Dawn: A journey in space and time


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Abstract

By successively orbiting both 4 Vesta and 1 Ceres the Dawn mission directly addresses the long-standing goals of understanding the origin and evolution of the solar system. Ceres and Vesta are two complementary terrestrial protoplanets (one apparently "wet" and the other "dry"), whose accretion was probably terminated by the formation of Jupiter. They provide a bridge in our understanding between the rocky bodies of the inner solar system and the icy bodies of the outer solar system. Ceres appears to be undifferentiated while Vesta has experienced significant heating and likely differentiation. Both formed very early in the history of the solar system and while suffering many impacts have remained intact, thereby retaining a record of events and processes from the time of planet formation. Detailed study of the geophysics and geochemistry of these two bodies provides critical benchmarks for early solar system conditions and processes that shaped its subsequent evolution. Dawn provides the missing context for both primitive and evolved meteorite data, thus playing a central role in understanding terrestrial planet formation and the evolution of the asteroid belt. Dawn is to be launched in May 2006 arriving at Vesta in 2010 and at Ceres in 2014, stopping at each to make 11 months of orbital measurements. The spacecraft uses solar electric propulsion, both in cruise and in orbit, to make most efficient use of its xenon propellant. The spacecraft carries a framing camera, visible and infrared mapping spectrometer, gamma ray/neutron spectrometer, magnetometer, and radio science.

Keywords: Ceres; Main belt asteroids; Protoplanets; Solar system evolution; Vesta

1. Introduction

The Dawn mission investigates two of the first bodies formed in the solar system, 1 Ceres and 4 Vesta are complementary protoplanets that have remained intact since their formation. Ceres apparently incorporated water ice during accretion, slowing its thermal evolution while Vesta, smaller and closer to the Sun, apparently melted and differentiated. Dawn’s goal is to orbit both asteroids to obtain measurements that provide an understanding of the conditions and processes acting at the solar system’s earliest epoch. To do this Dawn investigates their internal structure,
density and homogeneity by measuring their mass, shape, volume and spin state with radiometric tracking, and im-
agery. It records their remnant magnetization, and elemen-
tal and mineral composition to infer their thermal history and evolution. It provides context for meteorites that are be-
lieved to have come from Vesta. Dawn provides images of the surfaces of these two objects to determine their bombard-
ment, tectonic and possibly volcanic history; it uses gravity, spin state and magnetic data place constraints on the size of
any metallic core, and it employs IR, gamma-ray and neu-
tron spectroscopy to search for water-bearing minerals.

Dawn focuses on Ceres and Vesta, not simply because they are the two largest rocky planets that remain unexplored but because they should provide important clues to the pro-
cesses taking place in the earliest phase of solar system for-
mation. In addition, they form a bridge in our understand-
ing, from the rocky bodies of the inner solar system to the
icy bodies of the outer solar system. Radiometric chronol-
gy from the howardite, eucrite, and diogenite (HED) me-
teors, believed to be from Vesta, suggests it differentiated
in perhaps only 3 million years (Yin et al., 2002; Kleine et
al., 2002). Similar evidence indicates that Mars continued
to differentiate for close to 15 million and Earth for 30 mil-
lion years. The early cessation of accretion in the asteroid
belt was presumably due to the formation of Jupiter whose
gravitational forcing countered the accretionary process, and
today is causing the disruption of the bodies that did ac-
crete. Although we do not have similar meteorite evidence
directly linked to Ceres, it too is expected to have formed in
the first approximately 10 million years. In addition the asteroid belt may have been scoured by comets, scattered by
the formation of the remaining gas giants (Gill-Bruton and
Bruni, 1999). Today only some of the largest aster-
oids remain relatively undisturbed. The most massive of
these (Hilton, 1999) are Ceres and Vesta, two most com-
plementary minor planets. The former has a very primitive
surface, water-bearing minerals, and possibly a very weak
atmosphere and polar cap. The latter is a dry, differentiated
body whose exterior has been resurfaced by basaltic lava
flows possibly possessing an early magma ocean like the
Moon. Vesta has experienced significant excavating events,
most notably indicated by the huge crater larger near its southern
pole (Thomas et al., 1997a). Cosmic ray exposure dating of
HEDs indicates that impacts have produced meteoritic ma-
terial at least five times in the last 50 million years (Fugicy
and Michel, 1995). These impacts may have occurred on
vastoids, pieces of Vesta released at early times. The mete-
orites that have reached the Earth have been used to piece
together a most probable scenario for Vesta's thermal evo-
lution (e.g. Ghosh and McSween, 1998).

No meteorites have unambiguously come from Ceres. Pos-
sibly the excavating events or interplanetary dynamics that
and provided the HED meteorites did not occur at Ceres, but
also, the reflectance spectrum of the surface of Ceres does
not give unique signatures of its crustal rocks. Microwave
studies suggest that Ceres is covered with a dry icy, in
contrast to Vesta's basaltic dust layer that reflects its crustal
composition (Webster and Johnston, 1989). To determine if
we have Ceres-derived meteorites and to understand Ceres’
origin, it is necessary to go there and obtain spectra inside
fresh craters.

Meteorites provide an incomplete glimpse of their parent
bodies. To understand the thermal evolution of Vesta and
Ceres a knowledge of their interior structure is required, as
is an understanding of their geological and geophysical
record. It is important to determine the geologic context for
the HED meteorites from Vesta, and search for similar data
for Ceres. We are especially interested in contrasting dry,
differentiated Vesta with its wet counterpart, Ceres, just a
little further from the Sun. It appears that a rather short
additional radial separation allowed Ceres to accrete wet
and stay cool while early heat sources (47 Al) in the accreting
material melted Vesta. Most importantly, because they both
lie near the ecliptic plane in near-circular orbits, it is possible
to rendezvous with and study—both using a single Discovery
mission.

While there have been three previous asteroid flybys and
utterly asteroid rendezvous, none of these missions
have been at all comparable to Dawn. Galileo has flown
by two small asteroids, the S-types, Gaspra and Ida, obtain-
ing visible imagery. In 1997, NEAR flew by the C-class
asteroid, 253 Mathilde, obtaining images and deriving its
mass. In 2000, NEAR coasted around orbit for the 30-km-long,
S-type asteroid 433 Eros with a payload similar to that of
Dawn but there the resemblance stops. Eros is a very ho-
mary asteroid, likely a fragment of a larger body. Vesta
shows signs of a metallic core, as implied from studies of the
HED meteorites, a Mars-like density and lunar-like basaltic
flows, so Mars and lunar data comparisons may be more rel-
levant than those with Eros. Further the action of water on
the surface of Mars will be compared and contrasted with the
possible effects of water on Ceres. In addition Voyag.
Galileo, and Cassini provide contrasting data on the struc-
ture of water-rich small bodies in the outer solar system.

While our first closeup data from asteroids was obtained
only slightly over a decade ago, remote sensing data have
been obtained for over 200 years. In the late 18th century
it was recognized that the planets were spaced in a regular
manner according to a formula now called the Titius-Bode
law. Baron von Zach, a German astronomer, believed that
this law predicted a planet between Mars and Jupiter and
initiated the first international science campaign to discover
its location. However, an Italian observer, not part of the
search team, Giuseppe Piazzi, found Ceres at the expected
distance from the Sun on January 1, 1801. It was with some
surprise that a second object Pallas, was discovered during
the course of monitoring Ceres. Pallas’ discovery was fol-
lowed by 3 Juno. Later, on March 29, 1807 a member of
von Zach’s team, the German astronomer, H. Olbers, dis-
covered 4 Vesta. Owing to their small size and large distance
even today we have little information on these two bod-
ies. The Hubble Space Telescope enables us to resolve only
the very largest scale features on their surfaces as shown in Fig. 1, for Vesta. To determine the detailed elemental and mineral composition, the tectonic and thermal evolution, the internal structure, and the possible presence of magnetic fields and a metallic core we must travel to these bodies.

While the scientific community has long recommended missions to Vesta and/or Ceres, the Deep Space 1 mission's demonstration of the solar-electric ion thruster has only now enabled a mission to visit these bodies successfully, enabling each, and lifting within the Discovery cost envelope. Our science strategy and instruments are optimized for this mission as we build on previous ground-based and HST-based studies of both objects and studies of their parentage analogs.

2. Current understanding
A Vesta and Ceres are among the most interesting asteroids. Both orbit the Sun and are large enough to have experienced many of the processes normally associated with planetary evolution. They could rightly be considered small planets, but because of their locations within the asteroid belt, they have not been classified as asteroids. Unlike most other objects in the main belt, which are banded relics of larger bodies, Vesta and Ceres have evolutionary survivals intact through 4.5 billion years of collisional history that must have seen the destruction of most of their neighbors. These protoplanets carry retrievable records of physical and chemical conditions and nebular and geologic processes during the early planet-forming epoch.

