Dawn: An Ion-Propelled Journey to the Beginning of the Solar System

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The Dawn mission is designed to perform a scientific investigation of the two heaviest main-belt asteroids Vesta and Ceres. These bodies are believed to preserve records of the physical and chemical conditions present during the formation of the solar system. The mission uses an ion propulsion system to enable the single Dawn spacecraft and its complement of scientific instruments to orbit both of these asteroids. Dawn's three science instruments – the gamma ray and neutron detector, the visible and infrared mapping spectrometer, and the primary framing camera – were successfully tested after launch and are functioning normally. The ion propulsion system includes three ion thrusters of the type flown previously on NASA's Deep Space 1 mission. A minimum of two ion thrusters is necessary to accomplish the Dawn mission. Checkout of two of the ion thrusters was completed as planned within 30 days after launch. This activity confirmed that the spacecraft has two healthy ion thrusters. While further checkout activities are still in progress, the activities completed as of the end of October indicate that the spacecraft is well on its way toward being ready for the start of the thrusting-cruise phase of the mission beginning December 15th.

I. Introduction

Dawn, the ninth project in NASA's Discovery Program, was launched on September 27, 2007. The Dawn spacecraft has been developed to enable the scientific investigation of the main-belt asteroid (4) Vesta and the dwarf planet (1) Ceres. The mission has been designed to provide new answers to questions about the formation and evolution of the early solar system. To accomplish this, the spacecraft will rendezvous with and go into orbit about each of these asteroids. Dawn will be the first mission to orbit a main-belt asteroid and the first to orbit two target bodies. The mission is enabled by Dawn's ion propulsion system which, apart from a Mars gravity assist, provides all of the post-launch ΔV including the heliocentric transfer to Vesta, orbit capture at Vesta, transfer between science orbits at Vesta, escape from Vesta, heliocentric transfer to Ceres, orbit capture at Ceres, and transfer between science orbits at Ceres. The trajectory is show in Fig. 1. The ion propulsion system provides a total ΔV of approximately 11 km/s to the spacecraft which had an initial wet mass of 1218 kg including 425 kg of xenon propellant and 46 kg of hydrazine.

This paper provides an overview of the Dawn mission objectives, the flight system, and summarizes the results from the first 30 days of the initial checkout activity after launch. A more thorough description of mission and system design is given by Rayman et al. [1].

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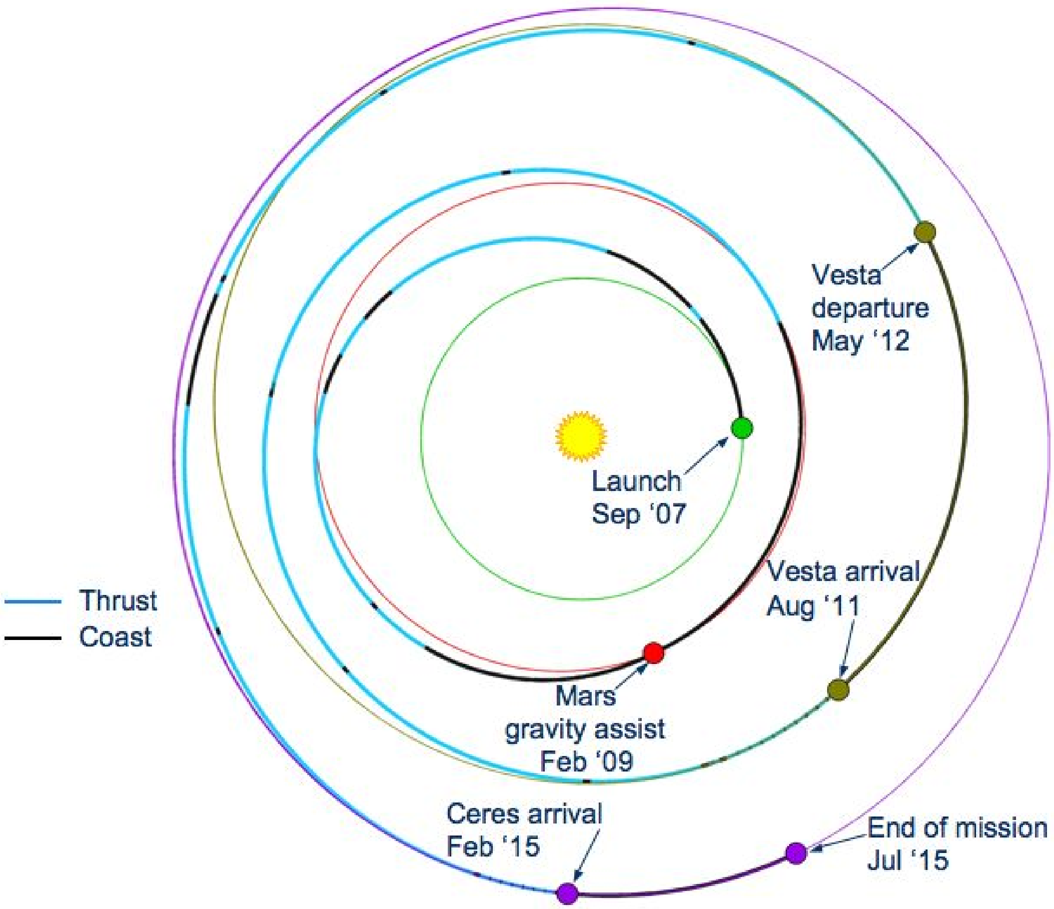


