COMETARY SPECTROSCOPY AND IMPLICATIONS TO THE CHEMICAL COMPOSITION, PHYSICAL PROPERTIES AND ORIGIN OF COMETS

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ABSTRACT

Recent spectroscopic observations of comets, obtained especially in the vacuum ultraviolet spectral region from sounding rockets and satellites, have considerably increased our knowledge of the chemical composition of comets, and the physical and chemical processes occurring in their head and tail. From the UV spectra of comets observed so far, one can perhaps conclude that they have a very similar, homogeneous chemical composition, and possibly also a common origin.

1. INTRODUCTION

The spectroscopy of comets has repeatedly been discussed, e.g., by Arpigny (1977), Delsemme (1977), Donn (1981), Feldman (1982), Festou et al. (1982), Huebner (1981), Lüst (1981), Rahe (1982), Wyckoff (1982), and many others. The following remarks will concentrate on results obtained recently from UV spectroscopy of comets. Most of the measurements have been obtained with the IUE (International Ultraviolet Explorer) satellite.

Ultraviolet observations are for cometary studies especially important since the basic atomic elements, H, O, and C, have their strongest resonance transitions between 1200 and 1700 Å. The most prominent features in all cometary spectra are the Lyman-alpha emission of atomic hydrogen at 1216 Å, and the (0,0) band of OH near 3090 Å. The intensity of these transitions is due to the large abundances of H and OH in cometary comae, (about 2 orders of magnitude larger than those of CN or C_2), and their large g-factors of about 10^{-3} sec^{-1} at 1 AU.

In the following, recent spectroscopic ultraviolet observations of comets are presented, and the results derived from them are discussed.

Richard M. West (ed.), Highlights of Astronomy, Vol. 6, 333–345.

2. COMETARY NUCLEI

In the cold storage of the outer parts of the solar system, (at distances from the sun >5 AU) a comet consists in effect of a solid core that merely shows a reflected solar spectrum. In telescopes it has an almost starlike appearance, its brightness being given essentially by the product of its reflectivity or albedo, A, and the cross section area of the nucleus, $S = \pi R^2$. The product AS can be deduced from nuclear brightness observations at large heliocentric distances when the light contribution of the coma is practically negligible relative to the brightness of the nucleus. Under normal circumstances, the true size of a cometary nucleus cannot be resolved.

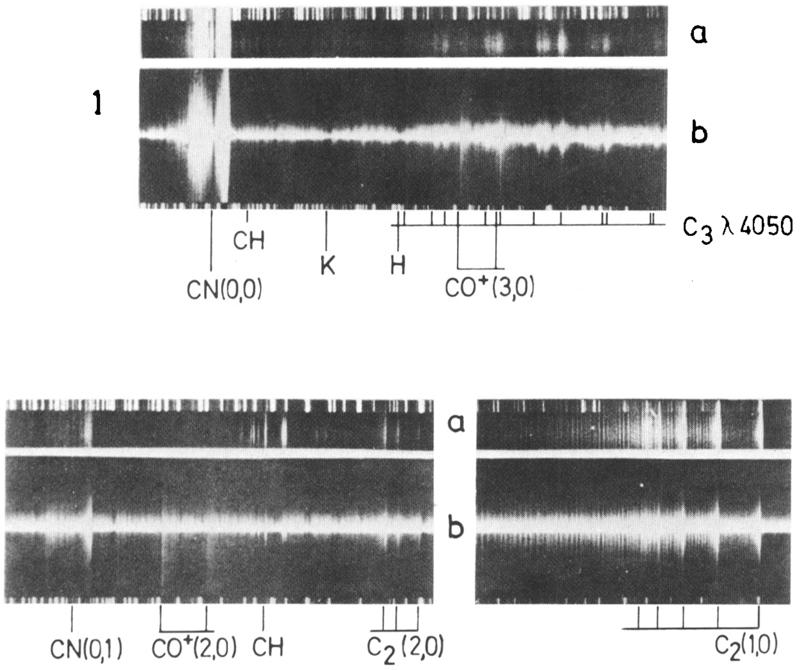
Photometric observations (Roemer, 1965), (Delsemme and Rud, 1973) yield values for cometary radii of the order of 0.5 km to several tens of km; the radii of short-period comets are on average a few km smaller than those of nearly parabolic "young" comets, implying a reduction in radius of roughly $\Delta R \sim 10$ m per revolution.

