PHYSICAL AND CHEMICAL PROPERTIES OF COMETS*

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INTRODUCTION :

Although comets do not contribute significantly to the mass of the solar system, they do form an important constituent from a cosmogonic point of view. Due to their small sizes, comets have undergone little metamorphic change due to the effects of gravity, internal heat, weathering and high velocity meteoritic impact, unlike the larger bodies : planets and satellites. They probably constitute the most primitive material in the solar system, and a proper understanding of them could throw light on the chemical composition and the physical state of the primitive solar nebula.

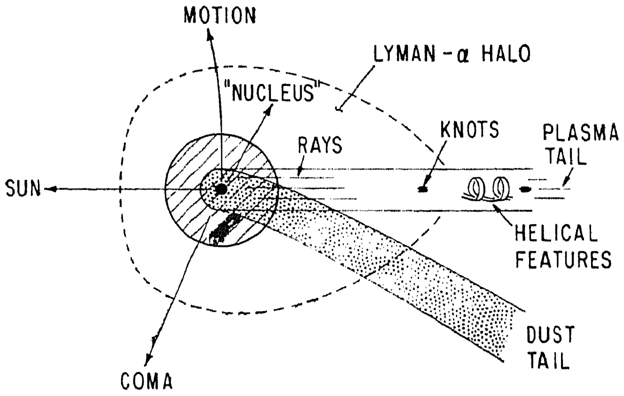
The important role of comets, as natural probes of the interplanetary plasma, has been realized since the pioneering work of Biermann (1951). Indeed, it was the behaviour of the plasma tails of comets which provided us the earliest information regarding the continuous outflow of matter from the sun, which we now call the solar wind. In this role, comets have not been entirely superceded by the advent of artificial space probes; while these latter are confined to regions close to the ecliptic plane, long period comets approach the sun at all inclinations. Furthermore, comets are the most distant voyagers of the solar system, sampling regions that are genuinely 'interstellar'.

Finally, comets act as cosmic laboratories, providing us with an opportunity of studying matter under unusual physical conditions, not easily reproducible in the laboratory. The free radicals observed in the comas and tails can exist there despite their extreme chemical instability, only by virtue of the extremely small densities that prevail.

THE OBSERVATIONAL STRUCTURE OF A COMET :

A typical bright comet when sufficiently close to the sun ($r \simeq 1$ a.u.) exhibits 3 essential features : a coma, a starlike optical centre or 'nucleus' and a tail, which may be of type I (plasma) or type II (dust) or both. These are shown schematically in Figure 1.

The coma is a diffuse luminous region, approximately spherical in shape, whose visible boundary merges with the sky background. In the optical region, in which it was exclusively observed until recently, it is seen by the emission bands of various unstable radicals, a few atomic lines, including the forbidden (red) lines of neutral O and also the emission bands of ions occurring in the tails. The excitation mechanism is (except in the case of O I resonance) fluorescence by solar radiation. The coma further shows the reflected Fraunhofer spectrum of the sun (slightly reddened), indicating the presence of solid bodies, a component of which must be in the form of finely divided dust.



SCHEMATIC FEATURES OF A COMET

Fig. 1 : Observational structure of a comet (schematic)

More recently, three long period comets, Tago-Sato-Kosaka (1969g), Bennett (1968i) and Kohoutek (1973f), as well as the short period comet Encke, have been observed in the ultraviolet. They all show extensive envelopes of strong Ly-α emission. These 3 long period comets have further been observed in the infrared and they show, besides the reflected solar spectrum, a strong thermal component containing also the silicate signatures at 10 μ and 20 μ, which have been observed in circumstellar dust clouds. The dust mimics a temperature somewhat higher than the expected blackbody temperature, indicating either very small grains ($\sim 1\ \mu$) or complicated, fairy castle structure.

The spectral identifications in comets, thus far, is shown in Table 1. The contribution of Kohoutek to this list is worth noting : They include the first ever detection of stable neutral parent molecules CH_3CN (Ulrich and Conklin 1974) and HCN in the millimetre range, H_2O^+ in the optical range (Herzberg and Lew 1974), and atomic C and O in the ultraviolet (Opal and Carruthers 1974). Neutral H_2O itself has been identified in the latest comet Bradfield (Jackson et al 1974).

