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DETECTION OF CO AND ETHANE IN COMET 21P/GIACOBINI-ZINNER: EVIDENCE FOR VARIABLE CHEMISTRY IN THE OUTER SOLAR NEBULA

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ABSTRACT

Ethane and carbon monoxide were detected in a short-period comet of probable Kuiper Belt origin. Ethane is substantially less abundant compared with Hyakutake and Hale-Bopp, two comets from the giant-planet region of the solar nebula, suggesting a heliocentric gradient in ethane in precometary ices. It is argued that processing by X-rays from the young Sun may be responsible.

Subject headings: comets: general — comets: individual (P/Giacobini-Zinner) — infrared: solar system — solar system: formation

1. INTRODUCTION

Knowledge of the composition and structure of cometary nuclei is central to understanding the evolution of material in our natal interstellar cloud and in the preplanetary nebula (Mumma, Weissman, & Stern 1993; Irvine et al. 2000). A key question is whether the composition of precometary ices varied with distance from the young Sun.

Oort cloud comets likely formed in the giant-planet region of the nebula, where temperatures ranged from ~200 K near Jupiter to ~40 K near Neptune. Kuiper Belt comets formed in situ beyond Neptune where temperatures as low as ~20 K may have prevailed. Chemical variations could result from a number of (poorly constrained) processes, such as partial vaporization of icy grain mantles during nebular infall, condensation fractionation of nebular gas, thermal processing of ices, hydrogenation of icy grain mantles, energetic processing by X-rays, and UV photochemistry. The efficacy of such processing probably varied greatly with heliocentric distance and/or with time, enforcing corresponding differences in the volatile fractions of comets. For example, comets formed in the Kuiper Belt (21P/Giacobini-Zinner is probably one example) may have incorporated unusually large amounts of apolar volatiles such as nebular CO, neon, methane, and acetylene (and ethane, if it existed in the nebular gas), if temperatures there were as low as 20 K. Icy grain mantles may have been more efficiently hydrogenated in regions of high H atom density (e.g., an X-ray dissociation region), converting condensed phase CO to H_2CO and CH_3OH, and C_2H_2 to ethane. Thus, the native abundances of these volatile species comprise a key test of cometary origins and of nebular processing.

Cometary abundances do seem to reflect local conditions in the comet-forming regions. A dichotomy in carbon chemistry was found in a study of 85 comets (A'Hearn et al. 1995), suggesting that origin-related chemical differences are general. About one-half of the Jupiter-family comets (mainly of Kuiper Belt origin) were depleted in C_2 and C_3 relative to CN, compared with "typical" comets (including those formed in the giant-planet region), and A'Hearn et al. suggested that this was evidence of different processing in the trans-Neptunian region. The volatile composition of the long-period comets Hyakutake and Hale-Bopp (probably formed in the giant-planet region) is similar to icy grain mantles in dense interstellar cloud cores (Mumma 1996, 1997; Crovisier 1999), and neither is depleted in C_2 (Schleicher et al. 1997; Hicks & Fink 1997).

The meaning of the C_2 depletion observed in some Jupiter-family comets is uncertain because the origin of C_2 is poorly understood. Combi & Fink (1997) critically reviewed the possible production mechanisms and suggested CHON grains as the likely source, based on the strict R^{-2} dependence of the scale length for the C_2 precursor. Possible gaseous precursors (acetylene and ethane) were first detected in comet Hyakutake (Brooke et al. 1996; Mumma et al. 1996), and both species were later detected in comet Hale-Bopp (Mumma et al. 1997a, 1997b; Weaver et al. 1999a). Sorkhabi et al. (1997) suggested acetylene (C_2H_2) as the source in Hyakutake based on photochemical considerations and laboratory measurements. Photochemical production of C_2 from ethane (C_2H_6) is not as well studied. Molecular structure considerations suggest that the quantum yield for C_2 should be small, but this may be compensated by the higher production rate of ethane in these comets (~0.6%). In the absence of direct measurements of C_2H_6 and C_2H_2, the depletion of C_2 in some Jupiter-family comets cannot be uniquely interpreted.

