Dawn at Ceres: The First Exploration of the First Dwarf Planet

Marc D. Rayman

Jet Propulsion Laboratory, California Institute of Technology,
4800 Oak Grove Dr., Pasadena, CA 91109, USA
mrayman@jpl.nasa.gov.

Dawn has conducted an extensive exploration of dwarf planet Ceres, the largest object between the Sun and Pluto that had not previously been visited by a spacecraft. Following its arrival at Ceres in March 2015, Dawn acquired all the planned data from four circular polar orbits ranging in altitude from 13,600 km to 385 km. After the successful conclusion of its primary mission in June 2016, Dawn's mission was extended, and new investigations, not previously considered, were conducted from three new orbits. The mission has provided a uniquely detailed view of the first dwarf planet discovered. The overall strategy for exploring Ceres was based strongly on the extremely successful 16 months of Vesta operations. Nevertheless, the loss of two of the spacecraft's four reaction wheels before arrival at Ceres necessitated some important changes in order to conserve hydrazine. These changes were so effective that Dawn has been able to operate beyond the expected end of life, acquiring significantly more data than planned. This paper describes Ceres operations in the primary and extended missions as well as some of the major findings there.

INTRODUCTION

The Dawn mission has conducted extensive orbital explorations of Vesta and Ceres, the two largest objects in the main asteroid belt. Together they contain about 40% of the mass of the entire main asteroid belt. Studies of these two protoplanetary remnants from the epoch of planet formation are expected to yield insights into physical and chemical conditions and processes then as well as during the subsequent evolution of the solar system.

Dawn orbited Vesta from July 2011 to September 2012. The spacecraft acquired panchromatic (in stereo) and narrowband images in the visible and near infrared; neutron, infrared, visible, and gamma ray spectra; and gravimetry. The mission operated in six science orbits. With a mean radius of 261 km, Vesta is geologically more like a small terrestrial planet than like the smaller undifferentiated asteroids. Vesta operations and scientific findings have been described in detail.[1–3]

Dawn's second destination was dwarf planet Ceres. Ceres was discovered by Giuseppe Piazzi in 1801, 129 years before Pluto's discovery. Dawn is not only the first spacecraft to explore a dwarf planet, it is the first spacecraft to explore the first dwarf planet discovered. With a mean radius of 470 km, Ceres is the largest body between the Sun and Pluto that had not previously been visited by a spacecraft.

Dawn is the ninth project in NASA's Discovery Program and is managed by the Jet Propulsion Laboratory (JPL). The principal investigator is from the University of California, Los Angeles. The spacecraft has strong inheritance from previous projects at Orbital Sciences Corporation (now Orbital ATK), which was responsible for the design, building, testing, and launching. (JPL delivered some subsystems and components to Orbital for integration into the spacecraft.)

The scientific payload includes visible and infrared mapping spectrometers integrated into one package known as VIR. VIR was contributed to NASA by the Agenzia Spaziale Italiana (Italian Space Agency). It was designed, built, and tested at Galileo Avionica and is operated by the Istituto Nazionale di Astrofisica (National Institute for Astrophysics).

The nuclear spectroscopy is accomplished with the gamma ray and neutron detector (GRaND). GRaND was delivered by the Los Alamos National Laboratory and is operated by the Planetary Science Institute.

Dawn's imaging (both for science and navigation) is accomplished with a prime and backup camera (framing camera 2, or FC2, and FC1, respectively). The instruments were contributed to NASA by the Max-Planck-Institut für Sonnensystemforschung (Max Planck Institute for Solar System Research) with cooperation by the Institut für Planetenforschung (Institute for Planetary Research) of the Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center) and the Institut für Datentechnik und Kommunikationsnetze (Institute for Computer and Communication Network Engineering) of the Technischen Universität Braunschweig (Technical University of Braunschweig).

The spacecraft and payload design, as well as the mission design and scientific objectives, have been described in detail elsewhere.[4,5]

Dawn is the only spacecraft to have orbited an object in the main asteroid belt, and it is the only spacecraft to have orbited *any* two extraterrestrial destinations. The mission is enabled by solar electric propulsion (SEP), implemented as an ion propulsion system (IPS). Without SEP, a mission to orbit either Vesta or Ceres alone would have been unaffordable within NASA's Discovery Program. A mission to orbit both would have been impossible.

Dawn was launched on 27 September 2007. Mission operations at Vesta in 2011–2012 and in the entire interplanetary cruise through 8 September 2014 have been documented in detail.[1,2,6–9]

CRUISE OPERATIONS

The interplanetary flight between escape from Vesta on 5 September 2012 and Ceres orbit insertion required about 2.5 years, with most of that time devoted to thrusting with the IPS. Indeed, Dawn (and the first interplanetary mission to use SEP, Deep Space 1) has spent more time since launch thrusting than coasting. In important ways, the default state of the spacecraft is thrusting. Together with SEP's tight coupling of mass, power, and thrust time, this has many significant implications for system engineering that are very different from missions with chemical propulsion.[10,11] The full trajectory is shown in Fig. 1.

The sensitivity to unexpected missed thrust varies significantly throughout the mission, and the missed-thrust margin is a carefully managed resource. The sensitivity for the travel from Vesta to Ceres was well understood. For most of that mission phase, the spacecraft paused ion thrusting once every 28 days to turn its high gain antenna (HGA) to Earth. The long thrust periods were one of the measures implemented to conserve hydrazine following the second loss of a reaction wheel in August 2012.[8] In addition to these monthly high-rate telecommunications sessions, Deep Space Network (DSN) coverage was

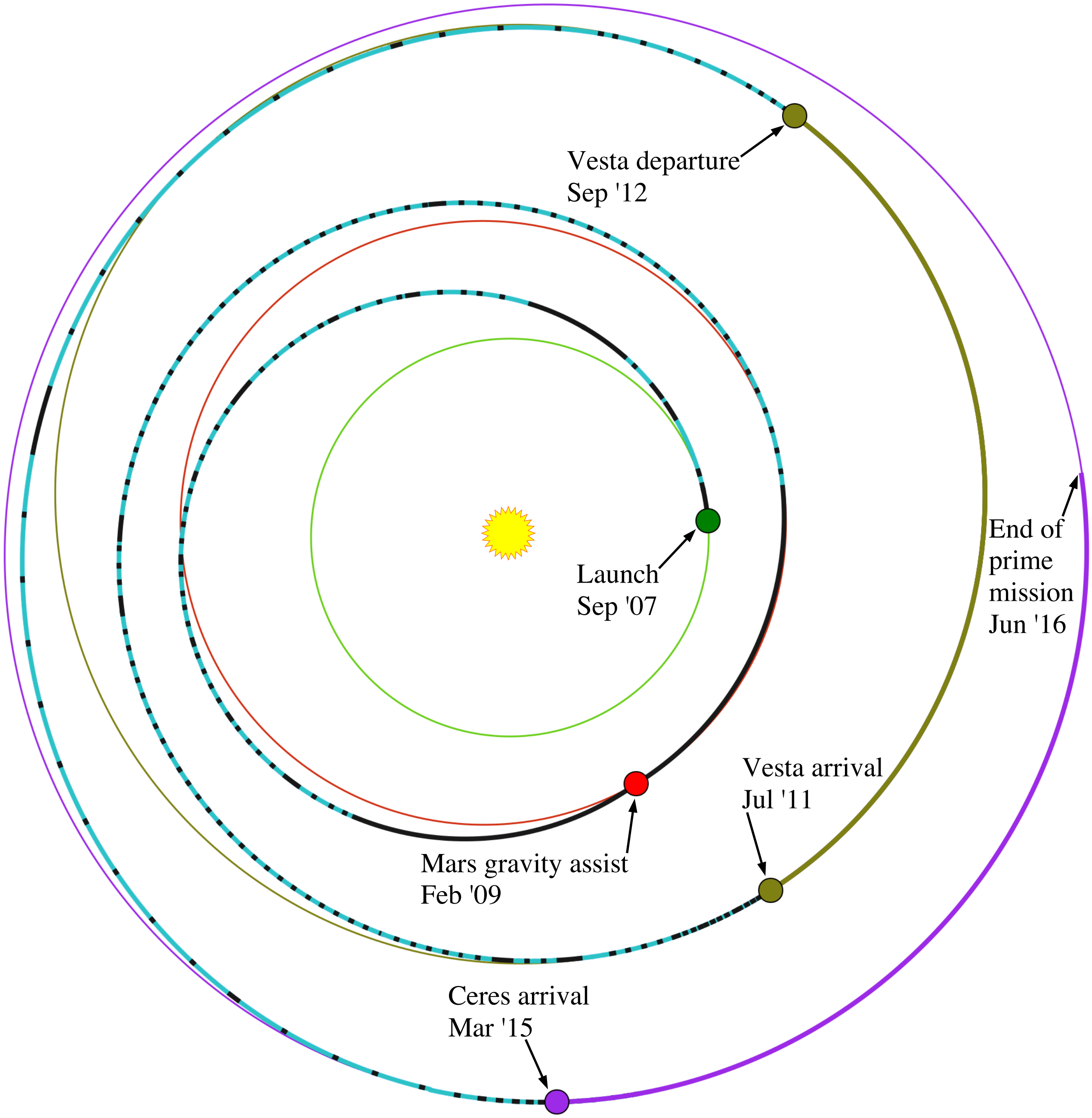

Figure 1. Dawn's interplanetary trajectory. The trajectory is blue where the spacecraft is thrusting and black where it coasts. Thrusting in orbit around Vesta and Ceres is not shown. The regular interruptions in thrust are for conducting activities incompatible with optimal thrusting, usually pointing the high gain antenna (HGA) to Earth. Most are exaggerated in duration in this figure. For most of the cruise to Vesta, the spacecraft thrust 95% of a typical week, and the remaining 8.4 hours was devoted to turning and pointing the HGA to Earth. Note the reduction in the frequency of such telecommunications sessions following departure from Vesta, as explained in the text.

scheduled for occasional contact through a low gain antenna (LGA). Some of the DSN sessions were to return low-rate telemetry and to reset the command loss timer, and all of them were to help verify that the spacecraft was still thrusting. The frequency of these thrust verification (TV) sessions depended on the sensitivity to missed thrust. In many cases, the TV passes used the no downlink thrust verification (NDTV) strategy.[9] The peak sensitivity occurred in mid 2014. At that time, the ratio of delay at Ceres to missed thrust duration was about 9:1. While a long delay would not have been fatal for the mission, it would have been inconvenient for mission planning and, if long enough, could have affected the project's cost.

