COMET DUST: CONNECTIONS WITH INTERSTELLAR DUST

R. F. KNACKE
Department of Earth and Space Sciences
State University of New York
Stony Brook, New York 11794 U.S.A.

ABSTRACT.   The Comet Halley campaigns resulted in an enormously better understanding of the composition of comets. Silicates, organic compounds, and volatile ices comprised of H_2O, CO, CO_2, S_2, CN, and possibly CH_4 and OCS occur in comet grains. These are all known or suspected constituents of interstellar dust. We review the chemical, elemental, and isotopic compositions of comet dust and compare this with interstellar matter. The many intriguing parallels suggest, but do not yet establish, a direct connection between comet dust and interstellar dust.

1.   INTRODUCTION

Comets may be the most primitive objects in the solar system. Do they preserve a more or less pristine accumulation of interstellar grains? If so, comets would hold the key to the interstellar dust problem. Comet dust studied by remote sensing, investigated in situ by spacecraft such as the proposed CRAF mission, or collected by sample return missions would give us direct access to interstellar dust. Fragments of interstellar grains may also be cemented in interplanetary dust particles (IDPs) or in meteorites.

This may be how it will turn out, but it is hard to prove connections between interstellar and solar system material (cf. Spinrad, 1987). We still don't know how or where comets formed, and the origins and processing of cometary material are complicated issues. However, there are two points we are fairly sure of. First, research in the last twenty years, especially of Comet Halley (1982i), show that the compositions of interstellar and cometary dust are indeed similar. Second, even in the most conservative view, comet and interstellar dust must have evolved under at least somewhat comparable conditions, and knowledge of one may yield insights into the other.

This paper will concentrate on results of observations and on parallels between cometary and interstellar dust. Results of the Comet Halley dust-mass spectroscopy measurements are available elsewhere (Kissel and Krueger, 1987). Recent reviews of comets, including many topics omitted here, are by Ney (1982), Greenberg (1982), Sekanina (1987), Spinrad (1987), and Jessberger *et al.*, (1988*a*, 1988*b*). General
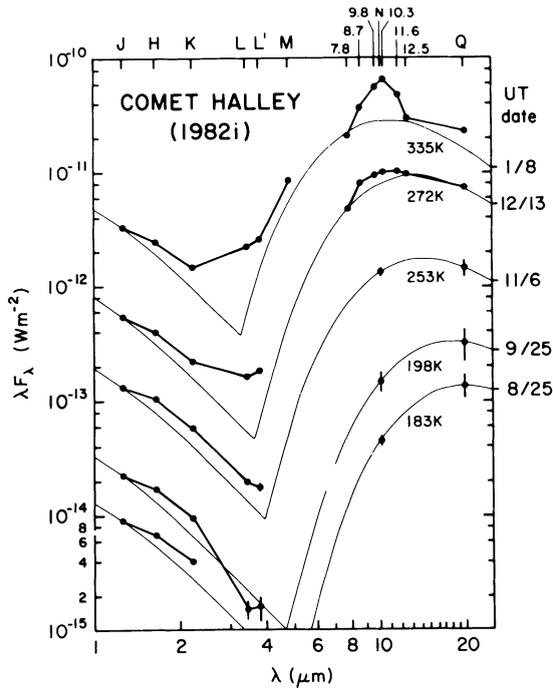
Fig. 1. Photometry of Comet Halley (Tokunaga *et al.*, 1986). The thermal spectra were fitted with blackbody functions with the temperatures shown. The relative solar flux density normalized at *J* is also shown.

sources include the review volumes, *Comets* (1982) and *Comets in the Post-Halley Era* (1989), and *Astronomy and Astrophysics*, Volume 187 (1987).

2. OVERVIEW OF COMET DUST PROPERTIES

Figure 1 shows recent low resolution visible-to-infrared spectra of Comet Halley. The spectra consist of a reflected solar component (shortward of about 3 μm) and a thermal emission component (longward of 3 μm). Comet dust temperatures follow a power law

$$T = 329/r^{0.53} \tag{1}$$

pretty nearly, where *r* is the heliocentric distance in AU (Green *et al.*, 1986; Danks *et al.*, 1988). The grains are "super thermal," hotter than a blackbody at a given heliocentric distance and therefore must be micron-size or smaller (Ney, 1982).

Spectral models require both silicates and absorbing material, but the model mixture is not unique (Lamy *et al.*, 1987; Krishna Swamy *et al.*, 1988). GIOTTO and VEGA measured the compositions and abundances of comet particles directly.
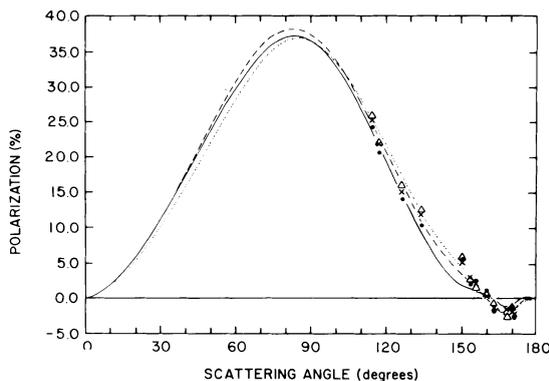
Fig. 2. Infrared polarization of Comet Halley (Brooke *et al.*, 1987): filled circles for $J(1.25\ \mu\text{m})$; crosses for $H(1.65\ \mu\text{m})$; triangles for $K(2.2\ \mu\text{m})$. Lines are model fits incorporating silicates and absorbing particles.

