JOINT DISCUSSION NO. 5

ORIGIN AND EVOLUTION OF INTERPLANETARY OBJECTS

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COMETS: NATURE, EVOLUTION AND DECAY

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A brief summary is given of the current concepts of the icy conglomerate cometary nucleus and of the origin of comets. Evidence that the cores of comets may contain less than average volatile material, whether in formation or by radiative heating, raises the question of why at least two very faint short-period comets suddenly experienced violent outbursts (~4000 times in brightness). A preliminary study of close double comet nuclei as affected by differential nongravitational forces shows that a collision of a cometary satellite with its primary is a likely outcome. Thus double nuclei may possibly explain these rare but extreme outbursts. Statistics suggest, however that most comet splitting and comet outbursts represent intrinsic activities in extremely nonhomogeneous nuclei.

COMMENTS ON THE NATURE AND ORIGIN OF COMET NUCLEI

The nucleus of a comet is now generally accepted as a poorly consolidated conglomerate consisting primarily of ices, C, N, O compounds with H, and half or less by weight of heavier elements as compounds that freeze at relatively high temperatures, mostly in the form of dust and mixtures. The author's concept (Whipple 1950, 1951) has been sharpened to include clathrates of hydrides caught in H_2O ice (Delsemme and Swings 1952), free radicals, perhaps produced by cosmic rays (Haser 1955; Donn and Urey 1956; Whipple, 1977a), amorphous ices (Donn 1976), and other amorphous compounds perhaps typical or actually arising from interstellar grains (Greenberg 1982). For a review of nuclear compositions see Delsemme (1982).

The wide diversity of physical and chemical structure among comets as demonstrated by their widely different phenomenal activities is shown to exist also in the structure of the individual comet. Relatively small areas of high recurrent activity have been shown to exist on a number of comets by the author's success (Whipple 1982) in determining rotation periods by the repetitive halo method, and by Sekanina's (1981) detailed analysis of active areas on the nucleus of P/Swift-Tuttle. The phenomena accompanying comet splitting testify to the nonhomogeneity of comet nuclei (see Pittich 1972; Sekanina 1982).

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With regard to the origin, Delsemme's (1982) conclusion that the abundance of C with respect to O and N in comets is much below that in the Sun suggests that CH_4 and CO probably do not occur appreciably as frozen solids in cometary nuclei. If so, N_2, O_2, Ar and Kr, of comparable volatility, should not freeze out and certainly not H, He and Ne, which are much more volatile. There is strong evidence that CO_2 may be present, suggesting a range in the low temperature–pressure relationship perhaps indicative of the place of origin of comets. Should Xe be found, the T–P range would be reduced. Incidentally, Huebner et al. (1982) and Swift and Mitchell (1981) include CH_4 and CO as basic to their models of gas-phase reactions in cometary coma.

As for the place of origin, the work of Biermann and Michel (1978), Fernández and Ip (1981) and the earlier work by Safronov (1969) suggest that the classical place of formation, the Uranus–Neptune region, may still be valid. The Goldreich and Ward (1973) process of gravitational aggregation in a thin plane layer of solids provides a mechanism for formation in the outer planetary region. This is followed by expulsion from the region as the planets grew. More distant origins suggested by O'Dell (1973) and Hills (1982) seem less plausible at the moment. Cameron's (1978) rapid formation of comets followed by a rapid loss of a very massive solar nebula remains an interesting possibility.

COMET OUTBURSTS AND SATELLITES

A major problem connecting cometary origin with cometary decay concerns the occasional high activity of a few of the very old periodic comets, viz. great outbursts and splitting. Other evidence indicates that these cometary cores are relatively inactive, whether by the nature of their formation, by blanketing of meteoroidal material or by heating caused by normally occurring radioactivity if not by ^{26}Al, eliminating the more volatile ices from the cores. In fact, Öpik (1963) and others have suggested that some of the cores finally become Apollo-Amor asteroids, while the activity of old short-period comets appears to be limited mostly by the sublimation of H_2O ice (e.g. Kresák 1973). Nevertheless, in 1973 one of the faintest such comets, P/Tuttle-Giacobini-Kresák, exhibited two gross outbursts of some 9 magnitudes (4000 times in brightness!) separated by about 40 days. The brightness increased in about 2 days and mostly subsided after a week in both cases (Kresák 1974).