Fig. 1. Dawn baseline interplanetary trajectory. Planned IPS thrusting is shown in blue and coasting in black. The frequent interruptions in thrusting prior to Vesta and Ceres rendezvous are for acquisition of optical navigation and approach science data.

II. Science Objectives and Payload

A mission to Vesta and Ceres addresses important questions concerning the origin and evolution of the solar system. The science underlying the Dawn mission, as well as descriptions of the current understanding of Vesta and Ceres, are described in detail elsewhere [2]. The accretion of bodies during the earliest stages of the solar system led to the growth of planets. Jupiter's gravity is believed to have interfered with this process, thus depriving the region between it and Mars of a single planet and leaving instead a belt of protoplanets. Collisions during the subsequent 4.5 billion years have reduced the size and increased the number of the asteroids, and complex dynamics have caused some of the fragments to be transported from the asteroid belt to elsewhere in the solar system.

Vesta and Ceres are the two most massive asteroids, and they are far larger than the other asteroids visited by spacecraft. Both have survived largely intact through the collisional history of the solar system. They are believed to preserve retrievable records of the physical and chemical conditions during the solar system's early planet-forming epoch.

Vesta appears to be a dry, differentiated body, with evidence of lava flows. Ceres, the largest body in the asteroid belt and only slightly farther from the Sun than Vesta, is very different. Microwave observations suggest that it is covered with a material like clay, which would indicate water played a role in Ceres' history. Models suggest that subsurface water ice could be preserved within Ceres for the age of the solar system. Vesta, which is believed to have melted and differentiated, and Ceres, with its apparent inventory of water ice, form a bridge from the rocky bodies of the inner solar system to the icy bodies of the outer solar system. The profound differences in geology between these two protoplanets that formed and evolved so close to each other makes Dawn's comparison compelling.

Science Instruments

There are three types of science instruments on the Dawn spacecraft: a gamma ray and neutron detector; a visible and infrared mapping spectrometer; and two framing cameras. The locations of these instruments on the spacecraft are shown in Fig. 2. All instruments are mounted so the centers of their fields of view are aligned with the spacecraft's +z axis.

Gamma Ray and Neutron Detector (GRaND): The GRaND instrument was provided by Los Alamos National Laboratory. The instrument shown in Fig. 3 consists of a single box mounted to the exterior of Dawn on the +z deck. The GRaND electronics and software allow investigators to determine the energy of incident gamma rays and neutrons. It can distinguish between gamma rays and neutrons from the spacecraft and those from Ceres and Vesta. GRaND will provide global measurements of elemental composition for major elements (H, O, Si, Fe, Mg, Ti, Al, Ca) as well as radioactive elements such as K, U, and Th. The instrument can detect signatures of elements at the surface to a depth of approximately 1 m and can distinguish between volatiles such as water, ammonia, methane, and carbon dioxide. The instrument communicates with the spacecraft via an RS-422 data interface.

GRaND Flight Unit

Critical Components:

- Bismuth germanate scintillator for gamma rays.
- Array of 16 CdZnTe solid-state sensors for gamma rays (high-resolution)
- Lithium-loaded glass and boron-loaded plastic scintillators for neutrons
- Photomultiplier tubes and associated electronics for characterizing events.

General Characteristics:

- Mass: 9.2kg
- Power: 15 W
- Dimensions: 25x19x24 cm
- Data Rate: 3.1 kbps

Fig. 3. Gamma Ray and Neutron Dector (GRaND) Instrument.

Visible and Infrared mapping spectrometer (VIR): The VIR spectromenter was provided through the Agenzia Spaziale Italiana (Italian Space Agency), and was designed, built, and tested at Galileo Avionica in Florence, Italy. VIR is composed of an optics module (OM), which is mounted on Dawn's –x panel, and a Main Electronics module (ME), which is mounted on the interior of the spacecraft –y panel. The VIR instrument shown in Fig. 4 matches a reflective front-end telescope with a visible/infrared spectrometer cooled by a cryocooler and radiator. The optical head is thermally isolated from the base of the optics module and the spacecraft. A scan mirror near the aperture of the instrument can be used to collect off-axis observations. VIR will generate reflected light spectra from the surfaces of Ceres and Vesta to enable the science team to determine the asteroids' mineralogical composition. Mineral maps of 80% of the surface of each body will be produced at resolutions between 200 and 1600m per pixel, depending on altitude and selected data collection (spatial pixel binning) mode. The instrument communicates with the spacecraft via a MIL-STD 1553 data interface.