The details of the structure of the cometary nucleus are still uncertain, and details of its chemical composition remain as yet rather model-dependent. According to the "icy-conglomerate model" proposed by Whipple (1950, 1951), the nucleus is a porous body of frozen components , with micron-sized particles of meteoric matter (metals, silicates, etc.) embedded in it. As the distance from the sun decreases, solar radiation heats the solid nucleus of frozen gases, so releasing dust particles and gas molecules (parent compounds) which are photodissociated into radicals and atoms. These fragments can be observed in the visible spectral region, forming an almost spherical atmosphere or coma around the nucleus. The micron-sized dust particles scatter the solar radiation and produce a continuous spectrum superimposed upon the molecular band and atomic line emissions.

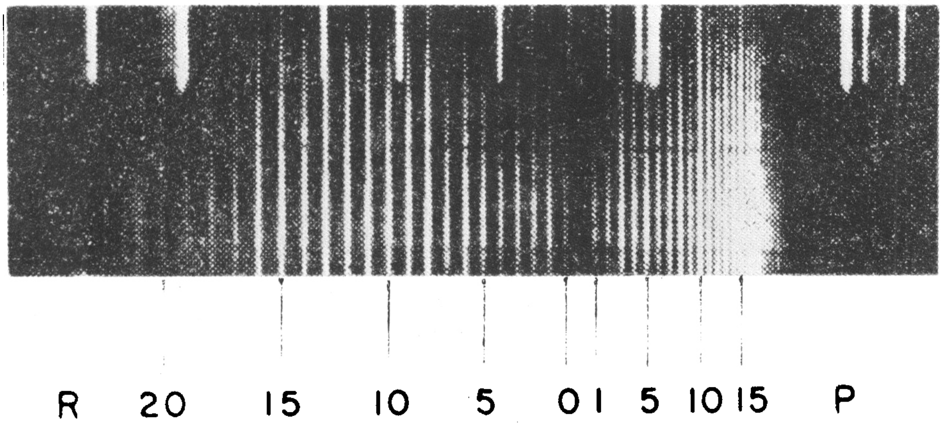
3. COMETARY ATMOSPHERES

The radius of the coma as seen from the ground extends to 10^5 to 10^6 km or about 100 Earth radii. The observed composition of a comet is given in Table 1. One finds compounds of C, N and O with H, and near the sun also terrestrial atoms such as Na, Si, Ca, etc. In the far UV, the L_α - line of H dominates the spectrum, in the IR we have essentially scattering and radiation from solid particles.

Of all coma molecules observed from the ground, CN shows the greatest extension (up to 10^6 km). We see mainly the violet-band system $B^2\Sigma - X^2\Sigma$ with the vibrational transitions $(v', v'') = (1,0)$, (0,0) and (0,1). The (0,0) transition at 3883 Å is by far the strongest and determines the shape and diameter of the coma in the photographic spectral region. The Swan system $A^3\Pi - X^3\Pi$ of C_2 does the same in the visible. C_2 extends to several times 10^5 km. Then come OH and NH ($\sim 10^5$ km), then C_3, CH, NH_2 ($\sim 5 \times 10^4$ km). The emissions decrease gradually with increasing nucleocentric distance, and their extensions are not sharply defined.



Comparison of the spectra of two comets: a. Ikeya (1963I) with no continuum; b. Bennett (1970II) with a strong continuum. a: Mt. Palomar Observatory; b: Haute-Provence Observatory. r=0.72 and 0.91 AU, respectively (from Arpigny, 1977).



