THE NEUTRAL COMA OF COMETS: A REVIEW

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I. INTRODUCTION

Most records of the first half billion years of the solar system have been wiped out from the planets and from their satellites by their evolution and their morphological differentiation. However, two sources of information seem still to be available on this early period: some meteorites give us clues on the non-volatile fraction that condensed from the primeval nebula, whereas the clues on a more volatile fraction, possibly condensed at a colder temperature, may come from the comets.

In order to study the chemical nature of this more volatile fraction, the best approach would probably be to send a space probe to a comet; waiting for this time to come, the study of the neutral coma probably is the next best approach. The study of the ion tail and of the nature of its source in the vicinity of the nucleus proposes another fascinating challenge but there, the number of unknown parameters is larger, because the ions' behavior depends also on electric and magnetic phenomena.

However, even the study of the neutral coma is not as simple as it looks, because most of the molecular processes are not yet quantitatively understood. The spectroscopy of the coma tells the story of that single step leading to the emission of light, usually a resonance-fluorescence, in a chain of several unobserved processes that we must reconstruct without enough clues.

II. PROCESSES WITHIN THE COMETARY COMA

The first step in this chain of processes is the vaporization of the nucleus, visualized as an icy conglomerate (Whipple 1950). The production rate of gas and dust is set by the vaporization rate of the nucleus

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(Delsemme and Miller 1971a). The brightness law of the comet versus its heliocentric distance may be used as a crude indicator of the variation of the production rate of gas and dust; in particular, the heliocentric distance at which the coma appears, gives clues on the volatility of the snows and therefore, on their chemical nature; (Delsemme and Swings 1952); the production rates of the major constituents (like H and OH) confirm the existence of a vaporization equilibrium (Delsemme 1973a, Keller and Lillie 1975) and set the size of the nucleus as well as its albedo; (Delsemme and Rud 1973).

As the dust is dragged away by the vaporizing snows, the hydrodynamics of the gas drag provides a confirmation of the production rate of gas (Finson and Probstein 1968). Volatile grains like hail grains or snowflakes are also probably dragged away by the vaporizing gases (Delsemme and Wenger 1970, Delsemme and Miller 1970, 1971a and b).

The gas production rates are such that molecular collisions take place only in a small region surrounding the nucleus, of the order of 10^3 to 10^4 km at 1 A.U. (Delsemme 1966). The existence of this region has been confirmed by the pressure-induced changes in the fluorescence equilibrium of CN (Malaise 1970). Outside of this nuclear region, the gases are steadily lost in space by a collisionless effusion in vacuum, and each individual molecule interacts only with the flux of solar photons and of the solar wind, which is going to dissociate or ionize them, depending on their individual cross-sections.

The dissociations take place for wavelengths that are shorter than a threshold set by the binding energy of the bond to be broken: most of them are in the ultraviolet. In the same way, most of the ionization energies correspond to the extreme ultraviolet. The ultraviolet end of the solar spectrum is now rather well known; it is rather constant in the range where there is much energy available (from 4000Å to 1400Å). At lower wavelengths,

the variability of Lyman α and of the other emission lines introduces some uncertainty.

With due consideration to these variations, the solar flux can be used to predict the lifetimes of the possible parent molecules against photo-dissociation and photo-ionization. However, none of these parent molecules were known until recently; only their dissociation or ionization products. (As discussed in detail later on, the situation has suddenly changed with the discovery of H_2O, HCN and CH_3CN in comets Kohoutek and Bradfield). But the early comparison of the predicted and observed lifetimes (Potter and Del Duca 1964) had not brought about any positive identification. As a matter of fact, the "observed" lifetimes never are really observed; they are deduced by dividing the observed scale length by the assumed mean velocity of the molecules; this velocity is probably known by and large within a factor of two.

However, the fact that identifications remain difficult in most cases suggests that we have neglected a possible source of dissociation. The primary agent that we have neglected so far is the solar wind; but dissociations by charge-exchange collisions with protons or electrons leading finally to neutral molecules, are less likely than straightforward ionizations, although some are possible through a chain of several steps. Many of them are poorly known, but some have been studied (Cherednichenko 1965). The probably existence of a shock wave in the flow of the solar wind, ahead of the comet (Alfvén 1957, Biermann et al. 1967), changes the energy of those protons and electrons that are going to reach the vicinity of the nucleus, and may therefore affect their charge-exchange process with the parent molecules. These phenomena are less quantitively understood than the flux of solar photons because they are more complex. Explaining quantitatively the production rates of the ions observed in the tail meets the same difficulty for the same reasons.

