THE NUCLEUS: PANEL DISCUSSION

Fred L. Whipple

In discussing the nucleus of comets and the role of comets in the evolution of the solar system I summarize the observation only in Table 1, the observed composition. Note that gas-phase chemistry obscures the nature of the active atoms, molecules and radicals in the nucleus.

I wish to stress the fact, so obvious from this symposium, that the comprehensive observational attack on Comet Kohoutek (1973f) has led to an enormous step forward in deciphering the comet enigma.

We may confidently assume the following basic facts and deductions about the character of cometary nuclei.

A. Comets are members of the solar system. No evidence exists for orbits of interstellar origin (Marsden and Sekanina, 1973).

B. 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 (Öpik, 1932, Oort, 1950). Perhaps 10^{11} comets with a total mass comparable tc that of the Earth still remain, as Oort suggested, perhaps many more.

C. The basic cometary entity is a discrete nucleous (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 com-

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Table 1

Observed Composition of Comets

HEAD:	H, C, C_2, C_3, CH, CN, $^{12}C^{13}C$, HCN, CH_3CN, NH, NH_2, [OI], O, OH, H_2O, Na, Ca, Cr, Co, Mn, Fe, Ni, Cu, V,
TAIL:	CH^+, CO^+, CO_2^+, N_2^+, OH^+, H_2O^+, and Continuum from particles including Silicate 10-um band.

parable amount of heavier elements as meteoric solids must occur in comets because of the observed radicals, molecules and ions, in Table 1. (Whipple, 1950, 1951. Delsemme and Swings, 1952, Swings, 1965).

D. Cometary meteoroids are fragile and of low density (McCrosky, 1955, 1958. Jacchia, 1955).

E. The comet nuclei as a whole must never have 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, by supernovae for example, are not excluded.

F. Comets were formed in regions of low temperature, probably much below 100 K.

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G. Comet nuclei are generally rotating, but in no apparent systematic fashion and with unknown periods in the range from about 3^h to a few weeks, based on non-gravitational motions and the delayed jet action of the icy nucleus.

H. The nuclei, at least of three tidally split comets, show evidence of a weak internal compressive strength the order of $10^4 - 10^6$ dyne cm^{-3} (Öpik, 1966) and evidence of little internal cohesive strength.

I. 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 distances. The evidence for clathrates by Delsemme and Swings (1952) coupled with the probable ejection of ice grains at great solar distances (Huebner and Weigert, 1966) and the behavior of Comet 1963f support 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 (1972) 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 (1964, C. Ikeya, 1963I) and Owen (1973, C Tago-Sato-Kosaka, 1969 IX).

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,

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C_2, C_3, and now CH_3CN and HCN in comets along with the low density and friability of the cometary meteoroids indicate non-equilibrium 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 a.u. 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 (Oort, 1950) (note exception in 4 below).

4. That the comets formed concurrently with the solar system some 4.6×10^9 years 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. P/Encke, for example, shows a low dust/gas ratio in its spectrum but has contributed enormously to the interplanetary meteoroid population.

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THE ROLE OF COMETS IN THE ORIGIN OF THE SOLAR SYSTEM*

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:

*The reader is referred to V. S. Safronov's comprehensive book "Evolution of the Protoplanetary Cloud and Formation of the Earth and Planets" (Izdatel ' stvo "Nauka, Moscow, 1969; translated into English by the Isael Program for Scientific Translation and published by NASA, 1972) 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 Kuiper (1951), Urey (1952), Levin (1958), Cameron (1962), Whipple (1964), Alfvén and Arrhenius (1970 a,b), Nobel Symposium 21 (1972) and Opik (1973). For concepts of comet or solar system origin deviating from the "classical," see Sourek (1946), Lyttleton (1948), Whipple (1948 a,b), Trulsen (1972), O'Dell (1973) and especially Cameron and other contributors to the Symposium at Nice "On the Origin of the Solar System" (1972, Edition du Central National de la Recherche Scientifique 15, Quai Anatole France, Paris).

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I. In the other regions of the forming planetary system beyond proto-Saturn (Kuiper, 1951; Whipple, 1951), or

II. In interstellar clouds gratitationally associated with the forming solar system but at proto-solar 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 (Whipple, 1951; McCrea, 1960; Cameron, 1962).

