Mem. S.A.It. Vol. 80, 295

Memorie della

VIR, the imaging spectrometer for the asteroid belt exploration

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Abstract. We describe the journey Dawn mission to the asteroid belt. The objective of Dawn is to explore backward in time via its observations of the primitive bodies, Vesta and Ceres. Dawn is the ninth mission in NASA's Discovery Program and is the first interplanetary mission that will orbit two solar system bodies: the massive main belt asteroid Vesta and the dwarf planet Ceres. Dawn is the first science mission to use ion propulsion. The spacecraft carries three scientific instruments: two redundant cameras, a visible and infrared spectrometer, named VIR, and a gamma ray and neutron spectrometer.

Key words. Solar system: general – Minor planets, asteroids: Ceres, Vesta

1. Introduction

The solar system formed from the gas and dust by accreting small bodies that collided to form larger bodies, leading eventually to planetary embryos, protoplanets, and the planets themselves, in a progression that takes tens of millions of years. 1 Ceres, 2 Pallas and 4 Vesta are the three largest minor planets, apparently intact survivors from the earliest period of the formation of the solar system. There are many mysteries about the earliest epoch that we can only unlock by visiting these primitive bodies in the asteroid belt. The asteroid belt is a region of transition from the rocky planets of the inner solar system to the icy, water-rich bodies of the outer solar system. Vesta and Ceres are the main representatives of the compositional gradient of the asteroid belt: each has followed a very different evolutionary path constrained by the diversity of processes that operated during the first few million years of solar system evolution. Dawn will visit Vesta and Ceres, with the aim to discover traces of the early epoch of the solar system evolution (Russel et al. 2007a,b). Dawn is the ninth mission in NASA's Discovery Program and is the first interplanetary mission that will orbit two solar system bodies: the massive main belt asteroids Vesta and Ceres and the first science mission to use ion propulsion. Dawn was launched on 2007, September 27, from Cape Canaveral, Florida. Dawn will fly by Mars on its way to Vesta, and then ignite its ion engines again to go to Ceres. The spacecraft carries three scientific instruments: two redundant cameras, a visible and infrared spectrometer and a gamma ray and neutron spectrometer. It also obtains gravity data through radiometric tracking.

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2. The Dawn targets

2.1. 4 Vesta

Vesta has a spectral reflectance signature of basaltic magma indicating extensive melting and thermal evolution (McCord et al. 1970). The reflectance spectrum of Vesta resembles greatly that of a class of meteorites, the howardites, eucrites and diogenites or HED meteorites. In order to evolve the minerals we see on 4 Vesta, Vesta needed to melt to form a magma ocean around a solid mantle or perhaps to melt completely. Vesta shape, according to observation with Hubble Space Telescope and with adaptive optics on ground-based telescopes, is that of a triaxial ellipsoid with a huge crater over the southern pole (Thomas et al. 1997). Vesta is a dry differentiated body covered with a pyroxene-bearing basalt whose composition was like that of the HED meteorites (e.g. McFadden et al. 1977; Feierberg & Drake 1980a; Feierberg et al. 1980b). The composition of the surface is not uniform (Binzel et al. 1997; Drummond et al. 1998) but has variations that are believed to reflect impact excavations and lava flows in different regions. The spectral similarity of HED meteorites and Vesta surface suggests a common origin. The analysis of HED meteorites indicates that the parent body formed 4.56 Gyr ago (Nyquist et al. 1997; Lugmair & Shukolyukov 1998). This early rapid evolution requires an early heat source, probably ^{26}Al. A thermal model consistent with these constraints suggests that the interior of Vesta remained hot for considerably longer than the ages of the HED meteorites derived from the crust (Ghosh & McSween 1998). The traditional scenario is the following: great impacts excavated the surface of Vesta and produced a swarm of small fragments. Some of them approach the chaotic region associated with the 3:1 resonance from where fragments can be rapidly transferred to Earth crossing orbits. Further collisions ejected fragments into Earth-colliding orbits, becoming the HED meteorites recovered on Earth. This hypothesis was confirmed by the identification of a Vesta dynamical family (Zappalá et al. 1990) and the discovery that these objects have a surface composition similar to Vesta (Binzel et al. 1993; Burbine et al. 2001). The spectroscopic link between the Vestoids, the V-type asteroids in the vicinity of Vesta and in near-Earth orbits, and the HED meteorites seems to be quite consistent, especially if we take into account that basaltic material is very rare in the asteroid belt. However, some problems still remain open. For example, the recent discoveries of basaltic asteroids not dynamically related to Vesta pose new questions on the differentiation process in the early Solar system.

