COMETS

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INTRODUCTION:

The study of the physical structure and chemical composition of comets during their apparitions constitute a basic source of information concerning both the state of the interplanetary medium and more fundamentally the origin and evolution of the solar system. There are valid reasons to believe that these rare visitors form the relics of the matter that was once dispersed in the primordial solar nebula. Hence the study of cometary physics holds forth clues to our understanding of the history of the solar system.

Most of the comets of recent years have been discovered by professional astronomers, these comets being detected on photographs taken as part of the general observatory programmes, although Japanese amateurs have to their credit many comets during the last decade. Comets are named after their discoverers. Halley's and Encke's comets are exceptions and bear the names of persons who computed the orbits of these comets. Edmond Halley in 1705, applying the Newton's law of gravitation showed that the comets with perihelion passage in the years 1531, 1607, 1682, were really periodic apparitions of the same comet moving in a highly eccentric elliptical orbit and predicted on this basis its reappearance in 1758. This provided the first proof that comets belonged to the solar system. Besides Halley's comet, periodic comets of interest are comet Encke (period 3.3 years), and comet Schwassmann-Wachmann (period 16.1 years). The latter comet has its orbit between those of Jupiter and Saturn and can be seen in all parts of its orbit. According to the I.A.U. convention, comets are designated in the order of their discovery or reappearance in the year (like 1969a, 1969b, 1969c and so on) and are catalogued finally in the order of their perihelion passage (e.g. 1969I, 1969II, 1969III and so on).

The nucleus of a comet which presents a stray appearance consists of gas and dust in the form of "ices". The gaseous molecules and dust flowing out from the nucleus, form the spherical coma or the cometary atmosphere surrounding the nucleus, commonly known as the head of the comet. The visible dimensions of the coma extend to 3×10^5 km in a bright comet. The tail consisting of materials expelled from the nucleus by the solar radiation often reach dimensions of 20-30 million km. Both gas and dust may be present in the tail. These become separated in space and show different curvatures.

SPECTRA OF COMETS:

The spectra of the head of comets exhibit:

a) emission bands of neutral molecules such as CN, C_2, C_3, NH, OH, CH and NH_2 which are products of dissociation of more complex molecules;

b) atomic lines of neutral sodium and oxygen at small perihelion distances; the lines of ionized calcium and nickel are seen in sun-grazing comets; and

c) a continuum which is the solar spectrum reflected by the solid particles in the nucleus.

The tail spectrum shows the emission bands of ionized molecules such as CO^+, CO_2^+, N_2^+ and CH^+.

The main instrumentation for obtaining spectra of comets are the objective prism set up or the slit spectrograph. The objective prism spectra inherently are of very low dispersion (of the order of 250Å/mm), but have the advantage of providing monochromatic images of the head and the tail simultaneously over the entire wavelength region of interest. The earliest objective prism spectra of comets are those obtained by de la Baume Pluvinel in 1902. The first objective prism spectrum to show discrete emissions of CO^+ in the tail was by Hans Rosenberg of comet Daniel (1907II). Spectra of the same comet by Evershed revealed for the first time the ultraviolet emissions of the tail. Slit spectra of low dispersion (250Å/mm) show well the emission bands of the head (Figure 1). Table 1 summarizes the main molecular and atomic emissions in comets. Excellent reproductions and descriptions of the spectra covering the regions 3000 to 6800Å obtained till 1956 have been given by Swings and Haser (1956). The CN and C_2 emissions form the striking features of the spectra of cometary heads. The CN has the largest extension into the head. The C_3-4050Å group, which is one of the prominent spectral features, was identified only recently.

