A CORE-MANTLE MODEL FOR COMETARY NUCLEI AND ASTEROIDS OF POSSIBLE COMETARY ORIGIN

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Arguments for a long time have been brought forward in support of the idea that the minor planets with orbits approaching Earth's orbit might be of cometary origin. Our feeling is that before such hypotheses are considered for any particular object, it is necessary to prove that differences in physical appearance and dynamical behavior between a typical asteroid of the Apollo or Albert types and a typical short-period comet can be interpreted in terms of cometary evolution.

In this paper, we discuss models of cometary nuclei, transition of an object from cometary phase into asteroidal phase, and specific asteroidal objects that may be of cometary origin.

PHYSICAL MODEL

Nongravitational (NG) activity in a comet essentially measures the rate of mass output from the nucleus in units of the nuclear mass. An obvious method of studying the NG effects, therefore, is to test various models of mass transfer in the nucleus and the related mass loss rate from the nucleus.

The most obvious possibility is to consider a cometary nucleus composed of freely deposited ices (upper part of fig. 1), which gradually shrinks at a constant rate. The NG effects increase in proportion to the decreasing nuclear dimensions as the comet passes through the *early* phase (E) into a *fading* phase (F). The free ice model finally sublimates out completely, leaving no compact debris whatsoever.

Dynamical calculations (e.g., Marsden, 1969, 1970) show that, by contrast, for most comets the NG activity tends to decrease rather than increase with time on a secular scale. Such behavior can be explained in terms of a core-mantle model. This model is composed of a porous core of nonvolatile materials surrounded by an icy envelope. The envelope may be contaminated by loosely distributed solid grains. Secular variations in the NG activity of a core-mantle comet is schematically represented in the lower part of figure 1. The icy shell, of considerable thickness in the *early* phase, gradually sublimates under the effects of solar radiation; the diameter of the nucleus decreases as

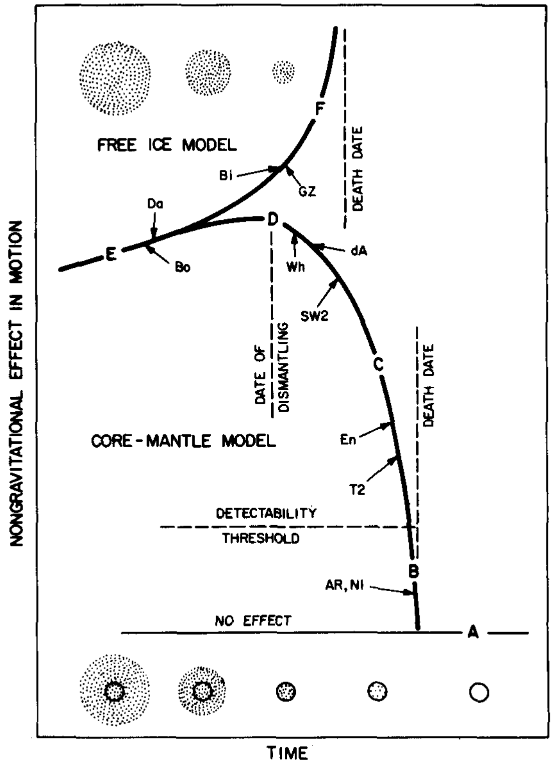

Figure 1.—Evolution of cometary nuclei and NG activity. Evolution of the free ice model is outlined in a sequence of schematic pictures at the top of the figure, that of the core-mantle model at the bottom. Dotted areas of various density show the degree of concentration of ices, empty area within a circle marks the presence of solid materials only. Secular variations in the NG effects on the free ice model are represented by the upper curve, those on the core-mantle model by the lower curve. Present approximate locations of several short-period comets are indicated by arrows and the following abbreviations: GZ, Giacobini-Zinner; Bi, Biela (in the first half of the 19th century); Bo, Borrelly; Da, Daniel; Wh, Whipple; dA, d'Arrest; SW2, Schwassmann-Wachmann 2; En, Encke; T2, Tempel 2; AR, Arend-Rigaux; and N1, Neujmin 1.

