PART I
PHYSICAL NATURE OF COMETS

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THE PRISTINE NATURE OF COMETS

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Abundance considerations suggest that comets are likely to be the most pristine minor bodies in the solar system. In proportion to solar abundances, the present scanty data suggest that cometary oxygen is not depleted, whereas carbon is by a factor of 4 and hydrogen, by a factor of 2000. This implies that comets are less depleted in H, C, N, O than CI chondrites, namely 10:1 in hydrogen, 4:1 in carbon and 3:1 in oxygen. These results have been obtained by using dust-to-gas ratios in comets, to measure the relative abundance of silicon and metals to volatile material, and the spectra of atomic lines, mainly from the vacuum ultraviolet, to determine the H/O and C/O ratios of the mixture of volatile molecules.

The CI Carbonaceous chondrites are considered by many to be the least differentiated and most homogeneous meteorites (Mason 1971) and their analogy with comets is well known. Of all meteorites, the C I chondrites contain the largest proportion of volatile and Herbig (1961) has remarked that, if these volatiles were vaporized in the interplanetary space, they would decay by ionization or dissociation from the solar light or wind, into all fragments required to explain the neutral radicals and ions observed in cometary heads and tails. However, the rare C I chondrites known in our museums have a rather dense compaction, whereas comets yield fragile low-density meteors (McCrosky 1968) suggesting a spongy matrix containing larger amounts of volatile "ices" or "snows" of solidified gases. After all, comets may be of a more pristine nature than even the most primitive chondrites. In C I chondrites, hydrogen, carbon, nitrogen and oxygen are depleted by factors of 10^4, 20, 80 and 3 respectively relative to solar abundances (Mason 1971), whereas the enormous amounts of gas released by the cometary nucleus, when it is heated by solar radiation, imply that C, N and O are not much depleted in comets. Recent numerical data will be used here for the first time to transform this qualitative statement into a quantitative assessment.

THE DUST/GAS RATIO

The dust visible in cometary tails is dragged away from the nucleus by the sublimation of the volatile gases. From the cometary spectra (Table IIa) the gases are clearly H, C, N, O molecules and, from its infrared silicate signature (Ney 1974), the bulk of the dust must be silicates. We can arbitrarily define a *primitive* dust/gas ratio by assuming that: free hydrogen is missing along with helium and neon, but that all other abundances are solar. The oxygen fraction used to make silicates, and all metals, silicon and sulfur are then assumed to be imprisoned in the dust. Since the oxygen/silicon+metal

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(number) ratio goes from a low 4/3 for olivine to a high 9/5 for serpentine, the primitive mass-ratio may go from 0.54 to 0.66 if we use Cameron's 1973 abundance table, or from 0.61 to 0.76 if we use strictly solar data (Ross and Aller 1976). At any rate, the *primitive* ratio turns out to be in the general range of 0.65 ± 0.11, whereas the solar dust-to-gas mass ratio (including volatile H, He and Ne) nominally is 7.5 x 10^{-3}, that is about two orders of magnitude lower.

An observational value of the dust-to-gas ratio can now be deduced in comets from the momentum exchanged by the gas that drags the dust away (Finson and Probstein 1968a). It is given in Table I for two comets. Is it representa-

TABLE I

THE DUST-TO-GAS MASS RATIO

Solar abundances			0.0075				(1)
Primitive mixture			0.54 - 0.76				(2)
Comet Bennett 1970 II			0.5 (mean)				(3)
Comet Arend-Roland 1957 III			1.7 (mean)				(4)
Time variation in Comet Arend-Roland:							(5)
Days after perihelion:	-9	-6	-3	0	+3	+6	+9
Dust-to-gas ratio:	6.2	5.6	1.4	1.2	1.2	1.0	0.8

(1) Dust: silicates (with all metals) and sulfur; Gas: H, He, Ne, C, N, and about 2/3 O.

(2) *Primitive* mixture: starting from (1), uncombined H and all He and Ne have been removed from the gaseous phase.