Phototriangulation from Vesta and Ceres formed by the accretion of smaller objects over short time scales. Accretion in the main belt apparently was terminated before the formation of planetary objects larger than Ceres and Vesta, presumably due to Jupiter, whose gravitational focusing caused the accretionary process. As we discuss in more detail below, Ceres has a much lower density than does Vesta (about 2.023 g cm⁻³ versus 4.059 g cm⁻³, respectively) and Ceres is inferred to be volatile rich, while Vesta is dry. Yet these very different objects were apparently formed relatively close together in the solar system, this is one of Davin's main science objectives to determine how and why.

Before describing the mission we present below a brief summary of what we understand about each object beginning with the object we visit first, Vesta. For those desiring even more details on our current understanding, Kelly (2003) has provided a recent comprehensive review of what is presently known about Vesta. McCord and Seulin (2003) have provided a recent comprehensive review of what is presently known about Ceres and its possible thermal evolution tracks. Several other recent publications also give useful summaries of the general knowledge of Ceres and discuss and improve on the knowledge of its principal characteristics (Parker et al., 2002; Britt et al., 2002).

3.1. Vesta
Vesta has a triaxial ellipsoidal shape with radii of 270, 280, and 259 ± 5 km, based on HST imagery (Thomas et al., 1997b). Its main radius is thus 258 ± 12 km, equivalent to a volume of 2.19 x 10¹⁰ m³, versus 4.3 x 10¹⁰ m³ for an assumed density of 2.03 g cm⁻³. Vesta's mean density has been estimated at 1.39 ± 0.12 g cm⁻³ for 30 solar masses (Michalski and Mainzer, 1990); 1.3 ± 0.3 g cm⁻³ for 50 solar masses (Stern, 1990); and 1.36 ± 0.05 x 10⁻¹⁰ solar masses (Michalski, 2000). The density calculated from these values range from 1.39 ± 0.12 g cm⁻³.

Vesta is a dark, differentiated body whose surface has been covered by pyrolytic-heating which has composition like HED meteorites (McCord et al., 1976). Alumina-based materials reveal anomalous variation, as the observed cations. As seen in both Earth-based (Galileo, 1997; Chapman and Veverka, 1988) and HST (Bibring et al., 1997) spectra, the surface of Vesta contains abundant pyroxenes—Mg-rich and Ca-poor pyroxenes as the eastern hemispheres, and Fe- and Co-rich pyroxenes in the western hemisphere. These variations, inferred to reflect impact-evacuated phyloric rocks in the past, have not been petrologically homogenized by regolith formation or spectrally observed by space weathering. The lack of space weathering has been attributed by Hui et al. (1984) to a scarcity of olivine, which may be the principal mineral altered by this process (Yamada et al., 1989). However, the surface of the moon is weathered and it lacks olivine also. Whether the crust formed by sericite metamorphism or solidification of a magma ocean is unclear. Vesta has experienced significant impact events, one of which excavated a large (640 km diameter) crater near its south pole (Thornton et al., 1992). Spectral variations within this large crater (Thomas et al., 1997b) demonstrate compositional stratigraphy, probably reflecting a mantle and/or lower crust enriched in olivine relative to surficial flows.
The largest (100 meteorites) class of achondrites, the HED association, is commonly believed to have been de-
erved from Vesta (Consolmagno and Drake, 1977). The spectral characteristics of Vesta conform to those of HEDs, an almost unique match (only one other basaltic asteroid, 1459 Magnya, has been identified in the main belt (Lazzaro et al., 2000), and it is not located in a position that should be easily sampled). With the discovery of small, impact-erected "Vestoids" spanning the gap between Vesta's orbit (Bisot and Xu, 1995) and the \[ \text{mean motion and } \text{ecc. secular reso-
nances with Jupiter which serve as escape hatches (Wisdom, 1985,}\]
the hypothesis that Vesta is the HED parent body has become widely accepted. Vestoids exhibit spectra similar to those of eucrites and howardites (Burbine et al., 2001), al-
though subtle spectral differences exist (Vilas et al., 2000). Those might have been erected during formation of the south pole crater, which excavated \( \sim 1 \text{ km}. \) Vesta. However, cosmo-ray exposure ages of HEDs form clusters, suggest-
ing they were produced possibly from vestoids, during sev-
did impact events (Ragaller and Michel, 1995; Welten et al.,
1997).

The HED achondrites crystallized under dry, reducing conditions very early in solar system history. Members of this group define a unique oxygen isotope mass frac-
tionation line displaced below the terrestrial line (Clayton and Mayeda, 1966) and exhibit distinctive pyroxene (iron/manganese) and plagioclase (potassium/calcium) compositions (Pupke, 1998). Cumulate and noncumulate eucrites are iron-rich gabbros and basalts composed mostly of pigeonite and calcic plagioclase. Diogenites are cumula-
late orthopyroxenites, sometimes with minor olivine, and howardites are regolite breccias composed of fragments of eucrites and diogenites. Attempts to relate eucrites and di-
genites require complex igneous models involving melting scenarios that generated diverse liquids which produced a variety of cumulate rocks (Stolper, 1977; Longhi and Pan, 1988; Grove and Bartels, 1992) or fractional crystallization of an extensive magma ocean (Richter and Drake, 1997; Ruicka et al., 1997; Warren, 1977). Assuming serial mag-
magmatism, Wilson and Keil (1996) modeled the sizes and flow rates of conduits that carried magma from source regions to Vesta's surface.

The widths of augite exsolution lamellae in one cumulate eucrite indicate slow cooling, equivalent to a burial depth of \( \sim 8 \text{ km} \) (Miyamoto and Takeda, 1994). This measurement may be taken as a minimum thickness of Vesta's crust, in agreement with the largest \( \sim 10 \text{ km} \) eucrite Vestoid (Bisot and Xu, 1995). Many eucrites have suffered brec-
ciation, recrystallization, or impact melting. Although much thermal modification is due to impact processes, Yamaguchi et al. (1996, 1997) suggested that subjacent parts of the crust of Vesta were metamorphosed when they were buried by successive lava and cooled slowly from peak temperatures.

Radiometric ages indicate that HEDs crystallized at \( \sim 4.56 \text{ Ga} \) (Nyquist et al., 1997; Tera et al., 1997; Lugmair
and Shakrovsky, 1998, and references therein) and sup-
port an early and limited duration of igneous activity for Vesta. The heat source for melting was probably rapid de-
cay of short-lived \( ^{26}\text{Al}, \) since evidence for this now-extinct isotope has been found in eucrites (Krivanov et al., 1999). Rapid melting is also supported by the former presence in eucrites of \( 26\text{Al}, \) another short-lived radionuclide (Carlson and Lugmair, 2000).

Metal segregation and likely core formation on Vesta is indicated by depletion of siderophile elements (Ni, Co, W, P) relative to non-siderophile elements in HEDs (Hewins and Newsom, 1988; Righter and Drake, 1996). By model-
ing siderophile element abundances, modest core sizes (per-
centages of the asteroid by mass) of 21.7% (Debues et al.,
1997), 0–25% (Ruicka et al., 1997), and 5–25% (Righter and Drake, 1997) have been estimated. Natural remanent magnetization in HEDs suggest that this core generated an ancient global magnetic field, with a surface field similar to that of the Earth \( \sim 50 \text{ mT} \) (Morden, 1992; Collins and Morden, 1994). Based on HED \( ^{12}\text{C}/^{13}\text{C},^{26}\text{Al}/^{27}\text{Al} \) ratios, core for-
mation is thought to have occurred within 3 Ms of the solar system's formation (Yin et al., 2002; Kleine et al., 2002). This recently derived age is consistent with \( ^{26}\text{Al} \) playing a significant role in the heating of asteroids. A thermal evolu-
tion model for Vesta, based on heating by \( ^{26}\text{Al} \) and con-
strained by HED chronology, geochemistry and phase rela-
tions, was developed by Chosh and McSween (1998). This model suggests that the interior of Vesta remained hot for considerably longer than the ages of crustal HED meteorites.

2.2. J Ceres

With its greater heliocentric distance, lower albedo, more spherical shape and fewer spectral features, we know less about the composition of Ceres than we do about Vesta. Fig. 2 shows our best present images of Ceres. Its location is compared to that of the semi-major axis of Vesta and other asteroids in the main belt in Fig. 3. Three different methods of measuring the size and shape of Ceres have been employed: occultation of a star by Ceres as seen from the Earth, direct imaging by the earth-orbiting Hubble Space Telescope camera, and adaptive optics while imaging from ground-based telescopes. These results are summarized in Table 1.

The mass of Ceres has been determined repeatedly with ever improving results. (Michelak, 2000; Vitek and Rappo-
port, 1998; Standish, personal communication 2001; Hilton, 1999). McFadden and Sohn (2001) have reviewed the various mass and shape determinations and arrived at a model mass of \( 2.4 \times 10^{20} \text{ kg} \) solar masses or \( 9.4 \times 10^{20} \text{ kg} \) with an estimated uncertainty of \( 0.05 \times 10^{20} \text{ kg} \) or about 0.5% relative uncertainty. They calculated a formal model radius value of 475.04 km or a diameter of 950.08 km, with an estimated uncertainty of order 10 km in radius, or about 2%. This gives a density for Ceres of 2100 kg/m³.
From bulk density can be drawn some inferences about the general composition of the asteroid. Ceres is similar in density to the two outer Galilean satellites, Ganymede and Callisto. These two objects are less evolved than the inner Galilean satellites, Europa and certainly Io, and are thought to contain considerably larger amounts of water. Vesta is considerably more dense and is known to be highly thermally evolved. 2 Pallas is also denser, but the reason (thermal evolution or less water at birth) presently is unclear. Bratt et al. (2002) discuss at some length the topic of asteroid densities in general, although concentrating on the smaller objects where porosity can be significant. Thus, Ceres seems water and less evolved, more like Callisto or Ganymede than Vesta or Europa.