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Whatever the dissociation or ionization mechanism, when a radical has been produced that can be excited by the solar light, we observe its bands in emission in the cometary spectra. We usually can explain their intensities by a fluorescence mechanism, by taking into account the accurate flux of photons available in the solar spectrum at all those wavelengths that are needed for the excitation, properly corrected for the radial velocity of the comet. We have even enough high-dispersion spectra to try to explain minute differences in terms of collisional effects in the vicinity of the nucleus (Malaise 1970) or radial velocity differences from different parts of the coma (Greenstein 1958).

The only known exception is the 6300Å red line of forbidden oxygen, that had to be explained by another mechanism, (Biermann and Trefftz 1964) its excitation stemming from the dissociation of its parent molecules, and not directly from the solar light.

The decays of the observed radicals can be assessed from their photometric profiles. We have not yet succeeded in explaining all of them quantitatively, but at least we believe that we understand them qualitatively, as being further dissociated or ionized by the solar light and/or by the solar wind.

The major problem that we were facing, before Comet Kohoutek, was therefore the identification of the parent molecules, in order to bridge the gap between the vaporization of the nucleus and the presence of neutral and ionized radicals in the coma and in the tail.

III. THE IDENTIFICATION OF THE MAJOR CONSTITUENTS

Circumstantial evidence suggested that water was controlling the vaporizations (Delsemme 1973b) but no neutral parent molecule had ever been

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positively identified. After comets Kohoutek and Bradfield, three of them have been found, namely H_2O (Jackson, Clark and Donn 1974, in Bradfield), HCN and CH_3CN (Ulich and Conklin (1973), Snyder, Buhl and Huebner (1974) in Kohoutek), without mentioning the spectacular identification of the H_2O^+ ion in comet Kohoutek (Herzberg and Lew 1974).

The list of the atoms or molecules that have now been observed in comets is given in Table I. There is not much doubt left that H_2O is the parent molecule which explains the bulk of H and OH, (although minor contributions to H and OH are still possible from the photodissociation of minor constituents); whereas the molecular bands of H_2O^+ do not show the bulk of water. From the photo-ionization and photo-ionization thresholds of water, which are 12.62 and 5.114 eV respectively (Herzberg 1966) some 99.9% of H_2O should photodissociate whereas some 0.1% should photo-ionize into H_2O^+, although ionization by the solar wind could multiply the share of H_2O^+ by more than one order of magnitude (Cherednichenko 1965).

However, the most significant discovery, whose importance has not yet been properly assessed, is probably the identification of the resonance lines of carbon and oxygen, in the far ultraviolet spectrum by two Aerobee rockets (Feldman et al., 1974; Opal et al., 1974). The C line at 1657Å is approximately four times stronger than the O line at 1304Å. The number of solar photons available is approximately 10 times as large at 1657Å as at 1304Å. Taking transition probabilities and lifetimes into account, Feldman et al. think that the production rate of carbon could be of the order of 0.24 that of oxygen. Assuming that all molecules containing carbon and oxygen are finally dissociated into their elements, we probably detect the total ratio of C/O of the volatile fraction lost by vaporization.

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Table 1

atoms	radicals	stable molecules	
		neutral	ionized
H, O	OH, OH^+	H_2O	H_2O^+
C	C_2, C_3, CH, CH^+		CO^+ CO_2^+
	CN, NH, NH_2	HCN, CH_3CN	N_2^+
metals			

The first results coupled with the production of hydrogen seem to suggest a H/O ratio between 2 and 3,and leave little leeway outside a production rate of CO or CO_2, possibly of the same order of magnitude as, although probably somewhat smaller than that of water. As comet Kohoutek's orbital data suggest that it is likely to be a "new" comet in Oort's sense, these results should certainly not be extrapolated to older comets, that might have lost most of their CO or CO_2 excess during earlier passages through the solar system. Another factor casts some doubt on these preliminary results: in order to deduce how many fluorescence cycles take place during the lifetime of the atoms against ionization, that is, the number of photons emitted per atom produced, the lifetimes of the C and O atoms in the solar field were needed. No actual measurements were available and therefore, the lifetimes used are theoretical assessments. The present writer submits that one of the most important measurements to be done on future comets is the establishment of the brightness profile of the resonance lines of C and O (and possibly N which has not yet been observed), in order to check the actual lifetimes of these atoms, against all actual sources of ionization in the solar field. Waiting for new bright comets to be observed from space, a reassessment of the ionization lifetimes of C, N and O, using the most recent solar data being obtained by the Naval Research Laboratory, seems to be in order in the near future.

IV. THE BRIGHTNESS PROFILES OF THE NEUTRAL COMA

The brightness profiles of the neutral coma, observed in the monochromatic light of the different radicals or atoms, also remain one of the principal clues for the understanding of the nuclear region. The importance of the brightness profiles stems from the fact that in a first approximation, isophotes

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of neutral radicals are always circular. Barring rare cataclysmic events, as mentioned by F. Miller (1957), the observed departures from circularity seem to be second-order phenomena that are rather well understood. In particular, a slight distortion coming from the light pressure of the sun is easy to discount. The single feature then to be explained is the average brightness profile itself, that is, the law of variation of the monochromatic brightness with radial distance from the nucleus.