By 11 September 2014, Dawn had thrust 100% of the time planned since departing Vesta, which was 93.2% of the time. On that day, a single event upset occurred in the controller for the IPS. The same phenomenon occurred in 2011, 19 days before the spacecraft smoothly and gently entered orbit around Vesta.[1] (A similar event occurred on 15 May 2017, although Dawn was not thrusting at the time.) The consequence was that thrusting terminated, and the spacecraft responded by entering one of its safe modes, in which the HGA is pointed at Earth.

In the transition to that safe mode, a previously unknown bug in the attitude control software, which had not manifested itself even with eight years of flight operations, caused the spacecraft to have trouble holding its attitude. When the attitude error grew large enough, a deeper safe mode was invoked, this one doing all pointing relative to the Sun rather than Earth and using an LGA.

Because of the frequent DSN passes at that phase of the mission, the spacecraft's anomalous condition was discovered quickly. Attitude behavior was correct for the safe mode, but telemetry showed that the normal attitude control mode would still experience the pointing problem. The operations team made several attempts through 13 September to correct it, none of which succeeded.

Because of the high sensitivity to missed thrust, the flight team wanted to return to thrusting quickly. However, at a geocentric range of 3.2 astronomical units (AU), with a corresponding round-trip light time of 53 minutes, and a downlink rate of 10 bits/s, operations in safe mode were not rapid. Moreover, although extra DSN coverage had been scheduled for TV/NDTV sessions, the passes were short (sometimes as little as one hour) and inadequate for recovery from safe mode.

Although the flight team normally worked a single shift, as soon as the difficulty of resolving the problem became evident, they changed to two shifts. In addition, to improve the efficiency of operations, the DSN used Deep Space Station 35 (DSS-35), which was not yet operational. The Canberra complex was undergoing maintenance at that time, thus limiting the availability of other stations, so DSS-35's coverage was particularly valuable.

Following the normal Dawn sequence process, a new thrust sequence covering 28 days was already scheduled for uplink on 15 September in preparation for a thrust period that would commence on 16 September. Using that mature sequence could be lower risk than devoting effort to developing a new sequence with a later start (or even truncating the beginning of the sequence). That defined a target for recovery and readiness to resume normal operations. Nevertheless, throughout the recovery efforts, the project investigated trajectories with a range of assumed thrusting restart dates.

On 13 September, with the root cause of the attitude anomaly still elusive, the team determined that the most likely way to meet the self-imposed deadline was to reset the main flight computer. That was commanded later that day, and it was confirmed the next day that the software was no longer exhibiting the problematic behavior. In subsequent months, the root cause was identified, and operational methods were devised to avoid triggering it.

Thrusting resumed on schedule on 16 September without some of the subsequent coast periods that had been included in the mission for nonessential activities incompatible with optimal thrusting.

With the 95 hours of missed thrust, orbit insertion at Ceres shifted by less than 24 hours, from 5 March 2015 to 6 March. However, the first targeted science orbit was delayed from 18 March to 20 April because of the subsequent thrusting required to reach it. Fig. 2 shows the approach trajectory both as it had been planned before the interruption in thrust and after.

Operations continued normally through the rest of the cruise phase, which formally concluded on 26 December 2014.

Dawn had lost one of its four reaction wheel assemblies (RWAs) in June 2010[1] and a second in August 2012.[8] As a result, a major focus of work in the cruise phase was the conservation of hydrazine, both during cruise and in reformulating and refining plans for Ceres. In addition, following the loss of the first RWA, the team developed and uplinked an attitude control mode that used two RWAs in combination with the hydrazine-based reaction control system (RCS). This "hybrid mode"[12] was planned for use at Ceres. All RWAs were powered off during the travel from Vesta to Ceres. When Dawn thrusts with its IPS, RCS controls the attitude around the thrust vector, and the two orthogonal axes are controlled by gimballing the ion engine.

Shortly after departure from Vesta, the predicted hydrazine expenditure through the end of the interplanetary cruise was 12.5 kg, assuming no anomalies. The flight team implemented some important changes, both on the spacecraft and in operational procedures, to reduce that, yielding a prediction of 4.4 kg for the cruise phase. Upon completion of the cruise phase, the actual hydrazine consumption turned out to be 4.4 kg.

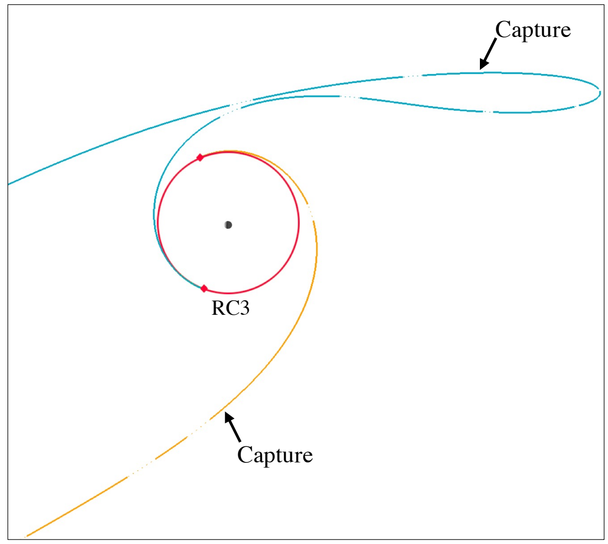

Figure 2. Dawn's trajectory to capture at Ceres and then to the first science orbit. The targeted circular orbit (labeled RC3) is shown in red and is described on page 8. The lower curve shows the plan before the September 2014 interruption in ion thrust, and the upper curve shows the revised plan, which Dawn did implement. Ceres' north pole is up and the Sun is to the left (Ceres' orbital motion is into the plane of the figure). The orange and blue curves are solid for ion thrusting and dotted for coasting, as described on page 6. Each trajectory ends in a red diamond at insertion into the science orbit. On the actual (blue) trajectory, Dawn initially was out of the plane of this figure (closer to the reader) so that Ceres was ahead of it in orbit around the Sun. Then after capture, as it continued to higher altitude and then descended, it thrust to move into the plane and raise its orbital inclination around Ceres.

CERES OPERATIONS

The plan for exploring Ceres during the prime mission was based strongly on the plan successfully executed at Vesta.[13] Nevertheless, there were two significant reasons for making changes.

The first was the continuing need to manage hydrazine use very carefully. That translated principally (although not exclusively) into reducing the number of spacecraft turns.[13] Hybrid mode was more hydrazine efficient than pure RCS control but was planned to be used only in the fourth and final orbit.[9] In that orbit, at the lowest altitude, RCS control would be the most expensive, so the limited life of the remaining two RWAs would be the most valuable. For the rest of the mission at Ceres, RWAs would be powered off, as they were during the interplanetary cruise.

The second major reason for a difference from the plans at Vesta was that Dawn would not depart from Ceres. Therefore, there was no motivation to ascend from the lowest altitude orbit. It is interesting, however, that with Dawn's unexpected capability to operate beyond its prime mission at Ceres, the first part of the extended mission made the mission even more like that at Vesta.

At Vesta and Ceres, Dawn's science observations were conducted principally from circular, polar orbits. The IPS was used to transfer to each science orbit.

Ceres command sequences were designed, built, and reviewed during the interplanetary cruise from Vesta to Ceres. Some portions were tested on the project's spacecraft simulator as well. Updating them at Ceres was significantly less work and lower risk than would have been necessary without this extensive preparation. All plans included substantial margin to ensure requirements would be met even in the presence of typical classes of anomalies.

Operations followed the plan very closely, and Dawn exceeded all of its requirements, acquiring far more valuable data than anticipated. The highlights of each phase are described below.

Ceres approach

The principal objective of the approach phase was to deliver the spacecraft to its first science orbit. Approach began on 26 December 2014 and concluded on 24 April 2015.

About 88% of this phase consisted of ion thrusting targeted to the science orbit. (Indeed, thrusting even during the interplanetary cruise phase targeted that orbit.) Along the way, Dawn was captured into orbit.

Most of the rest of the time was devoted to optical navigation imaging sessions (opnavs) and telecommunications. Based on experience at Vesta, Dawn conducted seven dedicated opnavs at Ceres (plus two other observations described below, both of which provided optical navigation data). This was a significant reduction from the 24 planned for Vesta and provided a valuable hydrazine savings by eliminating the extra turns as well as the additional time that would have been needed with the HGA pointed to Earth to downlink the image data. (Note that telecommunications were conducted in all-RCS control, which uses more hydrazine than when ion thrusting.)

Opnav 1 was on 13 January at a range of 383,000 kilometers, when Ceres had a diameter of about 27 pixels (px) in FC2. (See Fig. 3.) Opnav 2, on 25 January at a range of 237,000 km, provided images with 22 km/px, the first time Dawn improved upon the best Hubble Space Telescope (HST) images of 30 km/px.[14]

The first two opnavs acquired images for one hour each, and the rest imaged for two hours. Although the purpose of the observations was to improve the spacecraft-Ceres ephemeris, VIR acquired data as well. In addition, for all but the first two opnavs, additional images were included to search for moons of Ceres. Periods immediately before and after opnav 3 were dedicated to acquiring an even larger set of images dedicated to the search.

In addition to the seven opnav sessions, Dawn observed Ceres on two other occasions during the approach phase. On 12 February and 19 February (between opnav 3 and 4), FC2 and VIR collected data throughout a full Ceres rotation. (One Cerean sidereal day is 9.07 hours.) These observations were designated rotation characterizations, or RC1 and RC2.

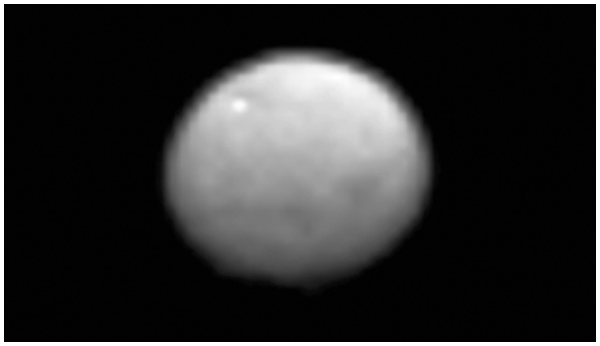

Figure 3. Opnav 1 image. Acquired at a range of 383,000 km, each pixel is about 36 km. Note the bright spot, later determined to be a collection of bright features in Occator Crater, as discussed on page 18.

