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# GROUND-BASED COMETARY SPECTROSCOPY

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## Abstract

The return of comet Halley presents a rallying point for astronomers to discuss data on recent comets in the light of new developments in the field of cometary astronomy. The observational problems presented by bright comets near perihelion are discussed. High and low resolution spectra (3100-8000Å) of the bright comets Kohoutek, Kobayashi-Berger-Milon, West and d'Arrest are presented. Digital reduction of calibrated photographic spectra to relative intensity versus wavelength can provide useful information. The reduction of comet spectra to absolute intensities involves, however, large uncertainties and should be interpreted cautiously.

New data on recent comets lead to the following results: (1) tentative identification of a new ion in the tail of comets, namely, $NH^+$, (2) spectroscopic resolution of the fragmented nucleus of comet West, and (3) an accurate monochromatic intensity profile of the $CO^+$ emission (4020Å) in comet West which shows a striking asymmetry in the sunward and antisunward directions, $2 \times 10^4$ km $< |\rho| < 5 \times 10^5$ km.

## I. Introduction

Although dirty snowball models of comets have received general acceptance, specific details of such models are poorly determined. One of the primary goals of cometary spectroscopy is to determine abundances in comets and thereby infer conditions prevalent in the proto-solar nebula. We have as yet little understanding of cometary surface compositions, nor how they vary from comet to comet or with successive perihelion passages. In fact we cannot yet identify with certainty parents of the large majority of unstable molecular ions and radicals observed in the comae and tails of comets. To determine the abundances of cometary ices, understand the complex interactions of the molecular ions with the solar magnetic field, and eventually to determine the overall physical characteristics of comets will require a concerted and cooperative effort on the parts of both ground-based and space scientists in the coming years. The return of comet Halley provides an opportune rallying point and impetus to improve our understanding of comets.

The purpose of this paper is to present ground-based spectroscopic observations of recent comets to illustrate the use of modern detectors in probing cometary gases. Evidence is presented for (1) the possible identification of a new molecular ion, $NH^+$, in the tail of a comet, (2) the spectroscopic resolution of a fragmented comet nucleus, and (3) the monochromatic surface brightness profiles of $CO^+$ emission in comet West 1976n in the sunward and antisunward directions.

## II. Problems of Ground-Based Spectrosocopy

A typical moderately bright comet might have an apparent integrated visual magnitude, $m_V \sim 6$, but a surface brightness, $\mu_V \sim 15$ mag arcsec$^{-2}$. Hence even the rare moderately bright comets present challenges due to their faint surface brightnesses to spectroscopic observers with even moderate aperture (1-2 m) telescopes. Moreover, the difficulties of optical cometary spectroscopy are further compounded by the fact that comets (with highly eccentric orbits) are brightest only near perihelion passage which necessitates their observation at heliocentric distances, $r < 1$ a.u. For the ground-based observer this means that comets with large orbital eccentricites near perihelion passage must be observed near or during twilight hours with the telescope at very large zenith angles and with a time window for observation typically only 1-2 hours. Furthermore the comet's apparent proper motion when near perihelion is appreciable. Hence the telescope must be driven to compensate for both the earth's rotation and the comet's motion for the long integration time required to accumulate a reasonable S/N ratio.