The surface composition of Ceres’ surface has been suggested at times to be most similar to but not exactly like carbonaceous chondrites-like material (e.g., Gaffey and McCord, 1978; Larson et al., 1979), from its relatively flat spectrum and suggestions of the presence of water, but with a higher albedo. Mills et al. (1987) reported a $\lambda = 550$ nm geometric albedo of 0.373. Parker et al. (2002) calculated geometric albedos of 0.055 near UV ($\lambda = 363.6$ nm), 0.029 mid-UV ($\lambda = 279.5$ nm), and 0.008 for UV ($\lambda = 162.9$ nm). Tedesco et al. (1989) gives a visual albedo of ~0.10. Radar observations indicate Ceres is smoother than the Moon at decimeter wavelengths but much more irregular at longer wavelengths (Mitchell et al., 1994). From passive microwave observations Webster and Johnson (1989) suggested that Ceres is covered with dry clay-like material at least 3 cm thick.

The reflectance spectrum of the integral disk of Ceres is relatively flat and featureless (e.g., Gaffey and McCord, 1978; Bell et al., 1989; Bell, 1997; Gaffey et al., 1993a, b) but there is a UV absorption band and there is an absorption near 3 nm that has been interpreted as indicative of hydrated minerals (Lebofsky et al., 1981). However, although less likely, this absorption feature has also been attributed to ammonium-bearing clay, possibly ammoniated olivine (King et al., 1992) or ammnoniated monomineralic (Rivkin, 1997), implying temperatures of ~400 K since the surface minerals are frozen. Alcock and Feldman (1992) reported evidence for the absence of OH from the southern limb, consistent with a model in which a winter polar cap is replenished by subsurface percolation that dissipates in summer. Modeling studies using the OH evidence by Tasaka and Salvati (1999) suggested water ice could be preserved within 10-150 m of Ceres’ surface for the age of the solar system.

In the end, (876), unlike Vesta, we cannot link any known meteorites to Ceres (e.g., Barbrie, 1998; Sato et al.,...)
It is possible that Ceres is covered by a veneer of material that does not survive meteoroid-producing impacts or terrestrial atmospheric passage. It is also possible, even likely (McCord and Stofin, 1983), that the thermal evolution of Ceres has produced a multi-banded carbonaceous chondrite surface material, such as containing hydrated salt minerals that produce brighter albedos than for normal carbonaceous chondrite materials. In any case, Ceres is mysterious and perhaps unique object in the solar system, but probably representative of some of the earlier objects that formed the major terrestrial planets.

3. Mission overview

Dawn is presently scheduled to be launched on a Delta 2925H launch vehicle from the Eastern Test Range in late May or early June 2006 on a direct trajectory to Vesta (Fig. 4) arriving at Vesta at the end of July, 2010. Ion propulsion is used during the interplanetary cruise to match trajectories with the asteroid. A low approach ensures these are no sub-critical thruster firings for orbit insertion. Insertion is computed using the ion propulsion system.

Dawn completed a survey of the region around Vesta for sunlight, dust and debris and then moved under S/C thrust to its polar elliptical mapping orbit at 700 km altitude where it obtains measurements with the camera and the mapping spectrometer in a multi pointing orientation. During science operations and data transmission the thrusters are off, Momentum wheels maintain altitude and hydrazine burns execute any emergency maneuvers.

Dawn plans to operate at Vesta for 11 months (31 science operations, 4 under thrashing), acquiring imagery with 2 micrometers over both poles and precise elemental composition measurements. In Fig. 5 the left panel shows the latitude of the sub-Solar point over the course of the stay at Vesta. Varying sun angles provide illuminations of first the northern and then the southern hemispheres. Interest is very high in the southern polar regions where the large crater visible in Figs. 1 and 4 has excavated deep into the differentiated interior. The bottom panel shows Vesta’s heliocentric distance during this period. This period coincides with perihelion and the highest possible ion thrashing levels. Later departures from Vesta will result in lower possible thrashing levels.

Fig. 4. Planetary summary of the Dawn mission.
mission is scheduled to end in July, 2015. The bottom panel of Fig. 6, shows the heliocentric range of Ceres. Since Ceres is receding with time, power available for thrusting is decreasing and any mission delays risk mission completion as the thrusters become less efficient. A possible solution to this problem is to delay arrival at Ceres until it is well past apohelion. Whether such options have to be considered await further testing and knowledge of the final spacecraft mass, that will not be known until much later in the project.

During the cruise to Vesta and from Vesta to Ceres, the trajectory can be minimally altered to pass arbitrarily close to a number of asteroids, a selection of which are shown in Table 2, listing the flyby distance prior to any orbit adjustment. Owing to the efficiency of SEP, the number of candidate flyby targets is expected to be large with many opportunities for low-velocity encounters. Ground-based observations of these asteroids will be critical to a selection of targets on the basis of science return as opposed to simple dynamical convenience.

Dawn carries four instruments: a framing camera (FC), a visible—IR mapping spectrometer (MS), a gamma ray and neutron spectrometer (GR/NS), and a magnetometer (MAG). It also obtains radio science data to determine the asteroids’ gravity fields. A fifth instrument, a laser altimeter, was dropped during Phase B when its expected costs rose well above the amount budgeted. As illustrated in Fig. 7 the instruments are body-mounted on the nadir-facing panel of the spacecraft with no articulation. The magnetometer does not require pointing control. In each orbital phase, one instrument controls the pointing (Table 3). In the optical mapping orbit, spacecraft pointing is determined by the needs of the framing camera, which views 5300 km² at a resolution of 69 m/pixel. Short exposures are used to avoid image blur. Pointing is nadir, except for targets of opportunity for the camera. Over 30-day period, the entire surface of Vesta (and Ceres) will be mapped twice in each of seven filters under different lighting conditions (Table 4). Solar phase angles as small as 20° are obtained in this orbit at an angle ideal for the mapping spectrometer, scanning the entire surface at a resolution of 170 m/pixel. High solar phase angles, best for the framing camera, are principally obtained in the second optical mapping period near departure. The spacecraft then uses ion propulsion to descend to a polar, 130-km altitude,
Table 1
Orbital parameters at Vesta and Ceres. For each phase, one instrument controls pointing and there is no compensation for spacecraft attitude.

<table>
<thead>
<tr>
<th>Body</th>
<th>Period (h)</th>
<th>SMA (km)</th>
<th>Altitude (km)</th>
<th>GY (km)</th>
<th>Pole (°)</th>
<th>Pointing optimized for</th>
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<td>959</td>
<td>663-123</td>
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<td>44</td>
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<td>404</td>
<td>15-75</td>
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<td>5</td>
<td>Hi-res imaging†</td>
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<tr>
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<td>130-156</td>
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<td>2.7</td>
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<td>49-75</td>
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<td>Hi-res imaging†</td>
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*Framing camera.
†VTC and IR.
‡Current relay and magnetic field included.
§Shared control but generally needs coarse pointing.

Table 4
Images obtained in each phase of the mission.

<table>
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<tr>
<th>Phase</th>
<th>Sheriff's Cricket</th>
<th>Ring Map</th>
<th>Ceres II</th>
<th>V Ceres 1</th>
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<th>C Survey 3</th>
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NA—Not applicable.
*Excluding targets of opportunity.
†In each of 7 colors.
‡In each of 3 colors.

mapping orbit. This orbit is used to determine topography and shape of the asteroids, develop a comprehensive gravity field up to 2nd degree at both Vesta and at Ceres, to measure the magnetic field of the body (MAG), and to determine its elemental composition (GRINS). The magnetometer covers the asteroids with mapping grids on the average of 0.4 km apart at the equator on Vesta and 1.0 km at Ceres, much more than is needed to resolve any magnetic field present. Once the gravity field is known and it is safe to proceed, a lower-altitude high-resolution mapping orbit is entered providing a resolution of 5 m/pixel. GRINS has a 2-steradian field of view and a spatial resolution comparable to its altitude.
above the surface. The GR/NS obtains 5 months of medium and low altitude data at Vesta and slightly more at Ceres, enough to resolve all major elements and to spatially resolve the most abundant elements with a resolution that will depend on that abundance. At the end of the high-resolution mapping at Vesta, Dawn returns to the high altitude mapping orbit and remaps under yet different illuminations and stereo angles. At Ceres the nominal mission ends at low altitudes.