the comet approaches the *dismantling* phase (D). NG effects are relatively large and reach their maximum before the date of dismantling. At this point solid materials start extending over the nuclear surface in the form of a rigid, continuous matrix whose tensile strength is high enough to withstand pressure from activated ices below; the comet no longer loses substantial amounts of dust. Reduction in the nuclear radius is stopped, free evaporation of volatiles is replaced by their activated diffusion through the pores of the solid core, and the mass output is reduced more significantly. Because the dismantling process is accompanied by increasing lag effects in the direction distribution of mass ejection, the dynamical effects of output deficit are partly or completely compensated, and the magnitude of NG forces may vary in a fairly smooth though complicated way in the D phase. More energy is spent on heating deeper layers of the core, so that the average nuclear temperature increases secularly. The comet passes through its *core* phase (C), the NG effects decreasing progressively. The ability of the nucleus to regenerate icy supplies at the surface gradually weakens. Physical activity becomes less regular, and the reactivation mechanism of the comet *breaks down* (phase B). NG effects are no longer detectable, and the comet is stellar or almost stellar in appearance. Finally the object, a chunk of solid materials, is completely deactivated and enters the ultimate *asteroidal* phase (A). The comet becomes a minor planet. Consequently, the core-mantle model is of interest from the point of view of possible cometary origin of some minor planets.

DYNAMICAL EVOLUTION

The Apollo and Albert type objects have aphelia well inside Jupiter's orbit. Practical calculations show that after one or more successive close approaches to Jupiter a comet can occasionally be captured into an eccentric orbit with aphelion Q as small as 4.5 or 4.6 AU. If, in addition, the revolution period of the comet in the new orbit slightly exceeds 3:1 (perihelion q about 0.5 AU) or 5:2 (perihelion slightly over 1 AU) resonance with Jupiter and if the comet has a fairly strong NG acceleration, we get the most favorable conditions for the comet to escape from disastrous encounters with Jupiter forever. The NG acceleration reduces the comet's aphelion distance approximately at a rate of $(4/3)a(\dot{\mu}/\mu)$ (AU per revolution), where a is the semimajor axis, μ the corresponding daily mean motion, and $\dot{\mu}$ the NG change of the latter per revolution. For a comet with $q = 0.5$ AU, $Q = 4.5$ AU, and secular acceleration of 0.1 day per revolution per revolution, the NG aphelion reduction rate amounts to 0.006 AU per century. The abovementioned conditions insure no close approach to Jupiter for, statistically, almost 200 revolutions after the capture. During this interval of time, the total NG decrease in the comet's aphelion distance can be estimated at almost 0.05 AU, a rather significant amount. Perturbations due to moderate approaches to Jupiter can increase, under favorable circumstances, the rate of reduction of the aphelion distance even more.

The above scheme includes implicitly a transition of the comet through a 3:1 or 5:2 resonance with Jupiter. A discussion of Marsden's experimentation with hypothetical NG forces in the motion of 887 Alinda suggests that a secular acceleration of about 0.04 day per revolution per revolution would be sufficient to overpower the coupling of the 3:1 resonance libration. Therefore, in the absence of close encounters with Jupiter, the NG acceleration of a moderate magnitude is dominant, over very long intervals of time, in reducing systematically the comet's aphelion distance. When the nucleus is completely depleted of volatile materials, the NG mechanism stops. The final aphelion distance depends on the original structure and dimensions of the comet's nucleus. The core-mantle model provides a possibility of estimating the lifetime of a comet in its short-period orbit in terms of physical constants of the nucleus and the difference in aphelion distance between the time of capture and the death date.

NUCLEAR CORE IN AN ACTIVE COMET

The core-mantle model was designed with the aim of putting the interpretation of the NG effects in periodic comets on a quantitative basis and of following–also quantitatively–how a comet can possibly turn into a minor planet. The model proved successful in fitting very satisfactorily the secular variations in NG activity of periodic comet Encke over the past 150 yr (Sekanina, 1971). The model can be handled mathematically very easily, but more work should be done on its physics. The dismantling phase may particularly appear to be troublesome because of severe changes in the physical properties of the surface layer and, correspondingly, in the mass-output and heat-delay mechanisms.

A completely coreless nucleus is probably fictitious. However, a comet with a tiny solid core should behave in much the same manner. Its nucleus can be expected to have lower tensile strength, so that it obviously can be subject to catastrophic events more easily than a comet with a more sizable core. On the other hand, the secular fading of an almost coreless comet is likely to proceed more slowly than for a comet with a massive core.

Dynamically, the most important difference between the two models is in the sign of Marsden's B_2 coefficient (defined as a logarithmic derivative of the NG transverse component with time): the icy model cannot explain any positive B_2, whereas the core-mantle model cannot explain any B_2 more negative than about -0.01, a value that is extremely hard to detect in practice. In other words, one cannot distinguish between the two models unless B_2 is well determined and clearly different from zero.