Giacobini-Zinner (G-Z) is one of the comets "depleted" in C_2. It is in a short-period (6.61 yr.), prograde, low-inclination (31°.86) orbit and is thought to have originated in the trans-Neptunian (Kuiper Belt) region. Its last favorable apparition was in 1985, when observations confirmed earlier findings that it is depleted in C_2 and C_3 by factors of about 5–10, even though CN/OH was "normal" (Cochran & Barker 1987; Schleicher, Millis, & Birch 1987; Konno & Wyckoff 1989; Beaver et al. 1990). The present apparition presented the first opportunity to test directly the abundance of potential C_2 precursors.

We report herein the first detections of ethane and CO in a Jupiter-family comet. When compared with two comets from the giant-planet region (Hyakutake and Hale-Bopp), our production rates and abundance ratios for G-Z imply that ethane was depleted in precometary ices from the trans-Neptunian region of the solar nebula.

2. OBSERVATIONS AND RESULTS

We obtained preperihelion observations of comet G-Z spanning UT 1998 October 2–10, using the Cryogenic Echelle Spectrometer (CSHELL; Greene et al. 1993) at the NASA Infrared

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Telescope Facility (IRTF), Mauna Kea, Hawaii. During this interval, the heliocentric distance decreased from $R = 1.25$ to 1.19 AU, the geocentric distance decreased from $\Delta = 1.08$ to 1.03 AU, and the geocentric velocity of the comet was roughly constant at approximately -9.5 km s^{-1}. CSHELL features a 256 × 256 pixel InSb array, a 30″ long slit that we oriented east-west on the sky, and a single-pixel spectral dispersion of ~2.7 km s^{-1}. The plate scale is 0.″2 pixel^{-1}. At each grating setting, cometary data were acquired using a sequence of four scans (ABBA), with an integration time of 5 minutes on source per sequence of ethane scans (2 minutes for CO). Images of the comet at 2.2 μm were taken before and after each sequence of scans, in order to monitor and correct for cometary drift. For each grating setting, spectra of infrared standard stars (obtained through a 4″-wide slit) were acquired for absolute flux calibration of the comet spectra.

The data were processed using algorithms specifically tailored to our cometary observations (Dello Russo et al. 1998). Initial data processing included flat-fielding, the removal of high dark current pixels and cosmic-ray hits, and the registration of spectral frames such that the spectral dimension falls along a row and the spatial dimension is orthogonal to this. Atmospheric transmittance models were obtained using the Spectrum Synthesis Program (SSP; Kunde & Maguire 1974), which accesses the HITRAN-1992 Molecular Database (Rothman et al. 1992). SSP models were used to assign wavelength scales to the spectra and to establish absolute column burdens for relevant absorbing species in the terrestrial atmosphere. The transmittance model was binned to the instrumental sampling interval, convolved to the resolution of the comet spectrum, and normalized to the cometary continuum. The extracted comet spectra reveal emission from two Q-branches of C_2H_6 (Fig. 1*a*) and two emission lines from CO (Fig. 1*b*), all at the correct Doppler-shifted frequencies.

On October 9.2 and 10.3, we observed emission from the $^RQ_0$ and $^PQ_1$ branches of the ν_7 band of ethane (Fig. 1*a*). The C_2H_6 observations employed a 2″ slit width resulting in a spectral resolving power of $\nu/\Delta\nu \sim 1.5 \times 10^4$. The telescope was nodded 15″ along the slit (placing the comet in the A- or B-beam) to cancel background sky and telescope emission. On October 2.2, we detected emission from the $R0$ and $R1$ lines of the CO $v = 1$–0 fundamental band near 4.7 μm. We used the 1″-wide slit, providing $\nu/\Delta\nu \sim 2.1 \times 10^4$. This higher resolving power was necessary for separating the cometary emissions from corresponding absorption by CO in the terrestrial atmosphere, given the relatively small geocentric Doppler shift (Fig. 1*b*). For CO, the telescope was nodded 60″ between position A (comet in slit) and position B (blank sky), so as not to cancel possible extended CO emission.