The actual profiles observed, sometimes show humps or distortions that probably come from violent variations in the instantaneous production rate of gas in the nucleus. These variations probably come from corresponding fluctuations in the solar wind or in the ultraviolet flux emitted by the sun (flares), but they have never been explained quantitatively. The light curve in global light also reflects this type of variations, usually referred to as the "activity" of the comet, (whatever that means). However, there often are long periods where the activity of the comet is at a minimum, and where the brightness profiles show a smooth and regular curve (as in figure 1). There is little doubt that the outside drop of the curve, for values exceeding 10^5 km, can be interpreted in terms of the exponential decay of the light emitters into unobservable species (Delsemme and Moreau 1973). However, the production of the light emitters from unobserved species takes place in a range of the order of 10^4 km, and the length of the profile in this region is not large enough to provide a criterion in order to distinguish between different models. For instance, based on Wurm's (1943) ideas, Haser's (1957) model uses an exponential decay for the parent molecules. Malaise (1966) introduces two decays to take into account the possibility of a chain of two processes: unobservable grandparent molecules decaying into unobservable parent molecules. Based on Delsemme's (1968) ideas about a halo

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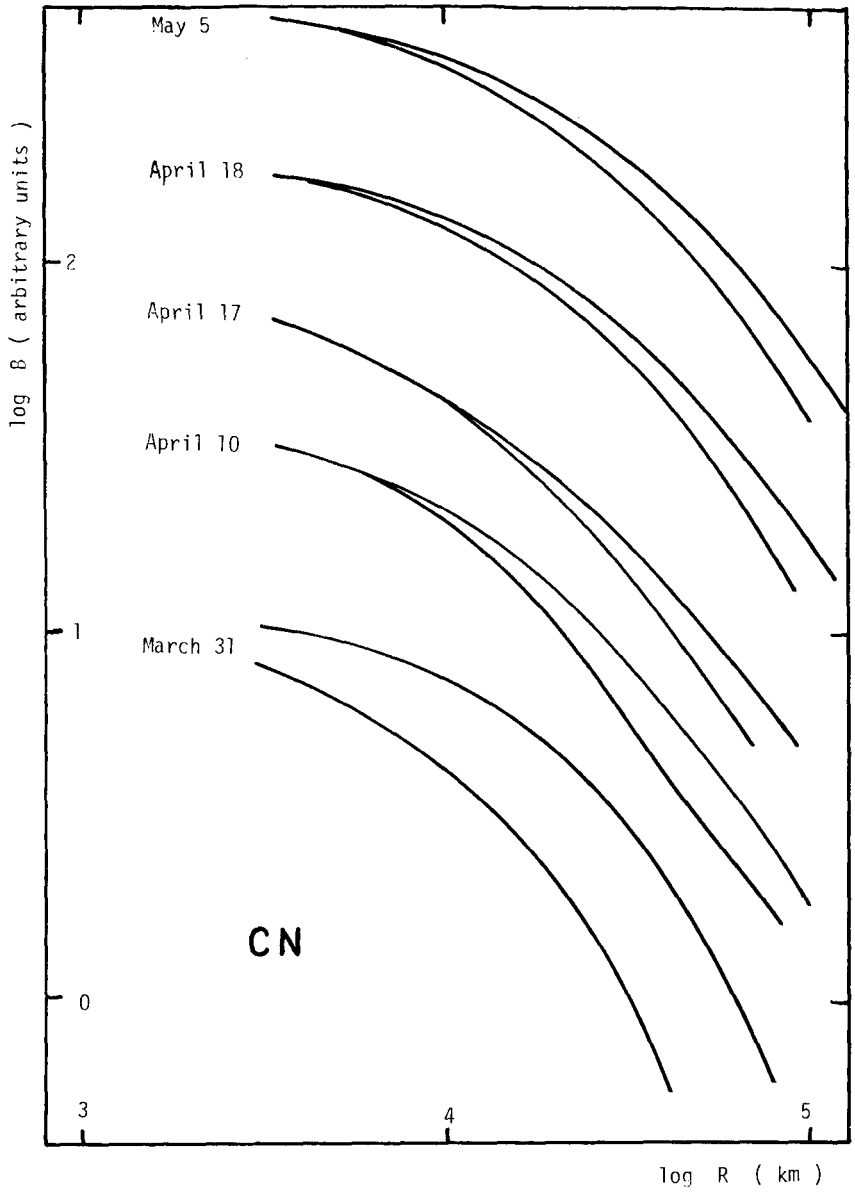

Figure 1. Example of Brightness Profiles in the monochromatic light of CN(0-0) observed in the coma of Comet Bennett (1970 II). B is the brightness in arbitrary units, R is the distance from the nucleus in kilometers; s and a label the sunward and anti-sunward profiles, respectively. The profiles have been shifted vertically from date to date, in order to avoid their superposition, (from Delsemme and Moreau, 1973).