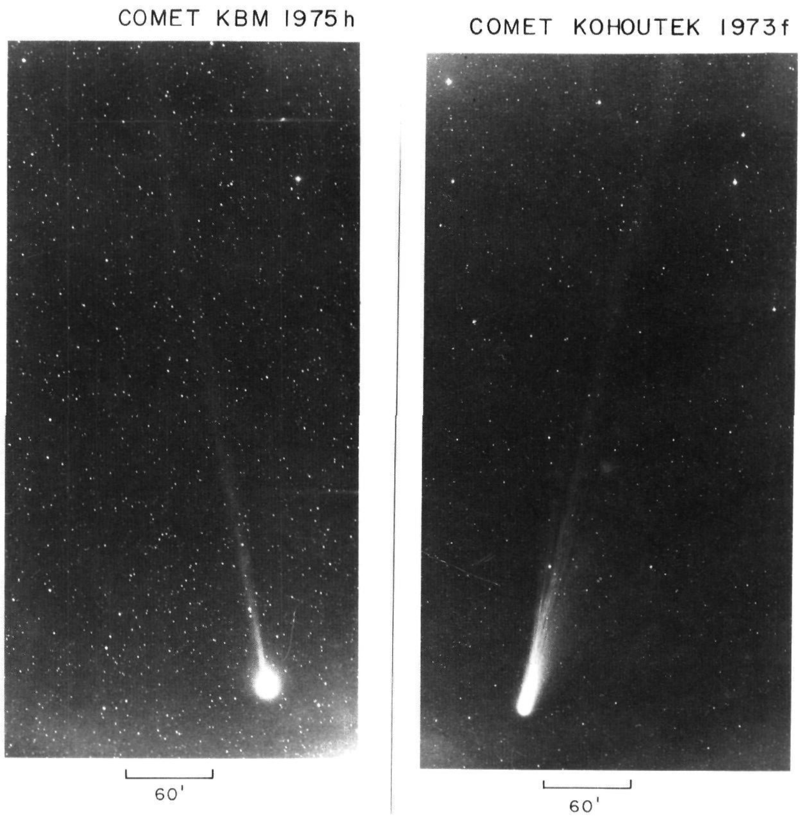

Figure 1. Photographs (3100-5000Å) of comets Kobayashi-Berger-Milon 1975h and Kohoutek 1973f taken by the Joint Observatory for Cometary Research (JOCR), operated by NASA-Goddard Space Flight Center and the New Mexico Institute of Mining and Technology. The photographs were taken on IIa-O emulsions with B passband filters on 12 August 1975 and 17 January 1974 for comet KBM and Kohoutek, respectively.

The observation of comets near twilight makes calibration without sunlight contamination extremely difficult, while observation at large zenith angles makes accurate correction for atmospheric extinction virtually impossible. Also mechanical flexure of the telescope/detector at the Cassegrain focus makes accurate wavelength calibrations complicated. [Coude spectroscopy minimizes this problem.] Mechanical limits on most telescopes do not permit observations at zenith angles > 75°. Ideally to observe even a moderately bright comet requires a telescope of moderate aperture (1-2 m) with a detector of high quantum efficiency, and, perhaps, a sympathetic telescope operator willing to override the telescope limit switches to permit observations of the comet to zenith angles of 80-85°.

The above problems are unique to ground-based cometary observations and limit considerably the accuracy of any photometric and wavelength calibrations. These facts should be realized by theorists when modeling cometary observations of even the brightest comets, and by observationalists when assessing their observational errors.

## III. Examples of Optical Spectra

Optical spectroscopy has been essential in the discovery of over 20 molecular radicals and ions in cometary atmospheres during the past 70 years. However, it should be realized that spectroscopic data obtained in the optical window (~ 3100-8000Å) are only "the tip of the iceberg" when it comes to understanding the overall physics of comets. The stable molecules such as $H_2$, $O_2$, CO, $CO_2$ which are expected to be abundant in cometary atmospheres have ground state transitions outside the 3100-8000Å region. Nevertheless the spectra of comets in the optical window are useful for probing the complex chemistry of cometary atmospheres.

Although approximately ten radicals and the same number of molecular ions have been identified in comets today, there remain several strong unidentified molecular features in the spectra of comets. In fact, because each spectrum is unique, each new comet presents an opportunity for discovering a new radical or ion.

Figure 1 illustrates that the optical morphology of two comets can vary considerably due in this case to whether or not a strong ion tail develops. The photographs kindly made availble by J. Brandt were taken by the JOCR and obtained when the comets were at approximately the same heliocentric ($r \sim 1$ a.u.) and geocentric ($\Delta \sim 0.8$ a.u.) distances under similar solar conditions (i.e., in the absence of both solar flaring activity and solar maximum).

Yet comet Kohoutek developed a prominent ion tail and comet KBM only a very weak tail. The primary molecules contributing to the emission in the tail of comet Kohoutek in Figure 1 are $CO^+$ ions emitting by the mechanism of resonance fluorescence with the solar radiation field. Figures 2 and 3 illustrate that the optical spectra of the two comets in Figure 1 naturally reflect the difference in morphology between the two comets. In Figure 2 the spectrum of comet Kohoutek shows strong $C_2$ and $NH_2$ emission within a projected nuclear distance $\rho \leq 10^4$ km, and the 5000–8000Å region of the tail dominated by $H_2O^+$ emission. The 3100–5000Å region in comet Kohoutek (depicted by the JOCR photograph in Fig. 1) was dominated by emission from the $CO^+$ ion. In contrast Figure 3 illustrates the optical spectrum (3000–6000Å) of comet KBM 1975h which shows strong bands of CN, $C_3$, $C_2$ and $NH_2$, and the only extremely weak $H_2O^+$ emission. Also $CO^+$ is notably absent from the spectrum in Figure 3 even though the detection limit of this spectrum was equivalent to that of comet Kohoutek (Fig. 2).

