Abstract IT-3-1

RADIO OBSERVATIONS OF MOLECULAR AND ISOTOPIC SPECIES: IMPLICATIONS ON THE INTERSTELLAR ORIGIN OF COMETARY ICES

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We present here a review of the radio observations of the remarkable comet Hale-Bopp C/1995 O1 in which most major radioastronomical facilities have been involved. These observations started in August 1995, soon after the discovery of the comet, when it was at $\sim$ 7 AU from the sun and well before its perihelion on April 1st, 1997; they are still going on, hopefully up to end 1998. Extended cartographies have been obtained using multibeam receivers and on-the-fly techniques. High spatial resolution (a few ") has been achieved with interferometers. Submillimetric observations are playing an increasing role, and high resolution (R $\sim 10^6$-10^7) spectroscopy of cometary lines is now performed from centimetric to submillimetric wavelengths.

The number of species observed at radio wavelengths reaches now $\sim$ 28, when it was $\sim$ 14 for 1996 comet Hyakutake. Most of these species are parent molecules. However ions have been observed for the first time at radiowavelength, and their velocities measured. Several isotopic species (involving D,^{13}C,^{34}S,^{15}N) have been detected, allowing enrichment determinations.

The abundances of cometary molecules present many similarities and some differences with the abundances of interstellar molecules in regions where grain mantles are believed to be evaporated to the gas phase (hot cores, bipolar flows). They will be discussed for their implications on the origin of cometary ices, and of comets themselves.

Abstract CT-3a-1

NEW MOLECULAR SPECIES IN COMET C/1995 O1 (HALE-BOPP) OBSERVED WITH THE CALTECH SUBMILLIMETER OBSERVATORY

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We present millimeter-wave observations of HNCO, $H^{13}CN$, HC_3N, SO, NH_2CHO, and H_3O^+ in comet C/1995 O1 (Hale-Bopp) obtained in February-April 1997 with the Caltech Submillimeter Observatory.

HNCO, first detected at the CSO in comet C/1996 B2 (Hyakutake), is securely confirmed in Hale-Bopp via observations of four rotational transitions at 219.798, 241.774, 263.749, and 351.633 GHz. The derived HNCO abundance with respect to HCN is approximately 50%. The 259.012 GHz transition of $H^{13}CN$ is detected and the implied $HCN/H^{13}CN$ abundance ratio is 90 ± 15, consistent with the solar value. HC_3N, SO, and NH_2CHO are detected for the first time in a comet. The fractional abundance of HC_3N based on observations of three rotational lines at 218.324, 254.700, and 263.792 GHz is 7% with respect to HCN, similar to that measured for CH_3CN. Two transitions of SO at 251.826 and 304.078 GHz are detected and the derived fractional abundance relative to water is higher than that implied by previous upper limits in the UV.

Observations of the 254.877 GHz transition of NH_2CHO imply a fractional abundance of 4% with respect to HCN. H_3O^+ is detected for the first time from the ground through its 364.797 GHz line. In addition, a number of other molecular species are detected, including HNC, OCS, HCO^+, CO^+, and CN (the last two are first detections in a comet at radio wavelengths). The HCN/HNC abundance ratio is found to be highly variable between December 1996 and April 1997.

Abstract CT-3a-2

K-BAND RADIO OBSERVATIONS OF COMET HALE-BOPP: DETECTIONS OF AMMONIA AND (POSSIBLY) WATER

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K-band radio observations of comet Hale-Bopp (C/1995 O1) were conducted in March/April 1997 at the 100-m Effelsberg Telescope of the Max-Planck-Institut für Radioastronomie. Emission was firmly detected from the five lowest metastable (J=K) inversion transitions of ammonia. Assuming a thermal distribution for the metastable states of NH_3, we derive a rotational temperature of 104±30 K, a value consistent with other estimates for the kinetic temperature in the inner gas coma ($R < 5000$ km). An ammonia production rate at perihelion of $6.6 \pm 1.3 \times 10^{28}$ s^{-1} is calculated from the measured line strengths. The ammonia-to-water abundance ratio at this time is estimated to be between 1.0% and 1.8%, implying that ammonia is a fairly prominent trace constituent in cometary nuclei. The results are compared with the only other sightings of NH_3 emission in the comets Iras-Araki-Alcock (1983 VII) and Hayakutake (C/1996 B2) as well as with a few surprising nondetections. We also report a marginal detection of the 6_{16}–5_{23} transition line of water at $\lambda = 1.35$ cm during the same observation epoch.