The relative intensities of the emission features depend to a certain extent on the heliocentric distance, although the nature of the spectrum is dictated primarily by the physical state and chemical composition of the cometary nucleus. At large heliocentric distances, $r \approx 3$ a.u., the spectrum shows a continuum with hardly any gaseous emission. Band or line emissions have never been observed in comet Schwassmann-Wachmann (1925II) which is at 5.5 a.u. at its closest approach to the sun. Around $r \approx 2$ a.u., the C_3 and NH_2 emissions appear. Swan bands of C_2 appear when the comet is at $r = 1.8$ a.u. The vibrational intensities of C_2 correspond to a high temperature distribution. Around $r = 1.5$ a.u. all the molecular emissions (OH, NH and CH) appear. The molecular emissions become very predominant over the continuum in some comets like comet Burnham (1960II), comet Seki (1961f) and comet Ikeya (1963a).

On low resolution spectrograms, the CN (0,0) band structure can be seen as two emission blobs, which in objective prism spectra may even overlap. Under

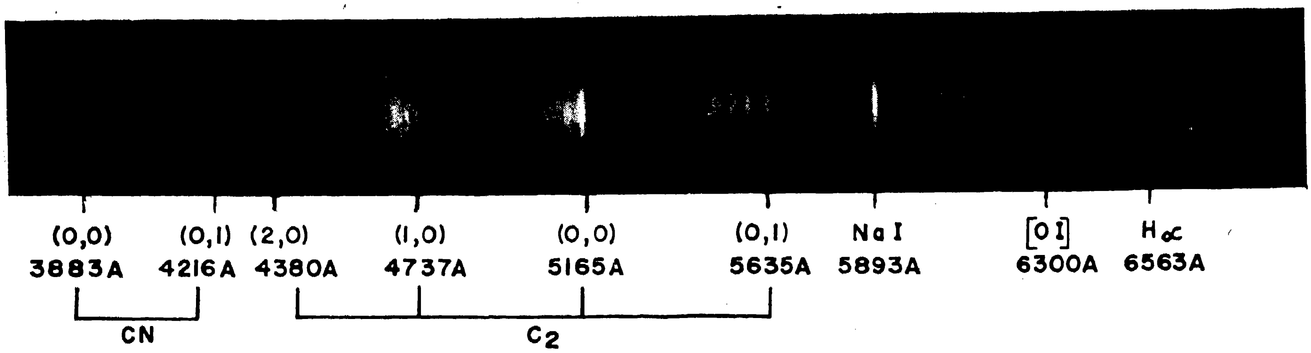


Figure 1 : Slit spectrum of Comet Ikeya-Seki (1965f) obtained with the Cassegrain grating spectrograph on the 50-cm reflector of Kodaikanal on October 30.985, 1965 (r=0.497 a.u.) Dispersion : 250Å/mm.

moderate dispersions (70-80Å/mm) the structure in the P and R branches of the CN (0,0) band shows a complex intensity distribution. Also different comets differ in their profiles of the CN bands. Complex profiles are seen for CH, OH and NH bands, although to a lesser degree.

The observed cometary emissions are produced by resonance fluorescence excited by the solar radiation. The general interpretation of the complex profiles of CN (0,0) band based on this mechanism was given by Swings in 1942. He pointed out that the intensity of any cometary emission depends upon the amount of energy available at that wavelength, in the incident solar radiation on the comet. The presence of absorption lines in the solar spectrum weakened the CN fluorescence spectrum at these wavelengths. Swings succeeded in showing that the rotational lines weakened exactly at those wavelengths where the Fraunhofer lines are present in the exciting solar radiation. In such an interpretation, the effect of *dr/dt*, the radial velocity of the comet relative to the sun, has to be included. The variation of the intensity profiles from comet to comet was also explained qualitatively by Swings as due to the changes in the value of *dr/dt* from one comet to another. The different values of *dr/dt* would bring the cometary emission lines inside or outside the strong Fraunhofer lines. This confirmed the resonance fluorescence as the mechanism responsible for the observed molecular emissions. Quantitative estimation of the profiles computed by McKellar and by Hunaerts showed a fair amount of fitting between the theoretical and observed intensities. The population of the ground state rotational levels was assumed to be controlled by a Boltzmann distribution at a temperature chosen from the overall shape of the observed intensity pattern in the band system. This assumption is really not valid as the density is very low and collisions are rare.