First analyses give that 30% of the particles are dominated by light elements (C, H, O, N or "$CHON$" particles), 35% have compositions in ranges encountered in carbonaceous chondrites, and 35% are mixtures of the two components (Langevin *et al.*, 1987, but see also Kissel and Krueger, 1987; Clark *et al.*, 1987; Jessberger *et al.*, 1988).

The GIOTTO and VEGA missions to Comet Halley measured the mass distribution of comet dust directly (McDonnell *et al.*, 1987; Mazets *et al.*, 1987). A population of very small grains, $m \approx 10^{-15}$ g, in Comet Halley was missed by ground-based observers, evidently because observations tend to sample grains with sizes on the order of the wavelength. Models using the GIOTTO size distribution, which is generally consistent with power law distributions used earlier, give good fits to the infrared spectra (Hanner *et al.*, 1987).

The geometric albedo, a, of the grains is remarkably low. For Comet Halley, a(visible, 107 deg) = 0.036 (Lamy *et al.*, 1987) and $a(1.25\ \mu\text{m}) = 0.032$ (Tokunaga *et al.*, 1986). Grains in earlier comets also had low albedos (Hartmann *et al.*, 1985). For example, in Comet Crommelin (1983n), $a(1.25\ \mu\text{m}) = 0.015$, apparently the dark record (Hanner *et al.*, 1985). Hartmann *et al.* find that the dust colors most closely resemble D-class Trojan asteroids. The albedos are comparable to those of the rings of Uranus and the leading hemisphere of Iapetus, some of the darkest materials in the solar system. In March 1986, VEGA and GIOTTO revealed the black nucleus of Comet Halley to corroborate this picture. These low albedos were an early sign of carbonaceous, tarry substances in comets (§ 4).

Several programs measured polarization of the light scattered by the grains in Comet Halley's coma (Brooke *et al.*, 1987; Dollfus *et al.*, 1987; Kikuchi *et al.*, 1987; Le Borgne *et al.*, 1987). In Figure 2, the negative branch (meaning polarization direction in the scattering plane) at large scattering angles is characteristic of rough particles or of dielectric Mie spheres. The maximum polarization and the negative branch are larger than in the Moon and most asteroids (Bowell and Zellner, 1974).

This is probably an example of the "Umov Effect" – when rough particles scatter, polarization increases with decreasing albedo. Thus the polarizations are consistent with very low albedos. Models that fit the polarization curves also require silicates plus absorbing material (Brooke *et al.*, 1987; Lamy *et al.*, 1987).

From preliminary VEGA data, typical particle densities are ≤ 1 g-cm^{-3} and are probably of order 0.1–0.3 g-cm^{-3} in the outer coma (Smirnov *et al.*, 1987). The $CHON$s have densities of 0.3–1 g-cm^{-3} (Kissel and Krueger, 1987). The comet grains are fluffy, as had been predicted in early models (Greenberg, 1982). Interplanetary particles have densities of this order (Pailer and Grün, 1980), as does the whole Halley nucleus (0.1–0.5 g-cm^{-3}, Whipple, 1987).

3. SILICATES

Silicates were identified in comet dust many years ago from 10 μm and 18 μm emission bands that also occur in circumstellar and interstellar dust (Ney, 1982). The 10 μm silicate bump usually appears when comets come within 1.3 AU of the sun, probably because particles then break up to become optically thin in the infrared.

Before Halley there seemed reason to believe that silicate minerals in comets and interstellar dust are similar. The infrared bands appeared to have the same general shape and absence of structure that characterizes amorphous or possibly layer lattice silicates (Kratschmer and Huffman, 1979; Knacke, 1978). However, the interpretation depended heavily on a single spectrum of Comet Kohoutek (1973f; Merrill, 1974). New observations of Comet Halley are forcing us to reevaluate both comet and interstellar mineralogy.

Bregman *et al.* (1987) and Campins and Ryan (1988) found structure in the 10 μm spectrum of Comet Halley that was not apparent in the Comet Kohoutek spectrum (Figure 3a). The recent comet, Bradfield (1987s), also showed spectral structure near 10 μm (Lynch *et al.*, 1989). The features characterize crystalline silicates like olivines and pyroxenes. Figure 3b shows the striking similarity with infrared bands of an olivine-rich interplanetary dust particle (IDP). Sandford (1988) superposed spectra to find a detailed (although not unique) spectral fit with a mixture of 55% olivine, 35% pyroxene, and 10% layer lattice silicate IDPs.

The results parallel determinations by the GIOTTO and VEGA dust mass spectrometers. Most Halley dust particles are unlike carbonaceous chondrites (Types 1 and 2) or the majority of IDPs, which are dominated by hydrated materials (Jessberger *et al.*, 1988*a*). The composition is more similar to IDPs consisting of anhydrous minerals including Mg_2SiO_4, $MgSiO_3$, FeS, and black amorphous material. Ice could be sequestered in open spaces between grains in IDP-like comet dust (Brownlee, 1988).