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of ice grains surrounding the nucleus, Delsemme and Miller (1971) develop a model based on the linear decay of the ice grains by vaporization. None of these models changes the theoretical profiles of the production zone, enough to allow a direct observational test. Similarly, a model assuming random velocity vectors for the radicals, instead of the oversimplified assumption of a radial velocity vector, in Haser's model, does not change appreciably the profile of the production zone (Delsemme and Miller 1971b).

Of course, the probable existence of a halo of ice grains, acting as an extended source, is based on another evidence (Delsemme and Miller 1971b). Indeed it links the photometric profiles of C_2 and of the continuum in Comet Burnham (1960 II). This halo seems to have also been observed by its emission at 3.71 cm wavelength, in Comet Kohoutek (Hobbs, et al. 1975).

However, in doubt on the best theoretical profile to be used in order to fit the observations, it is clear that it does not make any harm to use Haser's model for obtaining two parameters: an exponential scale length (near 10^5 km) describing the simple decay of the observed radicals, and another exponential scale length (near 10^4 km) describing by one single parameter the extension of the probably more complex source function of the same radicals; this simple parameter sets the size of the zone produced by the possible existence of the parents, grandparents, halo of ice grains, and all unknown phenomena of the nuclear region.

V. VARIATION OF THE SCALE LENGTHS WITH HELIOCENTRIC DISTANCE

The previous discussion justifies the systematic use of Haser's model in order to describe the brightness profiles in terms of two parameters only: the exponential scale length of the light emitter (against decay) and an exponential scale length giving the scale of the source of these light

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emitters (possibly from an unobservable parent molecule, but also possibly scaling the largest of the other phenomena that may influence the size of the source, like the existence of a halo of ice grains).

However, different observers have either published photometric data without interpretation, or used different models to interpret their data. For this reason, the present writer has computed an homogeneous reduction of all the brightness profiles available in the literature, by systematically using Haser's model. The details of this reduction will be published elsewhere. It was based on 12 brightness profiles of CN from 7 different comets, and on 14 brightness profiles of C_2 from 8 different comets. The results (Delsemme 1975) are consistent with the following formula:

$$\log s\ (CN) = 5.17 \pm 0.04 + 2 \log r$$

$$\log s\ (C_2) = 4.82 \pm 0.06 + 2 \log r$$

$$\log s\ (\text{CN parent}) = 4.12 \pm 0.09 + \log r$$

$$\text{los s } (C_2 \text{ parent}) = 3.99 \pm 0.20 + \log r$$

where s is the scale length in kilometers and r the heliocentric distance in astronomical units.

These results deduced from all published data, confirm rather well the previous findings of Delsemme and Moreau (1973) on Comet Bennett. In particular, it is clear that the decay of CN as well as that of C_2 both depend on a square law of the distance to the sun, which is consistent with the usual assumption that the decay of CN and that of C_2 are both triggered by the solar flux.

Delsemme and Moreau had also found that the two scale lengths of the parents both vary less quickly than the square law, and were consistent with a proportional dependence on r. This law is inconsistent with a photodissociation of the parent into either CN or C_2, whereas the law is predicted

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by the theory of the halo of ice grains.

However, despite the fact that all data available in the literature rather confirm these findings, it is proper to be very cautious here, because half of the data are based on poor resolving powers.

If the seeing disk is large, it may simulate a spurious scale length; the seeing disk, projected to the comet's distance, would give a "scale length" in proportion to the geocentric distance Δ, which for faraway comets would not be statistically very different from the heliocentric distance r. A careful discussion rejecting all the poor resolving powers, and keeping the best space resolutions only, still definitely rejects a square law and suggests a dependence on distance which is no more than a proportional law, or possibly even less, for the size of the source of C_2 as well as of CN (Delsemme 1975).

In urgent need of an estimate for OH, the present writer has recently used (Delsemme 1973c) an unpublished brightness profile established by Malaise from a spectrum of Comet Burnham (1960 II) published by Dossin et al. (1964). The range of the tracing was too short, therefore the inaccuracy was large. Fortunately, two better determinations of the scale length of OH have been obtained recently.

Here they are, reduced for 1 A.U. (the scale length s is in kilometers):

log s (OH) = 5.1 ± 0.2 (c. Kohoutek, Blamont & Festou 1974).

log s (OH) = 5.2 ± 0.2 (c. Bennett, Keller & Lillie 1974).