In 1957, Greenstein (1958) placed cometary spectroscopy on a different pedestal, when he obtained the spectrum of comet Mrkos (1957V) at the coude focus of the 200-inch telescope. This gave a spectral dispersion of 18Å/mm in the blue and 27Å/mm in the red and a scale on the photographic plate of about 26 seconds of arc per millimetre. The Palomar spectra revealed the rotational fine structures of CN better than ever before. Structures of the C_2 Swan bands which were not seen earlier could be seen in these spectra. The high spatial resolution also showed intensity changes of certain lines of CN and CH from one location to another within the cometary head, caused by local changes in the radial velocities, now known as the "Greenstein effect". The high resolution spectra profiles fitted to the theoretical intensities only in a gross way. The way out of this difficulty was suggested by Arpigny (1965) who computed the relative populations of a lower rotational level, assuming steady state conditions. In a steady state, the number of transitions leaving a level and the number of transistions arriving at this level are equal. The steady state equations enabled the calculation of the relative populations of the lower levels. The profiles so computed matched very well with the observed ones for CN, CH, OH and NH. For the C_2 Swan system, the agreement is not satisfactory, as the theoretical treatment of resonance fluorescence in this case becomes complicated due to the large number of levels and transitions involved. Another discrepancy arises from the disagreement between the theoretical and observed vibrational Boltzmann temperatures. Many comets consistently yield 3000^0K for the C_2 vibrational temperatures, while the theoretical predictions are almost twice this value.

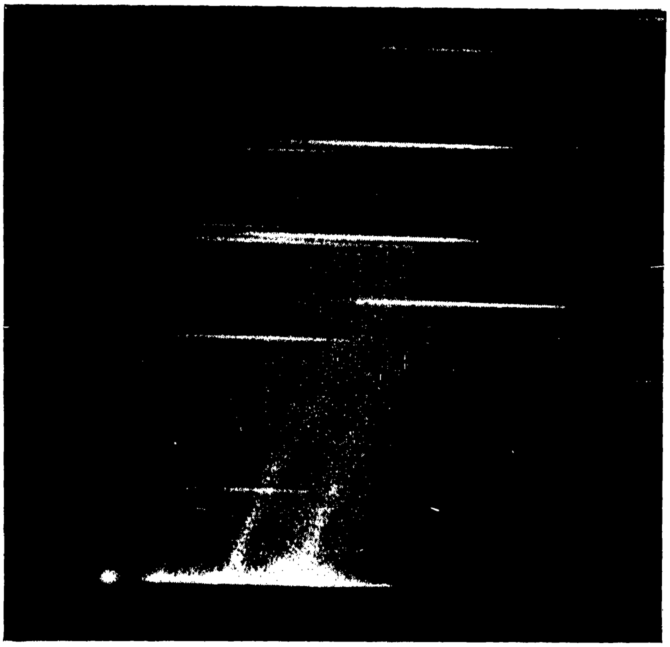
It is known that the D-lines of sodium appear in comets when r is less than 0.8 a.u. The dependence of the D-line emission on the phase of the solar cycle was first noted by Bappu and Sivaraman (1969). For comets appearing during the period of solar maximum, the cometary head displays sodium emission out to greater heliocentric distances than for those appearing during solar minimum. Also the farthest distance to which the D-line emission can be seen for a high heliographic latitude comet is much less than for comets appearing between 15° and 40° latitudes. This is possibly due to the differences in the spatial properties of the solar wind between a solar maximum and solar minimum.

