Mon. Not. R. astr. Soc. (1980) **192**, 641–650

Emission band and continuum photometry of Comet West (1975n) – II. Emission profiles of the neutral coma, lifetimes of molecules and distribution of the molecules and dust within the coma

M. K. V. Bappu, M. Parthasarathy, K. R. Sivaraman and G. S. D. Babu *Indian Institute of Astrophysics, Bangalore-560 034, India*

Received 1979 October 5; in original form 1979 September 3

Summary. The scale lengths of the CN and C_2 molecules and their parents are derived based on Haser's model from drift scans across the coma of Comet West in the light of CN(0, 0), C_2(0, 0) and the continuum around 5000 Å. The analysis provides evidence to show that the CN molecules are produced by the dissociation of two species of parent molecules having entirely different lifetimes. A similar result is also obtained for the C_2 molecules.

The step scans of 1976 March 19.96, covering the spectral range 3700–5300 Å and at five independent locations inside the coma show that there is an increase of reddening of the continuum, from the centre of the nucleus outwards. These provide evidence that the coarser particles are confined to the centre and the finer ones towards the periphery. A study of the radial distribution of CN, C_3 and C_2 molecules and of the dust particles shows that the C_3 (4050 Å) intensities fall most rapidly, compared to CN or C_2.

1 Introduction

Brightness profiles of the coma in the light of the neutral molecules hold forth valuable information on the lifetimes of the different molecular species. They also provide enough material to test the validity of different models of the cometary coma. Photometric profiles derived from photographs of the coma (Dewey & Miller 1966; Ishida & Kosai 1970; Kumar & Southall 1974), have the advantage of a two-dimensional aspect; they, however, lack spectral purity and most often are from images of low resolution. The contamination by the continuum can result in a substantial departure from the true shapes of the isophotes, leading to unrealistic estimates of scale lengths and lifetimes, particularly for continuum-dominated comets. Malaise's (1966) profiles of the inner coma, based on high dispersion spectra, falls in a better class and this technique has been modified to study the outer coma by Delsemme & Moreau (1973). The first attempt to obtain brightness profiles from photoelectric scans of the comet's head, with a diaphragm small compared to the image size of the coma, was made by Schmidt & Van Woerden (1956). A similar technique has also been utilized by Vanýsek (1969) to estimate lifetimes of molecules and their parents in the coma. Scans using high spatial resolution images and good spectral resolution can yield very accurate brightness profiles that are important in studies of cometary physics.

2 Observations

Our observational programme on Comet West with the 102-cm reflector at Kavalur (see also Sivaraman *et al.* 1979, hereafter Paper I) included scans of the coma in the emission bands of CN(0, 0) at 3883 Å, C_2 (0, 0) at 5165 Å and in the continuum around 5000 Å on 1976 March 23.97. The image has a scale of 16 arcsec mm^{-1} at the Cassegrain focus of the telescope. On March 23.97 the head of the comet was isolated by a circular diaphragm of 25.9 arcsec as projected on the sky and centred around the nucleus. The exit slot of the scanner had a 50 Å band pass in the first order; with this arrangement a scan was obtained with the entrance aperture on the nucleus from 3700 to 5300 Å. Immediately following this scan, the telescope was drifted from the north to the south across the coma and passing through the nucleus (see Fig. 1). This was done by the use of the declination slow motion control at a drive rate of 1 arcsec s^{-1} and with the scanner centred at 3883, 5165 and 5000 Å one after the other. Three drift scans across the entire coma in the light of CN(0, 0), C_2 (0, 0) and continuum around 5000 Å were thus obtained. Scans of the neighbouring sky taken before and after each drift scan enabled elimination of the contribution by the background sky which, however, was not of a significant level. The extinction coefficients and the system calibration were computed from observations of standard stars 58 Aql and θ Crt made before the commencement of the cometary observations. The drift scans are then converted into absolute flux (F_λ).

