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Ultraviolet Spectroscopy and the Composition of Cometary Ice

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The coming apparition of Halley's comet in 1986 has stimulated a degree of scientific activity unmatched in the history of this or any other comet. Current planning includes missions to the comet by instrumented spacecraft from the European Space Agency (ESA), the Soviet Union, and Japan. As this armada approaches the comet in March 1986, the comet will be scrutinized, both from the surface of the comet, induced by solar radiation, often produces one of the most spectacular celestial displays visible to the naked eye: a diffuse coma extending for tens of thousands of kilometers and a complex tail system, sometimes reaching more than 10^7 km from the head of the comet. All of this from an icy nucleus a few kilometers in diameter containing about 10^{-11} of the mass of the earth.

Summary. Our current knowledge of the composition of the cometary nucleus is largely inferred from observations of the gas and dust comae that are produced by sublimation of cometary ice when a comet is near the sun. During the past decade, far-ultraviolet spectroscopy from above the terrestrial atmosphere has shed new light on the physics and chemistry of the gaseous component of the coma. The advent of interplanetary missions to Halley's comet in 1986 and the development of a new generation of earth-orbiting observatories promise further insights into the nature of these frozen remnants of the primordial solar system.

surface of the earth and from near-earth orbit, by a network of professional astronomers and by millions of curious amateurs and casual observers, many lured by the comet's fame or by the accounts of its "near miss" of the earth in 1910, the year of its last apparition.

Comets constitute a minuscule fraction of the total mass of the solar system. They are normally uninteresting objects, marking time in the cold outer reaches of the solar system except when their highly elongated orbits bring them close to the sun, typically within 1 or 2 astronomical units (AU; 1 AU is the mean earth-sun distance). At these distances, the sublimation of volatile material from the

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While some 10 to 20 comets are discovered and reported each year, including recoveries of known periodic comets, the number of bright, naked-eye objects is more like one or two per decade. Halley's comet, with an orbital period of approximately 76 years (this changes slightly due to planetary perturbations on each return), is the only reasonably short-term periodic comet to be a naked-eye object and to display all the phenomena usually associated with "new" comets. Apparitions of bright comets are sufficiently infrequent that such events were regarded by our ancestors as being inexorably linked with the important events of the day (for instance, the invasion of England by William the Conqueror in A.D. 1066), and so we have records and images of some comets (including Halley) that go back more than 2000 years.

Nowadays, the apparition of a bright, new comet is a stimulus to astronomers to apply the latest technology routinely available to observers of stars, planets, or extragalactic objects—all fixed in the heavens—to the study of these small, frozen visitors. However, the time scales for such apparitions, except in rare cases such as the widely publicized comet Kohoutek (1973 XII), are only of the order of a few months, making it impossible to send instrumented spacecraft for in situ exploration and limiting the space study of comets to observations made from earth-orbiting observatories designed for the study of objects quite different from comets. The predictability of Halley's return in 1985–1986 removes this problem, and in fact planning for the now nonexistent NASA mission to Halley was begun as early as 1970.

Even for comet Kohoutek the available time before perihelion was only 9 months, but this afforded the astronomical community the opportunity to plan and launch several far-ultraviolet sounding rockets; to place an existing far-ultraviolet camera on board the Skylab space laboratory, which was expected to be operating near the time of perihelion; and to obtain telescope time for an extensive program of ground-based visible and radio observations. An important lesson was learned from this experience: even though the comet "fizzled" as a naked-eye object to the casual observer, the scientific return was prodigious. Two years later, when comet West (1976 VI) appeared with scarcely 3 months notice and blossomed into the spectacular naked-eye object that comet Kohoutek was advertised to be, the scientific enterprise was markedly inferior, and a number of important discoveries made on Kohoutek were not followed up and remain questionable to this day.

As an example of the results from comet Kohoutek, a pair of images published 8 years ago (*1*) is shown in Fig. 1. The image on the left was taken in visible light, while the one on the right is an ultraviolet image in the light of HI Lyman-α (wavelength $\lambda = 1216$ Å) and shows the extent of the atomic hydrogen cloud produced by photodissociation of the primary water ice constituent. Both images were obtained from sounding rockets launched a few days apart approximately 1 week after perihelion. The extended hydrogen envelope was actually discovered a few years earlier from observations of comets Tago-Sato-Kosaka (1969 IX) and Bennett (1979 II) by two orbiting observatories, OGO-5 and OAO-2 (*2*, *3*), but the rocket image of Kohoutek was the first direct image of this phenomenon, an atomic cloud several times larger than the sun. A similar camera on Skylab provided images of the hydrogen envelope over a period of a few weeks (*4*), and both rocket experiments provided spectroscopic evidence for a large abundance of carbon and oxygen atoms in a rather extended ($\sim 10^6$ km) coma (*1*, *5*). The impression of the comet, viewed in the ultraviolet, is quite different from that in the visible, where what mainly is seen is sunlight reflected from the dust component in the coma and resonance fluorescence of sunlight by radicals such as CN, C_2, and NH—dissociation products of still uncertain polyatomic species that exist as impurities (< 1 percent) in the water ice. In other words, in the ultraviolet we see the "ice" products from the "dirty ice" nucleus, whereas in the visible we see, and have seen quite spectacularly for millennia, only the "dirt."

