Comets: Data, Problems, and Objectives

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A highly abridged review of new relevant results from the observations of Comet Kohoutek (1973f) is followed by an outline summary of our basic knowledge concerning comets, both subjects being confined to data related to the nature and origin of comets rather than the phenomena (for example, plasma phenomena are omitted).

The discussion then centers on two likely places of cometary origin in the developing solar system, the proto-Uranus-Neptune region versus the much more distant fragmented interstellar cloud region, now frequented by comets of the Öpik-Oort cloud. The Comet Kohoutek results add new insights, particularly with regard to the parent molecules and the nature of meteoric solids in comets, to restrict the range of the physical circumstances of comet formation.

A few fundamental and outstanding questions are asked, and a plea made for unmanned missions to comets and asteroids in order to provide definitive answers as to the nature and origin of comets, asteroids, and the solar system generally.

A Few of the Major Advances in Comet Knowledge From Observations of Comet Kohoutek (1973f)

The first radio observations of a comet leading to the discovery of the new parent molecules methyl cyanide (CH_3CN) and hydrogen cyanide (HCN) were made by Ulrich and Conklin (ref. 1) and Snyder et al. (ref. 2), respectively, both near 3-mm wavelengths. The latter investigators (ref. 3) find that HCN contributes approximately 1 percent and CH_3CN approximately 2 percent of the cometary molecular loss rate near perihelion, the total exceeding 100 T/s. They find evidence for radiation from ethyl alcohol (C_2H_6OH) at 86.247GHz and possibly SiO at 86.242GHz. Biraud et al. (ref. 4) and Turner (ref. 5) observed OH in absorption in two 18-cm lines, while Rydbeck et al. (ref. 6) and Black et al. (ref. 7) observed CH in emission at 9-cm wavelength. Hobbs et al. (ref. 8) observed continuum radiation at 3.7 and 2.8 cm, the first from a comet.

Lew and Heiber (ref. 9) and Herzberg and Lew (ref. 10) made a major step forward by identifying H_2O^+ bands which were measured by Benevenuti and Wurm (ref. 11) and by Wehinger et al. (ref. 12). Definitive studies of this vital ion should solidify our knowledge of the abundance and behavior of H_2O, apparently the most abundant and controlling material in comets.

From the Ames-NASA Convair 990, Blamont and Festou (ref. 13) established that the OH radical has a half-life of only 8.5 hours at 0.62 AU solar distance, an order of magnitude shorter than previously estimated. They thus find the radical being created within 15 000 km of the nucleus at a total rate of 10^{29} OH/s at 0.62 AU post-perihelion, January 15, 1974. This result, as a minimum rate loss for H_2O atoms, confirms beautifully the conclusion of Code and Savage (ref. 14) by $L\alpha$ measurements from the Orbiting Astronomical Observatory (OAO) that Comet Bennett (1970II) was losing 10^{29} H_2O/Ster/s at a comparable solar distance, with an absolute magnitude about 2.5 magnitudes brighter than Kohoutek.

The prediction of an antitail by Sekanina (ref. 15) and its observation near perihelion first by Gibson from Skylab (ref. 16), then by Ney and Ney (ref. 17) in the infrared, followed by many observations in the post-perihelion period, establishes the expulsion of large particles (~ 1 mm) from the nucleus. Even though Kohoutek was not a "dusty" comet, based on its color (ref. 18) and the appearance of its visual spectrum, its red continuum (ref. 19) was very strong, and the comet was excessively bright in the infrared as measured by many observers. The observed microwave continuum probably represented thermal radiation from large particles, perhaps icy grains.

There is no time here to discuss the invaluable results from observations of Lα and the far ultraviolet from Mariner 10, Skylab, and rockets, the numerous infrared measurements, and the extensive classical observations. Comet Kohoutek has been the most thoroughly observed comet in history. The completeness of the spectral record from He I at λ304 Å (negative result) to the cm-wave radio region will provide answers to a number of critical questions concerning comets. In particular these extensive data will give us the first precise measure of the mass ratio of volatile ices to meteoric solids, a ratio that is vital in determining the nature and place of origin. The extensive data, including a number of important negative results (NH_3, CH_4, He, and acetone), will certainly add other knowledge to restrict substantially the possibilities regarding the origin of comets.

