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The Continuing Exploration of Saturn by Cassini

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Abstract
The Cassini/Huygens mission to explore the Saturn system is a joint international endeavor among NASA, the European Space Agency (ESA), and the Italian Space Agency. The original mission as agreed to and funded by the partner agencies was for four years of active science data collection from in orbit about Saturn, which began on July 1, 2004. When this part of the mission was completed and the spacecraft was still in an excellent state of health with much valuable science still remaining to be accomplished, a mission extension of 27 months was approved. This first extension is now more than half completed and a proposal is being developed for a further extension with one of the primary science goals being the observation and study of seasonal change at Saturn as it moves into summer in its northern hemisphere for the first time since Cassini arrived. This paper describes highlights of the mission to date, summarizes the current spacecraft health and status of its consumables, and gives an overview of what is planned for further exploration of the Saturn system by the Cassini Project.

Introduction

The original concept for the Cassini-Huygens mission was conceived in the early 1980s after one of the two Voyager spacecraft flew near Titan on its pass by Saturn and confirmed the existence of the dense, nitrogen rich, atmosphere of this mysterious body. A group of European and US scientists, their interest piqued by the Voyager results, began the development of a mission concept that would deliver an atmospheric probe to Titan. This concept, with the support of NASA, ESA, the Italian Space Agency, and several other European member states, was developed to the point that a new Program start was approved by all participants for the start of fiscal year 1990. The Program survived the usual development phase challenges and the spacecraft was launched on October 15, 1997, on a trajectory with two Venus flybys, one of Earth, and one of Jupiter to acquire the needed energy via gravity boosts to reach Saturn on July 1, 2004. Saturn orbit insertion (SOI) was accomplished with a flawless 96 minute burn of the main engine, and the spacecraft was placed in an initial orbit with a 120 day orbit period. This rather large orbit period was designed into the mission profile in order to limit propellant consumption at SOI, and two relatively close Titan flybys were used to reduce the orbital period to 32 days using only the effects of Titan's gravity. Then on December 25, 2004, the Huygens atmospheric probe was released on its final three-week ballistic cruise to Titan, where it entered Titan's atmosphere on January 14, 2005, and completed a highly successful descent on parachute to the surface, revealing for the first time the surface of this body without its obscuring atmospheric shield. From this point, the Cassini orbiter continued for another three and a half years to complete its original plan of a four-year tour of the Saturnian system. The mission continued when NASA approved a 27 month extension to continue the mission to September 30, 2010. Plans are currently being developed and pending approval to continue the exploration for a number of years even beyond this point.

Completing the Original Prime Mission

The original prime mission for Cassini was planned to be completed in four years. During these four years, the spacecraft completed 75 orbits about Saturn, 45 close targeted encounters with Titan, four with Enceladus, and one each with Tethys, Hyperion, Dione, Rhea, and Iapetus. In addition to these, there was an encounter with Phoebe on approach to Saturn twenty days prior to arrival at Saturn and insertion into orbit. Phoebe was of particular interest to the scientists because of its retrograde orbit and evidence that it had not formed as part of the original Saturn system, but rather had been captured from outside at a later time, and the approach to Saturn was the only opportunity to get a close look at this body since, once in orbit, Cassini would never again get as far out from Saturn as Phoebe's orbit. Another highlight of the first four years was the release of the Huygens probe from the Cassini orbiter, which had carried it to Saturn, on December 25, 2004, to begin its three-week free-fall cruise to the atmosphere of Titan. Here the probe accomplished its entry and descent sequence, and after about a 2.5 hour descent on parachute, reached the surface of Titan, survived impact, and continued to transmit data from the surface for about another hour. All data transmitted from the probe, both during descent and while on the surface, were received and recorded by the Cassini orbiter flying overhead, which subsequently turned and relayed the data back to Earth. The data received from the surface of Titan were actually a bonus in the sense that, while survival of impact was considered probable, it was not a design criterion for the probe, and was not required to achieve the objectives of the probe mission. A second data set which further contributed to the success of the mission, but had not been part of the original mission plan, was the Earth-based real-time acquisition of the signal transmitted by the probe during its descent and active time on the surface. This signal did not provide telemetry data since the received signal strength was too weak to support the acquisition of telemetry, but the Doppler effect visible in the carrier signal provided valuable data on the winds experienced by the probe during its descent, this data set was useful in determining more accurately where the probe landing point was, and it would also have been potentially useful for failure analysis in the event of an anomaly during the probe mission phase. Fortunately, this possible use turned out not to be needed since the probe system performed as designed all the way to the surface of Titan.