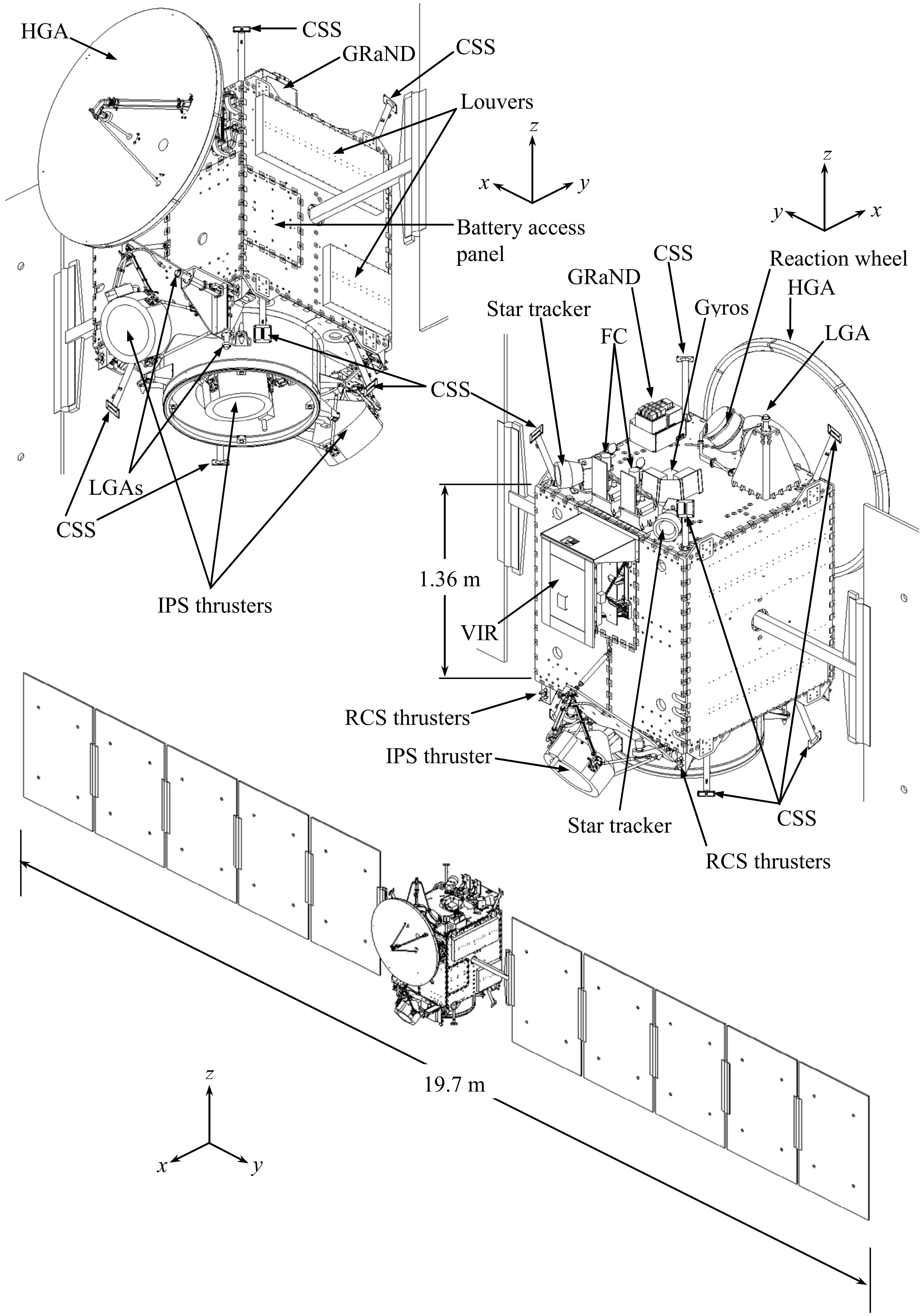
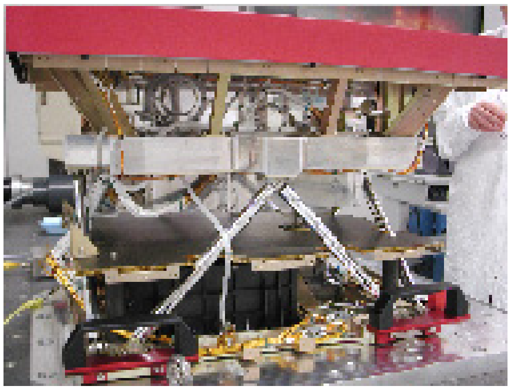


Fig. 2. The Dawn spacecraft configuration.



