DAWN'S EXPLORATION OF VESTA

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On 16 July 2011, after completing nearly four years of interplanetary flight, Dawn entered orbit around (4) Vesta, the second most massive body in the main asteroid belt. Dawn used solar electric propulsion to spiral to a series of six different orbits to accomplish its science campaign. Although the transfers to progressively lower orbits presented significant challenges, all were executed smoothly. During its nearly 14 months in orbit, Dawn spiraled down to 210 km above the surface and back up, before initiating the gradual departure to travel to dwarf planet (1) Ceres for a 2015 rendezvous. Dawn's exploration of Vesta has shown it to be geologically complex and fascinating, resembling terrestrial planets more than typical asteroids. Among the principal features is a 500-km-diameter impact basin within which is the second tallest mountain known in the solar system. This paper presents Dawn's operations at Vesta and summarizes the principal findings.

INTRODUCTION

Launched on 27 September 2007, Dawn is designed to explore Vesta and Ceres, the two most massive objects in the main asteroid belt. The accretion of these bodies into full-sized planets was interrupted by Jupiter's gravitational stirring of the asteroid belt. Dawn's investigation of the geophysical properties of these surviving protoplanets is expected to help elucidate the physical and chemical processes and conditions during the epoch of planet formation at the dawn of the solar system.

Dawn is the ninth project in the National Aeronautics and Space Administration’s (NASA’s) Discovery Program. NASA’s Jet Propulsion Laboratory (JPL) manages the project and conducts the mission operations. Scientific leadership is provided by the principal investigator, from the University of California, Los Angeles (UCLA).

Dawn's scientific measurements include panchromatic (in stereo) and multispectral imagery; neutron, near ultraviolet, visible, infrared, and γ ray spectra; and gravimetry. To acquire these data, Dawn’s instrument payload comprises a γ ray and neutron detector (GRaND), a visible and infrared mapping spectrometer (VIR), and a pair of identical cameras (framing camera #2, or FC2, the prime unit, and FC1, the backup). Gravimetry is accomplished via the telecommunications subsystem, and does not require dedicated flight hardware.

GRaND was delivered by the Los Alamos National Laboratory and is now operated by the Planetary Science Institute. VIR was contributed to NASA by the Agenzia Spaziale Italiana (Italian Space Agency, or ASI). ASI funds the Istituto Nazionale di Astrofisica (National Institute for Astrophysics) to operate VIR, which was designed, built, and tested at Galileo Avionica. The cameras 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 Dawn spacecraft was designed, built, and tested by Orbital Sciences Corporation. JPL delivered the ion propulsion system (IPS) and components of other subsystems to Orbital.

The mission to orbit both Vesta and Ceres is enabled by the use of solar electric propulsion, implemented on Dawn as the IPS. Without it, even a mission to only one of these bodies would not have been affordable within the Discovery Program. A mission to both would have been impossible. The design is inherited directly from the IPS flown on Deep Space 1.[1]

The design of the spacecraft and payload and of the mission as well as the scientific objectives have been presented in detail elsewhere.[2,3]

Dawn launched on 27 September 2007. Mission operations from launch through the end of 2008 was described by Rayman and Patel,[4] and the progress through 2009 was presented by Rayman and Mase.[5]

INTERPLANETARY CRUISE

Following a successful gravity assist at Mars in February 2009,[5] Dawn spent most of the next two and a half years thrusting with the ion propulsion system to accomplish the rendezvous with Vesta in July 2011. (See Figure 1.) During that time, activity on the spacecraft other than high-duty-cycle ion thrusting was planned to be minimal, principally limited to occasional engineering activities such as routine instrument calibrations. The operations team focused on a concerted development effort to prepare for the Vesta science campaign. In November 2009, Dawn passed 1.67 AU from the Sun for the last time. It would spend the rest of its operational life (and likely well beyond) in the main asteroid belt.

Cruise operations consist primarily of thrusting with the IPS about 95% of the time, with weekly communications contacts with the Deep Space Network (DSN) for data downlink, commanding and radiometric navigation. The team followed a repeating pattern of designing and sequencing five weeks of thrusting, installing those commands on the spacecraft, and then working on the subsequent thrusting plan.

5 June 2010 was a mission milestone as Dawn surpassed Deep Space 1 in accomplishing the largest propulsive velocity change (Δv) by a single-stage spacecraft of 4.3 km/sec. The IPS is singularly effective at providing the Δv that is needed to accomplish the Dawn mission. The spacecraft will ultimately achieve about 11 km/s, equivalent to the Delta 7925H launch vehicle that started Dawn on its interplanetary journey.

Also in June 2010 the team installed new software in the spacecraft's main computer that would provide enhanced operational capabilities at Vesta.

On 17 June 2010, after the majority of flight software installation and reconfiguration activity was complete, reaction wheel assembly #4 (RWA4) faulted. The wheel experienced a sudden onset of unusually high drag torque over a period of several hours.