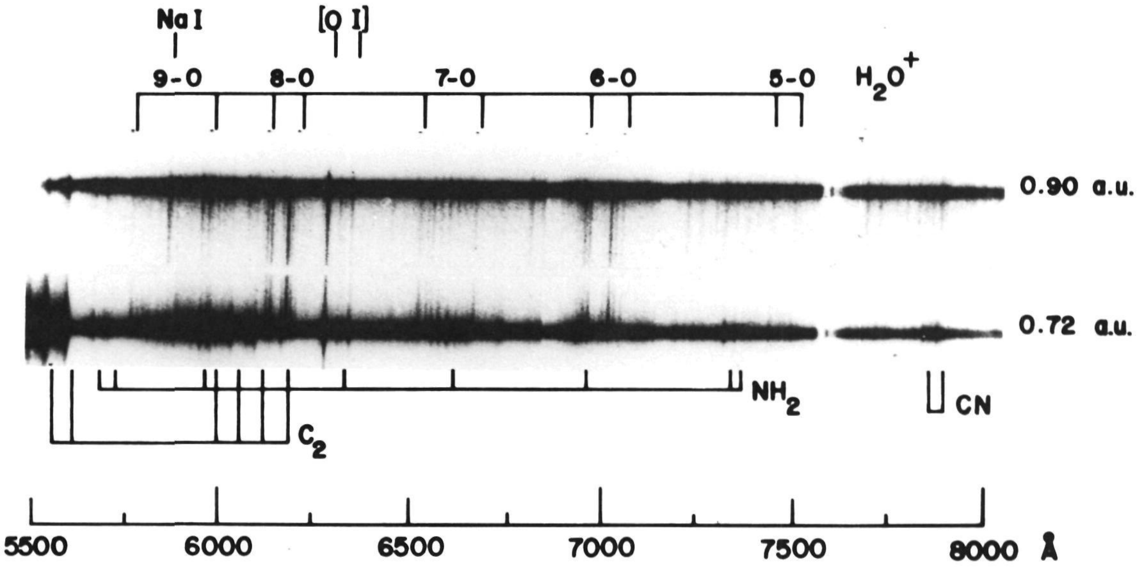

Figure. 2. Pre-(lower) and post-(upper) perihelion spectra of comet Kohoutek showing strong emission bands of the $H_2O^+$ ion in the tail (tail spectrum extends downward in upper spectrum and upward in lower spectrum). Image tube spectra taken with the Wise Observatory 1-m telescope. Heliocentric distances indicated at right.

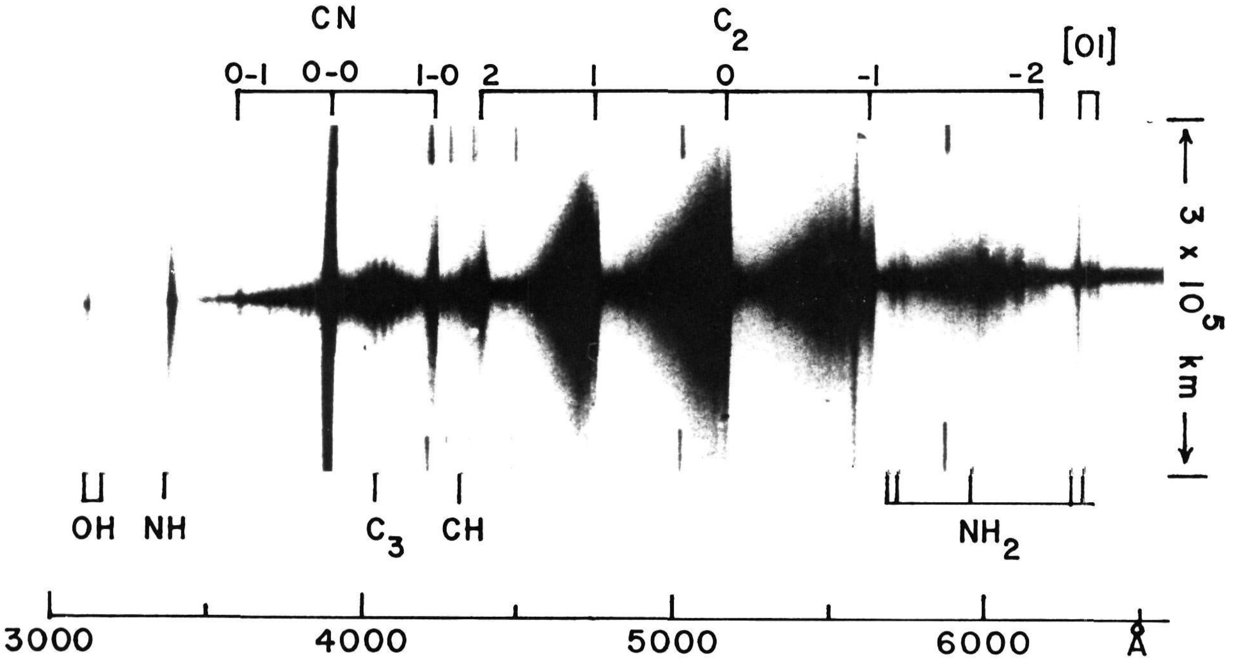

Figure 3. Spectrum of comet Kobayashi-Berger-Milon 1975h showing strong emission from neutral radicals, and extremely weak emission from molecular ions. Image tube spectrogram taken with the Wise Observatory 1-m telescope. Obtained 7 August 1975 when $r = 0.78$ a.u. and $\Delta = 0.58$ a.u.