As Dawn thrust on 6 March, it was gravitationally captured by Ceres at about 12:50 UTC. Traveling at 45 m/s relative to Ceres, Dawn was at an altitude of 60,600 km. Like capture at Vesta, this was not a critical event, thanks to the nature of the low-thrust trajectory with the IPS. No special precautions were necessary for the sequence nor for managing fault protection, and there were no special operational procedures for the flight team. Thrusting at that time was essentially the same as it had been for the previous 45,000 hours of thrust in the mission (69% of the spacecraft's time in space).

The scheduling of DSN coverage in that phase of the mission had no need to account for the time of capture. As it turned out, there happened to be a TV pass only about one hour later. The simple verification that the spacecraft was still thrusting proved that it was captured. Although there was special personal interest by members of the flight team (including this author) and by the news media, there were no special activities on that TV pass. The next time Dawn used its HGA for contact was more than 6.5 days later, following the normal schedule for thrusting in that phase of the mission.

As seen in Fig. 2, Dawn's initial trajectory in orbit went far to the anti-Sun side of Ceres. From 2 March to 9 April, the Ceres phase angle was too high for useful optical navigation. On 19 March, Dawn reached its highest altitude in orbit, denominated *apodemeter* by the team, at 75,400 km. (Demeter is the Greek counterpart of the Ceres, the Roman goddess of agriculture.)

GRaND was powered on on 12 March. Useful nuclear spectra of Ceres could not be acquired until the fourth and lowest altitude orbit in December, but the early activation provided a long baseline for optimization of instrument parameters. As we will see below, its early data also provided a serendipitous and valuable scientific result.

The last two opnavs were conducted on 10 April and 15 April. Thrusting concluded on 23 April, with Dawn in the targeted orbit.

Dawn's X-band transmitter was off for most ion thrusting at heliocentric ranges greater than 1.93 AU (reached in May 2010), so electrical power could be devoted to the IPS. During the science orbits, however, the transmitter was on. When the spacecraft was not using the HGA, command sequences selected whichever of the three LGAs provided the best signal at Earth. This allowed frequent radiometric measurements and hence increasingly accurate determination of the gravity field throughout the prime mission.

First science orbit: RC3

RC3 (rotation characterization 3) was a circular, polar orbit at an altitude of 13,600 km with a period of 15.2 days. (Note: we use

Dawn project nomenclature for the science orbit phases, but all names are derived from outdated mission concepts. Their literal meanings should be disregarded.) At that altitude, Ceres was ~ 710 pixels in diameter in FC2 and so fit easily in the instrument field of view. Dawn had observation objectives on both the lit and dark sides.

Although ion thrusting targeted this orbit, it did not target the orbital phase. (In conventional orbital elements terms, this is equivalent to not targeting the true anomaly at epoch.) That is, each time the approach trajectory was updated, the location in orbit at which Dawn arrived was not a constraint. The data acquisition plans had been separated into five groups of sequences to allow execution in the order that was most efficient based on the actual orbit. After each observation session, the spacecraft pointed its HGA to Earth and downlinked the data.

Dawn completed ion thrusting at about 60°S on the sunlit side of Ceres and continued orbiting to the south. Before the RC3 phase could begin, the orbit knowledge had to be refined and the spacecraft configured for science operations. The time required to prepare for data acquisition then dictated that it begin with the dark side observations in the southern hemisphere.

A procedural error in configuring for science operations caused the spacecraft to enter a safe mode with the HGA pointed to Earth. The resulting delay reduced the number of observations in the first session. All subsequent data in RC3 were acquired as planned.

While on the dark side, Dawn observed the limb and the space above it over the southern and then northern hemisphere with FC2 and VIR to search for evidence of dust. Prior observations from the Herschel Space Observatory indicated occasional presence of water vapor.[15] Designed to study the solid surfaces of bodies with no atmosphere, Dawn's instruments would not be able to detect water vapor at the very low density measured by Herschel. Even the detection of dust entrained with lofted water was considered to be very unlikely, but the observations were conducted. As expected, no evidence of dust was found.

When over the lit hemisphere, Dawn observed Ceres as it orbited above 45°–35°N, 5°N–5°S, and 35°–45°S. Each session covered a full Cerean day.

RC3 yielded more than 2,500 images in the clear and seven color filters, providing global coverage at 1.3 km/px. VIR acquired more than 254,000 spectra of Ceres (as well as others in the space above Ceres).

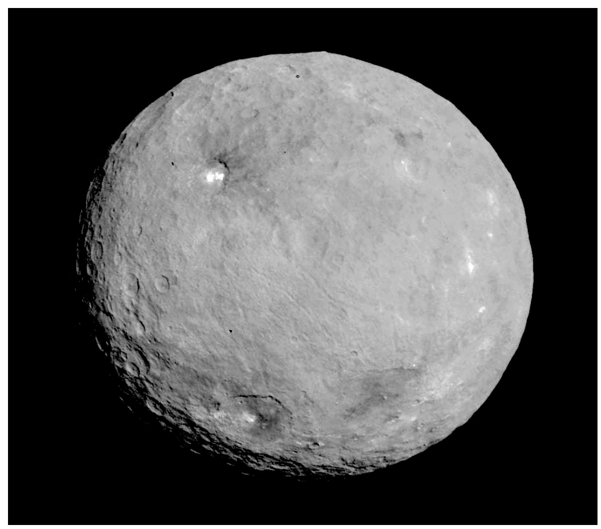

Figure 4. Ceres imaged from RC3 orbit. Occator Crater (upper left), with the brightest features, is 92 km in diameter.

Second science orbit: survey

Following the return of data, Dawn departed RC3 on 9 May. After 534 hours of ion thrusting and 57 m/s, thrusting concluded on 3 June in the targeted circular, polar orbit at an altitude of 4,400 km. (See Fig. 5.)

The survey phase had been planned to last for seven 3.1-day orbits. The project maintained flexibility in the mission timeline not only to accommodate anomalies but also for human factors. It turned out that if Dawn had left survey orbit after seven revolutions, much of the work for the subsequent transfer to the third science orbit would not have been well aligned with standard workdays. Therefore, survey was extended by one full orbit, making the alignment quite good.

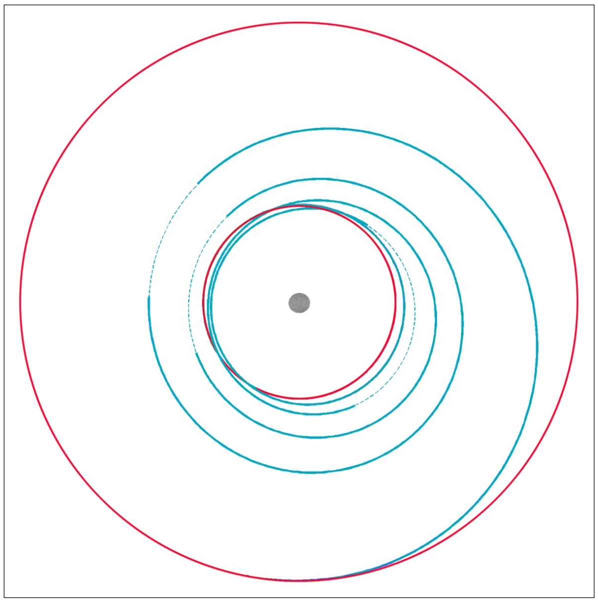

Figure 5. Transfer from RC3 to survey orbit. The two science orbits are shown in red, and the transfer trajectory is in blue (with solid for ion thrusting and dashed for coasting). The first two coast segments, both on the left) are for opnav 8 and 9 (and the subsequent downlinks), the final dedicated opnavs of the prime mission.

During each pass over the illuminated hemisphere, Dawn acquired VIR and FC2 data. Most observations were at nadir, but portions of the second and fourth orbits included observations of the limb. During each pass over the unilluminated hemisphere, Dawn pointed its HGA to Earth.

As is evident in Fig. 4, Ceres has some regions of significantly highly albedo than the typical surface. In particular, Cerealia Facula, at the center of Occator Crater, and the nearby Vinalia Faculae (see Figs. 4, 6, 8, 10, 11 and 14), are so bright that FC images of those areas before survey orbit were saturated. Therefore, in survey and subsequent science phases, additional images with shorter integration times were included in the observation plans.

During the fourth and eighth orbits, VIR autonomously reset. FC2 also reset during the eighth orbit (although there is good reason to believe the reset was unrelated to VIR's). Both instruments had experienced multiple resets at Vesta. It was not a surprise that resets occurred again at Ceres, and margin in the survey plans was more than sufficient to cover the missed data.

Survey yielded more than 1,600 images in the clear and color filters providing global coverage at 0.4 km/px. VIR acquired 4.3 million visible spectra and 2.9 million infrared spectra.

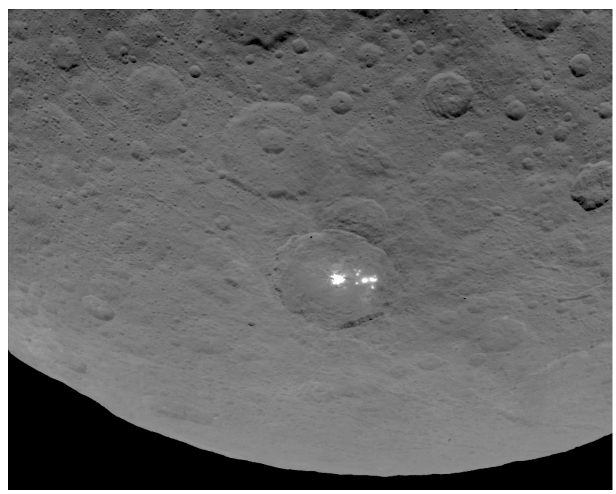

Figure 6. Ceres' limb imaged from survey orbit. Occator Crater is readily recognizable.

<u>Third science orbit: HAMO</u>

Before the survey orbit phase, the flight team had been monitoring, studying, and managing occasional slips in some of the gimbals used by attitude control to point the ion engines. Gimbal motion would need to increase as the orbit altitude decreased. As the influence of the higher order gravity terms increased, the required thrust vector would change more rapidly. Because control of two spacecraft axes was accomplished by pointing the ion engine (with RWAs powered off, the third axis used hydrazine), greater demands were placed on the gimbals.