By any measure, the four-year prime mission was a complete and unqualified success. The formal scientific objectives stated for the mission (ref 1) were general in nature, but adequately detailed to characterize the areas of investigation that the project was expected to address.

The First Mission Extension

As the prime four-year orbital mission for Cassini progressed with practically flawless performance by the spacecraft, and with the consumables usage following right on budget with ample planned reserves, and with new, unique, and exciting science data being returned on a daily basis, discussions naturally turned to what might be in store in the way of a mission extension. Even though the original four-year mission was well on track to accomplish everything it had been expected to, there still remained a number of areas that could benefit from further exploration. In general terms, one of these areas was to follow up on unexpected discoveries and new questions raised in the first four years. A specific example of this was the discovery of ice particle plumes emanating from the south polar region of Enceladus that was made within about the first year of the prime mission. Another general category was to further extend observations that simply couldn't be fit within the prime mission. A specific example of this is high-resolution Synthetic Aperture Radar coverage of the surface of Titan. Since each Titan pass that is dedicated to Radar can cover about 1% of Titan's surface, obviously many Radar passes would be necessary to cover a sizeable portion of the surface area of the body. Of the 45 Titan encounters in the prime mission, about half were assigned to Radar during the closest approach phase, resulting in about 22% surface coverage. Seasonal variation within the Saturn system was another general area of scientific interest that could only be partially completed in the four-year prime mission. Since Saturn's orbital period around the sun is approximately 29 Earth years, the four Earth-year prime mission corresponded to about one and two-thirds months of Saturn seasonal time, clearly insufficient time to develop any depth of understanding of the seasonal variations of the Saturnian system.

For a large and complex flight project such as Cassini, the time from the initial development of a proposal for a mission extension to the time a sequence will first be available to go active on the spacecraft is considerable. For the Cassini extended mission, the process began in January, 2006, with the design of candidate orbital trajectories that used as initial conditions the end point of the prime mission trajectory, and that incorporated as many of the objectives as possible as defined by the various investigation teams. Several designs were developed, reviewed by the science teams, and then modified to better accomplish the scientific objectives. Several such iterations ensued over the following months, and in February, 2007, a proposal was made to NASA for a two-year mission extension based on a specific trajectory and which identified the science return that such a mission extension would provide. The proposal was approved by NASA, in fact a 27 month extension was approved, and the new mission began on July 1, 2008. Whether the trajectory to be flown for the additional three months would be designed as a three month extension or use the first three months of a trajectory that would be part of a proposal for a second further mission extension was still an open question at this point.

Cassini's arrival at Saturn on July 1, 2004, corresponded to a point approximately two years after Saturn's southern hemisphere summer solstice, and the end of the prime mission on July 1, 2008, occurred a little more than one year prior to the equinox crossing in August, 2009. One highlight of particular scientific interest in the proposed mission extension was this equinox crossing and the opportunity it would provide for observations of very small vertical displacements in the rings by the shadows they would cast as the sun passed through the plane of the rings. Two further scientific priorities were Titan and Enceladus; the former in order to obtain more high resolution Radar mapping coverage as well as to see seasonal changes in the dense atmosphere as summer went from the southern hemisphere to the northern, and in particular to see if the liquid