We calculated molecular production rates from the line emission contained within nucleus-centered spectral extracts (2″ × 2″ for C_2H_6 and 1″ × 3″ for CO), following the approach used for comet Hyakutake (Mumma et al. 1996). However, our work with comet Hale-Bopp demonstrated that these nucleus-centered rates are smaller than the true production rates for native release by approximately a factor of 2, largely owing to the slit losses imposed by the point-spread function (see Dello Russo et al. 1998 for details). The production rates presented below were scaled upward by two to account for this effect.

The extraction of total production rates requires knowledge of the rotational temperature when only a portion of the molecular band is measured. We detected too few lines in G-Z to permit determination of a self-consistent rotational temperature, so we adopt a value (35 ± 10 K) that is typical of comets with

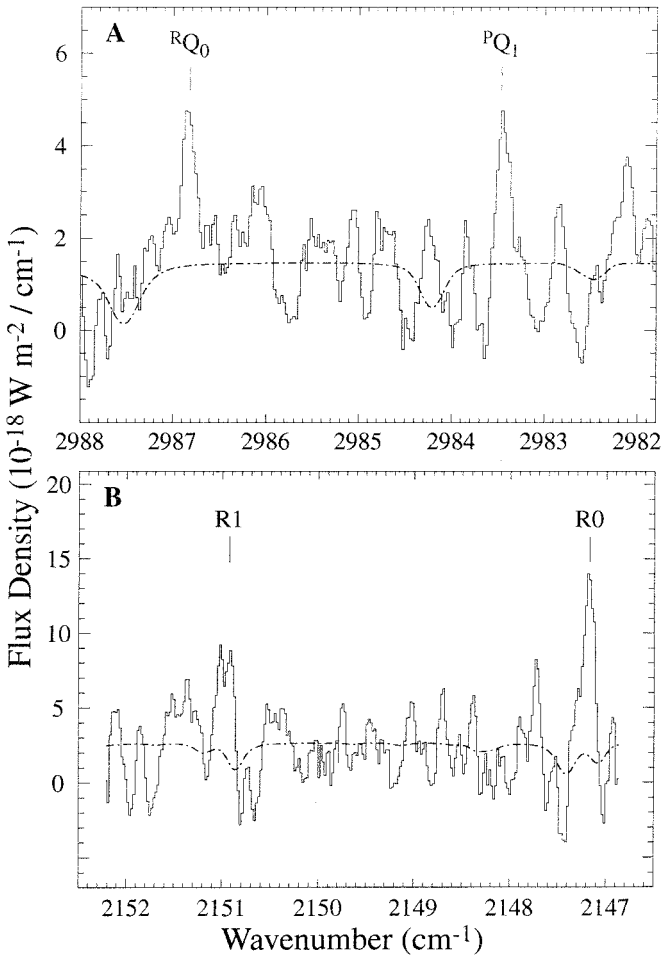

FIG. 1.—Spectral extracts of comet Giacobini-Zinner, smoothed by a 5 pixel–wide rectangular filter. (*a*) Two Q-branches from the ν_7 band of ethane observed on UT 1998 October 9.2 and 10.3. (*b*) Line emission in the CO $v = 1$–0 band observed on UT 1998 October 2.2. The vertical bars below the line assignments represent the expected Doppler-shifted line positions. The dot-dashed line is the synthesized atmospheric transmittance, convolved to the instrumental resolution (see text).

similar production rates and observed under similar conditions. Bockelée-Morvan et al. (1994a) measured rotational temperatures for methanol in comets C/1989 X1 (Austin) [$Q(H_2O) \sim 4 \times 10^{28}$ s^{-1}, $T_{rot} = 24 \pm 8$ K] and C/1990 K1 (Levy) [$Q(H_2O) \sim 25 \times 10^{28}$ s^{-1}, $T_{rot} = 23 \pm 15$, 41 ± 10, and 24 ± 7 K]. They recommend a temperature range of 20–40 K for methanol in these two comets. Methanol rotational temperatures in 22P/Kopff [$Q(H_2O) \sim 4 \times 10^{28}$ s^{-1} and $T_{rot} = 27 \pm 12$ K; Biver 1999] and in 109P/Swift-Tuttle [$Q(H_2O) \sim 50 \times 10^{28}$ s^{-1} and $T_{rot} = 45 \pm 7$ K; Bockelée-Morvan et al. 1994b] are consistent. The shape of the 3.52 μm ν_3 band of methanol in Swift-Tuttle was best reproduced by a rotational temperature of ~50 K (Davies et al. 1993). Rotational temperatures obtained for water in 1P/Halley [$Q(H_2O) \sim 22 \times 10^{28}$ s^{-1}, $T_{rot} \sim 40$ K and $Q(H_2O) \sim 140 \times 10^{28}$ s^{-1}, $T_{rot} \sim 50$ K) are also consistent (Mumma et al. 1986; Weaver, Mumma, & Larson 1987; Bockelée-Morvan & Crovisier 1987).

