# ULTRAVIOLET OBSERVATIONS OF COMETS

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Observations of comets in the ultraviolet have a brief history. It begins with the discussion by Biermann and Trefftz (1964) of resonance fluorescence radiation in the ultraviolet. They predicted that comets should be surrounded by a large exosphere of hydrogen atoms and thus possess a very large luminosity at Lyman alpha. These considerations were further developed by Biermann (1968). The first observations of a comet in the vacuum ultraviolet were obtained on January 14, 1970, when OAO-2 recorded the spectrum of the bright comet Tago-Sato-Kosaka (1969g) (Code *et al*. 1970, Houck and Code 1970). The observations revealed, among other things, the extensive hydrogen Lyman alpha halo predicted by Biermann and Trefftz. OAO-2 continued to collect spectrophotometric measurements of this comet throughout January of that year. On January 28, Princeton University astronomers obtained a photograph of the nucleus in Lyman alpha revealing finer scale structures (Jenkins and Wingert 1972). In February of 1970, the bright comet Bennet (1969i) became favorable for space observations. On the basis of the OAO discovery, OGO-V made several measurements of comet Bennet with low spatial resolution photometers. Since the OGO spacecraft is above most of the Lyman alpha geocorona and the wide field photometers are more sensitive, it was possible to follow the hydrogen halo out to much fainter isophotes (Bertaux and Blamont 1970). OAO-2 continued systematic observations both at Lyman alpha and in other spectral regions for about two months to follow the temporal changes as well as the spatial distribution of the comet's coma. Comet Enke was detected by OGO in January of 1971 at a large heliocentric distance from its Lyman alpha emission.

Figure 1 shows two spectra of comet Bennet that are typical of the results obtained on both bright comets. The spectrum