When this average value is used to interpret comet Burnham's profile, then the best fit is obtained with log s (OH parent) = 5.0 (reduced at 1 A.U.); this is consistent with the identification of the parent with water. This has also been verified for comets Bennett (Keller and Lillie, 1975) and Kohoutek (Blamont et al. 1975).

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A profile of the [OI] red line was measured by Moreau (1972) at the request of the present writer. No deviation of the inverse law of the distance was detected up to almost 10^5 km, where the red line intensity merged into that of the atmospheric night glow. This suggests a scale length larger than 10^5 km.

It is unfortunate that no good scale lengths have ever been published for the other radicals, although some indications on their order of magnitude for C_3 and CH can be deduced from Malaise's (1966) photometric profiles of comets Burnham and Ikeya.

VI. PRODUCTION LAWS AND BRIGHTNESS LAWS

The production law is the law of dependence on heliocentric distance, of the production rate of a given molecule.

The brightness law, in the monochromatic light of a given molecule, is the law of dependence on distance of the integrated light emitted by these molecules within the coma, during their lifetime, that is after their production and before their dissociation.

Levin (1943) pointed out that the two laws must be the same, because the solar flux (which excites the fluorescence of the molecules) varies with r^{-2}, whereas the lifetime of the molecules varies with r^2 (r heliocentric distance).

Of course the variation of the lifetime extends the coma for larger heliocentric distances and the previous statement is therefore true only if we integrate the total light of the coma from the nucleus to infinity. What does this mean in practice?

The writer (Delsemme 1973c) has shown that the two laws remain the same, only if we integrate the light to a distance of at least 7 to 8 times the largest of the two scale lengths of the brightness profile. If

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the integration is limited by a diaphragm smaller than this limit, if the production law is $P = P_0 r^{-n}$, then the brightness law is $B = B_0 r^{-n-\alpha}$, where α is the correction to add up to the exponent of the brightness law in order to obtain the true exponent n of the production law.

The correction α is given by Delsemme (1973c) as a function of the diaphragm radius, expressed in scale length units, with the ratio of the two scale lengths as a second parameter. This correction α varies from zero (for very large diaphragms) to an upper limit of +3.6 for diaphragms much smaller than the two scale lengths.

A consequence explaining the poor significance of the cometary light curves in global light must be mentioned first. As the reflection of the solar light by the dust makes all things even more complex, we will have to consider only the case of the non-dusty comets in order to make our point. In this case, CN + C_2 usually prevails in visible light. However, it can be seen that the light curve expressed in magnitudes as a function of the logarithm of the heliocentric distance, usually has a slope larger than the average production law of CN + C_2, for the following reason: only the center of the coma can be distinguished from the sky, therefore the sky brightness plays the role of an effective diaphragm. The fainter the comet, the smaller this effective diaphragm, and the larger the correction α to the slope of the light curve in order to establish the production law. The average production law of CN + C_2 cannot therefore be accurately deduced from the light curve. However, as $0 \leq \alpha \leq 3.6$, upper and lower limits of the exponent of the instantaneous production law can be deduced. In particular, it can be established that for large heliocentric distances, the exponent of the production law is often much larger than 2, because α cannot grow larger than 3.6, whereas $n + \alpha$ often is $>> 6$.

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Standing in contrast, observations of the monochromatic brightness law, in the light of a given radical, can now be used to establish its production law, when the diaphgram used for the observations is known.

For instance, Mayer and O'Dell's (1968) observations of Comet Rudnicki can now be used for this purpose. As they were obtained with a rectangular slot of 509" x 203", the α for circular diaphragms cannot be used readily, but the present writer (Delsemme 1975) has established that, although the apparent brightness laws of CN, C_2 and C_3 are very different, their exponents are brought in the same general range, when the three corrections α are taken into account. This suggests a single production law for the three molecules, its exponent being $n = 3.6 \pm 0.2$. (The value of this exponent could be lowered somewhat if the contribution of the continuum has not been properly taken into account).

A more recent example is given by the monochromatic brightness laws observed by Code (1970) with the OAO for the hydroxyl and the hydrogen comas. Here, as $(n + \alpha) = 5.9$ for both OH and H, Delsemme (1973c) deduced $n(OH) = 2.9 \pm 0.2$ and $n(H) \geq 2.8 \pm 0.2$. Here the sign $\geq$ suggests that the neglected, but growing optical depth in Lyman α, when the comet approaches the sun, may hide a larger and larger fraction of the production rate.

Using the more recent value of the scale length of OH quoted in the previous section, a revised value $n(OH) = 2.0 \pm 0.2$ is obtained. This new value removes the apparent excellent agreement of the two production laws previously given for H and OH, although the accuracy of the results is unlikely to be good enough for the observations to become inconsistent with a single production law.