The other area in which comet Kohoutek yielded interesting results was radio astronomy. Whereas in the vacuum ultraviolet we observe the strong resonance transitions of the atoms that constitute the molecules which make up the cometary ice only after the molecules have been completely photodissociated, we can detect the parent molecules, evaporating directly from the cometary nucleus, only by transitions in the infrared or radio-frequency region of the electromagnetic spectrum. At the time of the apparition of comet Kohoutek, radio astronomers were rapidly adding to the list of polyatomic molecules found in interstellar clouds, and many of these molecules, such as NH_3, HCN, HC_3N, and CH_3CN, were of interest as possible progenitors of the species then known to be present in comets, particularly C_2, C_3, CN, NH, and NH_2. Radio observations of the 18-centimeter lines of OH, a species known to be present in cometary comae from the OH ultraviolet band at 3085 Å, and detection of CH_3CN, HCN, and CH were reported, as well as upper limits for a wide range of other polyatomic species (*6*). Subsequently, OH has been observed by radio techniques in a number of comets (*7*), but none of the other species has since been detected, even though searches of a number of comets have been carried out with equipment considerably more sensitive than that used in 1974. A comprehensive survey of the radio results, both positive and negative, and a discussion of the problems inherent in these observations have recently been given by Snyder (*6*). A continuing discrepancy between the ultraviolet and the radio OH observations will be discussed below.

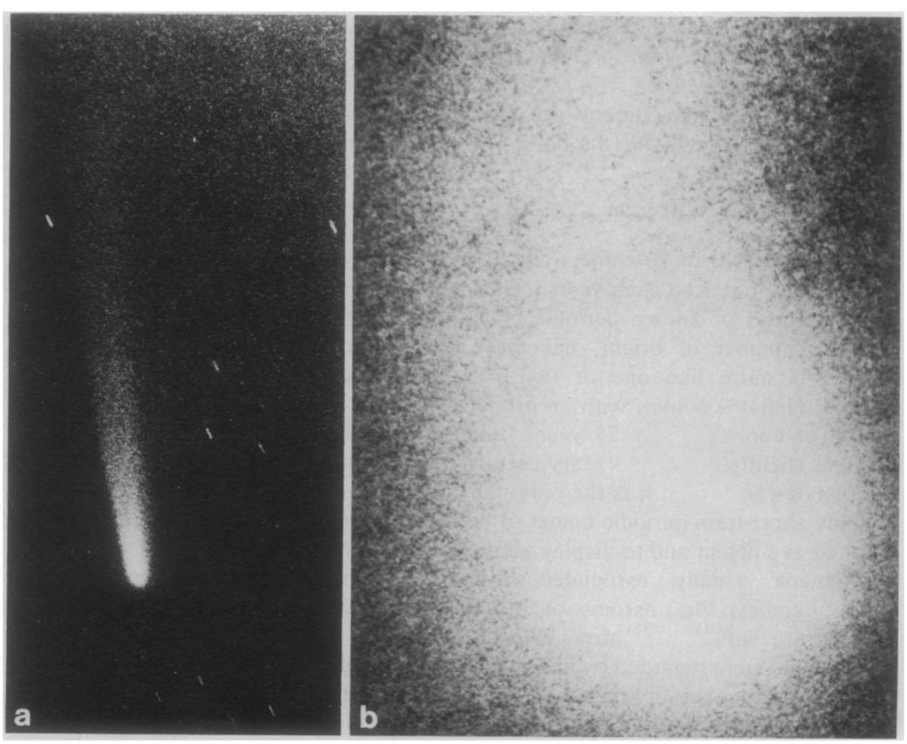

Fig. 1. (a) Visible image of comet Kohoutek (1973 XII) obtained on 5 January 1974. (b) Lyman-α image of the hydrogen envelope surrounding comet Kohoutek obtained by an ultraviolet camera on board a sounding rocket 3 days later, shown to the same scale (*1*).

Cometary Models

Comets are of particular interest because they may be frozen remnants of the primordial solar system and as such may provide clues needed to understand the evolution and differentiation of the planets and their satellites after the initial condensation of the solar nebula. Thus the basic questions to be answered concern (i) the composition and structure of comets and (ii) where and how they were formed. The answer to the first question can be obtained by direct measurement, even though the present group of Halley missions might not be equal to the task and it may require an eventual sample return mission. Also, the answer to the first question does not guarantee a unique answer to the second one. For the present, though, we must be content with models based on what can be observed by optical and radio techniques, namely the coma and tail when the comet is at small heliocentric distances and an unresolved asteroid-like inactive nucleus for comets at several astronomical units from the sun.

The generally accepted model of an icy conglomerate a few kilometers in diameter containing both volatile and refractory components was first proposed by Whipple (*8*, *9*) on the basis of his analysis of the "nongravitational" force perturbation of the orbit of periodic comet Encke. These forces arise from the jet action produced by nonuniform vaporization of matter from the surface of a rotating comet nucleus. Subsequent investigations (*10*) indicated that the major volatile component controlling the vaporization must be water ice, and recent ultraviolet spectra of a number of comets provide strong confirming evidence (*11*) for this idea. However, the ultraviolet observations are of the gaseous coma, not the nucleus, and as Oppenheimer (*12*) pointed out, gas phase reactions in the inner coma (within 10^3 km of the nucleus, a distance barely resolvable with available instruments) might drastically alter the initial gaseous composition, making inferences of the nuclear constituents based on derived coma abundances incorrect. This suggestion has not been substantiated by recent detailed photochemical models, which employ many hundreds of coupled molecular reactions in attempts to reproduce the observed cometary abundances, particularly for the simple radicals (*13, 14*). Moreover, the ultraviolet observations show remarkably similar spectra for comets with widely differing gas production rates, indicating little or no dependence of the composition on gas density. As a result, not only is water ice confirmed as the dominant volatile in the nucleus, but an initial composition of volatiles similar to what is found in interstellar molecular clouds is needed to account for the observed abundances of radicals (*15*). A different approach was taken by Delsemme (*16*), who ignored the details of the chemistry and simply counted the end-product atoms, which were then assembled into a hypothetical nucleus, but again water ice emerged as the dominant constituent.

