Section VIII

Fred Whipple Reflects

THE FOREST AND THE TREES

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ABSTRACT. Some 24 points are made concerning the author's understanding of the cometary nucleus as developed in this colloquium. Comparisons with an earlier report are noted, and most of the earlier advances in concept are substantiated. The mean density of the Halley nucleus may have been underestimated. The dust/gas ratio apparently needs to be increased by as much as two times, perhaps to unity or higher. The nature of the rotation remains puzzling. CHON grains now appear to be more important sources of gas than thought earlier. A very low temperature at, and subsequent to, the formation of the nucleus continues to receive support, as does a solar-system composition. The $^{12}C/^{13}C$ ratio may, however, be lower than expected.

This paper also presents problems and data relevant to the origin and aging of comets. Do the short-period comets have a different source than the long-period ones? Among the long-period comets, the data support their aging statistically as the periods decrease. Criteria for the ages of short-period comets are much needed. Data and discussions then center on the orientation of cometary axes with respect to the galaxy and the ecliptic for longer period comets. The physical properties of comets in clusters defined by these axes differ and are of potential interest with regard to the origin of both short- and long-period comets.

1.   Introduction

The title of this paper developed from my watching trees floating down toward the mouth of the Amazon River. Imagine an explorer who can study these floating trees and from this study alone must deduce the place and nature of the forest or forests from which they were uprooted. In analogy, where and how did our observed comets come into being?

As I was asked to make some comments about this colloquium, I have divided this paper into three parts: comments on the nature of comet nuclei, some problems regarding cometary origin, and some correlations among cometary data. The first part of the paper can only be sketched in character because of the finite space available to report on so many important contributions. I regret that a number of these contributions will be omitted. The third part of the paper contains correlations that are primarily suggestions of possibilities, because the data are insufficient to support most of these correlations as valid.

2. Comments on the Nature of Comet Nuclei

2.1. GENERAL REMARKS

At the symposium on the diversity and similarity of comets held in Brussels in 1987 (see European Space Agency publication SP-278), I presented some 19 comments concerning cometary nuclei. These comments were based on previous cometary lore augmented by the results from the space missions to Halley's comet and by other international research efforts on comets accelerated by the 1986 apparition of P/Halley. Here I shall list these comments with corrections and alterations induced by subsequent research and particularly by presentations at this Bamberg Colloquium. Most of the original comments have foundations in references that are included in a summary paper on "Comets in the Space Age" (Whipple 1989).

These original abbreviated comments about cometary nuclei follow as headings, augmented by explanatory notes or documented alterations expressing my personal point of view following the Bamberg Colloquium.

2.2. THE NUCLEUS

2.2.1. A Discrete Nucleus. The VEGA and Giotto space missions to P/Halley have confirmed this fact.

2.2.2. A Black Nucleus, With a Very Low Albedo. This fact has been confirmed by the space missions and many infrared observations. The geometric albedo appears to range from a minimum that is perhaps as low as 0.02 to values that are perhaps as high as 0.10 to 0.15 for large, distant comets, with a typical value being probably on the order of about 0.04 for comets more or less 1 AU from the Sun.

2.2.3. Low Density, $\rho \sim 0.1$ to 0.4 g·cm^{-3}. However, some investigators would raise this value to about 0.8 to 2.0 g·cm^{-3} for P/Halley. I suspect that the value is more like 0.4 to 0.6 g·cm^{-3} for P/Halley, but that it is much lower for small, new comets and is perhaps ~ 1 g·cm^{-3} for the nuclei of old, large short-period comets.

2.2.4. Increased Dimensions. Comets generally have increased dimensions as compared with the dimensions from previous calculations that were based on intrinsic magnitudes at large solar distances, when the comets were inactive (?) and not surrounded by clouds of particles (?).

2.2.5. Prolate Shape. The space missions have clearly demonstrated the irregular "potato" or "peanut" shape of P/Halley, while the light curves of distant comets, particularly the light curves by Jewitt and Meech (see Jewitt, this volume), show that such shapes (i.e., not rough spheroids) are probably also typical for distant, black-reddish asteroids.

2.2.6. Ultra-Fine Dust ($< 10^{-13}$ g). The space missions to P/Halley have shown the presence of dust down to $\sim 10^{-16}$ g in size, too small to scatter light effectively and hence not previously observed.

2.2.7. *CHON Dust.* The space missions have demonstrated that P/Halley dust contains a sizable fraction that is composed of the relatively abundant light elements C, H, O, and N. Apparently, CHON carries a considerable fraction of the rarer volatiles (see Section 2.2.13). Huebner *et al.* (this volume) show that the hydrocarbon POM (polyoxymethylene, nH_2CO, a long polymer chain) is carried by the CHON, while Jackson (this volume) shows that C_2 arises similarly (probably from acetylene, C_2H_2, via C_2H). Mukai (1989) finds the CHON grains to be hotter than the silicate grains. Jessberger and Kissel (this volume) find the CHON grains' density to be ~ 1.0 $g \cdot cm^{-3}$.

2.2.8. *A Poorly Known Gas/Dust Ratio.* The gas output of P/Halley is well-determined, and most investigators have placed the ratio at ~ 1.2, though Jessberger and Kissel have placed it at 0.9. However, Szegö (this volume) has found evidence for glitches, caused by impacts, in Giotto's motion, leading McDonnell, Lamy, and Pankiewicz (this volume) to credit dust with twice the mass abundance of gas (2 ± 1). The presence of sizable particles around some comets has been shown by radar (Campbell, Harmon, and Shapiro 1989), while West (1990) finds that P/Halley shows an asymmetric coma outbound at greater than 10 AU from the Sun.

