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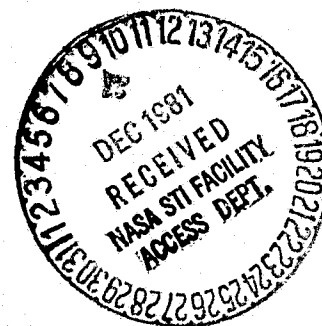
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Structure and Origin
of Cometary Nuclei

Bertram Donn and Jurgen Rahe

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Bertram Donn
NASA/Goddard Space Flight Center
Laboratory for Extraterrestrial Physics
Greenbelt, Maryland 20771

Jurgen Rahe*
NASA/Goddard Space Flight Center
Laboratory for Astronomy and Solar Physics
Greenbelt, Maryland 20771

* NAS/NRC Senior Resident Research Associate
Permanent Address: Astronomical Institute, University of Bamherg
Erlangen, F.G.R.

Abstract

There is strong evidence that a comet nucleus consists of a single object whose basic structure is Whipple's icy conglomerate. In this review we consider only such models. Derived radii fall in the range 0.3 – 16 km. With an adopted density of $1/g\ cm^3$, masses are between $10^{13}-10^{19}$ g. Two out of nearly 700 radii appear to be between 50 and 100 km. A number of cometary phenomena indicate that the nucleus is a low density, fragile object with a large degree of radial uniformity in structure and composition. Details of the ice-dust pattern are more uncertain. A working model is proposed which is based on theories of accumulation of larger objects from grains. This nucleus is a distorted spherical aggregate of a hierarchy of ice-dust cometesimals. These cometesimals retain some separate identity which lead to comet fragmentation when larger components break off. The outer layers of new comets have been modified by cosmic ray irradiation in the Oort Cloud. Current experimental research may account for the observed greater activity of new comets at large heliocentric distances. As a comet ages during successive perihelion passes, an inert dust layer gradually builds up on the surface, changing the characteristics of coma development. This process can ultimately cause comets to become inactive and become the Earth and Mars crossing asteroids. Meteoric fireballs are associated with comets and are consistent with the fragile and fragmentizable nature of the nucleus. The evidence for meteorite-comet association is still controversial. Current dynamical studies do not seem to require a cometary source of meteorites. Their presence in nuclei is not readily explained and requires a two-stage accumulation mechanism. The survival of comets in the Oort Cloud seems well established although the place of formation is uncertain. Various hypotheses have been proposed, from the asteroid zone to interstellar clouds. The most likely source appears to be the region of the outer planets or interstellar clouds in some way associated with the primordial solar nebula.

I. Introduction

Comets are best known for spectacular and nearly always unpredictable appearance of the brighter objects. It is this strange and awesome behavior which has given rise to early myths concerning their role in warning of coming

misfortune. In destroying the myth of comets as supernatural objects, modern science has endowed them with an equally engaging and more significant property. The changing appearance of a coma and tail tells us of the present environment of interplanetary space with which it interacts. Comets are also indicators of the remote past when they accumulated in a primordial cloud from which the sun, planets and stars also formed. They have also been proposed as a major stage in the accumulation of the giant planets (Whipple, 1964; Opik, 1973).

Because of their small size and remoteness from the sun, material was stored in comets in relatively unchanged form. The release of this material as they pass through the inner solar system, provides data about their original composition and present environment. Unfortunately, the information we receive from a comet at the present time is akin to transmissions from satellites and space probes whose telemetry data is only partially received, and for which the telemetry code is only partially known. This causes a great deal of uncertainty and confusion about the interpretation of the data.

In this review, attention is focussed on the cometary nucleus. This is generally conceived of as a solid structure which forms the permanent part of a comet as it revolves around the sun. As it approaches within about five astronomical units of the sun, the energy present in the inner solar system causes gases and small grains to be ejected from the nucleus, forming the coma and the tail. Material comprising these features is continuously released and lost to space when the comet is a few AU from the sun making it part of the interplanetary medium. Consequently, the coma and tail must constantly be replenished during the comet's apparition.

One is faced with devising a model of a permanent object that revolves around the sun, forms a coma and tail near perihelion and changes little at successive apparitions. Another important characteristic of the nucleus is its ability to survive extremely close solar passage. The "sun-grazers" come within a solar radius of the photosphere where bodies of 30 cm diameter would be destroyed (Russell, 1929). At much greater distances all volatiles would be lost and many-body nuclei would not survive at perihelion distances of a few tenths AU typical of many comets. An analysis by O'Dell (1973) concluded

that for dynamical reasons the only stable form of a many body nucleus is to collapse into a single object. Whipple (1963) has discussed models for the structure of the nucleus in more detail and raised several other difficulties with sand-bank and many-particle structures. The present analysis reaches the same conclusion as Whipple did earlier, and is now generally accepted, that the best working model is an icy nucleus with embedded solids.

In the following sections we first discuss various observational phenomena of comets that are relevant to this review. A brief presentation of basic statistics of comets is followed by a description of cometary phenomena associated with mass loss and disintegration. This leads to conclusions on cometary lifetimes and the preservation of comets over long times. Following this we come to the first details of the nucleus itself. A description of likely internal structures of an icy nucleus is given next. Next, the evolutionary changes in structure and composition are considered. We briefly comment on surface structure and composition including changes with time. The relationships among comets, asteroids and meteorites are discussed and the review concludes with considerations on cometary origin. The chemical composition is discussed in considerable detail by Delsemme in his chapter and omitted here.

We do not seek a definitive description of the nucleus. Rather, our aim is to present a working model, consistent with present data and which could serve as a sound base for further research. One has, however, always to keep in mind the individual nature of comets and the wide variations among their observed behavior, as well as the incomplete character of cometary data. Our knowledge of the cometary nucleus is fortunately increasing at a significant rate, especially due to ultraviolet observations and observations of comets at large heliocentric distances, many of which are reviewed in other chapters. These recent developments are fortunate for cometary studies, but present problems for the preparation of a review of the nucleus. An accurate description of a comet nucleus will require imaging from a spacecraft with high spatial resolution, remote sensing and sub-surface sounding capabilities.

II. Orbits and Statistics

Comets have the most variable properties of any objects in the solar system. This is true not only intrinsically, as with changing appearance as a comet approaches the sun, but also with regard to the range of orbital, luminous and spectroscopic characteristics.