Abstract CT-3a-3

THE HNC/HCN RATIO IN COMETS

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Hydrogen isocyanide (HNC) is a well known interstellar molecule, whose relatively high abundance has long been cited as evidence for the importance of gas phase ion-molecule chemistry in molecular clouds. The detection of HNC in C/1996 B2 was thus a surprise, particularly since the HNC/HCN abundance ratio was similar to that characterizing the non-equilibrium conditions found in dense interstellar clouds. The detection therefore raised the possibility that the HNC might be surviving interstellar material. Such preservation of molecular material during the energetic events associated with solar system formation would provide important constraints on these processes and on the chemistry of comets. Alternative origins for the HNC, however, included the possibility that it might be produced by photochemistry or by gas phase chemistry in the cometary coma. A discriminant among possible origins for HNC is the dependence of the HNC/HCN ratio on heliocentric distance. The apparition of C/1995 O1 has provided an opportunity to test these ideas. We find that the HNC/HCN ratio did indeed vary with heliocentric distance in that comet, such that HNC appears to be produced in the coma. We are modeling the emission in various ways to constrain the abundance ratio vs. heliocentric distance as tightly as possible. We have also adapted an interstellar chemical code to the cometary conditions, and calculations to investigate possible production pathways for HNC will be described.

Abstract CT-3a-4

FLUORESCENCE AND COLLISIONAL PROCESSES OF SO AND SO_2 IN COMET HALE-BOPP (C/1995 O1)

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SO and SO_2 have been successfully observed in comet Hale-Bopp (C/1995 O1) with the IRAM (Institut de Radio Astronomie Millimétrique) telescopes (e.g., Bockelée-Morvan et al. 1997, BAAS, 29, 1047) and Caltech Submillimeter Observatory (Lis et al. 1997, BAAS, 29, 1046). Preliminary results (Bockelée-Morvan et al. 1997) indicate that the SO and SO_2 mixing ratios are much greater than upper limits derived from IUE spectra of several previous comets (Kim and A'Hearn, 1991, Icarus, 90, 79). The preliminary production rates also suggest that SO is more abundant than expected from the photodissociation of SO_2. A model, which includes UV photodissociation, electronic, ro-vibrational, pure-rotational transitions, and excitation processes caused by electron/neutral collisions, must be developed in order to resolve the above discrepancies. We will present the model at the meeting.

Abstract CT-3a-5

OBSERVING OH IN THE COMA OF COMET HALE-BOPP VIA OCCULTATION OF RADIO SOURCES

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Since the bulk of the volatile portion of comets is H_2O, it is obviously important to understand H_2O in cometary comae. Unfortunately, the centimeter line of H_2O is weak, and has not been reliably detected. However, OH, the primary dissociation product of H_2O, is abundant and has strong centimeter transitions. So, by observing OH, something can be learned about cometary H_2O.

Hale-Bopp was observed in the 1665 and 1667 MHz OH lines at the NRAO's Very Large Array (VLA) in New Mexico on many occasions. I will discuss only the occultation experiments here, however. One such occultation experiment was also recently conducted at the Australia Telescope Compact Array (ATCA) in Narrabri, NSW. In these experiments, a bright, compact background radio source is observed as the cometary coma moves past it on the plane of the sky. As the emission from the background source passes through the OH gas in the coma, an emission or absorption line is produced, depending on the excitation of the ground state Λ doublet levels. So, by observing the lines as a function of position of the background source relative to the nucleus, we sample a pencil-beam along a chord through the gas in the coma, potentially yielding a profile of the column density of OH along the projected track of the background source, and a constraint on the production rate of H_2O from the nucleus. We can also get information on the excitation state of the OH molecules, by comparing the lines in the 1665 and 1667 MHz transitions. Such experiments were performed on 5 occasions: Sep. 30, 1996, and Feb. 12, Mar. 25, Apr. 14, 1997 (VLA) and Oct. 4, 1997 (ATCA), with the first 4 yielding clearly detected lines, and the last yielding a marginally detected line. At least 2 of these experiments had lines strong enough to give a profile of OH along the track of the background source. The results from all 5 of these experiments will be discussed.