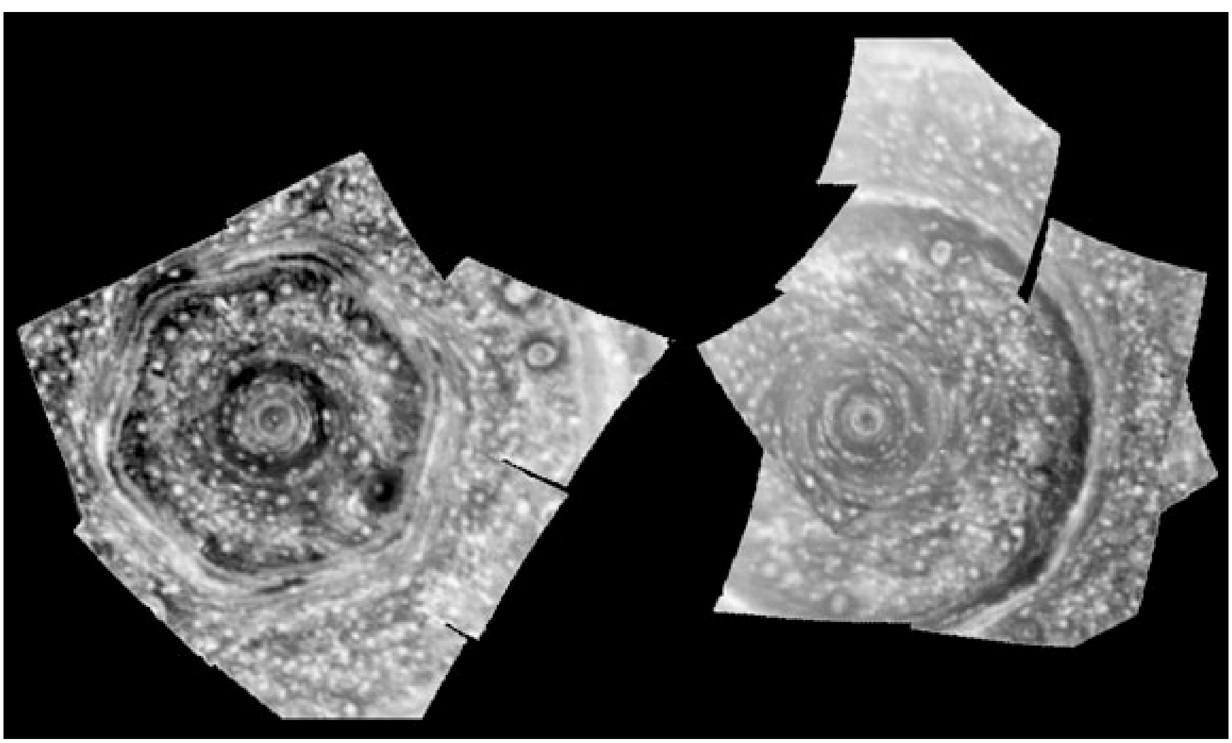

Figure 1 Saturn's Poles in Infrared (PIA11216)