Another example which illustrates that the spectra of individual comets are unique is shown in Figure 4 where the spectrum of period comet d'Arrest 1976e is shown. The image tube spectrogram is weakly exposed which may account in part for the absence of molecular ions from the spectrum. The spectrum in Figure 4 is unique in that it shows only weak CN and Swan bands yet relatively strong $NH_2$ emission. The spectrum of comet d'Arrest implies that our understanding the abundances in atmospheres of periodic comets may require knowledge of the depletion rates of volatiles as a function of exposure to solar radiation and wind during successive perihelion passages.

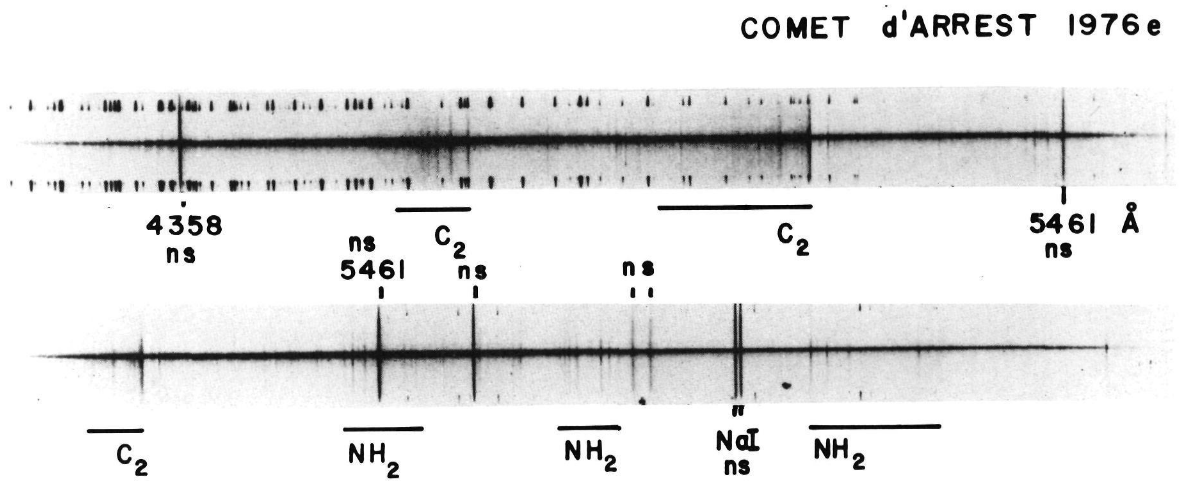

Figure 4. Spectrum of periodic comet d'Arrest 1976e showing relatively strong $NH_2$ emission and weak Swan $C_2$ bands. Spectra obtained with 3-stage EMI image tube at Cassegrain focus of the 2.5-m Isaac Newton Telescope at the Royal Greenwich Observatory. (Original dispersion 42 A $mm^{-1}$). Obtained 31 July 1976 with slit orientation east-west.

The spectrum of comet West 1975n in Figure 5 illustrates the usefulness of both high spectral and spatial information in observing comets. The spectral resolution (~ 1Å) shows rotational structure resolved in the $C_2$ Swan bands as well as the $NH_2$ bands. The particular telescope/spectrograph/photographic emulsion combination gave unusually large spatial resolution (~ 10 arcsec or ~ 7500 km at the comet). As can be seen from Figure 5, the splitting of the nucleus of comet West into at least four distinct fragments can easily be seen. Note also that the $C_2$ and $NH_2$ emission features are continuous across the fragmented continuum in Figure 5.

