THE COMET NUCLEUS TOUR (CONTOUR)

A NASA Discovery Mission

ANITA COCHRAN
Astronomy Department, University of Texas, Austin, TX 78712, USA

JOSEPH VEVERKA and JAMES BELL
Space Sciences Building, Cornell University, Ithaca, NY 14853, USA

MICHAEL BELTON
Belton Space Exploration Initiatives, LLC, 430 S. Randolph Way, Tucson, AZ 85716, USA

JOHANNES BENKHOFF
Institute for Space Sensoric & Planetary Exploration, Rutherford Str. 2, Berlin D-12489, Germany

ANDREW CHENG
Johns Hopkins APL, 11100 Johns Hopkins Rd., Laurel, MD 20723, USA

BENTON CLARK
Lockheed Martin, P.O. Box 179 MS S-8000, Denver, CO 80201 USA

PAUL FELDMAN
Department of Physics and Astronomy, Johns Hopkins University, Baltimore, MD 21218, USA

JOCHEN KISSEL
MPI für Astrophysik, Karl-Schwarzschild-Strasse 1, Postfach 1317, Garching, D-85741, Germany

PAUL MAHAFFY
NASA/GSFC, Code 915, Laboratory for Atmospheres, Greenbelt, MD 20771, USA

MICHAEL MALIN
Malin Space Sciences, 5280 Carroll Canyon Rd., Suite 310, San Diego, CA 92191, USA

SCOTT MURCHIE
Johns Hopkins APL, 11100 Johns Hopkins Rd., Laurel, MD 20723, USA

HASSO NEIMANN
NASA/GSFC, Code 915, Laboratory for Atmospheres, Greenbelt, MD 20771, USA

TOBIAS OWEN
Institute for Astronomy, 2680 Woodlawn Dr., Honolulu, HI 96822, USA

MARK ROBINSON
Northwestern University Geological Sciences, 1847 Sheridan Rd., Evanston, IL 60208, USA

GERHARD SCHWEHM
ESTEC, SO Division, Space Sciences Department of ESA, P.O. Box 299 NL-2200 AG, Noordwijk

STEVE SQUYRES and PETER THOMAS
Space Sciences Building, Cornell University, Ithaca, NY 14853, USA

FRED WHIPPLE
Smithsonian Astrophysical Observatory, 60 Garden St., Cambridge, MA 02138, USA

DONALD YEOMANS
Jet Propulsion Laboratory, 4800 Oak Grove Dr., MS 301-150, Pasadena, CA 91109, USA

Earth, Moon and Planets **89:** 289–300, 2002.

(Received 8 March 2002; Accepted 19 May 2002)

Abstract. In 1997, the COmet Nucleus TOUR (CONTOUR) was selected by NASA for a new start as part of the Discovery line. In this paper, we review the status of the mission, the mission timeline and the instruments to be flown. Detail is given of the science goals and how they are to be accomplished.

Keywords: Comets, missions

1. Introduction

In 1997, NASA selected the COmet Nucleus TOUR (CONTOUR) for a new start as part of the Office of Space Sciences' Discovery Program of small, inexpensive, planetary missions. The Principal Investigator for this mission is Joseph Veverka of Cornell University. The spacecraft is being built by the Advanced Physics Laboratory of The Johns Hopkins University.

The goal of the CONTOUR mission is to assess the diversity of comets by flying past and observing at least two comets. In accomplishing this goal, the CONTOUR Science Team will determine the properties of the nuclei, measure the composition of the gas and the dust and study the coma. CONTOUR will fly past the target comets as closely as 130 km allowing the imaging of detail as small as 4 meters.

The spacecraft/comet encounters will take place when the comets are relatively near the Earth and around 1 AU from the Sun. The small geocentric distance allows for excellent communications with the spacecraft. The small heliocentric distance maximizes the chance that the comet will be very active. In addition, all flybys are chosen to have excellent viewing geometry for Earth-based observations.