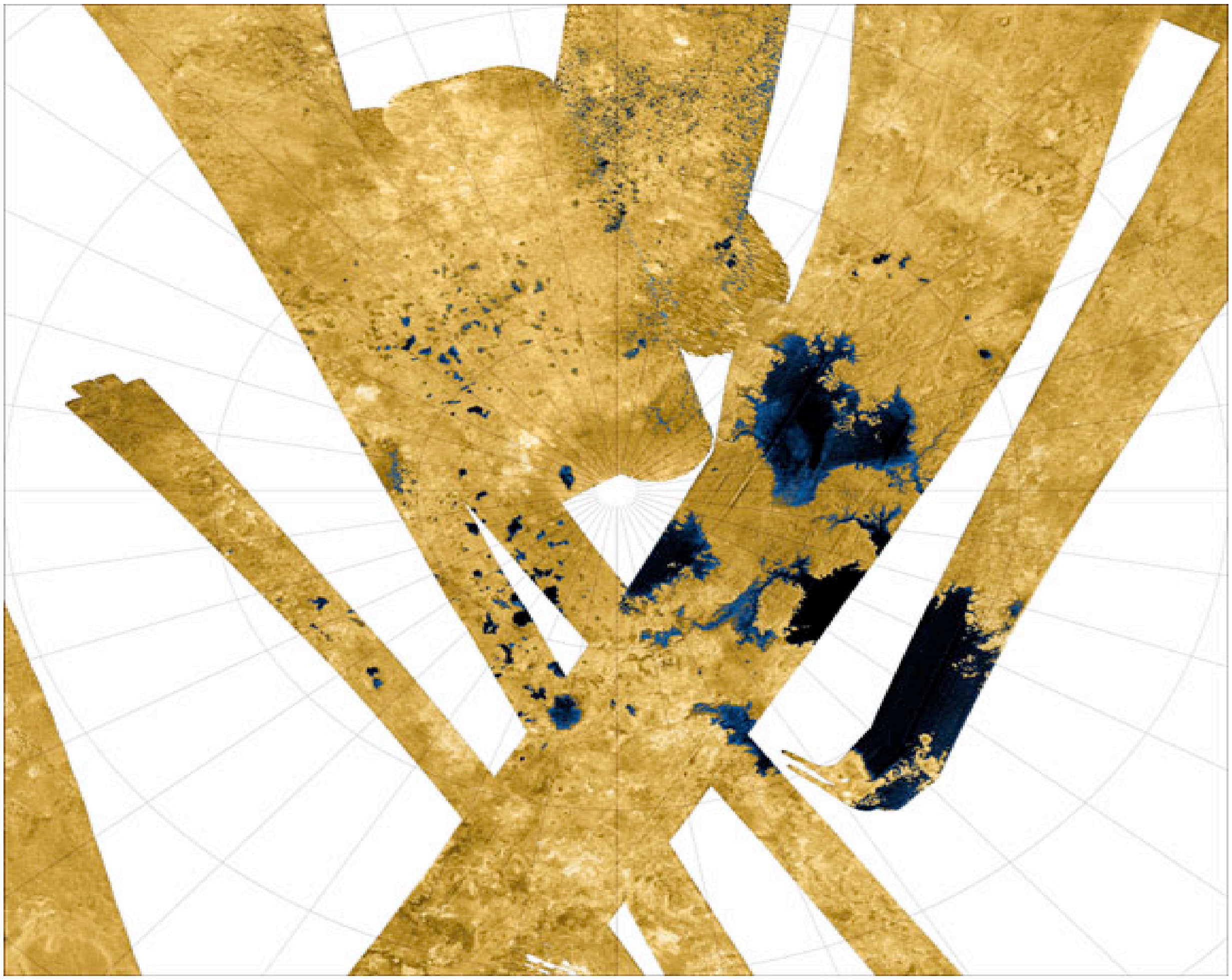

Figure 2 Radar map of Titan's north pole (PIA10008)

hydrocarbon lakes that were seen to exist mostly in the north would migrate to the south as southern winter came, and Enceladus with its mysterious and little understood icy plumes. The two-year tour extension contained 60 orbits of Saturn, 26 targeted encounters with Titan, seven close encounters with Enceladus, four of which would actually pass through the plumes, and many other more distant passes by both Titan and Enceladus. As of this writing, Cassini has completed sixteen Titan flybys and three Enceladus flybys in the extended mission phase, and the equinox crossing has occurred. The mission execution has gone well and virtually all of the planned science data acquisition has been accomplished successfully.

Some Mission Highlights

To this point in its mission, the Cassini Project has made many exciting and significant scientific discoveries about the Saturn system which have led to approximately 1250 refereed publications in various of the scientific journals. Here we highlight only a few of them.

Storms at both poles

Figure 1 shows a side-by-side view of large cyclones at both poles of Saturn as obtained by the visual and infrared mapping spectrometer onboard the Cassini spacecraft. These images were obtained on June 15, 2008 (left, north) and June 16, 2008 (right, south) from distances of 602,000 kilometers and 652,000 kilometers above the clouds, respectively. These high-spatial-resolution polar orthographic projections show rings of clouds and hazes circling the poles, as observed in the near-infrared at a wavelength of 5 micron. The resolution is about 200 kilometers per pixel.

Lakes on Titan

The false-color mosaic of Figure 2 shows all synthetic-aperture radar images to date of Titan's north polar region. Approximately 60 percent of Titan's north polar region, above 60 degrees north latitude, is now mapped with radar. About 14 percent of the mapped region is covered by what is interpreted as liquid hydrocarbon lakes. Features thought to be liquid are shown in blue and black, and the areas likely to be solid surface are tinted brown. The large feature in the upper right center of this image is at least 100,000 square kilometers in area, greater in extent than Lake Superior at 82,000 square kilometers, one of Earth's largest lakes. This Titan feature covers a greater fraction of the surface, at least 0.12 percent, than the Black Sea, Earth's largest terrestrial inland sea, at 0.085 percent.