The continuum contribution must be subtracted from these values of the fluxes for CN(0, 0) and C_2 (0, 0), in order to obtain the corresponding pure emission values. The spectral scan of the same night shows that the continuum at 5000 Å is contaminated by the contributions from the C_2 (0, 0) band which cannot be neglected. The continuum scan at 5000 Å was corrected for this excess and a pure continuum scan was derived, assuming that the contribution of the contamination does not vary significantly across the coma. This was

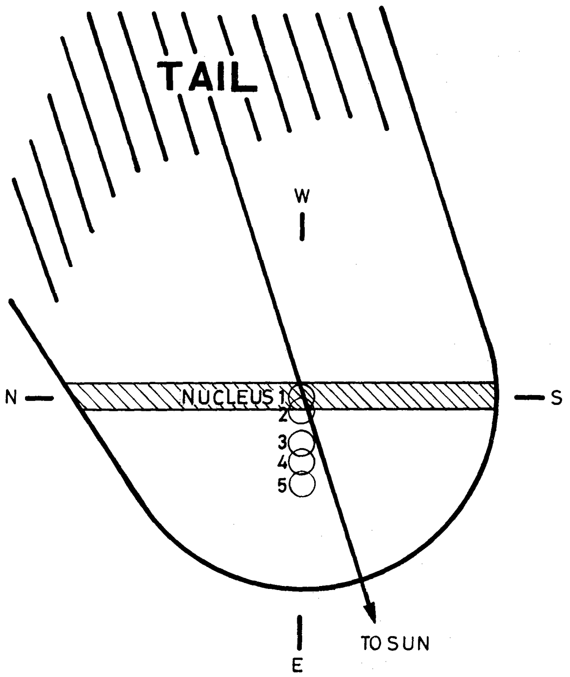

Figure 1. Schematic diagram of observations made of Comet West. The rectangular hatched area running N–S represents the locus of the 25.9 arcsec diaphragm across the coma during the drift scans. The circles designated 1, 2, 3, 4 and 5 represent the relative locations of the diaphragm at the nucleus and at 14, 48, 69 and 89 arcsec from it respectively.

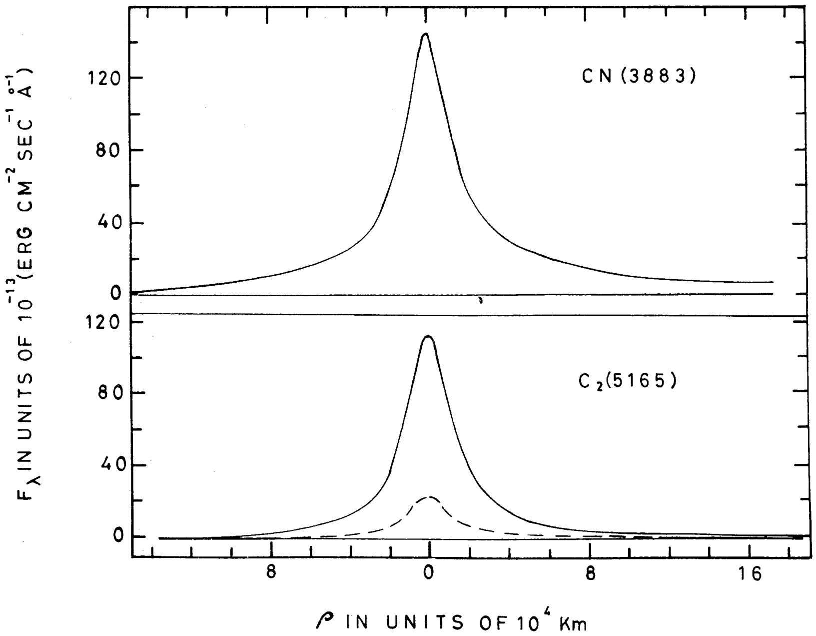

Figure 2. The brightness profiles in absolute flux units F for CN (0, 0), C_2 (0, 0) emission and continuum at 5000 Å (curve in broken line) as derived from the drift scans. The radial distance from the centre of the coma is represented by ρ.

used to compute the net emission due to the C_2 (0, 0) band. The continuum level centred around the CN (0, 0) band, in relation to that at 5000 Å, is known from the normal spectral scan of the coma. Using this ratio, a drift scan of the pure continuum located at 3883 Å was constructed from the pure continuum drift scan of 5000 Å. We have used this information to derive the flux due to pure CN(0, 0) emission. A plot of these corrected fluxes is shown in Fig. 2.

