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Comet Missions in NASA's New Millennium Program

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Abstract. NASA's New Millennium Program (NMP) is designed to develop, test, and flight validate new, advanced technologies for planetary and Earth exploration missions, using a series of low cost spacecraft. Such new technologies include solar-electric propulsion, inflatable-rigidizable structures, autonomous navigation and maneuvers, advanced avionics with low mass and low power requirements, and advanced sensors and concepts for science instruments. Two of NMP's currently identified interplanetary missions include encounters with comets. The first is the Deep Space 1 mission which was launched in October, 1998 and which will fly by asteroid 1992 KD in 1999 and possibly comet Wilson-Harrington and/or comet Borrelly in 2001. The second NMP comet mission is Deep Space 4/Champollion which will be launched in April, 2003 and which will rendezvous with, orbit and land on periodic comet Tempel 1 in 2006. DS-4/Champollion is a joint project with CNES, the French space agency.

1. Introduction

The advent of small, low-cost space missions has brought with it a need for new, advanced technologies which can enable productive missions with the smaller launch vehicles and payloads employed. In order to promote such technologies, NASA has created the New Millennium Program (NMP), administered by the Jet Propulsion Laboratory. New Millennium provides flight opportunities to validate new spacecraft, instrument, and operations technologies through a series of low cost missions. NMP missions also provide opportunities to test these technologies on actual targets and thus provide a meaningful science return from each mission. NMP missions include both Deep Space (DS) interplanetary missions, and Earth Orbiter (EO) missions.

The current New Millennium Program has four Deep Space missions under development or study, two of which involve comet targets. Deep Space 1 is an asteroid-comet flyby spacecraft which was launched in October, 1998. Deep Space 2 is a pair of Mars Microprobes (penetrators) to be carried on the Mars Polar Lander mission, which will be launched in January, 1999. Deep Space 3 is a space interferometry mission which will test precision formation flying by multiple spacecraft. Deep Space 4 is a comet rendezvous and lander mission to be launched in April, 2003 to periodic comet 46P/Tempel 1. Earth Orbiter 1 carries advanced land imaging instruments and will be launched in 1999. DS-1 and DS-4 are described in greater detail in the following sections.

2. Deep Space 1

The Deep Space 1 mission is the first of the New Millennium Program and is designed to test a suite of new technologies while performing flybys of an asteroid and a comet. The technologies include solar electric propulsion (SEP, also known as "ion drive"), solar concentrator arrays, autonomous navigation, a small deep space transponder, a Ka-band solid state amplifier, low power electronics, multifunction structure, beacon monitor operations, and the two science instruments described below.

The DS-1 spacecraft was launched successfully on October 24, 1998 on a Delta 7326 expendable vehicle. As of this writing (October, 1998) the spacecraft was performing well and two of the new technologies, the solar concentrator arrays and the small deep space transponder, had already been validated. The target of DS-1 is 1992 KD, a near-Earth asteroid with a perihelion distance of 1.33 AU and an orbital period of 3.58 years. The asteroid is believed to be 2 to 5 km in diameter. Its spectral type has not yet been identified and little is known about its physical properties. An Earth-based observational program is underway to characterize the asteroid.

The DS-1 trajectory is shown in Figure 1. The asteroid flyby will occur on July 29, 1999. Because of cost concerns, the DS-1 primary mission does not include a comet flyby, as was originally intended. However, if the spacecraft remains healthy, an extended mission is possible. Depending on available resources, the extended mission could be to periodic comet 107P/Wilson-Harrington and/or to 19P/Borrelly. The encounter with Wilson-Harrington would be in January, 2001, and with Borrelly in September, 2001. Flyby distances for the comet encounters are still to be determined, based on an assessment of the spacecraft's survivability as it passes through the cometary comae. P/Borrelly is a typical, active, Jupiter-family comet whereas P/Wilson-Harrington appears to be a near-extinct nucleus, and, in fact, was independently discovered and numbered as asteroid 4015 (Bowell, 1992).

2.1. Deep Space 1 Science Payload

The DS-1 science payload is shown in Table 1. The Miniature Integrated Camera/Spectrometer (MICAS) combines two visible imaging channels, and individual ultraviolet and infrared imaging spectrometers. The four instruments share a single 10-cm aperture telescope, though the effective focal length of each optical system differs. The visible detectors are a 1024 × 1024 CCD with an IFOV of 13 microradians (μrad) per pixel and a 256 × 256 APS sensor with IFOV of 18 μrad per pixel. The APS, or Active Pixel Sensor, is an advanced CMOS device that includes the timing and control electronics on the same chip with the detector. Both the CCD and the APS sensors operate between 5,000 and 10,000 Å.