The (0,0) 3883 Å band of CN in Comet Bennett (1970II), obtained by J.B. Tatum with the 1.8 m DAO telescope (from Aikman, Balfour and Tatum, Icarus 21, 303, 1974).

Table 1

Spectral identification in comets	Method of observation
Head (coma + nucleus)	
$CN, C_2, C_3, CH, C^{12}C^{13}, NH, NH_2$, (OI), OH, Na, Ca, Cr, Mn, Fe, Ni, Cu, K, Co, H, (Al, Si, He) †)	optical
H, C, O, S, OH, CO, C_2, CS	UV
CH_3 CN, HCN, H_2O, OH, CH	radio
$CO^+, CH^+, CO_2^+, N_2^+, OH^+, Ca^+, H_2O^+$	optical
CO^+, CO_2^+, CN^+, C^+	UV
Reflected sunlight	
Thermal emission, silicate features	IR
Plasma tail	
$CO^+, CH^+, CO_2^+, N_2^+, OH^+, H_2O^+$	optical
CO^+, CO_2^+, CN^+, C^+	UV
Dust tail	
Reflected sunlight	
Thermal emission, silicate features	IR

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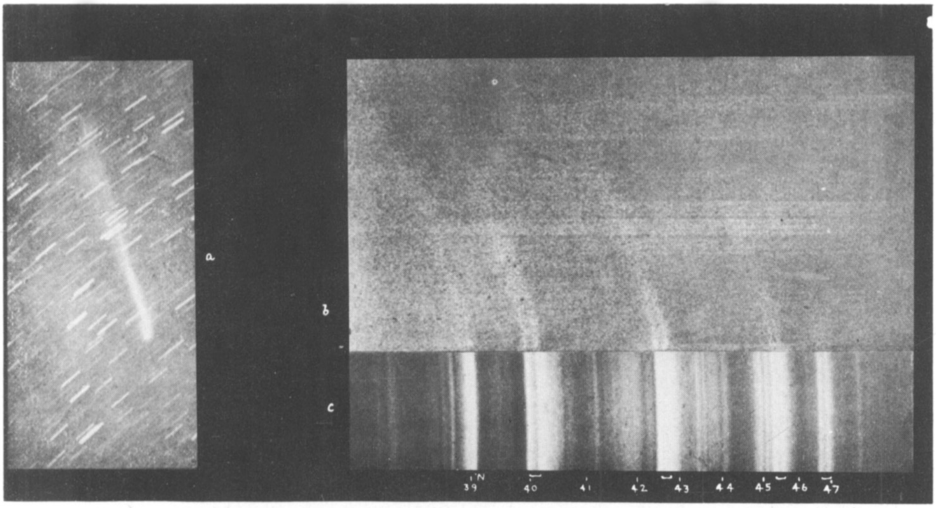
†) Tentative identification

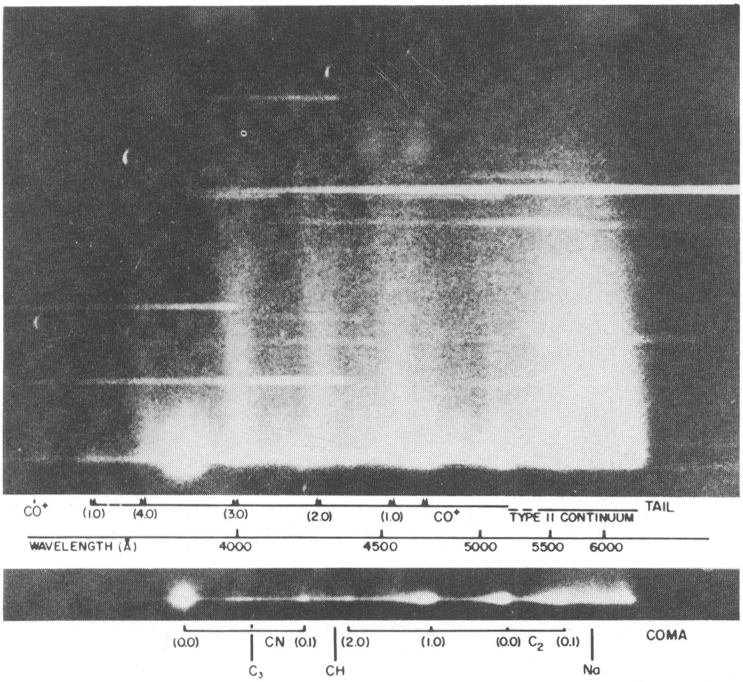
The heavier atoms are observed only when comets are near the Sun, indicating that they are realeased from earthy particles, i.e., meteoroids that strike the earth's atmosphere as meteors and show most of these same atoms in their spectra. The relative abundances of Na, Mg, Ca and Fe measured in meteor spectra, seem to be consistent with those measured in the Sun and in chondritic meteorites (Whipple, 1981).