(3) From Sekanina and Miller (1973). Ratio averaged over about 45 days.

(4) From Finson and Probstein (1968b). Ratio averaged over 20 days.

(5) Deduced from Finson and Probstein's data by the present author. Ratios averaged over 3 days. Day -6 coincides with violent outburst of no more than a day, with production rates of gas and dust multiplied by five at least. It is interesting that the ratio is not much influenced during the outburst, but diminishes drastically afterwards.

tive of the composition of the nucleus? The smoothness of the dust distribution in many dust tails is an indication that a steady state may prevail where the dust is dragged away in proportion to the sublimation of the nuclear gases. However, there are often outbursts that suggest inhomogeneities in the vaporization. In particular, it was the case for Comet Arend Roland: from Finson and Probstein's data, an outburst producing at least five times the previous rates of gas and dust happened six days before perihelion. I have deduced the time variation of the dust-to-gas ratio (for average values of the parameters), in Comet Arend Roland, from the wealth of data published by Finson and Probstein. It is interesting to note that, notwithstanding the outburst, the dust-to-gas ratio has steadily decreased throughout the whole episode, suggesting that, because of the steady increase in temperature before perihelion, a crust with more dust and less ice had first to be blown away (during the outburst) before vaporizing fresh inner layers of a more primitive nature. It is clear that we must not attach too accurate a meaning to these numerical results. In particular it is unclear whether the difference between (new) comet Arend-Roland and (young but not new) comet Bennett reaches any level of significance. Neverthe-

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less, it is now clear that the dust-to-gas ratio of the outer layers of a cometary nucleus must be close to the *primitive* ratio defined above, implying quasi-solar abundances for C, N, O in respect to silicon and metals, but the absence of the bulk of hydrogen.

THE PRODUCTION RATES OF THE MINOR CONSTITUENTS

Table IIa lists all the constituents observed so far in cometary heads and

TABLE IIa

OBSERVED CONSTITUENTS IN COMETARY HEADS AND TAILS

Organic:	C, C_2, C_3, CH, CN, CO, CS, HCN, CH_3CN;
Inorganic:	H, NH, NH_2; O, OH, H_2O;
Metals:	Na, Ca, Cr, Co, Mn, Fe, Ni, Cu, V, Si;
Ions:	CO^+, CO_2^+, CH^+, CN^+; N_2^+; OH^+, H_2O^+;
Dust:	silicates (infrared reflection bands)

TABLE IIb

REPORTED NEGATIVE RESULTS (MAINLY RADIO SEARCHES)

Organic:	H_2CO, CH_3OH, CH_3O-CH_3, CH_3-O-CH; CH_4 (infrared).
Organic with N:	HCN, HNCO, CH≡C-CN, CN-CH_2-CN.
Inorganic:	NH_3, SiO_2.

tails. Let's mention first that metals are seen in sun-grazing comets only, and can probably be attributed to the vaporization of the silicate dust at high temperature. For historical reasons, we will deal first with the minor H, C, N, O constituents, because they were identified first as major features in the visible and near-ultraviolet spectra. Arpigny's (1965) early approximate data for 10 comets, when translated into production rates reduced to 1 A.U., yield orders of magnitude of 10^{27} radicals of C_2 and of CN per second, 10^{26} for NH, 10^{25} for CH, for medium-bright comets of the type discussed here. (The OH emission bands were mentioned by him but were too much attenuated by atmospheric ozone to be significant). The previous results have been confirmed by A'Hearn and Cowan's (1975) careful analysis of comet Kohoutek's (1973 XII) spectrophotometry and are summarized in Table III in the same units as those of Table IV. However, for the first time on comet Kohoutek, radio-astronomical

TABLE III

PRODUCTION RATES OF MINOR CONSTITUENTS, 10^{28} RADICALS SEC^{-1}

Comet Kohoutek:	C_2	CN
before perihelion	0.10	0.04
after perihelion	0.04	0.01

observations have yielded results, and two possible parent molecules of the CN radical have been identified. These are CH_3CN (Ulich and Conklin 1974, Buhl *et al.* 1976) and HCN (Huebner *et al.* 1974). Production rates are extremely difficult to establish in radioastronomy, in particular because Bolzmann distributions can be overthrown by pumping mechanisms to the excited levels, and because