Olivines or pyroxenes in comets raise some interesting questions. These minerals are high temperature phases; magnesium silicates typically condense around 1400 K and further reactions go to completion by 500 K (Hartmann, 1983). How did the comet silicates get so hot? Certainly they must have reached these temperatures before accreting into the dirty snowball mixture. How pristine does this leave the comet material?
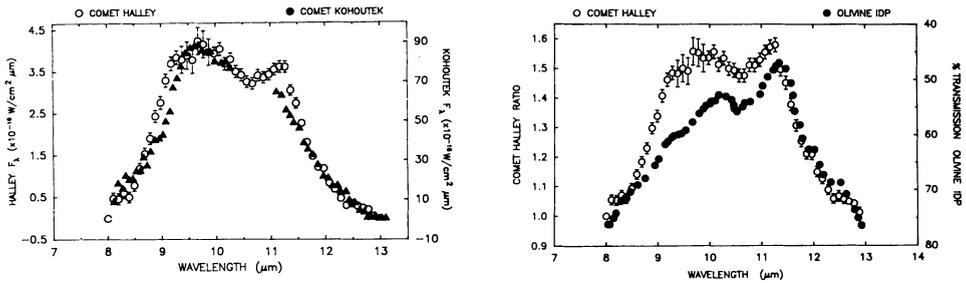
Fig. 3. (a. Left) Comets Halley and Kohoutek in the 10 μm region (Campins and Ryan, 1988) with continuum subtracted. (b. Right) A comparison of the Comet Halley spectrum with the inverted transmission spectrum of an olivine-rich IDP (Campins and Ryan, 1988).

Two issues should be settled, in my view. First, the Comet Halley and Comet Kohoutek spectra don't look all that different to me (Figure 3a). Does the silicate mineralogy really vary a lot, or are we just now getting good enough data to see the mineral phases? Second, 10 μm interstellar absorption bands (e. g. Willner *et al.*, 1982) really look smoother than the comet bands, but spectra of circumstellar shells (where the interstellar silicates must originate) are more complex. Spectra of some shells have structure in the 10 μm band, and the spectra aren't all the same (cf. Merrill and Stein, 1976). Recent IRAS-LRS spectra of Mira variables show considerable variation and evidence for different silicates, including high temperature phases (Vardya *et al.*, 1986; Onaka *et al.*, 1988). Silicate mineralogy of interstellar dust seems ready for reexamination – as emerged in several discussions at this conference.

4.   ORGANICS

Among the fundamental results of the Halley campaigns was the detection of organic compounds. The spacecraft discovered the $CHON$ particles (§ 2) which, together with volatile compounds, bring the elemental abundance of carbon in Halley to near solar (Kissel *et al.*, 1986; Jessberger *et al.*, 1988*b*). A feature near 3.4 μm, strongly suggestive of an organic signature, was discovered in VEGA IKS spectra (Combes *et al.*, 1986), which were quickly followed by ground-based observations (Wickramasinghe and Allen, 1986; Knacke *et al.*, 1986; Danks *et al.*, 1987). Figure 4 is a spectrum showing the 3.4 μm band, and a feature near 2.8 μm that was also discovered in Comet Halley (§ 5).

$C - H$ bonds have their fundamental vibrational frequencies near 3.4 μm, when the carbon atom is singly or doubly bonded to another carbon. The strong band requires something as abundant as C, N, or O, and only the $C - H$ group resonance falls near the right wavelength (Knacke *et al.*, 1986). The emitter is more refractory than ices which do not survive far from the comet nucleus when within 2 AU (Combes *et al.*, 1988).

Still uncertain is whether the 3.4 μm emission is by grains or gas. Gas phase
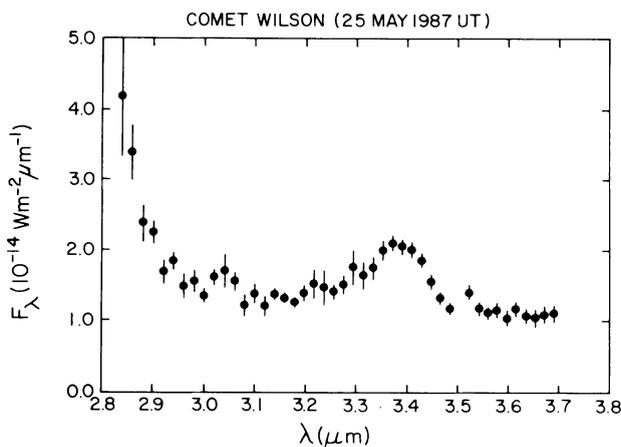
Fig. 4.   The 3 μm spectrum of Comet Wilson in a 2.7 arcsec aperture (Brooke *et al.*, 1988).

resonance fluorescence strains (but does not make impossible) the abundance requirements (Knacke *et al.*, 1986). Near the nucleus, the C abundance would have to be more than half that of H_2O (i. e. near or greater than cosmic) by this mechanism (Encrenaz *et al.*, 1988). There are no indications of narrow atomic or molecular lines in the band although it does have broader structure (Drapatz *et al.*, 1986; Baas *et al.*, 1986). If the mechanism is thermal emission by small grains or transient heating by single UV photons, the carbon required is only a few per cent of H_2O. *CHON*s or perhaps a mixture of organic grains and molecules are prime suspects for the 3.4 μm emission (Combes *et al.*, 1988).

Although there have now been three comets, Halley, Wilson (1986l), and Bradfield (1987s), which showed the 3.4 μm band, we don't yet know how common it is. It was absent in Comets P/Encke and West (1975m), near 0.5 AU at the time of the observations. Comet IRAS-Araki-Alcock (1983d) had no or at most a very weak feature at 1 AU (Hanner *et al.*, 1985). The issue of heliocentric variation should certainly be pursued, as should searches for longer wavelength emissions of organic compounds (Bregman *et al.*, 1987; Chyba and Sagan, 1987).

At resolving powers of 100–400, the band structures at 3.4 μm are very similar in the three comets (Figure 5). The spectra show three distinct peaks and substructure indicative of molecular functional groups (Encrenaz *et al.*, 1988; Colangeli *et al.*, 1989).