We also have spectrum scans in the range 3700–5300 Å over five locations within the coma. These were made on 1976 March 19.96 when the comet was at a distance of 0.756 AU from the Sun. The 25.9 arcsec diaphragm isolated five regions within the coma, starting from the nucleus and located at distances of 14, 48, 69 and 89 arcsec in the eastern direction (see Fig. 1). The scanner was operated with the grating in the second order and an exit slot corresponding to 20 Å. These scans together with those of the standard stars 58 Aql and θ Crt, provided flux values at each of these locations in the light of the emission bands and the continuum. A plot of these is shown in Fig. 3.

3 The drift scans

3.1 REDUCTIONS

We now proceed to determine the scale lengths and lifetimes. From Fig. 2, we notice that our drift curves cover the entire C_2 (0, 0) coma, but do not reach the very limits of the CN (0, 0) coma, particularly in the northern wing. The curves are symmetrical about the centre in the vicinity of the nucleus, whereas the two wings differ when they reach the outer parts of the coma. This asymmetry is due to the extension of the coma in the northern direction which experiences less solar radiation pressure than the south. We can, however, assign lower limits for the dimensions of the coma; these are 3.09×10^5 and 2.82×10^5 km for the CN (0, 0) and C_2 (0, 0) emissions respectively.

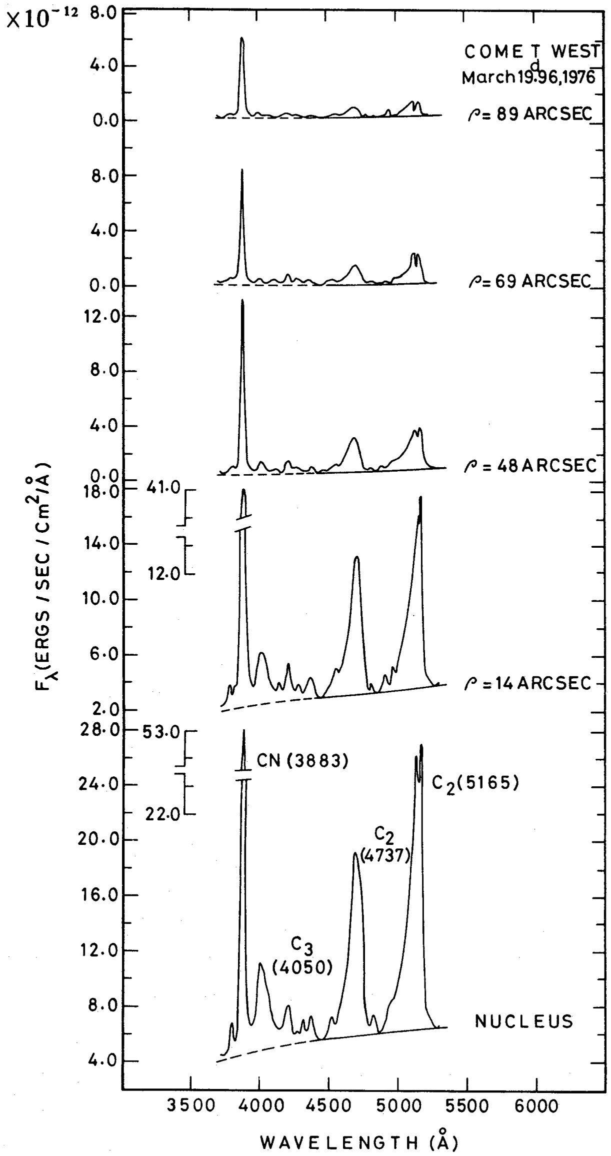

Figure 3. Spectrum scans in the region 3700–5300 Å at the five locations within the cometary coma obtained with the 25.9 arcsec diaphragm.

