Christopher Russell
Carol Raymond *Editors*

The Dawn Mission to Minor Planets 4 Vesta and 1 Ceres

Springer

The Dawn Mission to Minor Planets
4 Vesta and 1 Ceres

Christopher Russell • Carol Raymond
Editors

The Dawn Mission to Minor Planets 4 Vesta and 1 Ceres

Previously published in *Space Science Reviews* Volume 163,
Issues 1–4, 2011

Springer

Editors
Christopher Russell
Department of Earth and Space Sciences
Institute Geophysics & Planetary Physics
University of California Los Angeles
Los Angeles, CA, USA

Carol Raymond
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, CA, USA

ISBN 978-1-4614-4902-7
Springer New York Heidelberg Dordrecht London

Library of Congress Control Number: 2012942865

Cover illustration: Digital Terrain Model of Vesta constructed by DLR German Aerospace Center, Berlin, 2012

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

Contents

Space Sci Rev (2011) 163:1–2
DOI 10.1007/s11214-011-9853-1

Foreword

C.T. Russell · C.A. Raymond

Published online: 17 November 2011

When Christopher Columbus set off for his new world in 1492, he took three ships—the Nina, Pinta and Santa Maria—to mitigate the risk of such a perilous journey. Such a mission into the unknown requires much self-confidence. Will the promise of the journey be fulfilled? What if there is no short cut to China? Will the Queen be angry? Will we ever return to find out?

We still are explorers today but the stage has moved from the surface of the ocean to the vastness of space. The Queen no longer funds missions to foreign lands, but the individuals who are in charge of the public purse must be convinced of the worthiness of such adventures. Making the case for their expenditures requires promises of bountiful rewards of knowledge, if not gold, silk and spices. It also requires lots of self-confidence to counteract one's own creeping doubts. Can we really "travel back in time" by exploring asteroids that have been bombarded by collisions for 4.56 billion years? What if the new world is boring? When the Dawn mission to Vesta and Ceres was proposed we had meteorites we believed came from Vesta but none from Ceres. We were moderately sure we had the right instruments for Vesta, but were we carrying the right instruments for Ceres? And could we achieve everything we promised?

It is a long way to the heart of the asteroid belt and a very risky journey. To mitigate risk Dawn has redundancy. Most of the spacecraft systems are redundant and the propulsion system itself like Columbus's ships, is triply redundant. But not all the payload is redundant. Fortunately we know, as this volume is being completed, that Dawn has successfully reached Vesta but we do not know what will befall the mission in the months and years ahead. The spacecraft has proven to be remarkably robust but there is much still to be done and a long time to spend in space as the mission heads for Ceres. Hopefully we have planned and executed well.

C.T. Russell (✉)
University of California, Los Angeles, CA, USA
e-mail: ctrussel@igpp.ucla.edu

C.A. Raymond
Jet Propulsion Laboratory, Pasadena, CA, USA

This volume describes the Dawn mission to the two most massive asteroids 4 Vesta and 1 Ceres. This mission is the first to attempt to orbit one, let alone two, main belt asteroids. Each of these bodies are small planets, or protoplanets, that exhibit many of the properties and processes that we find on other larger planets including Mercury, and Mars. The ability to orbit one, leave it and go to and orbit the second is not science fiction. It is science reality enabled by the ion propulsion system.

The papers in this volume include the scientific background to understand the rationale for and objectives of the mission. Articles also describe the instruments and the flight system, the operations and the education and public outreach program.

The success of this volume is due to many people. We thank first of all the authors who distilled the information that formed the basis for these articles. We are grateful to Ayako Matsuoka who stepped in to edit the article for which the two editors were conflicted. The editors also benefited from an excellent group of referees who acted as test readers, and helped refine the articles provided by the authors. These referees included:

S. Asplund, D. Bass, W. Bottke, R. Binzel, S. J. Bus, A. Cellino, C. R. Chapman, J. Cuzzi, T. Fraschetti, K. Hack, P. Helfenstein, B. Jakosky, K. Keil, T. Larson, D. Mittlefehldt, G. Neukum, F. Nimmo, A. Rivkin, J. Polk, V. Reddy, K. Righter, B. E. Schmidt, L. Tamppari, A. Treiman, P. Tricarico, D. Turrini, J. Veverka, P. Warren, A. Wessen.

Equally important has been the strong support provided to this project by Springer and the extra effort provided by Fiona Routley, Randy Cruz and Harry Blom. At UCLA we were skillfully assisted by Marjorie Sowmendran who acted as the interface between the editors, the authors and the publisher.

November 1, 2011

Space Sci Rev (2011) 163:3–23
DOI 10.1007/s11214-011-9836-2

The Dawn Mission to Vesta and Ceres

C.T. Russell · C.A. Raymond

Received: 3 February 2011 / Accepted: 19 September 2011 / Published online: 15 October 2011

Abstract The Dawn mission journeys to the center of the main asteroid belt to orbit and explore the two most massive main belt asteroids, Vesta and Ceres. Dawn aims to increase our understanding not just of the present state of these two bodies, but also of the conditions during the time of their formation. It attempts this through achieving a set of measurement objectives in which the physical properties of these asteroids such as mass, slopes, size, density, and spin state are accurately determined, and in which the mineralogical and elemental composition of the surface and near-surface material are probed. Dawn employs ion propulsion technology to enable a modestly-sized launcher to start a moderately-sized spacecraft on its journey, to not only reach the two massive asteroids but also to orbit them, descending to near the surface. Unlike most orbital missions, the initial (Vesta) phase must be completed with sufficient reserves and within a time window that later allows Dawn to explore Ceres. Dawn carries a redundant framing camera, a visible and near-IR spectrometer, a gamma ray and neutron spectrometer, and achieves high-accuracy radiometric and optical navigation to enable gravity field determination. The spacecraft was developed by Orbital Sciences Corporation under the management of the Jet Propulsion Laboratory for the National Aeronautics and Space Administration. Dawn is a Principal Investigator-led mission of the Discovery Program. The PI institution, the University of California, Los Angeles, manages directly the science team, the Dawn Science Center, and the Education and Public Outreach program.

Keywords Dawn mission · Vesta · Ceres · Asteroid belt

C.T. Russell (✉)
Institute of Geophysics and Planetary Physics, Department of Earth and Space Sciences, University of California, Los Angeles, CA 90095-1567, USA
e-mail: ctrussel@igpp.ucla.edu

C.A. Raymond
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA

1 Introduction

The Dawn mission is a revolutionary concept in comparative planetary exploration. Never before has a spacecraft been designed to travel to another solar system body to orbit it, then to depart for a second body to undertake a new orbital exploration with the same instrumentation. The scientific return from either of Dawn's targets would lead to fundamental improvements of our understanding of the earliest epoch of the solar system and the growth of protoplanets. However, the ability to intercompare these two very different objects using the same instrument complement enables even deeper understanding of planetary origins. The enabling technology is Dawn's ion propulsion system that allows Dawn to change its velocity by an amount equal to that provided by the Delta II rocket that lifted it from the Earth.

The mission overview is the first of a series of articles describing the science, the instruments, and the techniques behind Dawn. These subsequent papers describe our understanding of the formation of the solar system (Coradini et al. 2011) and the history of the asteroid belt and its current state (O'Brien and Sykes 2011). They describe our understanding of the origin and evolution of Dawn's two targets, Ceres and Vesta (McCord et al. 2011; Zuber et al. 2011), and our present understanding of their surface composition (Rivkin et al. 2011; Pieters et al. 2011). We do not have meteorites that can be identified with Ceres, but we have abundant samples that we identify with Vesta (McSween et al. 2011). These are the Howardite, Eucrite, and Diogenite meteorites, and these meteorites provide many clues to the history and evolution of Vesta, preparing us for our journey back in time that we execute in parallel with our journey outward from the Sun and the Earth. The articles also discuss the Dawn spacecraft (Makowski et al. 2011), the ion engines (Brophy 2011), and its scientific payload: a framing camera (Sierks et al. 2011), a visible and infrared spectrometer (DeSanctis et al. 2011), a gamma ray and neutron spectrometer (Prettyman et al. 2011), and a telemetry system that can be used for radiometric measurements of the gravitational field of Vesta and Ceres (Konopliv et al. 2011). Multiple views of the same scene by the framing camera will be used under constant lightning conditions for stereographic height determination and under varied lighting conditions for photoclinometric height determination to obtain the topography of the bodies (Raymond et al. 2011). Other papers describe the operations and planning process including the role of the Dawn Science Center (Polanskey et al. 2011) and the Education and Public Outreach Program (McFadden et al. 2011).

