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Cassini-Huygens Solstice Mission

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I. Executive Summary

Our understanding of the Saturn system has been greatly enhanced by the Cassini-Huygens mission. Fundamental discoveries have altered our views of Saturn, Titan and the icy moons, the rings, and magnetosphere of the system. The proposed 7-year Cassini Solstice Mission would address new questions that have arisen during the Cassini Prime and Equinox Missions, and observe seasonal and temporal change in the Saturn system to prepare for future missions.

The proposed Solstice Mission would provide new science in three ways: first, by observing seasonally and temporally dependent processes on Saturn, Titan and other icy satellites, and within the rings and magnetosphere, in a hitherto unobserved seasonal phase from equinox to solstice; second, by addressing new questions that have arisen during the mission thus far, for example providing qualitatively new measurements of Enceladus and Titan which could not be accommodated in the earlier mission phases; and third, by conducting a close-in mission at Saturn that would provide a unique comparison to the Juno observations at Jupiter. In addition, we plan to study the evolution of activity on Enceladus and continue searching for activity on Titan and other icy satellites. These types of observations, absent Cassini, could not be fulfilled for decades to come. For all these reasons, we urge the Decadal Committee to be highly supportive of the proposed Cassini Solstice Mission (CSM).

II. Proposed Cassini Solstice Mission Overview

Cassini has been in orbit around Saturn for over 5 years, returning a wealth of scientific data on Titan, Enceladus, and the other icy satellites, Saturn, the rings, and the magnetosphere. This flagship mission is a cooperative undertaking by NASA, ESA, and the Italian space agency (Agenzia Spaziale Italiana (ASI)) with NASA supplying the Saturn Orbiter, ESA supplying the Huygens Titan Probe, and ASI providing hardware systems for the Orbiter as well as instruments for both the Orbiter and Probe. The primary and ongoing goal of Cassini-Huygens is to conduct an in-depth exploration of the Saturnian system.

Cassini arrived at Saturn in July 2004, roughly two years after the northern winter solstice and it has been in orbit around Saturn through spring equinox (August 2009), to date completing its 4-year Prime Mission and about half of its 2.25-year Equinox Mission. The Cassini Project recently completed tour planning for an additional 7-year phase informally called the Cassini Solstice Mission (CSM) that would, if approved by NASA, extend the mission lifetime through Saturn's northern summer solstice. This extension would permit observations of seasonal change across nearly half a Saturnian year.

Key scientific objectives for the CSM include:

Titan: Seasonal and temporal change, and emphasis on: surface lakes and other materials; internal structure; aerosols and heavy molecules; upper atmospheric density; surface topography; surface temperature and clouds; winds.

Icy Satellites: Potential temporal variability of Enceladus activity, and emphasis on: Enceladus ocean and interior structure; Dione activity; Rhea rings; Tethys magnetospheric interactions; Rhea differentiation state.

Rings: Opening angle and temporal variability, and emphasis on: ring age and mass; clearing gaps; compositional variations; microstructure; propeller structures, in situ D ring.

Saturn: Seasonal change, and emphasis on: rotation rate; polar storms; trace gases; lightning; ionosphere; internal structure.

Magnetosphere: Seasonal and solar cycle effects, and emphasis on: magnetotail dynamics; inner radiation belts; magnetospheric periodicities; coupling to Saturn's ionosphere and rings.

To achieve the CSM goals and objectives, the proposed Cassini Solstice Mission includes an additional 160 Saturn orbits with 56 targeted Titan flybys, 12 close Enceladus flybys and additional close flybys of Rhea (2) and Dione (3), as well as numerous non-targeted flybys of these targets and several radio, solar and stellar occultations by Saturn, Titan and the rings.

III. Titan

Titan is the only object in the solar system other than Earth that sustains an active hydrological cycle with surface liquids, meteorology, and climate change. The active working

fluid of Titan's hydrologic cycle is methane on seasonal (decadal) timescales and ethane on Croll-Milankovitch (millennial) timescales (Lunine and Atreya, 2008).