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Bertaux et al. (1973) report a production law of H for Comet Bennett which is consistent with $n = 2.5 \pm 0.5$; whereas Keller (1973) finds $1.0 \leq n \leq 2.2$ from the same OGO-5 data. From the OAO-2 observations of the same comet, Keller and Lillie (1975) find $n = 2.3$ for the two production laws of H and OH. This recent determination seems to merit a much larger weight than that from the OGO-5 data.

Now, Delsemme (1973c) has stressed that if n is definitely larger than 2, then the vaporization temperature of the snows cannot be much lower than 200°K. The reason is that at steady state, the radiative term of the energy balance equation is not negligible, compared with the vaporization term, otherwise the vaporization would follow a strict inverse-square law of the heliocentric distance.

Such a high temperature of vaporization rules out all snows of gases more volatile than water, and in particular CO_2, CO, CH_4, NH_3, etc. Of course this does not rule out the solid hydrates of gases whose vaporization temperature is practically that of water. It does not rule out either other materials less volatile than water, but the production rates of OH and H seem to confirm that water is indeed the major constituent that controlled the vaporization, at least in comets Tago-Sato-Kosaka and Bennett.

The accurate value of n can be predicted by the theory, but it still depends on the ratio of the visible albedo of the nucleus to the infrared albedo near 15 microns; and it is also a function of the heliocentric distance. There is however little doubt now that water controls the vaporization. In particular, Delsemme and Rud (1973) have listed eight different arguments in support of this fact. More recently the discovery of H_2O in comet Bradfield and the identification of H_2O^+ in comet Kohoutek, both already mentioned in section III, have much strengthened their argumentation.

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If the gas released by the nucleus is indeed a vaporization phenomenon, then the kinetic theory of gases gives the production rate per unit area per second, and if the size of the nucleus were known, we could predict quantitatively the observed production rates (Delsemme and Miller 1971a).

The production rates of different radicals have also been reported in the past, but most of them are obviously minor constituents, when compared with H and OH, therefore they can be neglected in the assessment of total production rates. Production rates have been reported for H or OH for comets Tago-Sato-Kosaka, Bennett and Encke. Preliminary values are known for Kohoutek. A list of the early assessments can be found in Delsemme and Rud (1973). A more recent result is found in Keller and Lillie (1975). These authors obtain for comet Bennett, reduced at 1 A.U.: 3.0×10^{29} molecules OH per sec, and 5.4×10^{29} atoms H per sec. In order to check numerically the theory of vaporization, the albedos of the nuclear snows are needed.

Delsemme and Rud (1973) have tried to disentangle the albedo A and the cross sectional area S of the nucleus, by using two determinations of AS and (1-A)S for three different comets. AS is given by the reflected light, from Roemer's assessments of the magnitude of the nucleus at large heliocentric distances; (1-A) is given by the energy absorbed in order to vaporize the observed rates of H and OH, assuming they come from water. The albedos deduced for comets Bennett and Tago-Sato-Kosaka are both very near 0.6 which is a rather high value, although consistent with a moderately dirty snow. The use of Roemer's magnitudes depends on whether they really are nuclear magnitudes, as correctly criticized by Sekanina. If a fraction of the light still coming from the coma has been included into the magnitudes used, the albedos could be diminished to 0.5 easily, but to 0.4 with great difficulty.

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It appears therefore that the vaporization theory is consistent with the numerical values obtained for the production rates of H and OH, the albedos and the cross sectional area of the nucleus, for comets Bennett and Tago-Sato-Kosaka. Standing in contrast, the numerical values obtained for the production rate of H in comet Encke is not consistent with a nucleus totally covered by water snow.

VII. CONCLUSION

A very significant progress in our understanding of the production of gases by the cometary nucleus, has been brought about by the observation of the recent bright comets (Tago-Sato-Kosaka, Bennett, Encke, Kohoutek and Bradfield); and in particular, by their observations from space and by radio telescopes.

The hypothesis that water snow controls the vaporization of the nucleus of the first two comets seems verified from the general order of magnitude of the size of their nucleus and of their nuclear albedo; the largest observed production rates are H and OH which both seem to originate from the photodissociation of H_2O, as also confirmed by the scale length of the invisible parent molecule producing OH. Some of the production laws are still inconclusive, but all seem to be consistent with water, whereas some of the results seem to be totally inconsistent with any of the more volatile gases. However Comet Encke is not uniformly covered by water snow, as it produces only one tenth of the expected vaporization. Early results on comet Kohoutek suggest that the conclusions could be slightly different for some of the "new" comets in Oort's sense. If the far ultraviolet observations confirm the early assessments of the production rates of C, O and H, from their far-ultraviolet resonance lines, then at least another major constituent

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competing with water has not yet been detected. Such a major constituent is suggested by the ratios C/O = 0.24 and H/O = 2.5; these ratios are probably known only within a factor of two. However, we have for the first time a suggestion of a possible redox ratio that prevailed in the cometary stuff when it was condensed from the primeval solar nebula.