The other physical clue relating comets to the solar system comes from an analysis of the $^{12}C/^{13}C$ abundance ratio. The terrestrial ratio of $^{12}C/^{13}C$ of 89 stems from the time when the solar system was formed out of the galactic gas and dust cloud, while this ratio in the interstellar medium reflects the present conditions. The observed interstellar ratio is still uncertain, but seems to be somewhat below the terrestrial value. The cometary ratio is also poorly determined because of blends, but appears to be close to the terrestrial value (Vanýsek and Rahe, 1978) - although Lambert and Danks (1982) found a value that seems to preclude a ratio as high as 89. But if the cometary and interstellar $^{12}C/^{13}C$ ratios could be measured with high precision, the important question could perhaps be answered, whether comets are outlying members of the solar system or intruders from interstellar space.

All molecular compounds observed optically in the coma are radicals, which implies that the densities must be very low; most



Comet Morehouse (1908III). a) direct photograph, 4 hours; b) objective spectrogram, 7 hours; c) Carbon monoxide, pressure 0.01 mm (from A. Fowler, 1912).



Comet West (1976VI). Objective prism spectrum, obtained by S.M. Larson (1982). The tail axis of the comet points upward, showing strong bands of CO^+ (4000-6000 Å) and H_2O^+ (5800-6500 Å).

emissions are produced by a resonance-fluorescence mechanism. A known exception is the forbidden red line of oxygen which is presumably produced in the excited ^1D state (Biermann and Trefftz, 1964). The intensity irregularities observed, e.g., in rotational lines of the CN (0,0) band, are clearly correlated with Fraunhofer absorption lines in the solar radiation.

The identity of the parent molecules in comets is still a major problem. A correlation with interstellar molecules is an attractive possibility, since many of the radicals identified in cometary spectra look like dissociation products of observed interstellar molecules, but until now, only three parent molecules (H_2O, HCN, CH_3CN) have been recorded in radio astronomical spectra – each in one comet only. The detections were, however, not confirmed in other comets, or sometimes even in the same comet. These searches are, of course, complex and almost always require going to the detection limits of current instrumentation (10^{11} - 10^{13} cm^{-2} at 1 AU).

4. COMETARY TAILS

The Type-I or plasma tail of a comet as seen from the ground consists of molecular ions, predominantly CO^+ with contributions from H_2O^+, $N_2{}^+$, $CO_2{}^+$, CH^+ and OH^+. The ions usually appear when the comet has a heliocentric distance of less than 2 AU; exceptions, however, are known. Humason's comet (1962 VIII), for instance, showed a strong CO^+ emission extending to over 5 AU from the sun.

The place of formation of the tail ions is still uncertain. Observational arguments point to CO^+ e.g., to an ion source close to the nucleus (Rahe et al., 1969) whereas laboratory dissociative recombination rates seem to exclude it (Biermann, 1970).

Type-II or dust tails show a reflected solar spectrum. Photometric and polarimetric studies reveal that they consist of dust particles with diameters typically of the order of 1 μm.

5. ULTRAVIOLET OBSERVATIONS

Ultraviolet observations are for cometary studies especially important since the major atomic species H, O, and C, have their strongest transitions between 1200 and 1700 Å.