A distribution of comets among the different categories of orbits taken from Marsden's (1979) catalogue, is given in Table 1. This catalogue lists orbital elements for 1027 cometary apparitions of 658 individual comets observed between 87 BC and the end of 1978. The orbits upon which Table I are based are the oscillating (instantaneous) orbits relative to the sun. To determine the major axis prior to the comets approach to the sun and planets two corrections are necessary. The change in energy caused by planetary perturbations and by the shift from heliocentric to barycentric orbits needs to be added. With the further inclusion of non-gravitational effects, there is no well determined original orbit that is definitely hyperbolic (Marsden et al., 1978). Comets are called "new" when they have extremely large semi-major axes, $1/a < 100 \times 10^{-6}$ AU^{-1} and presumably coming from the Oort Cloud into the planetary system for the first time. "Old" comets have made some tens of return (Marsden et al., 1978).

The perihelion distance of known comets varies from 0.005 to 6.88 AU (Comet 1975II). Long-period comets have an average perihelion distance $\bar{q} = 1.08$ AU, whereas short-period comets have $\bar{q} = 1.61$ AU. There are 9 "sun-grazers" with $q \approx 0.01$ AU. Eight of these are clearly related (Table 2) and are probably the fragments of a single parent (Marsden, 1967).

Aphelion distances, Q, range from 4 AU to infinity. If there are no comets originally coming from interstellar space (planetary perturbations do eject some from the solar system) the maximum aphelion distance is the outer limit of the Oort Cloud at about 10^5 AU. Of the 113 short-period comets, 50 (44%) have Q between 5-6 AU, corresponding to Jupiter's distance (5.2 AU). The 78 (69%) with Q < 7 AU can be classified as belonging to a "Jupiter family"; the longitude of the nodes of their orbits is strongly concentrated

near 0° and 180°, so that near perihelion and aphelion they are also near their nodes, and comets almost always come closer to Jupiter than to any other giant planet. No other planetary "family" is generally recognized.

Intrinsic brightness variations (bursts) exceeding 1-2 magnitudes are frequently observed among all classes of comets. P/Schwassmann-Wachmann 1 (P=15 years, q=5.4 AU) brightens by several magnitudes about 2 or 3 times a year; the luminosity of P/Tuttle-Giacobini-Kresak (P=5.6 years, q=1.2 AU) increased by 9 magnitudes twice in 1973.

The size of the nucleus cannot yet be determined by direct measurement. Photographic resolution may be as small as 0."5 (Dollfus, 1961) and visual observations can resolve about 0."1 (Kuiper, 1950). The closest a comet has approached the earth was 0.015 AU (Comet Lexall, 1770I). In this century the closest approach was 0.04 AU (Pons-Winnecke, 1927 VII). With modern observing techniques the minimum detectable diameter, visually, would have been 4.5 km and 12 km and photographically, 22.5 and 60 km, respectively. However, a serious problem to observing the nucleus occurs for nearby comets because of the surrounding luminous coma which will interfere with the resolution.

At some sufficiently large heliocentric distance the coma becomes apparently non-existent. The comet then has a sharp, stellar appearance and its luminosity is presumably caused by reflection of sunlight from the nucleus. The luminosity relative to the sun is readily estimated.

The radius R_c (in km) of the assumed spherical nucleus is given by:

$$\log R_c = -0.2\, m_c - 0.5\, [\log \alpha + \log P(\theta)] + \log r + \log \Delta + 2.81 \qquad (1)$$

where m_c is the comet magnitude at (r, Δ), r is the heliocentric distance and Δ the geocentric distance in AU; θ is the phase angle, $P(\theta)$ is the phase function and α is the albedo. The radius depends upon α and $P(\theta)$ which must both be assumed. The derivation of the radius is therefore subject to an uncertainty which depends upon the optical properties of the surface of the nucleus and a possible contribution to the luminosity from a still present coma (Sekanina, 1976).

The main uncertainty lies in the value of the albedo. For a clean, rough ice this can be near unity whereas for Whipple's dirty ice nucleus with a crust the albedo can be very low. This point is considered later. Roemer (1966) tabulates dimensions for two values, $\alpha = 0.7$ and 0.02. Table 4 includes her listing and those of Whipple (1978a) and Kresak (1973). Values were recalculated for an assumed albedo of 0.3.

Radii range upward from 0.3 km; they are typically 1 - 2 km for short-period comets and may be up to an order of magnitude larger for long-period comets. Very rare, much larger comets appear to occur with 50 - 60 km radius and masses of about 10^{21} g, e.g., the parent of the sun-grazers or the Great Comet of 1729 that could be seen with the naked eye at 4 AU from the Sun.

Cometary nuclei are also too small for direct determination of mass, except by some future comet probe. They have produced no detectable effects on the orbital motion of other objects which is the only way to measure masses in the solar system. Upper limits can be obtained in this fashion (Laplace, 1805). Roemer (1966), for Comet Wirtanen 1957 VI, found a radius of the comet before splitting of 16.5 km (with an assumed albedo of 0.3), and of the primary component after splitting of about 10 km; with unit density these correspond to masses of about 2×10^{19} and 4×10^{18} g, respectively.

Masses may be calculated from the radii of Table 4 and an assumed density. For an icy nucleus a density of $1 g/cm^3$ should be reasonable (Donn, 1963). The data yield cometary masses between 10^{13} and 10^{21} gm. Most nuclei would fall between 10^{14} and 10^{17} gm.

III. The Structure of the Nucleus

The concept to which the term "nucleus of a comet" is applied is often confusing. In this review we mean by cometary nucleus, the permanent structure which orbits the sun and is the bearer of the cometary mass. Observational descriptions of comets often refer to a "stellar nucleus" within the diffuse coma. This is best described as the "photometric nucleus." Other

uses of the term also exist (e.g., Vorontsov-Velyaminov, 1946).

The prevailing model prior to 1950 was some form of the "sand-bank" hypothesis, wherein the nucleus was thought of as a diffuse cloud of small particles, traveling together. Lyttleton (1953) has described his version of the sand-bank model and an interstellar accretion mechanism for its formation. However, following Whipple's (1950) description and analysis of the nucleus as a single aggregate of ices and meteoric matter, this icy conglomerate became the generally accepted hypothesis. A detailed analysis of the two models which offers strong support to the icy conglomerate structure and raises serious objections against the sand bank version has been given by Whipple (1964).