MICAS's two imaging spectrometers each operate in "push broom" mode where one dimension of the detector array provides columns of spatial resolution, and the perpendicular direction provides rows of spectral resolution. The second spatial dimension is then achieved by scanning the instrument FOV across the target at a uniform rate. The ultraviolet spectrometer uses a 35 × 164 pixel array and operates between 800 and 1850 Å, with a spectral resolution of 21 Å

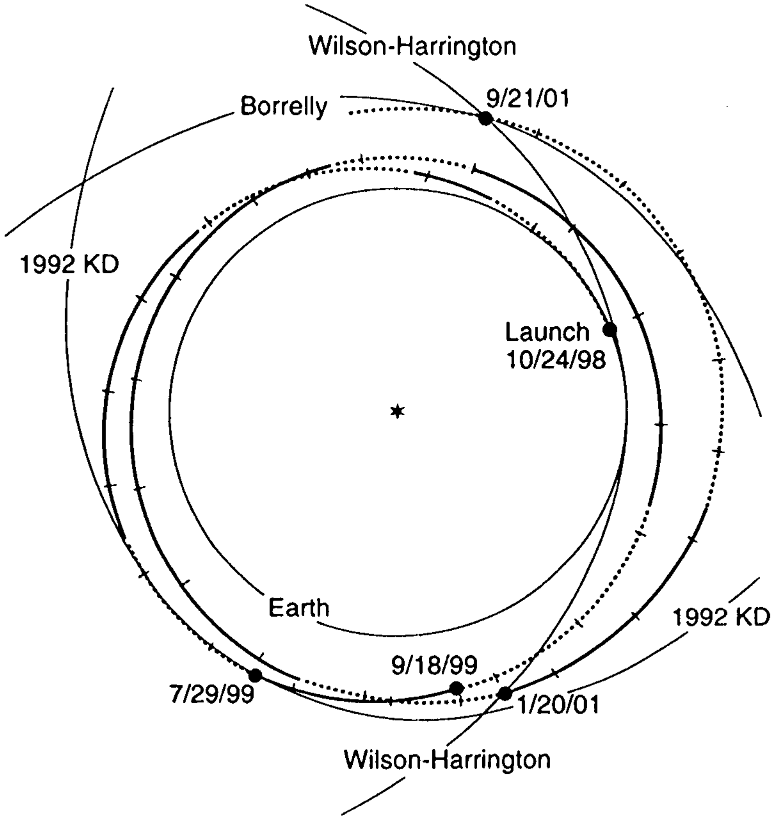

Figure 1. Heliocentric trajectory for the Deep Space 1 mission. The primary mission ends on September 18, 1999, following the flyby of asteroid 1992 KD on July 29, 1999. However, if funds are available, an extended mission to Comet Wilson-Harrington and/or to Comet Borrelly is a possibility. Dotted portions of the spacecraft trajectory indicate times when the ion engine is not operating.

Table 1. Deep Space 1 Science Payload

Name	Instrument type	Technology provider
MICAS	UV/Visible/IR imager	Jet Propulsion Laboratory
PEPE	Plasma ion/electron spectrometer	Southwest Research Institute & Los Alamos National Laboratory

and a spatial resolution of 316 μrad per pixel. The infrared spectrometer uses a 256×256 array and covers the wavelength range from 1.2 to 2.4 microns (μm), with a spectral resolution of 0.012 μm and a spatial resolution of 53 μrad per pixel. The MICAS instrument weighs 12 kg.

MICAS will obtain visible images of the asteroid and the comet nucleus (if there is an extended mission for DS-1) during each flyby, allowing determination of the size, shape, rotational parameters, albedo, and surface morphology of each target. At the same time, the imaging spectrometers will obtain multi-spectral maps of the targets which will make possible the identification of compositional units on the surface of each target as well as species in the cometary coma.

The Plasma Experiment for Planetary Exploration (PEPE) is an integrated ion and electron spectrometer which will determine the 3-dimensional plasma distribution over a field-of-view of 8.8 steradians (70% of the sky). Using electrostatic sweeping, PEPE will achieve resolutions of 45^o in azimuth and 5^o in elevation. PEPE will measure the energy spectrum of electrons and ions from 3 eV to 30 keV per unit charge with 5% resolution. PEPE will also measure ion mass in the range from 1 to 135 amu per unit charge at a mass resolution of 5%. The instrument includes a low-power consumption, low-mass microcalorimeter, provided by Stanford University, to help understand plasma/surface interactions. The complete integrated instrument weighs 6 kg.

PEPE will also be used to monitor the plasma environment generated by the SEP engine. In addition, a diagnostic package consisting of a quartz crystal microbalance, two calorimeters, a retarding potential analyzer, a Langmuir probe, a search coil magnetometer, a plasma wave spectrometer, and a flux gate magnetometer will provide environmental monitoring. This package may also be used to measure the solar wind interaction at the asteroid and the comet.