This points to a rather uniform complement of organic compounds in comets, more uniform than those of products that have been synthesized in different laboratory simulations of organic processing (cf. Greenberg, 1982). On the other hand, natural organics in kerogens generally show characteristic infrared spectra, although with real variations (Rouxehet *et al.*, 1980). We may be seeing fairly pristine material that formed in similar conditions in all the comets. Since Halley is an old comet, and Wilson and Bradfield were new, the data imply that comets assimilated organic compounds when they formed (Brooke *et al.*, 1988).
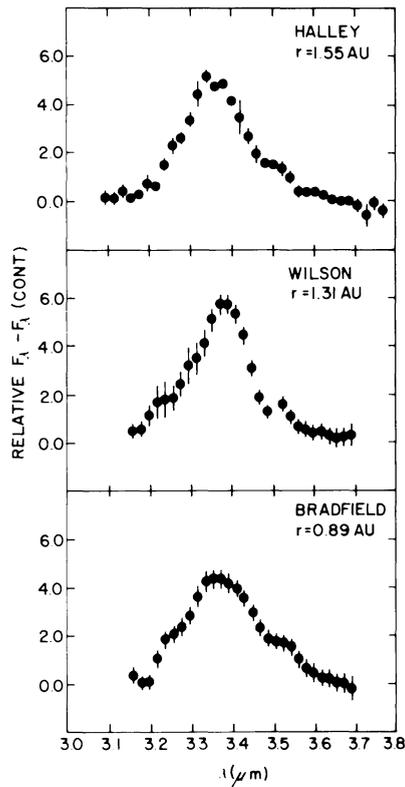
Fig. 5. A comparison of the 3 μm spectra of Comets Halley, Wilson, and Bradfield (Brooke *et al.*, 1988). The continuum was subtracted from each spectrum and the equivalent widths of the 3.4 μm feature were normalized.

How does the band shape compare with interstellar absorptions and emissions (Brooke and Tokunaga, 1988)? Absorption in diffuse clouds, which must be the signature of a fairly refractory absorber (Butchart *et al.*, 1986), matches the comet emission reasonably well near 3.4 μm but disagrees shortward of 3.3 μm (compare Figures 5 and 6a). Comet emission at 3.29 μm could be a signature of polycyclic aromatic hydrocarbons such as are strongly suspected in interstellar material (Baas *et al.*, 1986). On the other hand, the comet band is relatively stronger longward of 3.29 μm than nebular emissions are (compare Figures 5 and 6b). In short, comet and interstellar spectra near 3.4 μm resemble each other, but they are not identical.

These differences may reflect environmental effects, and do not rule out connections between the grain populations. UV and cosmic rays process comets and interstellar dust, and can drastically alter organics (Greenberg, 1976; Strazzula, 1986).
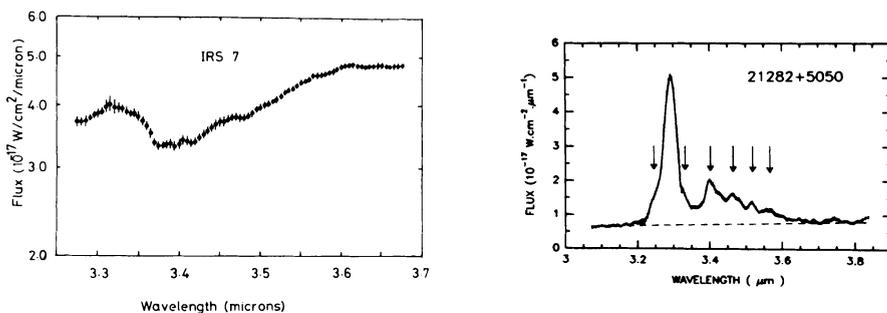
Fig. 6. (a. **Left**) Spectrum of source IRS7 in the Galactic Center (Butchart *et al.*, 1986). (b. **Right**) Spectrum of IRAS 21282+5050 (de Muizon *et al.*, 1987). Compare Figures 4 and 5.

One systematic effect may be showing up (Knacke *et al.*, 1987). Comets from the fairly benign environment of the Oort Cloud show emission attesting to the presence of both aromatic molecules and the less refractory 3.3 - 3.6 μm organic emitters. In the harsh surroundings of HII regions, the 3.29 μm emission of stable aromatic molecules dominates, and the signatures of the 3.3 - 3.6 μm emitters are weak (Figures 5 and 6b). Organics in diffuse clouds may be an intermediate case, but they and organics in molecular clouds are not well understood (in fact, there is evidence that stable aromatics are widespread [Léger and d'Hendecourt, 1987; Giard *et al.*, 1989; Smith *et al.*, 1989]). Carbon processes in space are complicated, reflecting carbon's diverse chemistry and its ability to form both refractory and volatile compounds.

5.   THE 2.6–2.8 μm EMITTER

Tokunaga *et al.* (1987) discovered comet emission near 2.8 μm at the edge of the earth atmosphere water absorptions (Figure 4). This feature also appeared in Comets Wilson and Bradfield (Brooke *et al.*, 1989). The band is strong and must arise in an abundant constituent, but identifications are still tentative. Recently Weaver *et al.* (1988) obtained spectra of the feature in Comet Wilson that extend through the 2.6–2.8 μm spectral region. The band center is near 2.7 μm, and the integrated absorption intensity is comparable to that of H_2O.

The band center and intensity point to OH, but the feature is too strong to be fluorescence by OH radicals (Combes *et al.*, 1988). Combes *et al.* suggested population of excited OH levels by the dissociation of water. However, detailed examination of this process shows that the band shape disagrees with that observed (Knacke and Brooke, 1988).