During the survey phase, the flight team tested and implemented a mitigation for the gimbal that slipped the most. At the beginning of the transfer to the third science orbit on 1 July, the gimbal pointing errors were large enough to trip an attitude fault monitor and trigger a safe mode with the HGA pointed at Earth. Hydrazine consumption was very low in survey orbit, and the mission timeline remained very flexible, so recovery was not considered urgent.

The flight team switched to one of the other ion thrusters with a pair of gimbals that had not shown any evidence of slipping. (Dawn has three ion thrusters, all of which had been used extensively for routine thrusting, but no more than one is ever used at a time.) As before, the descent schedule was adjusted to align with standard workdays, and the transfer resumed on 15 July, so activities would occur on the same days of the week as for the transfer that had been planned for 14 days earlier.

After 645 hours of ion thrusting and 73 m/s, thrusting concluded on 13 August in the targeted circular, polar orbit at an altitude of 1,470 km. (See Fig. 7.) Dawn mapped Ceres in each science orbit, but for historical reasons, this second lowest orbit is designated the high altitude mapping orbit (HAMO). The HAMO period was 18.8 hours.

Unlike HAMO at Vesta, Dawn could not afford to point its instruments at Ceres on every pass over the lit hemisphere and then point its HGA to Earth on every pass over the dark hemisphere. The hydrazine cost of so many turns at Ceres was deemed too high. It was more efficient to turn less often and spend longer in HAMO. Therefore, sometimes Dawn kept pointing to nadir even over the dark side, storing more data before downlinking during multiple revolutions.

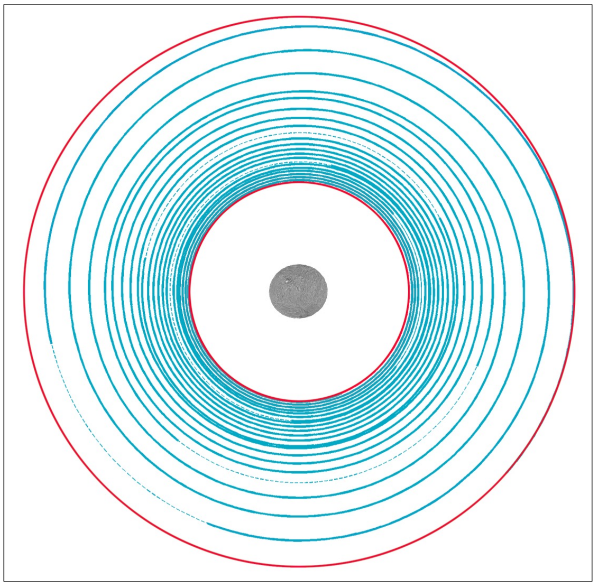

Figure 7. Transfer from survey orbit to HAMO. The two science orbits are shown in red, and the transfer trajectory is in blue. The transfer required 22 revolutions.

It took 12 observation orbits to map Ceres fully with FC2. Because some orbits did not include observations, 14 orbits were needed to acquire and downlink the data. This 11-day period was designated one cycle.

By the time Dawn arrived in HAMO, the hydrazine consumption had been lower than predicted. Therefore, additional hydrazine was allocated to perform more turns than had been planned, increasing the amount of data the spacecraft could acquire and downlink.

Dawn planned for six complete maps, each made with the camera held at a different angle relative to nadir. As at Vesta, with views of the ground from multiple angles, the topography can be measured. Planning for six cycles provided significant redundancy.

The topographical mapping required using the clear filter in every cycle. Different combinations of color filters were used in different cycles. Because VIR produces so much data, it was not possible to acquire data throughout every pass over the lit side, but the timing of VIR observations was adjusted to build up extensive coverage over the course of the 66-day HAMO.

All operations were executed as planned with only a subset of images in one cycle not obtained because of another FC2 reset. The loss was small compared to the margin in the plans, however, and HAMO yielded a rich set of data for all investigations. Dawn acquired more than 6,700 images in the clear and color filters, providing global coverage at 140 m/px. VIR returned 3.5 million visible spectra and 9.1 million infrared spectra. In addition, the gravity data were so good that Dawn met its gravity science requirement for Ceres in HAMO. It had been expected that the requirement could only be satisfied with data from the fourth and lowest science orbit.

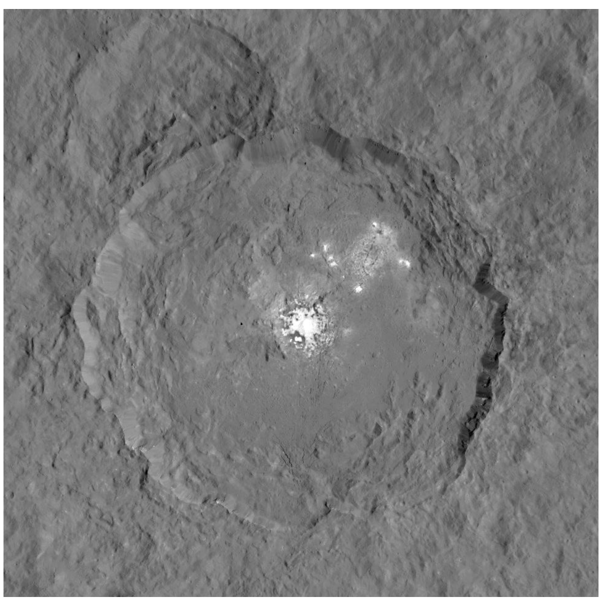

Figure 8. Occator Crater observed in HAMO. The central bright region is Cerealia Facula, and the collection of others is Vinalia Faculae. This view combines two images with different integration times.

Fourth science orbit: LAMO/XMO1

The first three science orbits were dominated by FC and VIR observations, but gravity and GRaND measurements were made in all phases as well. GRaND began to detect Ceres in HAMO, but the signal was too weak for useful nuclear spectroscopy. As at Vesta, the motivation for going to the lowest orbit (the low altitude mapping orbit, or LAMO, later designated extended mission orbit 1, or XMO1, when Dawn was in its extended mission) was to satisfy the GRaND and gravity requirements. (When the project formulated detailed plans for Ceres, it did not anticipate being able to meet the gravity requirement above LAMO. Of course, LAMO measurements remained highly desirable to refine the gravity field.) There had been no FC or VIR requirements. Indeed, in an early plan for Vesta, those two instruments would not be operated at all so that all resources (including onboard data storage and operations team focus) could be devoted to the acquisition of the high priority data. Ultimately, however, once sufficient confidence in the capability to meet the requirements was established, FC and VIR observations were included in the plans. Earlier in Ceres operations, new VIR requirements and bonus objectives were established, and FC objectives were defined as well.

Dawn began its descent to LAMO on 23 October. As expected, this was the most challenging orbit transfer because of the deep penetration into the gravity field. Moreover, the orbit perturbations from increasing RCS activity became more significant. Extensive Monte Carlo analyses had supported development of a plan for how often to update the thrust vectors as Dawn descended. It turned out to be possible to maintain a cadence of updates every seven days, each taking about four days to design, build, review, and uplink. That allowed the team to keep most of the work on a standard prime shift schedule. Unlike the transfers to the higher orbits, analysis showed that a pair of final, purely statistical trajectory correction maneuvers

(TCMs) would likely be needed.

When Dawn began its transfer from HAMO to LAMO, it was at a heliocentric range of 2.97 AU, as Ceres approached its 6 January 2016 aphelion at 2.98 AU. Dawn's solar arrays provided about 1.35 kW. The IPS was throttled down to 0.7 kW, delivering 25 mN at a specific impulse of 1,800 s. (At lower heliocentric ranges, the specific impulse exceeded 3,000 s.)

After 976 hours of ion thrusting and 110 m/s, thrusting concluded on 7 December. As expected, TCMs were needed. Thrusting for 20.3 hours on 11–12 December and again for 15.3 hours on 12–13 December provided another 4.1 m/s to bring the orbit closer to the design of a mean altitude of about 385 km and period of 5.4 hours. (See Fig. 9.)

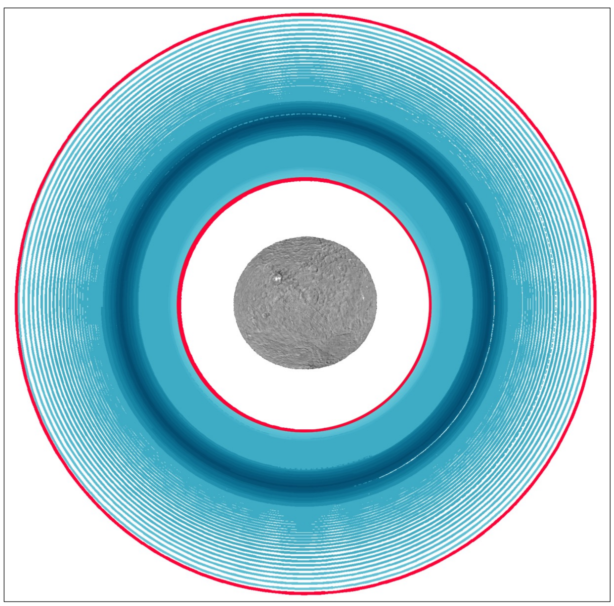

Figure 9. Transfer from HAMO to LAMO. The deterministic part of the transfer required 118 revolutions.

Variations in orbital radius and Cerean topography (dominated by the difference between the polar and equatorial radii) together had contributed only to a relatively small variation in orbital altitude in the first three science orbits. The altitude in LAMO varied regularly between about 355 and 410 km, with roughly equal contributions from the orbit and from Ceres' shape.

Following the plan established in 2013, with arrival in LAMO, the two operable RWAs were activated on 15 December and Dawn operated in hybrid mode. Given the two prior failures, the RWAs were not considered reliable, so all LAMO plans were independent of the control mode. The team was always ready to continue LAMO in RCS control (with greater hydrazine consumption) if an RWA failed.