2.2. Deep Space 1 Spacecraft

The Deep Space 1 spacecraft is shown in Figure 2. The 3-axis stabilized spacecraft has a dry mass of 373 kg and is about 1.5 meters high. It carries 81.5 kg of xenon propellant for the single 30-cm SEP engine and 31 kg of hydrazine for attitude control. The ion engine is steerable and generates a continuous thrust of 20–90 millinewtons, while the 8 hydrazine thrusters provide 1 newton force each. The solar concentrator arrays generate 2.5 kilowatts at 1 AU (beginning of mission); 400 watts are used to power the spacecraft and the remainder is used to power the SEP engine. The engine is throttleable in discrete steps from 0.6 kW up to full power. The telecom system utilizes X-band uplink and downlink operating through the high gain antenna and three low gain antennas. In addition a Ka-band downlink is one of the technology experiments on the spacecraft. The spacecraft's central computer uses a 25 MHz RAD-6000 CPU with 128 Mbytes of main memory and 16 Mbytes of non-volatile storage.

3. Deep Space 4/Champollion

The Deep Space 4/Champollion mission is designed to test and validate technologies for landing on and anchoring to small bodies, and sample collection and transfer, in preparation for future sample return missions from comets, asteroids, and satellites. In addition, DS-4 will test technologies for advanced, multi-engine

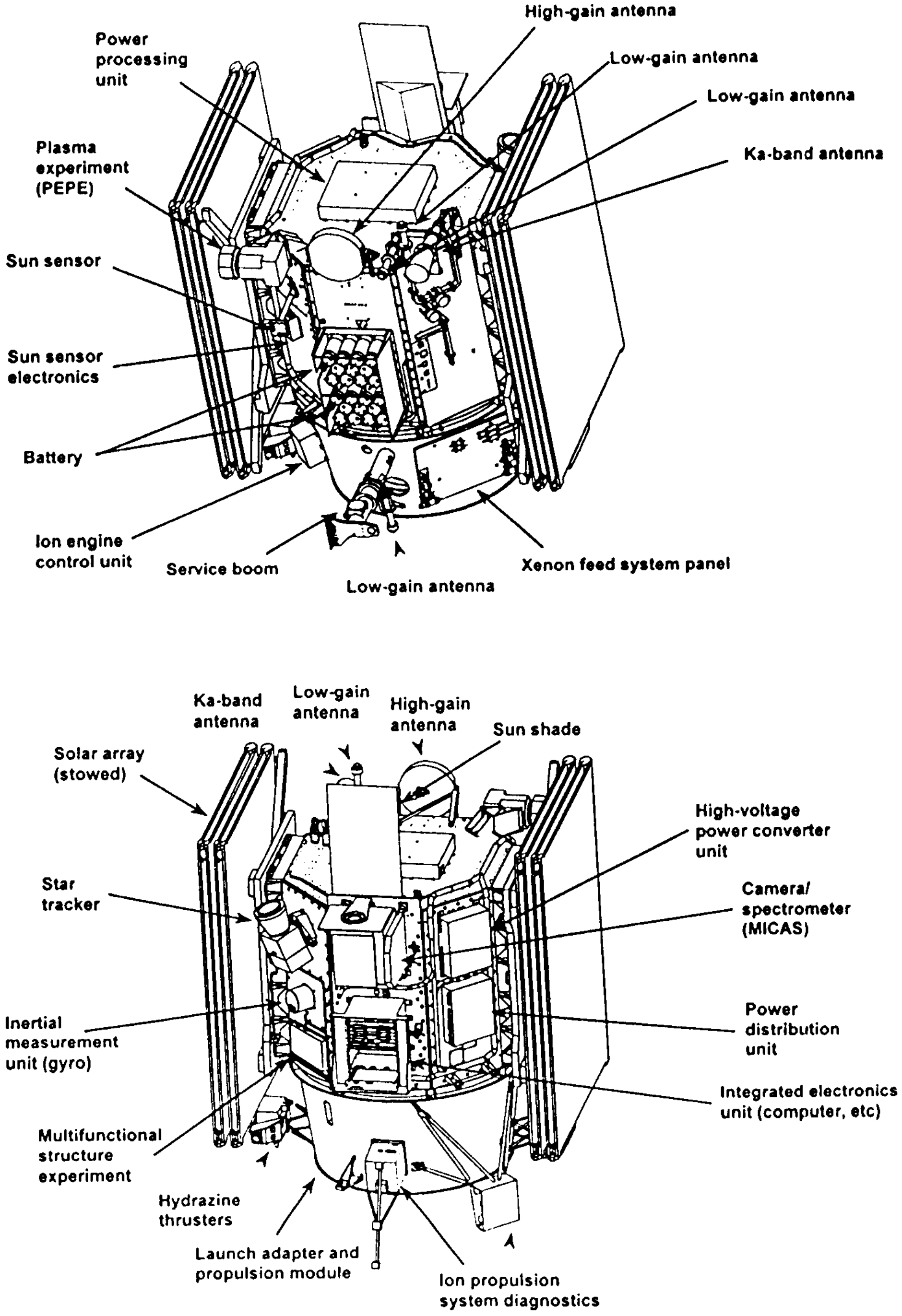

Figure 2. Deep Space 1 spacecraft in launch configuration showing major subsystems and instruments.