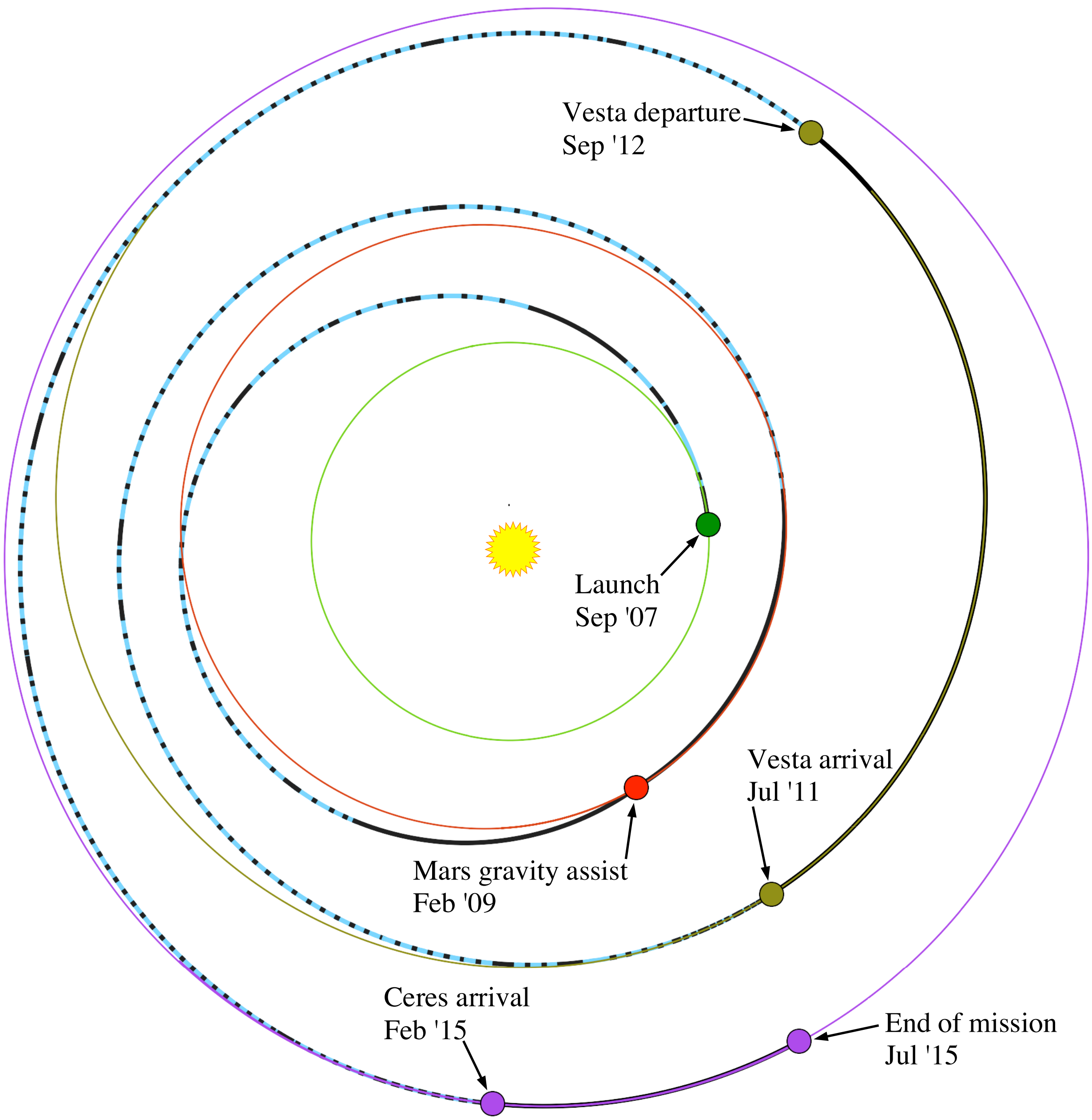

Figure 1. Interplanetary trajectory. The trajectory is blue where the spacecraft spends most of its time thrusting and black where it spends most of its time coasting. The regular interruptions in thrust are for 8-hour DSN sessions and are exaggerated in scale here. Thrusting in orbit around Vesta and Ceres is not shown.

When the drag torque exceeded a preset level, system fault protection detected the situation and powered the wheel off.

Over the subsequent 10 months, three attempts were made to operate the wheel. In each case it exhibited excessive friction before being powered off again. Dawn has four RWAs, however, and only three were needed for normal operations. So although RWA4 has not been recovered, the fault has not affected the ability to operate the spacecraft as originally intended.

As the root cause of the RWA4 anomaly was not known and a significant number of reaction wheels had faulted on other spacecraft, the project moved quickly to protect the remaining three wheels. In August 2010, the team powered all RWAs off and controlled the attitude with the hydrazine-based reaction control system (RCS) thrusters for the remainder of the cruise to Vesta. (When thrusting with the IPS, the ion thruster is used for two axes of attitude control; it is only the third axis that is controlled by RWAs or RCS.) In November 2010, the team updated the control gains in the attitude control software to optimize the hydrazine propellant usage, thereby preserving that precious resource for the long-duration mission. The RCS-based attitude control strategy operated very well during the remainder of cruise.

During the final year prior to Vesta approach, several risk-reduction activities were executed on the spacecraft to retire first-in-flight concerns. The team performed two gyro propagation activities, one each in December 2010 and January 2011, to characterize the ability to propagate attitude knowledge when the star trackers are unavailable, as would be the case at times in orbit around Vesta when they are occulted. The gyro performance proved to be excellent, and quite sufficient to encompass the planned usage at Vesta.