The first ultraviolet observations of comets were made in 1970 when two bright comets, Tago-Sato-Kosaka (1969 IX) and Bennett (1970 II), were observed by Orbiting Observatories OAO-2 and OGO-5. These measurements revealed (Code et al., 1970) that both objects have a strong Lyman-α radiation with peak intensities several hundred times higher than the Ly-α radiation of the sky background (about 7×10^{10} transitions/cm^2/sec). This can be explained by resonance scattering of solar Ly-α radiation on the neutral hydrogen atoms that surround the cometary nucleus in an enormous cloud of diameter about 10^7 km or

1/10 AU. The hydrogen cloud is somewhat elongated into the anti-solar direction due to the effect of solar radiation pressure.

OAO-2 also provided data in the UV region on the (0, 0) bands of the hydroxyl radical OH at 3090 Å, indicating an optical depth of <1 out to about 10^5km. OH, H and (OI) are several hundred times as abundant as CN or C_2, which show the most intense bands in the visible region. OH and H very probably result mainly from photodissociation of ordinary H_2O molecules vaporized from the nucleus.

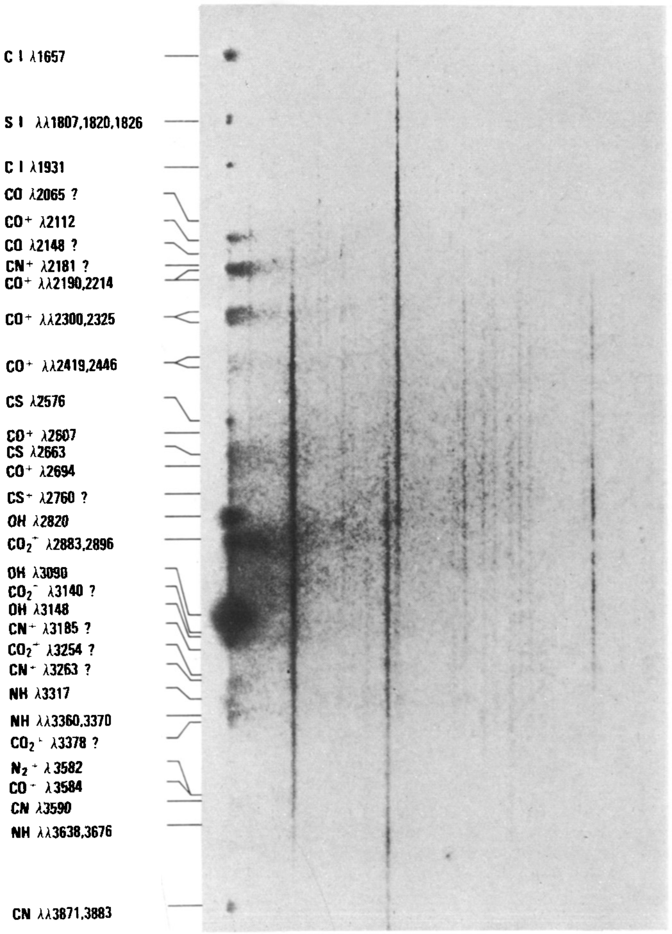
There are strong indications that H_2O is indeed an important, probably even the dominant, parent molecule of the observed hydrogen: the ratio of the H and OH production rates remains constant with changing heliocentric distance, which suggests that H and OH have a mutual parent, and the two species are produced in a ratio of about two to one, which one would indeed expect, if water is this common parent.