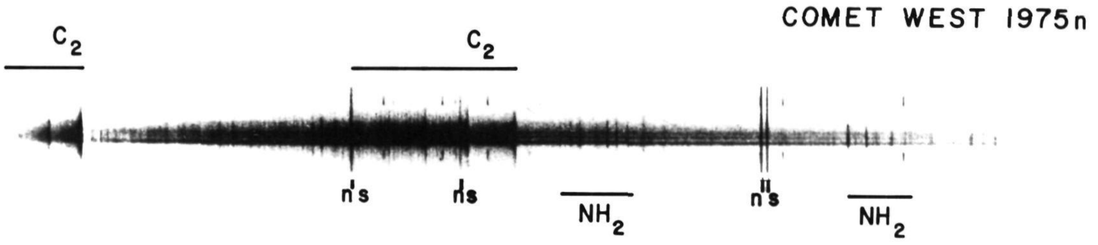

Figure 5. Image tube spectrogram of comet West 1975n showing rotational structure resolved in the $C_2$ and $NH_2$ bands. Due to the large spatial scale perpendicular to the direction of dispersion (60 arcsec $mm^{-1}$), the fragmented comet nucleus can be seen. Note that the $NH_2$ emission lines are continuous across the fragmented continuum. Spectrum obtained with the Cassegrain spectrograph of the 2.5-m Isaac Newton telescope at the Royal Greenwich Observatory 21 March 1976 with slit oriented east-west $r = 0.78$ a.u. and $\Delta = 1.04$ a.u. Original dispersion 42A $mm^{-1}$.

A longer exposure of the spectrum of comet West shows the extremely strong $CO^+$ emission spectrum which developed for this comet (Figure 6), yet comet West is similar to that observed by Greenstein (1962) in the unusual comet Humason 1961e when it was 5 a.u. from the sun. In addition to strong $CO^+$ emission and weak $CO_2^+$ bands Figure 6 shows weak emission from at least one additional molecular ion.

There are several weak unidentified emission features in the tail spectrum (4315-4360Å region) of comet West 1975n which correspond in structure and position with the laboratory spectrum of the $NH^+$ molecule (Colin and Douglas 1968). The measured position of the unidentified band head in Figure 6 is 4315+2Å which is coincident with the laboratory position of the $NH^+$ $B^2\Delta-X^2\pi$ head at 4313Å. Furthermore both the observed and laboratory bands are red-degraded, and the intensity maxima due to overlapping rotational lines in the laboratory spectrum of $NH^+$ appear to correspond to positions of unidentified emission features in the spectrum of comet West in the 4315-4360Å region. The identification is tentative, however, due to the low resolution of the comet spectrum and to features of the 3-1 $CO^+$ band superimposed in the 4360-4400Å region. High resolution spectra of a comet resolving the rotational structure in the 4316-60Å band features plus intensity measurements of individual rotational lines will be needed to confirm the proposed identification of $NH^+$ in the spectrum of comet West.

