ULTRAVIOLET SPECTROSCOPY OF COMETARY COMAE

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ABSTRACT. During the past decade, vacuum ultraviolet spectra of over 30 comets have been obtained with the *International Ultraviolet Explorer* (*IUE*) satellite observatory. With few exceptions, the spectra of these comets appear to be similar, with OH and H produced by the photodissociation of water being the dominant species and emissions of C, O, S, CS and CO_2^+ usually present. Although signs of variability of many kinds in comet spectra appear, the evidence from the ultraviolet observations suggests that all comets have the same basic chemical composition and that observed differences are due to evolution and ageing processes. The principal exception is S_2, which was detected by *IUE* in comet IRAS-Araki-Alcock (1983 VII), but not in any other comet to date. During the 1985-86 apparition of comet Halley, ultraviolet spectra were also obtained by other spacecraft and by sounding rocket instruments, including a long-slit imaging spectrograph. Further advances await future ultraviolet observations of comets by the *Hubble Space Telescope* and other planned ultraviolet astronomy missions.

1. Introduction

Ultraviolet spectroscopy in the spectral region inaccessible to ground-based observers has proven over the past decade to be a valuable technique in the determination of the abundances of the major gaseous constituents of the cometary coma (Feldman 1982). The *International Ultraviolet Explorer* (*IUE*) satellite observatory has observed over 30 comets since October 1978 and a review of the principal results through 1986 has been given by Festou and Feldman (1987). In addition to those observations made by the *IUE*, ultraviolet spectra of comet Halley (1986 III) were obtained by two different U.S. sounding rocket experiments (Woods *et al.* 1986, McCoy *et al.* 1986) and by the Soviet Union's *ASTRON* satellite (Boyarchuk *et al.* 1987). Two other spacecraft intended for other objectives were also able to obtain large-scale H I Lyman-α images of comet Halley, the *Pioneer Venus Orbiter* (*PVO*), in orbit around Venus since 1978 (Stewart 1987), and the *Dynamics Explorer-1* (*DE-1*) satellite, launched in 1981 (Craven and Frank 1987). The ultraviolet spectrometer on *PVO* also measured the coma emissions of atomic oxygen and carbon. The results from all of these observations have been discussed in detail by Feldman (1989) and will only be summarized briefly below.

The main thrust of this paper is to examine, with the hindsight of three years and a wealth of other data from both *in situ* measurements and remote observations, those

R. L. Newburn, Jr. et al. (eds.), Comets in the Post-Halley Era, Vol. 1, 139–148.

observations that either were not made because of insufficient instrumental capability or that appear to be of dubious value. The aim here is to identify the outstanding questions that are likely to be addressed by the next generation of space observatories.

2. Water Production Rates of Comet Halley

All of the ultraviolet observations cited above have in common the measurement of one or more of the dissociation products of water, a molecule which itself does not fluoresce in the ultraviolet or visible. From these measurements, together with a relatively straightforward model of radial outflow of H_2O molecules directly sublimated from the cometary nucleus, it is possible to infer the rate at which this sublimation occurs. The details of converting the observed surface brightness or flux into column abundances has been described in detail (Feldman 1982) and will not be given here. However, we do note the importance of using the proper heliocentric velocity dependent fluorescence efficiencies (Schleicher and A'Hearn 1988). The total water production rate, Q_{H_2O}, derived from observations of OH (*IUE* and *ASTRON*), H I Lyman-α (*DE-1*, *PVO* and NRL rocket), and O I λ1304 (JHU rocket), is shown separately for pre-perihelion and post-perihelion in Figures 1 and 2, respectively. There is clearly good general agreement between the different data sets despite a large scatter, particularly in March and April 1986, due to the intrinsic variability, with an apparent 7.4-day period, of the comet's activity. A detailed example of the effects of this variability on the coma emissions has been presented by McFadden *et al.* (1987).

