# DAWN'S OPERATIONS IN CRUISE FROM VESTA TO CERES

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On 5 September 2012, Dawn concluded its successful exploration of Vesta, the second most massive object in the main asteroid belt. The spacecraft departed after 14 months in orbit and is now using its ion propulsion system to travel to dwarf planet Ceres, the most massive main-belt asteroid. The principal activity now is thrusting with the ion propulsion system to provide the 3.3 km/s required to rendezvous with Ceres early in 2015. Because two of the four reaction wheels have experienced faults and are likely unrecoverable, a substantial effort has been invested in preparing for Ceres operations with alternate attitude control methods. The project has engaged in an intensive campaign to reduce hydrazine expenditures, which has resulted in a significant increase in the hydrazine expected to be available for Ceres. Based on this work, studies provide good confidence that the required activities at Ceres can be completed. This paper describes post-Vesta operations, including measures taken to conserve hydrazine as well as other preparations for Ceres.

## INTRODUCTION

The Dawn mission is designed to investigate the two most massive objects in the main asteroid belt, Vesta and Ceres. These protoplanets are believed to be remnants from the epoch of planet formation, and Dawn's exploration is intended to help reveal important physical and chemical processes and conditions present at that time and since then.

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 the responsibility of the principal investigator, from the University of California, Los Angeles.

The mission to orbit both Vesta and Ceres is enabled by the use of solar electric propulsion, implemented on Dawn as an ion propulsion system (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 IPS design is inherited directly from the one flown on Deep Space 1.[1]

The Dawn spacecraft was designed, built, and tested by Orbital Sciences Corporation. JPL delivered the IPS and components of other subsystems to Orbital.

Dawn's scientific measurements at both destinations 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 imaging cameras. Gravimetry is accomplished with 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 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 were described by Rayman and Patel,[4] and the progress through 2009 was discussed by Rayman and Mase.[5] The remainder of the cruise to Vesta and Vesta operations, including the three-month approach phase as well as activities from orbit insertion on 16 July 2011 through escape on 5 September 2012, were reported by Rayman and Mase[6] and by Polanskey et al.[7]

Many authors have presented findings from Vesta.[8] We will present an overview of some of the results before addressing the interplanetary cruise to Ceres.

## VESTA

Dawn returned 31,000 images, 20 million visible and infrared spectra, and thousands of hours of neutron spectra, γ-ray spectra, and gravity measurements of Vesta. Figures 1 and 2 show two views of Vesta. The IPS allowed Dawn to tune its six science orbits to optimize the investigations. The longest duration science orbit was 141 days at a mean altitude of 210 km.

Collectively the data yield a picture of the second most massive object in the main asteroid belt that shows it to be quite complex. With principal radii of 285 × 277 × 226 km, and GM = 17.3 $km^3/s^2$, this body is unlike typical smaller asteroids. It appears to have experienced many of the geological processes that characterize the rocky terrestrial planets.

One of the major distinctions from most asteroids is that Vesta differentiated into layers. Modeling of the gravimetry suggests Vesta has a dense solid core (composed principally of iron and nickel) 100 to 125 km in radius, a mantle, and a crust ~ 20 km thick.

One of the most prominent surface features is the Rheasilvia impact basin, with a diameter of 500 km or about 96%of the mean body diameter. This is the largest impact feature relative to body size yet observed anywhere. The central peak in this basin is about 180 km across at the base and rises 20 - 25 km above the variable elevation of Rheasilvia's floor.

Centered at 72° S latitude, the impact that excavated Rheasilvia 1 - 2 Ga ago deposited so much ejecta that the southern hemisphere was virtually resurfaced. As a result, Vesta now displays a pronounced hemispherical dichotomy, with the north much more heavily cratered than the south.

Rheasilvia lies on top of an older basin centered at 52° S. The 400-km-diameter Veneneia is the second largest impact feature observed on Vesta.

Near the equator is a system of almost 100 chasms that were formed as a result of these two impacts. They are believed to be graben produced from the propagation of energy through Vesta's interior, and models suggest that their formation depends on an interior consistent with a differentiated body.

Dawn has greatly strengthened the case for Vesta being the parent body of the large class of meteorites composed principally of howardites, eucrites, and diogenites (HEDs). Well in excess of 1,000 named meteorites are HEDs, far more than the number of meteorites identified as having originated on Mars or the Moon.