Comets begin to develop a tail at heliocentric distances from r=1.5 a.u. downwards. With decreasing r, the tail becomes very prominent. Comet Humason (1961e) was an exception to this ; in spite of the large heliocentric distance (r=2.6 a.u.) it showed strong tail emission of CO^+ and N_2^+. Among the tail emissions due to ionized molecules (CO^+, N_2^+, CO_2^+, CH^+), CO^+ emissions are the most important (Figure 2). The structure and dynamics of ionic tails (also known as Type I tails) are controlled by the interaction of the cometary plasma and the solar wind. According to Biermann, production of CO^+ ions in the tail is due to

TABLE 1

Some of the Prominent Molecular and Atomic Emissions in Comets

SOURCE OF EMISSION	TRANSITION	WAVELENGTH RANGE (Å)
	Head	
Molecular		
OH	$A^2\Sigma - X^2\Pi$	(0-0) 3090 (1-1) 3140
NH	$A^3\Pi - X^3\Sigma$	(0-0) 3360
CN	$B^2\Sigma - X^2\Sigma$ Violet band	(1-0) 3590 (0-0) 3883 (0-1) 4216
	$A^2\Pi - X^2\Sigma$ Red System	(2-0) 7906 (3-1) 8106
CH	$B^2\Sigma - X^2\Pi$	(0-0) 3920
	$A^2\Delta - X^2\Pi$	(0-0) 4310
C_3	$^3\Pi - {}^1\Sigma$	3880-4100
	$^1\Sigma - {}^1\Pi$	3970-4070
	$^1\Delta - {}^1\Pi$	4020-4070
	The most conspicous being at 4540Å	
C_2	Swan Band System $A^3\Pi - x^3\Pi$	(2-0) 4383 (1-0) 4737 (0-0) 5165 (0-1) 5635 (0-2) 6191 (0-3) 6677
Atomic		
Na I	$3^2S - 3^2P$	5890; 8596
Fe I	$^5F - {}^5D$	5260-5430
(O I)	$^3P - {}^1D$ $^1D - {}^1S$	6300; 6363 5577
	TAIL	
CO_2^+	$^2\Pi - {}^2\Pi$	(1-0) 3378 (0-0) 3509 (0-1) 3674
CO^+	$A\,^2\Pi - x^2\Sigma$ Comet tail bands	(4-0) 3781-3800 (3-0) 4000-4024 (2-0) 4250-4270 (1-0) 4543-4568
	$B\,^2\Sigma - A^2\Pi$ Baldet-Johnson System	(1-0) 3726 (0-0) 3951-3983
N_2^+	$B\,^2\Sigma - X^2\Sigma$	(0-0) 3914



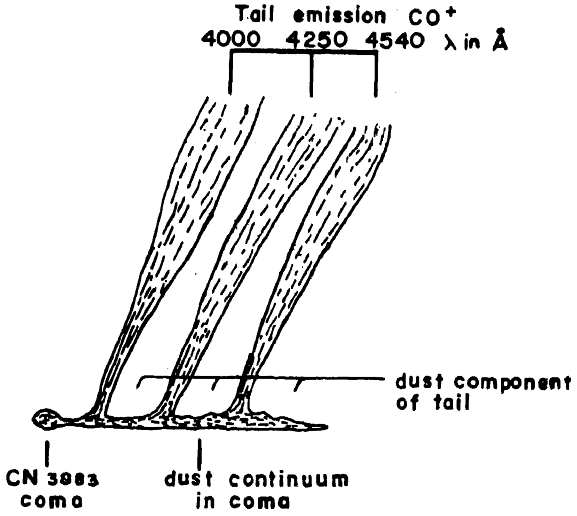


Figure 2 : Objective prism spectra of Comet Bennett (1969i) taken with f=180mm (f/2.8) camera at Kodaikanal on 9-4-1970 (r = 0.704 a.u.). Note the intense CO^+ emissions of the tail.

a charge exchange process by protons in the solar wind with the neutral molecules. The ionic tail shows considerable structure and changes from day to day. Compared to this, the dust tail (known as Type II tail) has no structure. Arpigny (1965) has successfully explained the observed intensities of the CO^+ bands in comet Humason (1961e) on the basis of resonance fluorescence mechanism. Thus the same mechanism seems to be responsible for the emission of the neutral radicals in the coma and the ionic emissions of the tail.

