

INFRARED SPECTROSCOPY OF COMETARY PARENT MOLECULES

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ABSTRACT. Most cometary parent molecules do not strongly fluoresce at ultraviolet and visible wavelengths, and some do not possess permanent electric dipole moments, preventing their study in the radio region as well. However, many of these molecules have strong ro-vibrational transitions in the near infrared ($\lambda \sim 2 - 5 \mu\text{m}$). Since the solar flux at these wavelengths is quite strong, parent molecules in cometary comae can be probed *directly* via fluorescence in these infrared transitions. The feasibility of this approach was convincingly demonstrated by the detection of H_2O in comet Halley (1986 III) from the *Kuiper Airborne Observatory* and by the detection of H_2O , CO_2 , and H_2CO using an infrared spectrometer (*IKS*) on *VEGA*. Tentative detections of near infrared lines of CH_4 were also reported during ground-based and airborne observations of comets Halley and Wilson (1987 VII). High resolution spectroscopy of the infrared water transitions has yielded a wealth of new information on cometary physics: the absolute line intensities and spatial brightness profiles are used to determine water production rates and lifetimes, the relative line intensities probe the kinetic temperature profile in the coma, the line widths and line positions shed light on coma outflow dynamics, and the temporal variability in the lines provides information on the structure of the nucleus. These observations also allow the determination of the water ortho-to-para ratio, which may provide fundamental insight into the origin and/or evolutionary history of cometary nuclei. Similar observations of other molecules (those mentioned above plus others) will provide important complementary data and will also allow us to compile a volatile inventory for cometary nuclei, but such observations are extremely difficult due to the low abundances of these molecules ($\leq 10\%$ relative to water) and the limitations of present infrared facilities. Recent advances in infrared instrumentation promise to extend sensitivities for parent molecule searches to relative abundances well below 1%, especially if cooled, Earth-orbiting facilities are available.

1. Introduction

The near infrared region of the spectrum (defined here as $\lambda \sim 2 - 5\mu\text{m}$) is fertile ground for studying cometary parent molecules. Except for homonuclear molecules, nearly all of the molecules that have been proposed as constituents of cometary nuclei have strong vibrational transitions at these wavelengths. Figure 1 shows the positions of some vibrational fundamental bands of various parent molecules. Also shown is the continuum solar flux (Labs and Neckel 1968) and infrared photometry (which primarily measures grain radiation) for a bright comet (Ney 1974). The latter two curves graphically illustrate why the region between 2 and 5 μm is particularly well-suited for probing parent molecules: there is abundant solar flux for exciting infrared fluorescence while the contaminating influence of grain radiation is minimized. Thus, fluorescence in molecular lines from parent molecules can easily stand out above the grain radiation when observing comets with high spectral resolution instruments.

The emission rates, or "g-factors", for the fundamental bands of some parent molecules are given in Table 1. (Although not a parent molecule, OH is included as well due to its continuing importance in cometary investigations.) While these values are considerably smaller than typical g-factors in the visible, they are comparable to some of the stronger ultraviolet g-factors. More importantly, these g-factors are large enough to produce *observable* emissions from comets under favorable circumstances.

TABLE 1. Infrared fluorescence rates at 1 AU

Molecule	Transition	Band Origin (cm^{-1})	Band Origin (μm)	Band g-factor (10^{-4} photons s^{-1} molecule $^{-1}$)
H ₂ O	ν_3	3756	2.66	2.8
*OH	(1,0)	3570	2.80	1.1
NH ₃	ν_1	3337	3.00	0.3
HCN	ν_3	3311	3.02	3.4
CH ₄	ν_3	3019	3.31	3.4
H ₂ CO	ν_5	2843	3.52	3.8
H ₂ CO	ν_1	2783	3.59	2.9
CO ₂	ν_3	2349	4.26	27.
CO	(1,0)	2143	4.67	2.4
OCS	ν_1	2062	4.85	30.

*The fluorescence rate for OH varies with the comet's heliocentric radial velocity. The value listed above is the maximum. Direct production of OH in excited vibrational states via H₂O photodissociation (Crovisier 1989) is another source of OH emission that has not been included here.