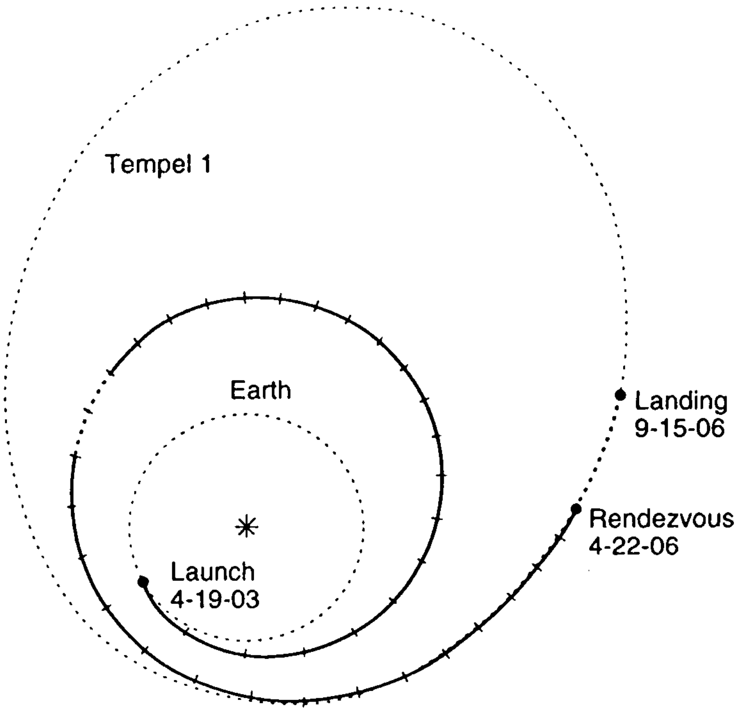

Figure 3. Heliocentric trajectory for the Deep Space 4/Champollion mission. Rendezvous with Comet Tempel 1 occurs post-perihelion at 2.8 AU in April, 2006, and the landing on the comet nucleus occurs in September, 2006 at 3.4 AU. Dotted portions of the trajectory indicate times when the ion engines are not operating.

solar electric propulsion systems, inflatable-rigidizable solar arrays, autonomous navigation and precision guidance for landing, autonomous hazard detection and avoidance, and advanced integrated avionics and packaging concepts.

Deep Space-4/Champollion consists of two spacecraft: an orbiter/carrier vehicle which includes the multi-engine SEP stage, and a lander, called Champollion, which will descend to the surface of the cometary nucleus (Jean Francois Champollion was the Egyptologist who translated the Rosetta stone in 1824). Deep Space 4/Champollion is a joint project between NASA and CNES, the French space agency.

The Deep Space 4/Champollion trajectory is shown in Figure 3. DS-4/Champollion will be launched in April, 2003 on a Delta 7925 expendable vehicle. The spacecraft will rendezvous with and orbit periodic comet Tempel 1 in April 2006, and will deploy a 160 kg lander to the nucleus surface in September, 2006. Rendezvous occurs post-perihelion at a heliocentric distance of 2.8 AU, and the landing occurs at 3.4 AU. The lander will operate for approximately 80 hours on the nucleus surface, making measurements with its suite of scientific instruments.

Periodic comet 46P/Tempel 1 is a typical Jupiter-family, short-period comet with a perihelion distance of 1.50 AU and an orbital period of 5.50 years. The comet nucleus is believed to be approximately 7.8×5.6 km, assuming an albedo of 0.04 (Lamy, 1998), and rotates in 25-40 hours. Gas production near perihelion has been measured at 1.1×10^{28} molecules $\sec^{-1}$ (A'Hearn et al., 1995). An observational program to characterize the comet more completely is underway.

Several options are available for the DS-4/Champollion mission. Given sufficient resources (i.e., funding, launch vehicle payload capability), the spacecraft could collect a sample of cometary material for return to Earth. The lander is capable of taking off from the nucleus surface carrying a sample return cannister, and then autonomously rendezvousing with the orbiter/carrier vehicle in orbit around the nucleus. The sample would be maintained at cryogenic temperatures and would be returned in a hermetically sealed re-entry capsule in 2010. A somewhat lesser goal is to take off from the nucleus surface and rendezvous with the carrier spacecraft in orbit around the nucleus in order to demonstrate some but not all of the elements of a sample return technology program. At present, both of these options are under consideration.