2.2.9. *Composition Like Type 1 Carbonaceous Chondrites; Lack of C in Gas Now Found in Dust.* Delsemme (this volume), however, believes Fe to be deficient in P/Halley (by a factor of 2) and Si to be similarly overabundant, which he attributes to thermal processes in the solar nebula. Otherwise, the elemental abundances appear to be satisfactorily equivalent to the solar-system abundances. Hanner and Tokunaga (this volume) find evidence for olivine grains in the infrared (IR).

2.2.10. *Solar-System Isotopes Ratios for $^{34}S/^{32}S$ and D/H.* The ratios for $^{14}N/^{15}N$ have also been confirmed in a review by Vanysek (this volume). The ratio for $^{12}C/^{13}C$ may, however, be uncomfortably low, at ~ 65 (not ~ 85), according to Wehinger (personal communication).

2.2.11. *Active Areas $< 10\%$ Even for P/Halley.* The evidence now suggests that periodic comets are active only over extremely small percentages of their surfaces. How about "new" comets and disappearing comets?

2.2.12. *Thick, Insulating Mantle (High T).* A thick, insulating mantle found for P/Halley, coupled with small active areas, suggests that there is a crust of deep crevasses, allowing the effects of wasting, slides, etc. that precipitate outbursts. Perhaps it is even a source of splitting?

2.2.13. *H_2O Is the Most Prominent Gas, But More Active Material (CO_2?) Is Present.* Consider Comet Bowell, a new comet with a large coma when the comet was discovered at > 7 AU from the Sun. However, Delsemme (1988) considers formic acid (HCO–OH) and formaldehyde (H_2CO) to be slightly more abundant than CO_2 in the gas from P/Halley ($\sim 4\%$ each, as compared with 80% for H_2O), with a large amount of CO evolving from the former two gases and the total amounting to $CO/H_2O = 13 \pm 3\%$. See also Eberhardt *et al.* (1986).

2.2.14. *Colors and Albedos Like Those of Far-Out Asteroids (e.g., Trojans).*

2.2.15. *Slow Rotation Values (Slower Than Whipple's Values).* Feldman (this volume) shows that variation in the Lyman alpha image is not a reliable criterion for the rotation of a comet nucleus. Belton (this volume) makes a strong argument that for P/Halley, the 2.2-day period and 7.4-day Euler nodding are not acceptable. The subject of P/Halley's rotation period remains controversial.

2.2.16. *S_2 Shows a Low T From Formation to the Present.* This conclusion is supported by Weaver, Mumma, and Larson (this volume) from their measures of the ratio of the para to ortho water in P/Halley. They also suspect that the ratio differs between old and new comets. Klinger (this volume) notes that CO_2 could also be amorphous and that amorphous ice can trap and hold atoms and molecules if $T < 77$ K. Bar-Nun (personal communication) stresses the importance of observing noble gases as measures of T conditions during formation and afterwards.

2.2.17. *Greenberg Interstellar Process.* This process is favored as the method of origin of icy mineral grains.

2.2.18. *Halley Nucleus Looks Battered (Made of Many ~ 1-km Cometesimals?).* Investigators have found a large variation in the composition over the surfaces of different comets. Weaver, Mumma, and Larson (this volume) have found the formaldehyde abundance to vary over Comet Halley, while Meech (this volume) has found CO^+ to be more prevalent in Comet Wilson than in Comet Halley, and Feldman (this volume) has found S_2 to be the most prevalent in a burst of Comet IRAS-Araki-Alcock.

2.2.19. *Probably Formed in the Solar Nebula.* But where—the cloud or the disk? Criteria to tell the differences have yet to be developed. Perhaps the basic temperature will be the clue?

2.2.20. *The Night Side of P/Halley.* Gombosi (this volume) has shown how the spreading of the jet action could account for dust on the night side without activity there.

2.2.21. *Theories of Comet Activity Are Many, With Major Differences.* Crifo, Horanyi and Mendis, Huebner *et al.*, Jessberger and Kissel, and Jackson have all presented somewhat differing viewpoints in this volume.

2.2.22. *Solar Nongravitational Force.* Yeomans (this volume) treats solar radial nongravitational force as the prime factor, so that the effect depends largely upon the comet's light curve rather than upon the orientation of its pole.

2.2.23. *Lightning?* I note, to my surprise, that no one has reported any effects of lightning measured in the Halley missions, although lightning should be prevalent in swarms of dust, ions, and electrons immersed in electromagnetic fields.

2.2.24. *A Vital Requirement for the Future.* Rendezvous missions and/or other more sophisticated missions to comets are vitally needed.

3.   Some Problems Regarding Cometary Origin

Four sources of the observed comets are being considered seriously:

(a)   Members of the Oort (1950) cloud originating in the Uranus–Neptune region and later thrown out of it.
(b)   Members of the Oort cloud aggregated originally from the solar nebula during the collapse (see, e.g., Hills 1982).
(c)   Comets captured from the interstellar medium.
(d)   Comets formed in the collapsed solar nebular disk beyond Neptune and Pluto (the "Kuiper belt") and somehow perturbed into short-period orbits.