The Cassini-Huygens mission has revealed the essential details of the methane hydrologic-like cycle that we understand today, and which we continue to elaborate upon with the discoveries of the Cassini Equinox Mission. The cycle is active but different from that of Earth because Titan lacks a surface methane ocean. It possesses, however, methane-ethane lakes and seas (two of which are larger in absolute size than the North American Great Lakes), fluvial erosion, rounded pebbles and liquid methane in the soil at the Huygens site, and equatorial dunes shaped by winds and formed of organic particles derived from methane (Lunine and Lorenz, 2009). Titan's seasons are longer by a factor of seven than Earth's, but the axial tilt is similar to that of our home world.

These lakes are signposts of climate change on Titan. Titan's pole precesses over tens of thousands of years, which—coupled with the eccentric orbit of Saturn around the Sun—leads to an asymmetry in the seasons that at present biases methane lakes toward the north, where we see them in abundance. The effect is somewhat akin to the famous Croll-Milankovitch cycles on Earth and is modulated by, and reverses with, dynamical variations in Saturn's orbital and spin state. The resulting cycling of methane and ethane between Titan's poles—with a period of tens of thousands of years—leads to active surface modification in the polar latitudes, but with two interacting fluids, ethane and methane, rather than one as on Earth.

To test these ideas requires Cassini observations on timescales that comprise almost half a Titan year. The prime and equinox missions allowed Sun-illuminated observations of the south polar region from early southern summer through autumnal equinox. At the present time, then, the north polar region is just coming into the first day of spring and hence becoming illuminated. As on Earth, the southern and northern polar regions are completely different. On Titan hundreds of lakes, observed in the dark by Cassini radar, occupy a significant fraction of the northern polar reaches, three of which are large enough to be designated "seas" by the IAU. A large number of depressions that appear to be empty of liquid are also seen in the north. In the south, only one medium sized lake, 250 km long, has been observed, along with a few smaller depressions, which appeared to fill after a convective rain event in the early summer.

The onset of solar illumination in the north has three consequences. (1) It would be possible to take spectra of the northern lakes with the Visual and Infrared Mapping Spectrometer (VIMS) to test for the presence of ethane (and potentially methane) in the lakes—current inference of liquid in the vast northern lakes and seas is from radar properties. (2) The potentially vastly larger amounts of liquid in the northern lakes/seas compared to the south should lead to dramatic meteorological consequences as spring progresses to the early-2017 summer solstice. (3). Relative temporal behaviors of the small versus large lakes as the Sun climbs higher in the northern sky over the next seven years would allow quantitative testing of the hypothesis that the lakes are connected to an underground methane "aquifer" system.

In Titan's stratosphere, a predicted change in global circulation could be observed during CSM. The current south-to-north single cell should evolve through a transient, symmetric two-cell equator-to-poles circulation sometime after the 2009 equinox, towards a single cell north-to-south circulation before the northern summer solstice. During this period, the current northern polar vortex containing enriched trace gases and aerosols should disappear, and reform in the south. Insights gained by studies of Titan's seasons would have implications for our understanding of the Earth's climate.

The proposed Cassini Solstice Mission provides a unique opportunity to study the seasonal progression of atmospheric and surface phenomena in the volatile-rich northern reaches of the solar system's second active liquid/hydrological system.

IV. Icy Satellites: Enceladus and Other Mid-Sized Satellites

The Cassini Prime and Extended Missions have taught us much about the mid-sized satellites of Saturn, and much remains to be learned. New discoveries require follow-up, and dynamic phenomena need to be explored further by extending the timebase of observations.

Cassini's most dramatic discovery relating to the mid-sized satellites of Saturn has of course been the ongoing endogenic activity of Enceladus, discovered by multiple Cassini instruments in 2005. Two of the highest-priority objectives for future Cassini studies thus relate to Enceladus.