In February 2011, the spacecraft executed a test of the attitude control agility that would be required to thrust to the lowest planned science orbit. The spacecraft performed as expected, correctly using the ion thruster as the actuator to follow the changing thrust direction, simulating a low-altitude, 4.7-hour orbit around Vesta, near the lowest altitude that would be attained.

In March 2011, the team performed an IPS thruster calibration to fine tune the models of the ion thrusters' thrust in the input power regimes that would be used at the greater heliocentric ranges during Vesta operations. The thrust is too low to be measured accurately by onboard sensors, so it is determined by radiometric navigation. The measurements would be important for navigation purposes once in orbit to accurately accomplish the thrusting plan to maneuver from one science orbit to another.

In April 2011, the team installed new software in the main flight computer that would allow the spacecraft to control attitude with a combination of two RWAs plus RCS.[6] This "hybrid" attitude control mode could be used as a contingency if another RWA faulted. In addition, before and during Vesta operations, simulations and testbed tests of hybrid control were performed so that the Vesta plan could be restructured to continue in hybrid control if the need arose. As it turned out, the three RWAs operated flawlessly until August 2012, by which time Dawn was close enough to departure that hybrid control was not necessary.

VESTA APPROACH

The Vesta approach mission phase began on 3 May 2011 with the first optical navigation image of Vesta with FC2. Dawn was about 1.2 million km from Vesta, which spanned only about five pixels That was quite adequate for navigation.

The approach phase was designed to be about 100 days in duration, consisting primarily of the engineering activities required to rendezvous with Vesta, navigation and ion thrusting, as well as several instrument calibrations. With the spacecraft back under RWA control, imaging of Vesta for navigation purposes began at a pace of one observation session per week for the first six weeks; the frequency increased later in the approach phase.

On 1 June 2011, the first set of instrument calibrations and preliminary science observations were executed with VIR and FC2. This activity, designated rotation characterization #1 (RC1), occurred at a distance of 120,000 km. The instruments observed Vesta for a full Vesta rotation of 5.3 hours.

Dawn is the first mission to reach close orbit around a large solar system body that had not previously been visited by a flyby spacecraft, and the project had to update the pertinent physical properties as it approached. One of the significant engineering challenges the team addressed during approach was the accurate determination of the location of Vesta's pole. Although Vesta had been observed with the Hubble Space Telescope (HST), prior to Dawn's arrival the pole was only known to about ±8°, which was not precise enough for the desired science orbit targeting. Optical navigation imaging allowed the pole knowledge to improve enough to keep up with the ongoing targeting to the science orbits. The knowledge of Vesta's mass (and, later, higher order gravity terms) was refined in a similar way. A baseline thrust profile was developed before approach began, but just as during cruise, each segment was updated with the latest estimate of the orbit and physical parameters before being implemented on the spacecraft. In contrast to the five-week thrust designs in cruise, during approach the sequenced thrust periods initially were one month and later were two weeks.

RC2 occurred on 9 - 10 July 2011. In addition to observing Vesta again, this time from a distance of about 37,000 km, this activity also included a search for moons around Vesta. The spacecraft was oriented to point FC2 in the space around Vesta that could possibly contain bodies that would create a potential hazard for the spacecraft. No objects were detected, which retired a risk that the project had been preparing for.

During a routine thrusting segment on 27 June 2011, the IPS unexpectedly stopped thrusting. This anomaly was discovered the next day during a planned DSN communications session. The team quickly determined that a component in the IPS controller had experienced a single event upset and that by power-cycling the electronics, the circuit would be reset and full functionality could be restored. The circuit was subsequently reset and operated as intended.

In parallel with the investigation, in order to resume ion thrusting to continue the approach, the spacecraft was commanded to switch to the other IPS controller. At the time of the anomaly, Dawn had been using controller #1 and thruster #3. The team swapped to controller #2 and thruster #2 for the remainder of the approach. The thrust profile was redesigned, taking advantage of some planned coasting to make up for some of the lost thrust time, and there was no delay in capture.

The remainder of the approach phase executed very smoothly and according to plan. Capture into orbit occurred on 16 July 2011 at 04:48 UTC at a distance of 16,000 km. (Note: all distances to Vesta in this paper are distance to the surface for a mean body radius of 265 km. As subsequently measured by Dawn, Vesta may be represented as a triaxial ellipsoid with principal radii of 286 km × 279 km × 223 km.)

The orbit insertion event was very different from typical planetary encounters, not because of anything special about Vesta but rather because of the low thrust propulsion. There was no critical burn, as Dawn continued with routine ion thrusting to spiral around Vesta. The radial velocity at the time of capture was only 27 m/s. No radio contact was planned or needed, as thrusting was no different then from any other time in the mission. (Dawn already had in excess of 23,000 hours of thrust, or 69.7% of its time in space. As thrusting was the most common state of the spacecraft, there was no risk associated with orbit insertion.) Routine DSN contact was established on schedule the next day, at which point the flight team could confirm that the spacecraft had indeed been gently captured by Vesta's gravity. Dawn was then the first spacecraft to orbit an object in the main asteroid belt.

