycle)
- What is the origin of Titan’s atmospheric methane and nitrogen?
- How is methane supplied to the surface?

Prime Mission/XM Icy Highlights: Enceladus

Endogenic activity discovered and studied by multiple Cassini instruments:
- Intense tectonism, active warm fractures with atypical composition
- Total heat flow greatly exceeding steady-state predictions
- Multiple dust plumes supplying the E-ring, with several particle types, including those that are salt-rich
- Gas plume with complex organic and inorganic chemistry, supplying magnetospheric ions and neutrals
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Prime Mission/XM Icy Highlights: Other Satellites

- Fringe complex geology and hints of mass loading
- Iapetus: Equatorial ridge and fossil bulge, thermal influence on albedo dichotomy, odd solar wind interaction
- Rhea undifferentiated or non-hydrostatic, hints of a ring(s)
- Hyperion: Unusual "sponge-like" appearance
- Rich chemistry of dark material on all satellites

March 3, 2009

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Paradigm-Shifting MAPS Discoveries

- Saturn's magnetosphere is "swimming" in water
- Plasma draping by interchange instability
- Enceladus is the mass source of the magnetosphere
- Curved, asymmetric magnetotail
- Curved water group ring current
- Heavy negative ions above Titan's homopause
- Both terrestrial and Jupiter-type magnetospheric convection patterns
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Major Discovery:

Enceladus is the Mass Source of Saturn’s Magnetosphere

During the E1 flyby the magnetometer observed magnetic field draping that is characteristic of magnetospheric plasma interaction with a neutral gas cloud. This led to the discovery of the plumes of Enceladus.

March 8, 2005

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Prime Mission/XM Highlights: Saturn Winds and Clouds

1. North polar hexagon, a stationary pattern in an eastward jet, is still there after its discovery by Voyager in 1981 (size is two Earths)
2. Rotation rate of the interior is unknown – Saturn may not be the windiest planet after all
3. Deep atmosphere is active – near-IR and microwave imaging reveals detailed structures 100 km below the visible clouds
4. South polar hot spot is a warm-core cyclone with eyewall clouds 75 km high (inferred from shadows)
Prime Mission/XM Highlights: Saturn’s Atmosphere

1. Dragon storms (rare - one every 1-2 years) are the source of Saturn electrostatic discharges (GED’s), i.e., lightning.
2. Aurora (shown in near-IR) is variable on all time scales. Blue = aurora, red = hexagon.
3. Waves in the tropical stratosphere resemble Earth’s quasi-biennial oscillation (QBO).

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Prime Mission/XM highlights: Ring Composition and particle size

Near-IR spectra with 150km res throughout the rings. 3-8 radio occultations show size variations with location.

Water abundance and visual color: some correlate well.

Radial variations of particle size and color.
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End of Mission Geometric Requirements for Science

- Periapsis orientation near noon (12:00 Local Solar Time) for continuous tracking of spacecraft
  - Radio Science (RSS) gravity mapping measurements
  - Low phase, high resolution imaging of main Rings
- Periapse below ring plane
  - Radio Science Earth occultations of planet and main rings
  - UVIS/VIMS Solar occultations of planet and main rings
- Approach to periapsis over northern hemisphere
  - Sunlit CIRS and VIMS observations (these instruments require pre-periapsis observations during these orbits because of expected radiator heating)
- End of mission phase designed to address key science