First, it is important to understand the temporal variability of the activity on timescales from hours to decades. Changes on timescales of hours may reveal orbital modulation of the activity that would illuminate the mechanisms controlling the activity (Hurford et al., 2007), and a continuation of the mission would give many additional opportunities for such studies. Changes on longer timescales would help to answer the question of how typical is the current level of activity (several lines of evidence suggest that the current output of energy and material cannot be sustained long-term, e.g. Meyer and Wisdom (2007)), would constrain the lifetime of individual vents and thus illuminate eruption processes, and would aid in the design of future missions to Enceladus.

Second, more detailed studies of Enceladus, enabled by the large number and variety of Enceladus flybys that a further extended mission would make possible, may provide much improved understanding of the mechanisms generating the activity, and the implications for the interior, and even the habitability, of Enceladus. These studies include the mapping of Enceladus' gravitational field to probe interior structure, searching for an intrinsic or induced magnetic field, more and deeper plume passages to understand the composition of the gases and dust released from the interior (e.g. Waite et al., 2008), mapping of surface thermal radiation at very high spatial resolution to constrain vent temperatures, and further imaging of the surface and plumes.

The third high-priority mid-sized satellite objective relates to possible ongoing or geologically recent activity on Dione. Cassini observations of Dione's plasma interaction hint that it may be outgassing material into the magnetosphere, in contrast to Tethys and Rhea, and some remote sensing data suggest that Dione has a particle halo. The surface is also second only to that of Enceladus in geological complexity among the mid-sized satellites, with fresh fractures and other enigmatic geological features (Schenk and Moore 2009). Future flybys could establish whether outgassing is occurring, and would investigate the endogenic geological features with high-resolution remote sensing, including searches for signs of current activity, such as plumes or thermal emission.

Second-level priority objectives for future studies of the mid-sized satellites include investigation of the possible ring of material orbiting Rhea suggested by energetic particle data (Jones et al., 2008), probing of interior structure and degree of differentiation (especially that of Rhea and Dione) using gravity flybys, and additional investigations of the enigmatic dark material on Hyperion.

V. Rings

The Cassini Prime and Equinox Mission have significantly altered our views of Saturn's rings. Cassini has made fundamental discoveries, directly addressing the major questions posed at the start of the mission. For instance, the microstructure of the rings has been characterized in three dimensions, at the 10-100 meter lengthscale, by numerous stellar and radio occultations (Colwell et al., 2009). Non-axisymmetric structures permeate all the moderate optical depth rings, which are analogous to the gravitational instabilities suggested to play a role in the early stages of planet formation. Radio occultations have constrained the optical depth and particle size distribution throughout the main rings, showing local variations in the relative abundances of cm- and dm-size particles.

Moreover, over a hundred spiral density waves have been used to measure the ring mass density directly in regions never before possible. These same density waves have determined the masses of all the close-in ring moons, which, combined with their measured sizes, have shown that they are all rubble piles which are largely accretional (built, perhaps, on a denser central shard of unknown provenance). One new moonlet has been discovered in an empty gap. An entirely new population of 100-500 m size objects, called "propellers" for their characteristic disturbances of nearby ring material, has been found to reside in three main bands in the A ring; some of these seem to be moving radially. The narrow, stranded F ring is a mélange of variation

on all timescales – days, weeks, years, and decades. Dense clumps of material appear and are then lost; orbits of new objects are hard to connect with orbits of those previously seen.

The ring composition has been determined to be extremely pure, crystalline, water ice with not a trace of other ices such as CO₂, NH₃, or CH₄. The reddish tinge of the rings at short visual wavelengths remains unexplained, as no other diagnostic spectral features have yet been found, but its radial variation correlates with water ice band depth suggesting the reddish material is intimately tied to the water ice component. Other more subtle spectral variations suggest other constituents with different radial distributions (Cuzzi et al, 2009). Regarding electromagnetic interactions of rings and their environment, the seasonal variation of spokes has been confirmed.