Three short-period comets have split. Frequently the process of splitting, when observable, is accompanied by outbursts (Pittich 1972; Hughes 1975; Sekanina 1982). In discussing comet splitting, Whipple and Stefanik (1966) dismissed the idea of double or multiple comet nuclei as the cause. The chief objection was that separation of two components by solar gravitational perturbations would not be disruptive to the components individually, i.e., not be the cause of outbursts. The intrinsic process that we suggested was heat transfer via volatiles by internal heating, followed by refreezing in the outer layers. Successful containment of gas pressures over the long time intervals involved seems quite impossible, although short-time expansion of such near-surface volatiles by solar heating remains a real possibility.

Van Flandern (1981) has revived the idea of comet satellites to account for splitting, so let us explore the subject further. None of the theories of comet formation seem to require or reject the concept that multiple comet nuclei, or even ring systems, might develop. Schatzman (1953) and O'Dell (1973) showed that the many-bodied nucleus with random orbits about the common center of gravity could not survive as a cloud but would coalesce into a compact nucleus. But if the cloud contained intrinsic angular momentum a double or multiple system might evolve. Van Flandern states that the "sphere of influence," R_i, against solar gravity, for a relatively small comet satellite is approximately

$$R_i = 200\, R_c\, r_{AU}\, \rho^{1/3} \quad , \tag{1}$$

where R_c is the radius of a comet nucleus of density ρ (g/cm^3) at a distance r_{AU} from the Sun.

Thus comet satellites with relatively great separation could move in stable orbits in deep space until separated by solar gravity when first approaching the Sun from the Oort cloud. The evidence for such comet pairs is weak (Whipple 1977b), or nonexistent (Kresák 1982). More compact systems might survive a number of perihelion passages before being separated, having lost mass by sublimation to increase their mean distances apart.

Van Flandern does not discuss the effect of differential nongravitational (NG) forces on multiple comet nuclei, an effect that markedly alters the orbital development. Classical perturbation theory can be applied instructively to the simple case of a cometary satellite that is relatively small compared to the major nucleus and is moving about it in the plane of the solar orbit. If the satellite orbit has semimajor axis, a, eccentricity e, and argument of pericomet, ω (measured in the sense of the motion from the comet-solar direction), and if the differential NG acceleration on the satellite is γ times (10^{-5} the solar acceleration on the main nucleus) directed away from the Sun, the classical theory gives for the timed-averaged perturbations

$$\frac{da}{dt} = 0 \quad , \tag{2}$$

$$\frac{de}{dt} = C\,(1-e^2)^{1/2} \sin\omega \quad , \tag{3}$$

$$\frac{d\omega}{dt} = C\,\frac{(1-e^2)^{1/2}}{e} \cos\omega \quad , \tag{4}$$

where

$$C = 0.0145\, \frac{a^{1/2}\,\gamma\, h(r)}{\rho^{1/2}\, R_c^{3/2}\, r_{AU}^{2}\, P_d} \quad , \tag{5}$$

in which h(r) measures the deviation of the NG acceleration from an inverse-square law and equals unity at $r_{AU} = 1$, time is measured in days, a and R_c are measured in kilometers, and P_d is the period of the satellite.

The effect of the solar gravitational term is relatively small when $\gamma \gtrless 1$, for comet–satellite distances considerably less than given by Eq. (1). Such values of γ are typically measured for a number of comets (see Marsden 1982). Note that for similar components originally different in size, uniform wasting by sublimation will increase the relative difference in radius and hence the value of γ in our problem. For a satellite similar to its primary but one half its radius, the differential NG acceleration will equal that of the primary.