In the following paragraphs, we give a brief overview of why the science team chose to fly the Dawn mission, why we believe it was selected for flight in the Discovery program, what questions we expect to resolve, and how we got from mission concept to mission execution. There are lessons for those who themselves would like to lead an investigation into the next frontier in space. Such a journey is not for the faint-hearted or those who believe in a rational universe.

2 The Scientific Context for the Dawn Mission

2.1 The Dawn of History

Today when we look out into the solar system, we observe a near-steady state and, while there are periodicities and occasional collisions, averaged over millennia there is little discernible change in the system. But there was a beginning, and in the beginning, change was rapid. The nebula of cold gas and dust that was to feed the formation of the solar system was beginning to accrete solid bodies, perhaps small at first, but then ever larger. A massive central gas body collapsed and eventually gas giants formed in orbit about this central body. At some point, maybe earlier than some of the above events or during them, a supernova seeded the solar system with ^{26}Al and ^{60}Fe. For a period of time, the solar system had an additional source of heat. Bodies that accreted during the ^{26}Al epoch heated more than those that accreted either earlier or later, leading to different evolutionary paths for bodies with and without a significant component of these short-lived radionuclides. In this earliest epoch of the solar system change was rapid. Suddenly there were many bodies present in the solar system. The bodies that reached sizes similar to those of Vesta and Ceres began to evolve thermally. Their interiors warmed to temperatures that led to iron cores and silicate mantles, or perhaps rocky cores and water-ice mantles, or perhaps very little alteration at all.

Without visiting the bodies that are the building blocks for the solar system, we can do very little to understand them. We do have the Howardite, Eucrite and Diogenite (HED) meteorites that have fallen onto Earth and appear to have been ejected from Vesta (McSween 1987). These vestan meteorites tell a very interesting story, but there is debate about the story they tell, and we cannot discern much about the geophysics of the parent body of the HED meteorites. In the case of Ceres, there are no identified meteorites. It cannot simply be that Ceres is too big to lose material through collisions. We have meteorites from Mars and the Moon, both much larger bodies than Ceres. Furthermore, the pathways that deliver the meteorites from Vesta to Earth do also exist for Ceres. A possible explanation for the lack of cerean meteorites is that the material on or near the surface of Ceres does not transport well. Whatever the explanation, the lack of meteorites from Ceres leaves us with few clues as to its central structure, and we must rely on ambiguous clues such as shape, color, and albedo, until we can visit.

One could be rightly skeptical that bodies orbiting the Sun for 4.6 billion years could tell us very much about the events that occurred at the birth of the solar system. The popular paradigm when we formulated the Dawn mission was that the initial epoch of growth of the protoplanets was cut short by the formation of Jupiter, and a period of destruction of bodies in the main asteroid belt began. The perturbed bodies collided and broke up into ever smaller bodies, a process that continues today. We do know that Ceres and Vesta did survive this bombardment. Even with the thick regolith that we would expect from such bombardment, there must be some vestiges of the earlier tectonic forces. Are there mountains, rift valleys, ridges, flows and other geologic constructs? Could there be evidence of continued evolution of these small bodies that we had been expecting to be frozen in time?

Just as we are curious about our human ancestry, we are curious about our planetary ancestry. We can gain insight into who we are and how we got to where we are from our genealogy.We can do the same with our planetological studies of these precursors to the Earth and her neighbors. The Dawn mission is therefore not just an exploration in space but also an exploration in time—a time machine that will help us to communicate with the events that occurred 4.6 billion years ago.

2.2 The Discovery of the Asteroid Belt

The discovery of the asteroid belt was a direct outgrowth of our understanding (or what we thought we understood) about planetary orbits. This understanding began with the careful work by Tycho Brahe in the 16th century measuring the precise positions of the planets in the sky. These positions were then used by Johannes Kepler to determine the planetary orbits and how the bodies moved around the Sun. Kepler felt that the gap between Mars and Jupiter was too large and wrote in 1596, "Between Mars and Jupiter I place a planet"

Fig. 1 Painting of Giuseppe Piazzi who on January 1, 1801, discovered the first asteroid, named 1 Ceres

(Peebles 2000). It was not until late in the 17th century that Isaac Newton explained the empirical laws of planetary motion with the universal law of gravitation that states that all bodies have a mutual attraction proportional to the product of their masses and inversely as the square of their separation. Another 100 years had passed when Johann Titius, a professor of mathematics, added a footnote to a book by Charles Bonnet that he was translating, which gave a mathematical progression that matched the positions of Mercury through Saturn with a gap between Mars and Jupiter. Johann Bode soon saw this footnote and added the same text to his own book but without immediate attribution (Peebles 2000). When later the Titius-Bode law predicted correctly the location of Uranus, Bode admitted Titius was the originator of the law of planetary positions.

The success of this law only intensified the search for the missing planet. Baron Franz Xaver von Zach was one of those most interested in the search and spent much time scanning the night sky. In 1798, frustrated by his lack of success and the vastness of the region to be searched, he proposed to undertake a cooperative effort in which the sky was divided among multiple observers.

The initial observers called themselves the Celestial Police. One of these observers was Giuseppe Piazzi (see Fig. 1), who on January 1, 1801, saw a dim 'star' that was not on his star charts, which on the next night had moved. Piazzi continued his observations until bad weather and illness brought them to a halt. He realized that he had found a minor planet, as the object was not comet-like in appearance. Fortunately, C.F. Gauss was able to develop a mathematical approach that simplified determining the orbit from the limited tracking available. On January 1, 1802, Zach, using Gauss' orbit calculation, was able to rediscover this new celestial body that was later to be named Ceres. Shortly thereafter on

Fig. 2 Statue of H.M. Wilhelm Olbers (1758–1840) in the Wallanlagen Park in Bremen, Olbers discovered 4 Vesta on March 29, 1807

May 28, 1802, H.M. Wilhelm Olbers (see Fig. 2) discovered 2 Pallas and on September 1, 1804, K. Harding discovered 3 Juno. On March 29, 1807, Olbers made his second discovery, 4 Vesta. Then, despite continued efforts, no more asteroids were discovered for 38 years.

2.3 Guiding Scientific Questions

While it is in humankind's psyche to explore, an undertaking like that of Dawn cannot take place without a well-defined set of scientific objectives or scientific questions that it will resolve. Considering our ignorance of the nature of these small distant bodies, at least when the mission was formulated, these questions were quite basic. Later, as a mission focused the scientific communities' attention on the problem, and the spacecraft was in development and then launched, the questions became more sophisticated. Even before the mission arrived at its target, much apparent progress had been made through available tools such as remote sensing, numerical modeling, and geochemical investigations of samples in hand.

Vesta and Ceres are considered intact survivors from the earliest days of the solar system and as examples of the building blocks from which the terrestrial planets were made. Clearly Vesta and Ceres are very different from each other. Why? Was one created inside the snowline and one outside? Was one formed at a different time than the other? Had the ^{26}Al decayed before Ceres accreted? And what are these bodies like today? What is their true density and density structure? Of what are they made? How do they relate to our meteorite collections?

3 The History of Dawn

3.1 The Road to Selection

The Apollo program not only enabled the human exploration of the Moon, but equally enabled geological, geochemical, and geophysical exploration of the Moon to an extent that far exceeded what could have taken place with a robotic program alone; but after Apollo 17, the program ceased, and the exploration of the Moon stopped. It was not until 1992 and the Discovery workshop held in San Juan Capistrano, California, that it became possible once again in the NASA program to fly a lunar mission as, in principle, investigators could now propose whole mission concepts. At that workshop, J. Mark Hickman, a young engineer from NASA Lewis Space Center (now, NASA Glenn Space Center) presented a paper on what an ion propulsion engine could do for robotic exploration. A collaboration was born and a team of planetary scientists under the direction of C.T. Russell worked on mission concepts leading up to the 1994 opportunity to propose. A mission called Diana resulted, that used ion propulsion to explore the Moon in polar orbit and then leave the Moon and match orbits with the low-activity comet Wilson-Harrington. The mission payload was similar to that of today's Dawn mission and would accomplish for the Moon much of what Dawn was later to attempt to accomplish for Vesta and Ceres. However, Diana was deemed to be too ambitious, and the Stardust cometary flyby with dust sample return and the low-cost Lunar Prospector mission were selected instead.