A plausible origin of the band may be radiation by OH groups bound in solids. This reduces the abundance requirements because small hot grains can radiate very efficiently. The idea finds support in Comet Halley spectra wherein the emission at 2.7 μm is unresolved, while the neighboring water band between 2.61 and 2.69 μm clearly is resolved (Mumma *et al.*, 1986). Weaver *et al.* (1988) suggest that emission by hydrated silicates is a possible mechanism. However, Tokunaga *et al.*

(1987) pointed out that the strong 10 μm band of silicates was absent at the time of their observations.

Another possibility is that the 2.7 μm feature is emission by bound OH in organic or $CHON$ particles (Knacke and Brooke, 1988). Since there are a lot of these particles, and they are likely to be the 3.4 μm source, they could also be the site of the 2.7 μm emitter. The mass spectra show that the $CHON$s are heterogeneous, so the observed band would be a superposition of solid OH bands with different wavelength shifts. Correlation studies of the 2.7 and 3.4 μm emissions would be a test in future comets.

There is weak absorption in the short wavelength wing (2.8 μm) of the ice band that could be an interstellar analogue of the comet emission (Smith *et al.*, 1989). However, there is no strong interstellar absorption centered at 2.7 μm (Knacke *et al.*, 1982).

6.   VOLATILES

6.1. H_2O

The Comet Halley campaigns confirmed the essentials of the dirty snowball model of cometary nuclei (Whipple, 1987). The expected water was seen as vapor in Comet Halley (Krankowsky *et al.*, 1986; Knacke *et al.*, 1986; Mumma *et al.*, 1986). However, the ice has been annoyingly difficult to find. Detection of a weak 3 μm ice band depends on knowledge of the continuum which is difficult because of the 2.8 and 3.4 μm emissions (Combes *et al.*, 1988). Ices also have short lifetimes; impurities in H_2O will absorb enough sunlight to vaporize the ice within a few hundred kilometers from the nucleus (Hanner, 1981). Here in the inner solar system we may to have to be content to observe mainly the gases.

If we assume that all the silicon and much of the iron and magnesium occur as oxides, 10–20% of O may be bound to silicon and metals (Encrenaz *et al.*, 1988). A further 10–15% may be bound to carbon, and the rest is in H_2O (the VEGA NMS spectrometer found that more than 80% of the molecules escaping from Halley were H_2O [Krankowsky *et al.*, 1986]). A comparable fraction of interstellar oxygen probably resides in oxides in grains, but only 5–35% is in ice in molecular clouds, and less in diffuse clouds. Other interstellar oxygen repositories include CO ($\sim$ 6–8%), but much of the oxygen in the ISM is still missing; significant amounts may be as O or O_2 (Tielens and Allamandola, 1987; Irvine and Knacke, 1988).

Mumma *et al.* (1988) argue that the H_2O ortho-para ratio of 2.3 $\pm$ 0.1 in Comet Halley implies freezing temperatures near 25 K, pointing to formation in the interstellar medium. The ratio is 3.2 $\pm$ 0.2 in Comet Wilson (3 is the equilibrated ratio). The formation temperature is sensitive to uncertainties in the ortho-para ratio, and to the assumption that no ortho-para conversion has occurred since comets formed.

6.2. CO, CN

Estimates of the CO abundances are between 5 and 20% of H_2O, making CO a major component of the Halley nucleus (Eberhardt *et al.*, 1987a; Festou *et al.*, 1986). The NMS experiment on GIOTTO found that CO actually increases with distance from the nucleus. The source in the coma is probably dust particles from

which either CO or a very short-lived parent evolve. CO evolving directly from the nucleus is less than 7% of the H_2O production rate (Eberhardt *et al.*,1987*a*; Combes *et al.*, 1988).

A similar process can account for jets of CN that extend to 60,000 km from the nucleus. A'Hearn *et al.*'s (1986) explanation is that submicron grains, probably $CHON$ particles, release CN.

These observations show that much of the CO and CN in Comet Halley is loosely bound in non-icy, probably $CHON$-type grains (Geiss, 1987), while the 1/3 or so of CO that evolves directly from the nucleus may be frozen in the ices. Since it freezes around 25 K, CO was first thought to indicate low formation temperatures for comets. Recently however, Sandford and Allamandola (1988) found that CO condenses on H_2O ice grains at temperatures up to 50 K, typical of the Uranus-Neptune zone.

6.3. CO_2

The VEGA infrared and the GIOTTO NMS mass spectrometers detected CO_2 in Comet Halley (Krankowsky *et al.*, 1986). The VEGA data give a production rate of about 0.027 of water, about consistent with the CO_2/H_2O ratio of 0.035 that NMS found (Combes *et al.*, 1988). CO_2 has not been observed in interstellar gas because it lacks a dipole moment.

6.4. CH_4

Methane, if present, is less than 4% of H_2O in Comet Halley (Drapatz *et al.*, 1987; Allen *et al.*, 1987; Kawara *et al.*, 1988). Larson *et al.* (1988) reported a possible detection of methane at the 3 sigma confidence level in Comet Wilson (1986l). The CH_4 abundance is $0.014 \le CH_4/H_2O \le 0.045$, similar to the range estimated for Comet Halley.