Basic Facts and Deductions About the Nature of Comets

In discussing the role of comets in the evolution of the solar system we may confidently assume the following basic facts and deductions about their character:

1. *Comets are members of the solar system.* No evidence exists for orbits of interstellar origin (ref. 20).
2. *Comets have been stored for an unknown length of time in very large orbits in the Öpik-Oort cloud out to solar distances of tens of thousands of astronomical units (refs. 21 and 22).* Perhaps 10^{11} comets with a total mass comparable to that of the Earth still remain, as Oort suggested.
3. *The basic cometary entity is a discrete nucleus (rarely, if ever, double) of kilometer dimensions consisting of ices and clathrates, including specifically H_2O, CH_3CN, HCN, CO_2, and probably CO.* Other parent molecules of the abundant H, C, N, and O atoms mixed in an unknown fashion with a comparable amount of heavier elements as meteoric solids must occur in comets because of the observed radicals, molecules, and ions, C_2, C_3, CH, CN, NH, NH_2, N_2^+, CO^+, and CH^+ (refs. 23 through 26).
4. *Cometary meteoroids are fragile and of low density (refs. 27, 28, and 29).*
5. *The comet nuclei as a whole must have never been heated much above a temperature of about 100 K for a long period of time,* otherwise new comets could not show so much activity at large solar distances (Kohoutek (1973f), for example). Possible internal heating by radioactivity and temporary external heating, e.g., by supernovae, are not excluded.
5. *Comets were formed in regions of low temperature, probably much below 100 K.*
6. *Comet nuclei are generally rotating, but in no apparent systematic fashion and with unknown periods* in the range from about 3 hours to a few weeks, based on nongravitational motions and the delayed jet action of the icy nucleus.
7. *The nuclei, at least of three tidally split comets, show evidence of a weak internal compressive strength the order of 10^4 to 10^6 dyn cm^{-3} (ref. 30) and evidence of little internal cohesive strength.*
8. *The surface material of active comets must be extremely friable and porous* to permit the ejection by vapor pressure of solids and ices at great solar dis-

tances. The evidence of clathrates by Delsemme and Swings (ref. 25), coupled with the probable ejection of ice grains at great solar distances (ref. 31), supports this deduction.

The following probable limits of cometary knowledge or negative conclusions appear valid:

1. *Roughly a solar abundance of elements may reasonably be assumed for the original material from which comets evolved.* Note Millman's (ref. 32) evidence regarding the relative abundances of Na, Mg, Ca, and Fe in cometary meteor spectra and the solar value of the $^{12}C/^{13}C$ ratio measured by Stawikowski and Greenstein (ref. 33) and Owen (ref. 34).
2. *The material in the region of comet formation (with roughly solar abundances of elements) could not have cooled slowly in quasi-equilibrium conditions from high temperatures.* The significant abundances of CO, CO_2, C_2, C_3, and now CH_3CN and HCN in comets, along with the low density and friability of the cometary meteoroids, indicate nonequilibrium cooling in which the carbon did not combine almost entirely into CH_4 and the meteoroids generally did not have time to aggregate into more coherent high-density solids before they agglomerated with ices.
3. *The existence of an original plane of formation of comets beyond some 3000 to 5000 AU appears to be unknowable.* The perturbations by passing stars would have so disturbed the orbits that the lack of evidence for a common plane in the motions of new comets tells nothing about the place or plane of origin (ref. 22). (Note exception in 4 below.)
4. *That the comets formed concurrently with the solar system some 4.6×10^9 yr ago is an assumption* based on the lack of a tenable theory for more recent or current formation. The lack of evidence for a common plane of motion implies an origin remote in time or, if recent, no common plane of origin.
5. *The highly variable ratio of dust to gas observed from comet to comet proves a large variation in particle size distribution,* but has not yet been shown to measure a true variation in the dust/gas mass ratio. Periodic Comet Encke (P/Encke), for example, shows a low dust/gas ratio in its spectrum, but has contributed enormously to the interplanetary meteoroid population.