The principle arguments favoring the icy conglomerate over the sand bank model are: (1) the relatively large ratio of volatile to non-volatile material required to account for the formation of the coma near the time of each perihelion passage and the repetition of this gas loss for the many revolutions of short period comets; (2) the occurrence of non-gravitational forces which are not consistent with a sand-bank model; (3) the similarity of pre- and post-perihelion appearances of sun-grazing comets, requiring nuclear aggregates which are at least meters in diameters; (4) the splitting of comet nuclei cannot be reconciled with a sand-bank model and is difficult to explain with a collection of large numbers of larger particles; and, (5) tidal and Poynting-Robertson forces would disrupt a sand-bank nucleus and a many particle model. These structures are not consistent with the observed splitting of sun-gazing comets. The icy conglomerate model on the other hand is reasonably consistent with the observed behavior of comets, and the arguments against the sand-bank model seem sufficiently strong that the remainder of this review will be based on the icy-conglomerate model.

Models for Cometary Nuclei

Several structures for an icy nucleus have been proposed since Whipple put forward the ice with embedded dust model, the icy conglomerate, in 1951. O'Dell (1973) showed that a gravitationally bound, many particle nucleus in the Oort cloud would collapse into a single icy-conglomerate structure if it

were to survive as a comet. The resultant structure would appear to resemble a Whipple type icy nucleus, except that the volatiles are interstellar material. During successive perihelion passages the volatiles gradually diffuse out and vaporize leaving the grain cores behind. These form a porous matrix as Mendis and Brin (1977, 1978), Brin and Mendis (1979) and Weissman and Kieffer (1981) have discussed in detail. O'Dell suggests that the non-volatile mantle, thus formed would be similar to carbonaceous chondrite meteorites. However, the residue left behind would be extremely porous and of low density. Such structures seem better associated with the fragile fireballs observed by the Prairie Network (Ceplecha, 1977) than with meteorites.

The model just described resembles that suggested by Sekanina (1972) consisting of a porous matrix of solid material, with ice filling the pores. Initially, the distribution of the two components is uniform throughout the nucleus. Sekanina rejected the ice nucleus with embedded dust for comet Encke because it yields a continuously increasing non-gravitational parameter proportional to $\Delta M/M$. Observationally, the non-gravitational force has been decreasing with time for Comet Encke. To get a more satisfactory fit with various features he proposes a core with an overlying ice mantle. In a recent paper Whipple and Sekanina (1979) derived a rotation period and orientation of rotation axis for Comet Encke. They showed that the time variation of the non-gravitational force results from precessing of the spin axis rather than a rapid decrease in the non-gravitational force. Although the reason for proposing this model no longer applies, the structure has features relevant to possible relationships between comet and asteroids (Sekanina, 1971) and is considered in that section of this review.

A modification of the snowball structure has been developed (Donn, 1980) based on theories of accumulation of planets (Safronov, 1972; Goldreich and Ward, 1973; Greenberg et al., 1978). This is a further development of earlier work (Donn, 1963). The concept of those investigations, that small solid grains produce gravitational instabilities in a cloud on an planetary scale, was shown by Biermann and Michel (1978) to apply to comet accretion also. In these unstable zones, gravitational collapse causes small grains to grow into larger aggregates on a short time scale.

Detailed investigations of the accumulation of planetesimals to form planetary objects have been carried out by Safronov (1972) and Greenberg et al. (1978). A recent review has been given by Wetherill (1980). These analyses show that a size distribution of planetesimals forms as illustrated in Figure 9 of Greenberg et al. (1978). The mechanism of comet formation can be expected to be similar on a much smaller scale, as the final objects have kilometer dimensions. The size distribution of aggregates leads to a comet nucleus composed of an agglomeration of cometesimals with a size distribution of the form $n(m) \propto m^{-5}$. Figure 1 is an attempt to portray such a nucleus. It is expected that the individual cometesimals retain some degree of their identity. This is exaggerated in the figure.

The larger cometesimals may be bound to the nucleus only over a fraction of their surface and therefore very weakly attached. Such fragments could readily break off from a vaporizing, rotating nucleus. The larger pieces would become visible as small comets breaking away from the primary nucleus, each fragment having the characteristics of a small comet. The behavior of fragmenting comets according to this model would follow the pattern described by Sekanina (1977). Although obtained in a completely different way from that considered by Whipple (1978b) and described in the section on the outer layer of a nucleus, the present model of nuclear structure appears to lead to a somewhat similar picture, particularly for the outer region.

Internal Structure of an Icy Nucleus

The general considerations on an icy nucleus were combined with views of planet accumulation from small grains to develop a model for the internal characteristics of the nucleus (Donn, 1963). Accretion of comets, with their high proportion of volatile species requires low temperatures and low relative velocities. Velocities below about 0.05 km s^{-1} would preserve grains of all but the most volatile species, H_2, CO and CH_4. This would yield aggregate with densities below 0.5 g/cm^3, based on the characteristics of wind-blown snow (see Donn, 1963).

Central pressures P_c, surface gravity, g, and escape velocity, v_e, respectively, are given by:

$$P_c \approx 2/3 \pi G \bar{\rho}^2 R^2 \qquad\qquad (2)$$

$$g \approx 4/3 \pi G \bar{\rho} R \qquad\qquad (3)$$

$$v_e = (8/3 \pi G \bar{\rho})^{1/2} R \qquad\qquad (4)$$

where G is the gravitational constant, $\bar{\rho}$ is the mean density and R the radius. From these equations we obtain Table 4 adopting a density of $1g/cm^3$. Measurements on the compaction of snow were summarized by Donn (1963) and we take Figure 2 from there. These results indicate that no significant compaction occurs for nuclei of less than 10 km radius. The impact velocity due to gravity also does not affect the structure until the comet grows well beyond 10 km.