VIR mapping specrometer optics module (radiator cover and handling fixtures in red)

Critical Components:

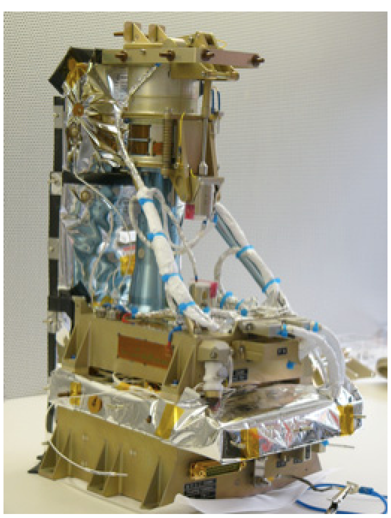
- HgCdTe Infrared dectector (270x438 pixels)
- CCD for visible light (256x432 pixels)
- Cryocooler and radiator for cooling infrared detector
- Recloseable aperture cover

General Characteristics:

- Mass: 19.7 kg (OM) and 4.5 kg (ME)
- Power: 50 W
- Dimensions: 60x38x42 cm (OM) and 21x28x13 cm (ME)
- Internal Memory: 2 GB (triply redundant)
- Data Rate: 156 kbps

Fig. 4. Visible and Infrared mapping spectrometer (VIR).

Framing Cameras (FCs): The framing cameras were provided by Germany's Max-Planck-Institut für Sonnensystemforschung (Max Planck Institute for Solar System Research) in cooperation with the Institut für Planetenforschung (Institute for Planetary Research) of the Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center) and the Institut für Datentechnik und Kommunikationsnetze (Institute for Computer and Communication Network Engineering) of the Technischen Universität Braunschweig (Technical University of Braunschweig). Dawn has two framing cameras for redundancy. Both framing camera are mounted on the spacecraft's +z deck. Each Framing Camera shown in Fig. 5 uses a refractive optical design with a 5.5° square field-of-view and an 8-position filter wheel. Data from the Framing Cameras will be used for imaging science, topography, and optical navigation. A minimum of 80% of the surfaces of Vesta and Ceres will be imaged with the clear and 3 color filters – Vesta at a resolution of 100m/pixel, and Ceres at 200m/pixel. These data will be used to construct topographic maps with a vertical resolution of better than 10m at Vesta and 20m at Ceres. Each unit communicates with the spacecraft via a MIL-STD 1553 data interface and can be commanded independently.



Single FC Flight Unit

Critical Components:

- CCD for imaging (1024x1024 pixels)
- 8 position filter wheel
- Radiators for cooling CCD and electronics
- Recloseable aperture cover

General Characteristics:

- Mass: 5.7 kg (per camera)
- Power: 12 W
- Dimensions: 20x21x42 cm
- Internal Memory: 8 GB
- Data Rate: 156 kbps

Fig. 5. Framing Camera.

III. Spacecraft

Orbital Sciences Corporation (Orbital) was responsible for the development of the flight system which includes the spacecraft bus integrated with the science instruments. The Dawn spacecraft design benefits from extensive inheritance from previous projects at Orbital and JPL. The mechanical design is based upon Orbital's STAR-2 series, and the avionics draw heavily from the LEOStar-2 series. The flight system shown in Fig. 3 is built on a core graphite composite cylindrical structure. The hydrazine and xenon tanks mount inside the cylinder, which provides a load path directly to the launch vehicle interface. Aluminum core panels with aluminum facesheets are attached to the exterior of the cylinder forming a box-like structure. Most of the spacecraft hardware is mounted to the interior surfaces of these panels.

Ion Propulsion System

The ion propulsion system (IPS) is an expanded version of the system operated extensively on Deep Space 1 (DS1) [3-6]. It consists of three 30-cm diameter xenon ion thrusters, two power processor units (PPUs), two digital control & interface units (DCIUs), a two-axis mechanical gimbal for each ion thruster, and a propellant feed system. A simplified schematic of the IPS is given in Fig. 6. A total of 425 kg of xenon was loaded into the main xenon tank prior to launch. The xenon tank has a mass of 21.6 kg resulting in a tankage fraction of 5.1%. The IPS is single-fault-tolerant and the entire mission can be completed using just two of the three ion thrusters. Each ion thruster produces a maximum thrust of 91 mN at a specific impulse of 3100 s for an input power to the PPU of 2,500 W. Only one thruster is operated at a time. The IPS can operate over the range of input powers from 2500 W down to 500 W. This enables operation of the IPS at solar ranges where the solar array can no longer produce sufficient power to operate the IPS at 2500 W. The IPS input power range is divided into 112 throttle levels called "mission levels" with an average separation of 18 W between levels. The two-axis gimbals for each thruster use stepper-motor driven actuators and provide a gimbal capability of approximately $\pm$12 degrees in one axis and $\pm$ 8 degrees in the other. The xenon feed system uses the same bang-bang pressure regulation system flown on DS1 [ref.] to control the propellant flow rate to within $\pm$ 3% for each of three propellant feeds to each thruster. The largest of the three flow rates to each thruster can be varied over a 3.8-to-1 turn down ratio (from 2.30 mg/s down to 0.060 mg/s).