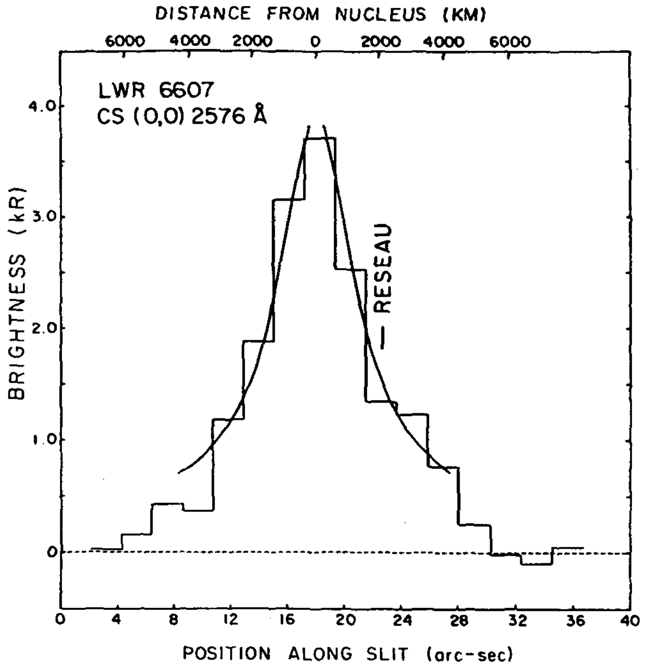
For several comets, the H_2O production could be determined. For Comet Kohoutek, e.g., we find at 1 AU, about 3×10^{29} molecules/sec, or a total mass loss of H_2O of 10^{15} g, which is about 1% of the total mass. The short-period Comet Encke has been in the inner solar system for a long time; it seems to have lost most of its volatile material and has a much smaller evaporation surface. Encke's H_2O-production rate is more than one order of magnitude smaller than that for bright "new" comets.

Already the first UV observations of a comet proved the existence of an enormous H-cloud surrounding the cometary nucleus. The subsequent study of the H and OH emissions in a number of comets strongly support Whipple's (1950) original model of the nucleus, and the typically found H_2O production rates of 10^{29}-10^{30} molecules/sec are of the same order of magnitude as those predicted by him already in 1950 from the analysis of non-gravitational forces.

H_2O has only once been detected in one comet in the radio region. In the UV, its emission cannot directly be detected. But its three dissociation products, H, OH, and O, can easily be observed. If one measures the amount of H, OH and O released, and if one assumes that practically all OH and most of the H and O come from the photodissociation of H_2O, i.e., water, one can almost immediately conclude that normal, frozen water, is a major constituent of a cometary nucleus. Another component with comparable abundance might be CO, which is the most heavy molecule so far observed in interstellar space, but not previously identified in comets. High CO production rates seem necessary to explain the cometary CO^+ tail ions.

We have a rather complete spectroscopic coverage for Comet West (1976 VI). Larson's (1982) objective prism spectrum covers the wavelength region between 3000 and 6000 Å. The tail axis of the comet extends upward; the dominant features are due to neutral CN, C_2 and C_3, and ionized CO^+ and H_2O^+. Smith et al. (1980) rocket-borne spectrum of this





Left: Rocket-borne objective grating spectrum of comet West 1976 VI, extending from 1620 to 3960 Å; exposure 32 sec (from Smith et al., 1980).

Top: Variation of the CS (0,0) band in the large aperture of IUE. The solid line illustrates the brightness variation of CS, if CS was produced from CS_2 via photodissociation (from Jackson et al., 1982).

comet extends from 1600 to 4000 Å. It illustrates the increasing richness of cometary spectra as one goes further into the ultraviolet. One sees a number of different pictures of the comet obtained in the light of different elements. This spectrum also revealed many previously unobserved features due to CO^+, $CO_2{}^+$, CS.