Equations (2), (3) and (4) lead to a most interesting configuration for a prograde small satellite, illustrated in Figure 1. The major axis turns (very quickly if e is small) normal to the comet–Sun line with $\omega \sim 90°$, and, by Eq. (4), $d\omega/dt \sim 0$. In turn, de/dt (Eq. 3) attains its maximum positive value. Because the secular change in semimajor axis is zero, eccentricity increases with time until $a(1-e) = R_C$, when the satellite encounters the nucleus. The result, even at a pericometary velocity of only a few meters per second would result in a massive crushing and breakup of material on both bodies – surely producing a cometary burst at a moderate solar distance! For retrograde motion the result is the same, the orbital configuration being the mirror image (along the comet–Sun line) of Figure 1.

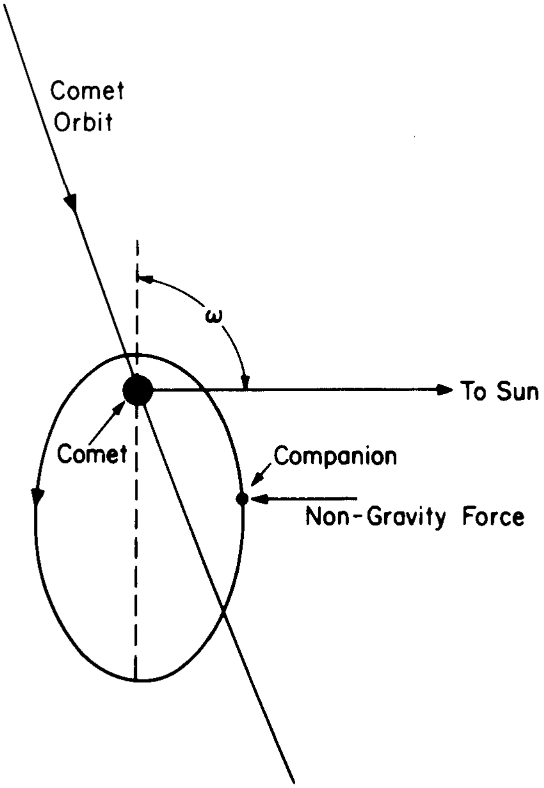

Figure 1. Coplanar comet companion.

In actuality, the orbital motion of the comet will introduce a change in ω given by

$$\frac{\Delta\omega}{\Delta t} = \pm\, k \sqrt{q_c(1+e_c)}\; r_{AU}^{-2} \quad , \qquad (6)$$

which q_c is the perihelion distance of the comet, e_c, its orbital eccentricity, and k, the gaussian constant. The sign is negative for prograde and positive for retrograde motions of the satellite.

The effect of the term (Eq. 6) added to Eq. (4) limits the stability of ω near 90°. This in turn sets a lower limit on γ for which the perturbation in ω, as calculated by the inclusion of $\Delta\omega/\Delta t$ in Eq. (4), can maintain ω in the neighborhood of 90° so that the secular increase in e can produce an encounter.

The period, P_d, of the satellite in days is given by

$$P_d = 0.138\, \rho^{-1/2}\, (a/R_c)^{3/2} \quad . \qquad (7)$$

The condition then, that e increases secularly and a "crash" becomes inevitable, is

$$\gamma \geq 68.8k\, [q_c(1+e_c)\, \rho\, R_c/a]^{1/2}\, (1 - R_c/a)\, R_c \sec\omega\, h^{-1}(r) \quad . \qquad (8)$$

Note that the r_{AU}^{-2} terms in $d\omega/dt$ and $\Delta\omega/\Delta t$ have cancelled out so that, were $h(r) = 1$, the condition of Eq. (8) would maintain a secular increase in e so long as ω remained within, say, ~45° from 90°. With this requirement the numerical coefficient, $68.8\, k \sec\omega\, h^{-1}(r)$, becomes ~1.7. Under these idealized conditions Table 1 lists minimum values of γ for a parabolic comet with $q_c = 2$ AU, a primary of radius $R_c = 2$ km, $\rho = 1$ g cm^{-2}, over a range of values of R_c/a.