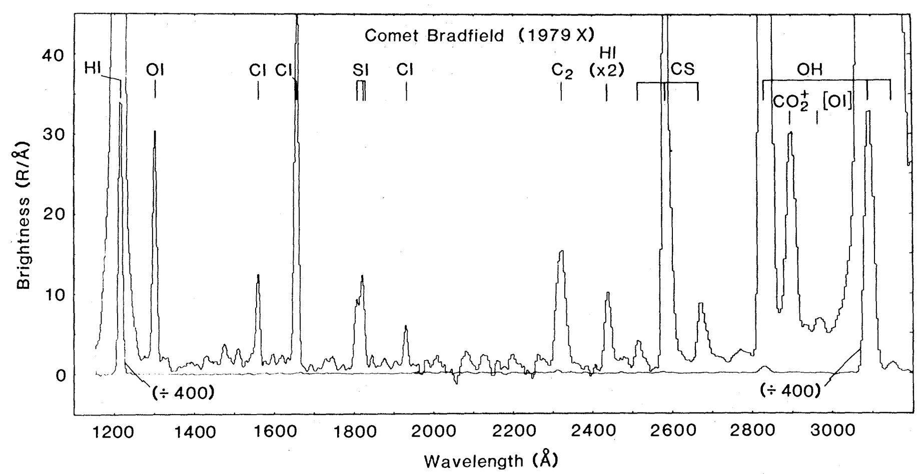

Fig. 2. Composite ultraviolet spectrum of comet Bradfield (1979 X) obtained by the IUE satellite observatory on 10 January 1980, when the comet was 0.71 AU from the sun and 0.62 AU from the earth (*11*).

Unlike planetary atmospheres, which are gravitationally bound and exhibit only relatively mild temporal variations, the atmosphere of a comet is a highly transitory and variable phenomenon. The most rudimentary coma models (*17, 18*) assume that the parent molecules sublimated at the surface of the nucleus flow radially outward, subject only to the solar ultraviolet radiation field, which progressively decomposes them into their constituent atoms (or ions), which continue to flow radially outward. This one-dimensional picture serves as a basis for the more detailed photochemical models (*13, 14*), which must still be regarded as only approximate since they ignore the excess photochemical energy that is available to the dissociative fragments and results in velocities that differ markedly from the monokinetic, radial velocities of the models. This is a severe constraint for the lightest species, particularly hydrogen, as demonstrated by Festou (*19*). Moreover, as Mendis and Houpis point out (*20*), there are actually two classes of models: those that concentrate on the chemical processes and assume simplified geometry and dynamics, and those that minimize the chemistry and emphasize the dynamics and geometry of the outward flow. Both approaches treat the radiative transfer problem, in the ultraviolet and the infrared, in only a rudimentary fashion, and this is of some concern for the interpretation of the ultraviolet observations of H and O, the atomic products of H_2O dissociation, both of which are normally optically thick. In addition, the refractory grains dragged out of the nucleus by the vaporizing gas are assumed to decouple from the gas close to the nucleus, yielding noninteracting gas and dust comae whose subsequent expansion is usually treated separately (*21*).

Despite these difficulties, the derived abundances of H, O, and OH in the coma (*11*) appear to be consistent with an H_2O source at least an order of magnitude more abundant than any other hydrogen-bearing molecule. This interpretation can be verified by the in situ mass spectrometer measurements that will be made by the Halley fly-through missions, particularly by the ESA Giotto spacecraft, which is to fly within 10^3 km of the nucleus. In situ measurements have an additional advantage of being able to detect species not observable by remote optical means. Examples of such species are atomic nitrogen, whose principal resonance transition at 1200 Å is masked, at least to presently available instrumentation, by the nearby intense HI Lyman-α emission at 1216 Å; H_3O^+, the presumed dominant ionic species in the inner coma (*22*), whose optical spectrum is unknown; and, of course, the whole range of possible parents of the observed radicals which have not been detected by any radio search to date (*6*). Even so, a number of species may escape detection if their photochemical lifetime is so short that they have disappeared at the distance of closest encounter of the spacecraft. This is the case for CS_2, which has been suggested as the parent of the S and CS observed in the ultraviolet spectra of a number of comets, and whose calculated photochemical lifetime of $\approx 10^2$ seconds is consistent with the observed intensity and spatial distribution of these species (*23*). With an abundance $\sim 10^{-3}$ that of H_2O, CS_2 appears to be present in the ice of most comets (*24*).