3.1. Deep Space 4/Champollion Science Payload

The Champollion lander instruments, Principal Investigators, and their institutions are shown in Table 2. The Chemical Analysis of Released Gas Experiment (CHARGE) is a gas chromatograph mass spectrometer. Cometary samples will be placed in a pyrolysis oven where they will be heated from ambient temperature to 700°C. Evolved gases from the sample will be analyzed directly during the pyrolysis cycle and a portion of the gases will be trapped for subsequent analysis by the gas chromatograph mass spectrometer. The gas chromatograph uses helium as the carrier gas. Two separate trap systems will be used to sample trace molecules. Noble gases and isotope ratios of common elements will be measured. Simple molecules will be directly detected by CHARGE while molecules of the complexity of amino acids will be identified through identification of their pyrolysis products. CHARGE is also equipped with a port to collect and analyze coma gases while the lander is still in orbit around the nucleus, prior to landing. Compositional data acquired during orbital operations will aid in the selection of the landing site.

The Champollion Infrared and Camera Lander Experiment (CIRCLE) consists of three near-field cameras with fields of view of 23° each, plus a microscope which incorporates a near-infrared spectrometer. One near-field camera is mounted on the drill assembly and images the drill site. This camera also includes a small light so that drilling operations can be monitored at night as the nucleus rotates. The other two cameras are pointed so that they view the area around the deployed CPPP physical properties probes. The cameras will use 1024 × 1024 detector arrays, either CCDs or APSs (active pixel sensors) and cover the wavelength range from 4,000 to 10,000 Å.

The combined microscope/spectrometer is mounted on the instrument table next to the sample collection drill. The drill is designed to take cometary samples and press them against a sapphire window where they can be viewed by the microscope/spectrometer. Following viewing, the samples are transferred to the CHARGE ovens for compositional analyses. The visible channel of the

Table 2. Deep Space 4/Champollion Science Payload

Name	Instrument type	P.I./Institution
CHARGE	Gas chromatograph/mass spectrometer	Paul Mahaffy/NASA-GSFC
CIRCLE	Near-field cameras/microscope	Roger Yelle/Boston University
CIVA	Panoramic and stereo cameras	Jean-Pierre Bibring/IAS
CPPP	Physical properties probes	Thomas Ahrens/Caltech
GR/NS	Gamma-ray/neutron spectrometer	NMP technology validation experiment
NAC	Narrow angle camera (orbiter)	Navigation subsystem
WAC	Wide angle camera (orbiter)	Navigation subsystem

microscope uses the same 1024 × 1024 detector as the near-field cameras, and the optical system provides a magnification of 4×. The IR spectrometer uses a cooled 256 × 256 HgCdTe detector. The wavelength range of the spectrometer is 1.0 to 4.0 microns with a spectral resolution of 10 cm^{-1}. Both the microscope and the spectrometer have their own internal illumination.

The Champollion Infrared and Visible Analyzer (CIVA) consists of seven panoramic cameras with fields of view of 70° each, mounted at 60° intervals around the periphery at the top of the lander, with one location housing a stereo pair. The cameras use 1024 × 1024 frame-transfer CCDs yielding an IFOV of 1.2 mrad/pixel with wavelength coverage from 4,500 to 9,500 Å. The large FOV allows the cameras to view from the base of the lander to the horizon in a 360° panorama; the spatial resolution at the base of the lander is ~2 mm per pixel.

The Champollion Physical Properties Probe (CPPP) consists of a pair of instrumented probes mounted on deployable arms, which will measure the physical properties of the nucleus surface, including hardness, friction, temperature, thermal conductivity, and thermal diffusivity versus depth. Each probe is approximately 1 cm in diameter and 20 cm long. Each probe contains four platinum resistance thermometers (PRTs), a friction sleeve, and a bar code reader for measuring depth of penetration. The probes are deployed following landing and are driven into the comet surface using momentum-compensated electric hammers. The capability exists to send small heat pulses into the nucleus surface using the PRTs and then to observe the decay of each heat pulse. Also, strain gauges mounted on the deployment arms allow monitoring of forces and torques imposed on the comet by the sample collection drill. CPPP sensors may also be included in the lander's central anchoring spike (see below).

Plans also exist to fly a New Millennium Program miniature gamma-ray and neutron spectrometer (GR/NS) as a technology validation experiment. The spectrometer experiment will be procured through a competitive process which is currently underway. The GR/NS will operate continuously during the orbital phase of the mission to help select a landing site that has optimum access to icy (i.e., hydrogen-rich) cometary material beneath the expected hydrogen-poor refractory crust of P/Tempel 1. The GR/NS will also operate continuously on the nucleus surface during the landed mission and return bulk compositional measurements on cosmogenically important elements such as H, C, O, Si, Fe, Ti, K, Th, Ca, and Mg.

The sample acquisition and transfer mechanism (SATM) is provided by Honeybee Robotics and consists of a 1.1-meter long drill which collects samples and transfers them to both CIRCLE and CHARGE. Also, located in the drill head is a Cs^{137} radioactive source which will be sensed by the gamma-ray spectrometer and which can be used to estimate the density of the cometary material as the drill descends beneath the surface.