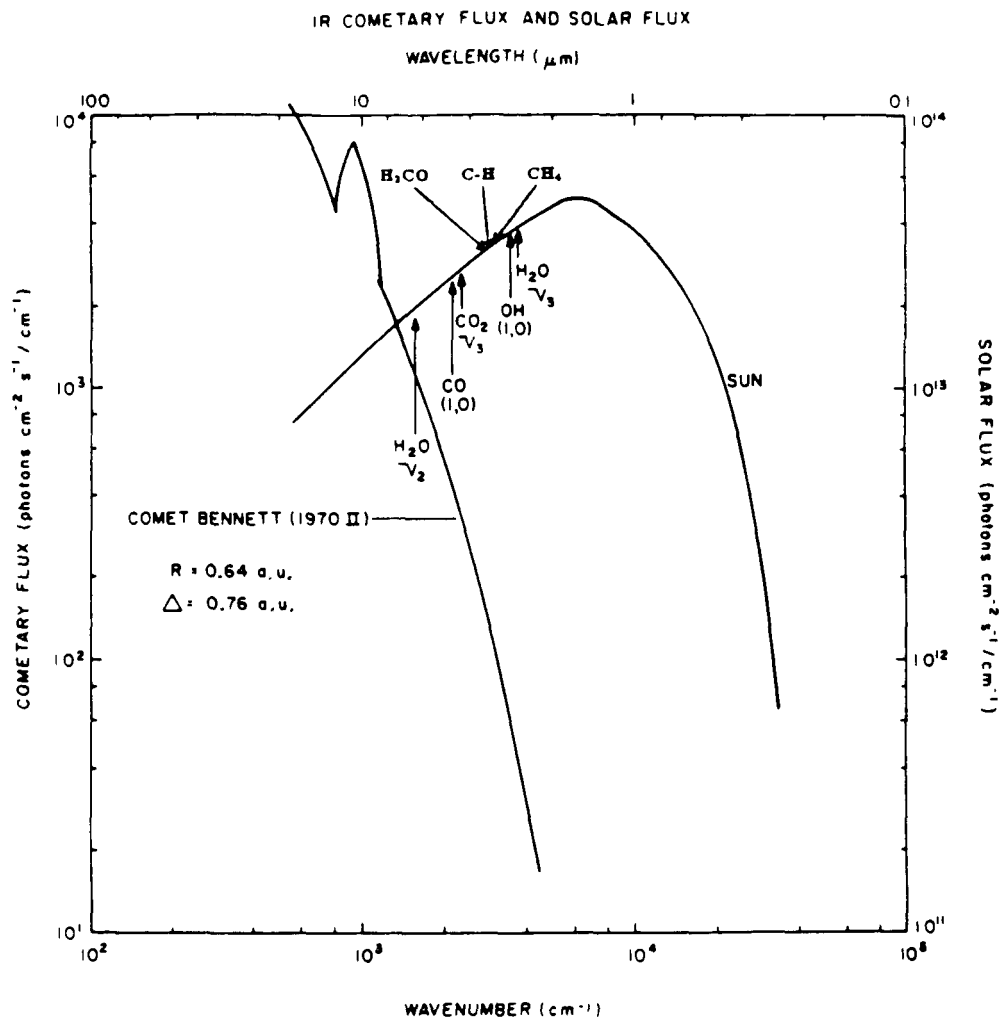


Figure 1. Strong vibrational bands of many molecules lie between 2 and 5 μm . The positions of such bands for several proposed cometary parent molecules are indicated. Also plotted is the solar continuum flux (Labs and Neckel 1968) at a heliocentric distance of 1 AU; this flux provides a powerful pump for infrared fluorescence by molecules in cometary comae. Detection of this fluorescence in the 2 to 5 μm region is enhanced due to the decreasing flux from cometary grain radiation at these wavelengths (the broad band continuum flux from comet Bennett [Ney 1974] is plotted to illustrate this effect). The position marked "C-H" represents the approximate location of C-H stretch vibrations associated with complex hydrocarbons that may be present in comets. Although OH is not a parent molecule, the position of its fundamental vibration band is shown as well because of the continuing importance of OH in cometary investigations. This figure is adapted from Weaver and Mumma (1984).

One of the major difficulties in cultivating the substantial potential of near infrared cometary spectroscopy is the problem of atmospheric absorption. Since most of the proposed cometary parent molecules are also constituents of the Earth's atmosphere, cometary infrared fluorescent emissions are often completely absorbed before reaching the ground. However, the use of air- and balloon-borne observatories, and of observatories in space, can overcome this obstacle. Furthermore, recent advances in infrared detector array technology promise to make infrared observations of comets an area of increasing importance. The purpose of this paper is to review the current status of near infrared spectroscopy of parent molecules and to discuss the scientific objectives of such observations.

A review of infrared cometary spectroscopy, including a discussion of grain radiation as well as gaseous emissions, has been given recently by Crovisier (1990). The reader is referred to that work for some of the details that cannot be covered in the shorter review presented here.