It should be stressed that the in situ measurements will give only a snapshot view of the coma of Halley's comet and that complementary remote observations will be necessary to fit this snapshot into an overall description of the evolution of the comet. Moreover, unlike the similar case that arises in connection with planetary exploration, the in situ measurements provide only a partial calibration of the remote observations made on other comets, whose composition may vary considerably from that of Halley. The degree of similarity or difference of composition may reflect on the various proposals for the site of formation of the comets in the solar nebula.

Far-Ultraviolet Observations

The fundamental compositional difference among various comets, as deduced from ground-based observations, is the dust-to-gas ratio. This is related to the amount of observed continuum (sunlight reflected from solid grains) relative to gas fluorescence produced by C_2, C_3, CN, and so on, which is taken as a measure of the total gas production rate. Among the species detectable in the visible, which represent less than 1 percent of the total volatile component, there appears little variation from comet to comet, provided observations are compared at similar heliocentric distances (*25*). The abundance of these species relative to H_2O (or at least to OH presumably derived from H_2O) is also relatively constant from comet to comet. One exception does exist, and that is CO^+, whose fluorescence in the comet-tail band system ($A^2\Pi_i$–$X^2\Sigma^+$) in the blue region of the spectrum gives the ion tail its visibility. However, sometimes this species is not detectable in the coma, and at best only a weak ion tail is seen, particularly in old, short-period comets.

On the grounds that spectacular ion tails are most often associated with bright, new comets (or at least those with very long periods, $> 10^6$ years) and that both CO and CO_2 are considerably more volatile than H_2O, it has been suggested that new comets contain a significant fraction of either of these species and that, for at least part of their orbit, the sublimation of gases from the nucleus is controlled by this more volatile fraction. This explanation could certainly account for the early discovery of comet Kohoutek (at $\sim$ 5 AU from the sun) and its subsequent fizzling (*16*).

Spectroscopy in the far-ultraviolet provides a convenient means of studying compositional variations of the dominant volatile species, as H_2O, CO_2, and CO all have signatures in this spectral region. As noted above, all three dissociation products of H_2O—H (1216 Å), O (1304 Å), and OH (3085 Å)—resonantly scatter sunlight strongly, as demonstrated by the spectrum of comet Bradfield (1979 X) obtained with the International Ultraviolet Explorer (IUE) satellite observatory (*11*) shown in Fig. 2. Carbon monoxide is detectable through its fourth positive band system ($A^1\Pi$–$X^1\Sigma^+$), as seen in the rocket spectrum of comet West (1976 VI) in Fig. 3 (*26*), and its ion by its first negative system ($B^2\Sigma^+$–$X^2\Sigma^+$) between 2100 and 2500 Å, although the latter provides the same information as the blue comet-tail system. While CO_2 is not directly detectable, its dissociation often leads to the product CO molecule in the metastable $a^3\Pi$ state with subsequent emission of a photon in the forbidden Cameron band system (1800 to 2200 Å), which is one of the dominant emissions in the dayglows of the CO_2 planets

Table 1. Principal ultraviolet emission features.

Species	Wavelength (Å)
H	1216
O	1304
C	1561, 1657
S	1814
CO	1510
C_2	2313
CS	2576
OH	3085
CO_2^+	2890

(*27*). An upper limit (*26*) and a possible detection (*28*) of this emission from comet West were reported from separate rocket experiments. The $\tilde{B}^2\Sigma_u$–$\tilde{X}^2\Pi_g$ double band of CO_2^+ at 2890 Å, also a feature of the Martian dayglow, appears to be present in most comets (*29*) (see Figs. 2 and 3), and atomic carbon is detectable through several multiplets at 1561, 1657, and 1931 Å (*26*).

Since the terrestrial atmosphere is opaque to wavelengths below 3000 Å, observations in the far-ultraviolet must be made from above the absorbing O_2 and O_3, either from earth-orbiting observatories or from sounding rocket platforms. Despite the initial successes with comet Kohoutek, comprehensive spectra spanning the entire wavelength range from 1200 to 3200 Å were not obtained until 1976, for comet West, by means of several rocket experiments (*26, 28*). Since 1978, the IUE has observed nearly a dozen comets, but most of these have been quite faint, and only comet Bradfield (1979 X), a moderately active comet similar in orbit and gas production rate to Halley (*30*), and periodic comet Encke were studied in any detail (*31*). An overview of cometary far-ultraviolet spectroscopy (*32*) and a summary of the IUE observations through 1981 (*24*) have recently been given, and I will limit the discussion here to aspects of the data relevant to the determination of compositional trends.

The interesting comparison to be made is between comet West, in Fig. 3, and comet Bradfield, in Fig. 2. However, this comparison is model-dependent as the two observations were made with widely differing viewing geometries. The IUE spectrographs have apertures of roughly 10 by 20 arc seconds, which translates to a projected size of 4500 by 8900 km^2 for the observation of comet Bradfield on 10 January 1980. The $\approx$ 5 arc second spatial resolution capability of IUE gives a linear resolution of 2200 km at the comet. The rocket spectrometers had much larger apertures and the linear size of the projected image on the short-wavelength slit for comet West was 3.7×10^5 by 1.3×10^6 km^2, about a factor of 10^4 in solid angle greater than that for the IUE. The higher signal-to-noise ratio of the rocket spectrum, despite the much shorter observation time, is in part due to the intrinsically brighter comet observed, but is mainly due to the increased sensitivity to extended objects of the rocket instruments. Furthermore, if the instrument field of view is large enough that the total photon flux in a given emission feature is collected—that is, if the projected distance of the slit on the comet is greater than the scale length for that species—then the derivation of the production rate of the species becomes model-independent. The large field of view also maximizes the sensitiv-