A slightly or moderately negative B_2 may suggest that the comet has a tiny nuclear core. Of the comets with reliably known NG parameters, P/Biela and P/Giacobini-Zinner seem to be the most likely candidates. (See fig. 1; Marsden and Sekanina, 1971; and Yeomans, 1971.) The Příbram meteorite might be, with its typically cometary orbit, an example of what possibly remains from an almost coreless comet.

A strongly negative B_2 (say, -0.3 or more) is troublesome to explain in any case. In terms of the coreless icy model it means that the nucleus is already almost completely disintegrated; such a comet, however, would be barely visible. We therefore tend to believe that a strongly negative B_2 (and also a strongly positive B_2, unless confirmed by independent runs covering many revolutions) is caused by a sudden impulse on the comet's nucleus, possibly as a result of its collision with a cosmic projectile. Such "jumps" have been detected in the motion of P/Perrine-Mrkos, P/Schaumasse, and P/Giacobini-Zinner (Marsden, 1969, 1970; Yeomans, 1971) and may have also occurred in the motion of P/Honda-Mrkos-Pajdušáková, P/Biela, and P/Forbes (Marsden, 1969; Marsden and Sekanina, 1971).

TRANSITION FROM COMETARY PHASE INTO ASTEROIDAL PHASE

The shape of the curve of NG activity varies from comet to comet. Specifically we note that a comet newly captured by Jupiter does not necessarily start its way across the graph in the E phase. The nuclear core could have already been dismantled by the time of capture, even if the comet had originally an icy envelope but had spent a very long time (at least, say, several thousand years) in low eccentricity orbits at solar distances comparable to that of Jupiter.

Similarly, the comet does not necessarily progress all the way down to complete deactivation. The regular course of events can be interrupted, for example, by expulsion of the comet back into a distant orbit if close approaches to Jupiter are not avoided. We must admit that some comets can undergo the capture-expulsion process several times during their lifetimes.

Therefore, only a small fraction of comets currently located on the core-mantle branch of evolution turn ultimately into minor planets. P/Arend-Rigaux and P/Neujmin 1 are apparently on the verge of the asteroidal phase, and both P/Encke and P/Tempel 2 are likely to reach the phase in a few tens of revolutions.

To see, on the other hand, whether the minor planets of the Apollo and Albert types could be extinct cometary nuclei, we have applied the core-mantle model to all of these objects that have perihelion distance smaller than 1.5 AU. We have found that nine of them may be of cometary origin. They are listed in table I. The cutoff at 1.5 AU has been applied because of the dimensions of Mars' orbit. Öpik (1963) has shown that about one-half of the original

TABLE I.–*Potential Extinct Cometary Nuclei Among Apollo and Albert Objects*

Object	Present orbit		Radius, km		Lifetime in cometary phase, yr
	q, AU	Q, AU	Present	Original	
Adonis	0.44	3.30	0.55	60	30 000
1953 EA	1.03	3.99	.3	3	3 000
Alinda	1.15	3.88	1.5	30	30 000
Albert	1.19	3.98	1.2	15	15 000
Ganymed	1.21	4.10	18.6	130	120 000
1963 UA	1.24	4.05	2.4	20	20 000
Beira	1.39	4.07	6.9	60	60 000
Kepler	1.43	3.93	2.3	40	45 000
Sirene	1.44	3.82	1.1	35	40 000

population of asteroidal objects crossing Mars survived since the time of origin of the solar system. The objects outside Mars' orbit (and well inside Jupiter's) must have collisional lifetimes much longer than the age of the solar system. There is, therefore, no point in attempting to prove their cometary origin.

The NG reduction in the aphelion distance, integrated over the comet's lifetime in the exposed orbit, amounts to less than 1 AU for objects with $q \geqslant 1$ AU and less than 1.5 AU for Adonis. Consequently, the mechanism cannot explain orbits with aphelia smaller than 3 AU and only exceptionally those smaller than 3.5 AU, unless the objects are allowed to have been originally huge bodies (more than several hundred kilometers in radius). For the same reason, Apollo itself was not found a likely candidate for this process, and also the strange orbit of Icarus cannot be explained solely by the effect of the NG mechanism.

Although it is difficult to give any specific figures at present, it is felt that the process of "permanent" capture of a comet into an eccentric orbit inside that of Jupiter is completed very rarely, and, therefore, the number of asteroids of the Apollo and Albert types that evolved in this way should be rather limited.

ACKNOWLEDGMENT

The writer's thanks belong to Dr. B. G. Marsden for a countless number of very valuable discussions about various aspects of the comet-asteroid relationships that helped to improve the quality of this paper.

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