Meteoric particles are embedded throughout the icy mass as demonstrated by meteor streams and intense showers associated with short period comets. These meteors have low densities and the latest results have been summarized by Millman (1972, 1975). Verniani (1969, 1973) found a populous low density group, $\bar{\rho} = 0.2$ gm/cm^3, consisting of 85%, and a high density group, $\bar{\rho}$ 1.4 gm/cm^3, consisting of 15%, of the total among sporadic meteors. Fourteen showers had low density meteors, $\bar{\rho} = 0.2$ gm/cm^3. The Draconids, associated with Comet Giacobini-Zinner, have extremely low density, 0.01g 1 cm^3, and are very fragile meteors. For such low density fragile aggregates to be embedded in icy masses, similar porous ices appears to be required as, e.g., Whipple (1955, 1970) suggested.

The occurrence of fragile meteors in comets is one of several lines of evidence that indicate cometary nuclei themselves must be low density, fragile objects. More direct evidence is the tidal disruption of sun-grazing comets (Opik, 1966a). Opik finds the nucleus of the two fragmenting sun-grazers (comets 1882 II and 1965 VIII) weaker than all materials except meteoric "dust balls". A third indicator is the occurrence of fragmentation among

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comets at heliocentric distances up to 9 AU (Sekanina, 1981a). He lists twenty-one split comets or about 3% of the total. Thus, theoretical ideas of comet accumulation and observations of cometary phenomena agree in predicting fragile nuclei, with low but finite cohesive strength.

Evidence for Radial Uniformity

Although a noticeable difference between the inner and outer zones of an icy nucleus might be expected, several observational phenomena do not suggest this to be the case. (1) The continuum/emission intensity ratio in the spectra of comets appears to have similar distributions for "new" and for short period ("old") comets (Donn, 1977). These extreme groups with regard to age show no difference in the dust/gas ratio or the character of the solid particles. (2) In addition, the emission spectra of new and periodic comets seem to be similar, in the visible as well as in the ultraviolet spectral region. Narrowband filter photometry for 6 comets by A'Hearn and Millis (1980) showed that the CN/C_2 production rate ratio was remarkably constant ($\pm$ 0.1 in the log) from comet to comet, except for a well defined variation with heliocentric distance. The relative production rates, specifically of CN, C_2, C_3, and OH, appear to be unrelated to either the emission-to-continuum (gas-to-dust) ratio or the dynamical age of the comet. The ultraviolet spectra (Feldman, 1981) of a number of long period (Seargent 1978 XV, Bradfield 1979 X, West 1976 VI), and periodic (P/Encke, P/Tuttle, P/Stephan-Oterma) comets were found to be remarkably similar, indicating again a homogeneous structure of the nucleus. There have been no ultraviolet spectra of new comets to date. (3) The seventeen fragmenting comets in Sekanina's (1981a) review which have well determined orbits and were not sun-grazers may be classified as; four periodic, five old, and eight new or nearly new. The proportion of these values to total comets in each category (Marsden, 1979) are; 0.04, 0.04, 0.02, respectively. In terms of total appearances rather than invididual comets these ratios become; 0.01, 0.04, 0.02. In view of the small numbers there does not seem to be any significant difference among the three age categories. If splitting is intrinsic to a comet, the nuclei of "new" and very old comets behave similarly. Sekinina (1977) also showed that the relative non-gravitational effects for the

fragments were proportional to the lifetime for all categories. He also suggests (Sekanina, 1980) that the behavior of these fragments is similar to that of comets that were observed to dissipate during their apparition.

IV. The Outer Layer of a Nucleus and Its Evolution

Our primary concern in this review is with initial characteristics of nuclei. During perihelion passage, very pronounced evolutionary effects will occur on the volatile, fragile cometary nuclei. The analysis and interpretation of cometary observations need to consider such changes (see e.g., Shul'man, 1972a Mendis and Brin, 1978; Whipple, 1978).

The initial surface change occurs while a comet is in the Oort Cloud undergoing irradiation by galactic cosmic rays. This process was discussed by Shul'man (1972b), Donn (1976), and Whipple (1977). It was pointed out that significant chemical effects are expected. Shul'man and Donn showed that the chemical composition of the outer layer, to a depth of about one meter, would be considerably transformed. Production of new species was emphasized by Shul'man. Both Donn and Whipple called attention to changes in the expected behavior of the material, with the first author suggesting the volatile matter may polymerize and become more inert and the latter believing the material would become more reactive. Experimental results of energetic proton irradiation of ice mixtures were presented by Moore and Donn (1980). They found evidence for gas release between about 15-40 K and near 150 K. A non-volatile residue was also produced and contained a few percent of the original material. Earlier, Patashnik et al. (1974) concluded that energy released by the amorphous to crystalline ice transition could cause enhanced gas release at about 150 K. More recent considerations of the role of amorphous ice have been given by Klinger (1980) and Smoluckowski (1981a, b).

In his initial presentation of the icy model, Whipple (1950) pointed out that the larger, non-volatile particles will not be carried away. An inert, insulating layer would form and have a large influence on the behavior of the nucleus. This effect was examined in subsequent papers (Whipple, 1951, 1955). Formation of a crust and its consequence has been examined in several investigations since then, e.g., Shul'man (1972); Mendis and Brin (1978)

(1979) Brin and Mendis (1979) Weissman and Kieffer (1981). The last papers
contain the most detailed study. Mendis and Brin assume an initially
homogeneous ice-dust nucleus. As the comet approaches perihelion some
fraction of the dust is not carried away by sublimating ices and remains
behind or falls back on the nucleus. Temperatures and vaporization rates were
calculated. From the latter, the authors determined monochromatic magnitudes
of specific species as a function of heliocentric distance, both before and
after perihelion. A significant past-perihelion decrease in luminosity was
predicted.

In a quantitive investigation of luminositiy variation with heliocentric
distance, Whipple (1978) found a significant difference between pre- and
post-perihelion brightness variation for new and very long period comets. The
exponent of r in the relation $m(r, \Delta=1) = H_{r,1} + 2.5 \, n \log r$ increased after
perihelion. The reverse was true for shorter period comets except for those
with P < 25 years for which the behavior was erratic. As pointed out earlier
Whipple believes "new" comets have active, irradiated surfaces which are
responsible for the "excess" luminosity of "new" comets at large distances.