2. Infrared Molecular Emissions

The advent of infrared spectroscopy of cometary parent molecules occurred during the recent apparition of comet Halley (1986 III). The two successful near infrared spectroscopic investigations performed prior to Halley (Oishi *et al.* 1978, Johnson *et al.* 1983) did not detect any emissions from parent molecules. (New emissions were observed but these were from well-known dissociation products.) Several theoretical works (Mumma 1982, Yamamoto 1982, Encrenaz *et al.* 1982, Crovisier and Encrenaz 1983, Weaver and Mumma 1984, Crovisier 1984) on infrared fluorescence from cometary parent molecules were published in the early 1980's that paved the way for the first successful observations on comet Halley. In December, 1985 the ν_3 band of the water molecule was unambiguously detected from the *Kuiper Airborne Observatory (KAO)* (Mumma *et al.* 1986), which flies above 99% of the terrestrial water vapor. In March, 1986 an infrared spectrometer on the *VEGA* spacecraft (the *IKS* experiment) observed emissions from H₂O, CO₂, H₂CO, and possibly CO and OCS (Moroz *et al.* 1987, Combes *et al.* 1988). Figure 2 shows the *IKS* spectrum near the time of closest approach to the nucleus. In this section we discuss fluorescent emissions from parent molecules on a case-by-case basis. Special emphasis is given to the H₂O results due to the extensive measurements made of this molecule.

2.1 H₂O

During the past two decades observers built a strong circumstantial case for H₂O ice as the dominant volatile constituent in cometary nuclei. However, the apparition of comet Halley provided the first opportunity to observe the H₂O molecule *directly*. Pre-perihelion *KAO* observations of Halley (Mumma *et al.* 1986) revealed intense, solar-pumped fluorescent emission in the ν_3 band of H₂O near $\lambda \sim 2.65 \mu\text{m}$. This band was subsequently observed post-perihelion from the *KAO* (Weaver *et al.* 1986) and *VEGA* (Moroz *et al.* 1987, Combes *et al.* 1988). Similar *KAO* observations were successfully conducted on comet Wilson (1987 VII) (Larson *et al.* 1988). Figure 3 shows examples of high resolution spectra ($\nu/\Delta\nu \sim 10^5$) taken from the *KAO* in which individual ro-vibration lines of H₂O are clearly resolved. These data allow one to address a diverse range of cometary problems.