HYDROGEN ATMOSPHERE :

Biermann (1968) predicted the existence of a cometary hydrogen envelope with a radius of about 10^7 km for a medium bright comet. If the main constituent of the nucleus is H_2O, then the neutral hydrogen will be produced by photodissociation at the rate of 10^{30} atoms per second. These H-atoms will remain neutral in the solar radiation field for about 10^6 sec and emit Lyman-alpha radiation. Code, Houck, and Lillie (1970) first detected the Lyman-alpha resonance line (1216Å) in comet Tago-Sato-Kosaka (1969g) using the OAO-2 (Orbital Astronomical Observatory) satellite. The (0,0) bands of OH at 3090Å were also detected in this comet. OAO-2 also observed Lyman-alpha radiation in the bright comet Bennett (1969i). In both comets the intensity from the central regions of the H-cloud was about 200 times the Lyman-alpha radiation of the sky background. The Lyman-alpha line had a width equivalent to a temperature of 1600°K. Observation of the Lyman-alpha radiation emission from comet Bennett by OGO-5 (Orbital Geophysical Observatory) during the whole of April 1970, provided the isophote maps of the hydrogen atmosphere for many days (Bertaux, Blamont, and Festou 1973). These showed clearly a variation in the intensity over the period of observation of the egg-shaped hydrogen envelope. The boundary of the isophotes extended upto 2×10^7 km along the sun-comet vector and 1.5×10^7 km in the perpendicular direction.

ABUNDANCES AND LIFE-TIMES OF MOLECULES :

Estimates of the number of molecules of the different species in the coma can be derived from a study of the monochromatic brightnesses corresponding to the emitting molecules. The observed luminosity of a band group is determined by the total number of emitting molecules, the f-value of the system, the relative transition probability for the different transitions and above all by the intensity of the solar radiation at the location of the comet. Spectrum scans and the use of interference filters to isolate the emission bands are convenient photoelectric methods to compute the total number of molecules of each species. Photographically, one can arrive at the same information with good monochromatic images of the comet and an accurate photometric scale of intensities. However, the observed abundances in the visual range do not completely represent the total gaseous output of the comet, as some of the molecules radiate in the ultraviolet or infrared regions. The number of molecules derived from photoelectric observations of the luminosities of the cometary coma are seen to be about 10^{30} in the C_2 (1, 0) band and about 10^{29} in CN (0,0) band.

The monochromatic images of the cometary heads in the C_2 and CN bands have nearly spherical shapes. The observed intensity depends upon the density distribution of the molecules with distance from the nucleus. This leads to the simple model in which the cometary molecules are produced at the nucleus and expand isotropically with a mean velocity V_O. The density falls off as R^{-2}, R being the distance from the nucleus. The density distribution D(R) is given by $D(R) = KR^{-2} \exp(-R/V_O \tau_O)$ where K is a constant and τ_O is the mean life time of the molecules before dissociation As a next step, if some kind of parent molecules are assumed to be produced at the nucleus and these decay to C_2 or CN with a life time of τ_1, then the density distribution is modified as

$$D(R) = KR^{-2} \left[\exp\left(-R/V_o\tau_o \right) - \exp\left(-R/V_1\tau_1 \right) \right],$$

V_1 and τ_1 being the corresponding parameters for the parent molecules. The observed surface intensity distribution with R in the nucleus depends on the ratio τ_O/τ_1 for the molecules of each kind. The life times of the parent molecules (τ_1) or the daughter molecules (τ_O) can be evaluated from the values of $V_1 \tau_1$ and $V_O \tau_O$ knowing the expansion velocities V_1 and V_O. From the C_2 brightness profiles of several comets, it is seen that $V_O \tau_O \approx 10^5$ km at a heliocentric distance of 1 a.u. and if $V_O \tau_O / V_1 \tau_1 = 9$, then $V_1 \tau_1 = 10^4$ km. Assuming $V_1 = V_O = 1$ km/sec, we find $\tau_1 = 10^4$ sec. This small value of the life time for parent molecules—though not very accurate—leads one to doubt whether photodissociation is the process at all responsible for producing the observed neutral molecules in comets. The value of τ_1 computed from the photodissociation cross-sections and the density of the solar radiation at the appropriate frequencies, for possible candidates as parent molecules lie in the range $10^{5.5}$ to $10^{6.5}$ sec whereas cometary observations of C_2 and CN surface intensity distribution yield a value of $\tau_1 = 10^4$ sec. One of the alternatives suggested is by Delsemme that the free radicals are embedded in ice in the form of clathrates. According to this hypothesis, various molecules are trapped in the form of clathrates in cavities in the water-ice lattice. The solar radiation destroys the lattice, and liberates these molecules.