From these observations emerges that CO in comets is more abundant than CH_4. This parallels to some degree the situation the interstellar medium. About 10% of the cosmic abundance of carbon is in CO in most molecular clouds. Some CO freezes out on the grains in the densest regions (Geballe, 1986). In the gas phase, $CH_4/CO \le 0.01$ in the clouds that have been studied (Knacke *et al.*, 1985). New observations indicate there is little solid methane either (Allamandola, 1988). Thus, in both comets and the ISM, much of the carbon bonds in CO and in hydrocarbons or organics more complex than methane.

6.5. S_2

S_2 evolved near the nucleus of Comet IRAS-Araki-Alcock (1983d) (A'Hearn and Feldman, 1985). Its photodissociation is so rapid that it is undoubtedly a parent molecule. A'Hearn *et al.* argue that S_2 probably forms by interstellar UV irradiation and evolves from recently exposed layers in the comet. This suggests that the S_2 may be stored in an interstellar dust remnant in the nucleus. A'Hearn *et al.* emphasize the need to test this and alternative origins, and to look for S_2 elsewhere in comets and the interstellar medium. Sulfur also occurs as S, CS, and possibly OCS (Combes *et al.*, 1988) in comet comae.
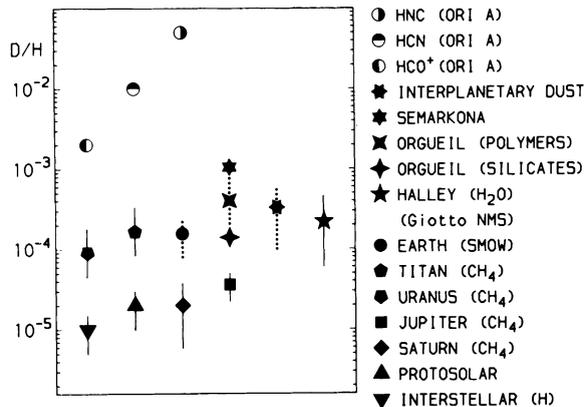
Fig. 7. Deuterium abundance in Comet Halley compared to different solar system and galactic reservoirs (Eberhardt *et al.*, 1987*b*).

7.   ISOTOPE RATIOS

The present, incomplete pictures of comet and interstellar dust show that the compositions of the two are similar, perhaps even strikingly so, but the parallels do not prove a common origin. Further evidence turns up in isotope studies of comets and other primitive matter in the solar system.

The $^{12}C/^{13}C$ ratio in Comet Halley spectra is 65 ± 8 compared to the solar system value of 89 (Wyckoff *et al.*, 1988). A ratio near 65 is more typical of current results for interstellar gas, although the number has been creeping upward over the years. Wyckoff *et al.* suggest that the low ratio implies significant chemical fractionation in a condensation environment different from that of other solar system bodies. Interpretation of isotope spectroscopy from the spacecraft is still incomplete with 12/13 mass ratios ranging between 1 and 4000 (Jessberger *et al.*, 1988*b*)!

Higher than solar or cosmic D/H ratios occur in meteorites, particularly in the carbonaceous material (Robert and Epstein, 1982; Kerridge and Chang, 1985), and in IDPs (Brownlee, 1987; Zinner *et al.*, 1983). The most plausible fractionation process enriching D/H is ion-molecule reactions at low temperatures and subsequent incorporation of the products in grains (Geiss and Reeves, 1981; Tielens, 1983).

A critical result from the Comet Halley missions is that the D/H ratio (from HDO/H_2O) is enhanced also, between 3 and 24 times cosmic (Eberhardt *et al.*, 1987*b*). This overlaps enrichments in carbonaceous chondrites and interplanetary dust as well as enrichments in Titan and Uranus, but is higher than the near solar Jupiter and Saturn ratios (Figure 7). This result strongly supports the idea that Comet Halley acquired hydrogen in volatile molecules and ices (Eberhardt *et al.*, 1987*b*). It is also evidence for distinct solid and gas reservoirs in the solar nebula (Owen *et al.*, 1986).