At arrival, Vesta and Dawn were 2.22 AU from the Sun. Vesta's perihelion is 2.15 AU, and its aphelion is 2.57 AU. With an orbital inclination of 7.1°, it is a difficult target to orbit. By arrival, Dawn had achieved a post-launch propulsive Δv of 6.7 km/s. That had been supplemented by the Mars gravity assist of 2.6 km/s.[5]

FIRST SCIENCE ORBIT: RC3

The first science orbit was designed to occur during the final stages of the approach phase. This observation campaign, designated rotation characterization #3 (RC3), began in orbit around Vesta at 5200 km above the surface on 22 July 2011. Over the course of the three-day observation period, the spacecraft moved through almost half an orbit, providing views of the entire illuminated surface. Although these observations did not directly address the primary science requirements, or level 1 requirements for mission success,[2] they were of great value in selecting instrument parameters for subsequent observations and providing a reconnaissance of Vesta.

SECOND SCIENCE ORBIT: SURVEY

Following the RC3 observations, the spacecraft resumed ion thrusting and achieved the survey science orbit on 2 August 2011. Over the course of the next week, the navigation team refined the orbit estimates and the flight team updated the flight sequences to accommodate the refined pointing and timing predictions.

Survey orbit was the first extended intensive period devoted to science data acquisition, marking the end of the approach phase. The survey science campaign began on 11 August 2011. In a polar orbit at 2735 km and a period of 69 hours, Dawn observed Vesta during seven orbital revolutions to survey the entirety of the illuminated surface. The subsolar latitude during this time was about 27° S, very near the solstice.

The operations strategy was designed to be very similar for most of the science orbits. Dawn pointed its body-mounted instruments to nadir as it traveled south over the sunlit surface. During its passage over the dark side, the spacecraft pointed the high-gain antenna to Earth to return the data.

Observations with VIR were the primary objective of the survey campaign, with a goal of collecting at least 5000 frames. (Each frame is a data structure consisting of one dimension of spectral samples and one dimension of spatial samples.) This orbit also provided an excellent opportunity to map the surface with FC2. Despite anomalies that interrupted VIR observations on two orbits, the survey campaign was completely successful, returning more than 13,000 frames, more than 3 million spectra, and covering about 63% of the surface. In addition, the imaging provided new global views of the body, covering 90% of the illuminated surface at 260 m/pixel.

During the survey science collection period, the navigation team continued to plan the thrusting that would be required to transfer to the next science orbit. With refined knowledge of the gravity field, they designed an orbit transfer to spiral down to the next science mapping orbit at an altitude of 685 km. The transfer began on schedule on 31 August 2011, thrusting with the ion propulsion system through 18 spiraling orbits to arrive at the first high altitude mapping orbit (HAMO-1) on 18 September 2011.

Following arrival at the new orbit, the team performed several engineering reconfiguration and checkout activities prior to the initiation of the science campaign. On 21 September 2011, the spacecraft memory was reconfigured to accommodate the large volume of science data that was about to be collected. During this activity, one of the software functions took longer than expected, causing the main computer to reset and trigger an entry to safe mode. The team quickly responded to the anomaly, and recovered the spacecraft back to normal operations within two days, again preserving the timeline for the science campaign. The only lingering issue from the safing was that following the recovery, GRaND experienced increased noise in one of its γ ray detectors. A few days later, power-cycling the instrument resolved this problem.

THIRD SCIENCE ORBIT: HAMO-1

Dawn began the HAMO-1 science campaign on schedule on 1 October 2011 from an altitude of 685 km, in a 12.3-hour, nearly polar orbit. During HAMO-1, the Sun moved from 27° S to 26° S latitude.

The HAMO-1 campaign was segmented into six "cycles," each consisting of 10 orbits around the body. Each cycle was designed to provide global coverage of the surface with FC2. In each cycle, FC2 was pointed at a fixed angle relative to nadir. Over the course of the six cycles, this yielded a rich set of images for stereo processing. With each orbit lasting just over half a day, the entire campaign lasted for nearly the entire month of October.

The primary HAMO-1 objectives were to map the surface of Vesta with the camera using multiple filters and produce the stereo images that could be used to determine the topography. The HAMO-1 plan would constitute the most comprehensive mapping of Vesta for the mission. Instrument pointing was dictated by imaging, but VIR and GRaND data were acquired throughout HAMO-1 as well.

Although the HAMO-1 phase was very busy and complex, it executed almost flawlessly, meeting all of the science objectives. More than 7000 images were returned. The observations revealed not only the startling diversity of exotic features at a resolution of 65 m/pixel, but also a varied composition and distribution of surface materials. VIR collected more than 15,000 frames, yielding more than 5 million spectra, far surpassing the objective of 5000 frames. Although not yet close enough for detailed radiation spectroscopy, GRaND did detect neutrons emitted by Vesta.

With all of the HAMO-1 objectives satisfied, the team prepared to embark on the most operationally challenging and demanding portion of the mission, the transfer to the low altitude mapping orbit (LAMO). The team would spend six weeks from 1 November to 11 December 2011 designing and implementing two maneuver sequences per week to achieve the desired 210 km altitude orbit. Along the way, the spacecraft was carefully navigated through the 1:1 resonance where Dawn's orbit period around Vesta matched Vesta's rotation period. While this region had been thoroughly studied for its potential impact on the transfer plan, it was easily accommodated with the robust architecture for the transfer.