The picture in Fig. 7 shows the Dawn spacecraft as it is being lowered onto the third stage of the launch vehicle and gives a good view of the three ion thrusters in the IPS. The center thruster is designated FT3 (for flight thruster #3), the thruster on the side of the spacecraft with the high gain antenna is FT2, and the thruster on the opposite side is FT1. Thrusters FT1 and FT2 are referred to as the outboard thrusters. The center thruster, FT3, can be operated from either PPU as indicated in Fig. 5 and is referred to as the shared thruster.

During IPS operation unregulated power from the solar array is converted by the PPU to the currents and voltages required to start and operate the ion thruster. The DCIU accepts commands from the spacecraft and provides telemetry on the health and status of the IPS over a MIL-STD 1553 interface. The DCIU controls the operation of the PPU through an RS-422 serial interface and directly operates all of the valves in the xenon feed system. The DCIU controls the operation of the xenon feed system valves to provide xenon flow to the operating thruster at the rate required for the selected mission level. The DCIU also contains the motor drive electronics for the thruster-gimbal actuators. Embedded flight software in the DCIU enables highly autonomous operation of the IPS requiring only simple commands from the spacecraft to thrust at any of the 112 mission levels.

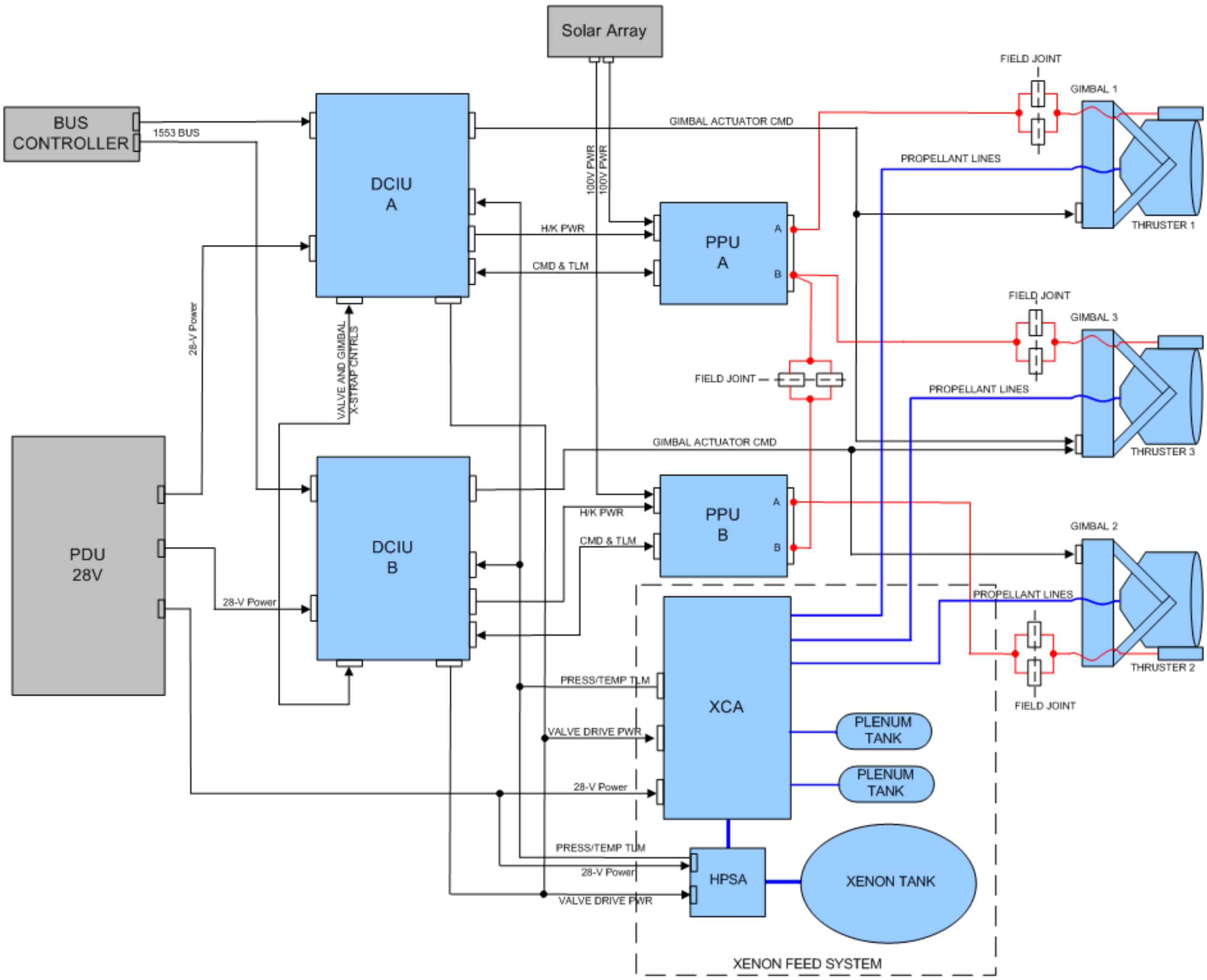


Fig. 6. Simplified block diagram of the ion propulsion system.