The Diana team decided to re-propose at the next opportunity, but believed that the selection of the Lunar Prospector mission would block the consideration of any lunar mission for a long time to come. An examination of other solar system bodies, accessible within a Discovery mission budget, that would obtain information complementary to that of the Diana lunar mission, produced Vesta as a promising target. Meteoritic and remote sensing data (McCord et al. 1970) indicated that Vesta, while less than a sixth of the radius of the Moon, had a basaltic surface like that of the Moon and most probably a small iron core. Thus, a mission to Vesta would help us learn more about both the origin of the solar system, since it formed very early, and the thermal evolution of basaltic bodies through comparative studies with the Moon. The scientific community had studied non-ion propulsion concepts that were not achievable within the Discovery budget and called these missions Main Belt Asteroid Rendezvous (MBAR) missions. To emphasize the community's desire for such a mission, the Diana team usurped the name, and an MBAR mission was proposed using ion thrusters. This mission was less ambitious than Diana, using one engine at a time with three engines needed to complete the mission, compared to Diana's six engines used two at a time. This version of MBAR would orbit Vesta and then leave to orbit two smaller asteroids. The MBAR proposal was submitted in 1996 and suffered the same fate as the Diana proposal. The GENESIS mission to gather solar wind composition data and CONTOUR to fly by two or possibly three comets were selected instead.

About the time MBAR was formulated and proposed, JPL proposed a New Millennium technology demonstration mission called Deep Space 1, in which a single ion thruster was employed to do ultimately an asteroid and a cometary flyby. Deep Space 1 was developed on a reduced time schedule consistent with its low-cost demonstration objectives and was launched in the fall of 1998, when the MBAR mission was again resubmitted for consideration to rendezvous with Vesta and another smaller asteroid. As the review committees were examining proposals, the DS1 engines proved to be balky when they were first ignited, and perhaps for that reason, MBAR was again not selected. The MESSENGER and Deep Impact missions, respectively, to orbit Mercury and to send an impactor into comet Tempel 1 were selected.

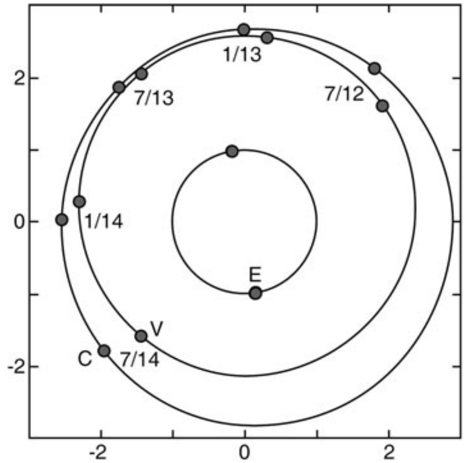

Fig. 3 Location of Earth, Vesta, and Ceres from July 1, 2012 to July 1, 2014 as Dawn leaves Vesta and travels to Ceres

When the MBAR mission was studied for the next Discovery opportunity in 2000, it was found that Vesta and Ceres had approached each other sufficiently that it was possible to reach Ceres and orbit it after completing the investigation of Vesta. Figure 3 illustrates the relative location of the two bodies during a period when such a transfer is possible. For the capability affordable under the cost cap of the Discovery program, this transfer could be made only over a two-year period during the 17-year synodic period in which Vesta lapped Ceres in their orbits around the Sun. Both objects provided compelling science return, and in the opinions of the team, each could justify a Discovery class mission. But the ability to do both missions with a single launch, and a single spacecraft was thought to be a winning concept. This mission, in fact, makes a powerful statement of the advantage of solar electric ion-propelled missions for planetary exploration in the inner solar system. Had either a Vesta or a Ceres orbital mission been launched with chemical propulsion, each would have required a larger spacecraft for the fuel and a larger launch vehicle, each mission totaling about $750 million in cost. Dawn will explore both bodies and for a cost of well under $500 million, saving NASA over $1 billion.

By the time the new proposal was submitted, the Deep Space 1 mission had successfully demonstrated the ion thrusters. The team changed the mission name to Dawn (which is not an acronym) and resubmitted the proposal once more. In January 2001, the mission was selected for the preparation of a Concept Study Report from which a downselect would be made. Three concepts were competed from which we expected only one to be selected.

3.2 Formulation

The selection for further study occurred in January, but we could not begin our study until April 2001, because of the availability of funds. Finally, Dawn had a "full-time" staff of engineers to begin a detailed design. These included not only a proposal manager, but a project manager, Sarah Gavit, who was to become the Dawn project manager for formulation, or Phase B, as it is called. Dawn's Phase A study lasted 6 months, culminating in a voluminous concept study report with a site visit scheduled after the study report submittal. The review committee submitted a set of questions beforehand, to be answered during the visit, in addition to the oral questions asked spontaneously during the review. Dawn's site visit was scheduled for September 12, 2001, and the team planned to hold a dress-rehearsal at Orbital Sciences Corporation in Dulles, Virginia, on September 11, 2001. When terrorists struck New York and Washington on this day, the review was cancelled. The team was also without the normal means to return home, as all planes were grounded and were to remain so for many days. The west-coast contingent banded together in a convoy of four vehicles, each holding three to four occupants, and drove night and day, reaching Los Angeles in about 48 hours. The review materials were frozen, sealed in a NASA vault until a later review could be held. In November, the review was finally held and, in December, NASA announced the decision, and both Dawn and Kepler, an exo-planet mission, were selected for formulation.

This very good news was accompanied by some bad news—NASA would have to delay the start of the formulation phase by effectively a year. Orbital and UCLA received no funds until early in 2003. Thus, the launch that had been originally proposed as taking place in 2005 would have to be delayed until 2006. Fortunately, this was possible, but not without a change in the launch vehicle to a Delta II heavy. The arrival time and lighting conditions at Vesta and Ceres also changed.

The project dealt with these changes and additional management directions that increased costs but were not accompanied by funding increments. It strengthened its management team by appointing Tom Fraschetti as project Manager and put together what it thought was a successful preliminary design review to complete Phase B, albeit without sufficient margin by the rules established for chemical missions on the Ceres leg of the journey. One casualty of the Phase B process was the laser altimeter. When Goddard Space Flight Center (GSFC) re-evaluated the cost of providing this instrument, it became totally unaffordable, and no acceptable solution could be found. Cost Pressure increased when NASA decided that projects needed to carry larger budgetary reserves than the Dawn project had been carrying when selected. A possible solution was floated in which Dawn was built to do both Vesta and Ceres but costed to the end of the Vesta portion leaving Ceres for an extended mission. This was not acceptable to NASA, so we went forward with the financial reserves with which we were selected. Then on Christmas Eve 2003 we received the news that Dawn was canceled. Fortunately, Orbital Science Corporation was strongly committed to Dawn and offered to forego their fee for Dawn's construction. This convinced NASA headquarters to give Dawn another chance and the project regrouped and replanned, shortening the time at each asteroid to reduce operations costs. Unfortunately, additional sacrifice had to be made in order to get this approval and the magnetometer was removed from the payload. The project then was allowed to prepare for its Critical Design Review. After a successful Critical Design Review, the spacecraft building began. More details of this early period of Dawn's implementation can be found in Russell et al. (2007).

3.3 Implementation

The implementation of the flight system followed the experience of most projects. Along the way there are surprises. A manufacturer changes processes; a part becomes unavailable; a supplier is sold and comes under new management. The planetary program, since its launch opportunities are generally fixed, must minimize delays that could result in a late delivery of the flight system to the launch pad. Thus, if choices have to be made between cost and schedule, schedule usually wins. In the summer of 2005, Dawn was entering the test and integration phase as more and more of the spacecraft was assembled and it became clear that, to remain on schedule, a greater rate of expenditure was required. The case was developed for the increase in expenditures and brought to NASA Headquarters. Since all Discovery projects before Dawn had to our knowledge made the same presentation and often for a much larger sum than Dawn was requesting, it was expected that the request would, after some grumbling and perhaps compromise, be granted. However, about one month after the presentation, a project stand-down was ordered, the likes of which none of us had ever heard before, let alone experienced. During the stand-down, the project team was allowed to do paperwork and be reviewed, but we were not supposed to do work that advanced the project. Many experienced personnel were taken off the project including the project manager, Tom Fraschetti, whom the team uniformly admired. Some were put on sister projects and others laid-off. This was a most unusual action for a mission that was as complete as was Dawn at the time. John McNamee became the interim project manager.

The stand-down lasted from October 2005 to March 2006, and the project was quite certain that nothing was wrong with the implementation of Dawn and believed that the mission would be restarted given the good reviews it had received during the stand-down. Unexpectedly, and following an appearance of the NASA Associate Administrator at congressional hearings, the word came down that Dawn had been cancelled again. This was a shock for JPL management because a process was supposed to be in place that required consultation in such situations. JPL appealed to the Office of the Administrator that the agreed-upon process was not followed and a special project review was expedited. The spacecraft was found to be well along in development and in good shape for completion. The project was then restored to full funding and the job of getting experienced personnel back on to Dawn begun. A new project manager, Keyur Patel, was appointed. Unfortunately, the 2006 launch opportunity had now slipped away and the launch was rescheduled for June 2007. Because of the delay introduced by the stand-down, the thermal vacuum facility at Goddard was no longer available for Dawn and thermal vacuum testing was performed at the Naval Research Laboratory instead. This went well and soon the flight system was shipped to Cape Canaveral and the Kennedy Space Center for launch preparations which by and large went very well for the flight system, but we were soon to feel the impact of launching on a vehicle that was being phased out. The Air Force was not planning to continue using Boeing's Delta II launcher, and NASA had too few launches to sustain the Delta II production line indefinitely.