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poor resolving powers have not allowed the establishment of smooth brightness profiles in order to check lifetimes. For this reason, we won't even be in a position to use the radioobservations of the H_2O molecule (Jackson *et al.* 1976) or of OH and CH (Biraud *et al.* 1974, Black *et al.* 1974). The best assessment of the production rates of CH_3CN and HCN is that they are of the same order of magnitude and in the range of 10^{26} to 10^{27} molecules/sec, (Delsemme 1976) which is consistent with the more accurate values found for CN, if interpreted as one of the by-products of their dissociations. The CN data from Table III will therefore be used as the only reliable source to set a lower limit on the relative abundance of N.

Radio searches for the list of molecules given in Table IIb have been reported with negative results in all cases (Snyder 1976). Snyder remarks that the upper limits implied for all these undetected molecules invariably lead to a production rate lower than 10^{26} or 10^{27} molecules per sec, that is, like those of the other *minor* constituents. Methane has not been found in infrared yielding an upper limit of 5×10^{29} sec^{-1}.

THE PRODUCTION RATES OF THE MAJOR CONSTITUENTS

None of the production rates of the major molecules has been so far accurately measured before their dissociation. However, a breakthrough has been brought about in the 1970'ies by the observation of the vacuum ultraviolet spectra of comets, from rockets or satellites. In the solar ultraviolet, most of the molecules photodissociate eventually into atoms, much faster than they photoionize. These atoms can be observed as they expand in the outer coma, for distances of 10^5 to 10^6 km from the nucleus, because the resonance lines of H, C, N, O (all between 1200 and 1700 A) are excited by the solar ultraviolet. They can therefore be used for a crude elementary analysis of the mixture of the volatile molecules. The results are given for the last four medium-bright comets in Table II. Only the nitrogen resonance line is assumedly weak enough to be hidden in the wing of the Lyman α line and has not been observed.

Since most observations were done at different heliocentric distances, they have been all reduced to r = 1 A.U. by an inverse-square law. The differences between different observations of the same line may come from slightly different reduction techniques, but the largest ones probably are real, and come from the fact that the inverse-square law although often applicable (see Drake *et al.* 1976 for Lyman α) is not always true in particular when modified by outbursts. A good example of this is that the hydrogen production rate of comet Kohoutek before perihelion, was for the same distances more than three times as large as after perihelion (O'Dell 1976); C_2 and CN varied in proportion to H (see Table III). To the best of my judgment, the references used for Table II (and given below the Table) represent the most accurate set of data available today.

The first two lines of Table IV (sustained by at least eight indirect lines of evidence, Delsemme and Rud 1973) suggest that H_2O is the major constituent. When comparing production rates, we must be aware that the observed production rate of hydrogen is reached asymptotically for distances between 10^5 and 10^6 km from the nucleus, where OH is being fully dissociated; whereas the production rate of OH is established at distances smaller than 10^5 km. Water dissociation would therefore predict a 2:1 ratio for H and OH. Two velocity components of the H atoms (respectively 8 and 20 km/sec) detected by model fitting of the Lyman α isophotes (Keller and Thomas 1975) have indeed been attributed to the two photodissociations of H_2O and OH respectively. Since H_2O, H_2O^+, OH, O and H have all been detected (although sometimes in different comets), there is not much room left for doubt in attributing the bulk of H and OH to water.

In Table IV, lines 3 and 4 refer to the two different states ^3S and ^1D of

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TABLE IV

PRODUCTION RATES OF MAJOR CONSTITUENTS, IN 10^{28} SEC^{-1}, REDUCED TO r = 1 AU.