Attitude Control System

The attitude control system (ACS) uses IPS for two axes of control whenever the IPS is thrusting. For control around the thrust axis and for all axes during coast periods, ACS can use reaction wheels or the hydrazine reaction control system (RCS). Some of the mission will be flown under reaction wheel control, with RCS providing the torque for desaturation of the wheels, and for other periods, RCS will provide primary attitude control. For most of the mission, one of the two redundant star trackers is used for attitude sensing. ACS also has redundant gyros for high accuracy pointing during FC and VIR data acquisition and for safe mode operation. Redundant Sun sensors provide inertial reference for safe mode and yield an independent check on the attitude established by the star tracker.

Reaction Control System

All nominal trajectory control will be accomplished with the IPS, but Dawn has a small reaction control system (RCS) used by ACS. While it is not planned for normal operations, Dawn can use RCS to provide trajectory control should a small maneuver be needed in a contingency during which the IPS either is unavailable for does not provide sufficient acceleration. On approach to Mars and in low orbit at the asteroids, RCS could provide up to about 10 m/s (a negligible fraction of the total mission Δv) if necessary. RCS carried 46 kg of hydrazine at launch and has two strings of six 0.9-N thrusters.

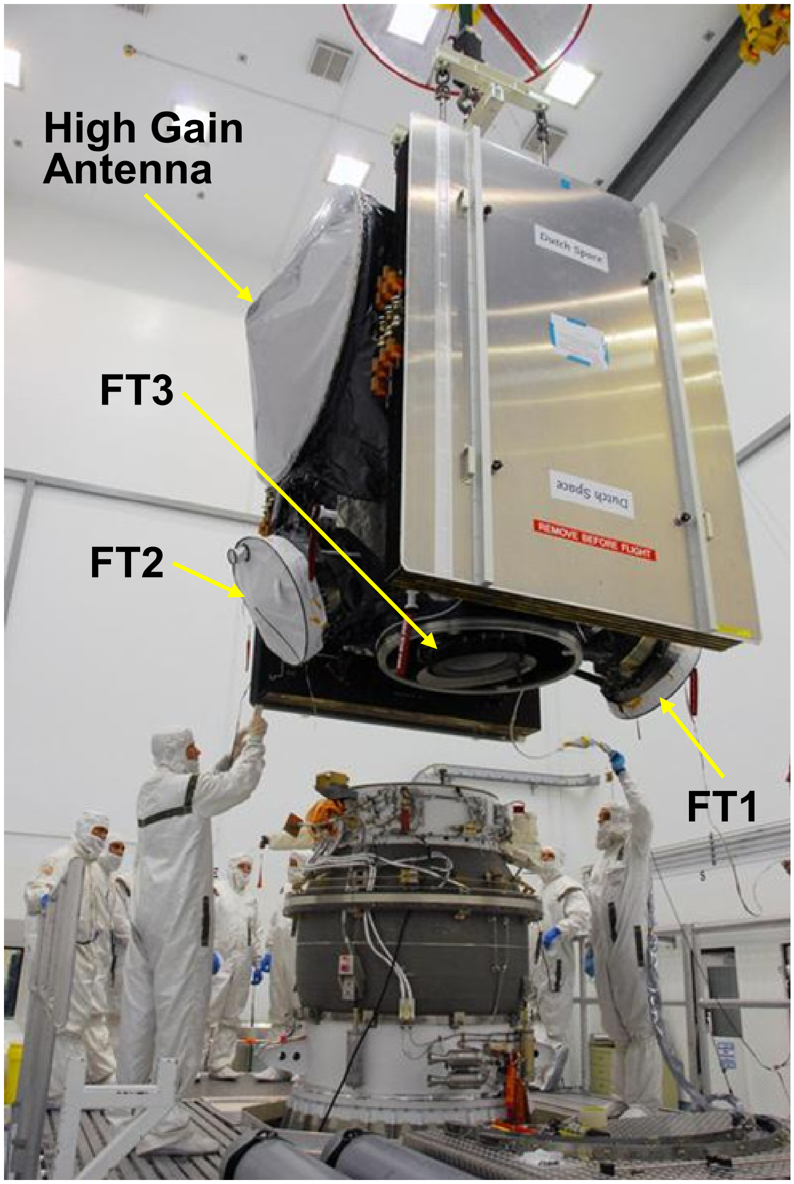


Fig. 7. The Dawn spacecraft as it was being lowered onto the third stage of the launch vehicle. The two outboard ion thruster, FT and FT2 still have their protective covers on.

