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A Review of Cometary Sciences [and Discussion]

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A review of cometary sciences

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This paper presents an elementary description of comets and their nature. It deals with the contribution from comets to the solid particles that produce the Zodiacal Light and discusses the possibility that some comets in short-period orbits may degenerate into asteroids. The evidence suggests that this may well have happened for the Trojan and other of the outer asteroids but that the near-Earth asteroids and the meteorites are largely not cometary in origin. The last section of the paper deals with the possible nature of comets and their origin such that some might become superficially indistinguishable from asteroids. Space missions are clearly needed, to answer some of these basic questions.

Introduction

This introduction is intended to present a broad elementary description of the phenomena and nature of comets. The reader who wishes to pursue the general subject in more detail is referred to books edited by Delsemme (1977), McDonnell (1978) and Wilkening (1982).

Emphasis centres on the relation of comets to the interplanetary complex and possibly to asteroids and planets, on the nature of the cometary nucleus and on its possible modes of evolution. Cometary phenomena such as ion tails will largely be ignored as will orbital characteristics, which are treated by Wetherill (this symposium).

At great solar distances, comets appear as pointlike sources of reflected sunlight, observationally indistinguishable from stars except for their motion across the stellar background. As comets approach the Sun, usually well within Jupiter's distance, they develop a hazy coma, sometimes with an apparently starlike central condensation. Because of the limited resolving power of telescopes, this condensation may be several hundred to thousands of kilometres in diameter. More active comets may develop diffuse comas in several tens of thousands of kilometres in diameter and also tails, up to 10^8 km or more in length, directed generally away from the Sun and lagging a few degrees behind the orbital motion about the Sun.

This activity arises entirely from the heart of the comet, its nucleus, an intimate mixture of ices and dust ranging in dimension from less than 1 km to the order of 10 km. When the Sun's radiation becomes adequate to produce significant sublimation of the ices, the resultant vapour escapes from sunlit areas on the nucleus carrying with it embedded dust and meteoroidal material. The dust becomes observable as it scatters and reflects sunlight whereas the gas shines by fluorescence. In this process, the gaseous atom or molecule absorbs a quantum of sunlight and then reradiates the energy usually in two or more quanta of lower energy, and therefore in redder light than that of the absorbed quantum. No evidence suggests that comets contribute any of the radiation observed, although the warming of extremely cold ices may release a certain amount of energy stored in the form of imperfect crystalline structure in *amorphous* ices. The Sun is overwhelmingly the prime source of cometary activity and observed radiation.

The fine dust of dimensions in the micrometre range frequently shows the silicate signature in its infrared reflection spectrum near a wavelength of 10 μm. This dust is forced away from the Sun by light pressure with accelerations rarely exceeding that of solar gravity. Thus, with the proper geometry, we often see such dust tails as relatively stubby, curving at conspicuous angles behind the orbital motion of the comet.

The composition of cometary comas and tails as observed by optical, infrared, ultraviolet and radio sensors is listed in table 1. The preliminary results from the missions to Halley's comet reported in subsequent papers of this symposium should add materially to the entries in this table and to their physical interpretation. Suffice it to say that gas-phase chemistry near the nucleus of a comet in the presence of solar radiation can make and destroy compounds, primarily of oxygen, carbon, nitrogen and hydrogen in such a way as to make detailed deductions about the ices in comets from the data of table 1 a quite impossible task. From the study of many comets, however, the observed lines and bands of H, O and OH lead to the sum of their abundances as roughly H_2O, indicating that water ice is the major icy component of comets. Carbon compounds, although numerous, constitute altogether only perhaps 2% of the total mass of the ices, carbon being deficient with respect to oxygen and nitrogen when compared with solar abundances. The observable dust component varies strikingly from comet to comet, some comets displaying almost none by reflected sunlight in their spectra. Perhaps a third of the mass of an average comet consists of dust and earthy particles.

TABLE 1. SPECIES OBSERVED IN COMETS

coma, head	H, C, C_2, $^{12}C^{13}C$, C_3, CH, CN, CO, CO_2, CS, HCN, HCO, CH_3CN, NH, NH_2, NH_3, O, OH, H_2O, S, S_2
(near sun)	Na, K, Ca, Cr, Mn, Fe, Co, Ni, Cu, V(?), Ti(?)
ions (tail)	C^+, CH^+, CN^+, CO^+, CO_2^+, N_2^+, OH^+, H_2O^+, Ca^+, H_2S^+
dust	silicates and hydrocarbons, mostly dielectrics (see later papers in this symposium for additions from Halley Comet missions).