	Species	Tago-S-K 1969 IX	Bennett 1970 II	Kohoutek 1973 XII	West 1975 n
1	H (Ly α)	4.3 (a)	54 (b) 65 (c) 58 (d)	34 (g)	46 (h)
2	OH (X $^2\Pi_i$)	1.3 (a)	30 (b)	20 (i)	20 (m)
3	O(^{3}S)	----	6 (e)	2.7 (j) 6.9 (k)	23 (m)
4	O(^{1}D)	----	12 (f)	1.1 (l)	----
5	C(^{3}P)	----	----	1.6 (j) 0.6 (k)	6.3 (m)
6	C(^{1}D)	----	----	----	2.7 (m)
7	CO (X $^1\Sigma^+$) (4th posit. syst)	----	(f)	----	8.5 (m)

REFERENCES FOR TABLE IV

(a) Keller, H. U., and Lillie, C. F. (1977), *Astron. Astrophys.*, (in press).

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(d) Keller, H. U., and Thomas, G. E. (1975), *Astron. Astrophys.*, *39*, 7.

(e) Lillie, C. F. (1975), *Bull. Amer. Astron. Soc.*, *7*, 507. (His value for CO is not quoted here because of the uncertainty of the deconvolution of the OAO-2 data).

(f) Delsemme, A. H., and Combi, M. R. (1976), *Astrophys. J. Letters*, *209*, L149, (value corrected in 1977, see text).

(g) Meier, R. R., Opal, C. B., Keller, H. U., Page, T. L., and Carruthers, G. R. (1976), *Astron. Astrophys.*, *52*, 283.

(h) Opal, C. B., and Carruthers, G. R. (1977), *Icarus*, *31*, 503 (at 0.38 AU after perihelion).

(i) Blamont, J. E., and Festou, M. (1974), *Icarus*, *23*, 538 (at 0.62 AU after perihelion).

(j) Opal, C. B., and Carruthers, G. R. (1977), *Astrophys. J.*, *211*, 294 (at 0.43 AU after perihelion); corrected by factor 1.33, because about 75% of the coma emission was accepted by their spectrometer entrance slit (personal communication).

(k) Feldman, P. D., Tanacs, P. Z., Fastie, W. G., and Donn, B. (1974), *Science*, *185*, 705, at 0.37 AU, multiplied by 2.9 to correct lifetime; (see discussion in Opal *et al.* 1977).

(l) Huppler, D., Reynolds, R. J., Roesler, F. L., Scherb, G., and Tranger, J. (1975), *Astrophys. J.*, *202*, 276.

atomic oxygen. $^3S \rightarrow {}^3P$ emits the resonance line at 1304 A, whereas $^1D \rightarrow {}^3P$ emits the forbidden red line at 6300 A. In bright comets, this red line is much more intense than the same emission in the airglow, and can therefore be observed from the ground. The oxygen seen in the ^3S state disappears with a scale length of $(1.2 \pm 0.2) \times 10^6$ km (Opal and Carruthers 1977), implying that photons and solar wind compete to ionize it. For the oxygen emitting the red line, the story is different: it must be directly produced in the ^1D state by the dissociation if its parent molecule (Biermann and Trefftz 1964), therefore its scale length of about 2×10^4 km, (Delsemme and Combi 1976, slightly revised downwards recently) can be directly connected to its *parent*; since one red photon is produced per dissociation, photon counting yields the production rate without any further hypothesis. The result should therefore be particular-

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ly accurate. Unfortunately, the absolute calibration we used was in error, because of an unsuspected vignetting of the calibration line. Table IV lists our new value for comet Bennett.

For comet Kohoutek, the $O(^1D)$ value was obtained by a ground based Fabry-Perot spectrometer. The production rates of hydrogen, using the cometary Balmer α line observed for the first time by this remarkable instrument, have not been quoted here because they depend too much on the pumping of the solar Lyman β, whose profile is poorly known and which is known to fluctuate. The production rate deduced from the $O(^3S \rightarrow {}^3P)$ transition also happens to depend on the intensity of the solar Lyman β, because of a chance coincidence with an oxygen transition to the ^3D state, that cascades through ^3S to ^3P (Byard and Newson 1974). This correction has been taken into account in Table II, but the final value remains anyhow somewhat uncertain.