Dawn met or exceeded all of its objectives at Vesta, and the wealth of data it yielded will continue to be analyzed for years. This is the only main belt asteroid that a spacecraft has orbited.

## REACTION WHEEL HISTORY

A crucial difference between the mission prior to Vesta and after Vesta is a result of the loss of two reaction wheel assemblies (RWAs). Dawn has four RWAs, and the baseline mission assumed the use of three at all times. RWA4 faulted in June 2010,[6] displaying a significant increase in drag torque. The unit was operated three times before the Vesta approach phase commenced in May 2011, but the friction remained high.

When RWA4 faulted, operations continued smoothly with the three remaining RWAs. Nevertheless, the project immediately undertook an effort to develop the capability to operate with two RWAs in combination with the hydrazine-based reaction control system (RCS). The software for this hybrid control system[9] was installed in the spacecraft in April 2011 in case it was needed for Vesta operations.

In the meantime, in August 2010, the operations team powered off the three RWAs to preserve their lifetime for use in orbit at Vesta and Ceres, and used RCS control instead. When thrusting with the IPS, the spacecraft uses thrust vector control (TVC), in which the gimbaled ion thruster controls two axes of attitude. In TVC, RCS was needed only to control roll around the axis containing the thrust vector. During coast periods, including pointing of the high gain antenna (HGA) to Earth, RCS controlled all three axes.

In November 2010, new gains were installed in the attitude control system (ACS) to reduce the expenditure of hydrazine in all-RCS control. The savings accrued principally from increasing the effective deadbands to ±5° in roll around the axis that contained the 1.52 m 39.6 dBi HGA. In each of the orthogonal axes, deadbands were limited to about ±0.64° in order to ensure good telecommunications link performance given the 3 dB half beam width of 0.9°.

The remaining three RWAs were powered on again at the beginning of the Vesta approach phase in May 2011, and they operated well throughout nearly all of Vesta operations. During the departure phase in August 2012, in which the IPS was used to spiral away from Vesta, RWA3 faulted. By then, the spacecraft was more than 2,100 km in altitude. Fault protection powered all RWAs off, switched to RCS control, and entered one of its safe modes.

Because the plan had been to deactivate the RWAs shortly after escape and leave them off until the Ceres approach phase commenced more than two years later, it was only a minor change in plans to leave them off following the RWA3 fault. Departure continued smoothly using pure RCS and TVC control modes.

## HYDRAZINE CONSERVATION

When RWA3 faulted, it was not evident that accomplishing the Ceres objectives in hybrid control was possible. Although hybrid control yields more efficient use of hydrazine than pure RCS control, it is not as efficient as full RWA control. Moreover, because two RWAs had faulted so long before their qualified lifetimes had been reached, the project had low confidence in the longevity of the other two RWAs. (Use of a single RWA is deemed not to be valuable enough to warrant the development effort.) Finally, the probability of recovering the long-term use of either of the two faulted RWAs is considered to be very low.

The immediate recognition that three healthy RWAs were not likely to be available for Ceres operations led the project's system engineering office to promptly undertake a major campaign to conserve hydrazine. Hydrazine expenditure has become a significant metric in most decisions about mission operations.

Even before Dawn completed its escape from Vesta, the operations team had identified 37 methods for conserving hydrazine in cruise and at Ceres, and the list grew to about 50 in the subsequent three months. Each method was rated according to the maturity of the concept, the scale of the anticipated hydrazine savings, the costs and risks, the dependence on or other interactions with other methods, and the work needed to refine it.

When assessing risk for a specific activity or development, it is important to consider the risk to the overall mission objectives. Risk should not be evaluated only in the context of the particular activity. With finite resources, reducing risk in one area may translate into greater risk in other areas. Undertaking lower priority work can place the primary objectives at risk, both by diffusing the project team's focus and by adding risk of causing flight system anomalies.

The project worked through the list of options quickly in order to realize benefits as soon as practicable. In addition, to keep the spacecraft on course and on schedule for Ceres and with a full Ceres operations plan to develop, the operations team could not afford to invest too much effort in conserving hydrazine.