For further calculations, we have used the average profiles of the north and south wings for both CN and C_2. From this average profile, the radiant energy $L_\lambda = 4\pi\Delta^2 F_\lambda$ (Δ being the geocentric distance in cm), emitted by unit area along the line-of-sight is worked out for various values of the projected distance (ρ) from the nucleus. This yields the number of molecules $N(\rho)$ contained in a cylinder of unit cross-section along the line-of-sight of the observer extending through the entire comet and located at a projected distance ρ from the nucleus. These were calculated for each of the ρ values. Adopting the values for the oscillator strength, relative transition probability and the density of the solar radiation at the comet given by Kohoutek (1974), the total number of molecules $M(\rho)$ contained in a cylindrical column of radius ρ centred round the nucleus was evaluated by an integration of $N(\rho)$ over ρ. We next prepared plots of $M(\rho)/\rho$ versus ρ for CN(0, 0) and C_2(0, 0) (Fig. 4) and these formed the observational curves for comparison with the Haser theoretical curves.

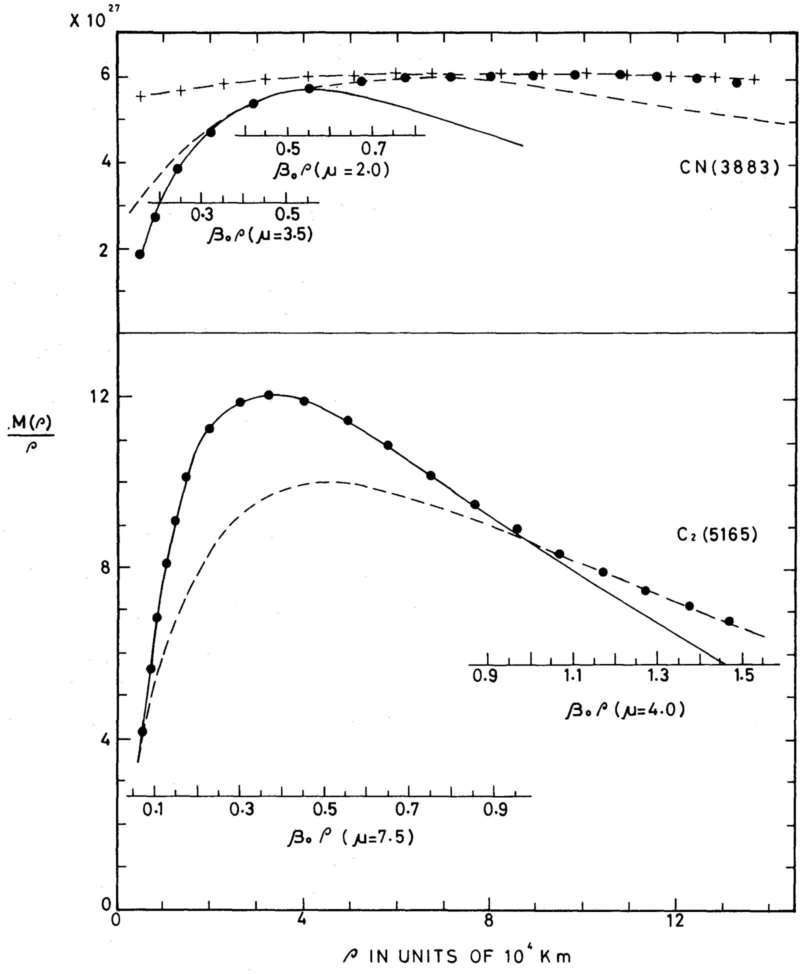

Figure 4. The total number of molecules $M(\rho)$ inside the cylindrical column of radius ρ per unit ρ of CN (0, 0) and C_2 (0, 0) are represented by filled circles. The matching theoretical curves for the specified values of μ over the ranges of values of $\beta_0\rho$ are denoted thus:

CN: ——— $\mu = 3.5$; $\beta_0\rho = 0.15$ to 0.55
– – – – $\mu = 2.0$; $\beta_0\rho = 0.5$ to 0.8
–+–+– $\mu = 1.1$; $\beta_0\rho = 0.8$ to the end of the curve.