The life times for the neutral hydrogen atoms (τ_H) derived from the intensity distribution in the Lyman-alpha isophotes by Bertaux et al (1973) show that $\tau_H = 2 \times 10^6$ sec for heliographic latitudes upto 30° and $\tau_H = 10^6$ sec for latitudes higher than 45°. This latitude dependence is attributed to the larger ionization caused by the solar wind protons at higher latitudes.

The composition of the dust component is an important parameter in cometary atmospheres. The solar light pressure accelerates the submicron particles into the tail and in this process particles of different sizes are separated out. The continuum for many comets simulate an energy distribution of stars redder than the sun. However, the spectrophotometric studies on three comets by Gebel (1970) show that the continuum energy distribution resemble the spectrum of an early G-type star.

POLARIZATION :

The pioneering efforts of Ohman in 1941 on comet Cunningham mark the first monochromatic measures of the polarization photographically of the light from the comet. Photoelectrically, similar measurements were first made by Bappu and Sinvhal (1960) of comets Arend-Roland and Mrkos. These and subsequent measurements of comet Ikeya-Seki by Bappu et al. (1969) show that at 90° phase angle, the polarization is about 17 per cent and increases upto 25 per cent. Similar measurements for the tail of comet Ikeya-Seki showed a value of 13.6 per cent. In a majority of comets, the polarization in the nucleus is higher than that in the tail. This indicates that the scattering properties of the particles in the head and in the tail could be different. This is confirmed by the polarization measurements on comet Bennett under high spatial resolution by Clarke (1971). He found that there is a range of directions for the vibration of the electric vector of the light from the head and the tail. This may be explained by the change in the grain size from the head of the comet to its tail.

Infrared measurements of surface brightness combined with photometry in the optical range is another important source of information on the size of these grains. O'Dell (1971) estimates the size of the particles to be 0.1 μm and finds that the reflectivity is close to that of stone meteoroids.

STRUCTURE OF THE NUCLEUS :

Observations indicate that the physical and chemical properties of cometary nuclei agree with Whipple's icy- conglomerate model. The others like the sand-bank model of a cloud of loose dust or the model of single solid block cannot be considered as realistic models consistent with observations. The nucleii of comets, most probably owe their origin to the solar nebula during its evolutionary stages and are still being dispersed into the inner regions of interplanetary space from a cloud of 10^7 comets at a distance of about 10^4 to 10^5 a.u. as proposed by Oort. We now believe that the solar system originated from a collapsing cloud of dust and gas. The temperature distribution in the solar nebula produces two distinct regions of different chemical compositions. The low temperature "comet region" may never have been heated to destroy the non-volatile interstellar dust. This may mean that a large amount of the primordial material is preserved in comets.

Although knowledge about cometary spectra—excitation mechanisms in the coma and the tail and the composition of the material etc.,—has considerably advanced, some of the fundamental problems remain enigmatic. Some of the radicals like H_2O, NH_3, C_2N_2, CH_4, N_2, CO_2 which can be considered as parent molecules have not been directly identified from cometary spectra, since their emissions fall in spectral regions inaccessible for ground based observations. We sincerely hope that the elaborate programme of observations planned for comet Kohoutek (1973f) will be helpful in answering some of the questions.

Added in press (*Editor*) : The lines of HCN, CH_3CN have been detected, ortho H_2O^+ has been tentatively identified and 200 previously unpublished cometary emission lines have been recorded from comet Kohoutek.

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