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Table 1

SPECTRAL IDENTIFICATIONS IN COMETS

HEAD:	CN, C_2, C_3, CH, $C^{12}C^{13}$, NH, NH_2,
	[OI], OH, Na, Si, Ca, Cr, Mn, Fe,
	Ni, Cu, K, Co, Y,
	H, C, O (UV)
	CH_3CN, HCN, H_2O (RADIO)
	CO^+, CH^+, CO_2^+, N_2^+, OH^+, Ca^+, H_2O^+
	REFLECTED SUNLIGHT
	THERMAL EMISSION (INFRARED), SILICATE FEATURES (INFRARED)-
PLASMA TAIL (TYPE I):	CO^+, CH^+, CO_2^+, N_2^+, OH^+; H_2O^+
DUST TAIL (TYPE II):	REFLECTED SUNLIGHT
	THERMAL EMISSION (INFRARED), SILICATE FEATURES (INFRARED)

The size of the coma of course depends firstly on the distance from the sun and secondly on the particular emission used. In the optical region, the (0—0) rotation-vibration band of CN in the blue ($\sim$ 4000 Å) is the strongest feature. It is also normally the first to appear (around $\sim$ 3 a.u.) and often defines the greatest extension of the coma.

INTERACTION WITH THE SOLAR WIND :

The most spectacular feature of a comet is its plasma tail (type I), which when fully developed (for a bright comet) may extend to 20-30 million km from the head. Normally the tail begins to develop when $r \leqslant 1.5$ a.u., although cases are known where it appeared much earlier. The strongest emission is from CO^+. These tails point almost radially away from the sun except for the slight dynamic aberration caused by the transverse motion of the comet. The plasma tail also shows considerable structure, e.g., rays, knots, helical features, sheets etc, which indicate the presence of magnetic fields. Velocities and acceleration of the cloud like condensations (knots) have been measured. Velocities range from 10-300 km sec^{-1} while accelerations range from 100-1000 cm sec^{-2}. The accelerations, which in units of solar gravity at the point, assume values typically around 100, cannot be explained in terms of radiation pressure, which is due to resonant scattering of solar radiation on various lines. In fact, the radiation force is typically less than 1/10 of the gravitational force. So one has to look for another mechanism (Wurm 1973). It is clear that the solar wind, with its frozen-in magnetic field, must play a dominant role in sweeping the ionized components of the coma into the tail and also in shaping and maintaining the tail as it streams away in the anti-solar direction. There is sufficient momentum in the solar wind and adequate coupling between it and the cometary ionosphere via the embedded magnetic field to be ultimately responsible for the acceleration observed in the tail. What is less clear is the manner in which the interplanetary magnetic field is mixed with the coma plasma in such a way as to produce the observed structure in the tail.

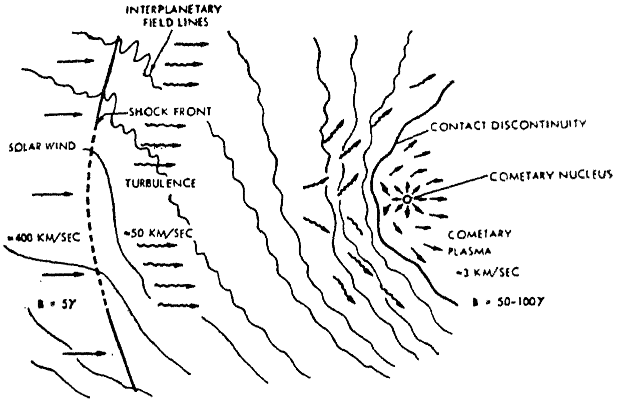

Fig. 2 : Solar wind-comet interaction (schematic)

The solar-wind-comet interaction is shown schematically in Figure 2. The interplanetary magnetic field, convected by the solar wind, cannot diffuse through the cometary ionosphere in a time comparable with the time it takes to flow past. Consequently, it piles up against the cometary ionosphere being separated from it by a contact discontinuity (magnetosheath). The contact surface would be typically around 10^4-10^5 km from the centre, while the enhanced magnetic field near the stagnation point would be around 50-100 γ. The solar wind being super magnetosonic and super-Alfvenic must prepare well upstream for the encounter with the ionized coma by decelerating via a collisionless (like the earth's bow shock) or via a transonic ion exchange sheet. While Biermann and his coworkers (1967) believe in a shock typically at 5×10^6 km upstream from the nucleus, Wallis (1971) has proposed a transonic process with no shock. The basis of the transonic process is that the incoming solar plasma loses momentum as it gradually picks up slow moving, heavy cometary ions (which are created by charge exchange) ahead of the contact surface. While it is difficult to choose between the models at this stage, it seems that at least the shock (if it exists) must be weakened by the charge exchange process. Wallis (1973) has subsequently shown in the case of comet Bennett and Tago-Sato-Kosaka that a weak shock does exist around 2-3×10^6 km from the centre ($r \approx 1$ a.u.). It has been pointed out that the contact surface may be liable to various (flute) instabilities because the magnetic field is curved in such a way, that it is likely to enter the coma plasma on contracting and that this may be the way in which the interplanetary field mixes with the plasma in the tail. However, this suggestion has not been supported by detailed analysis. Alternatively, it has recently been suggested that a comet, when sufficiently close to the sun, may be able to produce a significant magnetic field by the usual hydromagnetic conversion of kinetic energy to magnetic energy and sustain it for the period of coma activity ($\sim$3 months, Mendis and Alfven 1972). The general requirements for this process are a large enough volume and electrical conductivity and a degree of ordering of the turbulent velocity field such as would be provided by rotation of the nucleus which seem to exist in comets. The magnetic fields we derive this way could be 10-1000 γ, and such fields are indicated if one identifies the thickness of a typical tail helical feature with the gyroradius of a CO^+ ion.