C_2: ——— $\mu = 7.5$; $\beta_0\rho = 0.05$ to 0.9
– – – – $\mu = 4.0$; $\beta_0\rho = 0.9$ to 1.5

The theoretical expression for $M(\rho)$ based on Haser's (1957) two-component model with isotropic expansion,* has been expressed in a convenient form by A'Hearn & Cowan (1975). They tabulate the integral relating the production rate Q to $M(\rho)/\rho$ for different values of x and μ. Herein $x = \beta_0\rho$ and $\mu = \beta_1/\beta_0$; β_1 is the reciprocal of the mean distance travelled by the parent molecules before dissociation and β_0 that of the daughter molecules. Hence

$$\beta_1 = \frac{1}{V_1\tau_1} \quad \text{and} \quad \beta_0 = \frac{1}{V_0\tau_0}$$

where V_1 and V_0 are the velocities and τ_1 and τ_0 are the lifetimes of the parent and daughter molecules, respectively. We assume $V_1 = V_0 = 1\ \mathrm{km\,s^{-1}}$.

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* Haser's model is strictly valid only for a single nucleus comet, and while Comet West did have a split nucleus, our observations relate to an epoch when all component nuclei could still be approximated as a single nucleus.

3.2 RESULTS

We have found it necessary to extend the theoretical curves of A'Hearn & Cowan for smaller values of x and also for closer intervals in μ values. When the observational curves are matched with the theoretical curves we notice that no single theoretical curve can be selected which has a 'perfect fit' with the observed curve. This difficulty has been experienced by earlier workers also (O'Dell & Osterbrock 1962; Vanýsek & Tremko 1964; Dewey & Miller 1966; Ishida & Kosai 1970; Delsemme & Moreau 1973; Kumar & Southall 1974). We find a perfect fit possible if the $M(\rho)/\rho$ curve is split into two components where each fits with a theoretical curve of specific β_1/β_0 value. This is demonstrated in Fig. 4 where the observed points of CN fall on the theoretical curve of $\beta_1/\beta_0 = 3.5$ over the interval in $\beta_0\rho$ from 0.15 to 0.55 and with $\beta_1/\beta_0 = 2.0$ over the interval $\beta_0\rho = 0.50$–0.80. Beyond 0.80, the match is best with $\beta_1/\beta_0 = 1.1$. Similarly for C_2 (0, 0) the observed points fall on the theoretical curves of $\beta_1/\beta_0 = 7.5$ and 4.0 in the two different parts of $\beta_0\rho$ from 0.1 to 0.9 and 0.9 to 1.5 respectively.

From these values of β_1/β_0 and β_0, we obtain the lifetimes of CN and C_2 molecules and of their respective parents. The two values of β_1/β_0 lead to two entirely different values of the lifetimes for the parent molecules and a single value of lifetime for the daughter molecules. Assuming the velocity of expansion of CN, C_2 and their respective parent molecules to be $\approx 1\ \mathrm{km\ s^{-1}}$, we have calculated the corresponding scale lengths. These are set out in Table 1. Also presented in this table are the scale lengths obtained by earlier workers from different comets.

We interpret these results to show that the CN molecules are formed from two different parent molecules which possess different lifetimes. Also it is seen that the dominant parent for the CN molecules in the innermost region of the coma has a lifetime of 6 hr, while for the molecules seen outside this region, the dominant parent has a lifetime of 10.5 hr. A similar situation of two parents with lifetimes 3.3 hr and 6.2 hr respectively, dissociating into C_2 (0, 0) molecules, each with a dominant region of its own, is also observed. However, for CN (0, 0), beyond $\beta_0\rho = 0.8$ the match is with $\beta_1/\beta_0 = 1.1$. This value is taken to indicate that the CN molecules alone are present in the outer regions of the coma, unmixed with any parent molecules.

These observations in our opinion demonstrate clearly the existence of two lifetimes for the parent molecules. The detection of polyatomic molecules like CH_3CN, HCN, etc. in the recent past in comets has prompted workers in this field to speculate on the possible existence of more than one parent which dissociate into the emitter molecules or radicals.

Table 1. Scale lengths of parent and daughter molecules of CN and C_2.