Whipple envisages the outer, surface region of a comet as being irregular
in structure with some non-uniformity also in composition. This is the result
of formation by the agglomeration of cometesimals. He suggests these
cometesimals have cores more cohesive and less volatile than the matrix
materials. Whipple traces out an evolutionary process of such a nucleus
whereby more coherent, darker clumps, called globs, develop in comets. These
globs may give rise to fireballs as those associated with Comet Encke or
observed by the Prairie Network, some of which are associated with other
showers (Wetherill, 1974). With the passage of time surface globs develop
into mounds or column as ices sublime and carry away loose meteoric material.
Eventually, they crumble or may be are carried away as objects of considerable
size through rotation of the nucleus, after connnecting material has sublimed.

This picture of a nucleus developed by Whipple from a study of the
luminosity variation of comets is strikingly similar to Donn's (1980) model
based on a probable mechanism of accumulation. A consequence of these
pictures is an expected higher irregular surface structure on meter dimensions

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or smaller. Plans for a comet rendezvous need to take this into account. A mission involving landing on the nucleus must have detailed information on the surface.

Sekanina (1981b) has reviewed studies, mainly by himself and Whipple, of the asymmetrical structures often found in comae. These have been analyzed in terms of non-isotropic ejection from the nucleus. Their results support the picture of a heterogeneous surface consisting mostly of regions of relatively low gas emissions with small, discrete zones of high emissivity producing the jets. According to Sekanina's analysis, the active regions emit for times of the order of 0.1 day. The bursts of gas and dust tend to reoccur on several successive rotations.

The absence of jets in many comets would be indicative of a more uniform surface. There appears to be a variation of surface structure among comets of a given "age". Whipple and Sekanina did not discuss the spectral characteristics of the comets, particularly the emission/continuum ratio and its possible connection to surface behavior.

V. Comets, Asteroids and Meteorites

A definitive answer to the relationship between comets and asteroids or comets and meteorites will provide valuable insight into the origin and structure of the nucleus. These relationships are, however, still unresolved problems. Extensive discussions and further references appear in several symposia proceedings and reviews (Gehrels, 1971, 1979; Delsemme, 1977; Wetherill, 1981).

The earliest suggestion of such a relationship may have been by Kirkwood following the discovery of asteroids as (132) Althea with eccentric orbits. Following the detection of earth-crossing Apollo-type asteroids, Opik (1963) proposed them as possible cometary residues. As few comets are larger than a few kilometers, they only seem capable of accounting for the very smallest asteroids. However, the original comets may have been much larger (Sekanina, 1971). Earth crossing Apollo-type or near Earth, Amor-type, asteroids are small (Opik, 1963) and only a small fraction is expected to have been seen.

Opik concluded that these objects cannot have come from the asteroid belt but that a cometary source is not unreasonable. Later work by Wetherill and his associates, see Wetherill (1979), showed that resonance processes could transform asteroid belt objects to earth-crossing orbits. It now appears that Apollo-Amor Asteroids have a mixed asteroidal-extinct comet source. Kresak (1980) reached a similar conclusion. He points out that it is very unlikely that all types of objects in the solar system have been discovered and gives examples of recent findings. Chiron (1977 UB) between Saturn and Uranus and 1978 SB, an asteroid in an orbit closely resembling that of Comet Encke are significant examples.

If a comet developed into an asteroid, essentially all volatiles must have been lost and a substantial (> 1 km) residue remain. Such a structure is consistent with the nonvolatile matrix-embedded ice model. However, it is difficult to derive a mechanism to yield such a structure. The non-volatile matrix must be formed first and have sufficient cohesive strength to stay together. The pores must then be filled with ice. It is this process that presents problems as an outer ice layer will form first and prevent filling the interior. To avoid this and obtain a radially uniform composition would require an implausible temperature distribution and time variation.

An evolutionary history which would convert comets into Apollo-Amor type asteroids appears best explained by the vaporization of Whipple's ice-dust conglomerate (Whipple, 1951; Opik, 1963; Levin, 1977). An accumultion of non-volatile and icy grains or perhaps non-volatile cores with icy coatings forms a dirty snowball. As the ices sublime and larger non-volatile aggregates are left behind, a crust forms. This gradually encompasses the entire nucleus to a sufficient depth that the deeper lying volatiles no longer are heated sufficiently to vaporize. The inert residue, appreciably smaller than the original comet, becomes the Apollo type asteroids. Detailed treatments of dust layer formation by Mendis and Brin (1977, 1978), Brin and Mendis (1979) and Weissman and Kieffer (1981) were referred to previously. Opik (1963), Marsden (1971) and Sekinina (1971) have described a variation of the above procedure. They start with a nucleus consisting of a non-volatile core and an ice-dust mantle. Complete vaporization of the volatile material leaves an inactive residue.

Opik (1964, 1966a,b, 1969) proposed a cometary origin for meteorites because of the dynamical problem of getting objects from the asteroid belt into earth-crossing orbits. An efficient process seemed required in order to account for the short cosmic-ray exposure ages, tens of millions of years for stones and hundreds of millions for irons (Anders, 1963). Subsequently, Williams (1973) and Zimmerman and Wetherill (1973) found more efficient mechanisms for perturbing objects from the asteroid belt into earth-crossing orbits. These schemes can provide the differentiated iron and stony meteorites (Wetherill, 1979). Because of short collision lifetimes the direct source of chondritic meteors cannot be the asteroid belt. Wetherill and Williams (1979) conclude that the earth-crossing Apollo-Amor asteroids may be capable of yielding the entire flux of chondritic meteorites. They also conclude that the Apollo-Amor objects themselves may be derived from a mixture of asteroidal and cometary sources. At this time, there does not appear to be unambiguous evidence for a cometary source of meteorites although there may be a need to supply chondritic meteorites from comets. In addition, the necessity of postulating a cometary source of meteorites to account for the short cosmic ray exposure ages is unclear. The extremely complex dynamical aspects of planetary encounters and perturbations for small objects has not yet been completely analyzed.