The CONTOUR mission is an extremely flexible mission, with repeated flybys of the Earth for purposes of retargeting the spacecraft. Thus, we would be able to retarget to a new comet if one is discovered while the spacecraft is in operation. The mission timeline will be discussed in the next section.

The CONTOUR spacecraft will carry four instruments to achieve the mission scientific goals. These instruments are described below along with the key science tasks they will be used to accomplish. All instruments have been delivered and the spacecraft is in its final environmental test, on schedule for a July 2002 launch.

The spacecraft is quite compact with no deployable parts. The solar panels are body-mounted on all sides of the spacecraft except for the forward face. The forward face carries the Whipple bumpers (dust shields) which consist of 7 layers of Kevlar and 4 layers of Nextel fabric. The Whipple bumpers extend approximately 5 inches past the edge of the spacecraft to afford dust protection to the aft (trailing) part of the spacecraft. A high gain antenna and a pancake antenna are mounted on the aft face of the spacecraft.

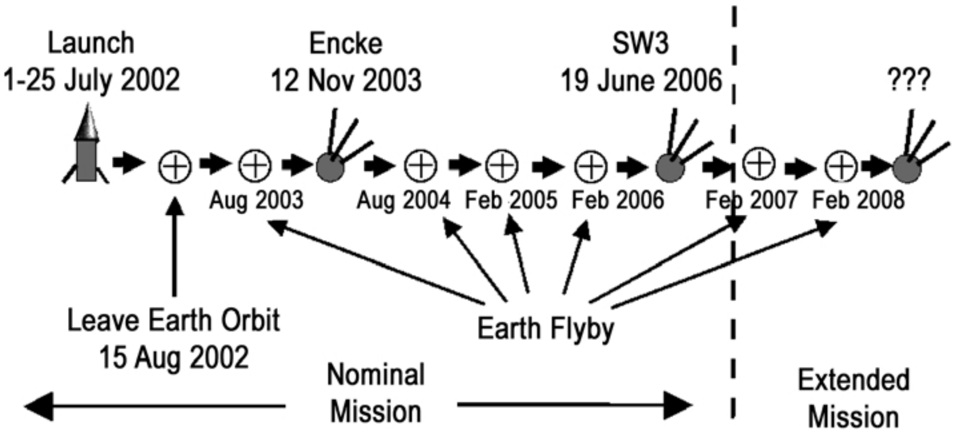

Figure 1. The nominal CONTOUR mission timeline with the flybys of Encke and Schwassmann–Wachmann 3 shown.

2. Mission Timeline

The CONTOUR spacecraft is scheduled for launch from Cape Canaveral aboard a Delta-2425 (Med-Lite) rocket with the launch window opening on 1 July 2002 and extending to 25 July 2002. The spacecraft will be placed into a high-apogee ($\sim$ 18.1 Earth-radii) phasing orbit with a period of $\sim$ 1.75 days. On 15 August 2002, a STAR-30 solid rocket motor will be used to place the spacecraft into a one-year Earth-return trajectory.

In August 2003, the spacecraft will utilize an Earth gravity assist to target the spacecraft past its first target, comet 2P/Encke, on 12 November 2003. After the flyby of Encke, the spacecraft will use an Earth encounter for trajectory modification approximately once per year. The nominal mission includes a second flyby of comet 73P/Schwassmann–Wachmann 3 on 19 Jun 2006. At the end of the second encounter, the nominal mission will be complete. However, the spacecraft carries enough additional ΔV margin so that it could be targeted to an additional comet if an extended mission were to be approved. Figure 1 shows a schematic of the nominal mission; the flyby parameters for the nominal mission are given in Table I.

The CONTOUR targets were chosen for a number of reasons. First of all, these targets are energetically reasonable for the spacecraft to fly by without very high encounter speeds. Second, the targets are well placed so that the comets are very active at the time of the flyby and the Earth is not far away, to aid communications. Additionally, the heliocentric distances of the flybys enable excellent power margins for the encounters. Finally, the targets were chosen so that they may be viewed from the ground during the flyby to allow for maximum support from telescopic observations.