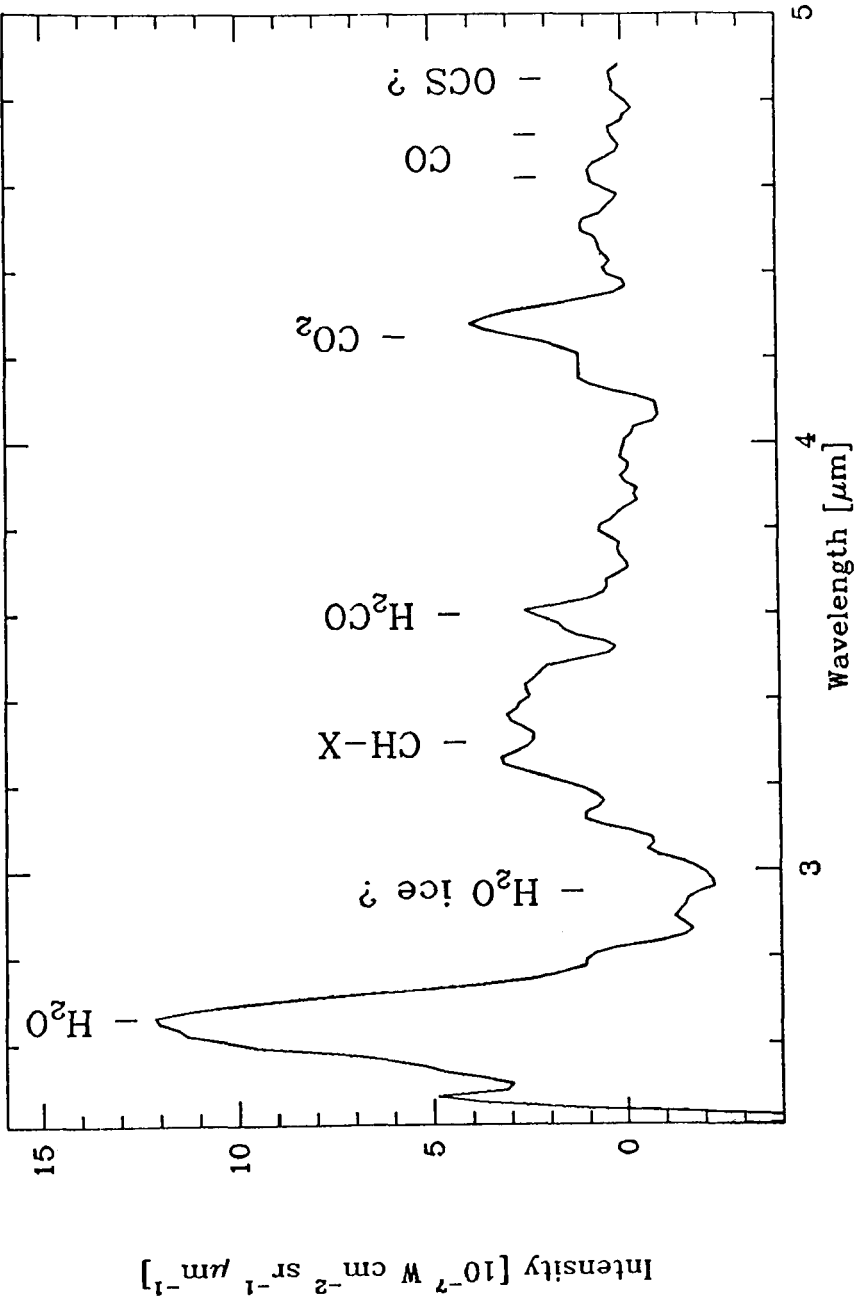


Figure 2. Low resolution ($\nu/\Delta\nu \sim 50$) spectrum of comet Halley (1986 III) between 2.5 and 5 μm is plotted. This spectrum was obtained using the infrared spectrometer (IKS) on the VEGA spacecraft near the time of closest approach to the nucleus. Infrared fluorescent emissions from several cometary parent molecules were detected; identifications are noted in the figure. The feature labeled "OCS" is marginal and can be used as a rough estimate of the noise in the data. This figure is taken from Combes *et al.* (1988).

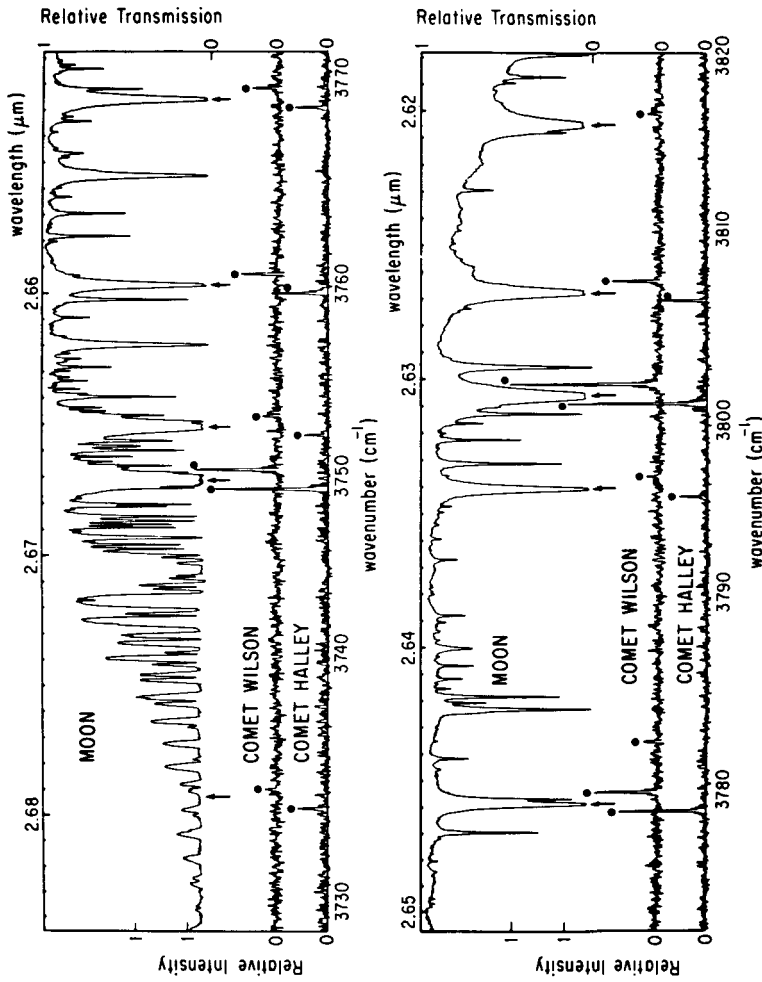


Figure 3. High resolution ($\nu/\Delta\nu \sim 10^5$) spectra of comets Halley (1986 III) and Wilson (1987 VII) between 2.6 and 2.7 μm as measured from the *Kuiper Airborne Observatory*. The comets were observed under nearly identical geometries and instrumental conditions and the spectra are remarkably similar. Neither spectrum has been corrected for atmospheric absorption or instrument sensitivity, but the lunar spectrum (also shown) can be used to estimate both effects. Dots show the positions of the cometary H_2O lines, and arrows show the positions of the corresponding lines in the terrestrial atmosphere. The paucity of cometary lines relative to the number of atmospheric lines is a consequence of strong relaxation of the cometary H_2O rotational population distribution. Both spectra are discussed in detail in Larson *et al.* (1988), from which this figure is taken.