The focus of the proposed Cassini Solstice Mission studies of rings is on seasonal and temporal variations in ring structure, and on selected campaigns to follow up on the most important new discoveries and unanswered questions. The seasonal and temporal measurements would make use of new tour geometries, and the varying ring opening angle as seen from Earth, to constrain microstructure in thick and thin rings (which have different amounts of self-gravity wake structure). A fundamental campaign is determination of the ring age, which is largely constrained by extrinsic meteoroid pollution and thus requires two separate measurements: a direct measurement of ring mass (which remains uncertain in the most dense central regions) and a (slightly indirect) measurement of incoming meteoroid mass flux. The first would be accomplished by gravity tracking of the spacecraft in the late Proximal orbits with periapse inside the main rings (see section VIII), and the second by several close flybys of inactive icy moons, to measure their haloes of ejected dust.

Another extremely high priority objective is the still-unanswered question of whether as-yet unseen small moonlets maintain the nine or so still empty gaps; optimal geometries and in-depth observations would be devoted to this critical goal. Moreover, targeted spectroscopic observations would be conducted of ring regions where compositional variations have been glimpsed, but so far at inadequate spatial resolution. Dedicated observations would track the oddly evolving “propellers” to see if they provide good analogs for “Type-1” migration of planetary cores in protoplanetary nebulae. The varying F ring would be tracked for occasional large collisions (seen from HST but not yet from Cassini) and other possible surprises.

The proposed Cassini Solstice Mission offers a unique opportunity to study both long and short-term temporal variations within the rings, to follow up on new discoveries, to measure the ring mass, and to explore the rings at unprecedented resolution during the Proximal orbits.

VI. Saturn

Seasonal change on Saturn is amplified by the rings, which shield the winter hemisphere from sunlight. An important objective of the Cassini CSM is to complete the documentation of these changes over one-half the Saturn year, from southern to northern summer. An equally important objective is to address the new questions that arose during the Prime Mission. The examples below are generally organized from the inside of the planet to the top of its atmosphere.

The axisymmetry of Saturn’s magnetic field complicates the determination of Saturn’s internal rate of rotation. The best opportunity to detect any small departures from axisymmetry would come at the end of the CSM when the spacecraft flies inside the D ring, skimming the planet’s atmosphere on a highly inclined orbit (see section VIII). These close-in orbits are ideal as well for probing the higher-order gravity harmonics, which are the key to estimating the planet’s internal structure, core mass, and internal rate of rotation.

A separate question is whether or not the winds change with the seasons at cloud-top levels. Comparison of Voyager, Hubble, and early Cassini observations suggests that they do change, but the result is complicated by possible changes in cloud heights. With its superior coverage and instrumentation, Cassini can answer this question during the CSM by employing new ways of peering into the deep atmosphere using images of thermal emission at 5 μ m and 2 cm wavelengths. These images show greater contrast and more features than are seen in visible light.

The helium to hydrogen ratio has proved difficult to measure using traditional occultation techniques. The CSM provides the opportunity to settle this issue using new methods and better data. The new method involves using stellar occultations instead of radio occultations to get T/m

and infrared spectra to get T . The molecular mass m then determines the He/H₂ ratio.

Both acetylene and ethane are products of methane photodissociation, but acetylene has a shorter chemical lifetime than ethane. Comparing their distributions with latitude and season helps separate the seasonal effects from the effects of the circulation and upwelling. Seasonal changes in temperatures, composition, and auroral emissions are clues to how the upper atmosphere works.

By matching the radio signals of lightning with storms seen in visible images, Cassini has identified the lightning sources and has shown that they are rare (Dyudina *et al.*, 2007). Lightning storms occur on average about once per year, and thus far have always been associated with a westward current at 35 degrees south latitude. Little or no evidence for equatorial lightning has been observed. The CSM would enable studies of seasonal trends in rates of lightning activity.