For the purpose of this review we examine the implications for nuclear structure if meteoritic material exists in comet nuclei. It is now well established that fireballs are associated with comets, e.g., Taurid shower fireballs with Comet Encke and Prairie Network fireballs (Wetherill, 1974) can be associated with several other cometary meteor showers. As indicated earlier such fragile and low density objects do not appear to present a serious problem. There are, however, serious difficulties with meteorites in comets. Anders (1971, 1978) has given several arguments favoring an asteroidal over a cometary source of meteorites. He has emphasized the large size of the parent needed to obtain a sufficiently large regolith to provide the solar-wind induced gas center. He concludes that no stony meteorites, including the carbonaceous chondrites, are derived from comets. Irons and stones (Wood, 1967) require large parent bodies to obtain the high temperatures and slow cooling necessary to produce the crystalline structure

of these meteorites. Levin (1977) also concludes that the high temperatures required and the complex history needed to account for brecciated meteorites rules out a cometary source. At the low temperatures and pressures found in cometary nuclei, no known physico-chemical processes can yield meteorites. One might say, as we just pointed out about the dynamical processes yielding earth-crossing fragment, that we do not yet completely understand all the factors entering this problem either. To some extent that is true but it is doubtful if the gaps in our knowledge allow for mechanisms producing the complex crystal structure of meteorites at low temperatures ($150°$ C) and pressures. Metallic iron-nickel masses have been produced (Bloch and Muller, 1971) by the condensation of vapor produced by the dissociation of iron and nickel carbonyl. Carbon, sulfide and phosphide phases could be formed by proper vapor composition. These experiments however, are still far from producing the complex meteoritic minerals.

Because of the inability to produce meteoritic material in comets, Opik (1966b) proposed a two stage mechanism. Meteorites are broken off fragments of larger bodies, where the pressure and temperature were sufficiently high to cause compaction and melting of the original loose condensate. The fragments become coated with ices and are then ejected to the outskirts of the solar nebula. In this way comet nuclei would have formed. Some comets, according to Opik's hypothesis, would be first generation products without meteoritic inclusion, those with meteoritic objects are second generation. As the ices subsequently sublimed during perihelion passage, meteorites or small asteroids developed. If the cometary origin of meteorites is accepted there seems to be no way of avoiding a process of this nature.

VI. The Origin of Comets

It is generally assumed that the formation of comets occurred at the time of formation of the solar system (e.g., Whipple, 1964; Opik, 1973, Delsemme, 1977). It has also been recognized that comets accumulated from a cloud of ice-dust grains at low temperatures and low relative velocities (Levin, 1962; Donn, 1963; Opik, 1973).

What is not generally agreed upon is the region where comets formed. Several authors (e.g., Strömgren, 1924; van Woerkom, 1948; Sekanina, 1976b; Noerdlinger, 1977) have shown that the absence of clearly hyperbolic original orbits strongly argues against comets coming from interstellar space; the largest eccentricity observed so far measures e = 1.006. It seems likely that observed comets have always been connected with the sun in some manner. Oort's (1950) proposal for a cloud of comets orbiting the sun at $\sim 10^4$-10^5 AU serves as the basis for investigating the history of comets, e.g., Everhart, (1981); Weissman, (1981).

The question that is most uncertain is how the Oort cloud was formed. Several regions have been proposed for accretion of the nucleus prior to their residence in the Oort Cloud. This subject was reviewed by Delsemme (1977). We discuss the regions here in order of increasing distance from the sun.

(1) The asteroid zone. This region was suggested by Oort (1950) but rejected by subsequent investigators because of problems of ice condensation and subsequent ejection to the Oort Cloud.

(2) The region of the outer planets, Jupiter to Neptune. This is a commonly adopted zone (Whipple, 1964; Opik, 1973; Safronov, 1977). Analysis of the ejection of comets forming between five and thirty AU from the sun has been studied by Opik (1966, 1973). He finds ejection by Jupiter to be inefficient; about one percent of Jupiter-crossing comets are perturbed into the Oort cloud on a time scale of 10^7 years. The remainder are ejected into interstellar space or destroyed by close solar passage. Uranus and Neptune are much more efficient because of the small steps by which 1/a changes but the time scales become too long and amount to $\sim 10^{11}$ years. Fernandez (1981) obtains similar conclusion concerning the efficiency but finds time scales of 10^8 years.

For an average radius of "new" comets of about 3 km and density 1 g/cm^3, the average mass is 10^{17} g. Weissman (1981) obtains 2×10^{12} comets initially in the Oort Cloud or a mass of 2×10^{29} g = 33 earth masses. Calculations indicate a combined efficiency of ejection of comets by the giant planets

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(Fernandez, 1981) and incorporation within the Oort Cloud by stellar
perturbation (Weissman, 1981) of about a few tenths percent. These results
require a cometary mass in the Jupiter-Neptune region of about 0.1 solar
masses.

(3) A comet belt beyond Neptune (30-50 AU). A residual comet cloud
beyond Neptune was suggested by Cameron (1962). Hamid et al. (1968) from a
study of perturbations on Comet Halley concluded that there is less than one
earth mass in this region. In a recent paper, Fernandez (1980) analyzed the
transformation of comets in the belt beyond Neptune to short period comets.
Close encounters between comets perturb some of them into Neptune-crossing
orbits. The Monte Carlo procedure adopts a comet population with the
following characteristics; mass distribution: $n(m) = Am^{-\alpha}$, with $1.5 < \alpha < 2$,
minimum mass of comets $= 10^{15}$ g, maximum mass $= 10^{21}$-10^{26} g, total mass in the
zone amounts to about one earth mass. Orbits of Neptune-crossing comets would
evolve as described by Everhart (1977). Fernandez concludes that short period
comets can be efficiently produced by a reasonable model for the hypothesized
comet belt with the mass at Hamid et al's upper limit. Long period and near
parabolic comets still require the Oort Cloud. There would be two comet
sources which are assumed to have much in common because comets from the belt
beyond Neptune are fed into the Oort Cloud via Uranus and Neptune. Cameron
(1973) has proposed that ejection of comets to large distances would be aided
by a mass loss from the solar nebula and sun during an early T-Tauri stage for
the sun.

(4) Asteroid belt-interstellar cloud. O'Dell (1973, 1976) has proposed a
structure and mechanism of formation of comet nuclei that combines the inner
solar system and interstellar clouds. In this hypothesis micron sized grains
are ejected from the solar system by radiation pressure. O'Dell considers an
interstellar region with a typical density of one hydrogen atom per cm^3 and
relative cosmic abundances. It is assumed that enough grains form a loose,
distant cluster to provide a comet of a few kilometers radius when they
collapse into a single object during approach to the sun. In the age of the
solar system of about 5×10^9 years, each grain has received an ice coating
sufficient to provide for the material lost in ∿ 100 orbits.