The capture of interstellar comets, even though they may be numerous in space, appears so unlikely that this source (c) is discounted by most students of the subject.
     The "classical" idea (a) of cometary origin in the region of the planets seems to be losing its appeal as the evidence grows for extremely low temperatures during and since formation. Delsemme (1988) holds, however, that the diversity of the grains in comets requires just such a region in which a mixture of grains could have occurred. Everhart (1977) concluded that Oort-cloud comets with low inclinations and perihelia in the planetary region could eventually (with enormous losses) be perturbed into short-period orbits. Duncan, Quinn, and Tremaine (1990), however, find that Oort-cloud comets, so perturbed from a "spherical population," would contribute short-period orbits with much greater orbital inclinations than those observed. On the other hand, they find that disk comets in low-inclination orbits as defended by Fernandez (1980 and, with Ip, 1983) will provide the short-period comets in low-inclination orbits without the prodigious losses arising in Everhart's calculations.
     Thus we seem to be left with short-period comets that may have been formed in the protosolar disk beyond the outermost planets in a rather cold region, while the nearly parabolic and long-period comets may have originated in the outer-planetary region, relatively warm, or collapsing with the solar nebula at very low temperatures more typical of the interstellar clouds.
     Can we, then, find any distinguishing physical characteristics of comets to indicate their source? In the search, we are confused by disturbing factors arising between origin and our observations from environment and also by factors depending solely upon cometary dimensions. As we have noted, each cometesimal in a comet nucleus may have experienced a somewhat individual history, while its velocity of impact may have greatly affected the volatility and cohesiveness of the shattered "matrix" material that it has contributed. The matrix may not have "sintered" enough to be as physically strong as the basic cometesimals and may also be less volatile. Hence, it may blow out more easily in the form of relatively large grains and hunks, but be less volatile and active than the cores of cometesimals.
     "New" comets may show unusual activity at large solar distances, because of cosmic-ray–induced volatility (C/Kohoutek 1973 XII) or because of a blow-off of an outer matrix or grain layer (C/Bowell 1982 I). Large, old comets may possess a radioactively

heated core of H_2O ice and grains and even packets of more volatile ices that are condensed in their outer shells and that are eventually exposed.

Hence, among comets of a common origin, we may observe confusing physical characteristics that might deceive us into classifying them as being different in basic nature or source. Typical variants to be expected among active comets include:

(a)   For "new" comets, an outer frosting of highly volatile material, amorphous in nature.

(b)   The blowing-off of thick grain mantles by "new" comets, after the comets have previously been exposed to hot stars or supernovae.

(c)   A typical mix of cometesimals and matrix with or without variation in composition, depending upon the position of the source on the nucleus.

(d)   Only shattered matrix.

(e)   Only cometesimals.

(f) H_2O ice and grains only, from the radioactively heated cores of old comets.

(g) H_2O ice almost alone.

(h)   More volatile ices than H_2O generally blowing out matrix grains.

Since the ground-breaking work by Oort and Schmidt (1951) suggesting systematic differences in the light curves between "new" and "old" comets, several investigators have studied the subject. Donn (1977) found no correlation among the spectra of 85 comets for a statistical difference in the ratio of continuum to emission for new and "evolved" comets. Nor did Kresak (1977) find a difference in the light curves. On the other hand, Kresak (1973, 1977) did find that short-period comets are rarely seen beyond 4 AU, with a sharp break near 3 AU, while comets with periods greater than 2,000 yr are frequently observed at far greater solar distances, an effect ascribed to H_2O ice in older comets versus more volatile ices in younger comets. This effect is supported by the observation of Marsden and Sekanina (1973) that new comets constitute such a large fraction of long-period comets with large perihelion distances (presumably the effect of thin, highly active layers on the surface of new comets, making them brighter at their first appearance than they are subsequently).

Meisel and Morris (1976) carefully analyzed photometric data for more than 100 comets and related the exponent n in the solar radial component of brightness, r^{-n}, to the "age" of the comet. They found a larger correlation with perihelion distance than with pre- and post-perihelion means of n for new and old comets. In other words, they found only an extremely weak confirmation of the Oort-Schmidt conclusion. In a somewhat similar study of more than 100 cometary light curves, Whipple (1978) found the exponent n to be significantly smaller for new comets than for older comets before perihelion, but statistically the same after perihelion for all comets of periods > 25 yr. For comets of shorter periods, n tends to be larger and erratic. Thus, the early indications by Oort and Schmidt appear to be fairly well confirmed.

In recent years, a number of observational studies have failed to detect real compositional differences between new and old comets (e.g., A'Hearn and Millis 1980; Weaver *et al.* 1981; Newburn and Spinrad 1984, 1985, 1989; Cochran 1987). As for aging, the period of a *long-period* comet is some measure, at least statistically, of the time since the comet was perturbed into an orbit with a small perihelion distance. For *short-period* comets, unfortunately, there exists no method for dating their capture. At best, we

Table 1. Nongravitational Forces vs. Dust/Gas

Period > 1,000 yr

Dust/Gas	N_o	$<q>_{AU}$	$<A_1>$	$<|A_2|>$	$<|A_2|>_{Max}$
High	4	0.77	1.9	0.15	--
Medium and Low	3	0.71	3.8	0.60	--

Period < 1,000 yr

Dust/Gas	N_o	$<q>_{AU}$	$<A_1>$	$<|A_2|>$	$<|A_2|>_{Max}$
High	3	1.32	0.21	0.014	0.016
Medium	4	1.03	0.60	0.045	0.056
Low	2	0.96	?	0.032	0.062

may be able to trace back an orbit to a close planetary approach, whereupon the earlier history becomes indeterminate. Similarly, a study of a derived meteor stream may give evidence of limited recent history. Although Kresak (1987) lists 10 observable phenomena associated with aging, none (except meteor streams) carry any mark of time.