The molecules in space generally have lifetimes of a number of hours to a few days against the dissociating and ionizing effects of sunlight. Because the gas leaves the surface of the nucleus with a velocity of the order of 0.5 km s^{-1} at the Earth's distance from the Sun, the coma may, therefore, attain an observed diameter of 30000 to 100000 km $(2 \times 0.5 \times 86400)$ km. The diameter of the coma may tend to decrease as the comet approaches the Sun because the lifetimes of the species decrease proportionally to the solar radiation while their velocity increases only as its square root.

Positively charged ions that are formed when solar radiation removes electrons from the various species receive especial treatment in the cometary coma. They become subject to the action of the *solar wind*. The Sun's high atmosphere blows off about 10^6 t s^{-1} of extremely hot gas at a speed of some 400 km s^{-1}. The gas of this solar wind is thoroughly ionized at temperature of the order of 10^6 K. Hence it becomes a *plasma*, meaning that the ions and electrons that compose it carry with them strong electrical currents and magnetic fields comprising total energies comparable to the total kinetic energy of motion of the ions and electrons. In the rare gases of a comet's coma, these magnetic fields of the solar wind can selectively entrap any electrically charged ions present and carry them along, away from the Sun. In this fashion the solar wind forms the huge nearly straight tails of comets, seen only by fluorescence of the ions present, particularly of carbon monoxide, which by chance is conspicuous in visual light. The main components of the solar wind, hydrogen and helium, constituting 98% by mass, are quite invisible because these gases are too hot to radiate. Their electrons have been removed by ionization leaving them radiationally impotent.

The solar wind largely ignores the neutral species in a comet's coma although some cometary atoms or molecules are ionized by charge exchange and then carried into the ion tail. The ionized gases in a comet's tail are so tenuous that the acceleration by the solar wind sometimes exceeds the Sun's gravitational acceleration by as much as a thousand times. These rapid motions and high accelerations in ion tails were mysterious, indeed, until 1950 when the late Ludwig Biermann recognized the function of the solar wind. The solar wind itself was observed directly in the early days of the space age. The plasma theory developed by Hannes Alfvén in 1957 is extremely difficult to apply. Hence the direct observations of fields and charged particles in the ion tails of comet P/Giacobini-Zinner by the ICE spacecraft and of Halley's Comet by the various space probes are substance for new theoretical developments in plasma physics.

Although comets are being continuously depleted by loss of matter and by perturbation of their orbits by the planets, the supply of comets appears to be maintained by comets disturbed from extremely long orbits because of the attraction of passing stars and the galactic centre. This cloud of comets postulated by Öpik (1932) and Oort (1950) is known as the Öpik–Oort Cloud and extends to about a thousand times Pluto's distance from the Sun. Comets attain short-period orbits by the attractions of the planets.

THE INTERPLANETARY COMPLEX AND ASTEROIDS

The major contribution of comets to the Solar System is the maintenance of small particulate matter in the interplanetary medium providing the material for the Zodiacal Light and the Gegenschein. The annual meteor streams of the Leonids and Perseids were first associated specifically with their parent comets in the 1860s. Some 15 such associations are now recognized and Elsson-Steel (1986) has recently produced evidence that essentially all sporadic meteors are of cometary origin.

Several lines of evidence point to the ejection of moderate sized masses from the surfaces of comets. Not only do many comets split but active comets such as Halley's for which near-nucleus observations are possible, show sharp condensations that must involve ejected coherent pieces. Comet P/Encke shows almost no continuum in its spectrum but its associated Taurid meteors sometimes include fairly bright fireballs. Radar observations of comet IRAS-Araki-Alcock, 1983 VII, in its near-Earth passage indicated an accompanying but detached cloud of particles large enough to be conspicuous at a wavelength of 13 cm (Campbell *et al.* 1983). Cometary antitails, seen when brighter comets are observed as the Earth crosses their orbit planes, arise from sizeable particles lying very close to the planes of the orbits. The difficulties of the Halley Comet missions as they crossed the orbit plane of the comet attest to the existence of these sizeable particles.

In view of the various methods now available to study cometary debris including infrared observation from spacecraft such as IRAS, perhaps it is time to re-evaluate the total contribution of comets to particulate material in the interplanetary complex. Several investigators including Delsemme (1976), Roser (1976), Kresàk (1980) and Mukai *et al.* (1983) doubt that comets can supply the few tonnes of material per second (Whipple, 1967) required to maintain the zodiacal particles, which are largely destroyed by collisions.