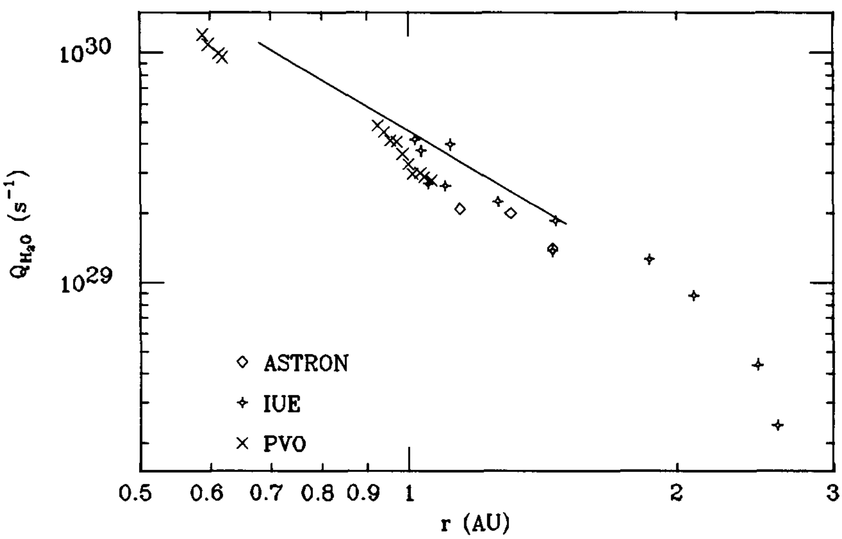

Figure 1. Pre-perihelion water production rate of comet Halley as a function of heliocentric distance from various ultraviolet observations: OH data from *IUE* (Feldman *et al.* 1987) and *ASTRON* (Boyarchuk *et al.* 1987); H I Lyman-α data from *PVO* (Stewart 1987) and *DE-1* [solid line] (Craven and Frank 1987).

There is also good agreement of the data obtained close to the time of the *Giotto* encounter with the water production rate derived from *in situ* neutral mass spectrometer data (Krankowsky *et al.* 1986), which additionally provided confirmation of some of the basic parameters of the radial outflow model used in interpreting the remote observations. Figures 1 and 2 also show good agreement with other indirect measurements of Q_{H_2O} such as the O I (^{1}D) emission at 6300 and 6364 Å (Spinrad *et al.* 1986), and give an asymmetric variation of Q_{H_2O} about perihelion similar to that seen in the visual light curve. The largest discrepancy reported to date is between the values of Q_{H_2O} derived from the direct infrared observations of H_2O made from the *Kuiper Airborne Observatory* (*KAO*) by Weaver *et al.* (1987) and the nearly simultaneous ultraviolet data from *IUE*. However, observations of comet Wilson (1987 VII), a "new" comet that exhibited no appreciable short-term variability, by both *IUE* and *KAO* gave consistent values of Q_{H_2O} (Larson *et al.* 1988, Roettger *et al.* 1989). A possible resolution to the long-standing discrepancy between water production rates derived from ultraviolet and radio OH observations (Schloerb *et al.* 1987, Gérard *et al.* 1987) has recently been proposed by Schloerb (1988). The radio OH measurements are discussed elsewhere in this volume.

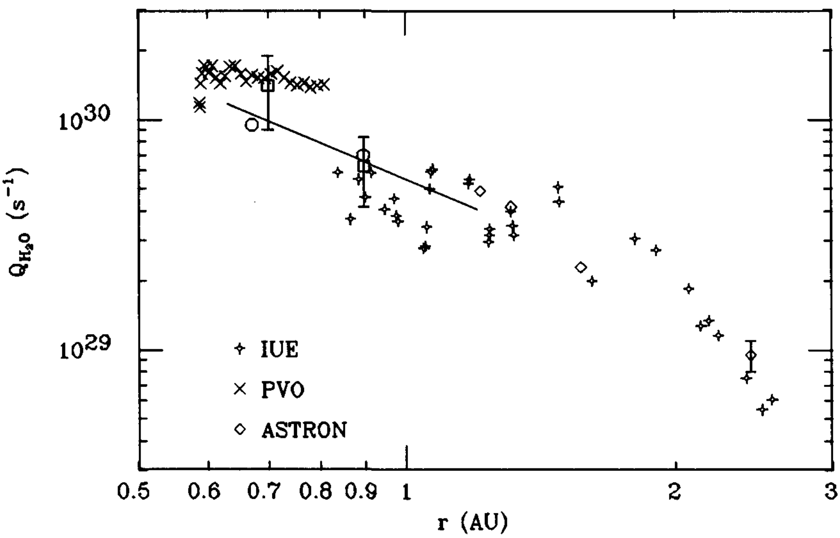

Figure 2. Post-perihelion water production rate of comet Halley. The data are from the same sources as for Figure 1, with the addition of rocket observations of H I Lyman-α [○] (McCoy *et al.* 1986) and O I λ1304 [□] (Dymond *et al.* 1989).