2.2. 1 Ceres

Ceres, a much larger minor planet, does not have a surface with basaltic composition, and we have few information about the physical state and chemical composition of Ceres. In particular we have no meteoritic evidence bearing on Ceres and its thermal evolution. Ceres surface seems to contain spectral features of an aqueous alteration product. Recently Thomas et al. (2005) have shown that Ceres is an oblate spheroid, similar to that of a Maclaurin spheroid. For a body in a relaxed state with the Ceres' density (2100 kg/m^3) and whose period is 5.34 hours, the observed flattening is consistent with a central condensation or core (Thomas et al. 2005): an internal structure with a rocky core and a mantle of water ice can explain the Ceres figure and average density. In a recent model of Ceres' thermal evolution, McCord & Sotin (2005), suggest that, in particular condition, Ceres can retain its primordial water and possibly even a global ocean over the period since accretion. There is additional evidence for water on Ceres. A'Hearn & Feldman (1992) have reported OH above the sunlit pole after perihelion as if a polar cap of water ice were subliming. A change in the reflectance spectrum of Ceres was interpreted in a similar way (Golubeva, & Shestopalov 1995). If these observations are not artifacts, then they indicate that water vapour is escaping through the crust and any dust mantle above it. Images of the surface of Ceres as well as measurements of its shape seem to be consistent with the icy planet scenario. No obvious surface relief is seen on the images, no mountain ranges on the limbs. The surface brightness is fairly uniform varying by about 0.1 magnitude with one very notable exception.

3. The Dawn instruments

Dawn has three scientific instruments: a pair of framing cameras; a visible and infrared mapping spectrometer, and a gamma ray and neutron detector. The camera is provided from the Max-Planck-Institut fur Sonnensystemforschung (MPS) in Lindau, Germany, with assistance from the Institut fur Planetenforschung of the DLR in Berlin. VIR, the mapping spectrometer, is an Italian instrument, provided by the Instituto Nazionale di Astrofisica (INAF) in Rome with support from Agenzia Spaziale Italiana. The gamma ray and neutron spectrometer is from Los Alamos National Laboratory in New Mexico. Dawn also measures the gravitational field with the use of its radiometric tracking system. Images are used for navigation and also for topography in addition to characterising the properties of the surface. In this section we describe the three instruments.

3.1. The Visual Infrared mapping Spectrometer

The Dawn mapping spectrometer (VIR) shown in Fig. 1 is a modification of the VIRTIS mapping spectrometer (Coradini et al. 1998; Reininger et al. 1996) on board the ESA Rosetta mission. It will be operated to map the compositions of Vesta and Ceres for about 2 years and spend 10 years in space.

VIR is an imaging spectrometer that combines two data channels in one compact instrument. The visible channel covers 0.25 to 1.0 micron while the infrared channel uses a mercury cadmium telluride infrared focal plane array (IRFPA) to image from 1 to 5 micron. The use of a single optical chain and the overlap in wavelength between the visible and the infrared channels facilitates inter-calibration. The VIR instantaneous field of view is 25 m/pixel at a distance of 100 km while the full field of view is 64 mrad. The spectrometer consists of three modules: optical system (5.0 kg mass); proximity electronics (3.0 kg and 5 W); and cryocooler including driving electronics (1.3 kg and 12.6 W). A mechanical and thermal mounting structure of 5.0 kg mass accommodates the spectrometer subsystems. The optical system, which includes foreoptics, dispersive elements, filters, focal plane assemblies as well as the cryocooler and proximity electronics is a complete re-build of the mapping channel of Rosetta VIRTIS spectrometer. The optical concept is inherited from the visible channel of the Cassini Visible Infrared Mapping Spectrometer (VIMS-V) developed at Officine Galileo and launched on Cassini in October 1997. This concept matches a Shafer telescope to an Offner grating spectrometer to disperse a line image across two FPAs. The Shafer telescope is the combination of an inverted Burch off-axis telescope with an Offner relay. The spectrometer does not use beam-splitters. Two different groove densities are ruled on a single grating for the Visual and IR channels. The grating profiles are holographically recorded into a photoresist 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 visible detector array is based on the Thomson-CSF type TH 7896 CCD detector. It uses a buried channel design and polysilicon N-MOS technology to achieve good electro-optical performance. The IR detector