Table 1. Minimum values of γ.

R_c	0.05	0.1	0.2	0.4	0.6	0.8	0.9
γ	1.4	1.9	2.4	2.5	2.0	1.2	0.6

In practice the NG acceleration falls off more rapidly with increasing solar distance than r_{AU}^{-2} so that the value of γ would be greater than indicated by Table 1 because of the decrease in h(r). Nevertheless, the nature of the effect of differential nongravitational forces on cometary satellite systems is clear. For orbital separations well within the "sphere of influence" of Eq. (1) the probability of encounter is relatively high for active comets with small satellites. Close double nuclei of comparable masses and activities would remain in stable orbits for very long times as would those with small differential nongravitational accelerations. The period of revolution for equal comet and satellite masses is, incidentally, $6.6\, \rho^{-1/2}\, (a/R_c)^{3/2}$ hours. For inactive small satellites such as rocky masses (or those depleted of ices) the effect of the nongravitational acceleration on the active nucleus is to reverse the signs of Eqs. (3) and (4) but to produce the same end result, an eventual encounter, if the other conditions are satisfied.

This preliminary study of double or multiple comet nuclei suggests that some comet outbursts may well be caused by the infall of small satellites. The striking example of P/Tuttle-Giacobini-Kresák in 1973 was mentioned earlier. No unusual outbursts were observed in its previous four appearances nor in its 1978 appearance although it had been unobserved in most of its apparitions since its discovery in 1858. If a small satellite with a period of 40 days was actually demolished in two successive encounters with its primary of radius, R_c, the value of the orbital semimajor axis becomes $a = 44\ R_c\ \rho^{1/3}$. The maximum distance from the primary would thus be nearly twice this value to be compared to $240\ R_c\ \rho^{1/3}$ at $r_{AU} \sim 1.2$, by Eq. (1), Van Flandern's "sphere of influence." For a direct orbit such a distance radially to the Sun probably would be unstable, but for an orbit oriented as in Figure 1 or for a retrograde orbit, stability might be reasonably possible.

Another glaring example of cometary outbursts was P/Holmes in 1892. Kresák (1974) suggests that two outbursts comparable to those of 1973 VI were separated by about 70 days. At a solar distance of over 2 AU, the corresponding semimajor axis of $64\ R_c\ \rho^{1/3}$ appears to represent a fairly stable orbit with respect to solar gravitational perturbations.

Thus the hypothesis that at least some comets have satellites may well explain certain extreme cases of cometary outbursts. Whether many of the "routine" smaller bursts may be so explained remains speculative as does the general problem of comet splitting. The case of P/Schwassmann-Wachmann 1 certainly cannot be explained in such a fashion because of the many repetitions of great outbursts. Intrinsic properties of the material must be responsible.

The celestial mechanics of the double nucleus is actually much more complicated than indicated by the simple discussion above because of:

1) Mutual shadowing of the nuclei as they revolve,
2) The three-dimensional character of the motions,
3) The effect of lag in sublimation,
4) The nature of NG accelerations as dependent on solar distance and comet type,
5) The effects of comet aging,
6) The effects of orbital changes by planetary perturbations,
7) The dependence on orbital characteristics,
8) The inclusion of a finite mass for the satellite.

All of these combine to make a definitive study difficult and, unfortunately, quite uncertain because of the many free parameters. If some comet nuclei are actually double, the final proof may well depend upon direct observations by space probes to comets.