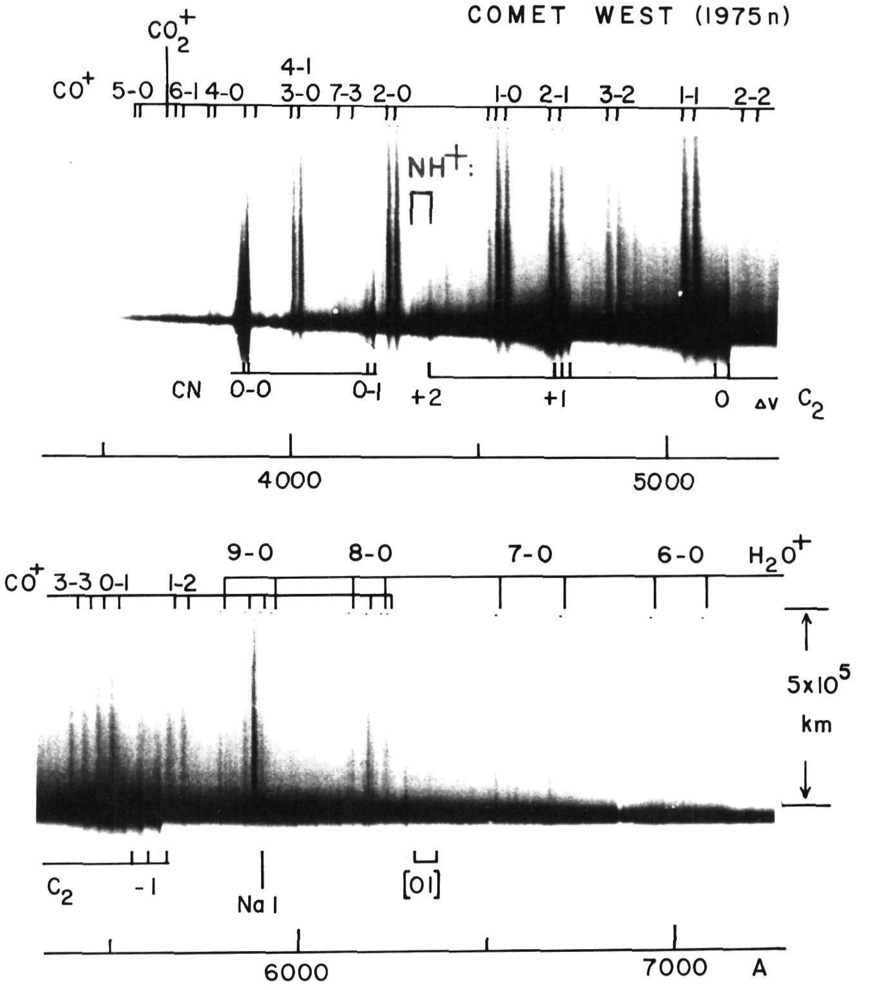

Figure 6. Spectrogram (original dispersion 120 Amm$^{-1}$) of comet West 1975n obtained with a single-stage ITT image tube at the Cassegrain focus of the Wise Observatory 1-m telescope by E. Leibowitz. Obtained 10 March 1976 when the comet had $r = 0.47$ a.u. and $\Delta = 0.94$ a.u. Slit width was 70μ and slit orientation was along tail axis. Note strong CO$^+$ spectrum and the tail features possibly identified with the NH$^+$ ion. (Tail spectrum extends upward away from the coma spectrum.)

## IV. Digital Techniques

Useful photometric information can be extracted from photographic spectra, provided care is taken in calibrating and avoiding the observational problems discussed in Section II. If a standard flux calibration star has been observed (preferably at the same zenith angle as the comet), then the comet spectrum once digitized can easily be converted to relative flux vs wavelength as shown for comet KBM in Figure 7. The figure shows a spectrum with original resolution ~ 5Å plotted on a relative intensity scale extending from 3600-8000Å which is virtually the entire length of the optical window. The Swan $C_2$ bands and the CN blue system are the most prominent band systems in the spectrum. Bands of NH, $C_3$, $NH_2$ and the red CN system are also visible.

To put any photographic spectrum on an absolute intensity scale requires the adoption of photometry from another source. In this case to convert from a relative to an absolute scale requires an accurate determination of the linear scale of the spectrograph slit width and length projected on the spectrogram, and also the microdensitometer slit aperture sizes used to scan the spectrum. Because of large uncertainties in these calibrations, any attempts at absolute calibrations of photographic spectra are crude at best.

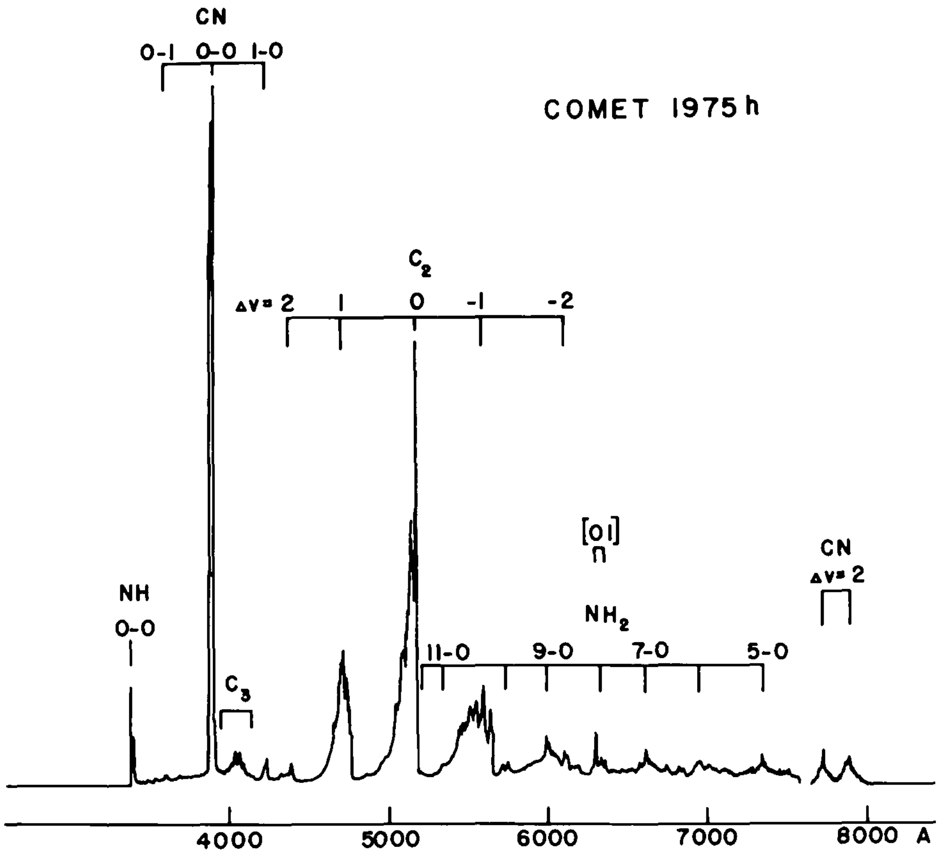

Figure 7. Spectrum of comet Kobayshi-Berger-Milon 1975h converted to a relative ($I_v$) vs. wavelength plot. Represents relative fluxes at a projected distance ~ $10^5$ km on the antisunward side of the nucleus.