Dawn launched with 42.7 kg of usable hydrazine. When RWA3 faulted, there were 29.6 kg onboard. If no changes had been made to the cruise plan following the RWA3 fault, Dawn would have arrived at Ceres with a useable supply of about 18 kg, assuming no further anomalies. Although the plan for Ceres at that time was too immature to quantify the hydrazine cost for implementing it in hybrid control, the expectation was that it would be unaffordable.

## CRUISE CHANGES

We discuss here the two most significant changes made in cruise operations.

For typical interplanetary cruise operations, Dawn used to thrust with its IPS for 95% of a week, or about 160 hours. The interval during which it did not thrust was used to turn from the thrust attitude to point the HGA to Earth, downlink engineering telemetry and uplink commands, turn back to the thrust attitude, and restart the IPS.

Among the most hydrazine-costly activities is turning. Therefore, a key element of the new plan has been a change to having one HGA session every four weeks rather than every week. By itself, this increased the hydrazine expected to be available at Ceres arrival by 4 kg, or about 20%.

Making this change required a careful reassessment of the engineering telemetry stored between HGA contacts. The new design stores enough data that a full contact session can be missed. So even if eight weeks elapse, the spacecraft will not lose the health and status data on each subsystem. In fact, enough additional data storage is allocated that a safing event can be accommodated at eight weeks immediately before return of all the data. The additional telemetry on the safing itself and for a few additional days before high rate communications can be restored can be stored without loss of the previous eight weeks of engineering data.

Extending the time between HGA sessions to longer than four weeks was considered but rejected for several reasons. In addition to making it difficult to store enough data to retain adequate insight into the performance of the spacecraft, the Deep Space Network (DSN) schedule could not be finalized far enough in advance to fit with the schedule for sequence development plus execution. Moreover, the differential benefit of extending the intervals beyond four weeks was deemed to be small.

Even when the spacecraft was pointing its HGA to Earth once a week, two-hour "thrust verification" sessions were conducted half way between the telecommunications sessions. The IPS throttle was reduced during these times so power could be allocated to the radio downlink. The spacecraft transmitted through a low-gain antenna just enough information to confirm it was maintaining thrust. This provided an opportunity to respond more promptly to an anomaly that might interrupt thrusting.

Now with four weeks between HGA contacts, the same strategy is used but expanded. Two thrust verification sessions are conducted each week, but one is increased to about five hours, providing greater insight to the status of engineering subsystems, even at low downlink rates.

Prior to the first RWA fault, the standard spacecraft turn rate was 0.1°/s. In November 2010, at the same time the effective deadbands were increased, that was reduced to 0.05°/s as another conservation measure. For Vesta operations, when three RWAs were used, the original rate was restored with the intention that it would be reduced to 0.05°/s for the cruise to Ceres.

In order to save still more hydrazine following the RWA3 fault, the rate was reduced to 0.025°/s. This provided an increase of 1 kg in the hydrazine at Ceres arrival.

Other changes have been implemented on the spacecraft as well, principally in parameters for ACS operation. In addition, the plan for spacecraft activities during the interplanetary cruise phase, particularly those that involve turns, were reconsidered and in some cases redesigned or even canceled in light of the importance of conserving hydrazine. The combined effect of all the changes was to raise the hydrazine predicted to be available for use at Ceres from 18 kg to 25 kg. (These values include 5 kg of hydrazine the project holds as contingency based on a conservative budget for anomalies from now through the end of the mission. Detailed simulations of safe mode behaviors in all-RCS control are under way now, and it is expected that the results will allow the contingency to be reduced, thus providing more hydrazine for implementation of nominal activities.)

## CERES PLANS

An even larger project effort has been

invested in devising methods to decrease the hydrazine needed for Ceres operations. The greatest change is the reduction to fewer than 20% of the number of turns executed at Vesta. In addition, slower turns, larger effective deadbands, additional ACS parameter changes, and other strategies are being applied. While the detailed design is continuing, the current assessment is that even with zero RWAs, Dawn is likely to be able to accomplish all the originally planned observations with the hydrazine predicted to be available.

The overall strategy for the science plan at Ceres is similar to that at Vesta and will be described in detail by Polanskey et al.[10] and elsewhere. As at Vesta,[6] there will be four circular near-polar science orbits of progressively lower altitudes. (Vesta had two additional orbits following the lowest, but there is no intent at Ceres ever to raise the altitude.)