3.1. Data return

The data are stored for later transmission at 64 kbps (2 Gbits in 8.6 h). Dawn has a 64-kbps data rate out to 3.5 AU with 3-dB link margin and can transmit at 128 kbps inside 2.5 AU. In sizing the telemetry needs we have conservatively used the 64-kbps rate. The weekly telemetry requirements (Table 5) indicate that the data buffer should be bumped only 1-5 times per week even at the most active times. In order to provide radiometric tracking for navigation as well as telemetry downlink, we have scheduled from 24 to 56 h of tracking per week in orbit and 4 h/week in cruise. In all mission segments, the downlink time required for navigation exceeds that needed by the science telemetry and by the field studies. Since telemetry is transmitted simultaneously with navigation tracks, Dawn has no contention for bits and has a flexible response to serendipitous discovery.

3.2. Performance floor

In the Discovery program each mission has a cost cap that triggers descopes when unexpected expenditures approach the cost cap. Furthermore, each mission is required to define a performance floor beyond which it may not pass without being terminated. Dawn’s performance floor mission preserves many of the objectives of the baseline mission

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**Table 5**

<table>
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<tr>
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<th>Duration (days)</th>
<th>Total science bits (Gbits)*</th>
<th>Track, h/week</th>
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*Assumed compression ratios: FC 6/1, MS 2.5/1.

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**Table 6**

<table>
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<th>Baseline Mission</th>
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<tr>
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<tr>
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<tr>
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<tr>
<td>Time in orbit (days)</td>
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<td>Dry mass (lbs)</td>
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</tr>
<tr>
<td>Hydrazine (lbs)</td>
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</table>

*Candidate.

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(Computer) with a reduced instrument complement and relies on a flyby to obtain the contrasting asteroid data. The framing camera and mapping spectrometer, the gamma ray/neutron spectrometer and radio science probe, explore a complementary asteroid, possibly 50 Virginia, a 100 km diameter C asteroid (indicating possible hydration processes), similar in spectral class to Ceres. This descoped mission provides mass, shape, volume, mineral (but not elemental) composition, information on surface processes and the role of water on the surface of the flyby asteroid. Dawn then orbits Vesta for 14 months (12 for science data) providing all the measurements of the baseline mission except the magnetometer data. The mission relies on optical tracking of features to obtain the navigation measurements necessary to deduce internal structure and constrain the size of any metallic core. Constraints on thermal evolution rely solely on optical and mineralogical data and not remnant magnetization. A longer (by 3 months) stay improves the topological data and increases the spatial and elemental abundance resolution obtained with the GR/NS. Questions directly related to Ceres are not addressed in the descoped mission unless Ceres is the flyby target. Table 5 compares
4. Measurements

4.1. Imagery

Imagery contributes to many of Dawn’s science objectives, often in combination with other data sets. For example the average density is calculated from the volume derived from images and the mass from radio science. The prime task for the camera is to decipher the geologic history and evolution of the asteroids by characterizing and mapping their surfaces. To do this, they are observed with a high-resolution spectral camera (0.4–1 μm) at varying distances from far-field global maps to local-site characterization under various observing geometries and lighting conditions. The analysis of geomorphologic features (down to the scale of a few meters in the high resolution phase) yields unique evidence on the different geologic processes responsible for the state of the asteroidal surfaces like volcanism, impact processes, water mobilization, and weathering. Clues to the formation age of the entire asteroid and its stratigraphy can be derived from the frequency-size distribution of craters, their morphology and interior structure. The vertical accuracy of the stereo data is similar to the spatial pixel resolution. Multispectral images allow mapping compositional units while multi-angle images provide hints to the textural properties of the asteroidal regolith and the surface roughness. The filter pass bands are optimized for the electronic absorption band in Vesta’s spectrum as shown in Fig. 8. We expect to use only three of these bands at Ceres.

The one clear and seven color filters take into account the spectral reflection characteristics of Vesta which is dominated in the visible/near IR wavelength range by a reflection maximum around 750 nm, a slope towards the ultra violet, and a characteristic absorption at 1000 nm due mostly to FeO in the mafic mineral pyroxene (McCord et al., 1970). Spectral observations from Earth reveal at least three different surface units (Gaffey, 1997) with a composition similar to eucrites, diogenites, and a smaller-sized patch (possibly a crater) similar to dunite, an olivine-rich assemblage. Discrimination between surface lithologies requires a good description of variations within the UV-slope as well as of the 1000 nm-absorption band. The color filters address these tasks. The one at the reflection minimum provides high sensitivity for distinguishing compositional units. The seven filters are centered at 430, 540, 650, 750, 830, 920 and 980 nm. They detect:

1. The edge of the UV absorption.
2. Slope variations.
3. Slope variations and a possible shift of the reflection maximum toward shorter wavelengths (i.e. due to olivine).
4. The maximum reflectance.
5. The bandwidth of the 1000 nm absorption and the presence of olivine (FeO in the M1 position of olivine).
6. The absorption maximum of pyroxene for Vesta located between 910 and 930 nm.
7. Broadening of the 1000 nm absorption due to variations in pyroxene composition and/or the presence of olivine.

The color filter at 430 nm allows for matching the high spatial-resolution color images with the visible and infrared reflectance spectrometer data. The camera is also used for optical navigation. At a distance of 10^3 km, a 0.1-s exposure generates either a target with signal-to-noise ratios larger than 100. The expected positioning accuracy is of the order of 10^-3 radian. More images are needed at Ceres to characterize its greater surface area, but fewer filtered images are needed because of its flatter spectrum.

4.2. Framing Camera

Two identical framing cameras, to be designed and built by MP Aerospace in cooperation with DLR Berlin and IDA Braunschweig will provide images of the surface of the target asteroids and will be used for navigation. The camera (see Fig. 9 for preliminary drawings of camera head and electronics box) uses an f/1.8 rad-hard reflective optics with a focal length of 150 mm. The field of view of 5.5° × 5.5° is imaged onto a frame-transfer CCD with 1024 × 1024 sensitive pixels. With a pixel pitch of 14 μm the camera samples the scene at 9.3 m/pixel from a distance of 100 km. Two identical camera systems including data processing units will be delivered to provide redundancy for optical navigation. One camera head consists of the housing, refractive lens system, filter-wheel, focal plane, and readout electronics with 2.5 kg total mass and 1.8 W power consumption.
The data processing unit controls the camera and handles the data by compressing and buffering them. Data compression of the 11-bit samples is implemented by software based on wavelet algorithms. Compression rates can be selected from lossless (about 2:1) to lossy 10:1 (and more) for which still acceptable images are provided.

The filter wheel has eight positions and is equipped with one clear filter and seven multispectral filters. The clear filter is used to support spacecraft navigation and for high signal-to-noise (S/N) observations, e.g., imaging at exposure times much less than the dwell time to achieve image contrast and sharpening of morphologic features, searching for dust at forward scattering observation geometries as well as high-speed imaging during the close approach of additional asteroids by flybys. Except for the clear filter covering the range 450-950 nm and the 986 nm filter with a full-width-half-maximum (FWHM) of 22 nm, all spectral channels have 30 nm FWHM. The sensitivity is sufficient for the surfaces of Vesta and Ceres to be imaged in each filter with a S/N of 100 for exposure times from 500 ms to 1 s. At lower altitudes when bluer might occur in longer duration color exposures the clear filter and shorter (25 ms) exposures are used. A strong light baffle shades the pupil from reflections from the spacecraft body and allows imaging as close as 20" on sun occultation angle.

The camera operates at a readout rate of 657 k pixels or 1 M k pixels per 0.4 s, HD capacity. The maximum exposure time is 3 ms. To improve the SNR data, pixels are binned under software control on the CDD or subsampled to increase the read rate. The digital processing unit has 12 bits of gracefully degrading instrument related readout equivalent to 5000 unprocessed pictures. Each DPU consumes 2 and 3 W and weighs 2.5 kg. The total resources per camera are 5 kg of mass and circa 12 W consumption. All data that is not recorded on storage or transmitted to the ground are stored on the onboard memory and can be transmitted later.

The camera data are recorded on optical storage media. The camera is capable of capturing images at high frame rates and can be used to capture details of the surface at resolutions up to 3200x2400 pixels. The camera is equipped with a high-speed data transmission system that can transmit images at rates up to 1000 frames per second.

The camera is designed to operate in a wide range of environments, including harsh conditions such as high temperatures and extreme vibrations. The camera is housed in a ruggedized housing that protects it from damage and ensures reliable operation in these conditions.

4.3. Mission

A primary objective of Dawn is to determine the mineral composition of the surface and to place it in geologic context. The nature of the solid compounds of the asteroids (silicates, oxides, salts, organics and ice) can be identified by visual and infrared spectroscopy using high spatial resolution imaging to map the heterogeneity of asteroid
surfaces and high spectral resolution spectroscopy to determine the composition unambiguously. The first use of spectroscopy to determine the composition of an asteroid was for Vesta (McCord et al., 1970). A variety of diagnostic absorption bands for key minerals occur in the visible and near-infrared and can be identified with spectroscopic measurements (e.g. Burns, 1993; Gaffey et al., 1993a, b). The olivine exhibits an asymmetric feature, a combination of three overlapping absorptions, near 1 μm. The orthopyroxene spectrum shows two symmetric features near 1 and 2 μm. Feldspar has a weak band near 1.25 μm from its trace content of Fe²⁺. Absorption band position is also diagnostic of the specific mineral chemistry. The substitution of a large cation for a smaller one expands and distorts the entire crystal structure, giving origin to diagnostic absorption bands.