Abstract IT-3a-2

INFRARED OBSERVATIONS OF VOLATILE MOLECULES IN COMET HALE-BOPP

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Infrared spectroscopy, by observing the vibrational bands of molecules, is an adequate tool for the identification and study of volatiles outgassed from cometary nuclei. It can also investigate the composition of ice-coated cometary grains. Infrared observations of the exceptionally bright comet C/1995 O1 (Hale-Bopp) benefited from the high spectral resolution and sensitivity of échelle spectrometers now equipping ground-based telescopes and from the availability of the Infrared Space Observatory (ISO). The present paper will review the results obtained by different groups.

From ground-based IR observations, several hydrocarbons (CH_4, C_2H_2, C_2H_6) were unambiguously detected for the first time in C/1996 B2 (Hyakutake) and then in comet Hale-Bopp. CO, HCN, OCS and several radicals were also observed. Carbon dioxide was directly observed for the second time in a comet (after its detection from the Vega probes in P/Halley) by ISO. The spectrum of water in comet Hale-Bopp was investigated in details by ISO (fundamental and combination bands of vibration at 2.7 and 6 μm and rotational lines in the far-infrared) and from the ground (IR hot bands). This permitted the evaluation of the rotational temperature of water, and of its spin temperature (presumed to be a tracer of the temperature formation of cometary material) from the ortho-to-para ratio.

Abstract CT-3a-6

THE INFRARED SPECTRUM OF COMET HALE-BOPP AS SEEN BY THE INFRARED SPACE OBSERVATORY

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Spectra of comet C/1995 O1 (Hale-Bopp) were observed at medium resolution with PHT-S and/or at high resolution with the long- and short-wavelength spectrometers of the Infrared Space Observatory in April 1996, September-October 1996 and December 1997. These observations covered the pre- and post-perihelion phases and with the comet between 3 and 4.6 AU from the Sun. For the first time, high-resolution spectra of a comet covering the entire 2.4 to 200 μm spectral range were obtained.

The vibrational bands of water, carbon dioxide and carbon monoxide are detected in emission with PHT-S, as expected from molecular fluorescence models. Relative production rates of 100:22:70 are derived for H_2O:CO_2:CO in October 1996. H_2O is observed at high spectral resolution in the ν_3 group of bands around 2.7 μm and the ν_2 group around 6 μm with SWS, and in several rotational lines near 180 μm with LWS. The rovibrational lines of the ν_3 band are observed with a high signal-to-noise ratio. This allows accurate determinations of the water rotational temperature and of its ortho-to-para ratio.

Longward of 6 μm the spectrum is dominated by dust thermal continuum emission, upon which broad emission features are superimposed. The wavelengths of the emission peaks correspond to those of Mg-rich crystalline olivine (forsterite).

Highlights of the first sets of two observations were briefly reported in Crovisier (Science, 275, 1904, 1997). We will present the latest developments of their analysis and a quick analysis of the latest set of observations.

Abstract CT-3a-7

UKIRT OBSERVATIONS OF COMET P/HALE-BOPP

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We will present near 1.4-3.5 and mid (10 and 20) μm spectra of Comet Hale-Bopp (C/1995 01) covering the period from September 1995 to April 1997. Observations in 1995, when the comet was 7 AU from the Sun, showed a broad absorption feature attributable to water ice (Davies et al 1997), but these had vanished by April of 1996 at which time the comet was at a heliocentric distance of 4.6AU. Mid infrared spectra in June 1996 clearly show a silicate emission feature in the 10um region with the additional feature at 11.2um attributed to crystalline olivine which has already been reported by Hayward and Hanner (1997). The overall shape of the 10 and 20um spectrum measured on September 29th 1996 is similar to that reported by Crovisier et al (1997) The spectral and spatial evolution of the 3.1-3.5um spectrum over a range of heliocentric distances will be illustrated.