The baseline plan for is not to use the hybrid mode at Ceres until the lowest altitude orbit (low altitude mapping orbit, or LAMO). Although the two RWAs that have not faulted have not displayed any anomalous behavior nor indications of incipient or impending problems, confidence in them is low. Therefore, we want to expend what may be a very limited life where the benefit is the highest. Hybrid provides the greatest hydrazine savings compared to all-RCS control in LAMO. The strategy of waiting until LAMO to use hybrid depends on the project's confidence that Dawn can reach that orbit using all-RCS control with enough hydrazine remaining to continue the mission there. To the extent hybrid control is available, LAMO operations will be more robust.

Not using RWAs prior to LAMO reduces operational complexity by avoiding the need for a backup all-RCS plan. Moreover, given the low confidence in the RWAs, it reduces the probability of an RWA-induced safing event during any of the earlier phases at Ceres.

While substantial refinements in the design for the Ceres mission are planned, the current estimate is that 18 kg of hydrazine will be expended even if hybrid control is not available, yielding a small but positive margin compared to the 20 kg available for nominal operations.

## CRUISE PROGRESS AND PLANS

Dawn's trajectory is shown in Figure 3. The Ceres approach phase is scheduled to begin in February 2015, with orbit capture occurring near the beginning of April 2015, and the spacecraft will spend the significant majority of the time until then ion thrusting. Dawn will thrust a total of about 20,500 hours from Vesta departure to Ceres arrival in order to provide the 3.3 km/s needed for the heliocentric transfer.

As of 31 August 2013, Dawn has thrust more than 8,300 hours since escaping Vesta on 5 September 2012, or 96% of the time.

It has accomplished in excess of 33,000 hours of ion thrusting in space, providing a total propulsive velocity change of 8.6 km/s. The spacecraft has expended 314 kg of xenon propellant.

Although most of the time is devoted to accomplishing the trajectory changed needed to rendezvous with Ceres, some special activities are conducted during the cruise phase.

Because accurate predictions of electrical power availability are so important for solar electric propulsion missions,[11,12] a solar array calibration was executed in June 2013 at a heliocentric range of 2.48 astronomical units

(AU). The wings were rotated to five different angles up to 47° off-normal to the Sun-spacecraft vector, reproducing the insolation that will be experienced at heliocentric ranges up to 3.00 AU. At each angle, the array output power was measured in order to refine the model for future power capability and hence IPS thrust level. The calibration will be repeated in October 2013 when Dawn is near its perihelion of 2.44 AU and occasionally thereafter as the spacecraft recedes from the Sun.

Engineering tests of the science instruments are conducted once or twice a year to verify their health and monitor changes. In addition, building on experience from Vesta, the software in each camera will be updated in November 2013 to provide improved operability and fault diagnosis.

In November 2013, hybrid control will be tested for the first time on the spacecraft. Although it is no longer required for Ceres operations, validating its performance and calibrating the simulations will be valuable in case both RWA1 and RWA2 operate well enough in LAMO for hybrid to be used.

No prescription is known that has a reasonable probability of reconditioning a faulted RWA. Nevertheless, a window is held open in October 2014 in case a protocol is developed by then.

In November 2014, the IPS thrust will be calibrated to refine the models to be used in maneuver design and orbit determination at the greater heliocentric ranges during Ceres operations. A similar activity was performed in March 2011 in preparation for Vesta operations. As then, the thrust will be determined by radiometric navigation. The IPS thrust was recognized during development to be too low to be measured with sufficient accuracy with onboard sensors; at Ceres it will be less than 30 mN.

## CONCLUSION

After nearly six years of flight operations, including the successful exploration of Vesta, Dawn is making good progress toward its second destination, dwarf planet Ceres. An intensive campaign to conserve hydrazine following the loss of two of its four RWAs has been very productive. The results, combined with the design of a hydrazine-efficient mission at Ceres, provide reasonable confidence that Dawn will be able to accomplish all of its objectives there regardless of the performance of the remaining two RWAs.

With cruise operations going smoothly and focused on routine IPS thrusting, the operations team is now devoting much of the time to completing the design for the Ceres mission. Later in 2013, the development of command sequences will begin.