Well detectable in the visible are also charge transfer absorptions involving electronic transitions between different shells or between adjacent cations. These generally occur at shorter wavelengths and are significantly stronger than the crystal field absorptions. The overlapping of several series of charge transfer features gives rise to the strong blue-ultraviolet absorption edges in many silicates (in the region < 0.7 μm).

Water vibrational modes around 2.84 and 3.05 μm are combined to give a large and strong feature around 3 μm in asteroid spectra. The presence of this feature at 3 μm in asteroidal spectra is indicative of a water-bearing phase such as hydrated silicates. In particular, the presence of the 1.4 and 19 μm bands is indicative of OH groups, while the existence of a 1.4 μm feature alone suggests OH groups in minerals. The carbonate minerals could be concentrated wherever aqueous alteration has taken place on asteroids. Weak absorptions bands are identified in reflectance spectra of some dark asteroids, suggesting that these features are due to iron oxides in phyllosilicates formed on asteroidal surface by aqueous alteration processes (Vilas and Gaffey, 1989) (Fig. 9).

Shown in Fig. 10 are reflectance spectra of minerals typical of asteroids and meteorites (Pieters and McFadden, 1994). Common rock-forming minerals in both meteorites and asteroids exhibit distinctly different and diagnostic absorption bands. The wavelength, shape and strength of various absorption features are determined by the minerals present. Each parameter must be measured accurately to make identifications and derive relative abundances. The mapping spectrometer has the resolution and accuracy necessary for this inversion process. Methods for compositional information extraction range from straightforward linear or nonlinear mixing models of multiple components to a more sophisticated quantitative analysis of individual absorption features (see summary in Pieters et al., 1996). Maps of the current surface mineralogy together with studies of cratering that excavates and redistributes materials lead to an understanding of the evolution of the surface and determine the processes affecting it.

Medium resolution spectral images in the visible and infrared regions reveal information on the mineralogical composition of the asteroid surface. Simultaneous spectral resolution and spatial resolution are needed to investigate surface geology, tracking possible the identification of mineralogical provinces, and producing compositional maps. Such maps will provide information on the relationship between global and local spectral characteristics. The Dawn Mapping Spectrometer covers the spectral range from the near UV (0.25 μm) through the near IR (5 μm) and has moderate to high spectral resolution and imaging capabilities. These characteristics make it an appropriate instrument for determining the asteroid’s global surface composition. Fig. 11 shows Vesta’s reflective spectrum with deep absorption bands that are diagnostic of the mafic silicates present on its surface. Laboratory calibrations of controlled mixtures are expected to allow us to determine the chemistry of the pyroxene and olivine minerals at Vesta, using observations with Dawn’s spectral resolution of Δλ/λ = 0.01–0.002 in the 1–5 μm region. Fig. 12 shows the spectrum of Ceres (Rivkin, 1997). It is relatively flat shortward of 2.5 μm, with strong features longward of 2.5 μm, attributed by some to amorphous phyllosilicate. An Fe charge-transfer feature at 0.7 μm (not shown) also arises from phyllosilicates (Vilas and Gaffey, 1989) which originated from aqueous alteration processes Vilas, 1994). This feature is weak on Ceres (Vilas and Gaffey, 1989), indicating iron-poor minerals or heating.
above 400°C (Hiroi et al., 1993). However, this is constrained by the presence of ammoniated phylllosilicate, which is destroyed at temperatures above 400°C. Clay formation may have arisen from the mobilization of water from internal heating or by cratering (as one of the oldest surfaces in the asteroid belt, the surface of Ceres is expected to be heavily cratered). It is not known whether some or all of Ceres’ surface will answer this question. Spatially resolved spectra of Ceres over the 0.7 μm feature, combined with maps of elemental abundance determined by GRNS, including Fe, will give us the opportunity to distinguish between surface materials that have undergone aqueous processing, and unaltered source material that may be exposed at the surface. We may find that the spatial resolution of the GRNS is not adequate to fully resolve exposed regions; however, depending on the contrast in composition between the processed and unaltered materials, it still may be possible to separate out their respective contributions. In addition spatially resolved spectra of Ceres out to 5 μm and comparison with hydrogen data from GRNS will allow us to identify a broad range of hydrated minerals and their distribution, providing further insight into the role of water in the thermal and geological evolution of Ceres and the conditions in the early solar system under which these processes occurred. Such spectra for both Vesta and Ceres, within craters and fissures, will reveal the compositional details of any underlying stratigraphy (and perhaps reveal any meteorites in our collections from Ceres).

In short, mineral identification using the location and depth of absorption features in the reflectance spectrum allows us to test existing hypotheses. We also determine the physical microstructure and nature of the surface particles. At Vesta we will test the link between Vesta and the HED meteorites. We will obtain the first in-depth view of a planetary interior through the spectral imaging of Vesta’s wide and deep impact basin. We reveal the nature of Vesta’s ancient magma ocean or volcanic emplacement history. We determine the mineralogy of a protoplanet that has remained at its formation location. Further we establish the abundances and mineralogy sufficiently to establish the source of meteorites recovered on Earth. At Ceres we investigate its primitive surface mineralogy. We identify water-bearing minerals and dry clay-like materials. We identify water-bearing minerals and clay-like materials, and map surface ices and frost-covered regions. Finally, we expect to be able to detect any weak atmosphere.

4.4. Visible and infrared mapping spectrometer

The Dawn mapping spectrometer (MS) is a modification of the VIRTS mapping spectrometer (Coradini et al., 1998; Reininger et al., 1996) on board the ESA Rosetta mission. It will be operated for 2 years and spend 9 years in space. It derives much design heritage from the Cassini VIMS spectrometer with an operational lifetime of > 4 years and a mission life > 10 years. The design fully accomplishes Dawn’s scientific and measurement objectives. The design uses a dual arm optical and focal design with mapping capability to 5 μm. The mapping spectrometer is an imaging spectrometer that combines two data channels in one
compact instrument. The visible channel covers 0.25–1.0 μm and the infrared channel covers 0.95–5.05 μm. The use of a single optical chain and the overlap in wavelength between the visible and infrared channels facilitates intercalibration. It utilizes a silicon charge coupled device (CCD) to image from 0.25 to 1 μm and a mercury cadmium telluride infrared focal plane array (IRFPA) to image from 1 to 5 μm. The spectrometer consists of three modules: optical system (3.9 kg mass); proximity electronics (3.0 kg and 5 W); cryocooler including driving electronics (1.3 kg and 12.6 W). A mechanical and thermal mounting of 5.0 kg mass accommodates the spectrometer subsystems. The optical system, which includes foroptics, dispersive elements, filters, focal plane assemblies as well as the cryocooler and proximity electronics is a complete re-build of the VIRTIS-M. The optical concept is inherited from the visible channel of the Cassini Visible Infrared Mapping Spectrometer (VIMS-V) developed at Office Galileo and launched on Cassini in October 1997.

This concept matches a Shaffer telescope to an Offner grating spectrometer to dispense a fine image across two FPs. The Shaffer telescope is the combination of an inverted Burch off-axis telescope with an Offner relay. By putting an aperture stop near the center of curvature of the primary mirror, coma is virtually eliminated. The result is a telescope system that relies on spherical mirrors, yet remains diffraction limited over a large spectral range and the whole spatial direction. The horizontal field is realized by rotating the telescope primary mirror around an axis parallel to the slit. The Offner spectrometer is matched to the telescope, and does not rely on a collimator and camera objective. This is possible because both telescope and spectrometer are telecentric and the telescope has its exit pupil on the gratings. The optical layout is illustrated in Fig. 13.

The spectrometer does not use beam-splitters. Two different groove densities are ruled on a single grating. The grating profiles are holographically recorded into a photostick and then etched with an ion beam. Using various masks the grating surface can be separated into different zones with different groove densities and different groove depths. The "V" regions, which make up the central 30% of the conjugate pupil area, correspond to the higher groove density needed to generate the higher spectral resolution required in the "visible" channel extending from the ultra-violet to the near infrared. The infrared channel utilizes the outer 70% of the grating, which is ruled with a lower groove density. The larger collecting area in the infrared compensates for the lower solar irradiance in this region. Table 7 lists the optics specifications.

The visible detector array is based on the Thomson-CSF type TH 7896 CCD detector. It uses a buried channel design and poly-silicon NMOS technology to achieve good electro-optical performance. Moreover, it includes a multi pinned phase (MPP) boron implant to operate fully inverted and substantially to decrease the surface dark current, residual images after strong exposure and other effects due to
ionizing radiation. The TH7896M is a full frame image sen-
sover 1024 \times 1024 sensitive elements, two registers and
four outputs. It will be used as a frame transfer device with
a sensitive area and a storage area. The first half is used to
acquire the data and the second half is used to send the data
to the proximity electronics to be converted.