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DISCUSSION

W. Jackson: I'd like to make a few comments about Professor Delsemme's talk.

The velocity of the daughter may be much greater than the velocity of the parent so that determination of the lifetime of parent from photometric profiles may be extremely difficult. For example the energy of the parent, if it is moving at 1 km/sec, is 0.1 eV and the daughter may carry away a much higher energy than this. The result is that the velocity vector of the daughter is much greater than the velocity vector of the parent and more isotropic. The net result is that the flow of the daughter is now determined by its recoil velocity.

A. H. Delsemme: It doesn't bring any difficulty in fitting the photometric profile because we don't find the life times. The photometric profile gives two scale lengths—but later on, when you want to deduce from these lengths the life-times, you may be in trouble. But this does not bring any difficulty in the fitting of the profiles in order to assess two scale lengths.

W. Jackson: But the point is to get the lifetime. You may run into a quite a bit of difficulty, and it's likely that in some cases there will be a large amount of translational energy.

The other thing that you mentioned—I do have the lifetime of HCN. The life-time of HCN determined by using Michael Berry's absorption coefficients and my solar fluxes, would be nine times 10^4 seconds—almost 10^5 seconds. The scale length for CN, which you gave, if I read your slide correctly, was the log of 4.1.

A. H. Delsemme: Your value is between the two values that I have in my slide, 4.1 for the CN parent and 5.2 for CN. But because of the symmetry of the expression one is not really sure which is which.

W. Jackson: Another lifetime that's much lower, if you need a lower parent—would be the lifetime for C_2N_2, which is 1.1 times 10^4 seconds, and that is very close to what you would like for the parent if the daughter is going to have the much longer lifetime.

The final thing is you put up acetylene as a possible source of C_2. Nobody has observed C_2 from acetylene, but supposing that you can get C_2 from the photo-dissociation of acetylene, the lifetime of acetylene at one A. U. is about 6 times 10^3 seconds, and that would be lower than any of the values that you have for beta.

A. H. Delsemme: I have not really proposed acetylene. I was listing the different possibilities as an example of our difficulties right now, and I was not, of course, using other considerations, as the spectroscopic evidence, for singlet or triplet states.

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B. Donn: One thing that probably needs to be kept in mind, is that all of this analysis assumes that single observed species comes from a single parent molecule. Now when you have an array of parent molecules in a comet it's very likely that C_2 can come from a number of different molecules, and that means, then, that this interpretation becomes much more involved, but that is a characteristic of most of our cosmic problems. We don't have the nice, neat, simple features we have in the laboratory where you can relate things one to one.

M. Shimizu: I hope to present two evidences to endorse the presence of CO in cometary nuclei from the finding of comet C atom emission in UV region.

1. Dr. Jackson pointed out a difficulty of large dissociation time of CO. This is certainly important. Please see the paper of Ogawa (J. Mol. Spectr. 45 (1974) 454) on high resolution spectra of CO. He found many diffuse bands in 980-1030 Å region whose rotational analysis was completely impossible. CO could be predissociated at these bands.

2. Another information comes from Venus. Mariner 10 recently observed strong C emission on Venus. Since the composition of Venus' atmosphere is almost 100% CO_2, C might come from the dissociation of CO_2. The estimated value on the basis of such expectation is, however, more than one order of magnitude smaller than the observed one. Mariner 10 observed a strong OI 1304A line and the CO 4th positive bands. Consequently C atom appears to be formed by the dissociation of CO. In this case, too, the situation may be similar to the comet.

L. Biermann: The extent of those regions in the coma in which collisions are important is sometimes underestimated. With the gas production rates known now, for a bright comet we have approximately $10^{24}/r^2$ molecules/cm^3. For a cross-section of 10^{-15} cm^2 collisions are therefore important out to $\gtrsim 10^4$ km; for ion-molecule reactions these cross-sections are still larger (cf. L. Biermann and G. Diercksin, Origins of Life, 1974) and in consequence so is the extent of the region over which such reactions and dissociative recombinations play an important role. This of course effects also the plasma-dynamical process in the same region (cf. L. Biermann, paper in Asilomar Conference on Solar Wind, 1974, and H. U. Schmidt, review paper given at this Colloquium).

P. D. Feldman: This question of CO, which Jackson brought up on Tuesday and which Shimizu just addressed, I looked up some calculations that were made on the disassociation of CO for the Martian atmosphere by McElroy and McConnell.