In retrospect, both the *in situ* and infrared measurements of water in the coma of comet Halley have confirmed the basic picture of a predominantly water ice nucleus first advanced by Whipple (1950) and subsequently accepted on the basis of the indirect evidence of the dissociation products observed in the ultraviolet (Feldman 1983). Moreover, the body of *IUE* data suggests that, in fact, there have been no recent apparitions of any comet that was not primarily water ice. The only other fairly abundant parent molecule to be detected in comet Halley was CO (at about 10% that of H_2O), and it had been observed in comparable abundance only once before, in comet West (1976 VI) (Feldman and Brune 1976). However, the question of the abundance of CO is complicated by the *Giotto* mass spectrometer discovery of an extended (~ 10,000 km) source of CO in comet Halley (Eberhardt *et al.* 1987a) and will not be pursued further here.

3. Hydrogen Lyman-α Emission

We noted above that a number of determinations of Q_{H_2O} were based upon observations of H I Lyman-α emission. These were made with instruments with fields-of-view of the order of degrees or larger (Craven and Frank 1987, Stewart 1987, McCoy *et al.* 1986), which were capable of observing most of extended (10^6 - 10^7 km) hydrogen envelope that results from the large excess velocities of dissociation of H_2O and of OH. Lyman-α was also observed by *IUE*, albeit with a much smaller field-of-view, 10" × 20". The *IUE* data, with the geocoronal contribution subtracted, are shown for comet Halley in Figure 3. It is immediately apparent that the column of atomic hydrogen along the line-of-sight (at a geocentric distance of 1 AU, the mean width of this column is ~ 10^4 km) is optically thick, as the Lyman-α surface brightness seems to vary only as the solar Lyman-α flux at the comet (i.e., proportional to r^{-2}) and not with variations in Q_{H_2O}, the latter being deduced from the nearly simultaneous OH data from *IUE* (Figures 1 and 2). The deviation of the Lyman-α brightness from r^{-2} for $r > 1.5$ AU is greater pre-perihelion than post-perihelion, reflecting the lower level of Q_{H_2O} inbound and a consequent less optically thick column.

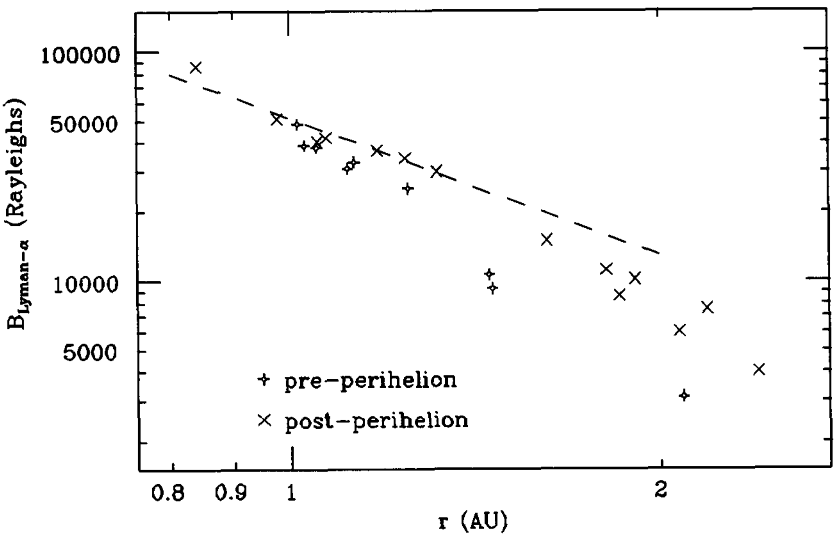

Figure 3. *IUE* observations of the brightness of H I Lyman-α emission from comet Halley as a function of heliocentric distance. The effective aperture was 10" × 15". The dashed line shows an r^{-2} variation.

https://doi.org/10.1017/S0252921100109662 Published online by Cambridge University Press

Thus, the *IUE* Lyman-α data provide almost no information, other than a necessary lower limit to Q_{H_2O}, and for this reason the number of data points taken is less than for OH. Nevertheless, there are sufficient data to demonstrate that the same result is obtained for comet Halley for every observation near 1 AU, showing no indication of any "breathing" or rapid time variability as claimed by Kaneda *et al.* (1986) on the basis of data from an imaging instrument on *Suisei.* Even though the hydrogen column density varies in response to the changes in Q_{H_2O}, it remains sufficiently optically thick so that the amount of scattered solar Lyman-α radiation remains nearly constant. The failure of the *Suisei* imager to obtain anything comparable to the Lyman-α images of McCoy *et al.* (1986) suggest an instrumental problem in the former.