The IR detector used in the spectrometer is based on a
broadband array of IR-sensitive photovoltaic mercury
cadmium telluride coupled to a silicon CMOS multiplexer.
The device is an array of 270 \times 435 HgCdTe photodiodes
manufactured by Raytheon Infrared Center of Excellence
(Santa Barabas USA) with a spacing of 38 \mu m between
diode centers. The spectral wavelength range is 0.95 - 5.0 \mu m
and an operating temperature of 70 K. The detector is pack-
ingaged into a housing which includes an optical window which
provides suitable mechanical, thermal and electrical inter-
faces for its integration on the focal plane. Furthermore,
the window functions as substrate for the order-sorting fil-
ters. These filters are used to stop the superimposition of
higher diffraction orders coming from the grating and also
to reduce the background thermal radiation from the instru-
ment housing. The transmission characteristics of the win-
dow are optimized for each corresponding detector position,
so that for each filter zone only the designated wavelength
range corresponding to the first diffraction order is allowed
to pass. Six segment filters are coated in the window with
the following bandpasses: 0.9 - 1.6, 1.2 - 1.9, 1.9 - 2.5, 2.4 - 3.75, 3.6 - 4.4, 4.3 - 5.0 \mu m.

In order to minimize the thermal background radiation
seen by the IR-FPA, the spectrometer itself needs to be
cooled to less than 135 K by radiating at least one, or pos-
sibly two of its surfaces toward cold space. Such a con-
figuration also provides the operational temperature needed
for the CCD. IR-FPA requires an operating tempera-
ture of 70 K to minimize detector dark current, which is
achieved by using a Stirling active cooler driven by dedi-
cated electronics. The Stirling cooler that best meets MS re-
quirements with off-the-shelf products is the RIECOR K008
tactical cooler. It is an integral cooler in which the re-
generator, where the heat exchanges at warm and at cold
conditions occurs, is directly connected to the compres-
sor. Without the transfer line characterizing the split cooler,
less heat losses occur and more efficiency is reached. On
the other side, due to the internal balancing device and
the reduced heat flow from the compressor to the cold lin-
ger, vibration and heat transmitted to the regenerator and
to the cold end (where the FPA is connected) are very
limited. A cover in front of the optics entrance aperture pro-
tects against contamination from external sources. Dedi-
cated heaters on the focal plane remove possible condens-
ing contaminants and provide for annealing of the dew-
r nor to reduce radiation damage. The cover-inside is not used and
was as calibration target in combination with two internal
illumination lamps (one for the VIS-FPA and one for the
IR-FPA).

4.5. Elemental composition

Planetary objects with thin atmospheres emit gamma rays
with energies characteristic of the emitting nucleus through
the decay of naturally radioactive elements, principally Th,
U and K. Gamma rays also stem from nuclear reactions in-
duced by neutrons generated by galactic cosmic ray inter-
actions with the nuclear constituents of all matter, which
for Dows includes both the asteroids and the spacecraft.
Underlying the gamma-ray line spectrum is a continuum
coming from the asteroids, the spacecraft, and the galaxy.
The gamma-ray/neutron data are obtained equally well for
all solar lighting conditions and increase modestly with in-
creasing heliocentric distance. With 130 days of observa-
tions at an altitude of 130 km or less above Vesta and Ceres,
where the asteroid Sils the GN/RS field of view (FOV), we
measure the abundances of Fe, Ti, O, Si, Cu, U, Th, K, H,
Al, Mg, Gd and Sm. This result holds both for the asteroids
as a whole and separately within major geologic regions.
This set constitutes all of the major rock-forming elements
as well as several important trace elements. Table 8 shows the expected statistical precision (σ), ex-
pressed as a relative standard deviation, for the determina-
tion of major---and radioactive elemental abundances for
three different dry materials: eucrite, ferroan anorthosite, and
basalt. Note that r is expressed as a percentage of the
listed abundance and is to be multiplied by, not added to,
the percent abundances listed. The measurements are as-
sumed taken over 120 h (5 days) at an orbital altitude of
130 km. The eucrite composition is representative of Vesta.
The expected precision in elemental abundances for the eu-
crite composition indicate that the sensitivity of the GR/NS
is sufficient to determine whether Vesta is the parent of
the HED meteorites. The elements listed here constitute over
99% of the mass of HED meteorites and can all be detected
in the expected stay times at Vesta and at Ceres. We create
composition maps of both asteroids for latitude and longi-
titude boundaries determined from the GRNS measurements
alone, as well as for geographical regions determined from
the cameras. Since the asteroids fill the GRNS FOV, its ef-
effective sensitivity greatly exceeds that obtained from NEAR
at Earth's similar altitudes.
The neutron measurements enhance our ability to detect
hydrogen and, by inference water, more than a factor of
3 in depth and a factor of 100 in concentration over that
derived from gamma-ray analysis alone. A mass fraction
of water greater than 0.02% can be detected at a neutron
measurement sensitivity of 1%. This sensitivity is to be
compared with the mass fraction of 3% H2O contained in
martian basalt. Neutron observations using the Lunar
Prospector Neutron Spectrometer (which had a similar sen-
sitivity to that for Dawn), yielded a hydrogen abundance
of about 50 ppm near the lunar equator, 150 ppm near both
poles, and 1700 ppm within the permanently shaded craters
near the south pole of the Moon (Feldman et al., 2000).
Dawn neutron measurements should therefore determine the
level of hydration of Ceres' crust. These measurements also provide an independent measure of the average atomic mass of soil particles, sufficiently robust to discriminate between basaltic and feldspathic lithologies.

A diagnostic indicator of the degree of volcanic element depletion in planet-forming material in the inner solar system is the K/U ratio, measured by the gamma-ray spectrometer. Fig. 14 shows the K/U ratio plotted vs. K concentration for meteorites and lunar and terrestrial samples (Taylor, 1992). The meteorites clearly fall into specific classes in this display. Rocks from the surfaces of Earth, Venus, and Mars appear to be similar to each other and quite different from the various meteorite types and the lunar surface.

4.6. Gamma ray/neutron spectrometer

The Dawn gamma-ray and neutron spectrometer (GRNS) maps the major (O, Si, Fe, Ti, Mg, Al, and Ca) and trace element (U, Th, K, H, Gd, Sm) composition. It shows in decades of experience at LANL, in measuring neutrons and energetic photons and is an improved version of the highly successful GRNS on Lunar Prospector (LP), and the presently operating Neutron Spectrometer aboard Mars Odyssey (MO). The design of the spectrometer and its expected performance is described in detail by Prettmann et al. (2003). The gamma-ray sensor is segmented into two parts and the neutron sensor into four parts. Onboard classification of the multiple signals from each event then allows directionality determination that can discriminate radiation of asteroid and spacecraft origin. The gamma-ray sensor is a spaced-off version of the LP scintillator, inset with a $4 \times 4$ array of $1 \text{cm}^2$ cadmium zinc telluride (CZT) sensors on the side facing upward from the deck toward the asteroid. The CZT sensors are a new technology demonstration (Prettmann et al., 2002). This sensor is surrounded by four segments of an anticoincidence shield (ACS) made of a borated plastic scintillator (BC454). The upward (asteroid) and downward (spacecraft) facing segments of the ACS are laminated with an $0.1 \text{mm}$ loaded glass scintillator (GS20) to provide a separation between incoming thermal (GS20) and epithermal/fast (BC454) neutrons. The epithermal and fast neutrons are separated electronically as was done for the Lunar Prospector and Mars Odyssey instruments.

The Dawn GRNS data at Vesta and Ceres are of comparable quality to that of the LP neutron spectrometers and have better than a factor of three higher spectral resolution than that of the LP gamma-ray spectrometer. Simulations verify that the present design provides a robust neutron and gamma-ray signal strength at Vesta and Ceres, adequately controls spacecraft backgrounds, yields a robust bismuth germanate (BGO) spectrum that is as good or better than that measured using the LP ORS BGO detector and is effective in suppressing the background from the spacecraft. If the CZT detector fails to achieve optimal resolution e.g., because of radiation damage to the space environment, the Dawn GRNS science objectives are still met. We have shown that annealing of CZT at moderate temperatures (40-60°C) for short periods of time can fully restore resolution following radiation damage. The exposure predicted for the CZT behind the ACS is low enough that we do not anticipate significant degradation in performance due
to radiation damage. However, to ensure performance, our design includes the capability to anneal the CZT array if damage is observed (Pretyman et al., 2003).

The Dawn GRNS consists of a 7.6 cm wide × 7.6 cm long × 6 cm high rectangular slab of BGO that is viewed by a 7.6 cm diameter photomultiplier tube (PMT). A 4 × 4 square array of 16 cm² CZT sensor elements positioned above the upward BGO face (away from the spacecraft deck facing the asteroid) as shown in Fig. 15. The BGO acts as an active shield, minimizing spacecraft contribution to the response of the CZT array. This compound gamma-ray sensor is surrounded on five sides by a rectangular borated plastic ACS that is composed of four separate elements, each viewed by its own 2.5 cm diameter PMT. The thickness of each of the plastic scintillator elements is 2.5 cm. The top and bottom ACS elements are laminated by 2 mm thick lithium-6 glass scintillator sheets, which are viewed by the same PMTs that view the plastic to which they are optically coupled. The top and bottom ACS faces are surrounded on their sides by 1 cm thick sheets of Li-loaded polyethylene to prevent access by thermal neutrons from the spacecraft.