Comet	r(AU)	Scale lengths in units of 10^4 km				Reference
		CN (3883 Å)		C_2 (5165 Å)		
		Parent	Daughter	Parent	Daughter	
West (1975n)	0.853	(a) 2.2	7.6	1.2	8.9	This analysis
		(b) 3.8	7.6	2.2	8.9	
Kohoutek (1973f)	1.0	1.2	14.8	1.0	6.6	A'Hearn & Cowan (1975)
Tago–Sato–Kosaka (1969g)	1.239–1.275	1.7	4.2	2.5	10–15	Kumar & Southall (1974)
Bennett (1969i)	1.0	5.0	14.1	2.0	6.3	Delsemme & Moreau (1973)
Ikeya–Seki (1967n)	1.830	3	30	2	20	Vanýsek (1969)
Seki (1961f)	0.935	—	—	4.6	8.3	Dewey & Miller (1966)

Our knowledge, at present on the lifetimes of these molecules is very scanty, and this prevents us from picking out those polyatomic molecules which could be considered as possible candidates for parenthood, from lifetime considerations alone.

According to Jackson (1974), $\tau(C_2N_2) \approx 3$ hr and $\tau(HC_2CN) \approx 3.6$ hr at 1 AU. If these are considered as the possible parents for CN, our lifetime estimations are almost double these values. Jackson's values are from laboratory measurements and might represent lower limits. These could be enhanced substantially in the environment prevailing in the cometary comas, and bring the lifetimes nearer to our determinations. Even now, the agreement could be considered as quite satisfactory considering the large uncertainty in the outflow velocity, which is taken to be $1\,\mathrm{km\,s^{-1}}$. Alternatively, there could still be some undetected species of molecules which could as well be the parents.

In the case of C_2H_2 which could be a possible parent of C_2 molecules, Jackson gives value of $\tau(C_2H_2) \approx 1.6$ hr. This value also is about half of one of our estimations. In this context, Malaise's determinations of $\tau(PCN) \approx 1$ to 10 hr and $\tau(PC_2) \approx 3.4$ hr at 1 AU (Mendis & Ip 1976) seem to fit well with our values.

Future observations, particularly in the radio frequencies will no doubt add to the list of stable molecules. Accurate determination of their lifetimes will enable us to pick out the possible parents, for which the dissociation reactions are known to give rise to daughter molecules. Side by side, it is necessary to obtain drift curve data across the entire coma scanned at close intervals for more comets to give an accurate two-dimensional picture of the entire coma of the comets. This will help considerably in improving the existing models of the coma and make them more realistic.

4 The continuum flux values from the spatially distributed spectrum scans

The continuum energy distribution corresponding to the five step scans were normalized to 4465 Å. A plot of these is shown in Fig. 5. The corresponding energy distribution of the Sun plotted on the graph serves as a reference. The continuum originating from the scattering by dust in the coma is reddened with reference to the solar continuum. The most interesting feature to be noted from these energy curves, is that they show a progressive increase in reddening with increasing values of the radial distance ρ within the coma from the nucleus. This reddening is approximately 0.5 mag at 5265 Å (with reference to 4465 Å) between the two extreme positions of the step scans, namely, the nucleus and the last location which is about 90 arcsec away. The amount of reddening with respect to ρ is shown in the inset of Fig. 5. Vanýsek (1960, 1974) has been able to detect an increase in colour index with increasing diameter of the entrance aperture using concentric diaphragms. His colour differences appear marginal because of the dominant contribution by the nuclear region. Our values, however, represent measures of higher accuracy and reliability.

In summary, two aspects of the energy distribution are thus very apparent. The coma continuum has an energy distribution that is redder than the Sun. There is also a tendency to find an increase in reddening with increasing distance from the projected centre of the coma.