Cassini scientists use views like that of Figure 3 to help identify the source locations for individual jets spurting ice particles, water vapor, and trace organic compounds from the surface of Saturn's moon Enceladus. This false color image product was specially processed to enhance the individual jets that compose the plume. Some artifacts due to this processing are present in the image.

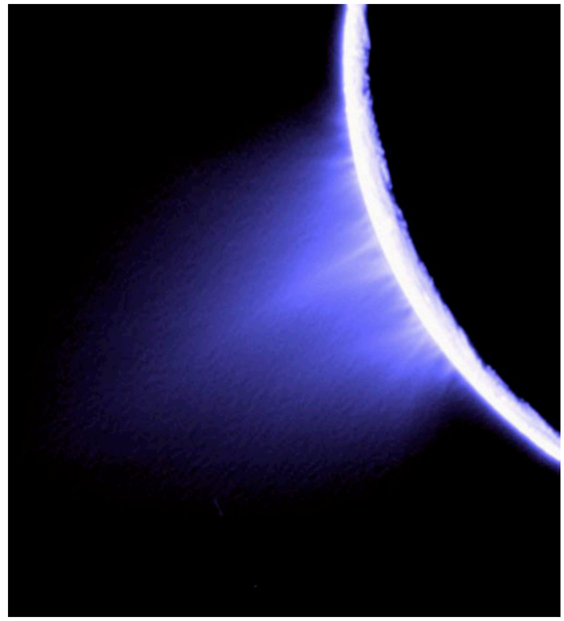

Figure 3 Plumes at Enceladus (PIA08386)

The image shown in Figure 4, taken by Cassini's ultraviolet imaging spectrograph, shows Saturn's aurora above the north pole. Saturn's auroral lights are the result of a rain of electrically charged particles from the magnetic bubble, called the magnetosphere, that surrounds the planet. When the particles strike gaseous hydrogen in Saturn's atmosphere, the hydrogen becomes excited and glows, creating aurora. Changes that occur in Saturn's magnetosphere can cause fluctuations in the aurora. Undulations in the aurora may be caused by waves moving along magnetic field lines. A surge in auroral

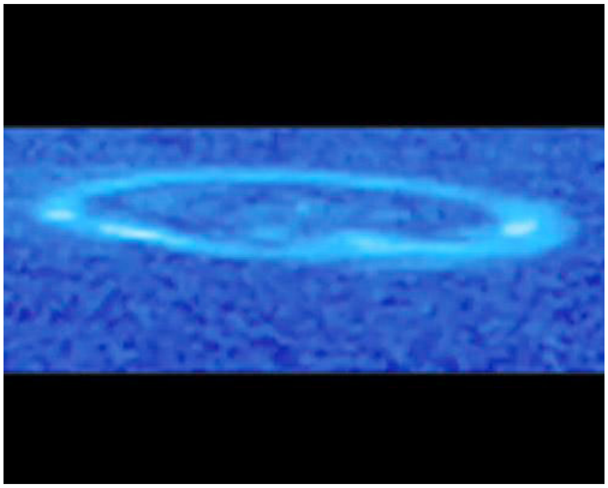

Figure 4 Aurora around Saturn's north pole

brightness is the result of a sudden injection of particles into the magnetosphere. These charged particles come from a variety of sources, including the sun, Saturn's rings, and the water ice plume of Saturn's moon Enceladus.

Some other exciting possibilities for which Cassini has obtained some evidence but has not yet proven conclusively are a layer of liquid under the surface crust of Titan, a ring of dust and particles around Saturn's moon Rhea, and liquid water internal to Enceladus as the source of the icy jets seen coming from the surface of Enceladus. Further observations to be made in the remainder of the current mission extension as well as in any further extension that may be implemented will be used to attempt to prove or disprove these possibilities.