The front-end electronics for the BGO and ACS portions of the GRNS are configured to classify each detected event into one of five categories. These categories are identical to that used on LP and MO. The five categories are: (1) an isolated BGO interaction, (2) a single coincident BGO and ACS interaction, (3) a subset of these coincident interactions where the energy deposited in the BGO and BC454 are defined by window discriminators to fall within narrow ranges centered on 478 keV in the BGO and 93 keV in the BC454, (4) a single ACS interaction, and (5) a time-correlated pair of ACS interactions that occur within 25.6 μs. Addition of the CZT sensors adds four additional categories: (1) an isolated CZT event, (2) a coincident CZT and BGO interaction, (3) a subset of these coincident events where the energy deposited in the BGO is 0.511 ± 0.075 MeV, and (4) a coincident CZT and ACS interaction where the energy deposited in the CZT and BC454 are defined by window discriminators to fall within narrow ranges centered on 478 keV in the CZT and 93 keV in the BC454. Simulated spectra have demonstrated the capabilities of these hybrid CZT/BGO detector operation modes.

All information is packaged in a 3 kb/s data string with an accumulation time of 60 s. A 478 keV gamma ray from Li provides a continuous calibration of gain as proven on LP. Gamma-ray spectra, both accepted and rejected by the ACS are recorded separately and telemetered to Earth. Thermal neutrons from the asteroid are measured using the GS20 of the upward-facing ACS element and those from the spacecraft use the GS20 of the downward-facing element. Separation of the Li-glass from the BC454 will be implemented using time-domain filters that have been developed at Los Alamos.

Epithermal neutrons having energy in the range between about 0.2 eV and 0.5 MeV from the asteroid are measured using the BC454 of the upward ACS element in coincidence with a 478 keV CZT or BGO interaction. Those from the spacecraft use the downward ACS element in coincidence with a 478 keV BGO interaction. Fast neutrons having
emergence between about 0.5 and 8.0 Mcm are measured using the ACS by isolating double interaction events. The pulse height of the first pulse of the pair provides a measure of the energy of the incident fast neutron.

4.7. Topography, geodesy and geomorphology

Planetary topography is a fundamental dataset for studies of the surface and interiors of solar system objects. It is required to interpret gravity data, provides a crucial third dimension to surface feature images and yields quantitative information on local surface properties such as roughness. These maps provide fundamental insight into volcanism, tectonics and cratering, and help constrain studies of the formation and evolution of the crust. Gravity studies map and model the internal density variations within the body using signals arising from the sum of the contributions from the interior density variations and surface topography. High-quality topographic information in the planetary context of mass reference frame is essential to interpret gravity data. The combination of gravity, and surface composition data is key to modeling the entire crustal composition. While the topography data for Vesta shown in Fig. 16 is the first available for any main belt asteroid, it is still far from sufficient to begin to interpret gravity data and the internal density distribution of the asteroid. The latter requires a precise determination of topography to remove its effects from the observed gravity signal. This is obtained by a mapping of surface elevations with the framing camera.

4.8. Intrinsic and induced magnetic fields

It is clear that many of the smaller objects in the solar system can generate or have generated intrinsic magnetic fields. This is true for the Earth’s Moon (Russell et al., 1975). Mercury (Ness et al., 1975), Ganymede (Kivelson et al., 1996). Moreover, a strongly magnetized disc has been detected at Mars (Acuña et al., 1998). The meteorites associated with Vesta, the Irinnoidei, comets and asteroids exhibit natural remanent magnetization that persists in a surface magnetic field equal to greater than that of the Earth (Collinson and Melson, 1994). The rendezvous with Vesta and Ceres by Dawn allows us to survey these objects at altitudes well below core body radius, and determine if they possess natural remanent magnetization and, through geologic correlations, when it was produced. The magnetometer also measures transition magnetic fields and how they are affected by the asteroid, providing constraints on the electrical conductivity of the interior. The response time of the Moon to step transients in the solar wind magnetic field is 88 s (Draz and Parker, 1972), and at Vesta should be in the range 2.8 s, easily resolvable by the 10 Hz bandwidth and 0.1 nT resolution of the magnetometer. Detector of transient magnetization or electrically conducting interior at Ceres would lead to a major reassessment of our present understanding of the body.

4.9. The magnetometer

These scientific objectives and our experience in the exploration of other solar system bodies enables us to develop a set of required specifications for the Dawn magnetometer. In the asteroid belt the ambient magnetic field is about 3 nT. Based on the maximum field strengths observed on the surface of the Moon on Apollo (300 nT) above the poles of Ganymede by Galileo (1000 nT) and above the crust of Mars by Mars Global Surveyor (1000 nT), we expect that the field at Vesta and Ceres at the altitude of Dawn is under 500 nT. We have conservatively chosen a ±1000 nT range for the magnetometer, sampled at 20 Hz. The data are digitized to 16 bits providing ±0.015 nT digitization.
Magnetic cleanliness is of concern on the Dawn mission because the magnetic field of the asteroids could be small over most of the orbit of Dawn. Dual sensors at the end of and 1/4 way down the magnetometer boom provide redundancy and a measure of spacecraft magnetic fields. Since the thrusters contain strong permanent magnets and since significant currents flow from the solar array to the thrusters, we use a 5 m boom extended away from the thrusters to minimize spacecraft fields. We reverse the polarity of the magnets in one of the thrusters and rotate each about their axes of symmetry to achieve the minimum field at the sensors. This procedure with the high-order nature of the thruster field leads to an expected steady field of less than 10 nT at the sensors despite their rather high (5000 nT maximum) field at 1 m. Key components are held at fixed temperatures to eliminate temperature-dependent effects. Current levels on board are monitored and telemetered at a rate sufficient to enable the removal of the effects of varying current levels. In addition the two sensors are sampled simultaneously to provide a null measurement that verifies that the time-varying field (e.g. solar array currents) has been completely removed. Techniques used to remove unknown spacecraft and sensor-drift levels using the properties of the interplanetary magnetic field as developed for Pioneer Venus and Galileo are used to maintain the instrument baseline to better than 0.1 nT. The time-varying field is measured to 5 x 10^-1 nT/Hz at 1 Hz. The success of the magnetometer investigation depends not just on the quality of the magnetometers but also of the entire system, thus the magnetometer team leads a low-cost magnetic cleanliness program that both identifies potential magnetic problems in the design stage and verifies the success of the magnetic cleanliness program after launch.

The V2A magnetometer (e.g. Russell et al., 1995) derives from a long line of missions including GOES (launched in 1966); ISEE 1 and 2 (1977), Pioneer Venus (1978), Galileo (1989), Polar (1996) and ST5 (in fabrication). The main electronics unit and a block diagram are shown in Fig. 17. The electronics unit drives the ring-core sensors shown in Fig. 18 at a frequency of 12 kHz. The amount of second harmonic signal in quadrature with the drive frequency is detected. A feedback error rolls the second harmonic signal by applying sufficient current to keep the ring core in zero fields. This current is a measure of the strength of the external field. The main electronics board contains a power supply, drive, sensor and feedback circuitry for the three sensors together with digital conversion and command and control circuits. The radio electronics and the sensors are completely redundant, a single range and data rate and continuous operation. The only commands to the analog magnetometer are on and off. A third new technology magnetometer with a design based on the sigma-delta modulator adds further redundancy. It is not needed to meet baseline requirements. This design was chosen because of its low-noise level, simplicity, low cost and its high tolerance from recent missions. The electronics unit weighs 2.5 kg.

Fig. 17. Magnetometer main electronics and block diagram (single unit).
metallic core of Vesta ranges up to 50%, corresponding to a fractional mass of up to 20%. If Ceres accreted water ice during formation as it presently appears, we do not expect it to be differentiated. The principal moons are determined directly from the second degree harmonics of the gravity field. The normalized polar moment of inertia (homogeneity constant) constrains the radial density distribution. Presently the densities of Ceres and Vesta are known to 2% and 3%, respectively, from perturbations on other asteroids and their optically determined shapes (Hillion, 1999; Koeplinger et al., 2002). The science objectives is to measure the bulk density to better than 1% and Dawn will achieve relative accuracies near 0.1%

The gravity field is determined in low, medium and high orbit radius. In the initial “low” orbit, only the mass is determined while optical images determine the rotational state. In the optical mapping (medium) orbit, the gravity field is determined to about degree 5. In the low altitude mapping orbit at altitudes below one body radius, the gravity field is determined up to the 12th degree. With a 12th degree gravity field, correlations with surface features on Vesta of 62 km or greater can be investigated. Including the range 90 km impact basins near the south pole (Thomas et al., 1997). This higher resolution gravity field allows for comparative modeling with lunar impact basins (Zuber et al., 1994). This higher resolution gravity field is available since Dawn uses reaction wheels for attitude control, thus eliminating disturbances due to thruster firings, except during orbital changes.