There remains a question as to whether the asteroid Phaethon (no. 3200, 1983 TB), apparently the parent body for the Geminid meteor stream, may be an old comet nucleus. The Geminid stream has a small aphelion distance (just beyond Mars's orbit) and a near-record small perihelion distance of 0.14 AU. The observed colour of Phaethon has been in doubt. Tholen (1985) reports that broad-band photoelectric photometry at five wavelengths from 0.3 to 0.9 μm show Phaethon to be slightly bluer than the Sun, implying a rare F classification, whereas Cochran & Barker (1984) and Belton *et al.* (1985) find it to be of S class on the basis of spectroscopic observations. The S classification would place Phaethon colourwise among typical asteroids whereas the F classification would mean it is possibly cometary.

The Geminid meteoroids themselves are very dense relative to cometary stream meteoroids. Verniani (1967, 1969) finds their density to be *ca.* 1.0 g cm^{-3}, about three times the average for those in streams. Whether this high density represents simply the survival of the toughest bodies in short-period orbits so near to the Sun, or whether it represents basically a meteoritic density of carbonaeceous chondritic nature remains an open question.

The general question as to whether ageing comet nuclei may become indistinguishable from rocky asteroids became an obvious issue with the introduction of the icy conglomerate model for the cometary nucleus. Substantive evidence to settle the question remained elusive until recent years. An important related question concerns the source of the near-Earth asteroids, the Aten–Apollo–Amor groups, in orbits somewhat resembling those of old comets. These bodies have quite finite lifetimes against planetary collisions, measured in tens of millions of years. Ageing comets seemed to be a likely renewable source for such kilometre-sized bodies whereas the asteroid belt seemed impotent to renew the supply.

Infrared spectroscopy and photometry have now been applied to a large number of asteroids and also to a few inactive comet nuclei at great solar distances. Photometry alone provides a comparison of the spectral reflectivities of the bodies in question, and the addition of diameter measures, either directly or via temperature measures, adds a knowledge of the albedos.

A very thorough study of the superficial appearances of comets compared with the various classes of asteroids has been made by Hartmann *et al.* (1987). Their compilation of cometary albedos (geometric reduced to visual wavelengths) from 13 measures or averages (17 comets in all) leads to a mean value of 0.051 ± 0.010. The values range from 0.01 to 0.13 with σ for one determination of ± 0.037. The scatter may well arise largely from measuring errors and from dusty atmospheres. The mean value is in excellent agreement with the values determined for the nucleus of Halley's Comet by the *Vega* and *Giotto* space probes, 0.04. The Moon's geometric albedo is 0.115, with a Bond albedo of 0.065. If the typical cometary nucleus geometrically scatters and reflects light like the Moon, the Bond albedo of comets would average about 0.02, extremely black indeed!

The distribution of infrared photometric colour parameters for comets are restricted on the V–J against J–K diagram and on the J–H against H–K diagram (see Hartmann *et al.* 1985) to regions occupied by asteroids of colour classes C, P, and D, particularly class D (see Gradie & Tedesco 1982, for definition). The C-, P- and D-class asteroids have extremely low albedos and are somewhat reddish. They occupy the outer regions of the asteroid belt, including the Trojans, which move near the lagrangian points in Jupiter's orbit. Hidalgo, long recognized as an asteroid having an orbit like that of a short-period comet, is, for example, in colour class D as are the tiny 1983 SA and 1984 BC, with aphelia also exceeding 5.3 AU. The three comets P/Neujmin 1, P/Arend-Rigaux and P/Schwassmann-Wachmann, 1, are also of colour class D, (Hartmann *et al.* 1987). The mysterious Chiron, in a 'chaotic' orbit between Saturn and Uranus, has a similar colour, a subset of class C. Thus Hartmann *et al.* (1986) find that 11 asteroids with orbits suggesting a possibly cometary origin fall in the colour classes of D(5), P(1), C(1), and C-like (4).

On the other hand, among 13 Aten–Apollo–Amor objects Hartmann *et al.* (1986) find only one in the C class (an Aten) and the others in more typical asteroidal colour classes. Because meteorites are probably mostly fragments from asteroids in near-Earth orbits, the apparent asteroidal character of these bodies is consistent with the chemical nature of meteorites as compared with Brownlee particles. In his accompanying paper Wetherill (this symposium) elaborates on Wisdom's (1983) theory concerning the chaotic perturbations of the Aten–Apollo–Amor asteroids from the heart of the asteroid belt.