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They indicate that the branching ratio

$$\frac{CO + h\nu \rightarrow C + O}{CO + h\nu \rightarrow CO^{+} + e} \approx 1$$

Therefore one expects roughly equal production rates of C and CO^{+} from CO.

In other words, we expect to get a large number of CO^{+} ions, as well as a large amount of carbon, and when I get around to presenting the paper later this morning, I'll show you how this can be tied in with the amount of carbon that was observed.

D. J. Malaise: In 1965 I made a model in which molecules were expelled from a source region with finite dimension, and then you had a chain of dissociation of one parent to the other, and we suppose that this is an observable one. And then I computed a profile.

This was ejected with a Maxwellian velocity, not with two-velocity component. And then you show the general result, which is well-known, that you get a profile with a production zone, an expansion zone with a gradient close to 1, and then a destruction zone. And whatever mechanism you invoke to produce the molecule, you always get this picture.

But in this formula, for sure, it is not symmetrical, so I don't know how Haser could get a symmetrical formula and -- well, I'm quite sure it is false, because you can prove it qualitatively here. If you had a lifetime of the mother molecule, and the lifetime of the observed radical if you change these two τ's, it is not symmetrical because you have a very short lifetime for the observed radical. So that what you observe essentially is the curve of the mother molecule alone.

So you will get this shape with the destruction of the mother, and on top of this you will be a little lower because of the destruction of the molecule you observed and -- well, this operates all along the curve, but you never get the characteristic slope here in the center. It seems to me quite clear that this has to be dissymmetrical

A. H. Delsemme: Malaise claims that Haser's formula is not symmetrical in respect to the two scale lengths. I disagree. Intuition does not help here. Apart from a factor which depends on the ratio of the scale lengths, and which only shifts the whole profile vertically when scale lengths are inverted, Haser's formula is totally symmetrical in respect to the two scale lengths. Malaise's statement that it is false that Haser's formula is symmetrical, is nonsense. The integration and its symmetry has been repeatedly checked at different times

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and places by O'Dell, by Arpigny and by myself, and we all agree. The integration is trivial and Malaise can check for himself. But I know that at the first time I thought about it, I had the same reaction as you do. I thought it was impossible to explain it symmetrically. Now I am convinced that his integration is right.

(Discussion here about the term and interpretation of the expression for the profiles.)

A. H. Delsemme: Well, we disagree on this point, but it's a technical matter.

D. J. Malaise: I thought this could be settled.

A. H. Delsemme: I hope so.

(Laughter.)

B. Donn: There's a point that we're not going to be able to settle here, and it needs to be cleared up.

M. K. Wallis: You commented on Haser's model in saying that when you analyzed your profiles, they could be fitted fairly well - I think was your quote - fairly well to Haser's model.

Now, for the inner region there are various reasons we wouldn't be very confident on this exponential formula for the inner region. Professor Biermann has mentioned one, ion-molecular interactions and collisions are occurring. There may be others, like you, or Bill Jackson said, on the dissociation products of parent molecules having higher velocities, and so on.

So, one wouldn't expect Haser's model to be very good, anyway, in the inner region - inside 10^4 km. Can you not say - can we not say anything yet, or can we not provide another model - or find any important discrepancies - where it is clear that Haser's model is breaking down?

A. H. Delsemme: The fitting of theoretical curves and of the observational curves is not satisfactory anymore when we reach the region where the seeing is involved; the seeing disc, plus the convolution with the resolution of the photographic plate and the microphotometer entrance port, brings what I will call a confusion zone of the order of five arc seconds.

Within these five arc seconds the observational slope is flattened; therefore when the scale lengths are smaller than this confusion zone, not only we cannot

measure them, but we are not even sure of their existence. The scale lengths of the parent molecules may be changed or even totally hidden by the spurious scale length of the confusion zone. In my work with Moreau, we stop the fitting at this limit of 5 arc sec. We use the scale length of the parent molecule as a convenient parameter that usually improves very much the fitting of the curves, say from 5 to 20 arc sec.

H. U. Keller: I think the difficulty is not that we do get different profiles. The difficulty is just the principal interpretation of the inner part. Even if you have a very complicated process acting like a parent molecule, the profile won't be changed very much. The differences are very small, and I think they are too small to be detected by ground based observations even by accurate measurements. The discussion should be how so you reasonably explain the profiles in the inner part - what is the parent molecule or what are the processes possibly going on and how many parent molecules do we possibly have?

I think it is difficult to conclude in one way or the other on the parent molecules from those profiles which we have, whereas on the daughter molecules, it's much more certain, because the extension is larger.

In the case where the parent molecule definitely has a shorter lifetime than the daughter molecule, the total profile, itself, I am sure, won't be changed very much, even by a hydrodynamical model.

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