Comet 2P/Encke is an excellent comet to study since its orbit is well determined and the comet has been near the Sun for a long time. The comet still displays a great

TABLE I
The nominal CONTOUR mission

Comet	Flyby speed (km/sec)	Phrase (degrees)	R_h (AU)	Δ (AU)	Solar[a] elong. (degrees)
2P/Encke	28.3	12	1.07	0.27	104
73P/Schwassmann-Wachmann 3	14.0	100	0.95	0.33	70

[a] Solar elongation as seen from Earth.

deal of gas activity, while the coma seems devoid of small dust (though large dust grains are known to be near the comet). Comet Encke is an excellent example of a highly evolved comet.

Comet 73P/Schwassmann–Wachmann 3 is also a short-period comet which has been observed for several apparitions. This comet underwent a splitting episode in 1995 into at least three fragments. One of the fragments has disappeared from view and a second may fade by 2006, but at least one fragment should be available for targeting with CONTOUR. Thus, the spacecraft will fly past a comet which has ices which have only been exposed to the Sun for a relatively short time and should prove an excellent contrast to Encke.

The repeated Earth flybys are useful not only for the nominal mission but to add flexibility to the mission. These flybys allow an adaptive mission plan so that if a bright, new comet were to be discovered while the CONTOUR spacecraft was in operation, we would have the opportunity to retarget the spacecraft to this newly discovered comet. The new comet would have to be discovered prior to the Earth flyby preceding the time of encounter and would have to be energetically reasonable to fly past. The encounter would have to occur between 0.8 AU (spacecraft heating) and 1.40 AU (spacecraft power). These conditions are not overwhelmingly difficult to achieve. Had the spacecraft been in space in 1995, we would have been able to retarget to Hale–Bopp, for example.

An important feature of the CONTOUR operations model is that the spacecraft will be put into "hibernation" during much of the mission. The spacecraft will be three-axis stabilized for all encounters. However, between encounters, the spacecraft will be put into a spinning attitude for maximum stability. Then, during these hibernation periods, no contact will be made with the spacecraft (though we could contact the spacecraft if needed). The hibernation mode minimizes the need for controllers on the ground to communicate with the spacecraft during a phase when basically little is taking place. During hibernation, minimal keep-alive power will be used.

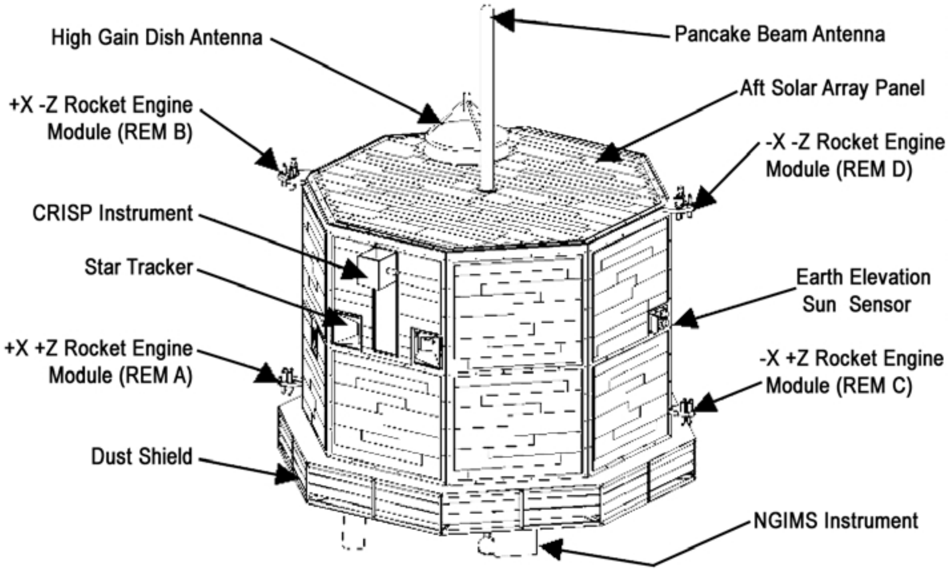

Figure 2. The layout of the CONTOUR spacecraft. Some of the instruments are marked.