THE STRUCTURE AND COMPOSITION OF THE NUCLEUS :

The least understood component with regard to its nature is the nucleus. Never seen with the naked eye, with large telescopes it has an almost star-like appearance at the centre of the coma. In some comets, the nucleus cannot be observed, whereas in others, multiple nuclei are observed. Even when no nucleus is observed, one cannot reach an unambigious conclusion about its existence or non-existence. The fractional contribution of the nucleus to the integrated brightness of the coma is typically less than 1 per cent. So only large telescopes with large magnification succeed in separating the starlike nucleus from the coma. From the lack of resolution, coupled with the resolution of the instrument, upper limits to its size may be obtained. Typically r is $\leqslant 100$ km. Coupling brightness with some assumption of the albedo puts r in the range of 0.1-10 km. If the assumption is made that the 'nucleus' represents a single monolith havng meteoritic bulk densities, the mass range is 10^{16}-10^{23} g (it could presumably be smaller). Lack of observed gravitational perturbations also point to masses of this order.

As regards the nature of the nucleus, the generally accepted model is some variant of Whipple's (1953) icy conglomorate model, which asserts that the nucleus consists of a matrix of frozen ices and meteoric dust. This physical model has been successful in explaining qualitatively a variety of phenomena such as (1) nongravitational effects (which are rocket effects on the nucleus due to outflowing gases), (2) sudden break-ups and flares , (3) spiral shaped jets (which presumably originate from a rotating nucleus), and (4) the general features of the expanding coma.

However, in order to interpret the activity of the coma quantitatively, one needs to know the chemical composition of the nucleus. The chemical instability of the radicals observed in the coma suggests that these could not be stored in the nucleus for a sufficiently long time and are likely to be the photodissociation products of more stable parent molecules (like H_2O, NH_3, CH_4, CO_2) and also perhaps the more exotic molecules seen in interstellar regions. Although the idea of parent molecules was due to Wurm (1943) over thirty years ago, they were first observed only a few months ago in comet Kohoutek. It has been shown by Delsemme and a number of his coworkers (1970, 1971), both experimentally and on thermodynamic grounds, that the stable states of these parent molecules are as clathrates (also called gas hydrates), if water is the abundant species in the nucleus. Clathrate hydrates are formed as a peculiar lattice of H_2O ice containing cavities where many types of guest molecules may be encaged by van der Waals forces. Since the potential wells in which these are held are very deep, they can be released only by the destruction of the 'host' H_2O lattice, and consequently their vaporization is also controlled by the latent heat of vaporization of H_2O. This beautifully explains the almost simultaneous appearance of all the major cometary emissions around 3 a.u., although the volatilities of their assumed parent molecules differ by over ten orders of magnitude.

THE RECENT ULTRAVIOLET OBSERVATIONS :

When the ultraviolet observation of Ly-α (H) halos around comets Tago-Sato-Kosaka and Bennett were first reported, there were a number of attempts to explain them.