Because of the similarities of the apparent surfaces of the outer asteroids to those of comets and also to some of the icy satellites of the giant planets, Hartmann *et al.* (1987) support the thesis that ices formed near Jupiter's orbit and beyond during the formation of the Solar System. In their picture, Jupiter comets, Saturn comets, etc., accreted as building blocks of the outer planets and also contributed to the satellite systems. Because of violent collisional losses near the giants, Jupiter and Saturn, the comets of the Öpik–Oort Cloud may have been derived primarily from the comets near Uranus and Neptune.

COMETS TO ASTEROIDS: HOW?

There are at least three obvious circumstances whereby comets could develop into bodies superficially like asteroids and yet another process that might lead to similar results

(*a*) In their growth, comets may have first accreted from rocky material and later added a dusty-ice envelope. Such a comet in a short-period orbit would eventually sublime away its icy envelope and become an inactive asteroidal body.

(*b*) Large comets with radii greater than perhaps 20 km may have accreted from dusty-ice particles but have been heated by radioactivity until the volatiles were removed from their cores. When finally exposed, these cores might appear asteroidal. This subject has been discussed by Whipple & Stefanik (1966). Only if the accumulation of comets occurred in a time less than a few million years could radioactive ^{26}Al, if present, have heated the cores of small comets. Otherwise the usual radioactive elements of ^{40}K, etc. could have, but only for rather large comets.

(*c*) The coarser meteoritic material in active comets may fall back to the surface, insulate and finally choke off cometary activity even though an icy core remains. Only H_2O ice would probably remain in the core as its temperature would probably have risen to a level that would sublimate more volatile ices or amorphous ices.

(*d*) More speculatively, collisions among comets during their accretion period or even later may have volitilized much of the ice and left large volumes of meteoritic material throughout the cometary bodies. The destructiveness of such collisions has not been studied in detail, being barely suggested by Donn (1963). Possibly, though, such collisions may have returned most of the materials of the comets to the solar (or primitive) nebula. The kinetic energy at a velocity of 2.3 km s^{-1} equals the latent heat of vaporization of extremely cold H_2O ice (49000 J mol^{-1}). If, for example, comets of the Öpik–Oort Cloud were the primary building block of Uranus and Neptune, those we have recovered must have been removed early in the evolution of those planets before large velocities were built up by the growing protoplants. Or perhaps these have luckily escaped head-on collisions. The nucleus of Halley's Comet, incidentally, appears to be a badly battered body.

The observations of comets produce indirect evidence that the active comets we observe may not have large meteoritic cores, thus weighing against circumstances (*a*) and (*b*). Sekanina (1977), in his study of split comets, finds that the smaller pieces broken from comets move away from their primaries by the action of differential, non-gravitational jet forces radial to the Sun. Their survival times correlate with their non-gravitational forces according to about the same logarithmic relation independent of the survival time or identity of the piece. Thus eighteen pieces broken off from a dozen different comets are somewhat similar in structure. No evidence to date suggests that split comets are inherently different from other comets but, of course, rocky cores may not have split off.

The various members of the Kreutz Sun-grazing family of comets appear to be much alike. They almost certainly are pieces recently broken tidally from a very large comet. For this, however, asteroidal inclusions, if present, probably would not have been observed.

Several comets appear to have disintegrated and disappeared while under observation. Sekanina (1984) has described the process for a half dozen, including the most famous, P/Westphal, 1852 IV, that faded out on the way to perihelion as 1913 VI, never to be found again. His description is: 'When discovered, they typically display a prominent, star-like central condensation, but a fading sets in very suddenly and the central condensation disappears usually in a matter of days. At the same time the coma is often (but not always) expanding gradually and becomes progressively elongated. Its surface brightness is decreasing (sometimes with erratic light variations superimposed) until the comet's whole head completely vanishes. The tail can become the brightest part of the object and survive the head.'

If these descriptions are truly to be accepted as recording the death throes of small comets, it is interesting that Sekanina usually finds the remnant dust tails to consist of particles greater than 50–100 μm. In contrast, the end of the Sun-grazer 1887 I, undoubtedly a broken piece, involved micrometre and submicrometre particles, typical of most ordinary comets. Were the initial grains at the very cores of comets typically greater than 100 μm in dimension? In any case, these disintegrating comets also tend to support the thesis that active comet cores do not consist of huge meteoritic or rock aggregates.

Half a dozen or so other short-period comets have not been rediscovered even after thorough searches with improved telescopic equipment. Probably they were active for a while and then lay dormant. Thus a few comets seem to have died passively, ceasing to show hazy or central condensations even near perihelion. If discovered now, their stellar appearance would cause them to be called asteroids in short-period cometary orbits. Marsden (1970) lists two such examples and discusses some of the orbital considerations. All of these comets probably have thick layers of meteoritic debris that insulate the ices of their interiors from rapid solar heating. One wonders how many of the Trojan asteroids or those of D, P or C colour classes would develop comas and appear cometary if they should collide with sizeable interplanetary bodies.