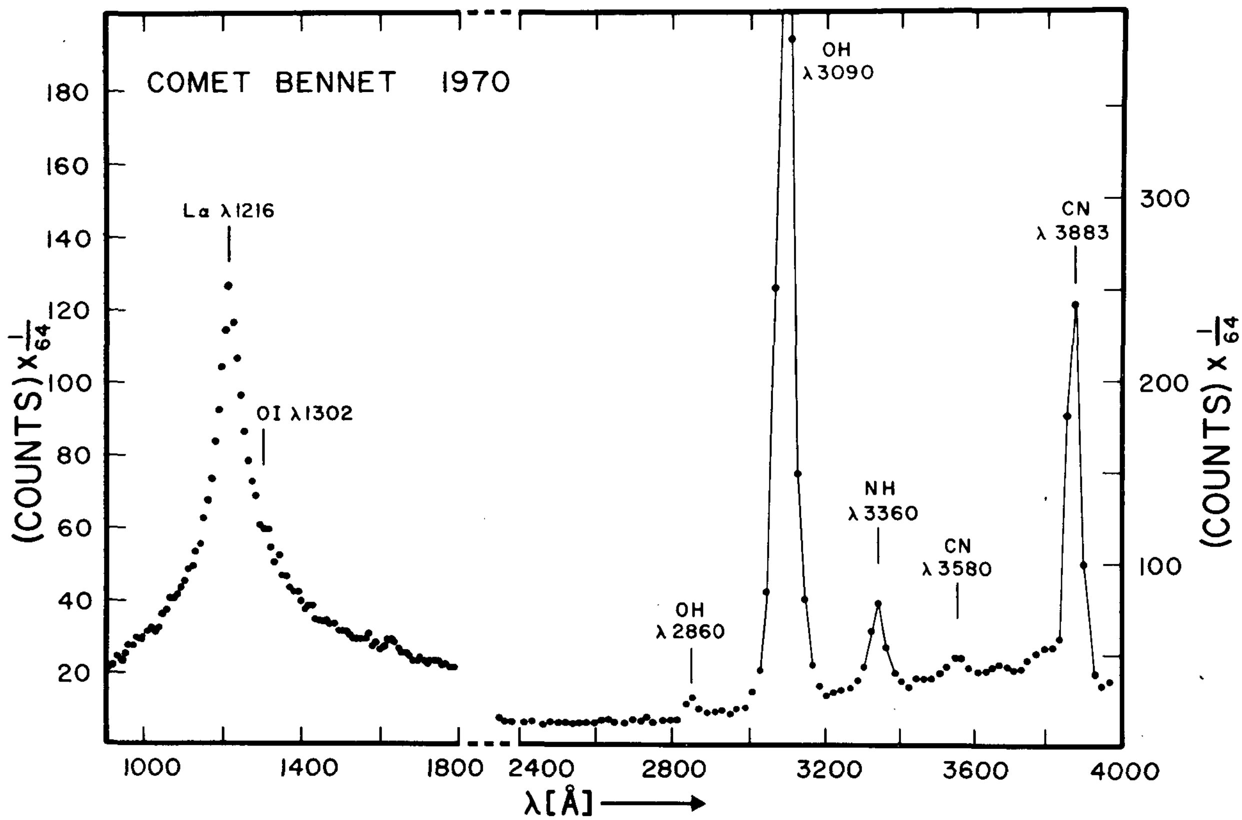


*Figure 1.*

on the left was obtained with the short wavelength spectrometer and shows the surface brightness in Lyman alpha. The long wavelength spectrometer shows the very strong 0-0 band of OH. The noise in these scans is no greater than the radius of the plotted points and the fine scale features are probably real. Since the spectrometers are objective grating instruments with a slot collimation, a spectral scan of a monochromatic feature represents the surface brightness distribution in a direction parallel to the dispersion. The spatial resolution at Lyman alpha is 1' by 8' in the plane of the sky. One minute of arc corresponds to 10 Angstroms on the spectral scan. The full width at half intensity on the scan illustrated in Figure 1 corresponds to an angular size of 13 minutes for the hydrogen coma, which at the time of observation is about $4.5 \times 10^5$ km.

Figure 2 shows Lyman alpha isophotes on April 16, 1970 for comet Bennet obtained by successively scanning the spectrum and offsetting the spacecraft perpendicular to the dispersion. The isophotes are reasonably circular, indicating primarily a radial expansion. The outer isophotes show an elongation in