4.   Some Correlations Among Cometary Data

4.1.   DUST/GAS RATIO AND NONGRAVITATIONAL FORCES

Although Donn (1977) found no correlation between the dust/gas ratio in new and "evolved" comets, his data do suggest correlations with nongravitational (NG) effects on the orbits. Table 1 lists the following in successive columns: his value of the dust/gas (ratio); N_o (comets); $<q>_{AU}$ (mean perihelion distance); $<A_1>$ (mean radial NG acceleration); $|A_2|$ (mean absolute tangential NG acceleration); and $<|A_2|>_{Max}$ (maximum observed $|A_2|$), where the dust/gas ratios are Donn's values and A_1 and A_2 are taken from and defined in Marsden's (1986) catalogue of cometary data. Values of these quantities are listed in successive lines for seven comets with periods > 1,000 yr and nine comets with periods < 1,000 yr.

The numbers in Table 1 suggest three conclusions:

(a)   For all types of comets, NG accelerations are smaller for comets with high
       values of dust/gas.
(b)   In each dust/gas category, NG accelerations are larger for comets with
       $P > 1,000$ yr than for those with $P < 1,000$ yr.
(c)   The effects of (a) and (b) are affected little, if any, by the perihelion dis-
       tances of the comets.

We may assume that the comets with shorter periods are older statistically than
those with longer periods. Hence, the data suggest the physical result that the older comets
are less active by an order of magnitude than the younger comets in terms of NG forces
and, therefore, in terms of gas ejection. This further implies the successive development of
grainy mantles as comets age. Despite the paucity of data, the effects appear to be so
strong as to invite serious consideration.

4.2.   COMETARY STATISTICS OF MAGNITUDE VARIATIONS

This section involves the reanalysis of the cometary magnitude variations published
by Meisel and Morris (1976), particularly their derived values of n, the exponent in r^{-n} for
the magnitude equation mentioned earlier (r = the solar distance in AU). Because n varies
so erratically from comet to comet, great weights need not be used for extremely long series
of observations. The value of n should only be fairly well determined. Hence, I have
adopted a weight of 1.0 for all values of n determined from 100 or more observations and a
weight equal to the number of observations divided by 100 for lesser numbers of observa-
tions, down to weight = 0.10, below which the n value is neglected. This choice of
weighting broadens the range of input to more comets without weakening the accuracy of n
for the average contributing comet.
The age classification was taken as:

I (new)	$1/a \times 10^{+6} \leq 50$ (AU)$^{-1}$; $(P) > 2.8 \times 10^6$ yr
II	$5 \times 10^{-5} < 1/a < 0.00215$ (AU)$^{-1}$; $10^4 < P < 2.8 \times 10^6$ yr
III	$0.00215 < 1/a < 0.01$ (AU)$^{-1}$; $10^3 < P < 10^4$ yr
IV	$0.01 < 1/a < 0.117$ (AU)$^{-1}$; $25 < P < 10^3$ yr

where P is the period. For the longer period comets, $1/a$ *original* values were taken from
the compilations of Marsden, Sekanina, and Everhart (1978), and Everhart and Marsden
(1983, 1987).
In each age group, the mean values of n and a were determined from the tables of
Meisel and Morris (1976) separately for the "Pre-Perihelion Dominated Solution," the
"Post-Perihelion Dominated Solution," and their "Combined Pre- and Post-Perihelion
Periods." The results of these calculations are presented in Table 2, where $< q >$ is the
weighted mean perihelion distance, $< n >$ is the weighted mean of n, and $\sigma(n)$ is the mean
error of $< n >$.
Perusal of Table 2 shows immediately that the mean values of q vary considerably,
while Meisel and Morris note that "the n values do not show a significant correlation." For
both the pre- and post-q data, $< n >$ increases strongly with comet age (i.e., with class or
inversely with period). The combined pre- and post-q data are mixed. Also, the post-q
values of $< n >$ are consistently greater than the pre-q values. These results are largely

Table 2. Aging of Longer Period Comets

Mean Values of $\bar{n}$

Orbit Class	I	II	III	IV
Maximum Period (yr)	∞	2.8×10^6	10^4	10^3
Minimum Period (yr)	2.8×10^6	10^4	10^3	25

Pre-Perihelion Dominated

	I	II	III	IV
Number of Comets	10	5	5	6
$<q>$ (AU)	0.43	0.90	1.17	0.71
$<n>$	2.45	3.11	3.32	3.83
$\sigma(n)$	±0.35	±0.71	±0.52	±0.49

Post-Perihelion Dominated

	I	II	III	IV
Number of Comets	15	16	9	17
$<q>$ (AU)	1.20	1.54	0.88	0.80
$<n>$	3.16	3.87	4.48	4.94
$\sigma(n)$	±0.26	±0.58	±0.53	±0.79

Combined Pre- and Post-Perihelion

	I	II	III	IV
Number of Comets	10	8	5	2
$<n>$	2.93	2.39	5.05	3.3
$\sigma(n)$	±0.54	±0.60	±1.86	±0.4

consistent with Whipple's (1978) conclusions, but, of course, the two data sets have much in common, since Meisel and Morris applied critical systematic corrections to the original observations. All in all, it appears that the long-period comets show aging in their light curves that is not just a "new"-versus-"old" relation, but is statistically a persistent aging on successive returns.