2.1.1 Coma Excitation Conditions. The kinetic temperature profile of the inner coma is determined by the competition among expansion cooling, photolytic heating, and radiative cooling by H_2O molecules (*cf.* Bockelée-Morvan and Crovisier 1987a). Collisions will cause the H_2O rotational temperature to equal the gas kinetic temperature in this region of the coma. The H_2O excitation in the outer coma is determined solely by radiative processes (*i.e.*, the molecules approach *fluorescence equilibrium*). Since the rotational Einstein A coefficients in H_2O are so large, the rotational temperature of H_2O molecules in the outer coma will be exceptionally low with only the lowest energy ortho and para levels having significant populations. (This explains why cometary observations of the water maser line at 1.35 cm have been unsuccessful; the upper state for this transition is ~ 640 K above the ground state.) The *KAO* observations of the relative intensities of individual ro-vibrational lines of H_2O yield direct information on all these processes. Sophisticated modeling of these emissions, including optically thick radiative transfer in addition to the effects mentioned above, has been developed over the past several years (Bockelée-Morvan 1987). Comparisons between theory and observation (Bockelée-Morvan and Crovisier 1987b) indicate that expansion and radiative cooling overcome the photolytic heating, thus producing low gas kinetic temperatures ($T \leq 100$ K) for distances $\geq 10^3$ km from the nucleus. (The observations made to date are not very sensitive to conditions within $\sim 10^3$ km of the nucleus.)

2.1.2 Water Production Rates and Temporal Variability. Water production rates ($Q_{\text{H}_2\text{O}}$) are used for testing sublimation models, for modeling the excitation conditions in the coma, for monitoring temporal activity, and for determining relative abundances of other species. (H_2O is the “standard” to which trace species are compared.) Until the Halley apparition, observations of H_2O dissociation products (*e.g.*, OH, O, and H) were used to derive $Q_{\text{H}_2\text{O}}$. In principle, *direct* observations of $Q_{\text{H}_2\text{O}}$, like those made from the *KAO*, should yield more reliable determinations.

The *KAO* Halley H_2O observations showed a large pre- to post-perihelion asymmetry in $Q_{\text{H}_2\text{O}}$ demonstrating that Halley was about a factor of 5 to 7 more active post-perihelion at $R = 1$ AU than at the same heliocentric distance pre-perihelion (Weaver *et al.* 1987). Short-term temporal activity was also observed in Halley on timescales ranging from a few days to two hours (Mumma *et al.* 1986, Weaver *et al.* 1986), and possibly even less (Larson *et al.* 1990).

The temporal variability in Halley reveals indirect information on the structure of the nucleus. The rather smooth, quasi-periodic behavior in Halley’s visible and ultraviolet brightness (Millis and Schleicher 1986, McFadden *et al.* 1987) has been attributed to the rotation of discrete active areas on the nucleus surface into sunlight. The *KAO* infrared observations showed evidence of large, random outbursts in $Q_{\text{H}_2\text{O}}$ that may imply the release of a significant amount of internal energy from the nucleus, as might occur, for example, during the transformation of nuclear ice from amorphous to crystalline form (Larson *et al.* 1990).

The water production rates derived from the *KAO* Halley observations were quite different (up to factor of 3) from those derived from *International Ultraviolet Explorer (IUE)* observations of OH (Weaver *et al.* 1987; radio OH observations are not discussed here since they are compared with the *IUE* OH observations by Gérard elsewhere in this volume), but at least some of this difference may be attributed to the large absolute calibration error

($\pm 50\%$) associated with the *KAO* observations. For comet Wilson, the *KAO* errors were smaller ($\pm 30\%$) and the water production rates derived from the *KAO* and *IUE* observations are in excellent agreement (Larson *et al.* 1988, Roettger *et al.* 1989). Neither the *KAO* nor the *IUE* observations detected any significant temporal activity in comet Wilson; it has been suggested that the large temporal variability in Halley could produce an “apparent” discrepancy when comparing Q_{H_2O} derived from H_2O and OH observations (Weaver *et al.* 1986).