On 3 December 2011, preparing for the final segment of deterministic thrusting to achieve the low altitude orbit, Dawn experienced an anomaly that resulted in a spacecraft safing. A command to turn the spacecraft caused it to attempt to turn at a slightly higher rate than it could achieve. As the spacecraft could not keep up with the attitude profile computed onboard, fault protection intervened and safed the spacecraft. The flight team quickly identified the problem, and recovered the spacecraft. Despite another minor anomaly, the Vesta plan had yet to lose one day of schedule margin.

FOURTH SCIENCE ORBIT: LAMO

On 12 December 2011 the LAMO science phase commenced on schedule. The primary goals were to map the gravity field at high resolution, and to map the elemental composition of the surface and near-surface with GRaND. Of course FC2 and VIR collected data as well during this period, obtaining their highest spatial resolutions of the entire mission.

When Dawn arrived at Vesta, the plan was for a 70-day LAMO mission phase, with a potential to extend that time with any operational schedule margin that had not yet been utilized. The project had set aside 40 days of operational margin in the overall Vesta mission timeline to accommodate any issues that might arise. As none of the anomalies so far had eroded that margin, the full 40 days were committed to the LAMO campaign.

At a mean altitude of 210 km (80% of Vesta's mean radius), Dawn orbited Vesta once every 4.3 hours. This orbital rate introduced a significant increase in the pace of operations. At this altitude, given Vesta's complex gravity field, a primary operational concern was the possibility of the spacecraft drifting into shadow, for which it was not qualified, so weekly orbit maintenance maneuvers were scheduled to maintain the orbit very precisely. Only about half needed to be executed during LAMO. As with all maneuvers in the mission, they were conducted with the IPS. All maneuvers were less than two hours, and some were less than 15 minutes.

During LAMO, GRaND collected data almost continuously, as the spacecraft was usually pointed towards the surface, except for the occasional periods of thrusting and three DSN communications sessions per week. The data were returned during the scheduled contacts, which had to be carefully coordinated around the radio occultations that would occur on every orbit until March 2012.

On 13 January 2012, a flight software bug caused Dawn to enter safe mode. Then on 21 February 2012, Dawn safed again, this time as the result of a temporary overload of the main computer. On both occasions, the team quickly identified the issue and returned the spacecraft to normal science operations.

In March 2012, an updated power analysis indicated that Dawn could accommodate an additional 40 days at Vesta and still maintain the Ceres arrival in February 2015. With ion propulsion, power translates directly into thrust.[7] Indeed, refinements in predictions of power available as a function of heliocentric range have been the principal reason for changes in the overall mission timeline. Based on this updated analysis, Dawn was approved to stay the additional time at Vesta, with the departure changed to 26 August 2012. This allowed the team to replan the remainder of the Vesta mission, including LAMO, which was extended again until 1 May 2012.

When LAMO completed, the spacecraft had spent 141 days at its lowest altitude orbit, compared with the 70 days originally planned. With this additional time, the gravity and GRaND elemental composition maps were refined, meeting their mission success requirement. In addition, VIR collected a total of 13,000 frames (2.6 million spectra), completing and far exceeding the mission requirement, and FC2 imaged nearly the entire illuminated surface at 20 m/pixel. This unplanned bonus was more than three times better than the HAMO-1 maps and five times better than the mission requirement. The subsolar latitude moved from 24° S to 12° S during Dawn's time in LAMO.

On 1 May 2012, for the first time since launch, Dawn began actively maneuvering away from Vesta, rather than towards it. The orbit transfer from LAMO to a second high altitude mapping orbit (HAMO-2) would mirror the transfer down, taking six weeks, with a similarly demanding operational schedule. The transfer concluded without incident on 6 June 2012.

FIFTH SCIENCE ORBIT: HAMO-2

Following some engineering reconfiguration activities, HAMO-2, again at 685 km, began on 15 June 2012. The Sun had moved to 7° S latitude, 20° north from the HAMO-1 campaign, illuminating much of the northern terrain that had been hidden during HAMO-1. By the end of HAMO-2, the Sun was 3° S latitude.

The HAMO-2 campaign was designed to be very similar and complementary to HAMO-1. The plan was to comprehensively map the surface with the multiple FC2 filters and at selected angles for topography, this time emphasizing the northern regions that were previously in darkness. With the additional time that had been granted to the mission, the HAMO-2 phase was extended from four to six cycles, matching the HAMO-1 campaign. In addition, almost ten days at the beginning of HAMO-2 were devoted exclusively to increasing coverage with VIR so the instrument did not have to share downlink bandwidth with FC2.

The HAMO-2 phase proceeded extremely smoothly, again accomplishing all planned observations, and exceeding all expectations. Dawn returned 4700 images of Vesta and nearly nine million VIR spectra. The full mission success requirements were achieved in HAMO-2 as the imaging in the northern regions increased the topography coverage well beyond the required 80%.