In addition, the DS-4/Champollion orbiter will carry narrow and wide-angle CCD cameras for navigation and for mapping the nucleus surface and candidate landing sites from orbit. The narrow angle camera will have a FOV of approximately 1.3° and will provide a spatial resolution of approximately 1.2 meters per pixel from an altitude of 50 km. The wide angle camera will have a FOV of ~12°. Each camera will have a 1024 × 1024 CCD, an 8-position filter wheel, and a closeable cover for dust protection. The NAC and WAC cameras will be mounted on a two-axis scan platform on the orbiter spacecraft. A technology experiment to be flown with the WAC will use autonomous software to detect changes in the comet such as outbursts or even disruption events, and then initiate a response by the spacecraft which would include both hazard avoidance and additional science data taking.

The DS-4/Champollion spacecraft may also carry some form of dust impact/accumulation sensor in order to monitor the particle environment during the rendezvous mission and to assess any potential damage to the spacecraft subsystems. A Science Team will be selected by NASA and CNES through an open, competitive process to validate and archive data taken with the orbiter cameras, the GR/NS, and other engineering/technology subsystems.

3.2. Champollion Lander Scenario

When deployed from the orbiter, the lander will maneuver autonomously to the selected landing site, using a scanning laser altimeter for surface topography recognition and positioning. In addition, a technology experiment to be carried onboard consists of a descent camera with a ~70° FOV, which will use feature recognition software to provide navigational inputs to the lander computer.

Upon touchdown, at a vertical velocity of 0.25 $\mathrm{m\ sec^{-1}}$ or less, the lander will fire a 3-meter long, telescoping spike into the nucleus surface. The spike is designed to anchor the lander to the surface in a variety of possible topographies and surface materials properties. If the cometary surface is hard, the anchor will only deploy a short distance, whereas if the surface is soft, it will deploy to its full length and will also extend capture devices outward into the surrounding material. Anchoring is required to allow drilling in the very low gravity cometary environment.

Surface operations with the lander are expected to last 80 hours, during which the landing site will be repeatedly photographed by CIVA and CIRCLE and multiple samples will be collected and analyzed by CHARGE and CIRCLE. The minimum requirement is to collect at least three samples: one from the surface and one each from depths of 20 and 100 cm. However, the nominal plan is to collect and analyze as many samples as possible from multiple drill holes during the 80 hours of surface operations. The SATM drill mechanism is mounted on an indexing circle which allows it to rotate to multiple drill holes at a single location. In addition, the entire lander is designed to rotate on its anchored base to permit selection of optimum drilling sites around the lander.

The CPPP sensors and the GR/NS will operate continuously over the 80 hours. The data obtained by the lander will be relayed to the orbiter and then back to Earth where the Science Team will use the knowledge gained early on to update later lander sequences. At the end of the 80 hours, the upper half of the lander will separate from the lower, anchored section and take off from the surface. Current plans call for the lander to rendezvous with the orbiter and to fly in formation with it.

3.3. Deep Space 4/Champollion Spacecraft

The DS-4/Champollion orbiter/carrier spacecraft is shown in Figure 4. The spacecraft consists of three stacked modules. The lower module holds the three 30-cm diameter SEP engines and a central tank holding 330 kg of xenon propellant for the engines (The 330 kg of xenon is the amount required for the rendezvous and landing mission only; sample return to Earth would require approximately 30% more xenon propellant). The SEP engines are steerable and are powered by 9 kilowatt solar arrays (end-of-mission). The lightweight solar arrays inflate following launch and deploy to their full width, then becoming rigidized structures. The arrays have one axis of articulation. As with the xenon propellant, the solar arrays are sized for the rendezvous mission; larger arrays would be required for the sample return option.

The solar arrays are mounted to the central module which also carries the spacecraft avionics in eight external bays mounted around its periphery. Also mounted on the central module is the fixed, 1.3-meter diameter high gain antenna and the scan platform with two axes of articulation, holding the NAC and WAC cameras. The scan platform will permit viewing of 2π steradians (50% of the sky) without the necessity for reorienting the orbiter spacecarft. The telecom subsystem consists of X-band uplink and downlink with Earth, and S-band between the orbiter and the lander

The upper module houses the attitude control system including the hydrazine propellant tanks and the thruster assemblies. Twelve 1-newton, hydrazine thrusters provide attitude control and small propulsive maneuvers. The attitude control system also includes wide-field star cameras, sun sensors, and an inertial measuring unit (gyro).

The Champollion lander is mounted at the top of the upper module. If the sample return option is included in the Deep Space 4/Champollion mission, the re-entry capsule for returning the sample to Earth will be carried inside the upper module. The total dry mass of the carrier spacecraft is 470 kg and it contains 45 kg of hydrazine propellant in addition to the 330 kg of xenon and the 160 kg lander.