Delsemme and Combi (1976) explain the origin of the $O(^1D)$, by the photodissociation of CO_2 into $CO + O(^1D)$. After the revision of the production rates mentioned before, Delsemme (1977) estimates that an upper limit of 1/4 of the observed $O(^1D)$ might still come from the dissociation of H_2O, whereas the CO_2 needed to explain the rest of it, would amount to $(12 \pm 3) \times 10^{28}$ sec^{-1}. The dissociation of this amount of CO_2 could also explain the bulk of the CO observed in comet West, and would be consistent with the upper limit set for CO_2 by Feldman and Brune (1976). The large amount of CO attributed to comet Bennett (Table II reference e) has not been mentioned because of the large uncertainty resulting from the deconvolution of the OAO-2 data. For the same reason, radio observations of OH which are not based on detailed brightness profiles, have not been included in the best data shown in Table II.

Finally, carbon lines have also been observed in the last two bright comets, Kohoutek and West. The observed brightness profile of the carbon resonance line at 1657 A implies (reference j) two approximately equal scale lengths for parent and daughter molecules, each of 8×10^5 km (within a factor of two). One of them is consistent with the lifetime for CO dissociation (6.9×10^5 sec., McElroy and McConnell 1971). The other one is consistent with the lifetime for carbon ionization (2.5×10^5 sec) combined with a radial mean outflow velocity of about 3 km/sec. This mean velocity is predicted by assuming that the average energy excess of the dissociation is transformed into kinetic energy (most of the CO absorption takes place in the Lyman continuum, below 912 A). Feldman and Brune (1976) propose to explain their important observation of $C(^1D \rightarrow {}^3P)$ as coming from the dissociative recombination of CO^+. Delsemme and Combi (1976) propose that the ionization of $C(^1D)$ by all wavelengths shorter than 1239 A (the solar Lyman α being very effective) is the prime source of C^+, also observed by Feldman and Brune (1976) and that the source of CO^+ is the charge-exchange reaction $C^+ + CO_2 \rightarrow CO^+ + CO + 3eV$. I submit here that the two proposed mechanisms make a cycle, whose energy is mainly provided by the steady pumping of Lyman α; this cycle may explain the appearance of CO^+ tails near 1.5 AU and their fast development for shorter heliocentric distances because the cycle is quenched for long heliocentric distances by the radiative lifetime of the $C(^1D)$ state.

Coming back to the major molecules, if H_2O is established as the major constituent, it seems difficult to reject the presence of some CO_2, if only because of the existence of its ion in the tails. Its amount would probably be one order of magnitude smaller than that of water. The third candidate is CO, but its existence in the nucleus is less certain, because it has not been proved that the bulk of the observed CO could not come from the dissociation of CO_2.

ATOMIC ABUNDANCES FOR COMETS

The scatter of the H/OH ratios is close enough to 2. To build our comet

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model, we will accept that the actual ratio is 2 exactly, and that there is no other major source of OH but water (except perhaps for Kohoutek after its perihelion). We also accept that the $O(^3S)$ is that fraction of oxygen coming from the dissociation of OH, which is not lost to other processes (for instance, to charge-exchange reactions yielding early ionizations).

