Odyssey, A Comet Nucleus Orbiter

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Abstract— Odyssey (not to be confused with the recently named Mars '01 orbiter) is an exciting comet nucleus orbiter mission submitted to the Discovery 2000 Announcement of Opportunity[1]. This mission will rendezvous with and orbit a comet nucleus, and will make detailed scientific measurements with unprecedented resolution and accuracy. It is widely recognized that the best obtainable clues to the origin of the solar system can be found in its small bodies, comets and asteroids. Only in these small, relatively unprocessed bodies is the cosmo-chemical and physical record of the early solar system preserved. Unprocessed volatiles can be found in only one place: in cometary nuclei. Odyssey will address elements of all three quests enumerated in the Solar System Exploration Strategic Plan.

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1. INTRODUCTION

Comets contain a cosmo-chemical record of the origin of our solar system and perhaps the origin of life on Earth. The Odyssey mission will reveal that record by rendezvousing with an active comet nucleus, orbiting it, and studying it in detail for 9 months.

The past 40 years of planetary exploration has revealed a myriad of worlds in our planetary system, each recording the complex and often violent history they have undergone over the past 4.5 billion years. As fascinating as that history is, it has obscured and often destroyed any evidence of how those worlds first came to be, how they formed out of a glowing cloud of interstellar dust and gas. It is now widely recognized that the best obtainable clues to the origin of the solar system can be found in its small bodies, comets and asteroids[2]. Only in these small, relatively unprocessed bodies is the cosmo-chemical and physical record of the early solar system preserved. Some of that record has already been realized in the study of meteorites, which appear to come primarily from asteroids. But asteroids have been both thermally and collisionally processed, and contain little of the volatile fraction of the primordial solar nebula. Unprocessed volatiles can be found in only one place: in cometary nuclei.

The Odyssey mission, submitted under the Discovery 2000 Announcement of Opportunity, will investigate the scientific record of the cometary nuclei by rendezvousing with a comet during its active phase. The mission will observe the nucleus over an extended period, using a scientifically selected set of instrumentation to observe and record the morphology and composition of the nucleus. Using an innovative orbiting technique, long term observations of the nucleus from varying distances will allow high priority science data to be collected while addressing the flight system risks of proximity operations with an active comet.

2. SCIENCE OBJECTIVES AND MEASUREMENTS

A central theme of NASA's scientific investigations is the search for origins: the origin of the universe, the origin of our solar system, and the origin of life[3]. This theme is so important that it was incorporated into the congressional legislation that created NASA in 1958. The science objectives of the Odyssey mission are to directly address the goals of the exploration program as embodied in the Exploration of the Solar System quests[4]:

Quest 1: To Explain the Formation and Evolution of the Solar System and the Earth Within It - Comets are icy planetesimals left over from the formation of the solar system, and the only ones containing substantial volatiles. They provide a cosmo-chemical record of the solar nebula environment and the natal interstellar cloud.

Quest 2: To Seek the Origin of Life and Its Existence Beyond Earth - Comets are the likely source of the Late Heavy Bombardment, which provided a volatile veneer to

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the terrestrial planets, and brought water, organics, and other pre-biotic molecules. These provided the necessary resources for life to evolve on Earth and perhaps other planets, as soon as conditions were amenable to that evolution.

Quest 3: To Chart Our Destiny in the Solar System - Comets make up between 10% and 25% of the impact hazard on the Earth. The structure and composition of cometary nuclei need to be better understood in order to plan mitigation strategies and technologies.

The Discovery Program in particular has recognized the importance of comets through the selection of three flyby missions: Stardust, CONTOUR, and Deep Impact. Each of these flyby missions has focused objectives that will help us to understand comets and reveal some of the information they can provide about the early solar system. But the very nature of high-speed flyby missions limits the science that can be accomplished and the time to do it.

A comet rendezvous mission is the next logical step in NASA's exploration of comets. The Odyssey mission has three central themes that describe its objectives:

1. *To understand the cosmo-chemical record contained in comets of the formation of our solar system and the origin of life*
2. *To understand how a comet works*
3. *To understand the cometary environment and the problems of operating a spacecraft within a cometary coma, as a precursor to future cometary exploration*

The Odyssey mission carries a focused payload of five scientific instruments (plus radio science) that will address these themes and provide a major advance in our knowledge and understanding of comets.