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 (Ramsey, 1967) 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 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 (1950) 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 comets 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 a.u. 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 an earth mass of comets in large orbits appears to be required as an end product but a hundred earth masses may originally have been involved. Öpik (1965, 1973) is doubtful about the process unless the comets formed near Jupiter; Everhart (1973) finds it highly unlikely while Levin (1972) provides the angular momentum from proto-Uranus and proto-Neptune by forming these planets at very great solar distances (up to 200 a.u.) 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 that the supply at great distances (Marsden and Sekanina, 1973) has been replenished by those in smaller orbits, more stable against stellar perturbations. Indeed Öpik (1932) 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 (see Hartmann, 1972) and volatiles on the terrestrial planets (Lewis, 1974).

Alternative II, of 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 (1973) 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 gm/cm^3) for meteoric "solids." Sekanina (this volume) 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 anywhere in space beyond perhaps 30 to 50 a.u. from the center of the proto-solar-system. Levin's (1972) concept of comet growth up to 200 a.u. is entirely consistent with such growth, as is alternative II, fragmented interstellar clouds at far greater distances. Safronof and Levin's requirement of excessive material (perhaps 30 - 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 might mot cohere when exposed to solar radiation sublimating the ices and thus not provide the much larger meteoroids or the large dust particles in Comet Kohoutek.

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 (1972) 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. Anders, however, presents strong evidence that even the most primitive carbonaceous chondrites (Type 1) are not of cometary origin (1974 private communication).

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 over-all 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 only 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 towards 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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DISCUSSION

B. Donn: I think that these volatile materials were collected not atom by atom but by condensation into your whiskers and snowflakes, which then accumulate, volatile or non-volatile, until you get a comet.

F. L. Whipple: So you go with the whiskers and snowflakes?

B. Donn: Yes.

F. L. Whipple: You then accumulate them rather than to collect them all? The point is that the solids have to be intimately associated with the volatiles to make the thing break up. You can't have very big solid pieces by themselves. You have to mix them together in some fashion like that. I think the point is rather technical. We'd have to define our terms rather carefully, I believe, to see where we agree to disagree; and I don't think if we voted we'd know for sure what we were voting on.

A. H. Delsemme: I have one question. When you speak about the solar abundance, do you accept my depletion of hydrogen?

F. L. Whipple: Oh, yes, of course. I'm talking about condensables and condensable materials; therefore, you've lost volatiles. But you started, I presume—you could start with something like that. I think that's a reasonable assumption. I certainly would defend that one very strongly.

M. Dubin: The isotope ratio of oxygen in Allende does not fit that?

F. L. Whipple: I didn't know there were any disagreements in isotope ratios. Oh, you mean that's a meteorite?

B. Donn: Yes.

F. L. Whipple: Well, we're not talking about meteorites we're talking about comets.

Where were they formed? It seems that we're pretty well limited to those two regions and interstellar clouds that were probably gravitationally associated

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with the solar system. It's hard to see how we can capture them unless they were originally there.

I presume capture is a possibility, but these two suggestions I made in 1950 or '51 and I still would like to know the answer. Last slide.

(Slide.)

This is a plug. Only space missions to comets and asteroids can give us this quantum jump knowledge that will lead to the solution of the most fundamental problems of the solar system. Enough of that.

Well, we have three minutes for discussion if we are going to give Dr. Mendus time for his presentation. Who wants to argue about something?

M. Dubin: What is the shape of the nucleus if you assume that all comets have an angular momentum and they condense way out in space? Would the shape be disk-like, donut-like, or spherical; and why?

F. L. Whipple: I think the answer is that whenever you accumulate things you've got an irregular body that's something like a sphere. What else can you get? There's a little angular momentum that might flatten it a bit, so maybe it's an oblate spheroid or nearly sphered with some irregularities on it. I don't know.

H. Keller: What is the importance now of clathrates as compared to ices? We seem to have both. Is it important to make a difference between ices and clathrates?

A. H. Delsemme: It's not really important. After all, I have emphasized that we shouldn't attach too much importance to this label "clathrates," because, after all, we have shown recently—I have shown with Miller—that the clathrates are, after all, limits of the absorption of gases in water ices or water snows. Therefore, if you are willing to speak about absorption, that's okay.

F. L. Whipple: I want to thank the participants for their patience in rushing through this. I want to make two last comments.

I think Dr. Huebner's suggestion of more laboratory work is extremely important, and I hope that none of you will forget about it. And I hope that NASA particularly will remember it.