We admit that the bulk of the carbon and the CO observed in other comets comes from the dissociation of CO_2, which is measured in comet Bennett by its production of $O(^1D)$; (we remind that there is no other explanation available so far for the bulk of the forbidden red line of oxygen). Since Bennett is the only comet for which we have simultaneous dust-to-gas ratios and production rates, we can make a heuristic model of this comet, based on the previous assumptions. The H/O ratio turns out to be 1.1 and the C/O ratio, 0.22 for its volatile fraction. If we assume now that our interpretation of Table I is correct, O must reach solar abundances, taking into account that about 1/3 is in the dust (silicates) and that some carbon is missing. Including dust, the final ratios turn out to be:

$$H/O = 0.7 \qquad C/O \simeq 0.15.$$

The model obtained for comet Bennett is described in Table V. It contains only

TABLE V

COMPARISON OF SOLAR, CHONDRITIC AND COMETARY ABUNDANCES

	Solar Abundances		Comets	C I Chondrites
Element	Cameron (1973)	Ross and Aller (1976) (1)	This Work (1977)	Mason (1971)
1 H	31,800	30,240	15	1.5
6 C	11.8	12.6	3	0.7
7 N	3.7	2.7	>0.1	0.05
8 O	21.5	21.0	21	7.5
14 Si (2)	1.0	(solar) 1.35 (met.) 1.00	1.0	1.0

(1) Lambert (1977) gives practically the same ratios for C/O and N/O as Ross and Aller.

(2) The average factor 1.35 is needed to normalize the solar scale to the meteoritic scale.

74% of the gas present in the "primitive" mixture, coming mainly from a carbon depletion (from solar) of 4:1. In particular, its gas-to-dust ratio, (depending on which abundance table, and which silicates) may vary from 0.72 to 1.05. The fact that this ratio fits comet Arend-Roland data better than those of comet Bennett probably has no significance, because the error bars in each case may extend up to a factor of 2. The depletions from solar abundances are described for comet and C I chondrites in Table VI: hydrogen is depleted by 10:1, carbon by 4:1 and oxygen by 3:1 by going from comets to C I chondrites. Comets are therefore more primitive than C I chondrites: the passage of a chondrite through the atmosphere could not explain either its compaction, or these large losses of volatiles. However the major differentiation of comets from the "primitive" mixture (as defined before) seems to lie in their carbon depletion of 4:1.

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TABLE VI

DEPLETIONS RELATIVE TO SOLAR ABUNDANCES

Element	Comets	C I Chondrites	Comets/C I
H	5×10^{-4}	5×10^{-5}	10:1
C	0.24	0.06	4:1
N	>0.03	0.014	>2:1
O	1.00	0.35	3:1
Metals	1.00	1.00	1:1

DISCUSSION

A possibility is that the missing carbon lies in the cometary dust. Indeed, a proposal by Vanysek and Wickramasinghe (1975) that formaldehyde polymers could be present in dust form, would offer an appropriate sink for carbon, but also an equal sink for oxygen, which is ruled out by the present analysis of the production rates. A more attractive possibility would be graphite particles. If the missing carbon were in graphite, it would yield a dust-to-gas ratio in the vicinity of 2, which seems rather high, perhaps not if compared only to 1.2 for Arend-Roland, but certainly so, if compared with 0.5 for Bennett.

Another possibility is that the missing 3/4 of carbon was never condensed out of the solar nebula, when comets were made. This would happen if it were in a very volatile gas, like CH_4, and it implies only temperatures larger than some $50^{o}K$ at the low pressures we imagine at the place of formation of comets, which makes the hypothesis very attractive.

Finally, an unsuccessful search for methane in Kohoutek, in the infrared band near 3.3 μm, is reported by Maran (1974), setting a production rate lower than 50×10^{28} molecules sec^{-1}; it is clear that our other data are not consistent with rates even an order of magnitude lower than this, but this does not rule out *small* amounts of methane that would still be undetected; the simultaneous presence of CO , CO_2 and CH_4, that are at the two ends of the redox scale, would however imply conditions so far from thermodynamic equilibrium that they would come as a surprise.

DIFFERENCES BETWEEN COMETS

Our discussion is based on scanty data from a set of four recent and one slightly less recent medium-bright comets. This set represents rather well the type of average-bright comets that astronomers have studied so far. However, it is not suggested by any means that intrinsic abundance differences between comets do not exist.