Science Objectives

The goal of Odyssey is to answer these and other questions about comets, by orbiting a typical Jupiter-family short-period comet nucleus. The objective is to study it over a period of many months as it proceeds outward from a point near the perihelion of its orbit where it is most active, to beyond 3 AU from the Sun where activity from water ice sublimation will have substantially declined. The following science objectives have been defined for Odyssey:

1. *Determine the elemental, molecular, isotopic, and mineralogic composition of cometary materials and their variation with location on the nucleus and with time.*
2. *Determine the size, shape, rotation, surface topography, internal structure, surface temperature and thermal inertia, normal albedo and phase function, mass, and bulk density of the cometary nucleus.*
3. *Determine the source(s) of cometary activity and their variation as a function of rotation and orbital position.*

These science objectives are readily translatable into a set of science measurements to be made at Comet P/Kopff, one of the most active and well-observed Jupiter-family short-period comets. Table 1 provides a matrix of science objectives and the related measurements.

Table 1 – Science Objectives and Measurements

Science Objective	**Science Measurement**
Determine the composition of the nucleus	Collect coma gas and dust *in situ* for elemental, molecular, isotopic, and mineralogic analysis
	Map the nucleus and coma to determine composition, heterogeneity, ices, and mineralogic units
Determine the size, shape, rotation, mass, density, & surface topography of the nucleus	Map lit nucleus at ~1.0 m/pixel in multiple filters under different lighting conditions over 1 or more rotations
	Nucleus mass to < 1%
	Lower order harmonics in nucleus gravity field
Determine and monitor activity sources	Temporal coverage of source vents
	Map thermally at 20-100 m/pixel, >10 local times over comet day
	Map dust ejected as function of time and location

3. INSTRUMENTS

The Odyssey scientific payload consists of five instruments. The instruments are all body-fixed to the spacecraft and boresighted so that they can all view the cometary nucleus simultaneously. The instruments are mounted to a common science shelf at the +X end of the spacecraft and have unobscured views of the target, with no spacecraft appendages or other instruments in their way. Three of the Odyssey instruments have very high heritage, from missions such as Galileo, Cassini, Hubble Space Telescope, and Rosetta. The remaining two instruments are new developments.

Kopff Imaging System (KIS) - The Kopff Imaging System will provide high resolution images of the nucleus of comet Kopff and asteroid 24 Themis. KIS consists of a narrow angle camera (NAC) and a wide angle camera (WAC). Both cameras use identical but independent focal plane arrays (a 1024 x 1024 STIS CCD), shutters, 12-position filter wheels, and closeable covers. Each CCD is passively cooled to –90° C by a radiator pointed at right angles to the camera boresight. The cameras share a common, redundant electronics package that provides a readout time of 5 seconds at 16 bits/pixel.

Chemical Analysis of Released Gases Experiment (CHARGE) - The Chemical Analysis of Released Gases Experiment is a combined gas chromatograph and mass spectrometer that will measure a broad range of chemical species with a sensitivity many orders of magnitude higher than would be possible in the short time available during a high speed flyby. The measurement of chemical abundances from the same homologous series will establish the dominance of kinetic or thermodynamic conditions in the formation of these molecules and the relationship of this solar nebular material to the parent molecular cloud. The isotopic distribution of deuterium and other elements in different molecular species will likewise establish the relationship of comets to the parent interstellar material and enable the diversity of comets to be understood from related measurements on the CONTOUR and Rosetta missions. CHARGE will be nearly identical to the instrument that was planned for the Space Technology 4/Champollion comet lander mission.

Grain Impact Analyzer and Dust Accumulator (GIADA) - The Grain Impact Analyzer and Dust Accumulator experiment is aimed at studying the cometary dust size distribution, flux evolution and grain dynamic properties. GIADA will monitor the flux of grains coming from the nucleus and from four orthogonal directions. GIADA will determine the velocity and momentum, and hence the mass, of individual grains with radii > 20 µm. This will allow the determination of the size and mass distributions of the grains. Since the size distribution strongly influences the dust mass-loss rate estimate, its determination is mandatory for understanding the formation of the dust coma. Dust flux monitoring will also allow very precise estimates of the cometary dust-to-gas ratio. GIADA is identical to the instrument included in the scientific payload of ESA's Rosetta mission (to be launched in January, 2003).