The optically thick atomic hydrogen column in Lyman-α also presents a problem for proposed *Hubble Space Telescope* (*HST*) measurements of the D/H ratio by means of simultaneous observations of D I and H I Lyman-α in a gassy comet. On the one hand, the problem of instrumental scattering (the lines are separated by $\Delta\lambda \sim 0.3$ Å) is reduced as the line intensity ratio (D/H) is enhanced due to the saturation of the hydrogen line. However, the atomic hydrogen abundance along the line-of-sight cannot be determined directly but needs to be inferred from measurements at large cometocentric distances together with modelling of the inner coma. The problem can be circumvented by measurements of higher members of the H I Lyman series, Lyman-β at 1027 Å, Lyman-γ at 973 Å or possibly higher, but these lie outside the capability of *HST*. An alternate approach using *HST* that is relatively free of optical depth effects is to measure the OD/OH ratio in the vicinity of the strong OH(0,0) band near 3090 Å. A'Hearn *et al.* (1985) have shown that at certain heliocentric velocities the OH and OD fluorescence efficiencies give a maximum OD/OH line ratio, but to date available *IUE* data on comet Halley allow only for an upper limit of 4×10^{-4} to this ratio (Schleicher *et al.* 1986), which is consistent with the range of values given by Eberhardt *et al.* (1987b) based on data from the neutral mass spectrometer experiment on *Giotto*. As OH (and OD) comes from the same parent molecules as does H (and D), the OD/OH abundance determination should give the same value as a direct measurement of D/H, independent of any chemical modelling.

4. Prompt OH Emission

Bertaux (1986) has pointed out another source of information regarding the remote determination of Q_{H_2O}. A small fraction of the photodissociations of water, primarily those induced by solar Lyman-α radiation, produces OH radicals in the excited A $^2\Sigma$ state, and these promptly decay to the ground X $^2\Pi$ state with the emission of an ultraviolet photon. Unlike the fluorescent OH photons (Schleicher and A'Hearn 1988), the "prompt" emission is characterized by a much higher rotational temperature distribution, and so can be distinguished from the fluorescence process. The advantage of the "prompt" emission is that it can be used to detect very short-term variations in H_2O production as well as spatial variation in the vicinity of the nucleus. The drawback, as Bertaux pointed out, is that this emission is significant relative to the total OH emission only at distances within $\sim$ 100 km of the nucleus (independent of Q_{H_2O}) and is likely to be attenuated in comets with very high water production due to the absorption of solar

https://doi.org/10.1017/S0252921100109662 Published online by Cambridge University Press

Lyman-α radiation by H_2O near the nucleus. The latter probably accounts for the lack of detection of "prompt" OH emission by the *TKS* experiment on *Vega-2* (Moreels *et al.* 1987).

Bertaux also suggested that "prompt" OH should be detectable in *IUE* spectra of comet IRAS-Araki-Alcock (1983 VII) taken during the close approach of this comet to Earth in 1983 (Δ varied from 0.032 to 0.048 AU). In order to avoid uncertainties due to instrument calibration and grating scattering, the approach that we have taken is to compare the spectrum of comet IRAS-Araki-Alcock with that of another comet observed with the same *IUE* spectrograph (LWR) at similar heliocentric distance and velocity and Q_{H_2O}, but at a significantly larger geocentric distance Δ. Fortunately, such data exist for comet Tuttle (1980 XIII) which was observed by *IUE* in December 1980. The data for comet IRAS-Araki-Alcock, which must be corrected for dust-scattered solar radiation and residual S_2 emission, nevertheless show a positive indication of "prompt" emission consistent with the model prediction. These results will be presented elsewhere. The use of the OH "prompt" emission as an indicator of water production rates in comets should be enhanced with the high spatial resolution to be provided by the *Hubble Space Telescope*.