DEPARTURE AND SIXTH SCIENCE ORBIT: RC4

Having exceeded all requirements and objectives for Vesta, on 25 July 2012 Dawn began its departure phase, spiraling upward with the IPS. The plan was to escape on 26 August, with four additional sets of observations during departure to see the highest northern latitudes with diminished spatial resolution but with the Sun having moved north from HAMO-2.

During the ascent on 8 August 2012, RWA3 experienced an increase in friction that appeared very similar to what was observed with RWA4 in June 2010. Fault protection powered RWA3 and the other two operating wheels off and commanded one of Dawn's safe modes and RCS control. Because all wheels were scheduled to be powered off in early September for the interplanetary cruise to Ceres, it was decided to leave the wheels off and resume the departure with RCS control. Following the reconfiguration of the spacecraft to normal operations and the replanning of the departure, thrusting commenced on August 17. The hiatus in thrusting caused a comparable delay in escape, but the flexibility of the mission timeline provided by the use of ion propulsion made this easy to accommodate.

The bonus departure observations had been considered low priority, so they were descoped to one set in order to preserve hydrazine. Because of the delay in departure, the observations yielded a better combination of spatial resolution and illumination than in the original plan.

On 25 - 26 August 2012, Dawn conducted RC4, its final observations of Vesta, from an altitude of about 6000 km. The subspacecraft latitude was north of 60° N, and the subsolar latitude was about 0.75° N, providing the best view of the region immediately around the north pole. Two full rotations were observed with FC and VIR.

The attitude deadbands in RCS control still used the values set in November 2010 for interplanetary cruise operations, in which pointing of the high-gain antenna had defined the requirements. Therefore, for RC4, deadbands for instrument pointing (on an axis orthogonal to the antenna) were ±5°. Although some of the FC images captured only a limb of Vesta and some of the VIR frames missed it entirely, the total data return was quite satisfactory.

Following the return of data from RC4, ion thrusting resumed. Escape from Vesta was on 5 September 2012 at about 06:26 UTC

CRUISE TO CERES

The cruise to Ceres will be operationally much like the journey to Vesta. Most of the time will be devoted to ion thrusting. Prior to Vesta, Dawn typically interrupted ion thrusting once per week for a communications session. In order to conserve hydrazine following the RWA faults, that frequency is reduced to once per two weeks for most of the time between Vesta and Ceres.

The team will spend the two years of cruise building on the success and experience gained at Vesta to plan a similar campaign to explore Ceres. Ceres arrival is targeted for early 2015.

SIGNIFICANT DISCOVERIES AT VESTA

The scientific discoveries at Vesta are the topic of numerous scientific papers.[8] A few of the significant highlights are included here for context.

Vesta was observed in HST images to have what appeared to be a large crater with a central peak in the southern hemisphere. Upon arrival, Dawn confirmed this and discovered that Vesta had not only one, but two large impact basins deep in the southern hemisphere. The older, Veneneia, was formed at least two billion years ago and is 400 km in diameter, centered 52° S latitude. The younger, Rheasilvia, is about one billion years old. With a diameter of more than 500 km and center at 72° S, it is the structure observed with HST. The large central peak of Rheasilvia rises about 20 km, significantly more than Mt. Everest or Mauna Kea (measured from the ocean floor). The only higher mountain known in the solar system is Olympus Mons.

Figures 2 - 4 show a sampling of views of Vesta. All are based on the shape model constructed from the HAMO-1 stereo imaging.

The Rheasilvia impact excavated about 1% of Vesta's volume, liberating much of that material into space. Thanks to efficient dynamical mechanisms for transporting material from there to Earth, some of those rocks arrived here as meteorites. Dawn has confirmed the connection to Vesta, the only body other than the Moon or Mars to which we have linked specific meteorites. It is estimated that about 6% of the meteorites found on Earth came from Vesta, far more than from those other two sources.

Also a remnant of the massive impacts is a vast system of troughs that nearly encircle the body near the equator, some extending for several hundred kilometers and 15 km in width. The troughs are thought to be the result of the near-fatal collision as each impact rippled through the body.

Dawn has confirmed that Vesta indeed differentiated and contains an iron-nickel core estimated to be 110 km in radius, a significant fraction of the body radius. This supports the