4.3.   SOLAR DISTANCES AT DISCOVERY AND AT LAST OBSERVATIONS OF COMETS

Kresak (1977) has used the solar distances of discovery (r_1) and last observations (r_2) of comets to correlate with their ages. A somewhat different approach to the same end is presented here. For comets with perihelia from 1800 to 1900, values of r_1 and r_2 were obtained from Vsekhsvyatskii's (1964) catalogue of comets, as were values of the comets' absolute magnitudes, H_{10}, defined as

$$H_{10} = m - 2.5\log(\Delta^2 r^4) \tag{1}$$

where, as before, m is the observed magnitude, Δ and r are the geocentric and heliocentric distances in AU, and the exponent 4 in r corresponds to $n = 4$ in Section 4.3.

The selection of comets was limited to the time period of primarily visual observations, largely with comparable telescopes. The comets were divided into groups of increasing age: I, II, III, and IV as in Section 4.2, except that group IV was cut off at an orbital period of 200 yr instead of 25 yr. As Kresak noted, the values of r_1 and r_2 are very sensitive to the cometary absolute magnitude. Hence, for each group, the relationship $\Delta r_i / \Delta mag$ was obtained by a least-squares solution of A_i and B_i in the equation

$$A_i + B_i H_{10} = r_i \tag{2}$$

where $i = 1$ or 2.

Therefore, $B_i = \Delta r_i / \Delta mag$ can be used to correct r_i from its mean value $< r_i >$ to a standard value, which is taken as $H_{10} = 6.0$. Hence, the correction to $< r_i >$ becomes $(\Delta r_i / \Delta mag)(6.0 - < H_{10} >)$, where $< H_{10} >$ is the mean value of the absolute magnitude for the group.

Table 3 presents the results of this effort in a form similar to that of Table 2. The mean errors of the r's are not given in the table, but they are roughly ± 0.15 AU for $< r_i >$ and ± 0.30 AU for $< r_2 >$. Comet Barnard 1889 I, a new comet, was omitted from the summation because of its extreme values ($r_1 = 2.55$ and $r_2 = 8.22$ AU), which would have unduly biased the averages in favor of new comets. The decrease in $< r_1 >$ and $< r_2 >$ with age for the comets as seen in Table 3 is strongly suggestive, but not yet definitive.

4.4.   ON THE ORIENTATION OF COMETARY ORBITS

The correlations discussed so far have involved only the aging of the long-period comets, providing strong evidence that the aging process continues beyond simply a "new"-versus-"old" type of criterion. R. Lüst (1984) has shown that the lines of apsides (or aphelia) of long-period comets tend to avoid a 20° strip centered on the galactic equator and also the two polar regions from galactic latitudes (b) $\pm 60°$; this has been confirmed by

Table 3. Another Search for Aging Effects in Long-Period Comets

Solar Distance of Discovery, r_1				
Orbit Class	I	II	III	IV
Maximum Period (yr)	∞	2.8×10^6	10^4	10^3
Minimum Period (yr)	2.8×10^6	10^4	10^3	200
Number of Comets	8	21	25	15
$< r_1 >_{obs.}$ (AU)	1.59	1.50	1.40	1.28
$< H_{10} >$	5.64	5.81	5.35	6.68
$< \Delta r_1 / \Delta mag >$	-0.14	-0.14	-0.15	-0.15
$< r_1 >_{corr.}$ (AU)	1.54	1.48	1.30	1.38

Last Observed Solar Distance, r_2				
Number of Comets	8	22	24	14
$< r_2 >_{obs.}$ (AU)	2.77	2.59	2.14	1.99
$< H_{10} >$	5.64	5.81	5.35	6.68
$< \Delta r_2 / \Delta mag >$	-0.33	-0.65	-0.33	-0.29
$< r_2 >_{corr.}$ (AU)	2.65	2.47	1.98	2.08

Delsemme (1987). The explanation by Harrington (1985), Morris and Muller (1986), and Heisler and Tremaine (1986) appears to be correct: the density gradient normal to the galactic plane perturbs comets in the Oort cloud proportionally to a $\sin b \cos b$ law, the so-called "galactic tide" effect.