Useful spatial information can also be extracted from photographic spectra of comets if untrailed and carefully guided exposures are obtained. After proper calibration from photographic density to relative intensity and for vignetting along the spectrograph slit, microdensitometer scans perpendicular to the direction of dispersion can be used to produce monochromatic profiles as a function of position in the comet head. For example, Figure 8 illustrates the intensity profile of 3-0 $CO^+$ 4020Å band in the head and inner tail of comet West. The projected distance from the nucleus is indicated in the bottom of the figure. Also included in the figure is a profile of the comet continuum ~ 10Å to the red of the 3-0 $CO^+$ band. The slit orientation of the original spectrogram was aligned with the tail axis of the comet. Hence one side of the intensity profile represents the surface brightness distribution of the $CO^+$ emission in the sunward direction and the other in the antisunward direction. Figure 8 illustrates that there is a significant difference between the $CO^+$ emission (and hence the column density of $CO^+$ ions) on either side of the comet nucleus, and with respect to the continuum emission.

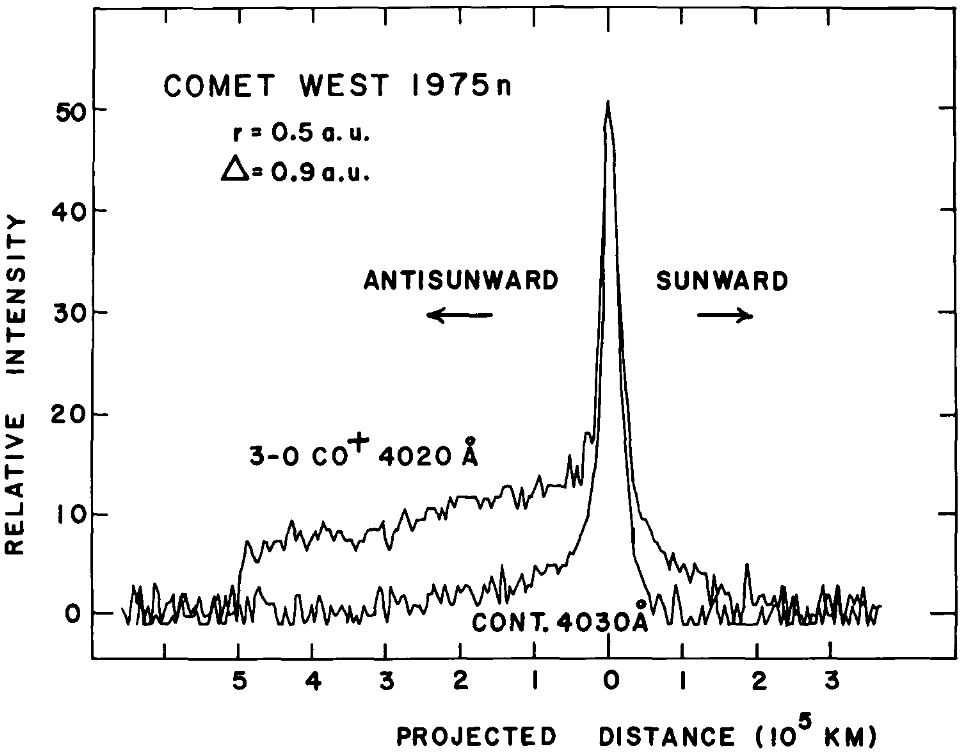

Figure 8. Monochromatic intensity profiles of the 3-0 $CO^+$ 4020Å band and the continuum 10Å away in the spectrum of comet West. The projected distance from the nucleus is given in the lower scale, where 0 corresponds to the nucleus. The data were obtained from the spectrum in Fig. 5. The discontinuous drop in intensity on the antisunward side of the $CO^+$ profile is due to the edge of the spectrograph slit decker. Note the strong asymmetry in the $CO^+$ profile between the sunward and the antisunward sides of the nucleus.

A point-by-point subtraction of the continuum profile from the $CO^+$ profile results in the monochromatic surface brightness profile plotted in Fig. 9 where the logarithm of the relative intensity (continuum subtracted) is plotted versus the logarithm of the projected distance ($\rho$) from the comet nucleus. For an optically thin gas, the monochromatic intensity, $I_\nu \propto gN$ where g is the excitation g-factor for resonance fluorescence and N is the column density of $CO^+$ ions. Hence the relative intensity in Figure 9 is directly proportional to the column density of $CO^+$ ions as a function of distance from the comet nucleus. As can be seen from Fig. 9 the intensity of the $CO^+$ emission is roughly constant (possibly increasing) in the antisunward direction and decreases sharply with distance from the nucleus in the sunward direction. The region, log $\rho \lesssim$ 4.3 km has been omitted from Fig. 9 since it represents the greatly overexposed portion of the original spectrogram and is subject to non-linear calibration effects (saturation). Nevertheless the continuity of the sunward and antisunward profiles across the nuclear region shows that any calibration effects are minimal. The regions shown in Fig. 9 presumably represent the collision-free regions of the comet. Though there is no obvious discontinuity of the $CO^+$ emission on the sunward side, there is an abrupt change in slope occurring $\rho \sim 10^5$ km from the nucleus. A model of the comet ionosphere is needed for a proper interpretation of Fig. 9.