3.4 Launch

A launch opportunity is a period of time, perhaps three weeks long, in which there is a short interval each day, called a launch window, when the rocket has a potential trajectory that will place the spacecraft payload on a path to its intended target. Generally, days in the center of the launch opportunity have the greatest launch margins and the days at the beginning and the end of the launch opportunity have the least. In July, the weather in Florida is usually hot and humid with afternoon thunderstorms. Dawn's launch window coincided with the time of maximum thunderstorms.

The first warning that the launch was at risk was the news that the rocket was going to arrive from the factory twelve days late, The assembly of the rocket went well until the crane lifting the solid rocket boosters seized up and required a week to repair, putting launch 19 days behind schedule, eroding much of the launch opportunity, The delay moved the launch into July where the launch margins were scanty at best.

Something we did not need ourselves but that future users of the Delta II rocket could want was telemetry data during Dawn's flight over the mid-Atlantic ocean where there were no telemetry stations. To satisfy this need a boat and a plane were ordered to receive the data. Both had difficulty reaching their intended stations within the period required and the plane was available to the Dawn mission for only a few days. As these further delays were occurring, not only was our launch opportunity heading into negative margins but, we were also beginning to encroach on the launch opportunity of the Mars Scout mission, Phoenix, that had launch opportunities only every two years. The pressure to fuel the rocket and press the launch button was strong.

Once the second stage of a Delta II is fueled, it must be used in a finite period of time or a new rocket procured. Dawn had a back-up opportunity in September, a very good one, but that opportunity was too far into the future to store the fueled Delta II, and there was no spare second stage available to replace the one now on the launch pad until well after the September launch opportunity was past. To make the situation even more dire, for any launch after about October 2007, at the time that Dawn would approach Vesta and then Ceres, the bodies' orbits would have diverged such that Dawn would be unable to achieve its exploration of both bodies (see Fig. 3). One of them would have to be sacrificed unless we waited for 15 years, at which time they would have approached each other again to enable the flight between them. Thus a September launch was the last opportunity. Even as poor as the July launch opportunity was becoming, the decision was made to fuel the rocket and launch. Costs were a consideration and the boat was getting close to the right spot in the Atlantic, and even if it did not reach its target, the data were not critical to Dawn.

Lightning is a continual concern at Cape Canaveral. Lightning arrestors surround each launch pad, and lightning strikes, which are common close to the pads, occurred during our preparations for the launch. Danger to the launches and personnel is especially high during fueling and as a result it is difficult to get a full day of fueling operations completed in July when afternoon thunderstorms often occur in the vicinity of the launch pad. After we made the decision to go ahead with launch, we lost another day to weather. In fact, we believe that even if we had been able to fuel a week earlier we could not have launched on any of the following days because of lightning activity during the launch window. We were in a quandary, and finally with all the stakeholders on the line including those who would have to fund any delay, we decided, to the relief of all, to wait for the September launch opportunity and allow the Phoenix project to start assembling their rocket on the adjacent pad for their August Mars launch. The Dawn spacecraft was carefully lowered to the ground and stored until the launch crew could begin to work on Dawn again in late September.

The weather on a September afternoon is better than in July, and the weather in the morning is much, much better. The September launch window was at sunrise when the air is still and the sky generally clear. The chosen day, September 27, was beautiful, with a few low clouds offshore and, as shown in Fig. 4, the launch took place without a hitch. The spacecraft was placed on the correct trajectory, the large solar panels unfolded as planned, and the ion engines started with no hiccups. Dawn was on its way to its gravitational assist from Mars and its subsequent rendezvous with Vesta and Ceres.

4 Mission Science and Measurement Objectives

Dawn's overarching goal is to understand the processes occurring in the early solar system as Vesta and Ceres were formed and evolved. To do this, Dawn characterizes their surfaces and probes their internal structure. It attempts to determine when and how Vesta and Ceres formed and how external and internal forces shaped them. It creates detailed shape models of the two bodies and map the geologic units on the surface. To achieve these science objectives, we have derived a set of measurement objectives that enable mission planners, instrument builders and operations managers to know to what specifications they are working and what accuracies they need to achieve. The Level 1 specifications are usually quite general but they lead to Level 2, Level 3, and Level 4 requirements that can be very specific. The project, if well managed, takes these requirements very seriously. Some of the Level-1 requirements are very easy to achieve with the Dawn mission; others push the team and the spacecraft to their limits. All have been very useful in keeping the project focused on the science objectives.

Fig. 4 Dawn leaving the launch pad on September 27, 2007. (Credit: Randy Pollock [photographs] & Johan Kiviniemi [photo stitching])

Dawn was designed to be a mapping mission in which the instruments are co-aligned and the spacecraft nadir pointing when in orbit. This choice was made to minimize operational complexity, and therefore cost. In addition, in each mission sub-phase (orbit) a single instrument is prime (controlling the spacecraft attitude) and the others do ride-along science. Since all instruments do principally nadir-oriented science, ride-along observations are usually simple. The one main exception is off-nadir observations to derive topography, which requires off-nadir viewing angles between 5 and 10 degrees. Since the measurements of the gamma ray and neutron detector (GRaND) degrade when the spacecraft points more than 5 degrees off-nadir, these two objectives are mutually exclusive. The spacecraft also points off-nadir for optical navigation images, and points to Earth for returning the stored telemetry.

The first Level 1 requirement is to determine the bulk density to 1%. The knowledge of the mass of Vesta and Ceres is already approaching 1% and the gravity measurement once Dawn is in orbit will be much more accurate than this. Thus this requirement is mainly one on the size and shape determination. The volume is proportional to the cube of the linear dimension of a body so the density is very sensitive to the size determination. We expect to satisfy this requirement during the first orbital sub-phase that we call Survey, at an altitude of 2460 km, using the framing camera and the radiometric gravity data.

The second Level 1 requirement is to determine the orientation of the spin axis to within 0.5°. We expect to satisfy this with the framing camera during the Survey orbit, or before using the rotational characterizations done while approaching Vesta. Knowledge of the spin axis orientation is very important because it determines when different illumination conditions occur on Vesta's surface. When Dawn arrives at Vesta, the Sun is shining on the south pole. We would like to image the entire surface of Vesta and to do that we must have illumination in the north during the high-altitude mapping orbits near the end of the orbital stay. The mission was originally planned using the 1997 Thomas pole (Thomas et al. 1997). A re-examination of all of the existing data that could constrain the pole orientation together with newly gathered data (Li et al. 2010) indicates that the pole is displaced in right ascension about 5° in the direction that delays illumination reaching the north pole. A decision to stay longer to complete mapping at Vesta requires consultation with NASA administrators as it involves risk, cost, and schedule issues.

The third Level 1 requirement is to obtain images of 80% of the surface with a resolution of 100 m/pixel (at Vesta; 200 m/pixel at Ceres) in the clear and 3 color filters. This will be achieved by the framing camera during the high-altitude mapping orbit (HAMO) and is fairly easy to achieve given the proper illumination of the surface, since adequate bandwidth exists to transmit the required data to Earth. The different resolutions for Vesta and Ceres result from the higher orbit altitudes planned for Ceres. The orbit radii scale to the body radius, and Ceres' radius is roughly twice that of Vesta's.

The fourth requirement is to obtain a topographic map of 80% of the surface with a horizontal resolution of 100 m (at Vesta; 200 m for Ceres) and a vertical resolution of 10 m (at Vesta; 20 m at Ceres). This requirement is much more difficult to meet. Originally, the mission had a laser altimeter that provided better than 1 m altimetry. When the laser altimeter was dropped, we examined the available techniques, which were classical stereophotogrammetry, in which two or more images are obtained from two different look directions under the same lighting conditions, and stereophotoclinometry in which three or more images are obtained from different look directions and lighting conditions and which solves for the surface albedo and slopes which are integrated to obtain heights. At the time the Level-1 science requirements were approved we felt that stereophotoclinometry would produce a better results and that stereophotogrammetry was a good backup plan. Since that time, those using classical stereophotogrammetry have improved their techniques and the Level-1 objectives can be achieved classically. Our plan, however, is to proceed to acquire the images necessary to pursue either approach, as each have advantages relative to our viewing conditions. The principal difficulty now in achieving this objective is that in order to obtain topography over 80% of the surface, we need to have sun angles of about 10° or more above the horizon. This, more than any other objective, sets our departure date from Vesta.