One of the earliest involved charge exchange excitation of solar wind protons with cometary gases (Tolk et al 1970), the idea here being that the neutral hydrogen so produced will find themselves in excited states, and would cascade dowr to the ground state, emitting Ly-α photons in the process. This treatment however fails to take into account the existence of Venus-type magnetosheath around the cometary head which separates the solar wind plasma from the cometary ions and whose existence is also indicated by the flow of tail ions, which seem to originate from a restricted region around the head. Consequently, charge exchange can take place only in an outer shell surrounding the cometary nucleus (where the density of cometary gases is already very low), and the Ly-α emission in such a case would give a projected structure in the sky similar to a planetary nebula showing a strong depletion towards the centre, whereas observation indicated that the emission was strongest towards the centre. Consequently, a different model was developed by us (Mendis et al 1972) where the source of Ly-α is neutral cometary H produced by the photodissociation of H_2O (as well as the resulting OH) flowing out of a central nucleus. The model was later extended to include a distributed source provided by the icy grains stripped off from the nucleus by the outflowing gases (Ip and Mendis 1972). All the processes taken into account are indicated in Table 2 and the velocity and density profiles of this hydrodynamic mode (the distributed source case) are shown in Figure 3. The observed high velocities of the neutral hydrogen as well as the brightness profile in Ly-α is explained quite well by this model. Figure 4 shows the computation for comet Bennett at $r=0.8$ a.u. Excellent agreement is obtained when T is taken equal to 1000°K.

Table 2

Collision frequencies, production rates and loss coefficients. R measures the heliocentric distance of the comet in AU. τ_1, τ_2 and τ_3 are optical depths appropriate to photodissociation of H_2O, photodissociation of OH and photoionization of H and O. X, X_1, and X_2 represent any one of the heavy molecules H_2O, OH and O. $\beta_2(H)$ and $\beta_2(O)$ are only considered in $r > 10^4$ km

Collision frequencies s^{-1} for H and X (representing H_2O, OH or O)

$\nu(H, X) = 6.3 \times 10^{-16}(2.1 \times 10^8 T(H) + [u(H) - u(X)]^2)^{1/2} \cdot n(X)$

$\nu(X, H) = 3.5 \times 10^{-17}(2.1 \times 10^8 T(H) + [u(H) - u(X)]^2)^{1/2} \cdot n(H)$

$\nu(X_1, X_2) = 3.3 \times 10^{-16}(2.4 \times 10^7 T(X_1) + [u(X_1) - u(X_2)]^2)^{1/2} \cdot n(X_2)$

Production rates ($cm^{-3}\,s^{-1}$) Loss coefficients (s^{-1})	Process
$\beta(H_2O) = 1.6 \times 10^{-5} R^{-2} e^{-\tau_1}$	$H_2O + h\nu \rightarrow H + OH$
$q(OH) = 1.6 \times 10^{-5} R^{-2} e^{-\tau_1} n(H_2O)$	$H_2O + h\nu \rightarrow H + OH$
$\beta(OH) = 1.4 \times 10^{-6} R^{-2} e^{-\tau_2}$	$OH + h\nu \rightarrow O + H$
$q(O) = 1.4 \times 10^{-6} R^{-2} e^{-\tau_2} n(OH)$	$OH + h\nu \rightarrow O + H$
$\beta_1(O) = 5.0 \times 10^{-7} R^{-2} e^{-\tau_3}$	$O + h\nu \rightarrow O^+ + e$
$\beta_2(O) = 4.2 \times 10^{-7} R^{-2}$	$O + H^+_{sw} \rightarrow O^+ + H_{sw}$
$q_1(H) = 1.6 \times 10^{-5} R^{-2} e^{-\tau_2} n(H_2O)$	$H_2O + h\nu \rightarrow H + OH$
$q_2(H) = 1.4 \times 10^{-6} R^{-2} e^{-\tau_2} n(OH)$	$OH + h\nu \rightarrow H + O$
$\beta_1(H) = 2.0 \times 10^{-7} R^{-2} e^{-\tau_3}$	$H + h\nu \rightarrow H^+ + e$
$\beta_2(H) = 4.0 \times 10^{-7} R^{-2}$	$H + H^+_{sw} \rightarrow H^+ + H_{sw}$

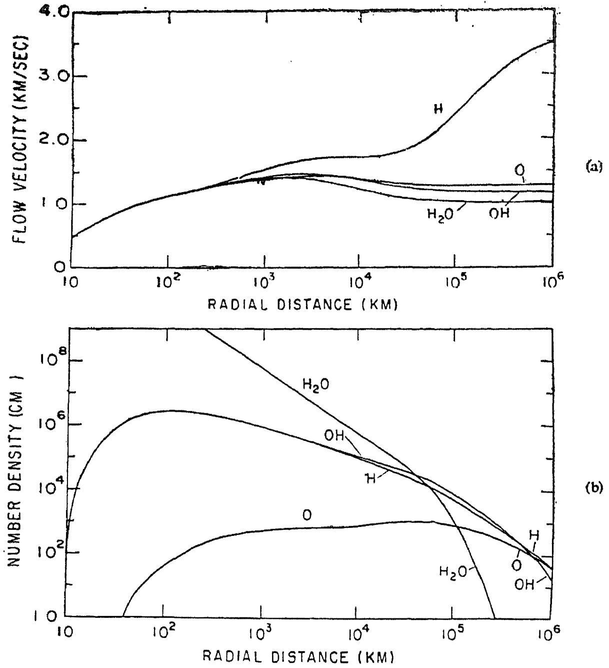

Fig. 3 : Velocity and density profiles in the hydrodynami model (distributed source case)