5. Sulfur-containing Molecules

The presence of sulfur as a common constituent in comets has been established by the detection of carbon monosulfide (CS) in nearly all of the comets observed by the *IUE* with a production rate $\sim 10^{-3}$ that of water. Atomic sulfur is also detected in many, but is a weaker emission and is seen only in the brighter comets. However, with one exception, no other sulfur-containing molecule has been detected in the cometary coma. The most probable of these, SH and SO, have their principal electronic transitions in the region of the long wavelength *IUE* spectrograph, but the SH bands are masked by the much stronger OH bands at similar wavelengths, and a significant upper limit for SO has been obtained only for one comet, IRAS-Araki-Alcock (1983 VII) (Kim and A'Hearn, 1989).

The exception mentioned above is S_2, which was discovered serendipitously in comet IRAS-Araki-Alcock by A'Hearn *et al.* (1983) on 11 May 1983, when the comet was at its closest approach to Earth, 0.032 AU. The deduced abundance of S_2, relative to H_2O, was $\sim 1 \times 10^{-3}$, comparable to the CS abundance, shortly after an outburst on 11 May, but had all but disappeared 28 hours later, despite the initial report by Feldman *et al.* (1984) that the S_2 flux had decreased by only a factor of 10. This is the only unambiguous reported detection of S_2 in any comet, or in any celestial object, and its discovery at the time prompted speculation that S_2 may serve as a unique indicator of the physical and chemical conditions at the site of comet formation in the primordial solar nebula. Thus, although the conditions for observing S_2 were unique to comet IRAS-Araki-Alcock (i.e., very small Δ), it is surprising that no trace of it has appeared in any *IUE* spectrum of comets at moderately small Δ ($\sim$ 0.2 to 0.5 AU). The claim by Wallis and Krishna Swamy (1987) of the presence of S_2 in several *IUE* spectra of Halley must be discounted as their analysis is highly superficial and, moreover, includes a spectrum (LWP 7766, 9 March 1986) in which a large number of pixels in the spectral range from 2850 Å to 3050 Å are saturated. The difficulty in using these data is that a reddened solar spectrum, due to scattering of sunlight by the cometary grains in the field-of-view, must be subtracted from the observed spectrum, and the non-statistical nature of the *IUE* camera noise leads to artifacts that resemble spectral features. We have begun a systematic determination of S_2 upper limits from our existing *IUE* data, using a least-squares technique to determine the likelihood that a given spectrum matches the observed S_2 spectrum in comet IRAS-Araki-Alcock at some reduced level. In doing so, we exclude the region of the spectrum around 2890 Å containing the CO_2 B-X doublet. The results of this analysis will be described in detail elsewhere, but we note here that for Halley at closest approach to the Earth on 9 April 1986 ($\Delta = 0.42$ AU), the derived value of $Q_{S_2}/Q_{H_2O} \leq 3 \times 10^{-4}$.

6. Other Species

We conclude with a brief resumé of other species whose abundance in the cometary coma would provide new information about the origin and composition of the nucleus ice. Primary amongst these are the noble gases, He, Ne and Ar, whose resonance transitions all lie at wavelengths shortward of 1150 Å (the nominal short-wavelength limit of both *IUE* and *HST*). Molecular hydrogen has also been proposed as a possible ice constituent (Bar-Nun and Prialnik 1988), but the most sensitive observations to date near 1608 Å, assuming solar H I Lyman-β pumped fluorescence (Feldman and Fastie 1973), only give an upper limit, which is a factor of three higher than that expected from the H_2O dissociation channel into H_2 and $O(^1D)$ (Dymond 1988). The other species of interest are atomic nitrogen, whose principal resonance transition at 1200 Å is masked by scattered radiation from the strong H I Lyman-α emission at 1216 Å, and O^+ at 834 Å, which should be the dominant ion tail component in CO-deficient comets. The detection of atomic nitrogen is also hindered by a low fluorescence efficiency and by a low inferred abundance of nitrogen-containing molecules in comet Halley (Krankowsky and Eberhardt 1989). A list of emission wavelengths of the important undetected species is given in Table 1. Many will require the capabilities of instrumentation designed for the extreme ultraviolet, such as the Lyman-FUSE mission planned for the mid-1990s.

Table 1. Species not yet detected in comae

Species	*Wavelength (Å)*
He I	584
He II	304
Ne I	736/744
Ar I	867/876
	1048/1067
O II	539, 834
N I	1134, 1200
H_2	1000-1610

Acknowledgements

The preparation of this review was partially supported by NASA grants NAG 5-619 and NSG-5393.

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