The next Level-1 requirement is to obtain 10,000 spectral frames at wavelengths of 0.25–5.0 μm with a spectral resolution of 10 nm to measure and map the mineral composition. At least half of these frames will be at a spatial resolution of ≤200 m (at Vesta; ≤400 m at Ceres) with the rest at ≤800 m (at Vesta; ≤1600 m at Ceres) spatial resolution. These data will be obtained by the VIR spectrometer during the Survey and HAMO orbits. There is no Level-1 requirement to get complete or nearly complete surface coverage, but it certainly is a goal of the mission to maximize surface coverage.

The next Level-1 requirement is to measure and map the abundances of the major rock forming elements to 20% precision and a spatial resolution of ∼1.5 times the mapping altitude over the entire surface to ∼1 m depth. The depth given is not so much a requirement as an acknowledgment of the depth to which the GRaND spectrometer is sensitive. This requirement will be achieved with the gamma ray and neutron spectrometer during the low-altitude mapping orbit. (LAMO) This measurement sets the duration of the LAMO orbit, and to some extent, its altitude. The spacecraft will descend no lower than is safe to do so or has the resources to do so. A second GRaND Level-1 measurement requirement is to measure the abundances of hydrogen, potassium, thorium, and uranium over the entire surface to ∼1 m depth. This constrains the mission orbital parameters and durations in the same manner as the previous requirement.

The last Level-1 measurement requirement is to determine the gravity field with a half wavelength resolution of 90 km. Given the previous constraints imposed by GRaND on the length of the LAMO sub-phase, and the amount of tracking data required to maintain

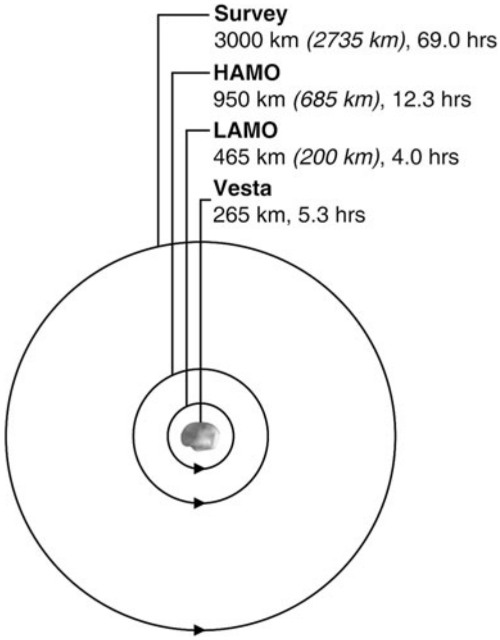

Fig. 5 Relative sizes of the three Vesta orbits: Survey, HAMO, and LAMO

the spacecraft and return the imaging and spectral data, this requirement is easily met. To achieve the best gravity information, a combination of quiescent coherent Doppler tracking and optical landmark tracking are used.

These Level-1 requirements dictate the properties of the three Dawn science orbits. As illustrated in Fig. 5, the orbits are all polar, with a Vesta Survey altitude of 2735 km, a high-altitude mapping orbit (HAMO) altitude of 685 km, and a low-altitude mapping orbit (LAMO) altitude of 200 km. Since the images and spectra require specific lighting conditions, this also sets the beta angle of the orbit, the angle between the orbit normal and the direction to the Sun. The framing camera images are in general optimized with shadows while the VIR spectrometer is optimized with no shadowing. The above requirements have been given for Vesta. The requirements for Ceres are similar but not identical.

The science planning associated with the mission is not trivial despite our mission design that was intended to make it so. A later article in this series describes the science planning and operations in more detail (Polanskey et al. 2011).

5 Operations

5.1 Instrumentation

Dawn carries three instruments: a framing camera; a visible and infrared spectrometer; and a gamma ray and neutron spectrometer. In addition, it undertakes a gravity investigation using the navigation system and a topography investigation using images returned by the framing camera.

The framing camera shown in Fig. 6 is provided and operated by the Max Planck Institute for Solar System Studies in Katlenburg-Lindau, Germany. The camera covers the wavelength range from 400 to 1000 nm and has a filter wheel with seven color bands and

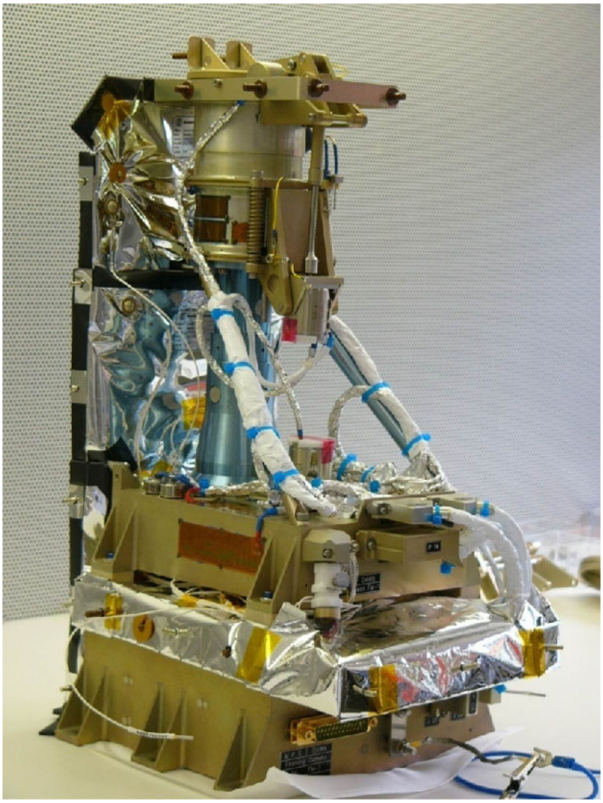

Fig. 6 The Framing Camera provided by the Max Planck Institute for Solar System Research. (Credit: MPS Personnel)

one clear filter. The second (redundant) unit is not used until required by some inadequacy of the first unit. In addition to the camera team members at Max Planck Institute for Solar System Research (MPS) there are team members in the Freie-Universitat in Berlin and the DLR's Planetary Institute in Berlin. These members aid in the analysis of the processed images. More details on the construction and operation of the framing camera can be found in the later article by Sierks et al. (2011).

The visible and IR spectrometer (VIR) shown in Fig. 7 is provided by the Italian Space Agency (ASI) and the Italian National Institute for Astrophysics (INAF) in Rome. The spectrometer has a visible channel from 250 nm to 1000 nm and an IR channel from 1000 nm to 5000 nm. This instrument builds up images in a pushbroom mode and can acquire image cubes using an internal scan mirror. More details of this instrument can be found in the later article by DeSanctis et al. (2011).

The gamma ray and neutron detector (GRaND) shown in Fig. 8 measures elemental abundances of material in the top meter of the soil by their gamma ray emissions, and hydrogen by detecting thermal and epithermal neutrons. This instrument is described in detail in a later article by Prettyman et al. (2011).

5.2 Orbital Phases

As discussed above, the mission has four main science data acquisition phases: Survey, HAMO-1, LAMO, and HAMO-2; data are also acquired as Dawn approaches each body. Orbit transfers, accomplished using the ion propulsion system, are lengthy. In fact, Dawn

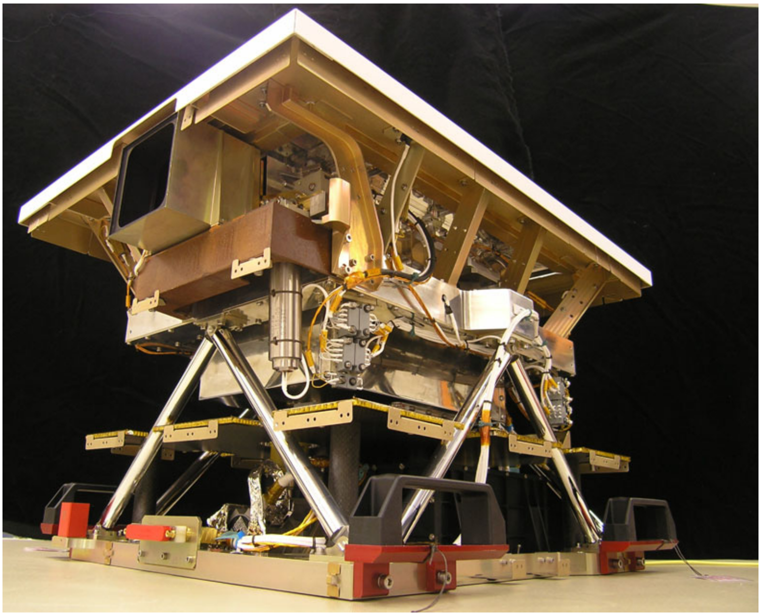

Fig. 7 The visible and infrared (VIR) spectrometer provided by the Italian Space Agency (ASI) and the Italian National Institute for Astrophysics (INAF). (Credit: Selex Galiileo, INAF, and ASI)