Comet Hyakutake at closest approach to Earth (0.1 AU) provided $T_{rot} \sim 70$ K for water, methanol, and formaldehyde, but Hyakutake is not a good analog for G-Z since the measured temperatures refer to a coma region much closer to the nucleus owing to the small geocentric distance. Hale-Bopp, with its

huge water production rate, is also not a good analog for G-Z since thermalization of fast H atoms is more efficient, leading to higher temperatures. Optical depth effects in the far-infrared water cooling lines are also far stronger, again leading to higher temperatures (Bockelée-Morvan 1987; Bockelée-Morvan & Crovisier 1987). We assume that methanol, water, and ethane attain similar rotational temperatures since electron collisions seem to control rotational excitation in the intermediate coma (Xie & Mumma 1992; Bockelée-Morvan et al. 1994a, 1994b). We therefore adopt the range of 25–45 K as reasonable for both CO and ethane in G-Z, with a most likely value of about 35 K, and we evaluate production rates for 25, 35, 45, and 50 K (Table 1).

Using a fluorescence efficiency (at 1 AU and 35 K) of 10.72×10^{-5} photons s^{-1} for the combined ${}^{R}Q_0$ and ${}^{P}Q_1$ branches and the measured combined line flux [$(1.0 \pm 0.2) \times 10^{-18}$ W m^{-2}], we find that $Q_{C_2H_6} = (3.5 \pm 0.8) \times 10^{25}$ molecules s^{-1} for the nucleus-centered extract. Including the correction factor of 2, we obtain $Q_{C_2H_6} = (7.0 \pm 1.5) \times 10^{25}$ molecules s^{-1}. (Note that these two *Q*-branches were mislabeled in Mumma et al. 1996 and that inappropriate *g*-factors were used. However, two other errors were made that largely compensate this error. Revised production rates are in preparation, and the revised mixing ratio is given in § 3. The parameters used here are correct.)

The line flux measured for the *R*0 line of CO was $(2.27 \pm 0.56) \times 10^{-18}$ W m^{-2}, and the fluorescence efficiency (at 1 AU and 35 K) is 1.53×10^{-5} s^{-1}, leading to $Q = (1.68 \pm 0.42) \times 10^{27}$ molecules s^{-1} after correcting for atmospheric transmission (0.70). The line flux measured for the *R*1 line was $(1.97 \pm 0.61) \times 10^{-18}$ W m^{-2}, and the fluorescence efficiency is 2.33×10^{-5} s^{-1} (at 1 AU and 35 K), implying $Q = (1.56 \pm 0.48) \times 10^{27}$ molecules s^{-1} after transmittance correction (0.43). The weighted mean of the two lines provides $Q_{CO} = (3.28 \pm 0.64) \times 10^{27}$ molecules s^{-1}, after including the scaling factor of 2. The small aperture emphasizes the contribution from native CO, although a small contribution from an extended source is possible (DiSanti et al. 1999a). For the rotational temperature of 35 K, the mixing ratio of native ethane to native CO is then $(2.1 \pm 0.6) \times 10^{-2}$. The mixing ratio is not very sensitive to the assumed rotational temperature (Table 1).