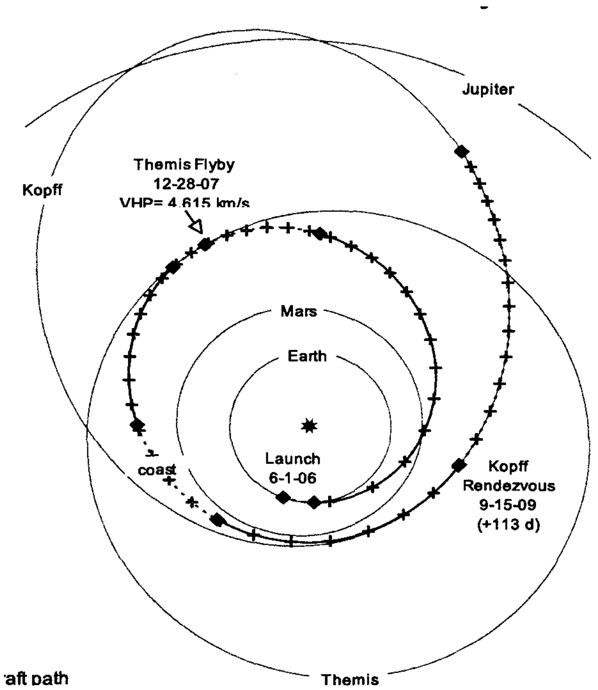
CHEmical and MINeralogical Dust Analyzer (CHEMIN) - The Chemical and Mineralogical Dust Analyzer will perform elemental and mineralogical analyses of 50 or more samples of 1–100 µm dust from the coma of Comet Kopff. Dust will be collected continuously at radial distances from 1,000 to 50 km. CHEMIN will utilize x-ray diffraction (XRD) to provide unequivocal identification of mineral phases within the dust and quantization of amorphous components. X-ray fluorescence (XRF) will be used to obtain quantitative analyses of sample composition for elements with atomic masses $5 < Z < 92$.

Odyssey Thermal Imager (OTI) - The Odyssey Thermal Imager is a compact, lightweight thermal infrared imager designed to map temperatures across the nucleus surface. Because the comet's activity and evolution is ultimately controlled by the temperature of its volatile species, thermal mapping provides key information for understanding the energy balance of the nucleus and the source(s) of cometary activity.

4. MISSION DESIGN

Odyssey will be launched on a Delta 2925-9.5 expendable vehicle (NLS medium) from Cape Canaveral in June, 2006 and will use a solar electric propulsion (SEP) spacecraft to achieve a rendezvous with P/Kopff in September, 2009. Flight time is 3.3 years. The rendezvous with Kopff occurs at 1.92 AU, approximately 113 days after perihelion; the comet will be active and will be moving away from the Sun. Odyssey's heliocentric trajectory is shown in Figure 1. En route to Kopff, Odyssey will fly by asteroid 24 Themis in December, 2007. Themis is a C-type (carbonaceous) main belt asteroid with an estimated diameter of ~215 km and a rotation period of 8.374 hours. This will be the largest asteroid ever encountered by any planetary spacecraft, by a factor of two. Science goals for the asteroid flyby are: imaging of the lit disk at 0.2 to 1 km/pixel resolution, IR radiometry of the entire surface at 4 to 21 km/pixel, a mass determination to an accuracy of better than 1%, and a search for potential satellites. Because Odyssey's primary goal is the comet rendezvous, the spacecraft will fly by at a safe distance of 10^4 km, well outside the dynamically stable zone for any orbiting debris or satellites. Table 2 lists the key trajectory parameters for this mission.

Figure 1 – Trajectory design



The SEP trajectory approaches Kopff along its orbital path, but ahead of the comet. The spacecraft trajectory will be offset out of the comet's orbital plane and inwards towards the Sun in order to avoid the associated cometary meteoroid stream. Only when the spacecraft's relative velocity has slowed to where it will not be damaged by meteoroid impacts, nominally <50 m/s, will it begin to move towards the comet nucleus.