Fig. 8 The Gamma Ray and Neutron Detector (GRaND) built by the Los Alamos National Laboratory, and operated by Planetary Science Institute. (Credit: S. Storms, LANL)

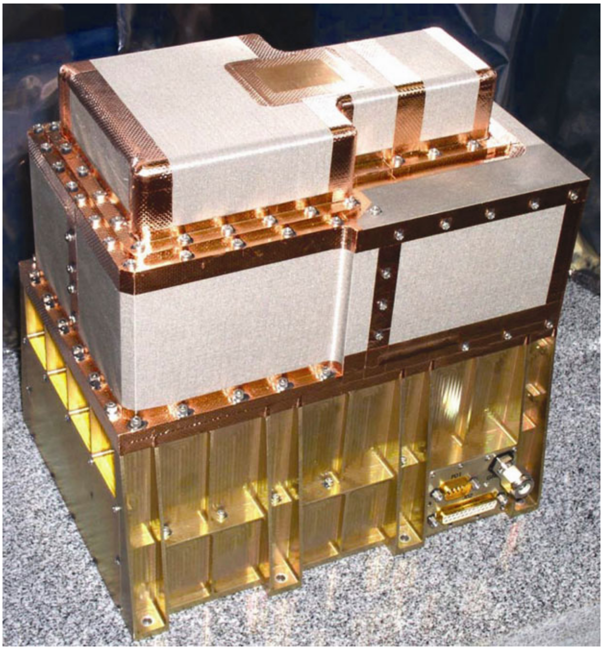

Table 1 Vesta orbit phase durations

Sub-phase	Duration
Approach to survey	96.2 d
Survey duration	17.0 d
S→H transfer	28.3 d
HAMO duration	30.7 d
H→L transfer	39.2 d
LAMO duration	70.0 d
Extra stay-time	18.8 d
Operational margin	40.0 d
L→H2 transfer	42.8 d
HAMO-2	20.5 d
Departure	38.2 d
Total:	441.8 d

spends roughly equal amounts of time observing in the science sub-phases and thrusting between orbits. Moreover, schedule margins must be included to ensure that critical data are obtained despite possible operational surprises. Table 1 lists the current operational sub-phases planned for Vesta, and their expected durations. At the end of each sub-phase as assessment is made of the success of the sub-phase in attaining the desired data coverage, taking into account the redundancy built into the science operations. In addition to these audits of the transition criteria, the operations plan has explicit schedule margin for gathering data.

5.3 Science Team Structure

The science team consists of the co-investigators included in the original mission selection and changes that have been approved since. It also includes 21 additional scientists who were selected in 2010 in response to a NASA Announcement of Opportunity to propose as Dawn Participating Scientists for the Vesta encounter. These scientists serve for three years: one year before encounter one, during mission operations at Vesta, and then for one year after Vesta departure. There are also associates of team members. These associates do not possess data rights but instead obtain data through the members who are expected to direct and oversee these associates.

A similar NASA Announcement of Opportunity to propose as Dawn participating Scientists will be issued before Ceres arrival. A set of Rules of the Road govern the operations of the team. The work of the team is guided by and divided into four working groups and thirteen subgroups that oversee the scientific activities. This working group structure is shown in Fig. 9. The overall science team participates in the work of the individual groups through frequent reporting back to the committee of the whole. This allows the efficiency of parallel processing while keeping the expertise of the whole team available to each group to solve problems. It is expected that when high-resolution images become available, interdisciplinary, ad-hoc task groups will be established to address specific issues.

5.4 Nomenclature

It has become traditional for the science team undertaking the initial exploration of a planetary body with a solid surface to suggest names for prominent features subject to the approval

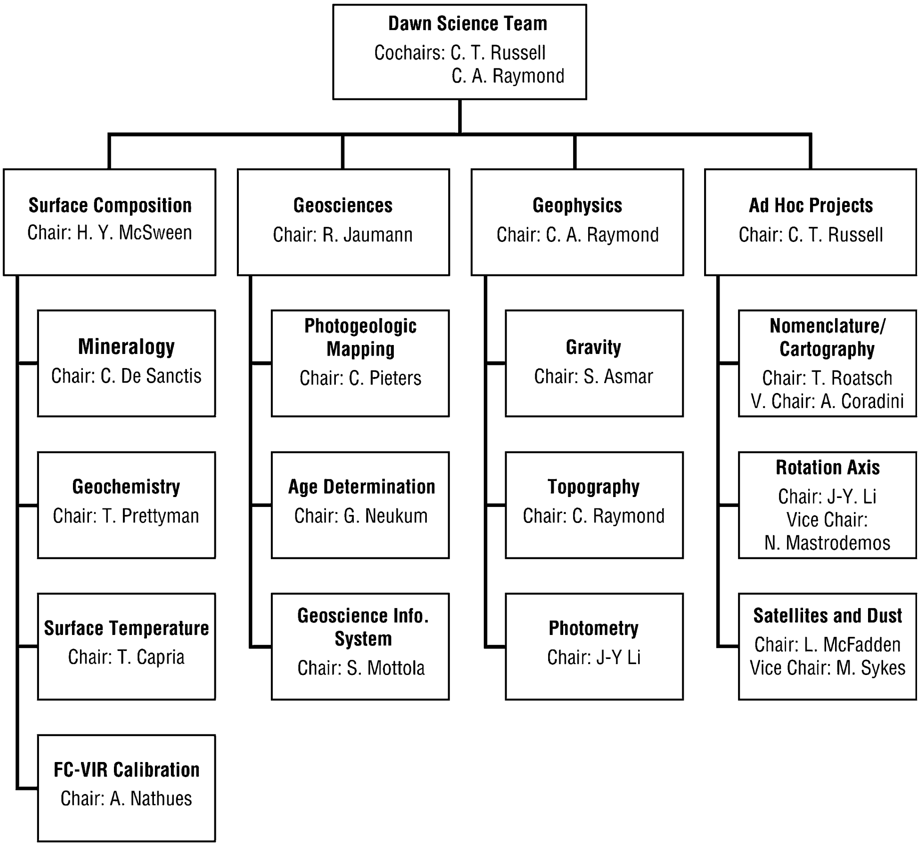

Fig. 9 Working groups of the Dawn Science Team

of the International Astronomical Union (IAU). In the case of Vesta, it seems appropriate, in fact compelling, to use the names of the Vestals, the Roman priestesses who devoted their lives (often giving their lives) in service to Vesta, the Goddess of the Hearth. The careers of many of these individuals were chronicled by the historians of the time, and documentation (as required by the IAU) exists for 56 Vestals whose names do not already appear on other bodies. See for example Wildfang (2006) and Worsfold (1934). Table 2 lists the names of 30 of the earliest chronicled Vestals. Since we expect that the surface of Vesta will be dominated by cratering, it is possible that many tens of names will be required. To maintain the Vestal theme, we have also constructed lists of early Roman festivals and towns where the Vestals were active to be used for other features of interest on the surface of Vesta.

It is also traditional to honor distinguished explorers and scientists engaged in the field. Most of the early pioneers of asteroidal discovery are already honored in this way on other bodies but there are enough later individuals to consider using their names for features on Ceres and we have begun to compile their names and the needed documentation. Further, it is possible to combine first and last names in naming asteroids (e.g. 21459 Chrisrussell) to form the preferred single word. Thus we may be able to use Ceres to honor the original pioneers as well.