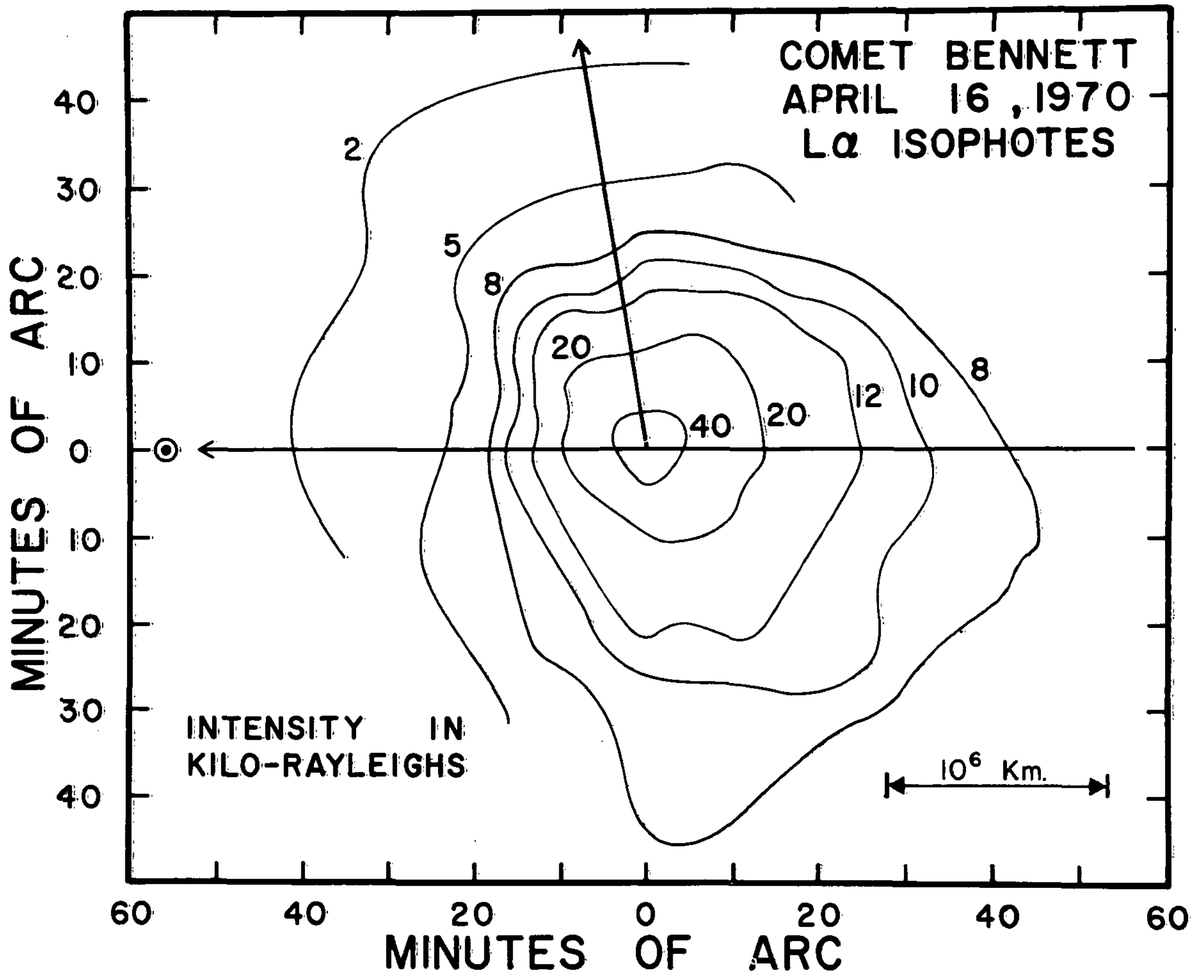


*Figure 2.*

the anti-sun direction and opposite to the comet motion. This distortion of the isophotes is in reasonable quantitative agreement with calculations of the acceleration produced by Lyman alpha radiation pressure. The isophotes found for April 1 by Bertaux and Blamont (1970) when the radiation flux was twice as great show considerably more elongation.

A lower limit to the number of hydrogen atoms in the coma may be estimated from the integrated brightness. The total number of Lyman alpha photons inferred from the April 16, 1970 isophotes is approximately $3.6 \times 10^{32}$ photons/sec. Hunten (1970) gives the g-factor for Lyman alpha as $g(L\alpha) = 2.1 \times 10^{-3}$ $sec^{-1}$ which corresponds to $3.2 \times 10^{-3}$ $sec^{-1}$ at .809 astronomical units. Hence for an optically thin coma the number of hydrogen atoms would be $1.1 \times 10^{35}$ or $1.9 \times 10^{11}$ grams. Bertaux and Blamont adopted a g-factor of $10^{-3}$ sec$^{-1}$, which would yield a mass of 3.8 × $10^{11}$ grams, on April 16th. From their measurements on April 1 they found a mass of approximately 2 × $10^{12}$ grams. Comparison of these results would suggest that the production of hydrogen varies approximately as $r^{-4}$. Another source of information bearing on this problem is provided by the variation of reduced surface brightness with heliocentric distance. Both H and OH vary approximately as the inverse 6th power. Delsemme (1972) interprets this result to imply a three-step process involving the evaporation of water ice, the photodissociation of $H_2O$ and the resonance fluorescence of the hydrogen and hydroxyl radical, where each step follows approximately an inverse square law dependence on solar flux. Since the lifetime of $H_2O$ is given as 20 hours by Potter and Del Ducca (1964), virtually all the $H_2O$ would be expected to dissociate well within the coma. In this case the inverse square dependence of the dissociation should not affect the observed surface brightness. The interpretation of these observations is therefore probably more complex than that described by Delsemme. From the above discussion one should have to invoke a different two-step process for the production of hydrogen, possibly the release of ice particles and the subsequent evaporation of a fraction of them. There was, however, a much stronger particle tail for comet Bennet than for comet Tago-Sato-Kosaka although both comets exhibited rather similar hydrogen envelopes.