Many cometary continua have demonstrated the generally prevalent reddening of the coma as a whole (Vanýsek 1974). It has been seen in Comet Mrkos, Comet Arend–Roland, Comet Bennett (1969i), Comet Ikeya–Seki (1965f), Comet Alcock (1963b) and Comet Kohoutek (1973f), though Gebel (1970) failed to notice it in Comet Ikeya–Seki (1967n). Perhaps his lone case is one of abnormality and demonstrates the need to accept an individuality in performance from comet to comet. This would make it difficult to pronounce in general terms certain cometary characteristics like particle sizes in the coma. A specific

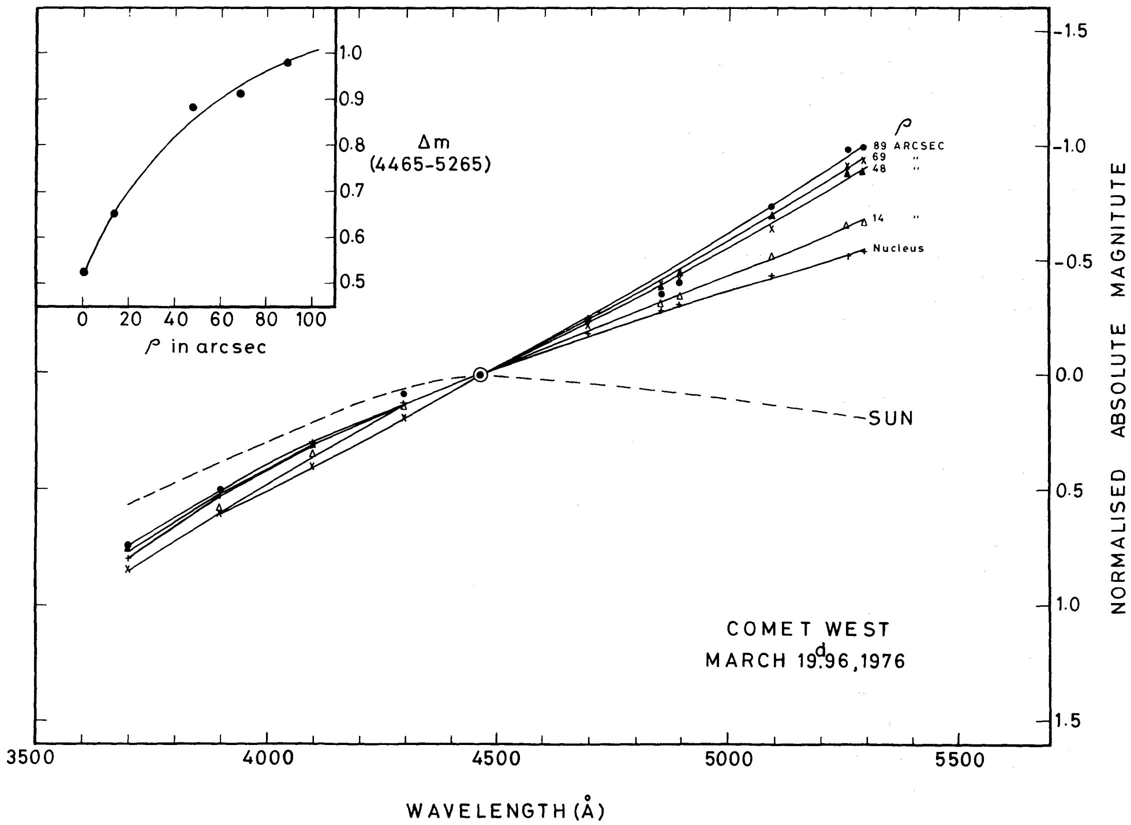

Figure 5. Energy distribution curves of the cometary continuum corresponding to the five locations of the 25.9 arcsec diaphragm within the coma. The inset shows the progressive increase in reddening with increasing ρ.

model for each situation may be warranted, if the observations are sufficient in scope and extent to do so.

The increase in reddening from the centre of the coma can be explained in terms of typical particle sizes that are smaller in the halo than in the centre. Since our continuum measures, which show this characteristic, can at best only be interpreted in terms of the property of optical scattering, we find that icy spheres with particle sizes in the 1–2 micron range can explain the observed curve. Sub-micron sizes of metallic constituents can also be used to explain the scattering. Measures over a wide wavelength base line would be necessary to elucidate this aspect. For the present it may be stated that our observations show that the outer layers of the coma have smaller sized particles than those nearer the centre.