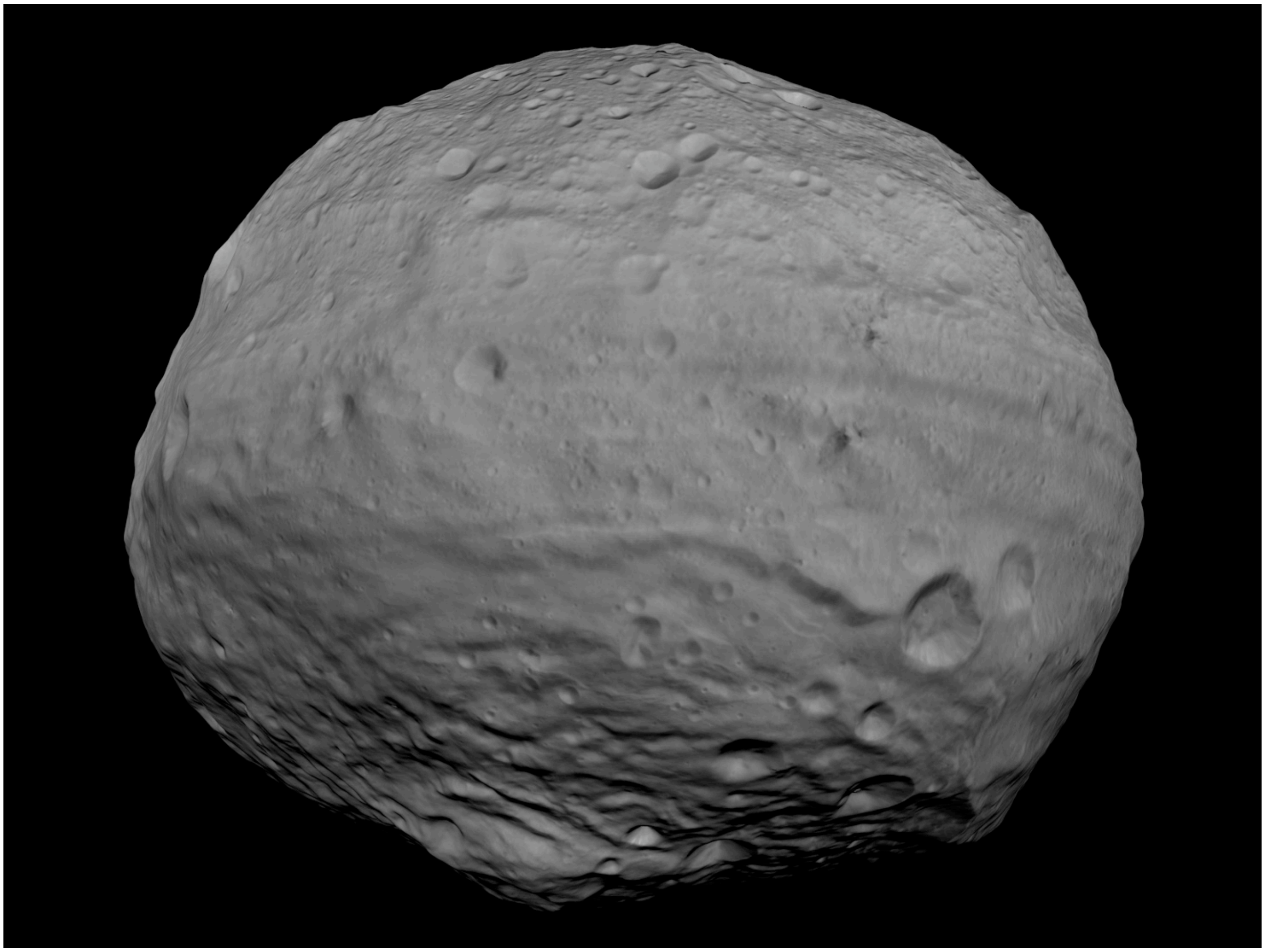

Figure 2. Global view of Vesta from shape model. The equatorial troughs, Rheasilvia impact basin, and central peak of the impact basin are easily visible. Vesta's equatorial diameter is 570 km. This image was developed through a collaboration of JPL, UCLA, DLR, MPS, and IDA.

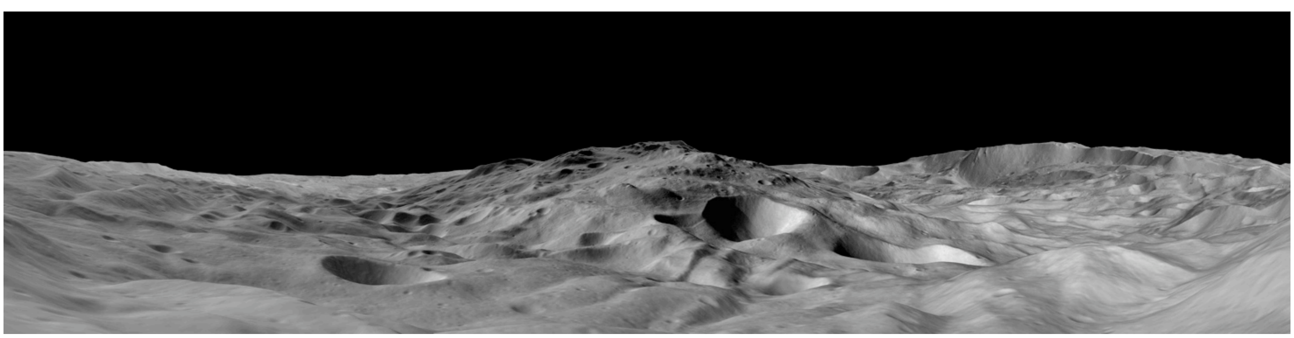

Figure 3. Central complex of Rheasilvia from shape model. In this view, the curvature of the reference ellipsoid has been removed, so the wall of Rheasilvia is visible on the right in the background. The actual curvature of Vesta is such that the crater wall would be over the horizon. This image was developed through a collaboration of JPL, UCLA, DLR, MPS, IDA, and PSI.