Table 2 Odyssey Trajectory Parameters

Parameter	Value
Launch	June 1, 2006, Delta D2925-9.5
Launch window	30 days
Energy, C_3	21.0 km^2/sec^2
Cruise	
Flight time	1202 days (3.3 years)
SEP thrusting	827 days
Xenon used	143 kg
Min / max Sun range	1.012 / 2.597 AU
Asteroid flyby	December 28, 2007
Target	24 Themis, $d \approx 215$ km
Flyby velocity	4.615 km/sec
Sun / Earth range	2.742 / 1.861 AU
Minimum distance	10,000 km
Approach phase angle	80 degrees
Kopff rendezvous	September 15, 2009
Days from perihelion	+113 days
Rendezvous distance	140,000 km
Sun / Earth range	1.922 / 0.940 AU

The scientific instruments onboard Odyssey will carefully monitor the cometary dust and gas environment as the spacecraft slowly approaches the nucleus, from 100,000 to 10,000 km distance. This slow approach is designed to enable the instruments to characterize the cometary environment and to warn of any potential hazards. At any time, the approach can be suspended and the team will wait for cometary activity to decline to acceptable levels.

When it is safe to do so (as determined by instrument data), the Odyssey spacecraft will perform an initial flyby of the nucleus at a closest approach distance of ~500 km. During the flyby the rotating nucleus will be repeatedly imaged at a resolution of ~10 m/pixel (radiometer resolution ~210 m/pixel) and onboard in situ instruments will determine the composition of the outflowing dust and gas, and the dust flux rate.

The slow flyby of the nucleus will be repeated several times, at steadily decreasing distances and speeds, as permitted by the decline in cometary activity. The flybys will permit a determination of the nucleus mass to better than 10%, in preparation for the orbital phase of the mission. The approach and flyby phase will last ~3 ½ months.

Odyssey will then be maneuvered into a circular orbit at a radius of 200 km or less from the nucleus. The goal is to eventually achieve an orbital altitude of 50 km. The nucleus surface will be mapped at visible wavelengths at a resolution of 1 m/pixel, and in the thermal IR at 21 m/pixel. The elemental, molecular, mineralogic, and isotopic composition of the nucleus will be mapped through in situ measurements of the outflowing gas and dust. The mass and velocity distribution of the outflowing dust grains will be measured and the nucleus mass will be determined to better than 1% accuracy.

The orbital strategy is designed around "ping-pong" orbits. These are essentially half orbits of the nucleus, designed to keep the spacecraft always on the day side of the nucleus. As the spacecraft nadir point approaches the terminator, a maneuver will be performed using the hydrazine thrusters, which sends the spacecraft back along the same orbit, or onto a new one, but always on the sunlit side of the nucleus. This is possible because orbital velocities at Kopff are estimated to be very slow, only ~11 cm/s for a 50 km radius orbit. Thus, a wide variety of orbital geometries can be achieved for a very modest expenditure of hydrazine propellant.

There are several options for an extended mission at the completion of the 9 months of operations at Comet Kopff. One option is to continue to orbit the nucleus at successively decreasing altitudes, mapping the entire nucleus at tens-of-centimeters resolution and obtaining thermal images at spatial resolutions of a few meters. This phase would be followed by moving the spacecraft into more eccentric orbits around the nucleus, with periapse of perhaps only 1 km or less above the nucleus surface. An alternative option for an end-of-mission experiment is to maneuver the spacecraft to a touchdown on the nucleus surface.

5. FLIGHT SYSTEM

The Odyssey spacecraft design takes advantage of SEP technology to rendezvous with the comet. Figure 2 shows the spacecraft configuration as it would look in flight. All subsystem units except for solar arrays, antennas, propellant tanks, and thrusters mount to the inner faces of the equipment compartment. The science instruments are all body-fixed, mounted on the science shelf on the +X face of the equipment compartment. This approach satisfies the instruments' Field of View (FOV) requirements, and simplifies alignment and integration. Twenty-four mono-propellant hydrazine reaction control system (RCS) thrusters and the two ion engines are mounted to the propulsion shelf and the thrust tube, respectively, at the opposite end of the vehicle to minimize contamination to the payload. The two large wings of the 6 kW Ultraflex solar array are located "above" and "below" the bus, and are articulated about the Y-axis to maximize insolation during powered flight, in nucleus orbit, and during downlinks when the High Gain Antenna (HGA) boresight is pointed at the Earth. The HGA is body-fixed and boresighted along the –Z axis.