5 Derivation of flux distribution with ρ from the spectral scans

We consider the ρ dependence of flux in the emission bands. These total fluxes in terms of $\mathrm{erg\,s^{-1}\,cm^{-2}}$ are plotted against the radial distance from the centre of the coma and are shown in Fig. 6. It is quite obvious that the strength of the emission features gradually decrease with increasing ρ. The most rapid decrease is shown by C_3 (4050 Å), indicating that this particular species of molecules ceases to exist at much closer distances from the centre of the coma as compared to, for example CN (3883 Å). The total number of molecules of each species contained in a cylinder of diameter 25.9 arcsec, and extending from the observer through the comet, have been worked out for these five positions and are given in

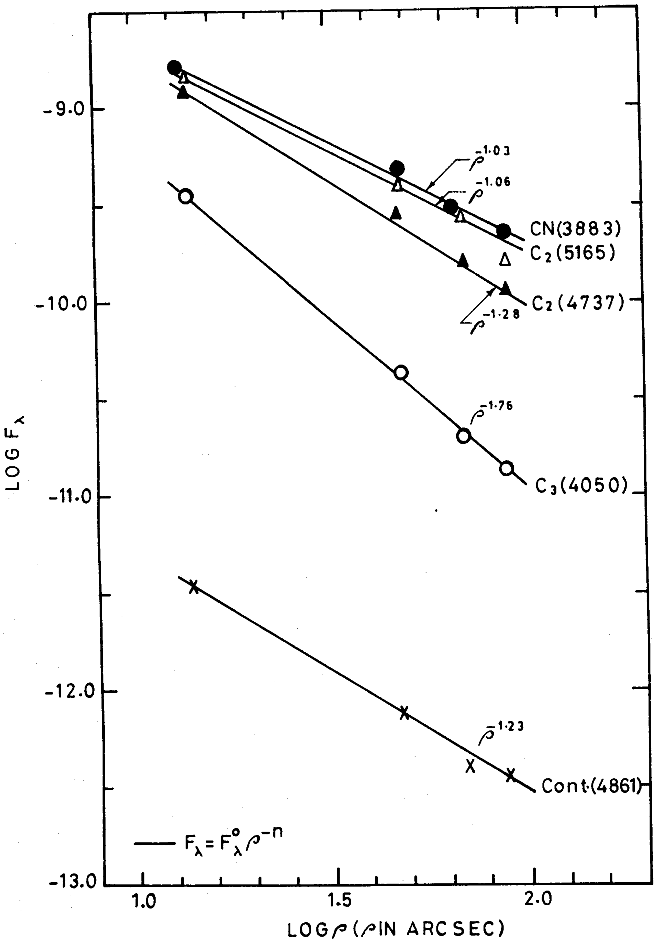

Figure 6. Flux variations in the CN, C_2 and C_3 bands as well as in the continuum with radial distance (ρ) within the cometary coma.

Table 2. These show the radial dependence of the column density of each of the species. The continuum also shows a gradual decrease with increasing ρ though not as rapidly as that of C_3 (4050 Å). The dust particles extend much beyond the coma of C_3 (4050 Å), and almost up to the edges of the coma.

These new observations reported herein hold forth much for future studies of bright comets. It would be worthwhile knowing the variation of the band and continuum emission from the nucleus out to the very periphery of the coma, and covering the entire visible

Table 2. Total number of CN and C_2 molecules in the line-of-sight with the 25.9 arcsec diaphragm at different locations in the coma of Comet West on 1976 March 19.96.

ρ (arcsec)	No. of molecules		
	CN (3883 Å)	C_2 (4737 Å)	C_2 (5165 Å)
0	8.2×10^{30}	9.2×10^{31}	4.0×10^{31}
14	7.1	6.6	2.5
48	2.2	1.5	0.7
69	1.3	0.8	0.5
89	1.0	0.6	0.3

region and near infrared. Such information along with polarization measurements of the coma will lead to improved understanding of the sizes of the dust particles and also of their constitution.

Acknowledgments

We wish to express our thanks to Mr P. Venkatakrishnan for computation of the $F(\mu, x)$ integrals.

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