Electrical Power System

Electrical power is generated by two solar wings, with a total of 10 panels, each of 2.3 m × 1.6 m. The triple junction cells yield a capability in excess of 10 kW at 1 AU, although the spacecraft loads, even during IPS thrusting, are less than 3.2 kW. The array will provide 1.3 kW at 3 AU, permitting IPS thrusting in all mission phases. The arrays are controlled to between 80 and 140 V to optimize power delivery to the PPU, and all other components are on the 22 - 35 V bus. Power was provided during launch by a 35 A hr NiH_2 battery. When the spacecraft is far enough from the Sun that IPS operation at the maximum throttle level cannot be sustained, the battery will source transient loads on the low voltage bus (such as heater activity) to avoid frequent throttle changes in the IPS.

Command and Data Handling System

The CDHS architecture is based on that used by Orbital for other missions. The system is built around a RAD6000 processor with the capability to switch autonomously to a fully redundant string. Software is written in C.

Thermal Control System

Thermal control is achieved with a combination of redundant heaters and sensors, louvers, heat pipes, and materials such as blankets and radiators. Most electrical components are mounted on panels that normally are parallel to the Sun-spacecraft vector, thus reducing the thermal environmental variation. This system is important but not interesting enough to merit 3 sentences.

Telecommunications System

All communications with Dawn are conducted at X-band through NASA's Deep Space Network. The spacecraft has a 1.52-m high gain antenna and three low gain antennas. Redundant 100-W (RF) traveling wave tube amplifiers enable high rate downlink of science data at the asteroids. The maximum downlink rate is 124 kb/s, and maximum uplink rate is 2 kb/s. Dawn uses JPL's standard small deep-space transponder, permitting not only data transfer but also ranging and coherent two-way operation for navigation and gravity science.

IV. Mission Operations

Dawn was launched from Cape Canaveral Air Force Station on September 27, 2007 on a Delta II 7925H-9.5. The Delta launch vehicle does not provide a communications interface during ascent, so no telemetry was received from the spacecraft between liftoff and initial acquisition by the Deep Space Network at about L+2 hours, by which time the spacecraft had nulled separation rates, deployed its solar arrays, and turned to point them to the Sun. The first three days of the mission were devoted to verification of the health of the spacecraft and transitioning to cruise configuration.

The focus of the first 80 days of the mission is on preparation for the extensive IPS thrusting required to conduct the mission. For most of the interplanetary cruise, the IPS will thrust at least 95% of each week, allowing one weekly thrusting hiatus to point the high-gain antenna to Earth. There also will be occasional planned periods of one day to a few months of no thrusting, but the thrust/coast and target arrival and departure strategies for a low-thrust mission require careful management [7].

The mission design is constrained to begin deterministic thrusting no earlier than 80 days after launch to provide adequate time to verify readiness for high-duty-cycle IPS thrusting. Checkout of the IPS began with the center thruster FT3. After the initial planned preparation activities the thruster was successfully started on October 6, 2007 and was operated for a total of approximately 27.5 hours at five different mission levels, ML27, ML48, ML69, ML90, and ML111, corresponding to input powers ranging from 950 W to 2500 W and thrust levels ranging from 31.4 mN to 91.0 mN. Radiometric measurements of the thrust were made at each mission level. Preliminary analyses of these data indicate that the measured thrust is within 1 mN and slightly greater than the expected thrust levels at each of the five mission levels tested. In addition, the ion thruster's key currents and voltages, the PPU efficiency, and the operation of the xenon feed system were all consistent with preflight test data. Closed-loop thrust vector control of the FT3 gimbal actuators by the attitude control system was successfully demonstrated. The duty cycles of the FT3 gimbal actuators were found to be less than 1% as expected. The actuator duty cycle, which is defined as the actual number of steps per unit time divided by the maximum possible actuator step rate, is an important parameter affecting the actuator service life. With actuator duty cycles of 1% or less the wear-out of the gimbal actuators is not an issue for the mission.

In addition to producing thrust, ion thruster operation also produces a small roll torque about the thruster axis. The angular momentum created by this roll torque must be eliminated by the reaction control system and, consequently, the magnitude of the roll torque affects the hydrazine consumption rate.

Measurement of the roll torque produced by FT3 at full power indicates that it is within the specified maximum allowed value.