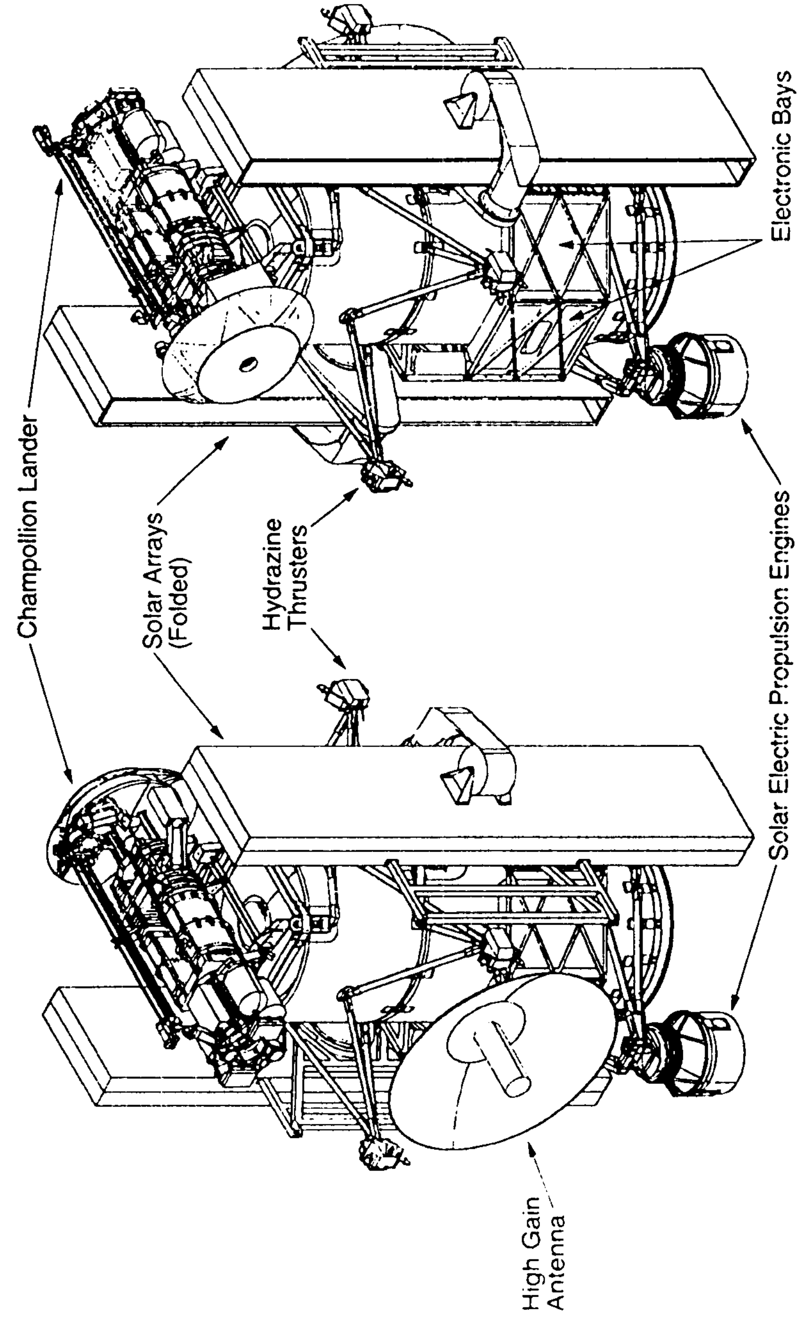

Figure 4. Deep Space 4 orbiter/carrier spacecraft showing major subsystems. Some elements of the design, such as the scan platform with the NAC and WAC cameras, are not yet shown in the drawings. The scan platform will be mounted to the electronics bay opposite to the high gain antenna.

The Champollion lander spacecraft is shown in Figure 5. The lander has a dry mass of 145 kg, carries 15 kg of cold gas (nitrogen) for attitude control, and stands about 1.5 meters high. The lander is constructed around the central anchoring spike which consists of three telescoping sections, each about a meter long. The spike sections are designed to swage together at deployment, resulting in a rigid anchor to the nucleus surface. If the nucleus surface is particularly soft, a broad, conical, 0.75-meter diameter "snowshoe" at the base of the lander prevents it from sinking in too far.

Several of the scientific instruments (CHARGE, the CIRCLE microscope-spectrometer, and the GR/NS technology experiment) are mounted on the instrument table just above the snowshoe. This table plus the entire upper body of the lander is designed to rotate so that the drill can be moved to the most opportune drilling sites around the lander, and so that the CIVA stereo pair cameras can image the entire 360° panorama in stereo. The CPPP probes will be mounted on deployable arms (not shown in Figure 5) which will be mounted to the anchored base of the lander around the snowshoe.