Both poles contained surprises for Cassini. The giant hexagon centered on the north pole is a cloud pattern that has persisted since the Voyager era (Fletcher *et al.*, 2008). The south pole contains a hot spot resembling the eye of a hurricane whose eyewall clouds tower 70 km above the central cloud or three times the height of eyewall clouds on Earth. The equator showed oscillations of the eastward wind with altitude that are coupled to temperature oscillations detected from Earth (Fouchet *et al.*, 2008). They resemble the oscillations in the Earth's equatorial stratosphere known as the QBO. All of these new phenomena would be studied further in the CSM.

VII. Magnetospheres

Observations from the Cassini Prime and Equinox Mission have answered questions and opened new ones regarding the periodicities observed in Saturn kilometric radio emission (SKR) and the relation to the rotation rate of the deep interior. It was thought that the SKR was related to a non-axial component of the magnetic field that rotated with the interior, and drove the observed periodicities, however, a non-axial component has not yet been found. The radio period has been observed to slowly change over time and certainly cannot reflect a change in the actual rotation period of the planet. Instead, the drift in period may be attributed to "slippage" of the magnetosphere of Saturn relative to its interior. Periodicities at or near a common rotation period of ~10.8 hours are ubiquitous in Saturn's magnetosphere. This makes the modulation particularly mysterious, and has generated a variety of suggestions for its cause that would be investigated. A second period near 10.6 hours has been recently observed in the radio emission, and the longer and shorter periods are associated with the southern and northern hemispheres, respectively. The CSM would enable us to determine whether the periods vary seasonally or if some other asymmetry in the system is responsible for this very curious effect.

A fundamental issue of magnetospheric physics is the sources of the plasma that populate the magnetosphere (Mauk *et al.*, 2009). Unlike Earth and Jupiter, neutrals dominate Saturn's magnetosphere. At Saturn, possible plasma sources are the solar wind, Saturn's ionosphere, Titan, the rings, and the icy satellites. A significant discovery of the Cassini mission was Enceladus' role as a source, presumably via relatively slow, ongoing ionization of the neutral torus. During the upcoming CSM we plan to examine how Enceladus' gas production, plume composition and dust to gas ratio (a measure of conditions within the vents) change with solar cycle or season and how the magnetosphere reacts to those changes. The variability in composition of the neutral gas from plume to plume can be examined for evidence of individual reservoirs or a global ocean.

Another discovery by Cassini is that the magnetospheric convection pattern of Saturn falls somewhere between that of Earth and Jupiter (Gombosi *et al.*, 2009). Earth is a slow rotator with a relatively small internal mass source and its magnetosphere is primarily dominated by the solar wind. The resulting magnetospheric convection is referred to as the "Dungey cycle". Jupiter is a fast rotator with a strong surface magnetic field and a significant plasma source (Io) deep inside the magnetosphere, hence, internal processes compete with the solar influence. Plasma flow at Jupiter is dominated by the "Vasyliunas cycle." Saturn falls somewhere in between, simultaneously exhibiting both a Dungey cycle and a Vasyliunas cycle. This makes the

Kronian magnetosphere even more fascinating and complex than those of Earth and Jupiter. Key questions to be addressed during the Solstice mission are: what controls the interplay between the Dungey and Vasyliunas cycles, and how does this vary over the solar cycle?

Cassini has completed several orbits through Saturn's magnetotail and has obtained evidence for magnetic reconnection (and subsequent particle acceleration) similar to Earth and Jupiter (Mitchell et al., 2009). Plasmoids, characterized by an oxygen-rich composition (similar to the inner magnetosphere), and a strongly tailward, subcorotational flow, have been identified. The association of plasmoid reconnections and substorms at Earth suggests that magnetotail dynamics at Saturn may be internally driven by the planet's rotation rather than by solar wind interactions as at Earth. Periodicities near the magnetospheric rotation rate observed in Saturn's magnetotail also imply it is driven internally by planetary rotation rather than externally by solar wind interaction. Saturn's magnetic axis is not tilted, however, so the magnetotail periodicities must arise by some unknown mechanism. There is clear evidence of strong perturbations of the magnetosphere driven by the interaction of high pressure regions in the solar wind called co-rotating interaction regions with Saturn's magnetosphere. Their effects are seen in brightening and the pole ward expansion of Saturn's auroras and the intensification of SKR.