The Second Mission Extension

Starting in December of 2007, about half a year before the prime mission was completed and the execution of the extended mission had begun, in fact even prior to receiving official approval for the first mission extension, planning was initiated for the development of a further mission extension. Perhaps this may seem inappropriately early, but a substantial amount of time is required to develop a new mission concept, design candidate tours to implement such a concept, iterate on these tours with the science community to reach a final design that is approximately optimal for the assumed available resources, and then go through the process of allocating observation opportunities to the various investigations, followed by the development and validation of observation sequences ready for execution on the spacecraft. A further complication in developing this extended-extended mission (XXM) was the going-in assumption that this mission phase would not be funded at the same level as had been the prime and first extended mission (XM). This meant that many of the processes and tools that had been developed prior to and throughout the course of the first six years in orbit were going to require modifications, in some cases very substantial, in order to perform a reduced scope but still scientifically worthwhile mission with a considerably reduced operations team. Initially a goal was set to develop a mission proposal at a funding level of 50% of the annual prime mission funding, inflation adjusted for the later years. The rationale for selecting this goal was that it was small enough that it would surely find the floor of what would constitute a minimum viable mission, and at the same time it was large enough to be credible and such that the operations and science teams could be expected to put a sincere effort into coming up with such a design. Work progressed in defining a streamlined and curtailed ground system and process design, as well as in designing and evaluating orbital tours, for several months into the XM time period. Guidelines were developed to limit the complexity of candidate tours by specifying minimum orbital periods and minimum times between targeted satellite encounters in order to reduce the staffing required to do navigation and spacecraft operations. However, these guidelines soon ran into a snag when it became apparent that they precluded the orbital tours from having any Enceladus encounters, which was a priority target for the XXM. So while these rules were relaxed somewhat relative to how they were originally stated, they did succeed in limiting the complexity of the candidate tours to something less than what had been used for the prime and XM periods. It was also recognized that the science teams' appetites were going to have to be constrained as well. In both the prime and XM phases, the team had done a lot of optimization of the observation designs which led to increased science return, but came at a cost. Rules and new design strategies were devised to limit the complexity and frequency of science observations to further limit the workforce that would be required to implement a mission.

In February 2009, the Cassini Project made a proposal to NASA for a second mission extension to go through September 2017. The rationale for this was that this date corresponds to the time of the summer solstice in Saturn's northern hemisphere, thereby providing observations over almost one complete half-year (Saturn year) of Saturn's seasonal cycles. It also would provide a significant period of time to make observations of other items of scientific interest that had not been completed previously, albeit at a lower rate of data collection. This proposal was for a level of funding at 60% of prime mission for engineering support operations and 75% for science operations. In the course of developing a reduced scope mission concept, it readily became apparent that a 60% level of funding was just about the minimum practical level to support the development and execution of reduced scope science observation sequences and to accommodate safe spacecraft operations. The workload for the Navigation Team, for example, is almost entirely independent of the intensity of the science observations, although surely dependent on the complexity of the tour being flown. The scope of the task for the Spacecraft Operations Team is certainly influenced by the nature of the science observations, but it also has a significant portion of its task that is not, such as implementing maneuvers in support of navigation, monitoring of spacecraft performance, and maintenance of spacecraft health. After completing a rather detailed study of the operations process, the conclusion was that 60% was right at the minimum level of support necessary to keep the spacecraft on course and functioning properly, and to be able to support a reasonable but reduced level of science observations.

The proposed funding level of 75% for science activities was arrived at in a different manner. The science effort can to some extent be a level-of-effort activity, that is to say, the level of effort can be adjusted to whatever level of funding resources is available, and be made to work. However, there is a limit to this as well. Just the operation of the instruments, including maintaining their health and safety, requires a minimum level of support. Beyond this is the task of negotiating for spacecraft pointing control and observation time, and then designing and implementing the observations that will acquire useful science data. Results of the XXM development study task showed that 50% of prime mission funding for science put it right at the ragged edge of being able to keep the instruments safe, operating, and collecting data, but with no support for doing data analysis and publication of the results. Overall, it was judged that at 75%, the science teams could operate the instruments properly, collect data at a level commensurate with the support able to be provided by the engineering teams at 60%, do a reasonable level of data analysis and publication, and support some new young scientists to participate in the process. This proposed mission extension at 60%/75% funding will be a clearly reduced scope mission compared to what was done in the prime mission as well as in the first extension, but can still provide a significant additional data set to what will have been accomplished in the first two missions. As of this writing, a final decision on XXM funding levels has not been made.