Abstract CT-3a-8

CSHELL OBSERVATIONS OF C/1995 O1 HALE-BOPP IN THE 3μm REGION: ROTATIONAL TEMPERATURES AND PRODUCTION RATES OF PARENT MOLECULES

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We present results of spectroscopic observations of C/1995 O1 Hale-Bopp obtained Apr 29 1997 UT (r = 1.01 AU, Δ = 1.752 AU). The data were obtained using the CSHELL instrument at the NASA Infrared Telescope Facility on Mauna Kea, Hawaii. The spectral resolution of CSHELL ($\lambda/\Delta\lambda$) was $\sim 2 \times 10^4$. Spectra were obtained with the slit (1" by 30") centered on the nucleus. Intensities of HCN, C_2H_2, and NH_3 were measured in 1 arc second increments along the slit. The measured production rates and their spatial character will be presented. Detections of numerous ro-vibrational spectral lines of HCN and a limited number of spectral lines of C_2H_2 were used to determine the rotational temperature for each molecule and study the spatial character of the measured rotational temperature.

Abstract CT-3a-9

QUANTIFICATION OF WATER AND CARBONYL SULFIDE IN COMET HALE-BOPP USING GROUND-BASED INFRARED SPECTROSCOPY

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Water is the most abundant cometary molecular species, and the volatile to which all other molecular abundances are compared. We detected multiple water lines in fluorescence emission from January to May, 1997 in comet Hale-Bopp using ground-based infrared spectroscopy. Six ro-vibrational lines of carbonyl sulfide were detected on UT April 16.0 and May 1.2, 1997. These observations were made using the CSHELL cryogenic grating spectrometer at the NASA Infrared Telescope Facility on Mauna Kea, Hawaii. Water production rate as as a function of heliocentric distance between January and May 1997 will be presented. In addition, carbonyl sulfide production rates relative to water will be reported.

Abstract IT-3a-3

THE NEUTRAL GAS PHASE OF COMET HALE-BOPP: RESULTS FROM OPTICAL OBSERVATIONS

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An impressive harvest of data concerning illustrious comet Hale-Bopp has been gathered in the optical domain, as in other regions of the spectrum, during the exceptionally long observational campaign devoted to this outstanding object. The campaign is, in fact, still going on and we are only at the beginning of the interpretative work on this wealth of information. Yet, so many people have been so active on so many different questions already, that a fairly severe selection of topics has to be made, even in an early review of such a limited area as optical observations related to the neutral gas phase of the comet.

While we shall not overlook some important results obtained with the aid of the techniques of narrowband-filter imaging (morphology and sources structure, motions, implications for the origin of the gas and some properties of the nucleus) and photometry (in particular, the run of production rates of volatile species over a remarkably wide range of heliocentric distance), the emphasis will be laid here upon a number of results secured by spectrocopy. Among possible items of interest I may quote : CN (attempt to evaluate the carbon isotopic ratio), C_2 (study of spatial variations of the excitation conditions within the coma), NH_2 (to investigate the evolution of the populations of the ground-state rotational levels with the distance from the sun), Na (results concerning the source and kinematics of sodium in the coma), the forbidden lines of carbon and oxygen (in relation with the determination of the production rates of the respective principal progenitors, carbon monoxide and water), as well as the search for new spectroscopic identifications.

Abstract CT-3a-10

SPECTROSCOPIC MONITORING OF COMET C/1995 O1 (HALE-BOPP)

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We report the preliminary results of a long term programme of spectroscopic monitoring of comet C/1995 O1 (Hale-Bopp). Flux calibrated spectra were obtained at 8 epochs between June 1996 and April 1997 as the comet moved from a heliocentric distance of 4.2 AU to near perihelion at 0.9 AU. From these spectra we have obtained the production rates at various heliocentric distances for the parents of the observed species CN, C_3, CO^+, C_2, CH^+ and NH. In addition we also monitored the dust continuum colour.