## ACKNOWLEDGEMENTS

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Figure 1. Global, near-equatorial view of Vesta from shape model. The central peak of the Rheasilvia impact basin is at the bottom. The difference in crater density between the northern and southern hemispheres can be seen. Vesta's mean equatorial diameter is 562 km. This image was developed through a collaboration of JPL, UCLA, DLR, MPS, and IDA.

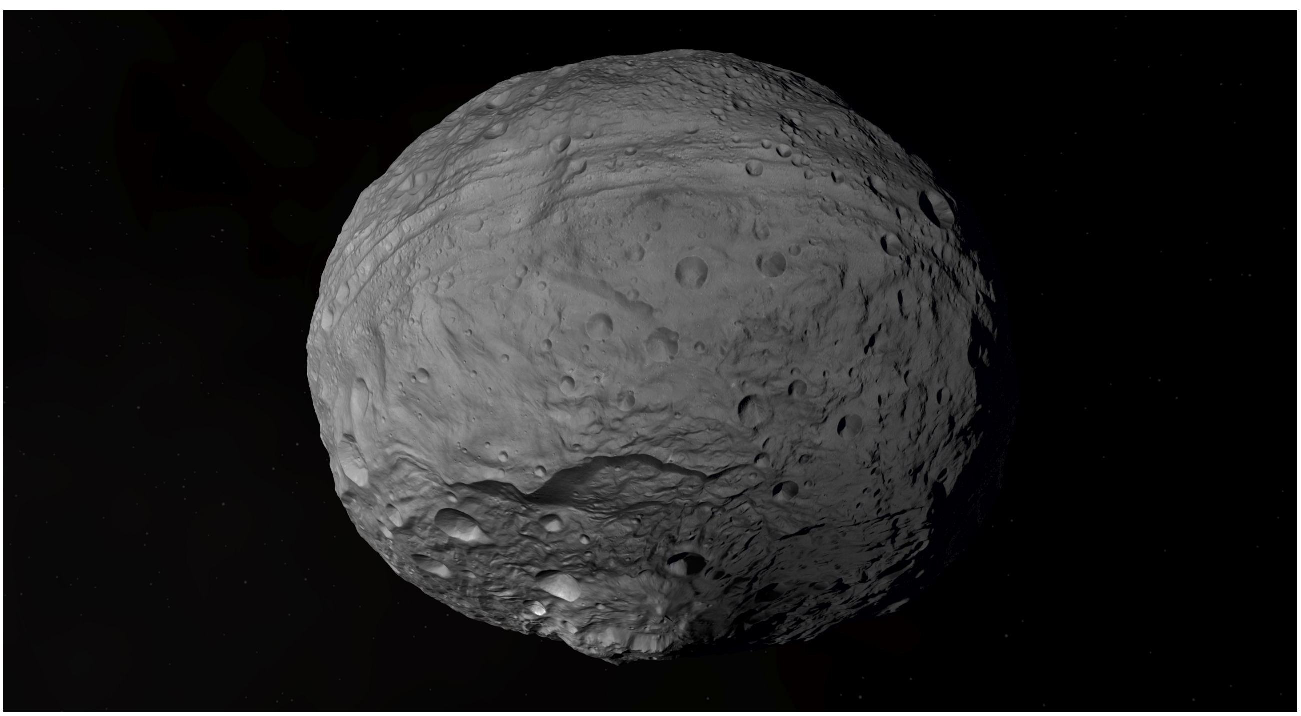

Figure 2. Global, southern hemisphere view of Vesta from shape model. The extensive network of troughs near the equator is evident in the top of the image. Part of the surviving wall of the Rheasilvia impact basin is prominent one-third of the way up from the bottom, and the central peak is clear at the bottom. This image was developed through a collaboration of JPL, UCLA, DLR, MPS, and IDA.