Biermann, Huebner, and Lüst (1983) have clearly established the reality of a cluster of aphelia of long-period comets in the region in galactic longitude, $180° \leq l \leq 248°$, and latitude, $-2° < b < +38°$ (the BHL cluster). The cluster fills in part of the depleted zone ($|b| < 10°$) and strongly calls for a stellar passage that perturbed the cloud comets. Delsemme (1986) finds another striking cluster (D), quite elongated, passing through the ecliptic pole, with most of the members moving in much the same direction at aphelion. He attributes this cluster to the slow passage of a brown dwarf star.
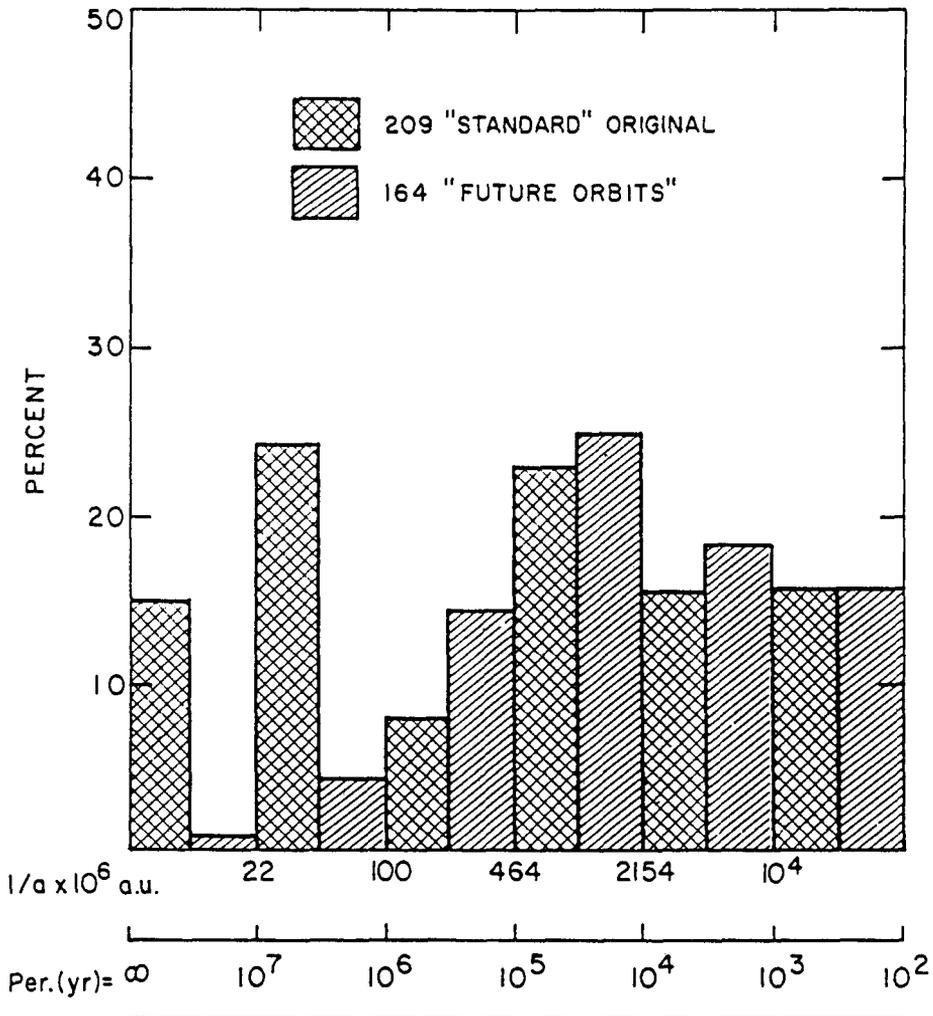
Figure 1. Original and future orbits of 209 long-period comets.

The populations of comets in terms of the galactic coordinates of their aphelia provide some possible clues about their origin and aging. To establish a base for comparison, 209 comets that have periods exceeding 100 yr and that have been observed since 1900 are presented in Figure 1.

The block diagrams show percentage numbers versus original values of $1/a$ $(AU)^{-1}$ from Marsden and Sekanina (1973), Marsden, Sekanina, and Everhart (1978), Everhart and Marsden (1983, 1987), and Marsden (the 1986 catalogue, including the table of "ellip-

tical orbits"). The corresponding percentage of "future" orbits of these comets compared with the "originals" is indicated in Figure 1, with 45 (22%) having been lost from the solar system as the result of planetary perturbations.

The apparent dearth of comets with periods of a few hundred thousand years had, in the past, suggested to me that there may have been a dearth of new comets over a considerable interval of time in the past. Figure 1, however, suggests that the large non-Gaussian distribution of $\Delta 1/a$ induced by planetary perturbations may account for the dip. Essentially no new comets enter the inner solar system with such short periods. The figure clearly shows that a continuous contribution of new comets is essential to the maintenance of the distribution shown.

The population of the BHL cluster appears in Figure 2, showing the present distribution of 30 members observed since 1900, not including the sungrazers, and the return of 18 after losses (37%) by planetary perturbations. Figure 3 shows the corresponding data for 29 members of the Delsemme cluster and the distribution of 21 possible returns (28% loss). The latter cluster has relatively fewer members with periods of less than 10^4 yr, compared with the BHL cluster and the "standard" distribution (also shown in Figures 2 and 3). Although the numbers are scant, Figures 2 and 3 suggest that the D cluster is relatively newer, not having been active as long as the BHL cluster.

Delsemme stresses the important point that members of his cluster preponderantly have motions at aphelion that are "almost perpendicular to the plane of the ecliptic." The members of the BHL cluster, on the other hand, are moving almost perfectly at random when at aphelion. It is interesting to study the motions at aphelion of the 18 members of the peculiar group that have aphelia lying less than 10° from the galactic plane and that are not members of the BHL cluster or sungrazers. The motion is within 30° of the normal ($\pm$) to the galactic plane for 12 of the 18, with only one directed within 30° (actually, 27°.7) of a parallel to the plane. The group also has a peculiar distribution of periods, with half lying in the range of $10^3 < P < 10^4$ yr, only three lying in the range of $10^4 < P < 10^5$ yr, and only one that has a longer period (the apparently new, unusually dusty C/Arend-Roland, 1957 III).

Seven members are of special interest, as they lie at the intersection of the galactic and ecliptic planes, all with ecliptic longitude, L, confined by $90° < L < 99°$, and with relatively small ecliptic latitudes, B. Let us call them the GE group (see Table 4). Whether or not they are statistically significant as a group, they lie in a region where "galactic tides" should be ineffective. All have intermediate perihelion distances ($0.48 < q < 1.64$ AU) and positive ecliptic motions ($13° < i < 79°$), but generally high ecliptic inclinations as compared with those of the short-period comets. The periods lie in three groups: 2 at 270 and 583 yr, 4 in the range of 1,398 to 2,800 yr, and 1 of the highest inclination, at 16,500 yr. The two extreme periods correlate directly with the orbital inclinations, with the other inclinations lying between these extremes, suggesting a reduction in inclination with period decrease. Four of the seven are among the six deviants from motion within 30° of normal to the galactic plane. The group seems worthy of further study, both from a physical and an orbital point of view.