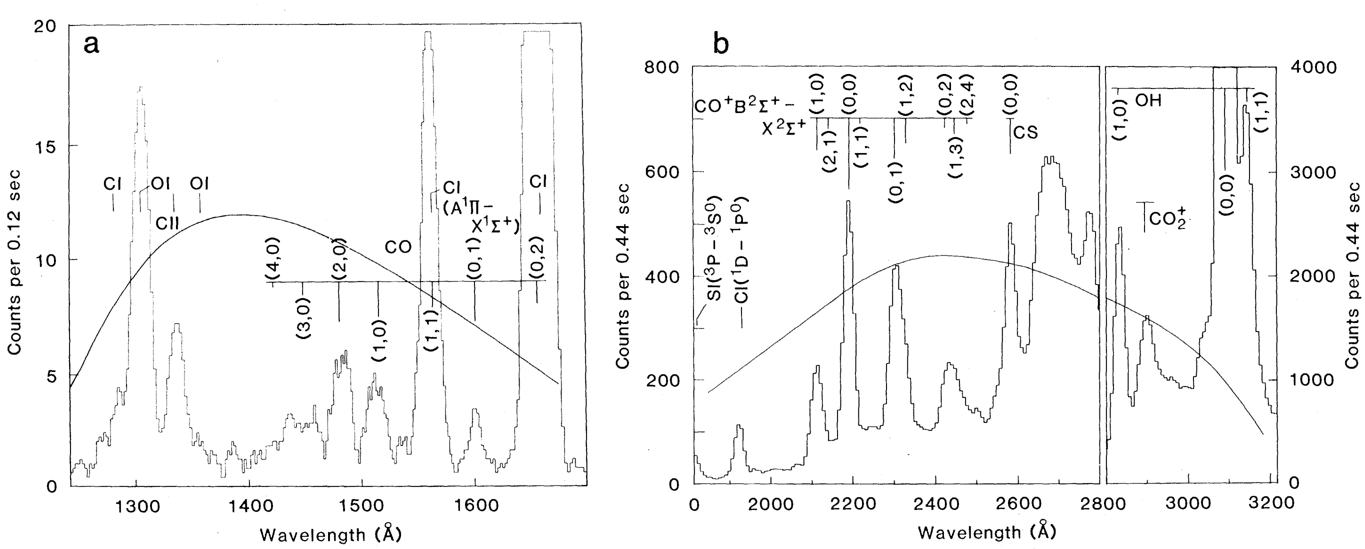

Fig. 3. Ultraviolet spectra of comet West (1976 VI) recorded by a sounding rocket payload on 5 March 1976 (*26*); (a) and (b) are short- and long-wavelength spectra, respectively. The solid line shows the relative response of the spectrometers. In (a) a CaF_2 filter was used to attenuate the transmission of HI Lyman-α to prevent grating-scattered light from masking the weaker emission features.

ity of the spectrograph to weak emission features. On the other hand, for studies of the chemistry and dynamics of the gas outflow the highest possible spatial resolution is warranted, even though it may be useful only for the strongest emissions.

A list of the spectral features usually observed in the IUE data is given in Table 1. Not all the comets observed by IUE were bright enough for all of these features to be discernible over the limiting camera noise, but in every case the strong OH emission bands were clearly detected. Table 2 summarizes briefly the comets observed to date by IUE. Since the conversion from observed surface brightness to gas production rate is model-dependent, these observations were compared (*24*) by considering groups of observations made when the comets were at roughly the same heliocentric distance, and, of course, the observations were all made with the same instruments. In the case of the water dissociation products, the different relative intensities of the observed O and OH emissions in different comets can be accounted for completely on the basis of the variation of the resonance fluorescence efficiency with heliocentric velocity, a differential Doppler shift first proposed by Swings (*33*) and more recently applied in detail to these species (*34, 35*). For the OH bands the effect varies in an irregular way with the comet's velocity as the individual rotational lines are displaced relative to the Fraunhofer absorption lines in the solar spectrum (*35*), and this results in a fluorescent pumping of the ground state Λ sublevels that gives rise to the observed variation in the radio OH emission (or absorption) (*7*). In this regard, a comparison between derived OH parent production rates from the IUE observations and from the 18-cm observations made at Nançay shows the ultraviolet results to be consistently about a factor of 2 higher than the radio results (*36*). This discrepancy is traced to the different model parameters used to interpret the data, particularly the OH scale length, whose value derived from the radio observations is a factor of 10 larger than that derived from either ultraviolet images (*37*) or photochemical analysis (*38*). Nevertheless, these systematic radio observations of about a dozen comets, beginning with comet Kohoutek, provide an invaluable data base for relating the production rate of the most probable primary volatile constituent to the visual brightness of the comet.

Two other compositional trends were noted in the analysis of the IUE data. The abundance of both CS (*24*) and CO_2^+ (*29*) relative to OH appeared to vary by no more than a factor of 2 between comets, which, considering the numerous uncertainties in the abundance derivations, implies a nearly constant fractional abundance for the parents of these species, presumably CS_2 and CO_2, respectively, in the cometary ice. However, for comets Bradfield and Encke, the only two comets for which observations were made over a range of heliocentric distance *r*, the production rate of CS appears to decrease more rapidly with *r* than does that of H_2O (*23, 24*).