Table 2 Thirty of the earliest Vestals

Rheasilvia	Varronilla	Occia	Tuccia	Perpennia	Praetextata
Pinaria	Claudia	Aelia	Sextilia	Fabia	Vibidia
Oppia	Licinia	Lepida	Caparronia	Arruntia	Torquata
Postumia	Marcia	Domitia	Iuinia	Fonteia	Rubria
Minucia	Claudia	Cornelia	Floronia	Scantia	Laelia

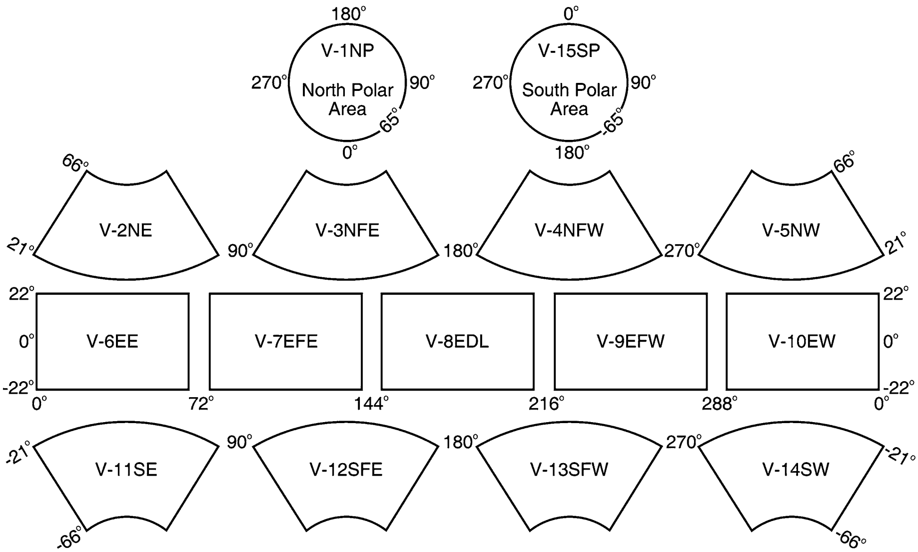

Fig. 10 Planned tiling scheme for maps of Vesta. The labeling quadrangles will use the names given above until the names of the dominant features are known

To do our initial analysis we need a mechanism by which we can refer to specific areas and sites on the surface prior to the approval of names by the IAU. To accomplish this we propose to divide the surface into 15 different tiles or "quadrangles" as shown in Fig. 10. Initially they will be labeled V-1N for the north circular tile, V-2NE for the northeast tile, V-3NFE for the north far-east tile, V-6EE for the equatorial east tile, V-7 EFE for the equatorial far-east tile, V-8EDL for the equatorial dateline tile, etc. Ultimately the quadrangles will be named for the dominant feature in the region. The use of this system of course necessitates the rapid choice of a reference point for 0° longitude. The team's preference is to use east longitude measured from the 0° meridian in the direction of rotation as is standard on the surface of the Earth and is consistent with the use of right-handed coordinates in mathematics and physics.

Lastly we need possessive adjectives for use when describing properties of these two bodies as substitutes for the phrases "of Vesta" and "of Ceres." While the adjective "vestal" means pertaining to Vesta, it has also acquired meanings of particular human behavior. This acquisition has occurred for other bodies such as Mars and Jupiter where martial and jovial are used for activities of humans that are characteristic of the gods Mars and Jupiter, while martian and jovian refer to the properties of the corresponding planets. Furthermore, a precedent has been set with the jovian moon Europa where the adjective "europan" is already in use (Eviatar et al. 1985). Thus, we recommend "vestan" as the possessive adjective for Vesta.

Similarly, Ceres has already produced the derivative "cereal" with a very specific meaning, leaving us the obvious choice of "cerean" which we recommend for use as the possessive adjective for Ceres.

6 Discussion

At this writing it has been almost 19 years since the Discovery workshop that initiated the Discovery PI-led Mission Program, and some very exciting science has been accomplished over a range of planetary objectives. Lunar Prospector has explored the Moon and returned a global magnetic map. Stardust has collected interplanetary and interstellar grains from comet Wild 2. Genesis has measured the composition of the Sun. Deep Impact has excavated a crater in the nucleus of comet Tempel 1. MESSENGER has entered orbit about Mercury. Kepler is discovering exoplanets. Dawn is approaching Vesta and GRAIL has been launched. Further, through extended missions, Stardust and Deep Impact have continued to produce new results. With only one failure in this array of missions, this low-cost planetary program has demonstrated its worth and shown that the low cost does not necessarily entail high risk. In addition, while breaking this new ground, we have learned new lessons, some generic to all low-cost missions, and some important lessons for missions using ion propulsion.

The Dawn project recorded these lessons learned in two papers (Fraschetti et al. 2005; Rayman et al. 2007), ironically both written at the time that the stand-down was about to be imposed in the Fall of 2005. One of the key issues concerns the box in which a mission developer finds himself. There is a lid on funding, on the mass that can be placed on the required trajectory and the time to accomplish it. This applies pressure to three sides of the box. Pressure can be relieved on this box on the other three sides by descoping the payload, reducing science operations or reducing data analysis.

The payload descope option in general is a bad road to travel because the instrument costs on a planetary mission are a small fraction of the overall mission cost and only a small cost savings will accrue for a large hit in science. Further, once made, this decision is irreversible. Thus instruments should not be removed from a mission if at all possible. The saving from the descope is never as great as the value lost to the science.

We found that managing a low-cost mission is just as difficult as managing a flagship mission. Thus centers need to assign trained senior personnel to these positions. Junior personnel can be mentored on the project but they should not lead such a project until they have experience. In addition to management skills, a project needs good communication and well-organized documentation. Risk management is also critical to project success. Identifying risks and retiring them should continue throughout all project phases. Unfunded mandates must be avoided. Establishing guidelines for financial reserves is not by itself a bad idea, but if the establishment of an increased reserve posture is mandated after the mission costs have been approved and the project is underway, then the mandate must be accompanied by the resources needed to carry it out.

The ion propulsion system of the Dawn mission is enabling technology. Within the cost guidelines of the Discovery program we believe it is impossible to build a mission to orbit and map either of Vesta or Ceres let alone both. Accompanying the cost advantage is a technical resource advantage that early in the mission development paradoxically became a disadvantage to the mission and almost sank it. This advantage/disadvantage is technical resource coupling. Generally resources such as mass, power and fuel are uncoupled. Adding more solar array area in a classic mission using chemical propulsion will not reduce the need for fuel or allow more payload mass but it can in a solar-powered, ion-propelled mission like Dawn. This means that margins can be shared across systems, much reducing risk, and allowing an extremely robust mission design as Dawn turned out to have. Dawn arrived at its target months early, adding schedule reserve for the possible occurrence of spacecraft anomalies and adding more observations at Vesta. Where the disadvantage occurred was in the JPL guidelines for mission management that dictated specific reserves in each subsystem, rather in the total spacecraft system. Thus Dawn was required to carry unnecessary technical reserves that it could not afford to carry, making it appear less robust than it really was. This coupling of technical resources has been documented (Rayman et al. 2007) but it is unlikely that the rules governing the management of technical resources will be revised to allow a different policy for reserves on ion-propelled missions. This coupling should be officially recognized by center management if ion-propelled missions are to be properly managed during development. Dawn's robustness in the face of all the changes made to its launch date as that date slipped from June 2005 to September 2007, while preserving its full observation program is a testament to the true depth of its mission margin. This advantage alone is well worth the added effort to include solar electric propulsion on many inner solar system missions that now rely on chemical maneuvering. The experience of Dawn that cost less than one-third of the alternative, a dual chemical launch while enduring a more than two-year slip well demonstrates the power of ion propulsion technology.

7 Concluding Remarks

In the more than three years of cruise operations the Dawn team has been able to check out the operation of the flight system, to practice procedures, and to plan operations. Nevertheless, as first Vesta and later Ceres come ever close to being known entities and not merely distant points of light, the excitement mounts, the adrenaline rises, and the realization dawns that the two decades of preparation for the dual rendezvous mission will soon be replaced by a rush of data, and discoveries about our solar system's formation and evolution.

Acknowledgements The success of the Dawn mission is due to many individuals, not just the scientists and engineers who planned, executed, launched and have operated the spacecraft, but also those involved in the development of ion propulsion; those who sat on selection and review panels; those who helped advance the technical readiness level of the ion propulsion engine, and those who supported Dawn during its darkest days when it lost the support of its immediate sponsors in NASA. We cannot give credit in this article to all those individuals, and in fact, we do not know all their names. But those involved in the Dawn mission are grateful for the tremendous effort that was expended by so many in the implementation of this mission.

Those with whom we worked most closely include personnel from NASA's Lewis Research Center (now Glenn), from JPL, from TRW, Orbital and their subcontractors, from NASA Headquarters, from the Discovery Program Office at NASA Marshall Space Flight Center, from Los Alamos, from the Max Planck Institute, from INAF, from DLR, from ASI and all the organizations supporting the members of the science teams deserve much thanks. We are especially grateful to the Project Managers at JPL and at the various contractors and subcontractors who were so dedicated to making Dawn a success that they put their jobs on the line to ensure it would be. Finally, we thank Robert Mase who has led the project during its operational phase since shortly after launch.

The preparation of this report was supported by the National Aeronautics and Space Administration under contract NNM05AA86C. A portion of the work was carried out at the Jet Propulsion Laboratory.