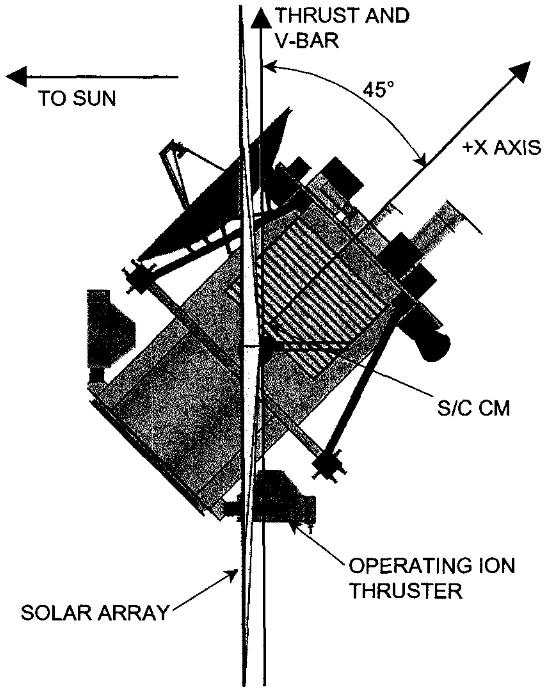


Figure 2 – Spacecraft Configuration during Flight

Electrical Power. The Odyssey spacecraft employs a dual string version of the DS-1 electrical power system which was designed for compatibility with SEP. Power generation is provided by a two wing, single axis articulated 6 kW (@1 AU, EOL) Ultraflex array sized for SEP propulsion and to support operations in nucleus orbit at a Sun range of 3.54 AU. Energy storage is provided by two 20 A-H Li-ion batteries selected to minimize mass. Battery charging is controlled by solar array switching implemented in the DS-1 heritage high voltage power control unit (HVPCU). Under-voltage and over-current protection are accomplished by the DS-1 heritage power distribution unit (PDU).

Command, Control and Data Handling. Odyssey's fully redundant, modular CC&DH approach is designed to minimize cost and development risk by providing standard interfaces (MIL-STD-1553B and RS422) to subsystem and payload elements, and by maximizing the use of flight proven and flight qualified components. The CC&DH subsystem uses the RAD-750 based S/C control unit (SCU) currently in full scale development for the Deep Impact and ST-3 missions, and a GFO/QuickScat heritage support electronics package configured to work with the MIL-STD-1553B data bus. The SCU provides 60 MIPS of computational capability, and selectable downlink telemetry rates from 16 bps to 330 kbps. The flight software code image is stored in EEPROM (8 Mbytes) and operates out of RAM (256 Mbytes). The core bootstrap and safe mode S/W is located in non-volatile ROM (8 Mbytes). The flight software is written in ANSI C, and runs under the VX-Works real-time operating system.

ADCS. The Odyssey Attitude Determination and Control Subsystem (ADCS) contains the sensors necessary to determine the spacecraft attitude, and sends control information to the control elements (thrusters and momentum wheels). The design is driven by the requirements for continuous powered flight and for pointing of the instrument payload during science operations. Table 3 shows the spacecraft attitude control system characteristics and pointing requirements. The selected attitude determination approach is a robust stellar/inertial reference design with redundant star trackers as the primary attitude reference. Coarse sun sensors and a laser gyro based IRU augment the trackers. The star trackers are pointed 90° away from the cometary nucleus to minimize dust contamination in nucleus orbit. Attitude control during powered flight is provided by gimbaling the ion thrusters. A 4 wheel, 3-axis, zero net momentum control system using reaction wheels is used for control when the ion engines are off. Periodic thruster RCS firings provide wheel desaturation. All control computations are provided by the CC&DH processor.