In the meantime, the statistics of comets can help clarify the question. Sekanina (1982) identifies 18 clearcut examples of well observed split comets for which close approaches to the Sun or Jupiter could not have produced tidal splitting. The double comet, du Toit-Hartley, 1982b and 1982c (Per. = 5.2y, i=3° and q=1.2 AU) brings the total to 19. The first of the list is Biela in 1846. Since then Marsden (1982) lists some 770 comet perihelion passages; thus about 1 in 40 involved splitting. If we limit the selection to those of $q \gtrsim 1.5$ AU the list is reduced to 15, or 1 in 51.

We now turn to Kresák's (1981) estimates of the mean lifetimes of comets. For comets of Jupiter's family with $q \simeq 1.5$ AU, he estimates 400 revolutions, and for Halley-type comets, 200 revolutions. Thus, statistically, we should expect splitting to occur several times during the lifetime of a comet. This imposes a severe restraint on the concept that splitting is caused by multiple nuclei. Can we reasonably assume that the average new comet nucleus harbors several satellites?

On the other hand, contrary to many statements in the literature, splitting is much more frequent among less developed comets with very long periods or nearly parabolic orbits than among the old short-period comets. The chance of splitting per perihelion passage is an order of magnitude greater for new or nearly new comets than for those with periods less than 200 years. The statistical numbers, if we neglect the poorly observed parabolic comets, are as follows: for very long periods, 11 out of 273 passages or a chance of 1/25; and for periods less than 200 years, 3 out of 520 passages or 1/170. We have little escape from the conclusion that comet splitting arises primarily from the intrinsic nature of the nucleus material and that less developed comets with a greater proportion of active volatile constituents have a much greater chance of splitting than the remnant cores of older comets.

Progress in understanding the sublimation, outbursts and splitting of comet nuclei appears to reside heavily in laboratory studies of solid-state chemistry and physics at low temperatures and pressures of complex compounds of C, N, O and H. Research such as that by Donn and his associates, particularly Moore (1981), and by Patashnick and Rupprecht (1977) have indicated the remarkable properties of such low-temperature condensates particularly when irradiated by high energetic protons. Greenberg (1982) has made extraordinary progress in his laboratory simulations of the formation of interstellar grains irradiated by UV photons. Both studies show that rising temperatures from the 20° K level can produce explosions by phase changes in these materials. The author hopes that these studies, coupled with continued observations and analyses of comet phenomena, can connect with the studies of comet origin to clarify the basic understanding of comets. The proposed space missions to Halley's Comet should add enormously to this understanding.

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DISCUSSION

BURNS: The dynamical situation shown for the comet pairs, where the differential non-gravitational force is radial, is identical to the case of solar radiation pressure on circumplanetary dust. Mignard´s solution (Mignard, F.: Icarus 1982, 49, pp. 347-366) for the later case is the most complete: he has found a completely analytic solution for the zero inclination case, that discussed by Whipple. In numerical simulations he finds that inclined orbits behave differently in that the inclination can grow to larger than $\pi/2$ so that the orbit becomes retrograde and the eccentricity growth can decay. Both libratory and circulatory motions are observed.

WHIPPLE: I used Kozai´s solution, including shadowing.

DONN: 1) Regarding changes in interior of comets, the spectra from ultraviolet and visible is strikingly similar for comets from Encke to very long period objects. 2) Would the satellites be stable long enough to cause the outbursts of very old comets?

WHIPPLE: 2) I think so.

MILLMAN: Have you any comment on how far a comet nucleus may deviate from a spherical body? Voyager 2 has clearly shown that, once we drop in size below a diameter of 100 or 200 km, planetary bodies tend to deviate widely from a spherical form.

WHIPPLE: I have no basis for judgement.

SEKANINA: Observationally, in some cases we have a splitting with an accompanying burst, in other cases, without such a burst. Apparently, there are different breaking mechanisms in operation in different split comets.

WHIPPLE: I agree.

WASSON: Could you be more specific regarding the mechanism that produces the flaring; is it simply an increase in the exposed surface area? Isn´t this essentially the same mechanism that would be involved when a comet splits?

WHIPPLE: Yes, except for the unknown mechanism that exposes more area.