To use the bulk density to model the interior structure, we measure the normalized polar moment of inertia. Fig. 19 shows the normalized polar moment of inertia, C, vs. core size for three densities and a Vesta-sized object (C = 0.4 implies a homogeneous body). A 1% determination of C would significantly constrain core size and composition. The detection of a wobble of the principal axes is necessary to enable C to be determined. For the NEAR mission, the detection of a 0.1'' wobble would have determined C to 1% for 433 Eros...
Table 9: Data products

<table>
<thead>
<tr>
<th>Instr.</th>
<th>Product</th>
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<tbody>
<tr>
<td>GRU/NS</td>
<td>K/Kb/s maps</td>
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<td>O map</td>
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<td>Fe maps</td>
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<td>Mg/Ti map</td>
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<td>H map</td>
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<tr>
<td>MAG</td>
<td>Magnetic map</td>
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<tr>
<td>FC</td>
<td>Global clear atlas</td>
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<td></td>
<td>Global color atlas</td>
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<td>Global mosaic</td>
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<td>Shape model</td>
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<td>MS</td>
<td>Pyroxene map</td>
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<td>Olivine map</td>
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<td>Spinel map</td>
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<td>Geologic map</td>
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<td>Gravity coeff. and currents</td>
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<td>Free air gravity map</td>
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<td>Geoid and uncertainty maps</td>
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<td>Biosphere map</td>
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(Miller et al., 1995). We note that at Eros, no wobble was detected that was greater than 0.01" (Konopliv et al., 2002). As for NEAR, a possible Vesta and Ceres wobble will be measured by precise photogrammetric mapping and radio tracking. Whether wobble is present is determined by the recent impact history of the object.

The navigation effort is a collaboration of the radio science, and imaging teams and involves processing data from both instruments. It is closely coordinated to optimize the science return and minimize duplication of effort. The optical images for landmark observations are required for accurate navigation. Shape observations are needed for mission planning, and gravity field determination is needed for orbit determination.

5. Data analysis and archiving

The Dawn science team is committed to providing fully documented and calibrated data products of long-term use to the community, with minimal latency. During the mission, data flows from the spacecraft to UCLA, where it is validated and distributed automatically to the science teams. The raw (Level 0) data are also sent to the Planetary Data System (PDS); full documentation and software to access the data and display them is included. The science team produces and validates Level 1 calibrated data, and immediately delivers them to the PDS. The Level 2 data products described in Table 9 are released with several months of data acquisition. Existing science analysis software developed on the MGS, LP, Rosetta, NEAR and Galileo programs will be used to obtain the measurements and deductions to achieve the mission objectives. UCLA is responsible for creating an integrated mission database with science, navigation and NAIF/Spice data, accessible by the community over the web. Fully documented images will be released daily over the World Wide Web for media, educators and the public alike.

During the mission, a participating scientist (PS) program will be conducted. The objective of the PS program is to provide postdoctoral and senior scientists with opportunities for research on projects of their own choice that are compatible with the interests and goals of the Dawn mission, thus contributing to the overall science return of the mission. A list of research opportunities, each with an associated advisor/colleague who is a member of the Dawn science team, will be offered for each competition. Proposed investigations that are unsolicited will be supervised by, or performed in collaboration with, the Dawn PI. The selected scientists will work closely with the Dawn Science Team, gaining valuable mission experience and sharing in the excitement of its discoveries. The terms of PS scientists will be for 2 years.

Data analysis by the science team begins in August-2010, upon arrival at Vesta, and ends one year after the receipt of the last Ceres data, nominally July, 2015. A data analysis program will begin at the end of the Vesta encounter and continue until 2 years beyond the Ceres encounter. To address the range of scientific questions addressed by the large volume of diverse data to be acquired by Dawn at Vesta and Ceres we envision a data analysis program more analogous to the Mars data analysis program than the program for analyzing Eros data from the NEAR mission. Most small asteroids like Eros exhibit relatively homogeneous composition and pose questions in the areas of crater mechanics and structural homogeneity (e.g., rubble pile or coherent). Vesta and Ceres similarly pose questions regarding cratering mechanics, yet they present cratering records extending over the age of the solar system (which smaller bodies do not), and heterogeneities of composition and structure over a large range of spatial scales. These protoplanets also pose questions of planetary evolution, such as differentiation, volcanism, water mobilization and transport, core formation and magnetic dynamo physics. Instruments have been chosen and data products have been designed to address these questions.

An extended mission at Ceres is possible, extending the observations there for an additional six months, to capture varying lighting conditions. If significant fuel remains after the Vesta and Ceres encounters, the spacecraft may be tasked to visit additional asteroids in a longer extended mission.

6. Education and outreach

Dawn’s EPO program supports NASA’s strategic plan to “Communicate widely the content, relevance, and excitement of NASA’s mission and discoveries”. Furthermore, the program will involve the education community in our
endeavors to inspire and train the next generation of the nation's scientists and engineers.

Using current national standards and practices in education, the EPO team will produce content modules consisting of learning and exploration tools. These modules each cover different scientific, historical and technological aspects of the mission. The learning tools feature emerging, classroom innovations such as Calibrated Peer Review, Percep-
tual Learning, and others. These tools have been shown to improve student learning and comprehension. The explo-
ation tools provide unique opportunities for students and the general public to participate in the science of the mis-
sion. For example, students will study the motion and dyna-
tical properties of Ceres and Vesta analyzing images from ground-based telescopes. The Telescopes in Education pro-
gram (TIE) will be a partner in this endeavor, using an ex-
luding infrastructure of access to telescopes to study physical parameters of our targets that are important to the success of the mission.

Another exploration tool is provided by our partnership with Clickworkers. Students will study and classify craters from existing images of other planets. The nature and num-
ber of craters on Ceres and Vesta are a critical part of the scientific analysis of images returned by the Framing Camera. If students begin their studies of craters as seventh graders, they will be graduating from high school by the time the Dawn spacecraft reaches Vesta and possibly en-
tering graduate school when we get to Ceres. The surprises gleaned from craters on Vesta and Ceres will be appre-
ciated by those who have studied crater morphology and frequencies on other planets.

A third major exploration tool involves the Southwestern Indian Polytechnic Institute’s Meteorite Identification Lab-
oratory. Students are taught about the different types of ter-
restrial rocks and are encouraged to find samples of them. They are also taught the difference between terrestrial and extraterrestrial material. Although the probability of finding a meteorite is small, this program offers an opportunity for students to make scientific observations (characterize the rocks), and to understand how the instruments of the Dawn mission will search for evidence relating Vesta and Ceres to the meteorites. Making such a connection will expand our understanding of the evolution of protoplanets in the solar system.

Dawn’s propulsion system is an emerging technology. We will partner with technology development efforts at JPL in bringing knowledge of ion propulsion to students and the public across the country. The history of exploration of these asteroids and the biographies of those involved in our current exploration invite students to learn and find common interests between themselves and those making the Dawn mission possible.

Dawn’s EPO program was created from the following considerations:

- Products must reflect current and best education practices.
- Dissemination of materials is practical, efficient and makes good use of technology.
- Activities will leverage existing programs through part-
nerships established by the EPO team.

The team consists of scientists, teachers and experienced educators. A science team member leads the program with responsibility for scientific accuracy and alignment with the mission. Daily operations are managed by an experienced educator and manager. A core planning team makes detailed plans, which are implemented by a team of experienced ed-
ucators from the Mid-Continent Research for Education and Learning laboratory (McREL) that have been reviewed and tested in schools across the country. McREL’s evaluation division will develop and carry out formal assessments of the materials produced by the EPO team.

Our materials and programs target key audiences includ-
ing K-14 students, teachers (both in training and as profes-
sional development), the general public, and underserved and underutilized populations. We reach these audiences through activities of the OSS Solar System Exploration fo-
rum, national meetings of science, math and technology teachers and the world-wide web. Partnerships with muse-
ums and informal science centers offer another important av-

due to an interested public as does the Ambassador’s pro-
gram sponsored by JPL. The print and television media also bring people to our web page where they can find updated information about the mission as well as access to our ed-

tucational products. The EPO program will prepare the gen-

eral public for the excitement of seeing these new planetary worlds and learning how they formed.

7. Concluding remarks

Dawn is clearly an ambitious mission both scientifically and technically. At the same time we believe that through maintaining simplicity and redundancy, by using proven de-
signs and by keeping ample margins, we have produced a very robust mission. Dawn builds upon the New Millen-

nium’s Program’s technological developments, transferring NASA’s solar electric ion propulsion technology to the com-
mercial sectors and putting it to work in solar system explo-
ration. The mission has much potential to garner the public’s attention, beginning just over 200 years from the discovery of Ceres and Vesta, and it can be used as a vehicle to enrich both pure and applied science curricula. Finally, the mission builds on decades of asteroid and meteorite studies, provid-
ing the first detailed assessment of the two largest asteroids in the main belt, and setting the stage for future exploration of the main belt.

Acknowledgements

The Dawn team wishes to thank the following peo-
ple who played early critical roles in assisting with the