The Role of Comets in the Origin of the Solar System[1]

The above evidence points conclusively to the origin of comets by the growth and agglomeration of small particles from gas (and dust?) at very low temperatures. But where? If concurrently with the origin of the solar system (and necessarily associated with it gravitationally), two locations in space are, a priori, possible: (1) in the other regions of the forming planetary system beyond proto-Saturn (refs. 24 and 35); or (2) in interstellar clouds gravitationally associated with the forming solar system but at protosolar distances out to a moderate fraction of a parsec; that is to say, in orbits like those in the Öpik-Oort cloud of present-day comets (refs. 24, 44, and 52).

There can be little doubt that comets were the building blocks for the great outer planets Uranus and Neptune. The mean densities of these planets (ref. 53) are consistent with their origin largely from the accretion of comets, assumed to consist of the compounds possible (excluding H_2) in a solar mix of elements. This process of building Uranus

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[1] The reader is referred to reference 36 for a modern development of the Kant-LaPlace concept, including the important contributions by O. J. Schmidt and a general historical background of this general concept. For less general special treatments see references 35 and 37 through 44. For concepts of comet or solar system origin deviating from the "classical," see references 45 through 50 and especially Cameron and other contributors to the Symposium at Nice (ref. 51).

and Neptune is precisely analogous to building the terrestrial planets from planetesimals. Temperature was the controlling factor, being too high within the orbit of proto-Jupiter for water to freeze. For this reason Oort's (ref. 22) suggestion that the comets formed within the Jupiter region appears unlikely because asteroids clearly formed there. Similarly, Öpik's requirement for solid H_2 in the proto-Jupiter region appears untenable. Nevertheless, Oort's idea that commets were thrown out from the inner regions of the solar system by planetary perturbations is highly significant.

Thus, the possible origin of the presently observed comets in the Uranus-Neptune region rests solely on the premise that the major planets (or protoplanets) could indeed throw the comets into stable orbits with aphelia out to some 50 000 AU or more. The low efficiency of the process is only restrictive in the sense that too much angular momentum may be required of the outer planets to accomplish the feat successfully. Approximately a solar mass of comets in large orbits appears to be required as an end product, but a hundred solar masses may originally have been involved. Öpik (refs. 43 and 54) is doubtful about the process unless the comets formed near Jupiter; Everhart (ref. 55) finds it highly unlikely, while Levin (ref. 56) provides the angular momentum from proto-Uranus and proto-Neptune by forming these planets at very great solar distances (up to 200 AU) from a very large nebular mass and drawing them into their present orbits by the ejection of comets (mostly to infinity).

Everhart's doubts may possibly be removed if the space density of comets originally fell off rapidly with solar distance and if the supply at great distances (ref. 20) has been replenished by those in smaller orbits, more stable against stellar perturbations. Indeed, Öpik (ref. 21) showed that stellar perturbations will systematically increase perihelion distances to remove the comets from the region of perturbation by the outer planets. The number of comets thrown into the inner solar system during the immediate post-nebula period could have been significant and may account for major crater formation on the Moon (ref. 57) and volatiles on the terrestrial planets (ref. 58).

Alternative 2—forming the comets directly in the orbits of the Öpik-Oort cloud—is highly attractive, except for the difficulty of agglomerating kilometer-sized bodies in the low-density fragmented interstellar clouds. Such a possibility must be demonstrated before one can accept the tempting solution to the problem. Öpik (ref. 43) finds the process quite impossible.