Table 3 - Attitude and Control Requirements

Control method	3 axis, zero-net-momentum
Control reference	Stellar/inertial
Attitude determination sensors	Star tracker, Sun sensors, Laser gyro IRU
Attitude control actuators	Four 2.5 N-m-s reaction wheels, 24 x 2.2 N hydrazine thrusters, 2 gimbaled ion engines
Attitude knowledge processing	Onboard: RAD-750 processor
Agility	Maintain nucleus nadir pointing, small mosaics, point HGA to Earth for downlink
On-orbit calibrations	None required
Deployments	Ultraflex solar arrays
Articulations	Ultraflex solar arrays – 1 axis Ion thrusters – 2-axes, each
Pointing accuracy	2.0 milliradians
Pointing knowledge	0.25 milliradians
Stability	30 microradians/sec
Jitter	< 0.01 milliradians/sec

Communications. Odyssey uses an X-band system for communications. This system uses redundant X-band Small Deep Space Transponders (SDST) and redundant 30 W TWTAs, combined with a 1.3-m aperture parabolic high gain antenna, an integral medium gain antenna (MGA) that is boresighted to the HGA, and two omnidirectional low gain antennas.

Hydrazine Propulsion/RCS. The chemical propulsion system is a hydrazine monopropellant blowdown system with 24 2.2 N thrusters. Thruster locations and orientations were selected to minimize contamination to the science instruments, and to provide 3 axes of delta-V and 3 axes of rotation using full couples. A single 39.1 cm (15.4") diameter fuel tank holds the required hydrazine and its helium pressurant. Fuel is managed using the tank's polymer diaphragm. In operation, the RCS provides 3 axes of reaction control torques for spin-down after separation and momentum wheel dumping. In addition to the RCS functions, the system provides up to 120 m/s of delta-V for maneuvers.

Solar Electric Propulsion. The Ion Propulsion System is a DS-1 heritage Solar Electric Propulsion (SEP) system. The SEP module is made up of two Hughes 30-cm xenon-ion thrusters, a xenon feed system (XFS), redundant power processing units (PPU), and redundant digital control and interface units (DCIU). The XFS incorporates a tank capable of carrying up to 220 kg of xenon. Both SEP thrusters are gimbaled over a 10° range to provide S/C attitude control during powered flight. Only one thruster is operated at a time in flight. Total xenon throughput for the nominal mission is 143 kg, or approximately 72 kg per thruster. An additional 15 kg (10%) of xenon is carried for contingency plus 7 kg (5%) for unusable fraction.

Thermal Control. Thermal control is simplified by an operational approach which keeps the equipment compartment radiator surfaces facing ecliptic north and south. This allows the use of standard MLI blankets, OSRs, second surface film, and heaters to cope with the reduced incident solar flux intensity on approach to, and in nucleus orbit. The two Y faces of the equipment deck mount all of the electronics including the SEP PPU's. The equipment compartment is enclosed with MLI blankets to minimize solar heating and heat loss during contingency modes of operation. North/south radiators covered by passive louvers maintain equipment compartment thermal balance over the full range of solar flux intensity and internal power dissipation.

6. CONCLUSIONS

The importance of comets was recognized by the Committee on Planetary Exploration (COMPLEX) in its most recent report, An Integrated Strategy for the Planetary Sciences 1995–2010: *"COMPLEX believes that the study of the composition of a cometary nucleus is the first among equals because such an investigation would contribute so much to understanding how our solar system originated."*
The Odyssey mission as proposed to the Discovery 2000 Program will perform the first ever rendezvous with and orbiting of a cometary nucleus, and will make detailed scientific measurements with unprecedented resolution and accuracy. This mission is the logical next step in the exploration of these important solar system bodies.

7. ACKNOWLEDGMENTS

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Dr. Paul Weissman *is the Principle Investigator for the Odyssey Proposal and is a leading expert on the physics and dynamics of comets in our solar system. His research interests include the origin and dynamical evolution of the Oort cloud, the dynamical evolution of long- and short-period comets in the solar system and their impact rates on the planets, thermal modeling of cometary nuclei, and the formation and structure of cometary nuclei. He served on the NASA Small Bodies Science Working Group from 1992 to1996. This is Dr. Weissman's first proposal to the Discovery program.*