Dawn pointed GRaND near nadir for up to 15 consecutive orbits, or 75% of every 4.5-day period on average. The remaining time was devoted to a five-orbit, 27-hour HGA telecommunications session. As in the higher orbits, when the spacecraft was not using the HGA, command sequences selected whichever LGA was closest to pointing at Earth to allow gravity measurements. (Roughly 70% of the nadir time had scheduled DSN coverage in order to meet the requirements of the gravity investigation.) In addition, FC2 and VIR data were acquired during some passes over the lit hemisphere. To provide additional perspectives, sometimes FC2 was commanded to take images even as Dawn rotated away from nadir to point the HGA to Earth.

LAMO was organized in cycles of 23 days. Each cycle consisted of five 20-orbit segments plus one more orbit to ensure that adjacent cycles did not point the HGA to Earth when flying over the same terrain. These phasing orbits helped improve surface coverage.

Two of the five segments per cycle had allocations for orbit maintenance maneuvers (OMMs) in case they were needed to provide the desired ground track. Each OMM window was three consecutive orbits of the 15-orbit nadir time. Although some of the OMMs were executed, most were not necessary, and in those cases, Dawn continued pointing to near nadir.

Two cycles of data were needed to meet the project's science data acquisition requirements, so four had been planned in detail as part of the sequence development work conducted during the interplanetary cruise phase. The need for four cycles in LAMO, the most hydrazine-expensive phase of the mission, also set targets for hydrazine conservation. Enough hydrazine had to be available (with margin) to allow operations for four cycles even if a third RWA failed by the beginning of LAMO, precluding the use of hybrid control.

When the Sun-Earth-probe angle (SEP) is less than about 20°, Doppler measurements tend to be too noisy for high-accuracy gravity science. SEP was less than 20° from 3 February to 3 April 2016. Normal operational navigation and telecommunications do not have such a wide, albeit soft, constraint. The minimum SEP was 7.9°, thanks to Ceres' inclination of 10.6°, and was large enough that it had no effect on operations other than reducing gravity science data quality.

The first four cycles were very successful. No anomalies interfered with data acquisition and return nor consumed hydrazine. The RWAs operated perfectly, and hybrid control kept hydrazine expenditures low.

With the successful acquisition of neutron and gamma-ray spectra for the first two cycles, by February, the project had met or exceeded every one of its prelaunch requirements for science data acquisition at Ceres.[16] (All requirements at Vesta had been met or exceeded as well.)

Variations in the gravity field and the perturbing effects of RCS activity reduced the accuracy of ephemeris predictions as far in advance as needed for sequence development. That made the bonus objective of building up complete surface coverage with FC2 more difficult. Nevertheless, by the end of February, Dawn had fully imaged Ceres from LAMO.

In January, when it became evident that the flight system likely would be capable of maintaining productive operations after the end of the fourth cycle on 19 March, planning for subsequent cycles began. They included acquisition of more GRaND and gravity data and VIR observations of selected regions. All FC2 imaging in the first four cycles had been with the clear filter at nadir. Subsequent cycles included color filter images of high priority targets. Moreover, instead of pointing to nadir, Dawn pointed slightly off-nadir for high-resolution topography.

The prime mission concluded on 30 June, and NASA approved an extension to continue Ceres science. Dawn continued in the same low altitude orbit, designated XMO1 starting on 1 July. The GRaND, gravity, VIR, and FC2 observation campaigns continued.

Prior to completing the prime requirements, Dawn had never attempted targeted observations (other than acquiring multiple FC2 exposures for Occator Crater), and none had ever been planned. Dawn is a mapping mission, designed to conduct the first investigation of the two largest unexplored bodies inside the orbit of Neptune. When targeted observations for VIR and FC2 color images began in LAMO, they were under the most challenging conditions of the mission because of the orbit perturbations. As LAMO/XMO1 progressed, strategies for making late adjustments to timing of data acquisition were developed, thus improving the probability of capturing selected targets.

Despite the flawless operation of the RWAs in LAMO/XMO1, their reliability was still considered low. Although Dawn exceeded expectations by operating as long as it had, the remaining lifetime at low altitude was strongly limited by hydrazine.

The project recognized that returning to a higher altitude, something not even contemplated prior to the middle of 2016, could provide a greater scientific return. There were several benefits. Rather than operate for a few more months at low altitude to increase the signal for the nuclear spectra, GRaND could operate for much longer at high altitude to improve the measurements of cosmic ray noise with the instrument parameters that had been finalized not long before LAMO/XMO1. Analysis showed that that strategy would yield a better improvement in the signal-to-noise ratio of the spectra. In addition, targeted observations in LAMO/XMO1 were inefficient, often requiring multiple attempts, but at higher altitude, areas of special interest could be observed with higher confidence in important geometries. The higher altitude also would provide opportunities to look for changes over time.

By the end of XMO1 on 2 September 2016, Dawn had completed more than 1,100 orbits in LAMO/XMO1. During its residence at low altitude, the flight system had acquired more than 38,000 images with 30–40 m/px. They provided complete coverage of the surface with the clear filter and views from at least three angles for topography of 95% of the surface. (For context, Dawn's requirement was to acquire topographic data of 80% of the surface at 200 m/px.) The images also included color coverage of such high priority sites as Occator Crater, the cryovolcano Ahuna Mons (Fig. 15), a region near Ernutet Crater where VIR had found organics, and Oxo Crater, which is the second brightest region on Ceres (after Occator) and site of the first clear detection of water on the surface (with infrared spectra from VIR). VIR had acquired 12.0 million visible spectra and 11.5 million infrared spectra. With a smaller field of view than FC2, targeted observations with VIR had been even more challenging, but the data included observations of a number of high priority targets, including Occator, Oxo, and Juling Craters. Ice was observed in Juling. As discussed below, Oxo and Juling also were priorities for XMO2.

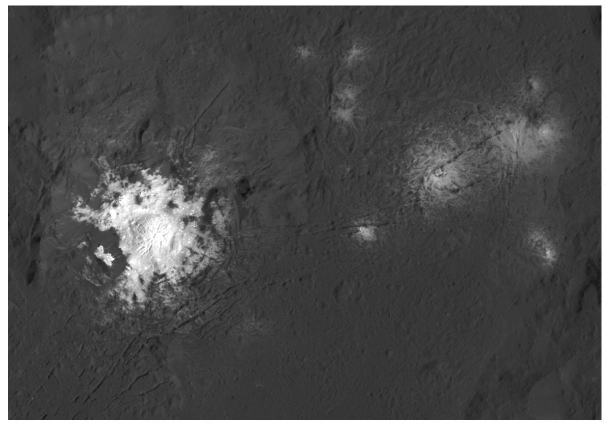

Figure 10. Mosaic of two LAMO images in Occator Crater. The center of Cerealia Facula (left) is a dome ~ 3.5 km in diameter and 0.3–0.7 km high. It is in a pit ~ 9 km in diameter and ~ 0.8 km deep. Also see Fig. 14.

GRaND had integrated neutrons and gamma rays for a total of 183 days each, exceeding the original LAMO objective by a factor of 5.2. There were 238,000 Doppler measurements with accuracy typically between 0.02 and 1.0 mm/s. The expectation upon arrival in LAMO was that Dawn would obtain up to 32,000 Doppler measurements.

Fifth science orbit: XMO2

The second extended mission orbit (XMO2) was to be similar in altitude to HAMO. The transfer from XMO1 to XMO2 differed from the transfer from HAMO to LAMO in several noteworthy ways. The most significant was that the gravity field was much better known in ascending to XMO2 than in descending to LAMO.

The project elected to continue in hybrid control until another RWA fault made that impossible. Therefore, during the transfer to higher altitude, the perturbing effects of RCS firings were negligible.

The nature of the XMO2 investigations allowed for greater flexibility in the orbit parameters than for previous science orbits. Rather than targeting a particular orbit at the end of the transfer, Dawn ascended from XMO1 by thrusting along the (nominal) velocity vector. The end of the transfer was determined simply by when the altitude would be close to HAMO altitude and within a range that would yield favorable ground tracks to allow full coverage in about a week. This strategy simplified the design of each thrust segment.

After 753 hours of ion thrusting and 92 m/s, thrusting concluded on 6 October in a polar orbit at a mean altitude of 1,480 km. Because Dawn had not targeted a circular orbit, the altitude varied between about 1,445 and 1,510 km, with 40 km of that variation caused by orbital eccentricity.

From an observing standpoint, XMO2 resembled HAMO. The principal difference is that the angle (ß) between the orbit plane and the vector to the Sun was very different. In HAMO, ß started at 24° and was allowed to increase naturally to 36°. It was held fixed near 45° in LAMO/XMO1 by controlling inclination, but it was allowed to increase again upon leaving XMO1. During XMO2, ß increased naturally from 54° to 56°. (The smaller change during XMO2 is simply because it lasted for 12 days rather than the 66 days of HAMO.)

All the phases at Ceres (and Vesta) prior to XMO2 were designed principally for mapping with one (and usually more) sensor. Other sensors were included to gather as much data as possible. In XMO2, FC2 mapped the entire surface with all filters in order to look for changes in the 12 months since HAMO, but that was not the highest priority.

The primary objective of XMO2 was to perform new VIR observations. VIR had detected ice in Oxo Crater in LAMO, but had not observed the crater at all in HAMO. In addition, there was reason to believe at the time that the amount of ice in Juling Crater might change over the course of a Cerean day. Dawn's plan included acquiring infrared spectra at multiple local solar times for each crater with dedicated pointing on different orbital passes. VIR also observed other regions in XMO2 that it had not covered during HAMO. In all cases, FC2 acquired data simultaneously.

Dawn also imaged Occator Crater when it was on the limb (Fig. 11) to aid in searching for evidence of haze that might be associated with its extensive faculae. At high northern and southern latitudes, FC2 used long integration times to search for evidence of ice in persistently shadowed regions of craters.

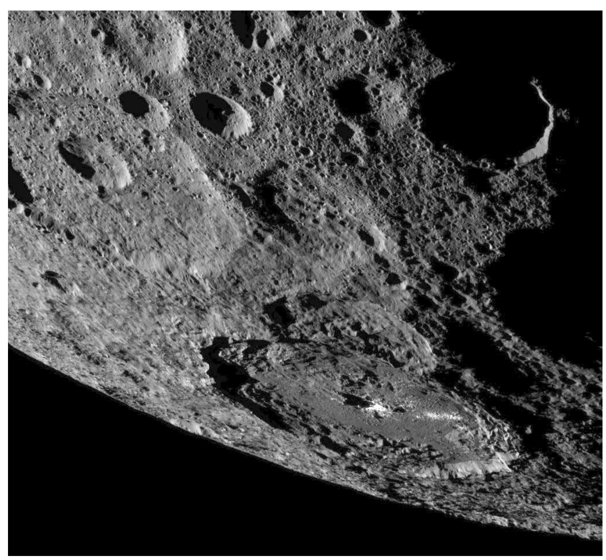

Figure 11. Occator Crater as observed in XMO2.