REFERENCES

A'Hearn, M. F., and Feldman, P. F. 1985, in *Ices in the Solar System*, eds. J. Klinger *et al.*, (Dordrecht: Kluwar), p. 463.
A'Hearn, M. F. *et al.*, 1986, *Nature*, **324**, 649.
Allamandola, L. J. 1988, private communication.
Allen, D. A., and Wickramasinghe, D. T. 1987, *Nature*, **329**, 615.
Allen, M. *et al.*, 1987, *Astr. Ap.*, **187**, 502.
Baas, F., Geballe, T. R., and Walther, D. M. 1986, *Ap. J. (Letters)*, **311**, L97.
Bowell, E., and Zellner, B. 1974, in *Planets, Stars, and Nebulae Studied with Photopolarimetry*, ed. T. Gehrels, (Tucson: U AZ Pr.), p. 381.
Bregman, J. D. *et al.*, 1987, *Astr. Ap.*, **187**, 616.
Brooke, T. Y., Knacke, R. F., and Joyce, R. R. 1987, *Astr. Ap.*, **187**, 621.
Brooke, T. Y., Knacke, R. F., Owen, T. C., and Tokunaga, A. T. 1988, *Icarus*, in press.
——. 1989, in *Interstellar Dust Contributed Papers*, eds. A. G. G. M. Tielens and L. J. Allamandola, NASA CP-3036.
Brooke, T. Y., and Tokunaga, A. T. 1988, in *Infrared Observations of Comets Halley and Wilson*, ed. M. S. Hanner, NASA CP-3004.
Brownlee, D. E. 1987, in *Interstellar Processes*, eds. D. J. Hollenbach and H. A. Thronson, (Dordrecht: Reidel), p. 513.
——. 1988, in *Infrared Observations of Comets Halley and Wilson*, ed. M. S. Hanner, NASA CP-3004.
Butchart, I., McFadzean, A. D., Whittet, D. C. B., Geballe, T. R., and Greenberg, J. M. 1986, *Astr. Ap.*, **154**, L5.
Campins, H., and Ryan, E. V. 1988, *Ap. J.*, in press.
Chyba, C., and Sagan, C. 1987, *Nature*, **330**, 350.
Clark, B. C., Mason, L. W., Kissel, J. 1987, *Astr. Ap.*, **187**, 779.
Colangeli, L. *et al.*, 1989, in *Interstellar Dust Contributed Papers*, eds. A. G. G. M. Tielens and L. J. Allamandola, NASA CP-3036.
Combes, M. *et al.*, 1986, *Nature*, **321**, 266.
Combes, M. *et al.*, 1988, *Icarus*, in press.
Comets, 1982, ed. L. L. Wilkening, (Tucson: U AZ Pr.).
Comets in the Post-Halley Era, 1989, eds. M. Matthews, M. Neugebauer, R. Newburn, J. Rahe, (Tucson: U AZ. Pr.).
Danks, A. C., Encrenaz, Th., Bouchet, P., Le Bertre, T., and Chalabaev, A. 1987, *Astr. Ap.*, **184**, 329.
Danks, A. C., Encrenaz, Th., Le Bertre, T., Chalabaev, A., Bouchet, P., and Epchtein, N. 1988, *Astr. Ap.*, in press.
de Muizon, M., d'Hendecourt, L. B., and Geballe, T. R. 1987, in *Polycyclic Aromatic Hydrocarbons and Astrophysics*, ed. Léger *et al.*, (Dordrecht: Reidel), p. 287.
Dollfus, A., and Suchail, J. L. 1987, *Astr. Ap.*, **187**, 669.
Drapatz, S., Larson, H. P., Davis, D. S. 1987, *Astr. Ap.*, **187**, 497.
Eberhardt, P. *et al.*, 1987a, *Astr. Ap.*, **187**, 481.
Eberhardt, P. *et al.*, 1987b, *Astr. Ap.*, **187**, 435.
Encrenaz, Th., d'Hendecourt, L., and Puget, J. L. 1988, *Astr. Ap.*, in press.
Festou, M. C. *et al.*, 1986, *Nature*, **321**, 361.
Geballe, T. R. 1986, *Astr. Ap.*, **162**, 248.
Geiss, J. 1987, *Astr. Ap.*, **187**, 859.
Geiss, J., and Reeves, H. 1981, *Astr. Ap.*, **93**, 189.
Giard, M., Pajot, F., Caux, E., Lamarre, J. M., and Serra, G. 1989, in *Interstellar Dust Contributed Papers*, eds. A. G. G. M. Tielens and L. J. Allamandola, NASA CP-3036.
Green, S. F., McDonnell, J. A. M., Pankiewicz, G. S. A., and Zarnecki, J. C. 1986, *20th ESLAB Symp.*, ESA SP-250, II, p. 81.
Greenberg, J. M. 1976, *Ap. Space Sci.*, **39**, 9.
——. 1982, in *Comets*, ed. L. L. Wilkening, (Tucson: U AZ Pr.), p. 131.
Hanner, M. S. 1981, *Icarus*, **47**, 342.

Hanner, M. S., Knacke, R. F., Sekanina, Z., and Tokunaga, A. T. 1985, *Astr. Ap.*, **152**, 177.

Hanner, M. S. *et al.*, 1985, *Icarus*, **62**, 97.

Hanner, M. S., Tokunaga, A. T., Golisch, W. F., Griep, D. M., and Kaminski, C. D. 1987, *Astr. Ap.*, **187**, 653.

Hartmann, W. K. 1983, *Moons and Planets*, (Belmont: Wadsworth), p. 130.

Hartmann, W. K., Cruikshank, D. P., and Tholen, D. J. 1985, in *Ices in the Solar System*, eds. J. Klinger *et al.*, (Dordrecht: Reidel), p. 169.

Irvine, W. M., and Knacke, R. F. 1988, in *Origin and Evolution of Planetary and Satellite Atmospheres*, eds. S. K. Atreya *et al.*, (Tucson: U AZ Pr.), in press.

Jessberger, E. K., Christoforidis, A., and Kissel, J. 1988a, *Nature*, **332**, 691.

Jessberger, E. K., Kissel, J., and Rahe, J. 1988b, in *Origin and Evolution of Planetary and Satellite Atmospheres*, eds. S. K. Atreya *et al.*, (Tucson: U AZ Pr.), in press.

Kawara, K., Gregory, B., Yamamoto, T., and Shibai, H. 1988, *Astr. Ap.*, in press.

Kerridge, J. F., and Chang, S. 1985, in *Protostars and Planets II*, eds. D. C. Black and M. S. Matthews, (Tucson: U AZ Pr.), p. 738.

Kikuchi, S., Mikami, Y., Mukai, T., Mukai, S., and Hough, J. H. 1987, *Astr. Ap.*, **187**, 689.

Kissel, J. *et al.*, 1986, *Nature*, **321**, 336.

Kissel, J., and Krueger, F. R. 1987, *Nature*, **326**, 755.

Knacke, R. F. 1978, in *Protostars and Planets*, ed. T. Gehrels, (Tucson: U AZ Pr.), p. 112.

Knacke, R. F., and Brooke, T. Y. 1988, in preparation.