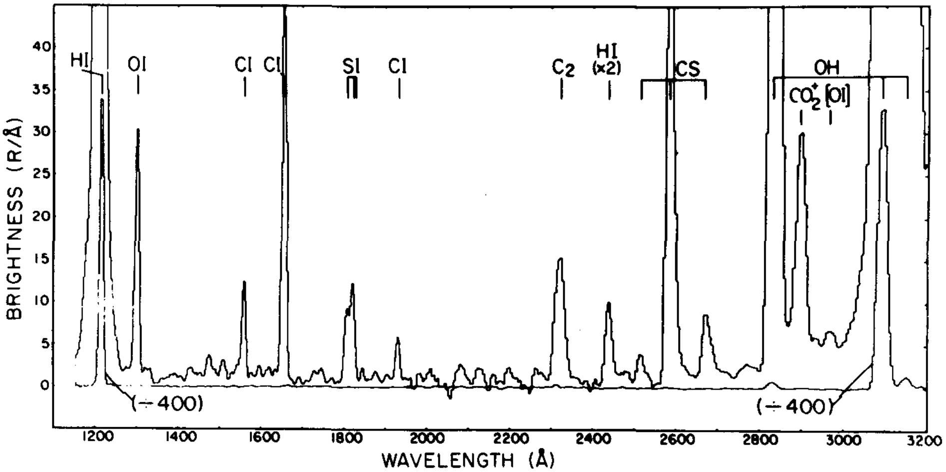
Since January 1978, the International Ultraviolet Explorer (IUE) satellite observatory has been available for cometary observations. Unfortunately, until today there have not been any new, bright comets, such as Bennett or West. But extensive observations of a number of recent comets could still be made. Two comets, Seargent (1978 XV) and Bradfield (1979 X) were relatively bright, and comet Bradfield was the first comet for which ultraviolet observations were made over a wide range of heliocentric distances, from 0.7 to 1.6 AU. The fainter comets include several periodic comets.

A typical spectrum of Comet Bradfield (see Feldman et al., 1980) shows in the short-wavelength region, the highly overexposed hydrogen Ly-α, and also OI (1302), CI (1561, 1657, 1931), and SI (1813). In the long-wavelength part of the spectrum, the dominant features are CO^+, CS, $CO_2{}^+$, and the OH bands. Shortward of 2500 Å, the Mullikan bands of C_2 and Ly-α in 2. order appear.

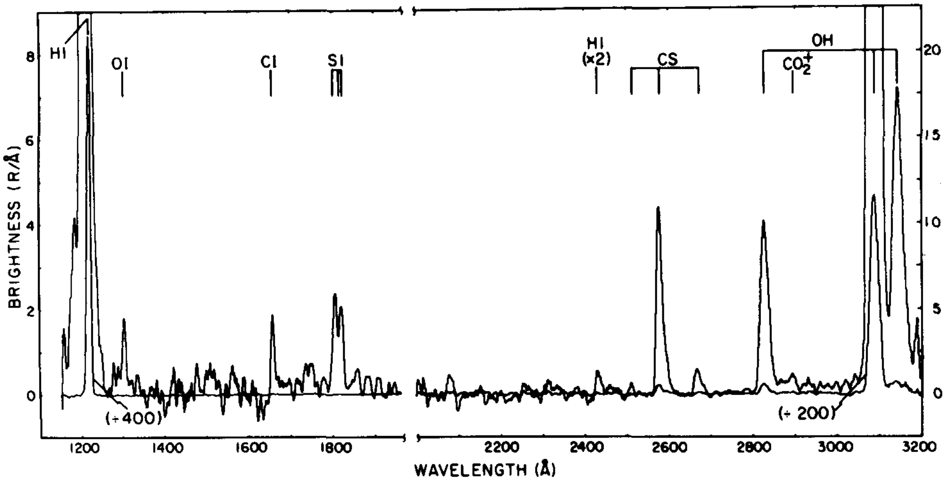
The continuum is very weak and indicates a very small dust-to-gas ratio for this comet, which is consistent with ground-based observations.

The spectra of Comet Bradfield also show that of all cometary emissions observed in the UV, only those from CS and S appear strongly concentrated near the nucleus. This suggests that CS and S have both a common, short-lived parent, such as CS_2 (Jackson et al., 1982). The lifetime of CS_2 at 1 AU is only 100 sec., i.e., it is shorter than that of any other known cometary radical. With an outflow velocity of 1 km/sec, it has a scale length of 100 km. The CS production rate appears to be at least 10.000 times smaller than the water production rate.