Table 2. Comets observed with the IUE.

Comet	Date	Heliocentric distance (AU)
Seargent (1978 XV)	October 1978	0.92
Bradfield (1979 X)	January to March 1980	0.71 to 1.55
P/Encke (1980 XI)*	October and November 1980	0.81 to 1.02
P/Stephan-Oterma (1980 X)	December 1980	1.58
Meier (1980 XII)	December 1980	1.52
P/Tuttle (1980 XIII)	December 1980	1.02
P/Borrelley (1980i)	March 1981	1.33
Panther (1980u)	March 1981	1.73
Bowell (1980b)	April and May 1982	3.4
P/Grigg-Skjellerup (1982a)	April 1982	1.02
Austin (1982g)	July 1982	0.80 to 1.10

*P indicates that the comet is periodic.

The abundance similarities are perhaps most significant for comet Encke, a periodic comet with the shortest known period (3.3 years) and smallest perihelion distance (0.34 AU), which has been observed at 52 different apparitions. The peculiar fan shape of this comet (Fig. 4) and its asymmetric light curve have been interpreted by Whipple and Sekanina (*39*) in terms of a rapidly rotating comet whose axis lies in its orbital plane and whose motion is such that opposite hemispheres, of quite different volatility, face the sun before and after perihelion. The IUE observations of this comet (*31*) show a similarly asymmetric OH cloud away from the nucleus, again supporting the idea of an irregular nuclear surface with scattered icy patches, the result of a long history within the inner solar system. The similarity of composition of the coma then implies a homogeneous ice, regardless of the details of the structure of the nucleus.

As noted above, IUE observations of comet Bradfield (1979 X) were made over a range of heliocentric distances from 0.71 to 1.55 AU over a 7-week time span in early 1980. The OH brightnesses and the derived water production rates

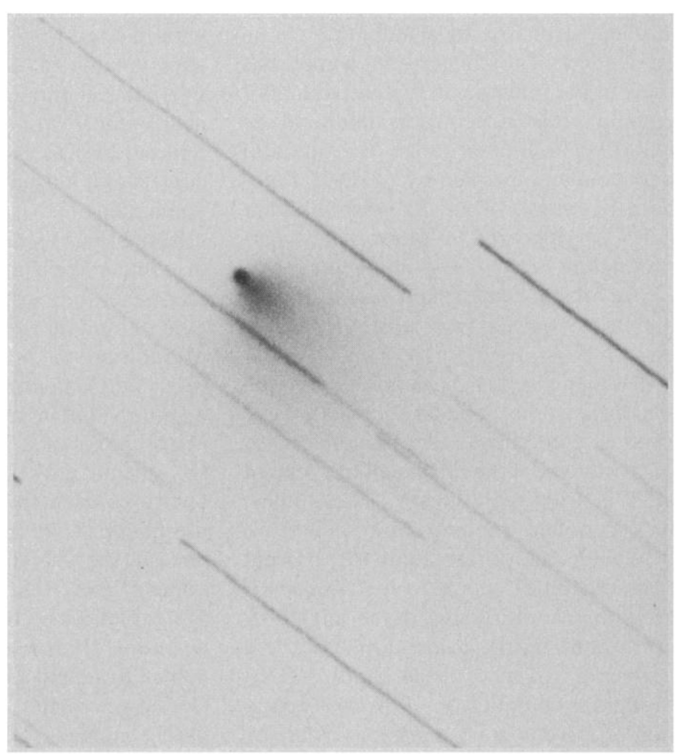

Fig. 4. Periodic comet Encke, as observed in October 1980, showing the sunward fan-shaped coma. [Photograph courtesy of H. Spinrad and J. Stauffer, University of California, Berkeley]

as a function of r are shown in Fig. 5 (*11*); the surprising result is that this variation is quite steep, being proportional to $r^{-3.7}$, whereas the conventional vaporization theory, as summarized by Delsemme (*16*), predicts an r^{-2} variation for H_2O ice at these heliocentric distances. Recent thermal modeling of the nucleus, including the effects of the infrared opacity of the dust coma (*40*), showed that the effect of the grains in absorbing additional sunlight can produce an enhancement in the vaporization rate when the comet is close to the sun. For a model of Halley at these distances, this model gives a variation proportional to $r^{-3.9}$, in good agreement with the observations of comet Bradfield. However, Bradfield was one of the least dusty comets ever recorded (*41*) (Fig. 6), and for the case of a nondusty coma the model prediction is $r^{-2.7}$ (*40*). Similar behavior was observed in July 1982 for comet Austin (1982g), an equally nondusty comet, but the observations were limited to a smaller range of heliocentric distances, 1.10 to 0.80 AU.

Ground-based observations of the OH band at 3085 Å (which is subject to severe attenuation by the atmosphere), as well as of C_2 and CN, appear to confirm the steeper variation of gas production rate for dusty comets. For periodic comet Stephan-Oterma (1980 X), Millis *et al.* (*42*) find that these three species all vary as $\sim r^{-5}$ for heliocentric distances between 1.58 and 1.95 AU. The discrepancy with the vaporization theory should be regarded not as evidence against H_2O being the dominant constituent of the cometary ice, but rather as suggestive of a rather complex surface structure in which the ice is embedded. The longer the comet has been in the inner solar system, the more complex this structure is likely to be (*43*). Over a limited range of r, the two new comets observed by OAO-2, Tago-Sato-Kosaka (1979 IX) and Bennett (1970 II), appeared to follow an $r^{-2.2}$ gas production law (*44, 45*)—quite unexpected for dusty comets and suggesting an almost pristine ice surface for these comets.