Knacke, R. F., Brooke, T. Y., and Joyce, R. R. 1986, *Ap. J. (Letters)*, **310**, L49.

——. 1987, *Astr. Ap.*, **187**, 625.

Knacke, R. F., Geballe, T. R., Noll, K. S., and Tokunaga, A. T. 1985, *Ap. J. (Letters)*, **298**, L67.

Knacke, R. F., and McCorkle, S. M. 1987, *A. J.*, **94**, 972.

Knacke, R. F., McCorkle, S., Puetter, R. C., Erickson, E. F., and Kratschmer, W. 1982, *Ap. J.*, **260**, 141.

Knacke, R. F., Noll, K. S., Geballe, T. R., Tokunaga, A. T., and Brooke, T. Y. 1986, *20th ESLAB Symp.*, ESA SP-250, III, p. 99.

Krankowsky, D. *et al.*, 1986, *Nature*, **321**, 326.

Kratschmer, W., and Huffman 1979, *Ap. Space Sci.*, **61**, 195.

Krishna Swamy, K. S., Sandford, S. A., Allamandola, L. J., Witteborn, F. C., and Bregman, J. D. 1989, *Icarus*, **75**, 351.

Lamy, P. L., Grün, E., and Perrin, J. M. 1987, *Astr. Ap.*, **187**, 767.

Langevin, Y., Kissel, J., Bertaux, J. L., Chassefiere, E. 1987, *Astr. Ap.*, **187**, 661.

Larson, H. P., Weaver, H. A., Mumma, M. J., and Drapatz, S. 1988, *Ap. J.*, in press.

Le Borgne, J. F., Leroy, J. L., and Arnaud, J. 1987, *Astr. Ap.*, **187**, 526.

Léger, A., and d'Hendecourt, L. 1987, in *Polycyclic Aromatic Hydrocarbons and Astrophysics*, eds. A. Léger *et al.*, (Dordrecht: Reidel), p. 223.

Lynch, D. K., Russell, R. W., and Campins, H. 1989, in *Interstellar Dust Contributed Papers*, eds. A. G. G. M. Tielens and L. J. Allamandola, NASA CP-3036.

Mazets, E. P. *et al.*, 1987, *Astr. Ap.*, **187**, 699.

McDonnell, J. A. M. *et al.*, 1987, *Astr. Ap.*, **187**, 719.

Merrill, K. M. 1974, *Icarus*, **23**, 566.

Merrill, K. M., and Stein, W. A. 1976, *Pub. A. S. P.*, **88**, 294.

Mumma, M. J., Blass, W. E., Weaver, H. A., and Larson, H. P. 1988, Paper presented at STSI Workshop, *The Formation and Evolution of Planetary Systems*.

Mumma, M. J., Weaver, H. A., Larson, H. P., Davis, D. S. 1986, *Science*, **232**, 1523.

Ney, E. P. 1982, in *Comets*, ed. L. L. Wilkening, (Tucson: U AZ Pr.), p. 323.

Onaka, T., de Jong, T., and Willems, F. J. 1988, *Astr. Ap.*, in press.

Owen, T., Lutz, B. L., and de Bergh, C. 1986, *Nature*, **320**, 244.

Pailer, N., and Grün, E. 1980, in *IAU Symp. 90, Solid Particles in the Solar System*, (Dordrecht: Reidel), p. 365.

Robert, F., and Epstein, S. 1982, *Geochim. Cosmochim. Acta.*, **46**, 81.

Rouxhet, P. G., Robin, P. L., and Nicaise, G. 1980, in *Kerogen*, ed. B. Durand, (Paris: Editions Technip.), p. 163.

Sandford, S. A. 1988, in *Infrared Observations of Comets Halley and Wilson*, ed. M. S. Hanner, NASA CP-3004, 68.

Sandford, S. A., and Allamandola, L. J. 1988, *Icarus*, **76**, 201.

Sekanina, Z. 1987, *Astr. Ap.*, **187**, 789.

Smirnov, V. N., Vaisberg, O. L., and Anisimov, S. 1987, *Astr. Ap.*, **187**, 774.

Smith, R. G., Sellgren, K., and Tokunaga, A. T. 1989, in *Interstellar Dust Contributed Papers*, eds. A. G. G. M. Tielens and L. J. Allamandola, NASA CP-3036.

Spinrad, H. 1987, *Ann. Rev. Astr. Ap.*, **25**, 231.

Strassula, G. 1986, *Icarus*, **67**, 63.

Tielens, A. G. G. M. 1983, *Astr. Ap.*, **119**, 177.

Tielens, A. G. G. M., and Allamandola, L. J. 1987, in *Interstellar Processes*, ed. D. J. Hollenbach and H. A. Thronson, (Dordrecht: Reidel), p. 397.

Tokunaga, A. T., Golisch, W. F., Griep, D. M., Kaminski, C. D., and Hanner, M. S. 1986, *A. J.*, **92**, 1183.

Tokunaga, A. T., Nagata, T., and Smith, R. G. 1987, *Astr. Ap.*, **187**, 519.

Vardya, M. S., de Jong, T., and Willems, F. J. 1986, *Ap. J. (Letters)*, **304**, L29.

Weaver, H. A., Mumma, M. J., Larson, H. P., and Drapatz, S. 1988, Paper presented at STSI Workshop, *The Formation and Evolution of Planetary Systems.*

Whipple, F. L. 1987, *Astr. Ap.*, **187**, 852.

Wickramasinghe, D. T., and Allen, D. E., McKeegan, K. D., and Walker, R. M. 1983, *Nature*, **305**, 119.