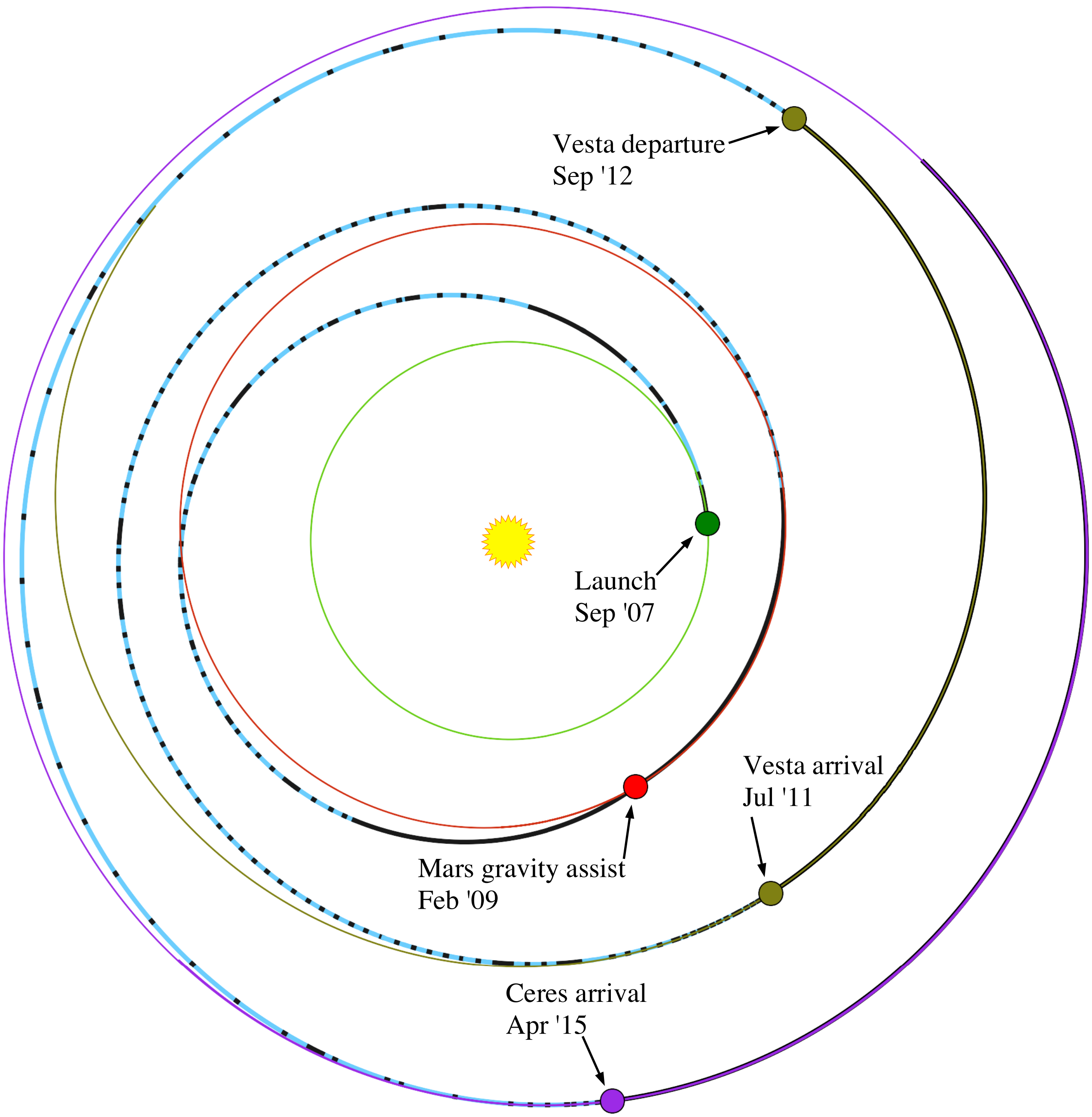


Figure 3. Interplanetary trajectory. The trajectory is blue where the spacecraft is thrusting and black where it coasts. Thrusting in orbit around Vesta and Ceres is not shown. The regular interruptions in thrust are for pointing the HGA to Earth and are exaggerated in duration here. Note the reduction in the frequency of such telecommunications sessions following departure from Vesta. The mission concludes with Dawn in orbit at Ceres.

## REFERENCES

1. Rayman, M. D., "The Successful Conclusion of the Deep Space 1 Mission: Important Results without a Flashy Title," Space Technology **23**, p. 185 (2003).

2. 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).

3. 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).

4. 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).

5. 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).

6. Rayman, M. D., R. A. Mase, "Dawn's Exploration of Vesta," *Acta Astronautica*, accepted for publication.

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

8. Russell, C. T. *et al.*, “Dawn at Vesta: Testing the Protoplanetary Paradigm,” *Science*, **336**, p. 684 (2012) and references therein.

9. 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.

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

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

12. 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).