References

J. Brophy, The Dawn ion propulsion system (2011, this issue)

A. Coradini, D. Turrini, C. Federico, G. Magni, Vesta and Ceres: crossing the history of the solar system. Earth Planet. Astrophys. (2011). doi:10.1007/s11214-011-9792-x

M.C. DeSanctis, A. Coradini, E. Ammannito, G. Filacchione, M.T. Capria, S. Fonte, G. Magni, A. Barbis, A. Bini, M. Dami, I. Ficai-Velotroni, G. Preti, V.I.R. Team, The VIR spectrometer. Space Sci. Rev. (2011). doi:10.107/s11214-010-9668-5
A. Eviatar, A. Bar-nun, M. Podolak, Europan surface phenomena, Icarus, **61**, 185–191 (1985). doi:10.1006/0019-1035(85)90100-9
T.C. Fraschetti, M.D. Rayman, C.T. Russell, C.A. Raymond, Dawn discovery mission: lessons learned, in *Proceedings of 6th IAA International Conference on Low-Cost Planetary Missions*, Kyoto, Japan, 11–13 October 2005
A. Konopliv, S.W. Asmar, B.G. Bills, N. Mastrodemos, R.S. Park, C.A. Raymond, D.E. Smith, M.T. Zuber, The Dawn Gravity Investigation at Vesta and Ceres. Space Sci. Rev. (2011). doi:10.1007/s11214-011-9794-8
J.-Y. Li, P.C. Thomas, B. Carcich, M.J. Mutchler, L.A. McFadden, C.T. Russell, S.S. Weinstein-Weiss, M.D. Rayman, C.A. Raymond, Improved measurement of Asteroid (4) Vesta's rotational axis orientation. Icarus **1**, 528–534 (2010). doi:10.1016/j.icarus.2010.09.019
J.M. Makowski, V. Thomas, K. Nelson, T. Meyer, M. Violet, J. Williams, G.M. Brown, C. Cardoso, B. Pavri, D. Bruno, M. Chiville, D. Termohlen, The Dawn spacecraft. Space Sci. Rev. (2011, this issue)
T.B. McCord, J. Castillo-Rogez, A. Rivkin, Ceres: Its origin, evolution, and structure and Dawn's potential contribution. Space Sci. Rev. (2011). doi:10.1007/s11214-010-9729-9
T.B. McCord, J.B. Adams, T.V. Johnson, Asteroid Vesta: spectral reflectivity and compositional implications. Science **168**, 1445–1447 (1970). doi:10.1126/science.168.3938.1445
L.A. McFadden, J. Wise, J.D. Ristvey, Jr. W. Cobb, The Education and Public Outreach Program for NASA's Dawn Mission. Space Sci. Rev. (2011). doi:10.1007/s11214-011-9840-6
H.Y. McSween, E. Ammannito, F. Capaccioni, M.T. Capria, J.-P. Combe, A. Coradini, M.C. DeSanctis, M. Farina, G. Filacchione, H. McSween, G. Magni, C. Pieters, C.A. Raymond, C.T. Russell, J.M. Sunshine, T. Titus, M.J. Toplis, D.W. Mittlefehldt, A.W. Beck, R.G. Mayne, T.J. McCoy, HED meteorites and their relationship to the geology of Vesta and the Dawn mission. Space Sci. Rev. (2011). doi:10.1007/s11214-010-9637-z
H.Y. McSween, *Meteorites and Their Parent Planets* (Cambridge University Press, Cambridge, 1987), p. 237
D. O'Brien, M.V. Sykes, The origin and evolution of the asteroid belt—implications for Vesta and Ceres. Space Sci. Rev. (2011). doi:10.1007/s21214-011-9808-6
C. Peebles, *Asteroids: A History* (Smithsonian Inst. Press, New York, 2000), p. 280
C. Pieters, L.A. McFadden, T. Prettyman, M.C. DeSanctis, T.B. McCord, T. Hiroi, R. Klima, J.-Y. Li, R. Jaumann, Surface composition of Vesta: issues and integrated approach. Space Sci. Rev. (2011). doi:10.1007/s11214-011-9809-5
C. Polanskey, S.P. Joy, C.A. Raymond, Dawn science planning operations, and archiving. Space Sci. Rev. (2011, this issue)
T.H. Prettyman, W.C. Feldman, H.Y. McSween, Jr., R.D. Dingler, D.C. Enemark, D.E. Patricl, S.A. Storms, J.S. Hendricks, J.P. Morgenthaler, K.M. Pitman, R.C. Reedy, Dawn's gamma ray and neutron detector (2011, this issue)
M.D. Rayman, 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 Astronaut. **60**, 930–938 (2007). doi:10.1016/j.actraastro.2006.11.012
C.A. Raymond, R. Jaumann, A. Nathues, H. Sierks, T. Roatsch, F. Preusker, F. Scholten, R. Gaskell, L. Jorda, H.-U. Keller, M. Zuber, D. Smith, N. Mastrodemos, S. Mottola, The Dawn topography investigation. Space Sci. Rev. (2011, this issue)
A. Rivkin, J.-Y. Li, R.E. Milliken, L.F. Lim, A.J. Lovell, B.E. Schmidt, L.A. McFadden, B.A. Cohen, The surface composition of Ceres. Space Sci. Rev. (2011). doi:10.1007/s11214-010-9677-4
C.T. Russell, F. Capaccioni, A. Coradini, M.C. De Sanctis, W.C. Feldman, R. Jaumann, H.U. Keller, T.B. McCord, L.A. McFadden, S. Mottola, C.M. Pieters, T.H. Prettyman, C.A. Raymond, M.V. Sykes, D.E. Smith, M.T. Zuber, Dawn mission to Vesta and Ceres: symbiosis between terrestrial observations and robotic exploration. Earth Moon Planets **101**, 65–91 (2007). doi:10.1007/s11038-007-9151-9
H. Sierks, H.U. Keller, R. Jaumann, H. Michalik, T. Behnke, F. Bubenhagen, I. Buttner, U. Carsenty, U. Christensen, R. Enge, B. Fiethe, P. Guierrez Marques, H. Hartwig, H. Kruger, W. Kuhne, T. Maue, S. Mottola, A. Nathues, K.-U. Reiche, M.L. Richards, T. Roatsch, S.E. Schroder, I. Szemerey, M. Tschentscher, The Dawn framing camera. Space Sci. Rev. (2011). doi:10.1007/s11214-011-9745-4
P.C. Thomas, R.P. Binzel, M.J. Gaffey, B.H. Zellner, A.D. Storrs, E.N. Wells, Vesta: spin pole, size and shape from HST images. Icarus **128**, 88–94 (1997). doi:10.1006/icar.1997.5736
R.L. Wildfang, *Rome's Vestal Virgins: A Study of Rome's Vestal Priestesses in the Late Republic and Early Empire* (Routledge, New York, 2006)
T.C. Worsfold, *History of the Vestal Virgins of Rome* (Rider & Co., Paternoster House, E.C., London, 1934)
M. Zuber, H. McSween, R.P. Binzel, L.T. Elkins-Tanton, A.S. Konopliv, C.M. Pieters, D.E. Smith, Origin, internal structure, and evolution of 4 Vesta. Space Sci. Rev. (2011). doi:10.1007/s11214-011-9806-8

Space Sci Rev (2011) 163:25–40
DOI 10.1007/s11214-011-9792-x

Vesta and Ceres: Crossing the History of the Solar System

A. Coradini · D. Turrini · C. Federico · G. Magni

Received: 4 March 2011 / Accepted: 27 May 2011 / Published online: 19 July 2011

Abstract The evolution of the Solar System can be schematically divided into three different phases: the Solar Nebula, the Primordial Solar System and the Modern Solar System. These three periods were characterized by very different conditions, both from the point of view of the physical conditions and from that of the processes there were acting through them. Across the Solar Nebula phase, planetesimals and planetary embryos were forming and differentiating due to the decay of short-lived radionuclides. At the same time, giant planets formed their cores and accreted the nebular gas to reach their present masses. After the gas dispersal, the Primordial Solar System began its evolution. In the inner Solar System, planetary embryos formed the terrestrial planets and, in combination with the gravitational perturbations of the giant planets, depleted the residual population of planetesimals. In the outer Solar System, giant planets underwent a violent, chaotic phase of orbital rearrangement which caused the Late Heavy Bombardment. Then the rapid and fierce evolution of the young Solar System left place to the more regular secular evolution of the Modern Solar System. Vesta, through its connection with HED meteorites, and plausibly Ceres too were between the first bodies to form in the history of the Solar System. Here we discuss the timescale of their formation and evolution and how they would have been affected by their passage through the different phases of the history of the Solar System, in order to draw a reference framework to interpret the data that Dawn mission will supply on them.

Keywords Asteroid Vesta · Asteroid Ceres · Asteroids · Meteorites · Solar system formation · Solar system evolution · Impacts

A. Coradini (✉) · D. Turrini
Institute for Physics of Interplanetary Space, INAF, Rome, Italy
e-mail: angioletta.coradini@ifsi-roma.inaf.it

C. Federico
Department of Earth Sciences, University of Perugia, Perugia, Italy

G. Magni
Institute for Space Astrophysics and Cosmic Physics, INAF, Rome, Italy