2.1.3 Spatial Brightness Profile and Water Lifetime. Comet Halley was bright enough that some limited mapping of the H_2O spatial brightness distribution was attempted during the *KAO* observations. A rather large sunward-tailward brightness asymmetry was observed, demonstrating clearly that H_2O was being released primarily into the sunward-facing hemisphere (Weaver *et al.* 1986).

The H_2O spatial brightness profile can be used to derive a water lifetime. Initially a surprisingly low value was retrieved which was about three times shorter than the calculated photochemical lifetime (Weaver *et al.* 1986). However, recent work has shown that the use of a constant H_2O outflow velocity in the radial outflow model used to interpret the observations (as was done in the original analysis) will significantly underestimate the H_2O lifetime and that the *KAO* data can be fit with the “canonical” lifetime (Hu and Larson 1990). We point out that the large temporal variability that took place during the mapping observations adds a further complication to any analysis of these spatial brightness profiles.

2.1.4 Kinematics. Line shape data from the high resolution *KAO* observations provide a “spectroscopic picture” of the H_2O outflow. The absolute line positions are diagnostic of asymmetries in the outflow, while the line widths yield direct information on the outflow velocity. Results from comet Halley indicate that the outflow velocity pre-perihelion was significantly less than the post-perihelion velocity ($0.6 - 1 \text{ km s}^{-1}$ vs. $1.4 - 2 \text{ km s}^{-1}$) even though both observations were taken at approximately the same heliocentric distance (Larson *et al.* 1986, Larson *et al.* 1987). Both pre- and post-perihelion data show evidence for strong asymmetry in the outflow with the post-perihelion velocity field being particularly complex. The *KAO* observations of comet Wilson also revealed asymmetric outflow and a rather large outflow velocity ($\sim 1.5 \text{ km s}^{-1}$; Larson *et al.* 1988).

2.1.5 Ortho-to-Para Ratio. Since transitions between the ortho and para “species” of H_2O are forbidden for both radiative and collisional processes, the ortho-to-para ratio (OPR) cannot be modified in the coma. Thus, the OPR presumably yields direct information on the history of the nucleus (Mumma *et al.* 1987, Mumma *et al.* 1988). For example, a “new” comet whose outer layers have been modified by cosmic ray bombardment during its storage in the Oort Cloud might be expected to have an $OPR=3$, the ratio of the statistical weights of the two species. Periodic comets that have lost their outer layers may have a different OPR. If the equilibration time for the OPR is very long (*i.e.*, as long as the age of the solar system), then the OPR in periodic comets may reflect their formation temperatures and will be significantly less than 3 if this temperature is $\leq 40 \text{ K}$. If OPR equilibration in H_2O ice is relatively fast, then the OPR may simply track the equilibrium temperature of the nucleus in its orbit, in which case the OPR would be 3 for most comets observed near perihelion.

Recent *KAO* observations of comets Halley and Wilson have yielded rather intriguing results on the OPR. The value derived for the “new” comet Wilson is significantly larger than that derived for the periodic comet Halley (Mumma *et al.* 1988). While this latter statement appears secure, it must be emphasized that the derived numerical values for the OPR are model dependent and may require revision as models are improved. Although individual ortho and para H₂O lines are cleanly separated in the *KAO* spectra, some important lines in the H₂O band are obscured by atmospheric absorption and this also affects the retrieval of the OPR. Moreover, reliable interpretation of the OPR in comets must await further laboratory data on the interconversion of the ortho and para species of H₂O in the ice phase.

2.2 LINEAR MOLECULES: CO, CO₂, HCN, and OCS

Crovisier (1987) has discussed procedures for calculating *g*-factors for linear molecules, including all the species given in the section title. The reader is referred to that paper for details. Below we focus on the status of observational searches for these species.

Prior to Halley, neutral CO had been observed directly in only two comets: the CO fourth positive group near $\lambda \sim 1500 \text{ \AA}$ was detected during sounding rocket observations of comet West (1976 VI) (Feldman and Brune 1977) and during *IUE* observations of comet Bradfield (1979 X) (A’Hearn and Feldman 1982). The CO (1,0) fundamental band near $4.7 \mu\text{m}$ is observable from the ground if the geocentric radial velocity of the comet is reasonably large ($\geq 15 \text{ km s}^{-1}$). Although a sensitive search was made on comet IRAS-Araki-Alcock (1983 VII) (Chin and Weaver 1984), the CO infrared band was not detected. The *IKS* spectrum shows evidence for CO (Combes *et al.* 1988; see Figure 2) but the signal-to-noise is poor. The relative abundance limit from the *IKS* CO observation is CO/H₂O $\sim 5\%$, but the *IKS* data measure only the component of CO sublimating directly from the nucleus. The *Giotto NMS* experiment showed that the total CO production rate is $\sim 15\%$ of the H₂O production rate, with most of the CO in the coma being derived from an extended source (*e.g.*, from evaporation of organic grains or from photodestruction of H₂CO). Thermal background limits the sensitivity of CO searches and definite detections of its infrared band might have to await the development of a cooled, orbiting infrared observatory, or of high resolution, cryogenic spectrometers on Earth-based or airborne observatories.