Data acquisition was designed to begin on the first orbit that allowed Oxo and Juling to be observed, which was on 17 October. Until then, hydrazine was conserved by keeping the

HGA pointed to Earth. But with the successful completion of the prime mission, two RWAs continuing to operate, and only one extended mission objective after XMO2, more frequent turns were included in XMO2 than in HAMO. In addition to turns for observing specific targets rather than maintaining a fixed angle relative to nadir, Dawn turned more often between pointing instruments at Ceres and pointing the HGA at Earth. The spacecraft acquired data during all 16 passes over the lit hemisphere, and the HGA was pointed at Earth during most of the passes over the dark hemisphere.

During XMO2, VIR acquired 569,000 infrared spectra. FC2 obtained more than 2,900 clear and color images. Despite all the pointing optimized for observing specific targets with VIR and FC2, images covered more than 98% of the surface.

Sixth science orbit: XMO3

By the conclusion of XMO2, Dawn had met all of the formal requirements established for its extended mission except one: measuring the cosmic ray background to reduce the noise of the LAMO/XMO1 nuclear spectra. Above 7,200 km, the contribution from Ceres to GRaND's measurements would be less than 1%.

The only requirement then on extended mission orbit 3 (XMO3) was that the altitude be greater than 7,200 km. Therefore, the same simple strategy of thrusting along the velocity vector used for the transfer to XMO2 was applied for the transfer to XMO3.

Ion thrusting began on 4 November. After 722 hours of thrusting and 95 m/s, thrusting concluded on 5 December in a polar orbit that ranged in altitude from to 7,530 km 9,350 km.

Since Dawn had left XMO1, ß had continued to increase, so the lighting on Ceres from the spacecraft's perspective was different from what it had been throughout the mission until then. The only requirement in XMO2 was to measure cosmic rays, but because the two RWAs continued to operate, a small amount of hydrazine could be allocated to additional FC2 and VIR observations of Ceres under this new illumination.

In January and February 2017, Dawn observed Ceres three times throughout a full Cerean day, each in a different part of the 7.7-day-long orbit. ß ranged from 73° to 79°. Images in the clear plus all color filters were generally acquired every 20 minutes as Ceres rotated (corresponding to intervals of about 13° of longitude), but when features of particular interest were on the limb, the frequency was increased to images every 3 minutes.

In the third observation, on 19 February, Dawn used FC1 and FC2 simultaneously for the first time in flight. The reason for carrying redundant cameras was that at least one was required for mission success, both for optical navigation and for the defined minimum science requirements. Prudence always dictated that before one camera could be powered on, the other camera would be powered off, with the cover closed and the filter wheel in the position necessary for navigation and most of the science. FC1 had been operated twice a year during the mission to verify its health and maintain its calibration.

The motivation for simultaneous operation was to verify flight and ground system functionality in preparation for a new, bonus measurement planned for XMO4. The risk of doing this for the XMO3 observations was assessed and found to be acceptable.

FC1 and FC2 together obtained almost 1,400 images in XMO3, and VIR acquired 668,000 visible spectra.

Seventh science orbit: XMO4

The acquisition of cosmic ray background data placed few unique constraints on the spacecraft apart from altitude. Therefore, with the mission going very smoothly, the project was able to adopt a new objective.

All of the observations of Ceres had been at phase angles (defined as Sun-Ceres-spacecraft) of 7°–155°. The plane of Dawn's orbit relative to the vector to the Sun for the first six science orbits is illustrated in Fig. 12. With the capability of the IPS, the mission targeted acquisition of new images in extended mission orbit 4 (XMO4) near 0°, requiring a plane change of ~ 90° by the time it would be executed in April.

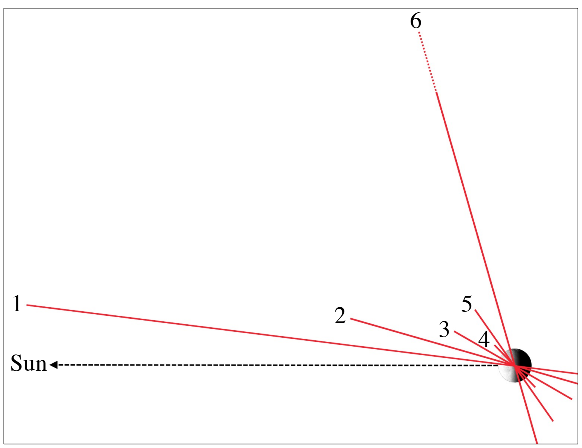

Figure 12. Dawn orbit planes and relative altitudes. Looking down on Cere's north pole, this illustrates the mean ß during imaging in the first six science orbits, numbered chronologically: 1 - RC3; 2 - survey; 3 - HAMO; 4 - LAMO/XMO1; 5 - XMO2; 6 - XMO3. Orbits 1, 2 and 6 all extend off the figure to the lower right. The dotted section of XMO3 illustrates the range of altitudes in the elliptical orbit.

Low-phase observations had been ruled out for low altitude orbits, because Dawn was not qualified for repetitive eclipses. (Even planning for a single eclipse was not deemed responsible, because an anomaly that prevented normal operation could leave the spacecraft in an orbit that was in Ceres' shadow half a revolution after being at low phase.) In a long-period orbit, however, the natural ß drift of almost 0.2°/day would avoid that problem. Even if Dawn were at 0°, the orbit plane would rotate enough to avoid eclipse by the time the spacecraft completed half a revolution. Indeed, it would require a maneuver to bring the spacecraft back to 0°.

A benefit of being at high altitude was that it would allow the entire visible hemisphere to be at very low phase, rather than only a small area. But the altitude needed to be low enough so that Cerealia Facula, the region of greatest interest, would subtend at least three FC pixels. The target was set at 20,000 km at the time that Cerealia Facula was at local solar noon.

Although hydrazine consumption was lower during ion thrusting than coasting, so many turns would be involved in reaching the new orbit and acquiring the data that it would consume significantly more hydrazine than remaining with the HGA pointed to Earth. Therefore, when the plans were formulated, their execution was predicated on the continued operation of the RWAs.

The transfer was conducted in three deterministic segments plus a purely statistical TCM, shown in Fig. 13. Ion thrusting began on 23 February. After 418 hours of ion thrusting and 60 m/s, the deterministic phase concluded on 13 April in an orbit with a period of 59 days. Navigational accuracy was more challenging than for other maneuvers at high altitude, so Dawn conducted three dedicated opnavs.

The TCM was broken into two segments. The first was executed on 22 April. The five hours of ion thrusting provided 0.7 m/s.

The second was planned for 24 April, with four hours of ion thrusting. Two hours before thrusting was scheduled to begin, an RWA failed. Dawn entered one of its safe modes and did not execute the maneuver.

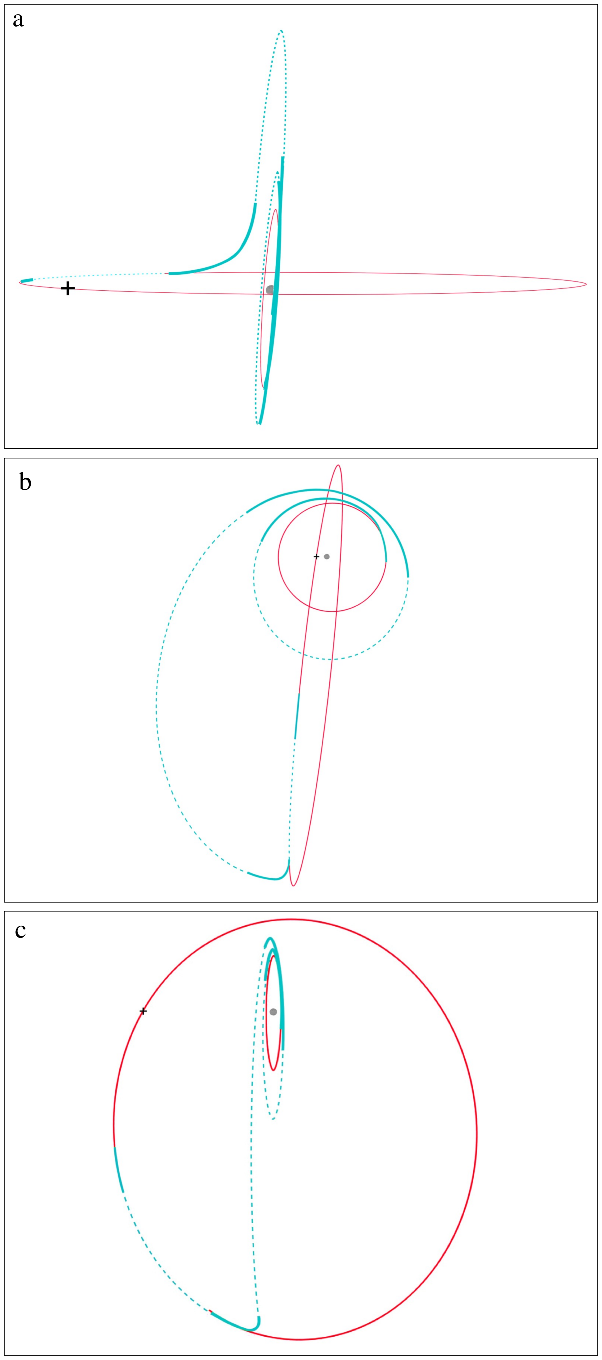

Figure 13. Transfer from XMO3 to XMO4. XMO3 is the inner red orbit. The three deterministic thrust segments plus the two-day window for the TCM are shown in solid blue, and coasting periods are dashed. In each figure, **+** is Dawn's location when Ceres was at opposition. (a) View from near Ceres' north pole with the sun to the left. (b) View from near the Sun (and hence near Cere's equator). (c) View from near Ceres' equator with the Sun to the left.