Physically, the BHL cluster demands attention because it contains the aphelia of P/Halley, C/Kohoutek 1973 XII, C/Morehouse 1908 III, two of the five comets with $100 < P < 200$ yr, and, if slightly enlarged, the Kreutz sungrazers and ten of the 20 comets listed as "Great" in Marsden's catalogue (1986). On the other hand, the comets in the Delsemme cluster appear to be *average*, as do those in the GE group. It is true that the
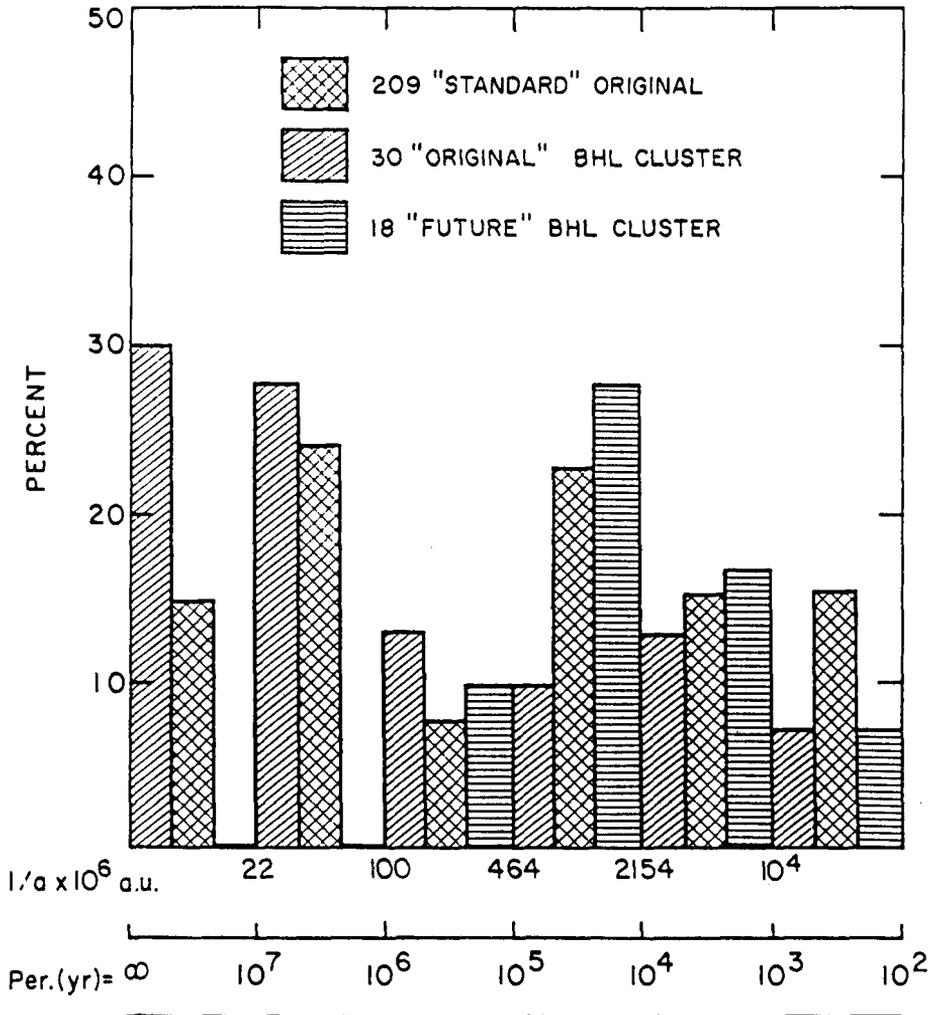
Figure 2. Original and future orbits of 30 BHL cluster comets.

presence of Halley's comet, the sungrazers, and those comets of $100 < P < 200$ yr was probably the result of perturbations, not representations of their "original" axial orientations, but nevertheless, the question still remains as to whether different sources or origins may have been involved.