Several key questions remain regarding Saturn's aurora (Kurth et al., 2009). Observations of emission of energetic neutral atoms from the ring current reveal the presence of an acceleration region in the equatorial plane that rotates in step with the bright auroral UV emission. An electric current mapping along Saturn's magnetic field connects the ring current enhancement with the ionosphere and stimulates the UV emission. CSM would look for evidence of currents connecting the ionosphere and magnetopause and for solar wind control of the aurora.

VIII. Proximal Science

The final 42 orbits of the CSM would offer unique opportunities for new discoveries and groundbreaking science as well as further prospects to observe seasonal and temporal change. This Proximal orbit phase, preceded by several orbits passing close to Saturn's F ring, is similar in many ways to the Juno mission at Jupiter. This phase would end with the spacecraft ultimately vaporizing in Saturn's atmosphere in accord with anticipated planetary protection requirements.

These orbits enable unique science, including: determination of Saturn's internal structure, the higher order moments for both the gravity and magnetic fields, and possibly the internal rotation rate for Saturn; measurement of Saturn's ring mass, currently uncertain by about an order of magnitude; in situ measurements of Saturn's ionosphere, innermost radiation belts, and D ring, and possibly in situ measurements of Saturn's auroral acceleration region; highest resolution studies of the main rings; and high resolution Saturn atmospheric studies. The Cassini magnetometer would determine the higher order coefficients of the magnetic field to degree 6, which may allow a determination of the depth of Saturn's metallic core. Using data from six gravity passes, Saturn zonal gravity harmonics would be estimated up to degree 10 with an accuracy of $< 10^{-8}$, at least two orders of magnitude less than current model values for J10.

This mission phase would consist of 42 short period orbits from Nov. 2016 to Sept. 2017. Twenty orbits would have periapses just outside the F ring. This geometry sets up Cassini for the final jump to the Proximal orbits, with periapse just inside the D ring. The F ring orbits are scientifically rich, including high resolution observations of Saturn's F and A rings, Earth and solar occultations of the rings, and auroral field line crossings inside 4 Saturn radii.

At least 22 orbits would have periapses in the 3,000-km clear region between the inner edge of the D ring, potentially containing an innermost radiation belt, and Saturn's upper atmosphere. These orbits have a critical inclination of 63.4° to prevent orbit rotation due to Saturn's oblateness. The periapsis orientation would be near noon local solar time to permit continuous DSN tracking of the spacecraft for gravity mapping measurements as well as low phase, high resolution imaging of the main rings. Periapse would be below the ring plane (south side of the rings) producing Earth occultations and solar occultations of the planet and main rings. The approach to periapsis would be over the northern hemisphere for observations of the sunlit rings inbound. Outbound trajectories would provide excellent views of Saturn's southern auroras.

The planned Saturn impact date is Sept. 15, 2017. If sufficient delta v is available, it would be possible to execute a maneuver to delay Cassini's atmospheric entry by a few more orbits.

IX. Summary

The Cassini-Huygens mission has considerably expanded our understanding of the Saturn system. Fundamental new discoveries have altered our views of Saturn, Titan, Enceladus and the other moons, the rings, and the magnetosphere of the system. The proposed 7-year Cassini Solstice Mission will address new questions that have arisen during the Prime and Equinox Missions, observe seasonal and temporal change in the Saturn system to prepare for future missions, and conduct a close-in phase that would provide unique new scientific results. These types of observations, absent Cassini, could not be fulfilled for decades to come. For all these reasons, we urge the Decadal Committee to be highly supportive of the proposed Cassini Solstice mission.

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