The high temperatures observed on the inactive surface of the nucleus of Halley's Comet demands that this surface be covered with a good insulating material, presumably dust. The evidence that Encke's comet (Whipple & Sekanina 1979) has one hemisphere that is now mostly inactive supports the hypothesis that accumulated particulate debris covers underlying ices and curtails comet activity.

Many of the larger particles raised by sublimation must fall back to the nucleus. The largest ones may never rise from the surface. Many must survive breakage from wasting on slopes and mesa-like elevations, from material falling back, and from thermal stresses of night to day on a rotating nucleus. In fact it seems easier to imagine processes to choke off comet activity than to promote it.

All of this evidence is consistent with comets having been formed by the accretion of interstellar-type dust at extremely low temperatures, the basic material being of the nature described and studied in the laboratory by Greenberg (1984).

Space missions to comets and asteroids are clearly needed to lead to an understanding of the nature and origin of these fundamental building blocks of the Solar System.

Conclusions

Comets contribute most of the particles that produce the Zodiacal Light and intercept the Earth's atmosphere as meteors. The colorimetric and reflective characteristics of comets and the outermost asteroids are so similar as to suggest that some short-period comets finally become inactive, indistinguishable from some asteroids. But this is probably not true for the near-Earth asteroids. The cometary evidence suggests that ageing comets may become inactive because they are choked by overlying particulate material that prevents solar heat from sublimating the underlying ices. No strong evidence suggests that pristine cometary cores are intrinsically rocky. Space missions to comets and asteroids are urgently needed.

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Discussion

G. Turner (*Department of Physics, University of Sheffield, U.K.*). To what extent is the surface roughness observed by Giotto thought to be the product of impacts or internal action such as that giving rise to the jets? With regard to impacts has anyone calculated the likely history of collisions during Halley's presumably brief time in the inner Solar System?

J. A. M. McDonnell (*Unit for Space Sciences, University of Kent at Canterbury, U.K.*). Regarding the question of the origin of surface features: a figure for the erosion rate from solar heating of 1 m per perihelion passage has been estimated before these spacecraft encounters. Considering the probable age of Halley of 20000 years in the inner Solar System, and the erosion rate that can be estimated now by the *in-situ* measurements of Halley, we would estimate some metres to be lost from the surface every 76 years. The surface is therefore fresh and its outer surface would not be expected to bear resemblence to its original state in the Oort cloud or carry the effects of impact cratering. We have to explain Halley's surface, therefore, solely in terms of ablation and erosion under solar heating.

M. K. Wallis (*Department of Applied Mathematics and Astronomy, University College, Cardiff, U.K.*). Professor Whipple was billed to give a review of cometary science; what I have heard amounts to cometary geography with perhaps a little cometary geology. It in no way justifed the preposterous claim that his icy-conglomerate model has been 'nicely substantiated by the space missions'. Indeed, the dust analysers on both missions have shown not a conglomerate mixture of ices with mineral dust, but largely organic grains with little metallic or silicon components. The black surface covering most of the nucleus is presumed carbonaceous, not the favoured mineral dust. There are two or three large ougrassing regions, not the small-scale 'weathering' inhomogeneities that he depicted. He has in recent years adopted the variation of 'exotic ices' following processing by cosmic rays, that give complex organic molecules in 'wild' comets arriving after some millions of years in the outer Solar System (Whipple 1986). Yet Halley's comet showed its complex organics after 76 years away from us. He has modelled a sublimating rotating nucleus as uniformly heated over the surface (Whipple & Huebner 1976). The Halley-environment modellers did not adopt that extreme of isotropic outgassing, but were still a striking failure with 35% of the total emission coming from the nightside in their model (Devine 1981). To many of us, the icy-conglomerate reference model, characterized by sublimating ices with inert dust, has turned out to be misleadingly inflexible. It is time for us to drop its restrictive outlook and develop models that can explain the wealth of phenomena detected by the spacecraft and ground-based studies.

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F. L. **Whipple**. I find only strong support for my 1950 icy-conglomerate model of comets in the space-probe observations of Halley's Comet. My theory always involved the ejection of material on the sunlit side of the nucleus. I never supported theories that involved heating of the side away from the Sun. The composition of the ices except for the predominate water ice still remains in question as does the mass fraction of 'earthy' material. Regarding Halley's Comet, I wrote in 1951 (Whipple 1951), 'Suppose the radius to be 10 km (probably a generous estimate)...'.

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