　　　New comets of low inclination to the ecliptic are of especial interest, as they may represent the progenitors of the short-period comets. Of the 209 orbits of high accuracy
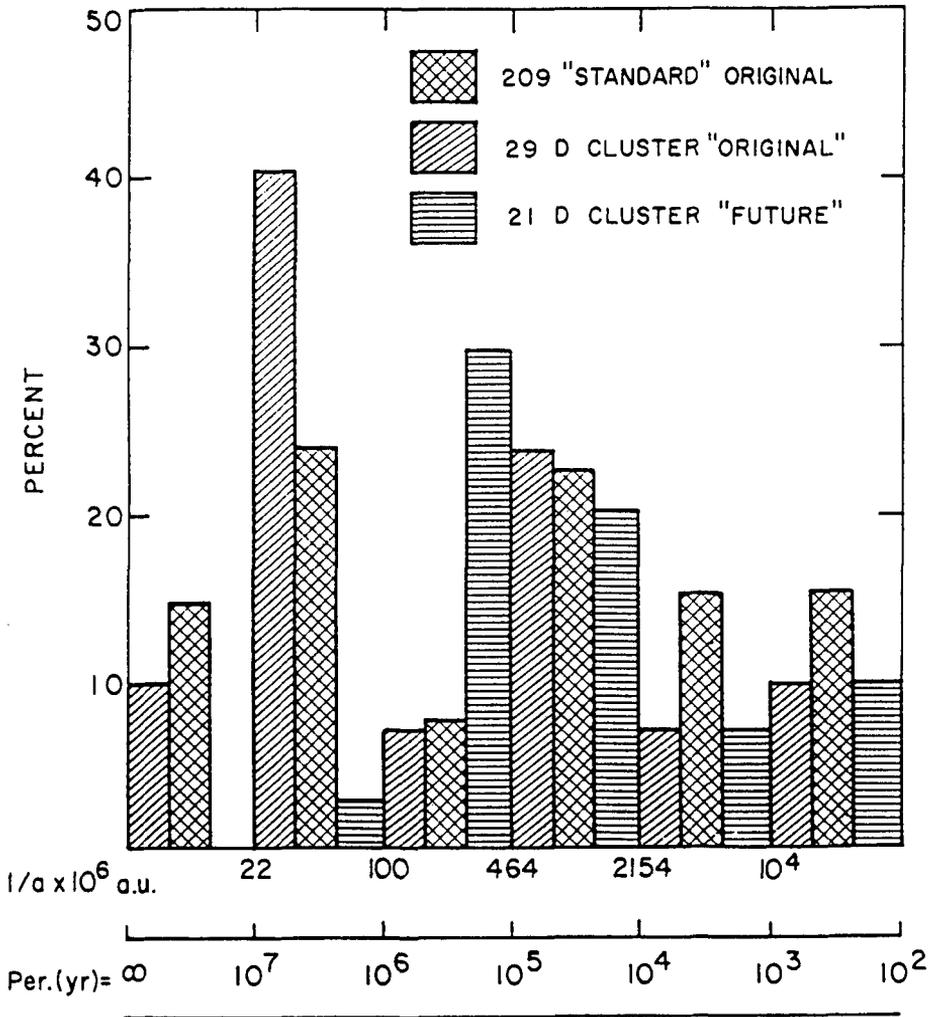
Figure 3. Original and future orbits of 29 D cluster comets.

studied in Figure 1, only eight meet the requirements of $1/a < 100 \times 10^{-6}$ $(AU)^{-1}$ and $i < 35°$. Of these eight, five are of extreme interest:

   (a)   Bowell 1982 I, which, when discovered at 7.3 AU, already had a well-developed disk of large grains, indicating activity at much greater solar distances (see, e.g., Sekanina 1982 and A'Hearn *et al.* 1984).

   (b)   Kohoutek 1973 XII, the notorious comet that was discovered near the orbit of Jupiter.

Table 4. The GE Group

Year	Name	q, AU	$1/a$(orig.), $(AU)^{-1} \times 10^6$	i, deg.	L, deg.	B, deg.
1846 I	de Vico	1.48	5,131	47.4	97.3	-16.0
1863 IV	Tempel	0.71	1,546	78.1	98.1	-2.7
1906 VII	Theile	1.21	14,328	56.4	90.2	+7.2
1911 V	Brooks	0.49	6,280	33.8	90.6	+14.6
1920 III	Skjellerup	1.14	5,023	22.0	90.3	-7.1
1921 V	Reid	1.63	7,999	32.4	98.0	-2.0
1985 II	Shoemaker	1.21	23,930	13.9	91.1	-10.5

(c)   Kopff 1905 IV, which split. There have been only nine split comets that have periods greater than 10^4 yr and that have been observed since 1900.

(d)   Wirtanen 1957 VI, which also split, at a greater solar distance.

(e)   Wolf 1917 III, which, like Bowell, had developed a disk at ~ 5 AU.

The remaining three comets in this category, Bester-Hoffmeister 1959 III, Mrkos 1959 IX, and Rudnick 1967 II, were not as well observed as the others. All eight have aphelia at great enough galactic latitudes to allow the likelihood of perturbation by the galactic density gradient. Therefore, we have no *a priori* choice as to their origin from a great Oort cloud or from a comet belt far beyond Neptune, but not too far from the ecliptic. On the other hand, if the short-period comets are derived from the latter source, comets such as these eight must provide the criteria for their physical character, if it is different from that of the long-period comets.

5.   Summary

Comments have been made concerning our understanding of the cometary nucleus as developed in this colloquium. Most of the advances reported earlier have been substantiated, but the mean density of the Halley nucleus may have been underestimated, while the nature of the rotation remains uncertain. The dust/gas ratio apparently needs to be increased by as much as two times, perhaps to unity or higher. CHON grains appear more and more to be important sources of gas. A very low temperature at the formation of comets receives continued support, as does a solar-system composition; a low $^{12}C/^{13}C$ ratio may be an exception. Following comments on more than a score of items, this paper has presented problems and data relevant to the origin of comets, particularly the short-period comets versus the long-period ones. Evidence has been added to support the thesis that aging among long-period comets increases statistically as the periods decrease. Dis-

cussion and data followed concerning the orientation of cometary axes with respect to the Galaxy and the properties of clusters defined by these axes. Of particular interest are the clusters or groups related to both the galactic plane and the ecliptic plane.

Clearly, space rendezvous missions or more sophisticated missions to several comets are mandatory if we are to unravel the threads of cometary origin and the relevance of comets to life on the Earth.

6. Acknowledgment

7. References

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