Abstract CT-3a-11

THE BEHAVIOR OF CARBON-BASED MOLECULES IN THE COMA OF COMET HALE-BOPP

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We obtained observations of comet Hale-Bopp with spectrographs on the 2.7 m Harlan Smith Telescope of McDonald Observatory. These data were obtained at a range of heliocentric distances from 7.1 AU to 0.9 AU. The earliest data were obtained at moderate spectral resolving powers (R=600), with later observations at high (R=60,000) and very high (R=200,000) spectral resolving powers. Spectra were obtained at a variety of cometocentric distances on 30 different nights.

In this paper, we concentrate on the distribution of the carbon-bearing molecules in the coma. The model we employ combines non-equilibrium chemistry along with dusty, multifluid hydrodynamics for the gas, dust, and plasma flow in a cometary coma. Three sources of gas release are included: sublimation of surface ices, transport of gas from subsurface regions through the surface, and release of gas from the dust in the coma. We use this model to probe features within the coma such as, spatial distributions of gas-phase species (e.g., CN, CH, C_3, C_2) and dust, the velocity and temperature structure, and to aid in assimilating a variety of diverse observations of comet Hale-Bopp.

Abstract CT-3a-12

ON THE IDENTITY OF THE CN COMETARY RADICAL PARENTS

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The identity of the parents of the "dirt" species in comet comae is one of the longest standing problems of cometary physics. Although CN was the second species to have been detected in the coma, just after C_2 in 1868, the identification of its precursor has always remained a puzzle. The standard technique employed so far consisted of interpreting near-UV photometric profiles of the CN B–X 0–0 band assuming that the observed radicals resulted from the photodestruction of a single (unknown) parent molecule. The putative parent species was always found to have a characteristic destruction scale length of order $2\,10^4$ km at 1 A.U. from the Sun. No obvious simple molecule presents this characteristic. In addition, observations of comet P/Halley in 1986 showed that coma dust particles were certainly contributing to the production of the CN atmosphere ("CN jets"), at least in dusty comets. Here, we re-examine all published past observations of the UV emission of CN radicals and complement our investigation by interpreting new data, namely high dispersion spectra of the CN B–X 0–0 band obtained at various locations inside the coma of comet Austin 1989c1, a velocity profile of the 2–1 radio line of CN and maps of the HCN molecule, both obtained in comet C/1995 O1 (Hale-Bopp). A single atmospheric model is used to interpret our data set. The characteristics of potential parent species are re-investigated. The scale length mentioned above is found to be a limiting case in which the parent species does not release any energy during its photolysis. Although no unique solution is found, we can identify a best case for a parent having a lifetime of order 3.5×10^4 s at 1 A.U. and a velocity in the 1–2 km s^{-1} range. Although the greatest care is required before making any predictions, let us mention that these characteristics fit those of the C_2N_2 molecule.

Abstract IT-3a-4

ULTRAVIOLET OBSERVATIONS OF COMET HALE-BOPP

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Ultraviolet spectroscopy and imaging of comet Hale-Bopp (C/1995 O1) were obtained from a variety of space platforms from shortly after the discovery of the comet through perihelion passage. Observations with the *International Ultraviolet Explorer* (*IUE*) and the *Hubble Space Telescope* (*HST*) spanned the range of 6.8 to 2.7 AU pre-perihelion, but *IUE* was decommissioned in September 1996 and *HST* was precluded from near-perihelion observations because of its solar avoidance constraint. In September 1996, observations were made by the *Extreme Ultraviolet Explorer* (*EUVE*) that showed the presence of soft X-rays offset from the optical center of the coma and provided a sensitive spectroscopic upper limit to the Ne/O abundance ratio.