3. Instrumentation

The CONTOUR spacecraft carries four instruments for targeting and science. These include the CONTOUR Remote Imaging SPectrograph (CRISP), the CONTOUR Forward Imager (CFI), the Neutral Gas and Ion Mass Spectrometer (NGIMS), and the Comet Impact Dust Analyzer (CIDA). Figure 2 shows a layout of the spacecraft with some of the instruments indicated. All instruments are mounted on the center deck of the spacecraft with the exception of the CRISP instrument, which is mounted towards the aft.

3.1. CONTOUR REMOTE IMAGING SPECTROGRAPH (CRISP)

CRISP is a combination narrow-angle optical camera and near-IR spectrometer. The light will be partitioned to the two parts of the instrument with a beamsplitter which will pass light at wavelengths below 800 nm to the imager.

The imager uses a Thompson 7888A frame transfer CCD with 1024 × 1024 pixels. The chip is front-side illuminated with anti-blooming circuitry. The CRISP imaging telescope is a 680-mm focal length, f/6.8 Ritchie–Chretien design. The operational bandpass of the CRISP camera is 0.45–0.79 μm; the camera has a field-of-view (FOV) of 1.2° × 1.2°. The camera has a 10-filter wheel and will have 40 nm-wide filters covering the bandpass (see Table II). The detector is passively cooled with a radiator with operational temperature expected to be around -30 °C. The usable exposures can be as short as 10 msec with up to 1 image per second.

TABLE II
The CRISP filters

Center λ (nm)	Filter FWHM (nm)	Purpose
650	300	Broadband, backup OPNAV
450	40	Geology (“blue”)
490	40	Geology
530	40	Geology (“green”)
570	40	Geology
610	40	Geology
650	40	Geology (“red”)
690	40	Geology
730	40	Geology
770	40	Geology

The signal-to-noise ratio (SNR) is expected to be >75 for multispectral imaging and >100 for short broadband exposures.

The near-IR spectrometer uses a Rockwell PICNIC HgCdTe detector with a 2.55 μm cut-off. The detector has 256 × 256 pixels; the FOV of the spectrograph is 0.86° × 0.003°. The detector is kept cooled with a Ricor K508 integral stirling cooler which will keep the detector at a temperature of 90K. The IR detector can be read out at a cadence of 5 Hz. The spectrograph should have SNR $>$ 175 over its full bandpass.

The CRISP instrument is mounted at one end of the spacecraft (see Figure 2) in order for it to be able to view around the dust shield but to be fully protected from dust impacts. The instrument employs a two-sided rotatable mirror in order to be able to track the nucleus. The CRISP instrument will have a full, unvignetted aperture from 6 to 30 degrees off the $+Z$ axis (the nominal velocity vector) and from 0 to 30 degrees off the $-Z$ axis (the nominal anti-velocity vector). The placement of the instrument, the dust shield and the mirror will allow for imaging up until 8 sec from closest approach inbound. During the period near closest approach, the “science” side of the mirror will be used. During this close approach phase, the CRISP instrument images will be used (by the onboard computer) for closed-loop tracking to ensure that we remain on target.

Prior to the inbound point when the CRISP mirror will be fully unvignetted, the spacecraft will perform occasional “tilt and peek” maneuvers to image the comet with CRISP. For these observations, the “flight” side of the mirror will be used since there is a non-zero risk of pitting of the mirror by dust during these observations. This will maintain an excellent surface on the science side for the closest approach observations.

The mirror rotation speed and readout speeds combine so that the tracking accuracy is < 1.5 pixels for the shortest (10 ms) exposures if the miss distance is >100 km. Thus, the smear will be less than 1.5 pixels for the highest resolution images. This factor drives the nearest miss distance to be at least 100 km from the nucleus. In practice, the nominal Encke flyby will be targeted to be no closer than 100 km plus the 3σ targeting error, or around 130 km.