Science instrument electronics are carried in horseshoe-shaped trays which fit around the central spike housing, just above the instrument table. Spacecraft avionics are in trays above that and spacecraft batteries are in trays mounted at the top of the stack. The lander is powered by primary batteries with 6,900 watt-hours of energy at deployment from the orbiter. Above the battery trays are the compressed nitrogen tanks for the cold-gas attitude control subsystem. Attitude control and propulsive maneuvers are provided by 16 1-newton, N_2 thrusters. At the top of the lander are the French provided telecom subsystem for communicating with the orbiter, including two S-band antennas, and the CIVA cameras.

4. Summary

The purpose of the New Millennium Program is to develop and flight validate advanced technologies for future spacecraft missions. In addition, NMP missions provide an opportunity to do meaningful science with these new technologies, though science is not a primary goal nor a driver in these missions (The Champollion lander is an exception to these guidelines because it was originally conceived as part of another science mission).

Fortuitously, two of the first four NMP Deep Space missions have focused on technologies useful in the exploration of the small bodies in the solar system, asteroids and comets. Thus, Deep Space 1 and Deep Space 4/Champollion are valuable not only for the scientific data which they will obtain on comets and asteroids, but also for the enabling technologies which they will validate, opening the way for more advanced and comprehensive *in situ* studies of small bodies in the 21st century.

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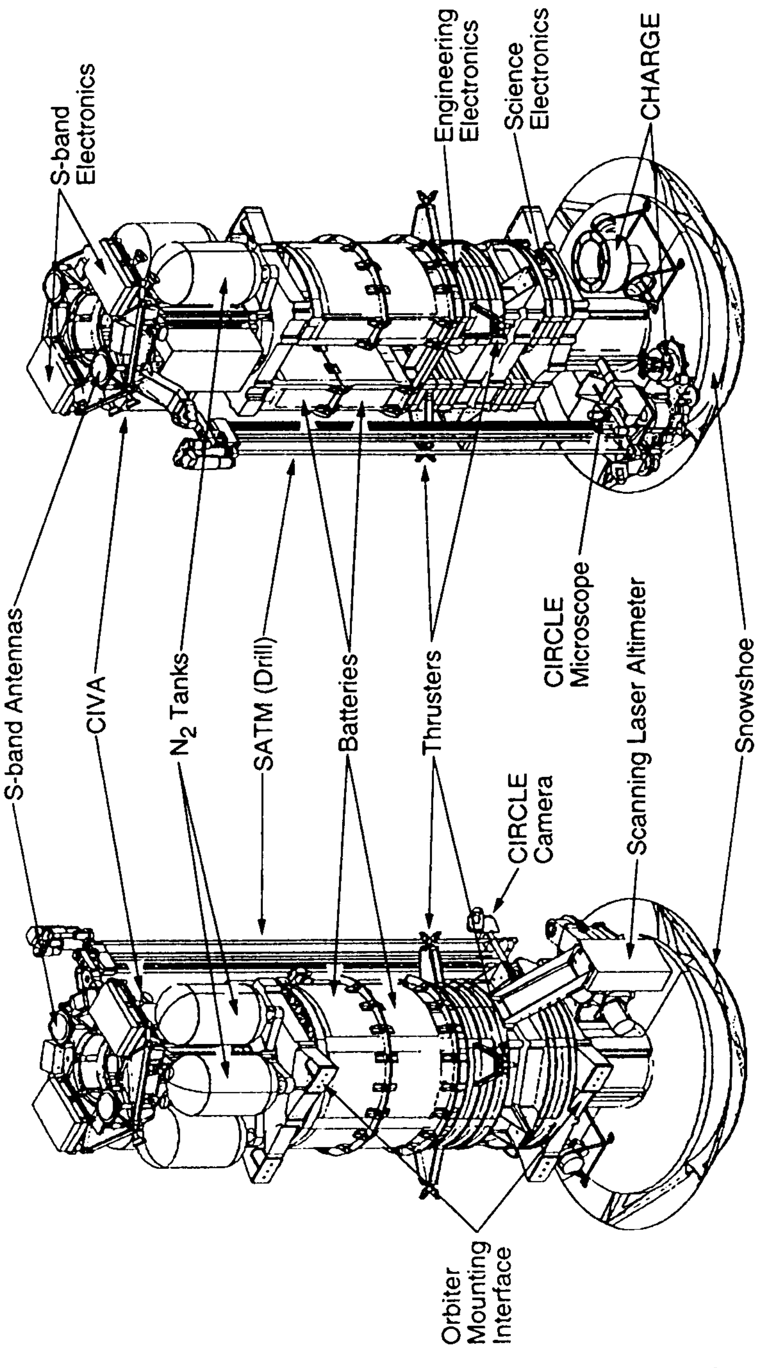

Figure 5. Champollion lander spacecraft showing major subsystems and instruments. As with the orbiter, not all instruments and subsystems are shown yet in the drawings. In particular, the deployable CPPP arms and two of the CIRCLE near-field cameras are not yet included.

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References

A'Hearn, M. F., et al. 1995 Icarus 118, 223
Bowell, E. 1992 IAU Circular 5585
Lamy, P. 1998 IAU Circular 7000