Cometary water is the paradigm with which all other native (parent) volatiles are compared. Its abundance can be estimated by indirect means [e.g., from radio and ultraviolet OH measurements and from visible O(^1D) emission]. Water can also be detected directly from the ground by infrared nonresonance fluorescence (Mumma et al. 1995), but the need for frequent imaging limited our time on source and constrained the application of this approach to G-Z. A line of H_2O (1_{11}–1_{10} in the $\nu_3 - \nu_2$ hot band; Dello Russo et al. 2000) should appear near the *R*1 line of CO, at a Doppler-shifted frequency of 2151.26 cm^{-1}. Although no strong line is seen, there is an excess flux at the proper frequency, and an upper limit to the water production rate can be obtained. The measured line flux is $(8.9 \pm 4.8) \times 10^{-19}$ W m^{-2} ($g_{line} = 5.1 \times 10^{-7}$ s^{-1} at 1 AU and 35 K), corresponding to $Q_{H_2O} = (3.2 \pm 1.7) \times 10^{28}$ molecules s^{-1} (a transmittance correction of 0.87 and a scaling by two are included). The water production rate on October 2.2 was less than 6.6×10^{28} molecules s^{-1}, at the 95% confidence limit.

Water production rates were obtained by several indirect methods during the 1985 apparition (McFadden et al. 1987; Schleicher et al. 1987; Gérard et al. 1988; Konno & Wyckoff 1989; Tacconi-Garman, Schloerb, & Claussen 1990; Combi & Feldman 1992). Measurements were taken at larger and smaller heliocentric distance, but not at the exact distance of our observations. Based on an interpolation of those measurements, the water production rate expected for G-Z during early 1998 October is $\sim 5 \times 10^{28}$ s^{-1}. Our measured production rate is consistent with this estimate, at the 1 σ confidence level. However, little can be inferred from this agreement, considering the low signal-to-noise ratio of our water detection. Also, the behavior of the comet may have differed in 1985, and it was not sampled at our exact heliocentric distance.

TABLE 1

PRODUCTION RATES FOR PARENT VOLATILES IN 21P/GIACOBINI-ZINNER

T_{rot} (K)	CO ($\times 10^{27}$ s^{-1})	C_2H_6 ($\times 10^{27}$ s^{-1})	H_2O ($\times 10^{27}$ s^{-1})	C_2H_6/CO Ratio
25	2.7 ± 0.5	0.062 ± 0.013	43 ± 23	0.023 ± 0.007
35	3.3 ± 0.6	0.070 ± 0.015	32 ± 17	0.021 ± 0.006
45	3.8 ± 0.8	0.077 ± 0.015	29 ± 16	0.020 ± 0.006
50	4.2 ± 0.8	0.080 ± 0.017	28 ± 15	0.019 ± 0.006

Comet Giacobini-Zinner was also observed by Weaver et al. (1999b) using CSHELL at IRTF (1998 October 25–29), several weeks after the observations reported here. They did not detect either ethane or CO, but they did detect water vapor. Their 3 σ upper limit for ethane represents an approximate 10-fold depletion (relative to water), compared with comets Hyakutake and Hale-Bopp. Their 3 σ upper limit for CO (~2%–3% relative to water) is considerably smaller than the abundance retrieved by us (~10% relative to water). Their nondetections of CO and ethane are surprising in view of the clear detections shown in Figure 1.

3. DISCUSSION

It is interesting to compare production rates for hypervolatiles in the Jupiter-family comet (G-Z) with those for comets from the giant-planet region. The preliminary production rates reported for Hale-Bopp (Mumma et al. 1997a, 1997b) were revised following more mature data reductions that account for slit losses and also separate the native and distributed sources for CO (ethane, Dello Russo et al. 1999a; CO, DiSanti et al. 1999a). The relative production rates for native ethane and native CO are $C_2H_6 : CO = 0.2 : 10$ for G-Z, compared with $0.6 : 12$ for Hale-Bopp. Their mixing ratio is $(2.1 \pm 0.6) \times 10^{-2}$ in G-Z (at 35 K), compared with $(4.7 \pm 0.4) \times 10^{-2}$ in Hale-Bopp. If the mixing ratios were constant in G-Z during the period of October 2–10, then the abundance ratio of apolar volatiles ($C_2H_6 : CO$) in these comets would differ significantly—in G-Z being less than one-half that in Hale-Bopp. The production rate of ethane relative to water in this Jupiter-family comet is also low compared with both long-period comets [$C_2H_6 : H_2O = (2.2 \pm 1.3) \times 10^{-3}$ in G-Z, $(5.6 \pm 0.4) \times 10^{-3}$ in Hale-Bopp, and $(6.4 \pm 1.5) \times 10^{-3}$ in Hyakutake (Dello Russo et al. 1999b)]. A comparison of native CO production among these three comets will be possible after our ongoing analysis of extended and distributed sources in Hyakutake is complete (DiSanti et al. 1999b).