A variety of circumstantial arguments have suggested that among the cometary ices of Whipple's comet model (Whipple 1950) water ice was the most abundant. Delsemme and Miller (1970) have indicated how the formation of clathrate hydrates on water snow can adequately account for the other observed constituents of cometary spectra. The conclusion that water is a major constituent of comets and that the hydrogen envelope must be primarily due to the photodissociation of $H_2O$ is strongly supported by the OAO observations. The relatively great strength of the OH emission shown in Figure 1 indicates abundances comparable to that of hydrogen and greatly in excess of other gases. The OH emission is about 3 times as strong as the strong 0-0 band of CN at 3883 Å, despite the fact that the solar spectrum is only 1/3 as bright at 3090 Å as it is at 3883 Å and the f-number for CN is about 24 times that of OH. Thus OH should be more than 200 times as abundant. The lifetime for the OH radical should be relatively short (of the order of $10^5$ seconds) and dissociate into H and OI ($^3P$). All OAO scans show a feature corresponding to a few digital counts centered at about 1300 Å on the wings of the Lyman alpha profile. This has been identified on Figure 1 as the OI resonance line at 1302-4-6. Hunten (1970) gives the ratio of g-factors for Lyman alpha relative to OI ($^3P$-$^3S$) as 21. The spectrometer is 1.47 times as sensitive at 1304 Å as it is at Lyman alpha. Therefore, the ratio of counts is

$$\frac{\text{OI counts}}{\text{Ly}\alpha\text{ counts}} = .07\,\frac{N_{OI}}{N_H} \;.$$

If we take the abundance of H to be twice that of OI and assume the same spatial distribution, then we would expect 3.5 counts for OI to correspond to the 100 net counts observed in Lyman alpha. If we compare OI with the intensity of Lyman alpha where the OH intensity has fallen to a few percent, we obtain about 2 counts. Thus, the identification of OI is consistent with the assumption that the parent molecule for H, OH and O is $H_2O$ and is several hundred times as abundant as other constituents.

The assumption that the coma is optically thin in Lyman alpha is probably not valid in the inner 10 minutes of arc. Although this fact would have little effect on the total masses discussed above, it would significantly modify the variation of surface brightness with radius in the inner coma. Using the value of 5.1 ergs $cm^{-2}$ $sec^{-1}$ given by Detwiler et al. (1961) for the solar flux in Lyman alpha at one astronomical unit, we find a photon flux of $5.33 \times 10^{11}$ photons $cm^{-2}$ $sec^{-1}$ at 0.772 a.u. If complete scattering over the line width of the comet emission is assumed, then the surface brightness would be 42 KiloRayleighs for a width 8 percent of the solar Lyman alpha line. This width is consistent with the measurements described below. This result indicates that the envelope must be optically thick in the inner isophotes. Even the peak intensity found by Bertaux and Blamont of 24 KR with their 40' resolution implies an optical depth greater than 0.5. If the intensity gradient is similar to the OAO results, then the OGO observations with 40' resolution would correspond to a peak surface brightness within 2 minutes of arc of 72 KR.

Optical depths greater than unity within 10 minutes of arc of the nucleus are not in contradiction with the bright core found by Jenkins and Wingert (1972). This is because the comet was observed nearly perpendicular to the direction of incident solar radiation. In this case solutions of the appropriate radiative transfer problem indicate a peak in the intensity slightly in front of the comet nucleus proper.

The width of the comet emission line has been determined by measurements during perigee where the telluric absorption reduces the intensity of the comet emission. The residual hydrogen above the satellite corresponds to an optical depth of the order of 0.6 and thermal doppler width of about 1000°K. As comet Tago-Sato-Kosaka passed through perigee the telluric absorption moved across the comet emission line at about 50 milliangstroms per day.

An upper limit to the width of the comet emission is given by the fact that no absorption was detected until the velocity difference between the earth and the comet was less than 10.4 km/sec or a doppler shift of 0.042 Å. Now the telluric absorption corresponds to a thermal width of the order 1000°K; thus the comet emission if Maxwellian would be less than 3000°K. A more detailed analysis of the decrease in Lyman alpha intensity during perigee passage yields a thermal doppler width for the emission in comet 1969g of 1600°K.

Comet 1969g was observed during the time in which its coma occulted the star π Psc and comet 1969i when it occulted σ Cas. Preliminary analysis of these data indicates absorption of starlight in the center of the OH band for comet 1969g.

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