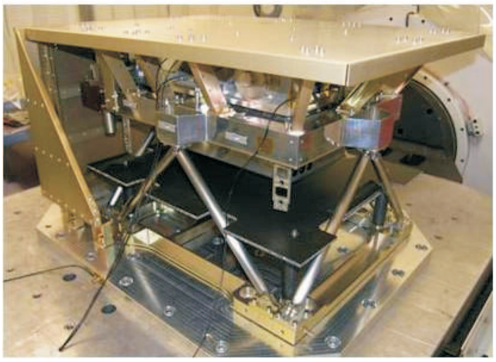

Fig. 1. VIR mapping spectrometer.

used in the spectrometer is based on a bidimensional array of IR-sensitive photovoltaic mercury cadmium telluride coupled to a silicon CMOS multiplexer. The spectral wavelength range is 0.95 to 5.0 micron and an operating temperature of 70 K. The detector is packaged into a housing which includes an optical window which provides suitable mechanical, thermal and electrical interfaces for its integration on the focal plane. In order to minimise the thermal background radiation seen by the IR-FPA, the spectrometer itself needs to be cooled to less than 135 K by radiating its surfaces toward cold space. Such a configuration also provides the operational temperature needed for the CCD. The IR-FPA requires an operating temperature of 70 K to minimise detector dark current, which is achieved by using a Stirling active cooler driven by dedicated electronics. A cover in front of the optics entrance aperture protects against contamination from external sources. Dedicated heaters on the focal plane remove possible condensing contaminants and provide for annealing of the detector to reduce radiation damage. The cover inside is coated and used as calibration target in combination with two internal calibration lamps (one for the VIS-FPA and one for the IR-FPA).

3.2. The Framing Cameras

Two identical framing cameras have been designed and built by MPS in Lindau Germany in cooperation with DLR Berlin and IDA Braunschweig. These will provide images of the surface of Vesta and Ceres and will also be used for navigation. The camera uses an f:1/8 rad-hard refractive optics with a focal length of 150 mm. The field of view of 5.5° x 5.5° is imaged onto a frame-transfer CCD with 1024 1024 sensitive pixels. With a pixel pitch of 14 micron the camera samples the scene at 9.3 m/pixel from a distance of 100 km. Two identical camera systems are designed to provide redundancy critical for optical navigation operations. The filter wheel has eight positions and is equipped with one clear filter and seven multispectral filters. Each camera has 5 kg of mass and about 12 W of consumption. The design of the camera is based on several lines of heritage. The detector and read out electronics are copies of the units implemented in the ROLIS Imager on the Rosetta lander. There are two mechanisms: a filter wheel operated by a Geneva-type drive and an optics cover. The lightweight filter wheel itself is based on a design flown in the Halley Multicolour Camera of the GIOTTO mission. The command software is high level and based on the operating system developed for OSIRIS (Science imagers for the Rosetta mission) and VMC (Venus Monitoring Camera).

3.3. The gamma neutron spectrometer

The Dawn gamma-ray and neutron detector (GRaND) maps the abundance of rock-forming elements (O, Si, Fe, Ti, Mg, Al, and Ca), radioactive elements (K, U, and Th), trace elements (Gd and Sm), elements such as H, C, and N, which are the major constituents of ices. It draws on decades of experience at LANL in measuring neutrons and energetic photons and is an improved version of the highly successful Gamma Ray Spectrometer (GRS) 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 Prettyman 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. There are three basic modes of operation and no moving parts. The telemetry rate is relatively low, 3.1 kbps. The mass of the instrument is approximately 10 kg and the power consumption is 9W. The Dawn GRaND data at Vesta and Ceres will be of comparable quality to that of the LP neutron spectrometers. Overall, GRaND is a relatively simple instrument that delivers significant science.

4. The Dawn trajectory and orbital operations

Dawn's trajectory to Vesta and Ceres includes a Mars gravity assist. As Fig. 2 shows, Dawn spends 8 months in orbit about Vesta and 5 months at Ceres. The operations at each body are similar. Let us examine, for example, the operations at Vesta.

Upon arrival Dawn enters a 3000 km altitude survey orbit of the entire surface over a period of several days. Then it descends to 900 km altitude, into the high altitude mapping orbit (HAMO) and completely maps the surface, also obtaining spectral data. Then it descends once more to 180 km altitude, into the low altitude mapping orbit (LAMO) where it stays for almost 3 months obtaining gamma ray and neutron data, gravity data and some high resolution imagery and visible and IR spectra. At Vesta the spacecraft spirals away from the body, stopping at key places to take some opportune measurements before setting out to Ceres. At Ceres it needs not take this escape route if it achieves a stable orbit around Ceres. The operations at Ceres are similar but scaled to the larger body radius.