During the perihelion period NASA mounted a successful campaign of four sounding rockets that were launched at the White Sands Missile Range, New Mexico, between March 25 and April 7, 1997. The payloads included long-slit spectroscopy (700 – 1150 and 1280 – 1850 Å) and ultraviolet imaging polarimetry. In addition, Hale-Bopp was observed near perihelion by ultraviolet instruments on orbiting spacecraft that were designed for solar or terrestrial observations. These instruments include the Solar Wind Analysis Experiment (SWAN) on the *Solar and Heliospheric Observatory* (*SOHO*), the SOLar-STellar Irradiance Comparison Experiment (SOLSTICE) on board the *Upper Atmosphere Research Satellite*, and the UVISI instruments on board the *MSX* (*Midcourse Space Experiment*). Observations with *HST*, using the Space Telescope Imaging Spectrograph (STIS), installed during the February 1997 servicing mission, resumed in August 1997.

An intercomparison of the ultraviolet observations and comparison with the results on gas composition and activity from ground-based visible, infrared and radio observations will be presented.

Abstract CT-3a-13

SEARCH FOR NOBLE GASES IN COMET HALE-BOPP: A JOINT VENTURE UVSTAR-EUVE

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The UVSTAR (Ultraviolet Spectrograph Telescope for Astronomical Research), an EUV-FUV telescope jointly designed and realized by the University of Trieste (CARSO) and the University of Arizona (LPL), was successfully flown on the Shuttle in August 1997 carrying out observations of Comet Hale-Bopp, of the Jupiter-Io system and of many stellar objects.

Spectra of the Comet were obtained in the wavelength range 500-1250 A when the Comet was at R=2.3 AU from the Sun.

The goals were the new detection of three noble gases : He (584 A),Ne (630 A) and Ar (1049/1066 A) and of neutral (H, H_2, O, N, C) and ionic (N+,O+,C+,Ar+) species. In this paper we will discuss the results obtained also in comparison with those achieved by EUVE in September 1996 in the 70 to 760 A range when the Comet was at R=3.07 AU from the Sun (1).

(1) V.A. Krasnopolsky et al.Science, 277, 1488-1491, 1997

Abstract CT-3a-14

ROCKET-BORNE LONG-SLIT ULTRAVIOLET SPECTROSCOPY OF COMET HALE-BOPP

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A sounding rocket observation of comet Hale-Bopp was made on 1997 April 6 03:51 UT, when the comet was at heliocentric and geocentric distances of 0.92 and 1.39 AU, respectively. The instrument consisted of a 40 cm f/15.5 Dall-Kirkham telescope, a sealed 400 mm Rowland circle spectrograph with a holographically ruled, astigmatism corrected grating, and a microchannel plate (MCP) detector with a double-delay-line anode. A long slit ($7'' \times 260''$, 7×10^3 km $\times$ 2.6×10^5 km at the comet) located at the focus of the telescope served as the entrance pupil to the spectrograph. Spectral resolution of ~ 5 Å was achieved over the entire bandpass (1280–1850 Å). The spatial resolution achieved during flight was $\sim 6''$ (6000 km at the comet).

During the observation the slit sampled the coma along the sun-comet line from $\sim 1\times10^5$ km sunward to $\sim 2\times10^5$ km tailward. Emissions from O, C, S and CO are detected. The O I λ1304, C I $\lambda\lambda$1561 and 1657 emissions fill the aperture and show little evidence of a peaked distribution. Several multiplets of S I are observed over a gradient of optical depths. The optically thin S I lines show a spatial distribution peaked at the nucleus while the most optically thick line shows no evidence of a peaked distribution. Numerous bands of the CO Fourth Positive system ($A^1\Pi$–$X^1\Sigma^+$) are present in the data and all show a peaked distribution, although the stronger transitions are less peaked than the weaker ones. The forbidden O I λ1356 transition is detected and exhibits a spatial profile peaked near the nucleus. C II λ1335 is detected with a spatial profile enhanced in the tailward direction. Preliminary analysis gives a derived CO production rate of $\sim 2 \times 10^{30}$ molecules s^{-1}, consistent with the value derived from millimeter-wave observations. This implies a CO/H_2O production rate ratio of $\sim 20\%$, similar to that of Halley near 1 AU.