There are several difficulties with this hypothesis. Among them is the difficulty of cluster formation by ejected grains at 10^4-10^5 AU and the long time scale for coating grains at interstellar densities. It may be that this process can be modified to provide for cometary meteorites. Instead of grains ejected by radiation pressure, consider fragments of asteroids ejected by planetary perturbations similar to Oort's original proposal. Then let the sun be formed as part of a star cluster with a number of small clouds very nearly gravitationally bound to it. The ejected meteorites are trapped in these clouds which have relatively high densities. Cameron's (1973) sub-discs have densities in the plane of 10^{-11} g cm^{-3} or about 5×10^{12} atom cm^{-3}. The accumulation process analyzed by Cameron (1973) and Biermann and Michel (1978) was used by Donn (1977b) to discuss comet formation directly in the Oort Cloud. If meteorite formation and ejection were rapid enough we can conceive of cometary nuclei containing meteorites as well as finer dust occurring in the Oort Cloud. Although this mechanism is speculative and qualitative, several of the steps have been analyzed in some detail. If it is necessary to explain meteorites as fragments of earth-crossing comets, this process seems to have fewer deficiencies than most other sequence of events leading to cometary meteorites.

(5) Outlying fragmentary clouds from the pre-solar nebula. Cameron (1973) postulated fragments of a few tenths solar mass breaking off from the outer limits of the primordial solar nebula and revolving around it. He suggested that in these smaller clouds numerous small objects could accrete and become the Oort Cloud comets. He applies the mechanism developed for planet accumulation, scaled to the mass and size of the cloud fragment, and concludes that large cometary objects could form in thousands of years. A few sub-disks are expected to provide a sufficient number of comets to form the Oort Cloud.

Biermann and Michel (1978) carried out a study of accumulation of comets from ice-dust grains in the outer regions of a primordial solar nebula with a few solar masses. Their analysis is based upon theories of planetary accumulation developed by Safronov (1972) and Goldreich and Ward (1973). In Biermann and Michel's model the cometary aggregates have aphelia $\lesssim 10^4$ AU. The dispersal of approximately half of the nebula not undergoing collapse into

the sun and planets will cause the orbits to enlarge and form the Oort Cloud. The main distinction to Cameron (1973) appears to be the larger nebular mass which permits sufficient density at great distances to form comets in the primordial nebula.

In yet unpublished work, Biermann (1980) concludes from recent studies on cloud collapse that comets could not form in the same cloud as the sun and planets. He modifies the above process to form comets in a neighboring fragment of the same interstellar cloud as the sun and planets form. This is generally similar to Cameron's scheme described above and essentially identical with that proposed by Donn (1976). That mechanism is described next.

(6) In situ formation in the Oort Cloud. It was pointed out (Donn, 1973, 1976) that the tendency of stars to form in clusters provides a means of comet formation in the Oort Cloud. Galactic star clusters contain the order of a hundred stars within a roughly spherical volume of 5 pc diameter (Hogg, 1959). The average distance between stars is 0.5 pc. The theory of star formation in clusters is essentially non-existent, but a considerable empirical-observational base is developing (de Jong and Maeda, 1977). Following the procedure of Cameron (1973), we accept the existence of subclouds of small mass which cannot produce stars but are capable of forming much smaller mass objects.

In these cloudlets small aggregates form. According to Cameron (1973) and Biermann and Michel (1978) these have masses in the cometary range, i.e., 10^{15}-10^{20} g. The low velocity dispersion of cluster stars, less than 3 km s^{-1} (Blaauw, 1964) and the velocity dispersion of the comet population ensures that many comets will have essentially zero velocity relative to the sun. Thus, the sun will have a comet family moving with it as the cluster disperses.

Greenberg (1977, 1981) and his colleagues (Baas, 1980) propose comet formation in dense clouds. The grains consist of refractory cores with icy mantles that have been heavily photolysed as pointed out by Donn and Jackson (1970). These grains may then accrete into cometary size aggregates as in the interstellar hypothesis just described. According to this hypothesis, the icy material exists on the same grains as the non-volatile component rather than

as separate particles. This is probably the case because of the much more favorable path for condensation on an existing grain compared to nucleation of an icy grain from the vapor.

(7) Periodic formation of solar system comets in interstellar clouds. The preceding hypotheses make comet formation approximately concurrent with the formation of the solar system. McCrea (1975) has adopted a few million years as the age of comets and proposed a mechanism for satisfying this criterion.

As interstellar clouds pass through the shock region in the inner edge of a spiral arm, some are compressed to a degree where dust concentrations are formed and then collapse into comet nuclei. If the sun is in the vicinity when this happens some are captured and become part of the sun's family of comets. Important consequences of this hypothesis are: (a) Comet ages are the order of the in-fall time, a few million years. (b) They appear at intervals approximately given by half of the galactic rotation period or 10^8 years and decay much more rapidly. (c) Sun-comet velocities would have a mean value of several km/sec. The occurrence of parabolic and near parabolic orbits without unambiguous hyperbolic orbits does not seem readily explained. In fact, the observed parabolic orbits are anomalous. (d) There is no way to have an association of meteorites and comets as some authors (Opik, 1966; Wetherill, 1977) propose.

In the process of ejecting comets into the Oort Cloud most cometary objects escape from the solar system. If this ejection phenomena occurred for the solar system it must have been a rather widespread occurrence throughout the galaxy. This would be in addition to the well established planetary ejection (see e.g., Marsden et al., 1978). There would thus be a considerable number of interstellar comets. The suggestion for comets coming from interstellar space has a long history (van Woerkom, 1948). Recent work on this subject is summarized by Noerdlinger (1977).

VII. Concluding Remarks

A review of the structure and origin of comets must bring together a great variety of information from many sources. We have attempted to describe the different phenomena that are involved in constructing a model for the nucleus. Those models that seem generally useful have been described. The same plan was used in preparing the section on cometary origin. Our objective had been to present the material in a form that will permit an investigator working on these problems to take advantage of previous efforts. Although this chapter is not as comprehensive and critical as we initially planned, it is our hope that it will provide cometary scientists with a good starting point for the exciting and often frustrating tasks of studying the structure and origin of comets.