First, a different type of photometric behavior (Oort and Schmidt 1951) has been distinguished between "new," young, older and (very old) short-period comets. Marsden *et al.* (1973), following my suggestion (Delsemme 1972), have shown that the best fit for the dependence law on heliocentric distance of the non-gravitational forces, is given by assuming that *water* ice only (or a solid hydrate of gases) controls the vaporization of the nuclei, for the set of all those *short-period comets* for which enough accurate data were available. The changing photometric behavior from new to old comets has been attributed (Delsemme 1974) to the effect of selective evaporation of materials more volatile than H_2O, in particular CO_2 in (new) comet Kohoutek *before* perihelion, but much less already *after* perihelion. Apart from this selective evaporation, it is not clear whether the physical differences observed in comets can be

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attributed or not to intrinsic abundance differences. For instance, famous comets like Morehouse (1908 III) or Humason (1962 VIII) showed an increase of some two orders of magnitude of the CO^+/CN brightness ratio; but the efficiency of ionizing CO may be very much size-dependent, because charge-exchange reactions depend on the extent of the collision zone, and in particular Humason was one of the intrinsically largest comets of this century. Smaller but still conspicuous variations of the $C_2 + C_3/CN$ ratio have been qualitatively illustrated by Herbig (1976), who also mentions the so-called "giant" comets whose perihelion is farther than 3 A.U.; the two known spectra show (mainly or only) an intense solar continuum, clearly suggesting that dust is dragged away by gases more volatile than water. Finally, the ratio of the solar continuum to the major molecular emissions (C_2, C_3 and CN) varies very much from comet to comet but again, when a Finson and Probstein's analysis is not done, we have no way of separating variations in the dust-size distribution, from variations in the dust-to-gas mass ratio. We may call "dusty" comets, only those showing *fine* dust!

CONCLUSION

Limited as they are, the present results seem at least to have established the fact that comets seem much less depleted in H, C, N, O. than C I chondrites, and that they probably are the most primitive objects still around in the inner solar system.

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DISCUSSION

ANDERS: I am not surprised by the deficiency of CH_4. There are at least two possible reasons for such deficiency. 1. The equilibrium $CO + 3H_2 \leftrightarrow CH_4 + H_2O$ shifts to the left at low pressures and if pressures were low in the region where comets originated, no CH_4 may have formed. 2. The reaction is slow in the absence of catalysts, and other, more complex organic compounds can form metastably at the temperatures where such catalysts become available (less than 400 °K0.

KELLER: How is your dust-to-gas ratio determined? We only know the ratio of the dust-to-gas of the expelled material (Finson and Probstein), can you deduct from these figures the ratio in the nucleus?

DELSEMME: In the Finson and Probstein's analysis, the dust-to-gas ratio is an average of the production rates of the expelled materials extended over several weeks of activity near perihelion. It represents an assessment of the mean composition of the outside of the nucleus only if a steady state is assumed, in particular if the vaporization does not leave a larger and larger curst behind it.

SEKANINA: The ratio of dust-to-gas derived from the Finson-Probstein approach refers of course to the outer shell of the nucleus lost by the comet along the observed path near perihelion.

DELSEMME: A final remark: the terminal velocity of a grain of a given size is reached within 20 radii of the nucleus and, because of the beautifully simple kinematics in space, is observationally known with an accuracy better than ±10%,

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since it is deduced from the widening of the isophotes of the tail. From Finson and Probstein's (1968a) Fig. 6, page 339, the deduced accuracy of the dust-to-gas ratio (in the general range of 0.5 to 2.0) should be within a factor of 2. (Of course the drag force is quite reasonably based on a free-molecular drag coefficient, but the dust has to be treated as spheres with perfect accommodation, which is a good approximation for cigarette smoke for instance). Eliminating the anomalously high values before and during the outburst of Arend-Roland, the geometric average for the two comets observed is $(1.3 \times 0.5)^{1/2} = 0.81$ *(+0.33, -0.23) if we assume they should have been the same. This is consistent with the comet model (Table V) we deduce from the H, C, O lines, because its dust-to-gas ratio (assuming O is in solar proportions) turns out to be 0.90.*

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