As with the two previous RWA failures, telemetry gave no indication of a problem until very close to the time of the failure, much too late for the operations team to intervene or even know. The project does not know the failure mechanism for the RWAs. The RWA lifetimes are often expressed in revolutions, although it is not at all clear whether that has any bearing on the lifetime. The RWA that failed on 24 April had 1.2 billion revolutions (Grev). The final operable RWA was within 3% of that. (The two previous RWA failures occurred at 0.5 Grev and 1.1 Grev.)

The flight team quickly returned Dawn to its normal operational configuration in all-RCS control. Studies following the first RWA failure in 2010 concluded that a one-RWA mode was not worthwhile. Therefore, the one operable RWA was left powered off, with no plans ever to operate it again.

Even without the second segment of the TCM, Dawn was on a trajectory to fly through opposition, although the phase at Cerealia Facula would not be as low as if the TCM had executed. Nevertheless, the value of the data was still recognized to be very high.

Dawn observed Ceres at (and near) 0° on 29 April from an altitude of 19,800 km. Although the measurements were a bonus for the extended mission, and not a requirement, both FCs were used, thus increasing the probability that the desired data would be acquired. As it turned out, all planned observations executed as planned. Dense phase coverage was obtained below 1.5°, and some observations were as high as 6°, filling the gap in the phase curve below 7°. The minimum phase observed at Cerealia Facula was 0.3°. The two FCs obtained a total of 382 images, and VIR acquired 131,000 visible spectra and almost 7,000 infrared spectra.

The operations team had developed a plan for a backup opposition observation in case the first was not fully successful. It would have occurred one revolution later, on 28 June, and required 1.5 days of ion thrusting on 27–28 May in order to counter the natural increase of ß. Because the data for the first observation were so good, the backup was canceled.

Dawn continued collecting GRaND cosmic ray background data through the end of its first extended mission. When this paper was completed on 4 September, NASA was considering options for a second extended mission to make the best use of the spacecraft before the hydrazine was exhausted.

CERES HIGHLIGHTS

The wealth of data Dawn acquired at Ceres yielded many new discoveries about the first dwarf planet discovered or visited. Fifty papers have been published and many more are nearing publication. (Readers of this paper are encouraged to read all of them.) There have already been almost 400 conference presentations as well. Here we describe some of the highlights.

More than 300 faculae have been catalogued on Ceres. Occator Crater[17] has the most prominent, with regions so reflective that they were visible as a single bright spot in HST's images. Ceres' average single scattering albedo is 0.094–0.11, but the albedo of the faculae is 0.67–0.80.[18]

The 92-km-diameter crater is relatively young, with age estimates ranging from a few million to a few tens of millions of years. The total area of the faculae is small, so age-based crater counting is less accurate, but the central facula could be as young as 3 million years, suggesting that the material has been emplaced recently.

The central pit is surrounded by a dense network of faults which may be a result of long-term tectonic uplift (Figs. 10 and 14).

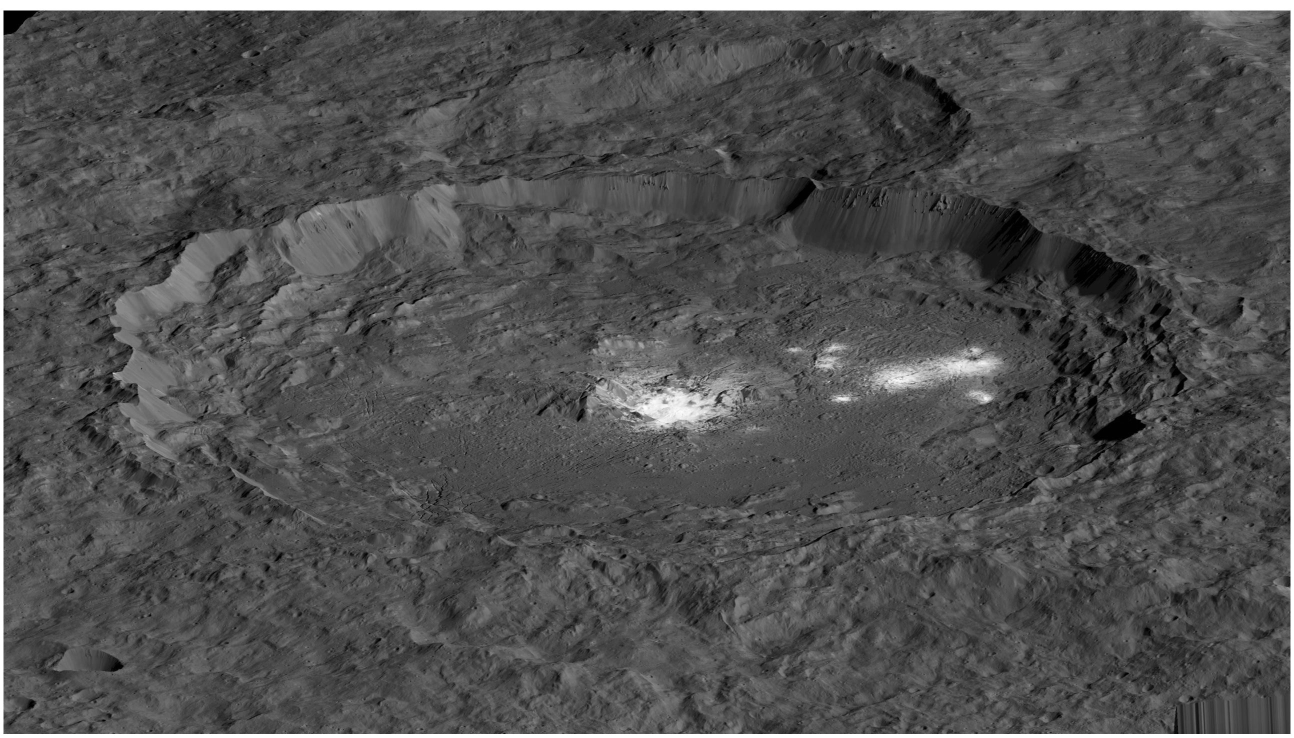

Figure 14. Occator Crater. This view was synthesized by D. P. O'Brien with a mosaic of LAMO images and the shape model derived from topographical imaging.[19] Zoom in to see details of the topography and the extensive fracturing.

Subsurface briny water came to the surface after the impact (and, it appears, long after the impact). Ice is not stable at such a low latitude on Ceres. It would sublimate quickly, but the dissolved salts would remain, and they are the highly reflective material. The faculae are sodium carbonate, a salt observed only on Ceres, Earth, and Enceladus. (When it was deposited, it may have been sodium bicarbonate.) It is also interesting to note that Occator Crater contains the highest concentration of any kind of carbonates known on kilometer-scales anywhere in the solar system except Earth.[20]

Another carbonate, dolomite, is omnipresent on Ceres and mixed with serpentine.[21] Those minerals are formed by chemical interactions between rocks and water under pressure. Their formation underground and subsequent transport to the surface are unlikely given how widespread they are. The temperature difference between the equator and high latitudes is large enough that convective forces should have yielded a latitude-dependent abundance that is not observed.

A better explanation is that early in its history, Ceres had enough radiogenic heating and water to have a global liquid ocean. An ocean ~ 5 km deep would have provided sufficient pressure to make the minerals Dawn has identified, although it could have been up to 100 km deep. As Ceres aged and cooled, some of the water would have ended up in minerals and some would have frozen, creating an ice shell. The ice would have subsequently been lost in a geologically short time both through sublimation and by impacts. The minerals that had been in that ancient ocean remain on the surface.[22]

Phyllosilicates are another class of minerals ubiquitous on Ceres that form through the interaction of water and rock. The phyllosilicates show distinctive evidence of ammoniation. Ammonia should have been common in the solar nebula, but conditions would have been too warm for it to condense and be incorporated into planetesimals at Ceres' current heliocentric distance. It isn't clear whether this indicates Ceres formed farther from the Sun and subsequently moved to its present location or rather that it formed near where it is now but accreted material that had formed farther away.[19,23]

Ammoniated salts lower the freezing point of water. Whether liquid persists in Ceres' interior is not clear. Thermal models allow it but do not guarantee it. But there is one particularly interesting structure that indicates it is possible. The tallest mountain on Ceres is Ahuna Mons, a 4-km-high cryovolcano.[24] (See Fig. 15.) It formed from a highly viscous but partially melted cryomagma composed of brines, carbonates and other minerals, and water ice. The edifice formed in a few hundred to a few hundred thousand years and is 50–240 million years old. The likely presence of a subsurface melted phase so recently suggests that there may be some now as well.

Ice was observed on the ground at multiple locations.[25] It should not be stable near the surface except at high latitudes and in persistently shadowed regions (PSRs), so it must have been exposed or delivered recently in those locations. It also was indeed found in some PSRs.[26] (Ceres' obliquity is only 4°. It may vary over a range of 2° to 20° in as short as 12,000 years, so many regions that are persistently shadowed throughout a Cerean year are not permanently shadowed on geological timescales.[27])

A large number of geological features best explained as ground ice flows also have been identified.[28] Neutron measurements that probe to decimeters show that Ceres is rich in hydrogen, a strong indication that water is abundant.[29] Some is ice and some is bound in hydrated minerals. The measured concentration increases with increasing latitude. Lower temperatures at higher latitudes would allow ice to persist closer to the surface for geologically long times without sublimating away.