Two star trackers provided by the Danish Technical University are hard-mounted to the CRISP instrument to provide absolute attitude information to the spacecraft. Two star trackers are needed to provide redundancy. The spacecraft uses this absolute information in combination with the gyros to provide the overall attitude solution.

CRISP's closed-loop tracking of the comet is based on our known encounter trajectory. The star trackers are used to measure small differences from the expected location of the nucleus and correct the encounter trajectory model. In doing so, we are effectively measuring the direction to the nucleus relative to the velocity vector of the spacecraft. By mounting the star trackers directly to CRISP, any bending of the structure between the two is minimized, especially since they are operating at the same temperature. Furthermore, any motion which does occur should be repeatable and will be able to be calibrated. A more conventional arrangement of mounting the star trackers to the spacecraft, instead of CRISP, would have had the star trackers and CRISP operating at different temperatures and would not achieve the accuracy required.

3.2. CONTOUR FORWARD IMAGER (CFI)

The CONTOUR Forward Imager is a wide-angle optical camera whose primary role is for optical navigation (OPNAV). CFI has a 300 mm focal length, f/5 telescope for imaging a $2.5^\circ \times 2.5^\circ$ FOV. The detector is a Marconi 47-20 1024×1024 pixel back-side illuminated CCD. With a broadband filter, CFI will achieve SNR ~ 14 in a single 1 sec frame for stars of $V = 11$. The high sensitivity will permit region-of-interest readouts (256×256 pixel) so that many frames may be obtained and downlinked quickly and then co-added on the ground for improved SNR. This will allow the detection of the comets far from closest approach, even when they are quite dim. In the event that there were a failure of the CFI, OPNAV responsibilities would be taken over by CRISP, though the CRISP imager is less sensitive.

Secondary roles for CFI are for multispectral imaging of the nucleus and jets and for coma emission imaging. The CCD in CFI has a peak quantum efficiency (QE) of $\sim$90%. In addition, the QE is $>$40% at 308 nm. Typical exposure times will be 90 msec to 10 sec, with a maximum cadence of 1 Hz. As with the CRISP imager, cooling will be achieved via a passive radiator with operational temperature expected to be < -40 °C.

CFI uses a hole in the dust shield and a baffle in the forward face of the spacecraft for viewing. The camera does not view directly out through the hole

TABLE III

The CFI filters

Center λ (nm)	Filter FWHM (nm)	Purpose
650	300	Broadband, OPNAV
309.0	6.0	OH emission
344.8	16.8	OH, CN continuum
387.0	12.4	CN emission
445	30	Geology ("blue")
514.1	23.6	C_2 emission
526	11.2	Geology ("green"), C_2 continuum
620	30	Geology ("red")
840	30	Geology
920	40	Geology

but instead, the light is directed into the camera with a flat diagonal mirror. This leaves the camera protected from the possibilities of dust impacts but leaves the mirror susceptible to dust pitting, causing a scattered light background. Of course, the dust hazard is greatest nearest to the nucleus. In order to have the best mirror surface possible for each comet encounter, CFI has four separate mirrors on a cube-like rotatable turret. Just before each encounter, a fresh surface will be rotated into the beam so that we will encounter each comet with the best possible surface.

CFI carries a 10-filter wheel. The filters are described in Table III. Five of the CFI filters are specially chosen for coma science. These filters are relatively narrow but the high QE of the system, coupled with binning the data, will allow coma images of SNR >5 in 10 s for these filters. Multiple frames can be co-added for higher SNR. The coma filters are closely matched to the "Hale–Bopp" filters currently in use by much of the comet community.

3.3. NEUTRAL GAS AND ION MASS SPECTROMETER (NGIMS)

NGIMS consists of two ion sources (open and closed), an electrostatic quadrupole deflector which selects ions from the desired source, an ion detector, and a quadrupole mass analyzer. The nominal mass range is 1–300 AMU. This can be sampled in a variety of programmed modes with scans of 1/10 or 1 AMU steps. The instrument has the sensitivity to detect noble gases and inert species to mixing ratios of several tens of parts per billion and reactive species such as radicals to better than 1%. Various isotopes, such as the D/H ratio in water, will be measured using a combination of neutral and ion measurements.