The same trends in gas production rate for dusty and nondusty comets have been detected from recent ground-based observations of the forbidden oxygen red lines at 6300 and 6364 Å. These lines, first identified in comet Mrkos (1957 V) by Swings and Greenstein (*46*), present two difficulties to the comet observer: they appear strongly in the night-sky spectrum, and the cometary 6300 Å line is overlapped by a broad band of NH_2. Modern techniques do allow for separation of the cometary emission, either by

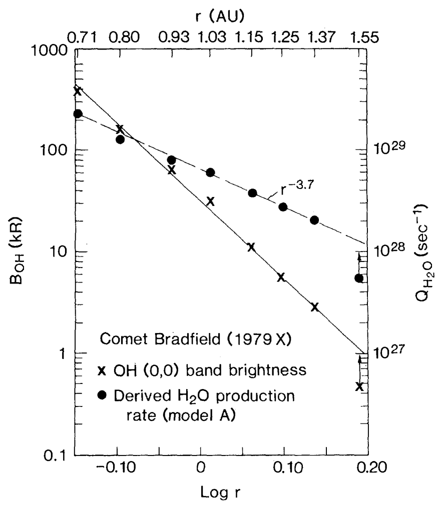

Fig. 5. Variation with heliocentric distance of the H_2O production rate in comet Bradfield (1979 X) as derived from IUE observations of the OH(0,0) band brightness (*11*).

high-resolution interferometric spectroscopy utilizing the relative earth-comet motion (*47*) or by careful sky subtraction with high-spatial-resolution spectrophotometry (*48*). The latter has been used to observe a number of recent comets, including several also observed by IUE, and the comparison between them provides strong support for the idea that this emission is produced by direct photodissociation of H_2O sublimating from the nucleus, the branching ratio to $O(^1D)$ being $\sim$ 5 to 10 percent (*49*). The auroral green line, at 5577 Å, should also be present, about a factor of 10 weaker, but the night-sky and cometary backgrounds are even more severe than at 6300 Å. The data of Spinrad (*48*) are consistent with this red-to-green ratio. If the dominant volatile in the cometary ice were CO_2 the red and green lines would be of nearly equal strength (*49*), and this led Spinrad (*48*) to conclude that all of the comets that he had observed were water-dominated.

This brings us back to the comparison of comets West and Bradfield, the former being the most recent CO-rich comet to exhibit an extensive ion tail system in addition to its spectacular dust tail (Fig. 7). Comparing Figs. 2 and 3, and qualitatively assuming that the spatial distributions of CO^+ and CO_2^+ are similar so that effects due to the different apertures used for the two sets of data are minimal, we notice a marked difference in the CO^+/CO_2^+ ratio for the two comets, the $(B^2\Sigma^+–X^2\Sigma^+)$ first negative system of CO^+ being below the IUE detection threshold in the spectrum of comet Bradfield (*50*). Thus, the neutral CO observed in comet West must be a parent molecule contained in the cometary ice rather than a product of the dissociation of CO_2, which must also be present in the ice. Recall that the IUE data show the CO_2^+ emission to be a regular feature from comet to comet. Assuming CO to be a parent, the comet West data imply a CO production rate about 20 percent that of H_2O (*26*). Since in the solar ultraviolet radiation field CO dissociates and ionizes with roughly equal probability, the radial outflow model used for comparison with the atomic carbon emission lines must be modified to include ion-molecule reactions in the inner coma (*51*). Inclusion of dissociative recombination of CO^+ with electrons is required to match the large abundance of metastable $C(^1D)$ atoms that resonantly scatter at 1931 Å. This model was able to match the observed carbon line fluxes quite well and demonstrated that CO was most likely the dominant carbon species in the cometary ice (*51*). This was not unexpected, as CO is, after H_2, the major constituent of interstellar molecular clouds, and its abundance is significantly higher than that of the polyatomic molecules that are candidate parents of the observed cometary radicals. However, CO is considerably more volatile and might have escaped from the collapsing solar nebula as the cloud heated during its collapse. It is also possible that the high abundance of CO observed in comet West resulted from the splitting of the nucleus into four pieces only a few days before the ultraviolet observations were made.

This model was considerably less successful when applied to the comet Bradfield data (*50*). The CO fourth positive bands were marginally detected in the spectrum of Fig. 2 (great care must be taken in examining IUE spectra to avoid misidentifying noise "features" as weak emissions), and the derived CO production rate was found to be only 2 percent that of H_2O, a factor of 10 lower than in comet West. While this abundance would account for the absence of the CO^+ bands, it predicted emission rates for the atomic carbon lines that were one to two orders of magnitude smaller than the observed values. This discrepancy was much too large to be resolved even by the inclusion of a factor of 4 increase in solar extreme ultraviolet flux between 1976 and 1980 in the model (*52*). Clearly, either an additional source of atomic carbon is present in the coma, or the basic model is incorrect and the agreement with the comet West data was fortuitous. One positive result of the IUE data is that the 1931 Å carbon emission, indicative of the abundance of $C(^1D)$ atoms in the coma, decreased much faster with heliocentric distance than any other emission, implying a collisional source as presumed by the model. Further study of $C(^1D)$ is possible with ground-based telescopes, using the ^1D–^3P transitions at 9823 and 9850 Å, which are analogous to the oxygen red lines discussed above. Despite the rather limited data sample, it seems safe to conclude that it is CO, and not CO_2, that is the variable, highly volatile species in the ice of new comets.