Neutral CO₂ was observed for the first time in a comet by the *IKS*, which detected the CO₂ ν_3 fundamental band near $4.3 \mu\text{m}$ in comet Halley (Moroz *et al.* 1987, Combes *et al.* 1988; see Figure 2). Although CO₂ is a trace constituent of the nucleus ($\sim 4\%$ relative to H₂O in Halley), its ν_3 band is exceptionally strong, making CO₂ a promising target for future study. However, CO₂ in the terrestrial atmosphere produces very strong absorption even up to balloon altitudes. Thus, systematic observations of CO₂ may also have to await the development of the appropriate infrared satellite observatory.

The $J=1-0$ rotational transition of the HCN molecule ($\lambda \sim 3.4 \text{ mm}$) was observed extensively in Halley (Despois *et al.* 1986, Schloerb *et al.* 1987), but its infrared fundamental band near $3 \mu\text{m}$ has never been observed. The *g*-factor of this band is fairly large (see Table 1), but the HCN abundance in comets ($\sim 0.1\%$ relative to H₂O) rules out its detection until significant improvements are achieved in instrumental sensitivities.

The ν_1 band of OCS near $4.9 \mu\text{m}$ is also exceptionally strong. There is marginal evidence

for the presence of OCS in the *IKS* spectrum (Combes *et al.* 1988; see Figure 2), but this result is more properly interpreted as an upper limit. From the infrared observation and from ultraviolet observations of atomic sulfur and other sulfur-bearing compounds (*cf.* Feldman, this volume), a conservative upper limit to the OCS abundance in comets is $\sim 1\%$. Thus, future infrared observations of this molecule will be extremely difficult.

2.3 H₂CO

Formaldehyde is frequently observed in molecular clouds via its radio transitions, but it had never been observed in a comet prior to Halley. There is a significant emission feature in the *IKS* spectrum that coincides with the position of the ν_5 and ν_1 bands of H₂CO (Combes *et al.* 1988; see Figure 2). However, the *IKS* team claimed that part of the emission was spurious and fit the remainder with a model H₂CO spectrum having a rotational temperature of 300 K. A reanalysis of these data (Mumma and Reuter 1989) indicates that the entire emission, including the "spurious" peak, is well-fit by an H₂CO spectrum having a much colder rotational distribution. The H₂CO abundance derived from both analyses agree and give a surprisingly high value ($\sim 4\%$ relative to H₂O). A rotational line of H₂CO (the $1_{11} - 1_{10}$ transition at $\lambda \sim 6$ cm) was detected from the *Very Large Array (VLA)* radio telescope from which a relative H₂CO abundance of $\sim 1.5\%$ was derived (Snyder *et al.* 1989). Moreover, modeling of this radio emission indicates that at least some of the observed H₂CO was derived from an extended source (*e.g.*, polyoxymethylene). Recent analysis of *Giotto NMS* data also indicates that the source of H₂CO in the coma of Halley is extended spatially (Krankowsky, this volume), very much like the case of CO.

The infrared H₂CO bands lie in a spectral region that is accessible from the ground, but no definite detections have been reported, although several sensitive searches have been made (Baas *et al.* 1986, Danks *et al.* 1987, Brooke *et al.* 1989). In fact, strong evidence indicates that the emissions observed near $3.5 \mu\text{m}$ and $3.6 \mu\text{m}$ (where the ν_5 and ν_1 bands occur) *cannot* be explained by H₂CO (Brooke *et al.* 1989). These negative results may indicate either that the H₂CO abundance is temporally variable in a comet, and/or that the abundance varies from comet to comet. A broad cometary emission centered near $3.4 \mu\text{m}$ and identified as C-H stretch vibrations in organic grains contaminates the region where the H₂CO bands occur, further complicating the detection of H₂CO. Future ground-based searches should yield valuable insight into these questions.