Spacecraft performance

For a spacecraft with twelve years of flight behind it, almost seven in transit from Earth to Saturn and over five in orbit at Saturn, the Cassini spacecraft continues to function remarkably well. At launch, all of the engineering subsystems were fully redundant except for the obvious ones where redundancy wasn't practical, such as the propellant tanks, the chassis, and the high gain antenna, and today all but two of those subsystems still retain full redundancy. The two exceptions to this are the Reaction Wheel Assembly (RWA) and the Reaction Control Subsystem (RCS). In the case of the RWA, there are three prime wheels and one spare wheel that can be articulated to replace any of the three prime wheels. Prior to SOI, bearing noise in wheel number three prompted the decision to take that wheel off line and move the spare to take its place. However, wheel three was still supporting the attitude control function just fine and could be brought back online again if necessary, albeit with limited expectations for its remaining lifetime. The RCS has two thruster branches, one prime and one to provide redundancy, referred to as A and B, each of which supports eight 1 Newton thrusters. The A branch has been in use since launch and supports attitude control, reaction wheel momentum management, and small maneuvers for trajectory control. Starting in late '08, it was observed that two of the four A branch Z-facing thrusters were showing signs of degraded performance, even though the consumables usage for these thrusters, hydrazine throughput and valve activations, were still less than 50% of the pre-launch specification. This wasn't a significant problem for the attitude control and wheel momentum management functions because these are closed-loop processes where the actual thruster performance is measured and accounted for, but it was a significant problem for the small maneuver function because this is an open-loop function, i.e., thruster burn duration is timer controlled rather than accelerometer controlled. This meant that burn magnitude errors were larger than the normal expected statistical variations, and the principal consequence of this was the larger than planned propellant costs to keep the spacecraft on course. As a result of this, and because thruster failure modes are not well known, the decision was made to swap to the redundant B branch thrusters. At this point, the B thrusters are working flawlessly, but the option exists to go back to the A branch thrusters for some additional mission life if that were to become necessary.

The two primary consumables on the spacecraft with the potential to end its continued operation are the fuel and oxidizer in the bi-propellant maneuvering system and the hydrazine in the mono-propellant, aka the RCS, system described above. A budget allocating the usage of these resources over the course of the mission was developed well before launch, and usage to date shows a very close match to this plan. For the proposed XXM, it will be necessary to use these resources at a slower rate than was done in the prime and first extended missions in order to reach 2017, but this is entirely consistent with the proposed reduced rate of mission activity. Barring any unexpected events using unplanned quantities, these resources will last through 2017 with positive although rather minimal margins. Another resource of frequent interest is that of electrical power. This one is different in nature from the previous two discussed. It isn’t a resource that is consumed in the sense of being depleted, but rather is always available in a limited and continuously decreasing supply. The Cassini spacecraft electrical power is supplied by three radioisotope thermoelectric generators, which generate heat and power by the decay of plutonium-238 dioxide, and over time the heat produced decreases as the radioisotope decays. At launch, the available electrical power was 878 watts, and today it is just under 700 watts. Power output declines at a rate of about three-quarters of a watt per month, and the actual performance in flight has matched very closely with the pre-launch prediction. The diminished level of power available by 2017 will impose some additional constraints on the simultaneous operation of engineering subsystems and science instruments, but not to an extent that it will significantly limit the science return of the mission. Overall the spacecraft is performing remarkably well and the prospects for continued effective operations through 2017 are excellent.

Summary

The Cassini Mission at Saturn continues to go very well. The spacecraft performance continues to be excellent, although some indications of its twelve years in space are beginning to show. The twelve science instruments on board are all performing well, although in a few cases, some signs of aging have begun to appear, but with very minimal impact on their overall performance. The prime mission is complete, and the 27-month first mission extension has now passed the halfway point in its duration. Overall science return, including surprises and new discoveries, can be fairly described as having exceeded expectations, and data return from new and unique observations continues. Further mission extensions are dependent on continued good spacecraft performance and budgetary approvals, but as of this writing, the prospects for both look encouraging.

Acknowledgements

The work described in this paper represents the efforts of the entire Cassini team, including the current flight team at JPL, a large group of scientists from across the United States and Europe, as well as the engineers and supporting staff who designed, built, and launched this marvelous spacecraft.

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