Future Directions

Although it is regrettable that the United States, which over the past two decades has pioneered in the exploration of the solar system, will not be represented among the fleet heading for Halley's comet, NASA does have two unique earth-orbiting observatories that will be available at the time of the 1986 apparition. Both of these will contain instruments employing state-of-the-art technology to provide observational capabilities never before available to astronomers. The symbiosis with the in situ measurements of Halley will add to the enormous scientific potential of these observatories.

The first orbiting observatory is the Space Telescope (*53*), scheduled for launch in early 1985. The capabilities of the Space Telescope are such that major advances in nearly every area of optical astronomy are expected. For cometary spectroscopy, however, the benefits will be limited since the two relevant instruments, the High Resolution Spectrograph and the Faint Object Spectrograph, both have maximum apertures of ≈ 2 arc seconds and will thus sample only a very small fraction of the total cometary photon emission. Nevertheless, the High Resolution Spectrograph should be able to spectrally separate the deuterium and hydrogen Lyman-α lines ($\Delta\lambda = 0.3$ Å) and provide a determination of the cometary D/H ratio if it is in the range of the "cosmic" value of 2×10^{-5} or higher. In addition, the Planetary Camera will obtain images of the nuclear region of the comet in several wide spectral bands to a limiting spatial resolution of ~ 50 km. This is still larger, by an order of magnitude, than the diameter of the nucleus (*54*), which in any case is obscured by the dust and gas comae, but the images should reveal much detail about the dynamics of the gas and dust outflow and the chemistry of the inner coma.

The other orbiting observatory, currently known as OSS-3, is a group of three ultraviolet telescopes assembled on a common pointing platform; these telescopes are designed for stellar and extragalactic astronomy and are scheduled to fly aboard the space shuttle, early in 1986. The three instruments are the Hopkins Ultraviolet Telescope (HUT), the Wisconsin Ultraviolet Photo-Polarimeter Experiment (WUPPE), and the Ultraviolet Imaging Telescope (UIT). Several features of these instruments as currently designed make them very well suited to cometary observations and provide capabilities not available in the cometary ultraviolet studies made to date. For example, the monochromatic imaging capability of the UIT will produce images of the spectrally well-separated O, C, S, CS, and OH features at ≈ 2 arc seconds resolution, which corresponds to a spatial resolution of ≈ 1000 km for a comet 0.7 AU from the earth. Fine details of the chemistry and dynamics of the inner coma can be studied with the aid of these monochromatic images, particularly those of O and C, whose scale lengths are in the range 10^5 to 10^6 km.

The HUT (*55*) will provide not only two to three orders of magnitude better

Fig. 6 (left). Comet Bradfield (1979 X) as it appeared at about the time the spectrum of Fig. 2 was obtained. The weak ion tail disappeared soon thereafter. [Photograph courtesy of F. D. Miller, University of Michigan] Fig. 7 (right). Comet West (1976 VI), photographed by a Nikon-F camera with an *f*/2.8 180-millimeter lens on board the rocket that obtained the spectra of Fig. 3.

sensitivity and better spectral resolution than instruments used for previous observations, but an increased spectral range that extends below HI Lyman-α at 1216 to 500 Å and includes the resonance transitions of the noble gases, in particular HeI 584, as well as several lines of neon and argon. The HUT has a unique capability in this regard as both the IUE telescope currently in orbit and the Space Telescope now being built have mirror coatings and other optical elements that limit the telescope transmission to wavelengths above 1150 Å. Because of the high volatility of helium, its presence in a comet would be an important indicator of the physical conditions present at the time of comet formation in the early solar system. An estimate of the HUT sensitivity at 584 Å indicates that a helium abundance 1 percent that of water in the coma would be detectable. As noted above, atomic nitrogen has not been observed in comets, although nitrogen-containing molecules such as CN, NH, and N_2^+ are known to be present in the coma. This is due to the low efficiency for scattering of solar radiation by the NI multiplet at 1200 Å and the presence of the very intense Lyman-α feature at 1216 Å, which tends to mask any weak emission nearby. The HUT spectral range will include N at 1134 Å and N^+ at 1085 Å, providing additional means of spectroscopically detecting atomic nitrogen. Finally, the WUPPE covers the spectral range beyond the long-wavelength limit of the HUT, thus ensuring complete spectral coverage from ~ 500 to 3200 Å, and it also provides polarimetry of the solar radiation scattered by cometary dust at the shortest wavelengths practical for such observations. Both HUT and WUPPE have selectable apertures ranging from a few arc seconds to 2 arc minutes, allowing for an optimum balance between spectral resolution, spatial resolution, and sensitivity to extended objects.

The current schedule for the OSS-3 payload includes a mission coincident in time with the European and Soviet encounters. If history is any guide, the ultraviolet perception of Halley so obtained will be as different from the visual image as the 1910 photographs were different from either the fantastic representation in the Bayeux tapestry of 1066 or the mannered drawings of Bessel's telescopic view in 1835. Whether our knowledge of the physical state of the comet's nucleus will improve accordingly remains to be seen.

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