Another very interesting result of UV observations is the following: Especially with the IUE satellite, a number of different comets have been observed. Several comets were observed at identical heliocentric distances, others at various heliocentric distances; they looked very different; they showed a different gas-to-dust ratio; and some of them were quite "old", others rather "new". Only the dust, and the CO^+ abundances seem to vary from one comet to the other. If one compares e.g. the spectrum of a "new" comet, such as Comet Seargent (Jackson et al., 1979), with the spectrum of an "old" comet, such as Comet Encke (Weaver et al., 1981), one finds an amazing similarity. In fact, the UV spectra of all comets observed so far are practically identical. The strongest emissions, i.e., those of the most abundant species in the coma, are the same in all UV spectra obtained so far. The presence of the weaker emissions, i.e., those



UV spectrum of comet Bradfield (1979X), taken with IUE at r=0.71 AU (from Weaver et al., 1981).



UV spectrum of comet P/Encke (1980 XI), taken with IUE at r=0.82 AU (from Weaver et al., 1981).

of the minor species, apparently depends only upon the comet's heliocentric velocity (so that the excitation factor remains large enough) and the instrument sensitivity (Festou et al., 1982). It should, however, be noted that as yet, e.g., no extreme CO^+-rich comet such as Comets Morehouse or Humason, have been observed in the UV, which could modify the conclusions drawn from the UV spectra of the comets observed so far.

6. CONCLUSIONS

The main distinguishing characteristic among comets studied in the UV, seems to be the dust-to-gas ratio. Some comets may appear to be "faint", but they are not inactive as indicated by their large water production rate. These comets produce as much gas as bright comets such as Bennett or West. Their "faintness" can be explained (Festou et al., 1982) by both their lack of dust and CO^+ ions, and by the fact that they stay at remote distances from the sun.

Summarizing these results with regard to the character of the cometary nucleus; we can perhaps conclude that several observations appear to point to an undifferentiated structure: According to a study by Donn (1981), the continuum-to-emission intensity ratio appears to have a similar distribution for "new" and for short-period ("old") comets. These extreme age groups show no difference in the dust/gas ratio or the character of the solid particles, and there seems to be no qualitative change in cometary spectra as they evolve.

The emission spectra of new and periodic comets were found to be remarkably similar, in the visible as well as in the ultraviolet spectral region, indicating again a homogeneous structure of the nucleus. Narrowband filter photometry by A'Hearn (1982) and Vanýsek (1976), showed that the CN/C_2 production rate ratio was quite constant from comet to comet, except for a well defined variation with heliocentric distance. The relative production rates, specifically of CN, C_2, C_3 and OH, appear to be unrelated to either the emission-to-continuum i.e., gas-to-dust ratio or the dynamical age of the comet.

Of the seventeen fragmenting comets studies by Sekanina (1977, 1979) which have well-determined orbits and were not sun-grazers, four were periodic, five old, and 8 new or nearly new. There does not seem to be any significant difference among the three age categories. If splitting is intrinsic to a comet, the nuclei of "new" and very old comets behave similarly.

From all this, we can perhaps conclude that the comets observed so far, have a very similar, homogeneous chemical composition, and perhaps also a common origin.

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DISCUSSION

DELSEMME: A word of caution about the chemical homogeneity of the comet population: we have not yet been able to observe in the vacuum ultraviolet, those comets like Morehouse or Humason whose CO^+ production rates are anomalously high in respect to the traditional C_2 and CN molecular bands. Of course, it may be only the result of a fractionation due to the higher volatility of pristine comets.

RAHE: I completely agree with Prof. Delsemme. Observations of such extremely CO^+-rich comets, could indeed give important new clues to the general chemical properties as well as reactions and processes taking place in coma and tail.

MÜNCH: The OH observed emission in comets is resonance radiation in the electronic $^3\Pi-^3\Sigma$ transition. As the spectrum of our Earth's atmosphere shows, the rotation-vibration spectrum in the ground $^3\Pi$ state should be far stronger. To your knowledge, has anybody attempted to observe or theoretically predict the intensity of this emission?

RAHE: As far as I know, such an attempt has not been made.