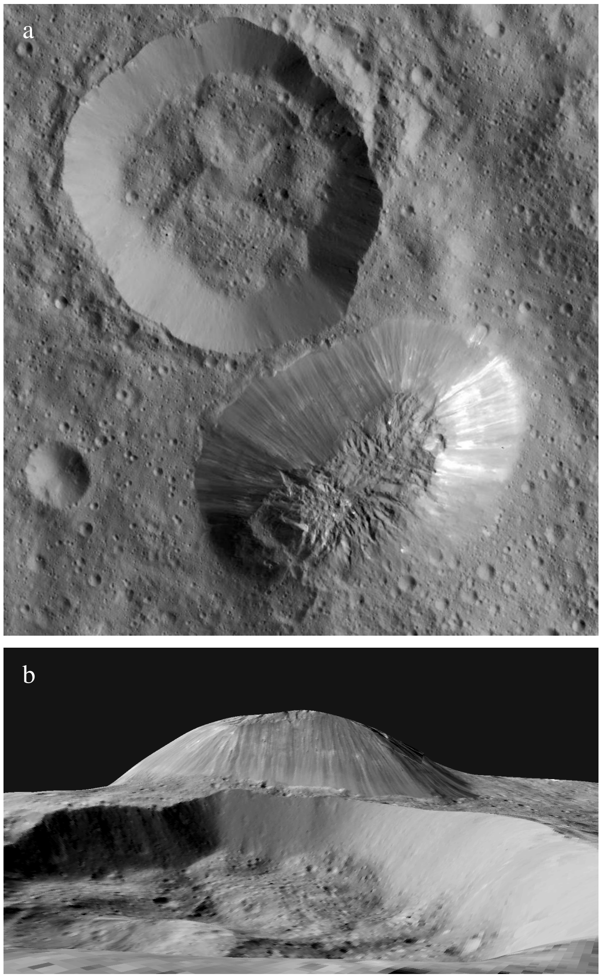

Figure 15. Ahuna Mons. (a) Mosaic of LAMO images. The cryovolcano is on the lower right. (b) Perspective from within the nearby, 17-km-diameter, geologically unrelated crater, constructed with LAMO topography data.[24] Ahuna Mons is about 17 km across at its base. Extensive fracturing is visible on the top, and bright material and streaks from rockfalls are evident on the slopes of up to 35°. Note the sharp contact between the base and the surrounding smooth area. From the lowest point in the crater to the summit of Ahuna Mons is 7.6 km vertically across a horizontal distance of 15.0 km.

Studies using models of the time-dependent flux of impactors combined with the measured size distribution of craters conclude that Ceres is deficient in large craters.[30] Vesta, the Moon, and other bodies seem to preserve their craters for much longer. Investigations of crater morphologies show crater relaxation over time. These provide support for ice also being present at greater depths, which would lower the viscosity.

The infrared signature of alkanes, a class of organic materials, was found in a region of ~ 1000 km^2 in and near Ernutet Crater.[31] This represents the largest area of extraterrestrial organics discovered in the solar system except for Titan. A smaller area near Inamahari Crater, ~ 400 km away, also has spectra consistent with organics.

The combination of water, organics and other chemicals, and heat left over from formation and radioactive decay makes Ceres of interest not only for planetary geology but also for astrobiology.

Many lines of evidence point to Ceres containing a substantial fraction of water, about 25% by mass, most or all of which is frozen. The dwarf planet is partially differentiated, with a rocky interior and volatile rich shell of water ice, phyllosilicates, carbonates, salts, and clathrate hydrates perhaps 70–190 km thick.[32]

Dawn's remote sensing instruments did not detect any evidence of the exospheric water vapor observed by Herschel, despite the dedicated search in the first science orbit. Küppers et al. had noted that some searches with Herschel, the International Ultraviolet Explorer, and the Very Large Telescope had seen evidence for water vapor production and others had not.[15] One interpretation was that the phenomenon was dependent on heliocentric range, although that was not definitive.

During Dawn's approach to Ceres, GRaND detected energetic electrons. In the second science orbit, energetic electrons were observed in the same location on three consecutive orbits. These serendipitous findings led to a new explanation for Ceres' transient exosphere: it is driven largely by solar energetic proton events that sputter water from the surface. This mechanism accounts for the electrons, which were reflected from the bow shock, and correlates well with solar proton activity both for prior detections and non-detections of water vapor.[33]

CONCLUSION

Even with the loss of two RWAs before departing from Vesta and a third during the extended mission, Dawn had extremely productive primary and extended missions at Ceres. It not only surpassed all the requirements but accomplished some distinct and valuable objectives that had not even been contemplated prior to arrival. Nearly a decade after launch, the spacecraft remains healthy, with hydrazine being the most likely limitation in operational lifetime.

The capability to conduct such extensive explorations of two energetically distant destinations, both of which are of great value to solar system science, depended on the IPS. It enabled not only orbiting both Vesta and Ceres but also maneuvering extensively in orbit, significantly enhancing and in some cases enabling the scientific return. As of 4 September 2017, the IPS had provided a total Δv of 11.3 km/s with more than 50,600 hours of thrust.

ACKNOWLEDGEMENTS

Dawn's many successes in reaching Ceres and conducting complex operations to acquire a wealth of important data there were achieved through the skill and dedication of the members of the operations team, with support from the instrument and science teams. Their impressive work is acknowledged with the greatest respect and gratitude.

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REFERENCES

1. Rayman, M. D., R. A. Mase, "Dawn's Exploration of Vesta," *Acta Astronautica* **94**, p. 159 (2014).

2. Polanskey, C. A. S. P. Joy, C. A. Raymond, "Efficacy of the Dawn Vesta Science Plan," Paper 1275915, SpaceOps 2012 Conference Proceedings, 2012.

3. See, for example, Russell, C. T. et al., "Dawn at Vesta: Testing the Protoplanetary Paradigm," *Science* **336**, p. 684 (2012) and references therein.

4. Rayman, M. D., T. C. Fraschetti, C. A. Raymond, C. T. Russell, "Dawn: A Mission in Development for Exploration of Main Belt Asteroids Vesta and Ceres," *Acta Astronautica* **58**, p. 605 (2006).

5. Russell, C. T. et al., "Dawn Mission to Vesta and Ceres: Symbiosis between Terrestrial Observations and Robotic Exploration," *Earth, Moon, and Planets* **101**, p. 65 (2007).

6. Rayman, M. D., K. C. Patel, "The Dawn Project's Transition to Mission Operations: On Its Way to Rendezvous with (4) Vesta and (1) Ceres," *Acta Astronautica* **66**, p. 230 (2010).

7. Rayman, M. D., R. A. Mase, "The Second Year of Dawn Mission Operations: Mars Gravity Assist and Onward to Vesta," *Acta Astronautica* **67**, p. 483 (2010).

8. Rayman, M. D., R. A. Mase, "Dawn's Operations in Cruise from Vesta to Ceres," *Acta Astronautica* **103**, p. 113 (2014).

9. Rayman, M. D., R. A. Mase, "Preparing for Dawn's Mission at Ceres: Challenges and Opportunities in the Exploration of a Dwarf Planet," 65th International Astronautical Congress, 29 September–3 October 2014, Toronto, Canada, Paper IAC-14,A3,4.5x21592.

10. Rayman, M. D., S. N. Williams, "Design of the First Interplanetary Solar Electric Propulsion Mission," *Journal of Spacecraft and Rockets* **39**, p. 589 (2002).

11. Rayman, M. D., T. C. Fraschetti, C. A. Raymond, C. T. Russell, "Coupling of System Resource Margins Through the Use of Electric Propulsion: Implications in Preparing for the Dawn Mission to Ceres and Vesta," *Acta Astronautica* **60**, p. 930 (2007).

12. Bruno, D., "Contingency Mixed Actuator Controller Implementation for the Dawn Asteroid Rendezvous Spacecraft," AIAA 2012-5289, AIAA SPACE 2012 Conference & Exposition, 11–13 September 2012, Pasadena, CA.

13. Polanskey, C. A. S. P. Joy, C. A. Raymond, M. D. Rayman, "Architecting the Dawn Ceres Science Plan," SpaceOps 2014 Conference Proceedings, 2014.

14. Thomas, P. C., et al., "Differentiation of the asteroid Ceres as revealed by its shape," *Nature* **437**, p. 224 (2005).

15. Küppers, M. et al., "Localized Sources of Water Vapor on the Dwarf Planet (1) Ceres," *Nature* **505**, p. 525 (2014).

16. Polanskey, C. A. S. P. Joy, C. A. Raymond, M. D. Rayman, "Dawn Ceres Mission: Science Operations Performance," SpaceOps 2016 Conference, 16–20 May 2016, Daejeon, Korea, Paper AIAA 2016-2442.

17. See Scully, J. E. C., et al., "Summary and Synthesis of the Special Issue: Occator Crater on Ceres," in preparation for *Icarus Special Issue: Occator Crater on Ceres* and other papers in that issue.

18. Li, J.-Y., et al., "Surface Albedo and Spectral Variability of Ceres," *ApJL* **817**, L22 (2016).

19. Jaumann, R., et al., "Topography and Geomorphology of the Interior of Occator Crater on Ceres," #1440, 48th Lunar and Planetary Science Conference, 20–24March 2017, Houston, TX.

20. DeSanctis, M. C., et al., "Bright carbonate deposits as evidence of aqueous alteration on (1) Ceres," *Nature* **536**, p. 54 (2016).

21. DeSanctis, M. C., et al., "Ammoniated phyllosilicates with a likely outer Solar System origin on (1) Ceres," *Nature* **528**, p. 241 (2015).

22. Castillo-Rogez, J. C., et al., "Impact-Induced Loss of Ceres' Ice Shell," in preparation.

23. Ammannito, E., et al., "Distribution of phyllosilicates on the surface of Ceres," *Science* **353** aaf4279 (2016).

24. Ruesch, O., et al., "Cryovolcanism on Ceres," *Science* **353** aaf4286 (2016).

25. Combe, J.-P., et al., "Detection of local H2O exposed at the surface of Ceres," *Science* **353** aaf3010 (2016).

26. Platz, T., et al. "Surface water-ice deposits in the northern shadowed regions of Ceres," *Nat. Astron.* **1**, 0007 (2016).

27. Ermakov, A., et al., "Ceres's obliquity history and its implications for the permanently shadowed regions," *Geophys. Res. Lett.* **44**, p. 2652 (2017).

28. Schmidt, B. E., "Geomorphological evidence for ground ice on dwarf planet Ceres," *Nature Geoscience* **10**, p. 338 (2017).

29. Prettyman, T. H., "Extensive water ice within Ceres' aqueously altered regolith: Evidence from nuclear spectroscopy," *Science* **355**, p. 55 (2017).

30. Marchi, S., et al., "The missing large impact craters on Ceres," *Nat. Commun.* 7:12257 DOI: 10.1038/ncomms12257 (2016).

31. DeSanctis, M. C., et al., "Localized aliphatic organic material on the surface of Ceres," *Science* **355**, p. 719 (2017).

32. Park, R. S., et al. "A partially differentiated interior for (1) Ceres deduced from its gravity field and shape," *Nature* **537**, DOI: 10.1038/nature18955 (2016).

33. Villarreal, M. N., et al., "The dependence of the Cerean exosphere on solar energetic particle events," *ApJL* **838**, L8 (2017).