The observations of OH in the near violet (3040Å) in these two comets (which also seem to suggest that it is the dominant radical, ~ 85 per cent of all observed radicals barring H) together with the fact that OH and H abundances seem to correlate to within a factor of 2, is further evidence in support of the H_2O hypothesis.

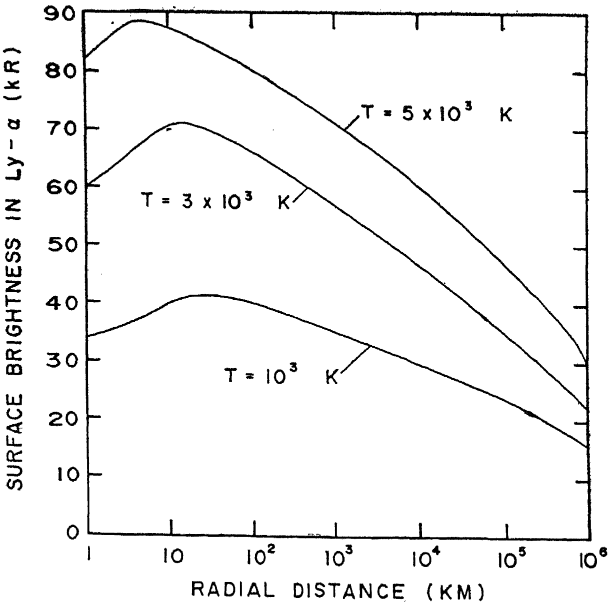

Fig. 4 : Brightness profile in Ly-α for comet Bennett

THE CASE OF COMET KOHOUTEK :

While the behaviour of most comets may be explained by such a model where the volatile component is dominated by H_2O ice, the behaviour of comet Kohoutek poses a dfficulty. It appears that Kohoutek had a dust halo ($R \approx 10^4$ km) even when $r=5$ a.u. This can happen only if the amount of the more volatile species (CH_4, CO_2 etc. are representative) constitute more than 15 per cent of the molecules. The amount over and above 15 per cent cannot be trapped in the clathrate and so must be frozen out. As the comet approaches the sun, these would gradually diffuse out, enriching a surface mantle. A sudden increase in the vapour pressure around 5 a.u. would produce an explosive situation, where the expanding gases would strip the upper mantle, causing a halo of dust around the comet. If the dust is sufficiently finely divided, the increase in effective surface area could be two orders of magnitude larger than the nuclear cross-section (Mendis and Ip 1974). This could qualitatively explain the original over estimate of the dimensions of the comet, which led to the subsequent disappointment as the less volatile clathrate was exposed when the comet got closer to the sun. Indeed, Kohoutek is not the only comet to behave this way. About 10 per cent of all comets approaching the sun within $r=5$ a.u. seem to flare in this fashion, and the sporadic outbursts of comet Schwassman-Wachmann which moves in a nearly circular orbit at $r \approx 5.5$ a.u. may be explained in terms of pockets of highly volatile material contained within the clathrate lattice, being exposed to solar radiation from time to time as the overlying material evaporates.

Any attempt such as this, to explain difference in cometary behaviour in terms of compositional differences runs into the difficulty of having to explain why such compositional differences exist. It should however be noted that only very small differences in cometary composition (≈ 1 per cent) are required to explain dramatically different behaviour. While such small differences may even be attributed to statistical fluctuation, it may also be the difference between a genuinely new comet and one which has been close to the sun before.

References :

Biermann, L. 1951, *Z. Ap.*, **29**, 274.

Biermann, L., Brosowski, B. and Schmidt, H. V. 1967, *Solar Physics*, **1**, 254.

Delsemme, A. H. and Wenger, A. 1970, *Planet Sp. Sci.*, **18**, 709.

Delsemme, A. H. and Miller, D. C. 1971, *Planet, Sp. Sci.*, **19**, 1229.

Herzberg, G. and Lew, H. 1974, *I. A. U. Circular* No. 2618.

Huebner, W., Synder, L. E. and Buhl, D. 1974, *Private Communication.*

(*Continued to page 75*)