Let us now look to the comets themselves to see whether their structure can help us distinguish between the two possible regions of origin. Most conspicuous are the numerous carbon radicals, molecules, and ions not in low-temperature equilibrium with excess hydrogen. The gas, if once hot, could not have cooled slowly. Note too the friability and low density (0.5 to < 0.01 g/cm^3) for meteoric "solids." Sekanina (private communication) finds evidence that for Comet Kohoutek the larger grains tend to shrink appreciably in a period of a few days. We must conclude that the ices, earthy material, and clathrates were all accumulated simultaneously at very low temperatures.

More specifically, the ices, clathrates, and "solids" collected together intimately in such a fashion that earthy molecules were somewhat bonded together in order to provide some degree of physical strength after the ices sublimated. Note that any sintering process to make the earthy grains coherent physically would remove the highly volatile substances necessary to provide the activity of Comet Kohoutek and other comets at great solar distances where the vapor pressure of H_2O is negligible. Thus, the process of grain growth must have involved the "whisker" type of growth commonly observed in laboratory crystals. *We can confidently visualize a comet as a complex lacy structure of "whiskers" and "snowflakes" that grew atom-by-atom and molecule-by-molecule while highly volatile molecules were trapped as clathrates.*

The temperature could have been sufficiently low for such cometary growth any-where in space beyond perhaps 30 to 50 AU from the center of the proto-solar-system. Levin's (ref. 56) concept of comet growth up to 200 AU is entirely consistent with such growth, as is alternative 2, fragmented interstellar clouds at far greater distances. Safronov and Levin's requirement of excessive material (perhaps 30 to 100 times the present-day mass of Uranus and Neptune) to provide a reasonably rapid growth rate for Uranus and Neptune confirms Öpik's vehement denial that fragmented interstellar clouds may be capable of producing comets. Careful analysis of grain growth rates under imaginative sets of assumptions as to the nature and stability of such clouds is clearly needed. Note that a comet does not appear to be an aggregate of interstellar grains if, indeed, these grains are solids covered with icy mantles. Such grains would not cohere when exposed to solar radiation sublimating the ices.

At the present, then, we have no criterion to identify the unique region in space where comets formed, if indeed they all formed in the same general region. We need more precise knowledge concerning the identity and abundances of the more volatile parent molecules. Did CH_4, CO, Ar, or Ne, for example, actually freeze out in comets? As Lewis (ref. 59) shows, the mass percentages of such volatiles can be used as thermometers. Even the dimensions of comet nuclei are uncertain, while we have no knowledge whatsoever of their detailed structure. Are they layered? Do they contain "pockets" of ices or "pockets" of dust? How fast do they rotate? What produces comet bursts in luminosity? What causes "new" comets to split?

Furthermore, we do not know whether comets generally or indeed any comets contain cores of asteroidal nature. It is tempting to identify many of the Apollo or Earth-orbit crossing asteroids as "burned-out" comets. Proof of a truly asteroidal core for an old comet would require a further knowledge of the chemistry and structure of the core to ascertain whether meteoric material collected first or whether radioactive heating drove out the volatiles. Such knowledge would, of course, be invaluable in ascertaining the physical and chemical circumstances of the origin. No definitive answer is likely without such data.

It is clear that far more ground-based and space-based research on comets is necessary. Comet Kohoutek has shown that a massive attack on one comet can produce extraordinary results. There are too many comets to permit an overall observational attack on each one. Nevertheless, we need to accumulate data on all observable comets. A reasonable program is to institute massive observing programs from time to time for especially selected comets, while accumulating basic data for all comets.

Only space missions to comets can give us the "quantum jump" in knowledge necessary to solve the most fundamental problems of comets. Equally, we need to study a few asteroids at their surfaces to understand their nature and to identify the sources of meteorites. Because meteorites have given us extraordinary insight regarding early conditions in the developing solar system, we can expect asteroid space missions to answer some basic direct questions, while "calibrating" our laboratory data on meteorites. Furthermore, the extraordinary successes in exploring the Moon and Mars have given us limited data concerning the early phases of solar system formation because these bodies have been severely altered since they were originally agglomerated.

Space missions to comets and to asteroids are the essential next steps toward understanding how the solar system came into being. Such missions are entirely feasible in the present state of our space technology.

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