Acknowledgments

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Table 1

Distribution of orbital forms for 1027 apparitions of 658 individual comets observed between -86 and the end of 1978.

Orbital Form	Eccentricity	N	%
Elliptical orbits	e < 1.0	275	42
Short-periodic comets (P < 200 a)	e < 0.97	113	17
long-periodic comets (P > 200 a)	0.97 < e < 1.0	162	25
Parabolic orbits	e = 1.0	285	43
Hyperbolic orbits	e > 1.0	93	15
Strongly hyperbolic orbits	e > 1.006	0	0

TABLE 2

ORBITAL ELEMENTS OF SUN GRAZING COMETS

Comet	T (UT)	q (AU)	e	P(yr)	ω	Ω	i	L	B
1668	Feb. 28.08	0.066604	1.0	...	109°.81	2°.52	144°.38	248°.61	+33°.23
1843 I	Feb. 27.91	0.005527	0.999914	512	82.64	2.83	144.35	281.86	+35.31
1880 I	Jan. 28.12	0.005494	1.0	...	86.25	7.08	144.66	281.68	+35.25
1882 II	Sep. 17.72	0.007751	0.999907	761	69.59	346.96	142.00	282.24	+35.24
1887 I	Jan. 11.63	0.009665	1.0	...	58.35	325.50	128.47	280.24	+41.79
1945 VII	Dec. 28.01	0.006305	1.0	...	50.93	321.69	137.02	289.73	+31.96
1963 V	Aug. 23.92	0.005161	0.999952	1111	85.82	6.77	144.52	281.90	+35.37
1965 VIII	Oct. 21.18	0.007761	0.999918	929	69.03	346.25	141.85	282.24	+35.21

T = time of perihelion passage
q = perihelion distance
e = eccentricity
P = period
ω = argument of perihelion
Ω = longitude of ascending node
i = inclination
L = longitude of perihelion
B = latitude of perihelion

Table 3

NUCLEAR RADII

SHORT PERIOD COMETS

	N	$\langle R \rangle$ $a = 0.3$	R_{MIN}, R_{MAX}
ROEMER	18	1.1 Km	0.3, 2.5 Km
KRESAK (R>3.2)	14	2.1	0.7, 6.2

LONG PERIOD COMETS

ROEMER	9	3.5	0.5, 16.5
WHIPPLE	3	4.0	3.1, 5.6

Table 4

Mechanical and Dynamical
Properties of Nuclei

R (km)	P_c (dynes/cm^2)	g (cm/sec^3)	V_e (km/sec)
1	1.4×10^3	0.02	8×10^{-4}
10	1.4×10^5	0.2	8×10^{-3}
100	1.4×10^7	2	8×10^{-2}

FIGURE CAPTIONS

Figure 1. Proposed model of a comet nucleus. The circular regions schemati-
cally represent the larger cometesimals. All cometesimals are
aggregates of the basic micron size ice-dust particles and are
expected to have irregular shapes generally similar to that
pictured for the nucleus. The identity of the individual
cometesimals is exaggerated.

Figure 2. Compaction of snow. Central pressures for a 1 km and 10 km radius
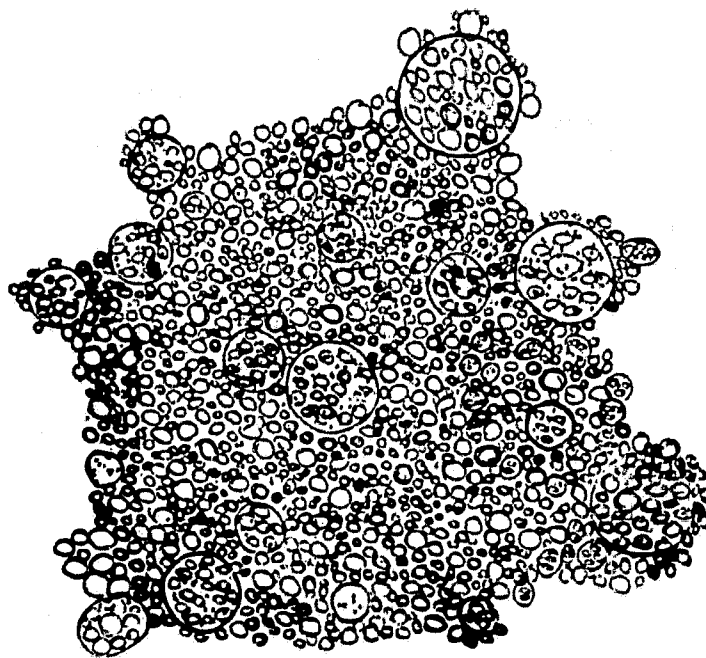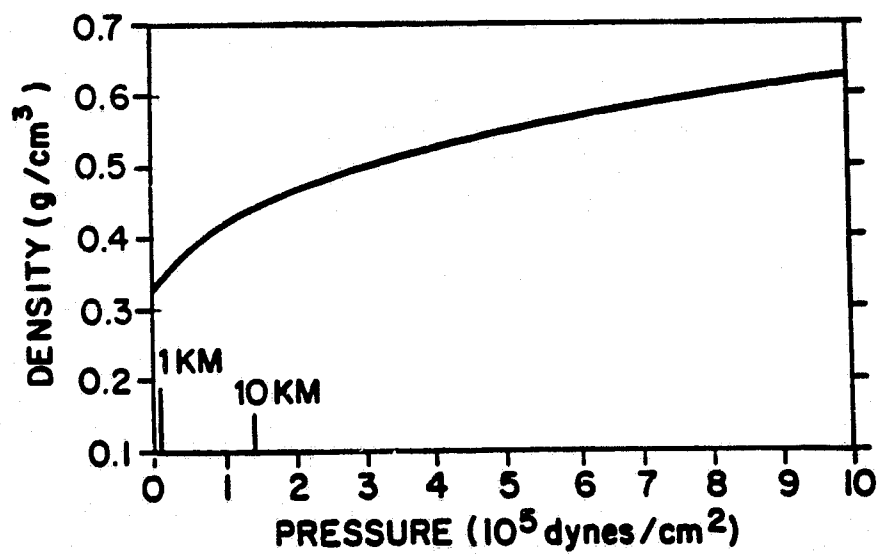nucleus are marked.

FIGURE 1

FIGURE 2