2.4 CH₄ and NH₃

Spectroscopic observations of the ν_3 band of CH₄ near $\lambda \sim 3.3 \mu\text{m}$ provide a direct probe of methane in comets. The R(1) line of this band was marginally detected in comet Halley (Kawara *et al.* 1988), while an average over six R-branch lines in this band gave a tentative detection during *KAO* observations of comet Wilson (Larson *et al.* 1988). *KAO* observations of comet Halley yielded only a sensitive upper limit to the CH₄ abundance (Drapatz *et al.* 1987). High spectral resolution ($\nu/\Delta\nu > 1000$) was used during these investigations in order to overcome problems associated with contamination from broad-band cometary emissions (*e.g.*, thermal radiation from grains including the feature centered near $3.4 \mu\text{m}$ that is thought to be associated with organic grains).

The interpretation of these results in terms of the CH_4 abundance is somewhat problematical. The derived abundance can vary significantly depending on the choice of the "effective" excitation temperature of the CH_4 molecules in the coma, especially if only one line is used (*e.g.*, the abundance derived in Kawara *et al.* varies by a factor of ~ 6 as the excitation temperature is varied from 50 K to 200 K). We simply note that the *KAO* observations of H_2O discussed earlier indicate that the appropriate excitation temperature of CH_4 is probably ≤ 100 K, implying that the CH_4 abundance is $\leq 0.5\%$ in comet Halley and $\leq 2\%$ in comet Wilson. The CH_4 abundance in comet Halley deduced indirectly from analysis of data from the *Giotto IMS* experiment is about 2%, but the uncertainties in this case are very large (up to a factor of four in either direction) (Allen *et al.* 1987).

The question about the excitation temperature for CH_4 is particularly interesting because CH_4 has no allowed rotational transitions, and fluorescence in the ν_3 vibrational lines does not efficiently redistribute the population of the ground-state rotational levels (Drapatz *et al.* 1987). Thus, the rotational level populations in CH_4 that are established by collisions in the inner coma remain "frozen" throughout much of the outer coma, so that a measurement of the relative intensities of the vibrational lines in the ν_3 band yields a direct measurement of the coma kinetic temperature. Unfortunately, the sensitivity required to exploit this effect is slightly beyond the capabilities of current instrumentation, except possibly for very bright comets.

There has only been one direct observation of NH_3 in a comet: a radio line was marginally detected in comet IRAS-Araki-Alcock (1983 VII) (Altenhoff *et al.* 1983). From observations of the NH_2 radical in the visible, we know that the NH_3 abundance in comets is probably $< 1\%$ (Wyckoff *et al.* 1990). This, coupled with the fact that the *g*-factor for the NH_3 ν_1 band is small, implies that NH_3 will probably not be detected via its near infrared band in the near future. Although the ν_2 band near $10 \mu\text{m}$ is stronger, this is a more difficult spectral region in which to observe. Heterodyne observations of the $10 \mu\text{m}$ band in comet IRAS-Araki-Alcock yielded upper limits on the NH_3 abundance on the order of $\sim 10\%$ (Mumma *et al.* 1984).

3. Conclusion

Clearly some very interesting results have already emerged during near infrared spectroscopic observations of cometary parent molecules. The work so far has concentrated primarily on the H_2O molecule due to its high abundance in comets and favorable observing circumstances (*e.g.*, the region of its ν_3 fundamental band is not strongly affected by thermal background considerations, and the atmosphere shows some transparency to the cometary emissions as long as the observations are above the tropopause). Three successful observing programs on comets have been conducted from the *KAO* and more are anticipated. The ability to deploy the *KAO* on relatively short notice for new targets of opportunity is a potential important advantage of the airborne cometary program.

However, the challenge facing the IR community is to extend the cometary work to the trace molecular constituents of cometary nuclei. Only then will we be able to compile a detailed inventory of cometary volatiles that can then be used to test theories of planetary system formation and evolution. The initial exciting results from the *VEGA IKS* experiment have given us a glimpse of what is attainable in the future. The introduction of

extremely sensitive infrared arrays during the next few years, and the use of cryogenic high resolution spectrometers on the *KAO* and its successor, the *Stratospheric Observatory for Infrared Astronomy (SOFIA)*, should bring at least several trace cometary parent molecules within detection limits. In addition, the deployment of Earth-orbiting observatories possessing near infrared capabilities, such as the *Infrared Space Observatory (ISO)*, the *Space Infrared Telescope Facility (SIRTF)*, and the *Hubble Space Telescope (HST)* (on *HST* the "second generation" infrared instrument is scheduled for orbit insertion about five years after launch), should further extend our grasp, especially in those cases where atmospheric absorption remains a problem even at airplane altitudes. Besides providing fundamental insight into the physics of cometary comae, near infrared cometary spectroscopy promises to improve significantly our knowledge of the trace volatile composition of cometary nuclei, allowing us to address some of the cosmogonic issues that make comets so important.

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