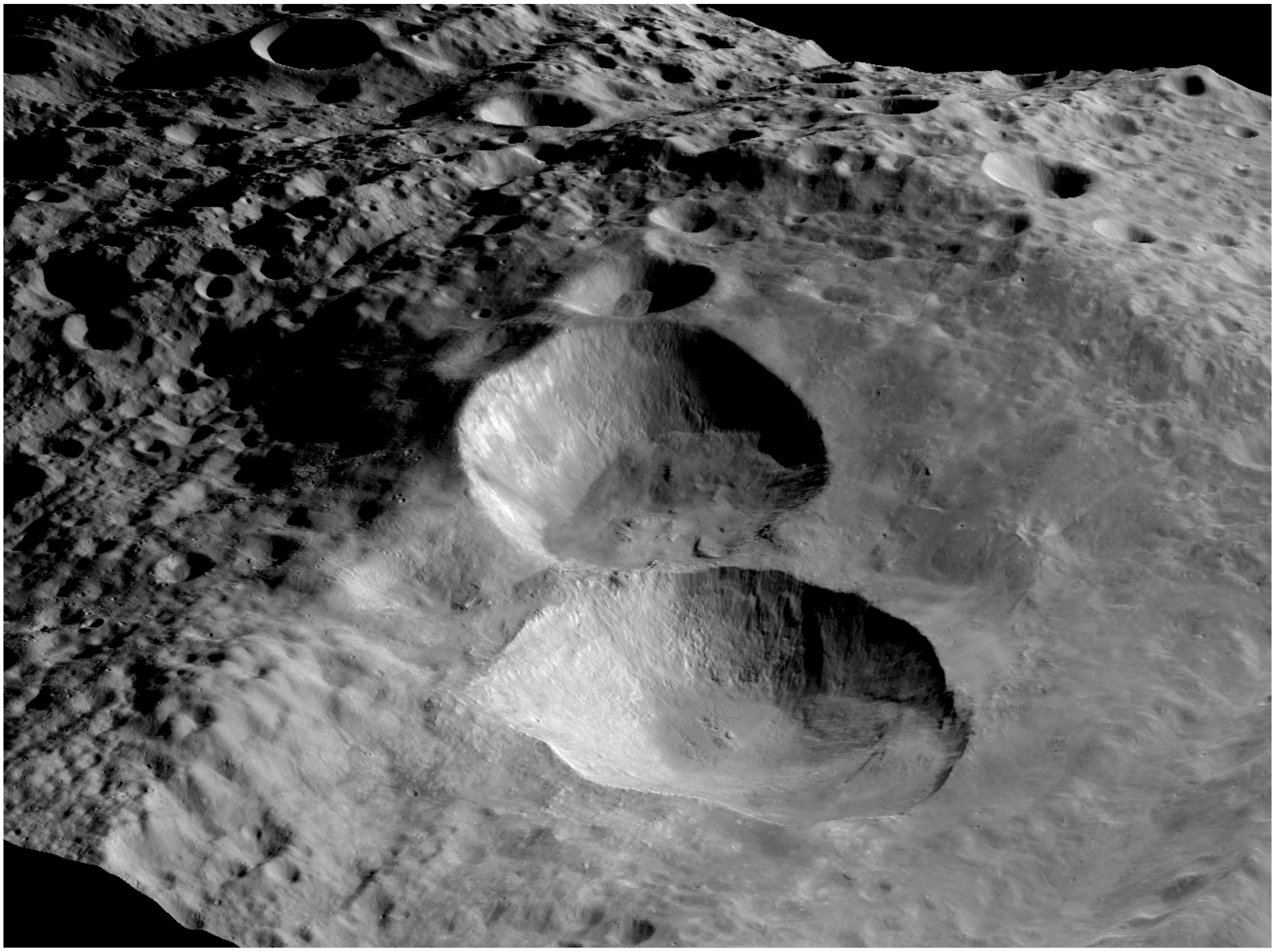

Figure 4. The Snowman from shape model. The triplet of craters in the center is nicknamed the Snowman. The largest, Marcia, is about 60 km in diameter. Bright and dark material are evident on the wall of this relatively fresh crater. The left side of the image shows the heavily cratered northern hemisphere and a section of the troughs near the equator. The right side shows the smoother southern hemisphere. This image was developed through a collaboration of JPL, UCLA, DLR, MPS, IDA, and PSI.

understanding of Vesta as a geologically complex body. Entirely unlike smaller asteroids, Vesta more closely resembles a small terrestrial planet, consistent with its being a surviving protoplanet from the early solar system.

Vesta is heavily crated in the north and less so in the south, which was resurfaced by the giant impacts. The cratering record has implications for the formation of the rocky bodies of the inner solar system, supporting recent theories of planetary migration and the significant transfer of material between the inner and outer solar system.

In addition to the dichotomy in terrain, Vesta shows far greater diversity in the nature of the minerals on the surface than small asteroids, reflecting its complex geological history.

CONCLUSION

Dawn's scientific and operational accomplishments at Vesta have been exceptionally successful. The flight team achieved all of the science objectives, exceeded the level 1 requirements, and even accommodated an additional 80 days of scientific observations. The spacecraft performed as designed, able to accomplish all of the complex tasks that were required of it. The benefits and operability of ion propulsion have been clearly demonstrated, and Dawn has advanced the state of the art of this technology. The scientific discoveries will continue to rewrite textbooks for years to come.

ACKNOWLEDGMENTS

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