Following the successful checkout FT3, thruster FT1 was prepared for operation. After completion of these preparations FT1 was successfully started and operated for approximately 28 hours at the same five mission levels, ML27, ML48, ML69, ML90, and ML111 used in the FT3 characterization. Again preliminary analyses of the radiometric thrust measurements indicate that the measured thrust for FT1 is also within 1 mN and slightly greater than the expected thrust levels at each mission level tested. The key currents and voltages for FT1 were all consistent with preflight test data and the roll torque produced by this thruster was found to be approximately half that produced by FT3. Closed-loop thrust vector of FT1 by the attitude control system was also successfully demonstrated, again with a thruster-gimbal actuator duty cycle of less than 1%.

The power processor units in the Dawn IPS are highly efficient devices. At full power they have an efficiency of approximately 92.4%. For an input power of 2500W, however, this means that 190W of power is dissipated in the PPU that must be removed by the spacecraft's thermal control system. Heat pipes in the -y panel, to which the PPUs are mounted, are used to distribute the PPU waste heat to the panel radiators. The initial checkout of both FT1 and FT3 were performed using PPU-A (see Fig. 6). The operation of PPU-A with an input power of 2500W demonstrated outstanding performance of the thermal control system with the steady-state temperature of the –y panel increasing to only 17C.

Functional tests of each science instrument were conducted during the week of October 15, and all were found to be in excellent health. All electronics, detectors, mechanisms, and optics performed as intended. In addition to verification of the flight system status, these tests demonstrated communications and data flow with investigators at UCLA's Dawn Science Center.

GRaND was activated on October 16. Its high voltage supplies were brought to 1 kV, and all 21 sensors were verified to be operational by observing galactic cosmic rays directly or via their interaction with the spacecraft. As the count rate is low, the instrument remained powered on for 6 days.

Following VIR's activation on October 17, its cryocooler successfully brought the IR focal plane array to 82 K. Internal IR and visible lamps provided calibrated sources for the detectors. The scan mirror and the aperture cover operated as expected. All data acquisition and processing worked correctly.

The prime FC was operated on October 18. The CCD cooled to 204 K, and the instrument acquired a total of 102 test images. No dedicated attitude was chosen for the instrument tests, but imaged with the FC cover open show a star field, demonstrating good focus. Images were exposed with all eight filters. The cover was closed before the unit was powered off.

A test of the capability to execute a contingency RCS trajectory correction maneuver was conducted on October 22. Two of the -z RCS thrusters fired for 120 seconds each, imparting about 8 cm/s to the spacecraft.

V. Conclusion

Investigation of the substantial differences in geology between the two large asteroids, Vesta and Ceres, that formed so close to each other makes the Dawn mission scientifically compelling. The ion propulsion system on Dawn enables this singles spacecraft to rendezvous with and orbit each of these bodies. The Dawn spacecraft was launched on September 27, 2007. Within 30 days after launch checkout of two of the three ion thrusters in the onboard ion propulsion system was successfully completed. Checkout of the third ion thruster is scheduled for November. In-flight thrust measurements were made at five different throttle levels on each thruster covering a range of input powers from 930W to 2480W. These measurements agree well with the predicted values over the full range of input powers. Operation of the other parts of the ion propulsion system tested by the end of October, including PPU-A, the xenon feed system, DCIU-A, and the thruster-gimbal assemblies for FT1 and FT3, are all consistent with the preflight test data. Spacecraft functions essential for the long-term operation of the IPS including power production by the solar array, thrust vector control by the ACS, and rejection of the PPU waste heat by the thermal control system have all been successfully tested.

Checkout of Dawn's three science instruments, GRaND, VIR, and the Framing Camera was conducted three weeks after launch. All three instruments were found to be in excellent health. The redundant Framing Camera was not tested. With three good instruments, two good ion thrusters, and all spacecraft bus subsystems functioning normally the Dawn spacecraft is in good shape for the start of thrusting cruise on December 15.

Acknowledgments

Dawn is the result of the combined work of very many talented people at JPL, Orbital, Los Alamos National Laboratory, the Agenzia Spaziale Italiana, Germany's Max-Planck-Institut für Sonnensystemforschung, the Institut für Planetenforschung, the Deutsches Zentrum für Luft- und Raumfahrt, and the Institut für Datentechnik und Kommunikationsnetze of the Technischen Universität Braunschweig. The authors gratefully acknowledge the contributions of these organizations and the people in them. This research was carried out, in part, at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

Acronyms

CSS	Course Sun Sensor
DCIU	Digital Control & Interface Unit
FC	Framing Camera
FT	Flight (ion) Thruster
GRaND	Gamma Ray and Neutron Detector
HGA	High Gain Antenna
HPSA	High Pressure Subassembly
IPS	Ion Propulsion System
LGA	Low Gain Antenna
JPL	Jet Propulsion Laboratory
PDU	Power Distribution Unit
PPU	Power Processor Unit
RCS	Reaction Control System
TGA	Thruster-Gimbal Assembly
VIR	Visual and Infrared (mapping spectrometer)
XCA	Xenon Control Assembly
XFS	Xenon Feed System

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