5. The Dawn and VIR scientific objectives

Dawn's goal is to achieve an understanding of the conditions and processes acting at the solar system's earliest epoch. The asteroid belt preserves information on these processes in its largest bodies and Dawn will investigate the internal structure, density and homogeneity of two complementary protoplanets that have remained intact since their formation, by measuring their mass, shape, volume, spin rate and composition, both elemental and mineralogical. The Visible-IR Mapping Spectrometer VIR will permit to study the mineralogical composition of the Ceres and Vesta surface, coupling high spectral and spatial resolution. The VIR main objectives are the following:

- Determination of the mineral composition of surface materials in their geologic context;
- Identify different materials and mixtures and determine their spatial distribution;
- Identify the the presence of silicates, hydrates and other minerals;
- Map, with a spatial resolution of a few tens of meters, the asteroid surfaces and determine the spatial distribution of the various mineralogical types;
- Determine the physical microstructure and nature of the surface particles by measuring the spectrophotometric phase curve.

VIR will have specific goals at Vesta, such as to confirm or not the link between Vesta and the HED meteorites with the determination of the compositional range of materials on Vesta and link with meteorites. Moreover, VIR will obtain the first in-depth view of a planetary interior through the spectral imaging of Vesta's wide and deep impact basin. The mineralogical investigation will reveal the nature of Vesta's ancient magma ocean or volcanic emplacement history. VIR will determine the mineralogy of a protoplanet that has remained at its formation location. When Dawn will arrive at Ceres, the mapping spectrometer will investigate its primitive surface mineralogy, trying the identification of water-bearing minerals and dry clay-like material. VIR will map frost-covered regions, identifying possible ices on Ceres' surface. Using the mineralogical information by VIR, will be possible to have indication of subsurface ocean, if any. Moreover, specific atmospheric measures will help to reveal the postulated very weak atmosphere.

6. Conclusions

The objective of the Dawn mission is not only to enhance our understanding of Vesta and Ceres, but to derive a deeper understanding of the early solar system. We have several information on these asteroids, from meteorites and from telescopic observations. We already have experienced the synergy between Dawn and the ground-based observation and the laboratory meteoritic study. Dawn's role is to put these data into their proper geological context. If the connection between Vesta and HED meteorites will be confirmed by Dawn mineralogical and elemental analysis, we can say to have in our hand samples from Vesta and Dawn will become a sort of "sample return mission".

Acknowledgements. We are grateful to the Italian Space Agency, ASI.

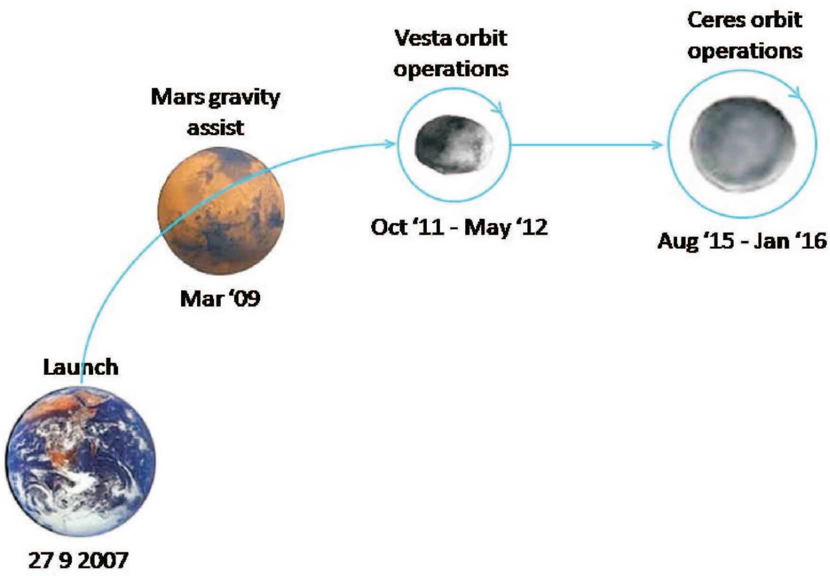

Fig. 2. Dawn trajectory from Earth to Vesta and Ceres.

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