The open ion source will measure the ambient particle density directly without any gas surface interactions. The closed source uses ram density enhancement to provide measurements of higher accuracy and sensitivity, especially for non-reactive species. The ram density enhancement is achieved by sampling the ambient gas through an array of collimated tubes pointing in the RAM direction. A comparison of the open source ambient number density with the closed source flux for the same species will yield the outflow.

Relatively minor switching operations are needed to optimize the instrument for ion, rather than neutral, particle detection. These operations consist of switching off the open source electron emitter and changing voltages on the electrostatic deflector and several lens elements to optimize focusing of the incoming ions into the analyzer.

Ions are directed to the mass analyzer from the selected ion source by changing the potentials on a quadrupole deflector. This electrostatic device allows each source of ions to be sequentially switched to a common exit lens system that focuses the ion beam into the quadrupole mass analyzer.

NGIMS sits in front of the Whipple bumper but the hazard presented by dust to NGIMS is greatly reduced by the choice of the ion source geometry. Dust particles will pass through the open source and not into the analyzer. Shielding baffles will minimize scattered dust from entering critical regions.

3.4. COMET IMPACT DUST ANALYZER (CIDA)

The CIDA instrument analyzes the elemental and chemical composition of individual dust and ice grains in the cometary coma. As each particle impacts a silver plate, the high impact energy due to the velocity of the spacecraft as it flies through the coma causes the elements and molecular compounds in the particle to become ionized. Using a fast scan time-of-flight mass spectrometer, a complete set of ions are detected for each impact, from a mass range of 1 (atomic hydrogen) up to several thousand atomic mass units, encompassing all elements in the periodic table and many molecules, such as organic compounds. This experimental technique has already been applied with excellent success at Halley's comet, and the sister instrument to CIDA is currently flying on the Stardust mission.

The CIDA instrument consists of the impact target, a set of electrically-charged, electrically-biased grids, flight tubes, and an ion detector. When ions are created at the time of impact, a special extractor grid "pulls" out the ions of interest. CIDA can be set to analyze either positive or negative ions by simply setting the voltage on the extractor grid from negative to positive (it cannot analyze both at once). Ions of the proper polarity are extracted and then subjected to 1000 volts of acceleration into two sequential drift tubes. Another set of grids at the end of the first tube are biased with a voltage which repels the ions and sends them down a second tube. This "reflector" arrangement allows CIDA to have better resolution of individual ion types by compensating for varying energies of the ions when they are created by the high-energy impact. After flying down the second tube, the ions hit a special, highly sensitive detector with very fast response. As ions impinge on the detector, they eject electrons which are then multiplied by successive accelerations and impacts onto subsequent targets designed to emit electrons with high efficiency. By this cascading amplification process, even a single ion can be detected by the flight electronics.

For hydrogen ions, the flight time down the tube is only 4 μsec. Heavier ions travel more slowly, in proportion to their mass, and it is by this principle that the "time-of-flight mass spectrometer" is able to determine the difference between each type of ion. Silicon ions take 21 μsec, while fully-stripped iron ions take 30 μsec to race down the flight tubes. By measuring the number of ions and time of arrival for each type, CIDA can determine the composition of each dust grain which hits the target. Complicating factors include the fact that each element or molecule can have charges ranging from one to many electrons, depending on the complexity of the impact process. Also, molecules can be torn apart into molecular sub-fragments or even down into their constituent elements. Using the results of laboratory studies with high-velocity particles created by a nuclear accelerator, plus theoretical understanding of the physics of the processes, the measurements made will be analyzed by the CIDA science investigators to determine the types, sizes, and abundances of several thousand particles in the coma of each of the comets to be encountered by the CONTOUR mission.