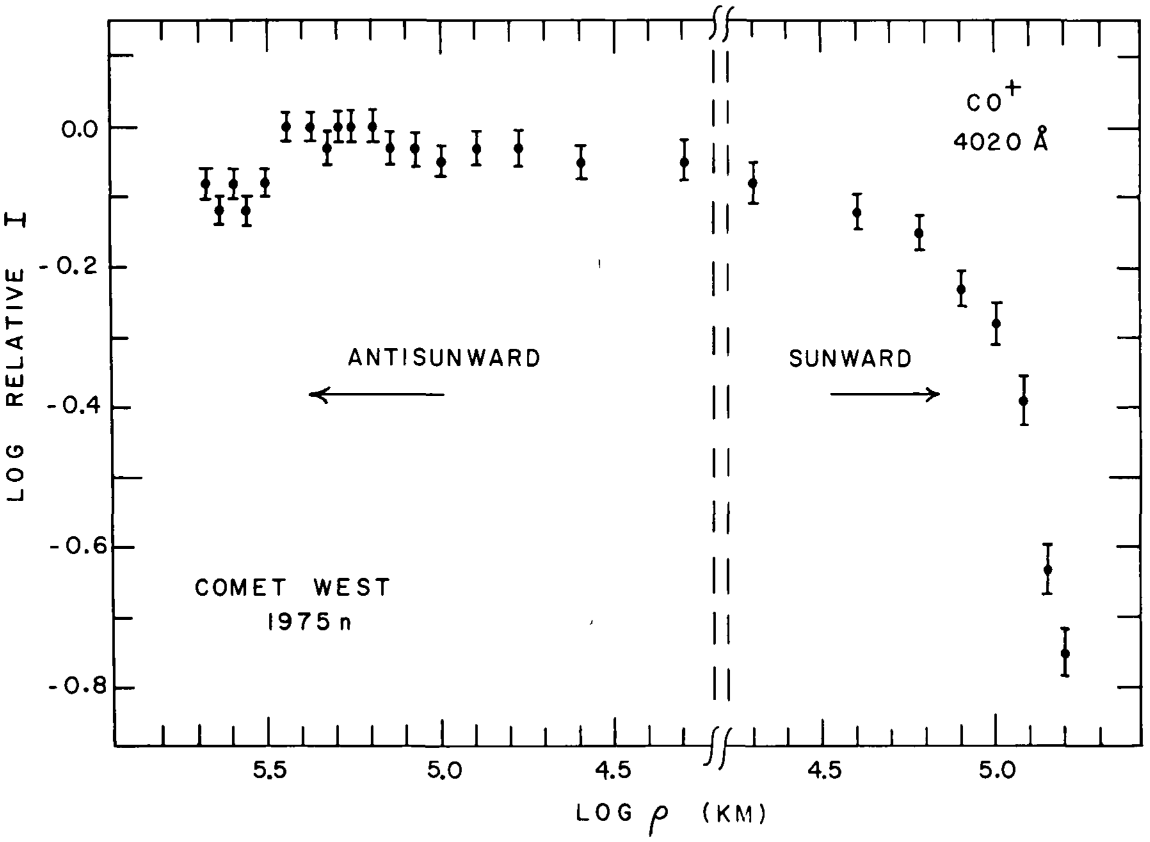

Figure 9. Monochromatic intensity profiles of $CO^+$ (3-0) band emission at 4020Å (continuum subtracted) in comet West. Data from Fig. 8. Note the pronounced asymmetry in the sunward and antisunward intensity profiles.

With the general use of modern detectors such as the Image Photon Counting System (IPCS) developed by Boksenberg and the Charge Coupled Device (CCD) now being used by several groups, two-dimensional spectra of comets can be obtained. These new detectors have both high spectral and spatial resolution as well as much higher quantum efficiencies than photographic plates. Also because they are linear devices, the new two-dimensional detectors will permit relatively accurate absolute calibrations of cometary data. In essence the new generation detector which is just now beginning to be used regularly with ground-based spectrographs will improve immensely the quality of optical cometary spectra in ample time for observing the return of comet Halley.

## References

Colin, R. and Douglas, A. E. 1968, Canadian J. Physics 46, 61.

Greenstein, J. 1962, Astrophys. J. 136, 688.