What could cause this depletion of ethane relative to CO in G-Z? It seems unlikely that selective loss of ethane during the comet's active phase could change the C_2H_6/CO ratio since both species are apolar hypervolatiles and should be affected in similar fashion. G-Z was observed at 1.2 AU heliocentric, well within the distance at which water sublimation controls cometary activity, so it seems unlikely that heliocentric frac-

tionation effects could affect the relative production rates. A simple view is that the ices in G-Z are depleted in C_2H_6 and that this difference is cosmogonic. It follows that some process affected C_2H_6 differently in the trans-Neptunian region compared with the giant-planet region of the nebula.

Mumma et al. (1996) argued that the abundances in Hyakutake were consistent with the conversion of condensed phase C_2H_2 to C_2H_6 and of CO to H_2CO and CH_3OH, through H atom addition reactions on grain surfaces (Tielens & Allamandola 1987; Charnley et al. 1995). The fivefold to 10-fold depletion of C_2 in G-Z suggests a large current deficit in C_2H_2, if acetylene is its precursor. If C_2H_6 in G-Z was produced by hydrogenation of C_2H_2, then its lower C_2H_6/CO ratio and low current C_2H_2 abundance could result from a lower initial abundance of acetylene in precometary ice coupled with a high conversion efficiency of acetylene to ethane in the trans-Neptunian region. (The possible generation of C_2 from CHON grains in G-Z is probably negligible since the small [submicrometer-sized] grains responsible for the continuum at optical wavelengths are underrepresented. However, a firm conclusion regarding C_2H_2 must await its direct measurement on a future apparition.)

The production of H atoms in nebular gas and solids undoubtedly varied with distance from the young Sun and with time. It is known that class I and II T Tauri stars are very intense X-ray emitters (Neuhäuser 1997), and it is likely that the young Sun passed through a similar stage before entering the main sequence (Shu et al. 1997). The principal loss mechanism for these X-rays is the photoionization of nebular H_2, a process that ultimately produces H atoms in great numbers through direct and dissociative recombination reactions (producing several hundred H atoms per keV; Glassgold, Najita, & Igea 1997). Before nebular clearing in the giant-planet region, the increasing attenuation of this exciting X-ray flux with greater heliocentric distance may have caused a significant reduction in hydrogenation efficiency for ices in the trans-Neptunian nebular region. As nebular clearing proceeds, X-rays will penetrate more deeply, and ionization fractions and H atom densities will increase. Comet formation is generally thought to proceed more slowly at large heliocentric distance. Thus, the ratio of C_2H_2 to C_2H_6 in Kuiper Belt comets could be larger or smaller than that in Oort cloud comets, depending on the time and place of their formation.

Weaver et al. (1999b) report a nondetection of both CO and ethane in comet G-Z, and their derived upper limits are significantly smaller than the production rates inferred from our detections. This discrepancy is most easily explained if G-Z is internally heterogeneous in its chemical composition. During its 1985 apparition, G-Z showed marked asymmetry in water production about perihelion, with a rapid reduction in Q(OH) occurring just prior to the heliocentric distance at which Weaver et al. observed in 1998 (R_h = 1.11–1.08 AU). It is possible that the vent responsible for gas release during our observations became increasingly inactive after $R_h \sim 1.2$ AU owing to seasonal effects and that, thereafter, gas was released from a different vent. The second vent could be depleted in the hypervolatiles CO and ethane. If so, the two data sets could provide evidence supporting the long-sought chemical heterogeneity within a comet nucleus. Such heterogeneity could result if cometesimals were scattered radially in the solar nebula before being embodied in the final nucleus or if they were formed at times when physical conditions (e.g., local H atom densities) differed greatly in the nebula. The depletion of hypervolatiles could also have a physical origin if the two vents experienced different thermal processing. These ideas can be more rigorously tested by measuring the compositions of other comets and of Giacobini-Zinner on its return to the inner solar system in 2005.

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