4. Science Goals

4.1. Nucleus properties

The top priority of the CONTOUR mission is to image the nuclei of at least two comets with a resolution of at least 10 m/pixel. With a closest approach distance for comet Encke of 130 km and the minimal smearing described for CRISP above, we should be able to better this goal. These images can be used to study the small-scale morphology of the nucleus, the surface roughness, possible craters or sublimation pits, etc. The highest spatial resolution images will be achieved with the broadband filter on CRISP.

Multispectral images with first CFI and then CRISP, coupled with hyperspectral maps with CRISP, will allow for a detailed study of variations on the nucleus. A correlation of the spectral variations with morphology will help constrain jet formation and mass wasting processes. Such maps will also provide evidence for spectral inhomogeneities with the ability to detect 1% variations in band depth over a spot covering 1% of the surface. The 0.4–2.5 μm bandpass to be used will allow for detection of the major likely ice and silicate absorptions.

On approach to the targets, CFI and then CRISP will be used to obtain moderate spatial resolution images of the nucleus. We plan to detect the comet at least 12 hours before closest approach and to track brightness variations for at least 6 hours. This will allow for the determination of the rotation state of the nucleus. In addition, any images for which the resolution is at least 500 m/pixel will be utilized to build a shape model for the nucleus.

4.2. THE NEAR-NUCLEUS ENVIRONMENT

The two *in situ* instruments, NGIMS and CIDA, will allow for the measurement of the properties of the gas and dust in the inner coma as a function of distance from the nucleus. Data will be collected on both the inbound and outbound legs to map the composition as a function of azimuthal and radial position.

CIDA can distinguish between silicate and CHON particles. It will be most sensitive to H, C, N, O, Mg, Al, Si, S, Ca and Fe. In combination with NGIMS, we can use these data to study the extended sources of the coma.

As the spacecraft approaches the nucleus, there is the possibility that it will pass through more and less dense regions due to jets. By mapping the composition in the different regions, we will be able to determine the contribution to the inner coma by active regions and by the more quiescent surface.

The imaging maps with the "coma" filters will be used to place the *in situ* observations into their broader context so that we can correlate the passage of the spacecraft through jets with the measurements made with CIDA and NGIMS. This will allow us to probe the nature of the jets and how they contribute to the coma.

4.3. THE COMA

While the comets will be observable with ground-based instruments, we will use observations of the comet with coma filters to monitor the nature of the cometary comae. The CFI coma filters will be used to obtain maps with SNR of 7–18. These observations will be the most directly comparable to ground-based observations and will provide the "ground truth" for the support observations.

NGIMS will begin sampling at around 100,000 km from the nucleus and will sample through closest approach. It will use an observing strategy of cycling between fine spatial sampling of key mass bins, more widely spaced sampling of other mass bins, and searches for new species. This will maintain the greatest flexibility to detect new species while affording excellent coverage of expected species.

4.4. DIVERSITY

The nominal mission consists of flybys of two comets, currently Encke and Schwassmann–Wachmann 3. While both of these are short-period, Jupiter-family comets they differ markedly since Encke is an old, dust poor comet and Schwassmann–Wachmann 3 is newly split. We will be flying past these two targets with identical instrument complements to allow direct comparison.

In addition to these two comets, the spacecraft carries enough additional ΔV that, if NASA were to approve, we could target additional comets. Alternatively, if a new, Oort cloud comet, were discovered, we could retarget to observe that comet. This flexibility offers the only opportunity to target a dynamically new comet in the foreseeable future.

5. Summary

The CONTOUR mission is an extremely capable and flexible mission which affords an opportunity to study the diversity of cometary nuclei. The data will increase our understanding of cometary nuclei and the environment around comets immeasurably. With the first target to be comet 2P/Encke, in November 2003, we will soon have a giant increase of our knowledge of a comet's nucleus.

Acknowledgements

CONTOUR, a NASA Discovery mission, is a cooperative effort between Cornell University and The Johns Hopkins University Applied Physics Laboratory.