A MONTE CARLO ESTIMATE OF THE FRACTION OF COMETS DEVELOPING INTO SIZEABLE ASTEROIDAL BODIES

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(Received 21 May, 1979)

Abstract. We present results of Monte Carlo simulations of orbital evolution showing that assuming a steady state there are roughly 50 extinct comets per active one in the Mars-crossing Jupiter family. The large number of extinct comets thus expected compared with the absence of observed Apollo or Amor asteroids with aphelion distances greater than 4.2 AU indicates that less than five percent of the extinct comets survive as sizeable asteroidal bodies.

Burnt-out comets have been frequently suggested as the major source of Apollo asteroids (perihelion distance \( q < 1.0 \) AU). Ėpik (1963) argued that the diffusion of perihelia inside the Earth’s orbit from an asteroidal source by means of Martian perturbations yields a ratio of Apollos/Mars crossers much smaller than the observed one. This would suggest the existence of another source for the Apollos. The cometary source appears abundant enough unless the fraction of the comets surviving as asteroidal bodies is extremely small. Recently Wetherill (1979) has investigated various asteroidal and cometary sources of Apollo and Amor objects, calculating the resulting steady-state orbit distributions. Again the cometary sources yield a slightly better fit to the observations, though the ‘Mars-crossing bottleneck’ for the asteroidal sources has been largely overcome by including the action of the \( \nu_6 \) secular resonance with Jupiter. Thirdly, we may mention several observed Apollo asteroids which from various dynamical or physical evidence (Kresák, 1977, 1979) are likely to be of cometary origin: 1978 SB, 1973 NA and 2101 Adonis. In particular for 1978 SB the orbit published by Kastel’ (1978) closely coincides with the one of comet P/Encke.

The problem about the cometary contribution to the population of Apollo–Amor asteroids is indeed an important one not only regarding the origin of these objects but also for cometary physics: it concerns the structure of the comet nucleus and the fate of this nucleus in the process of devolatilization or disintegration. A nucleus containing an asteroidal core (Whipple, 1977) would certainly leave an asteroid behind after the stripping of the ice. A ‘dirty iceberg’ with no core might develop into an asteroidal object by

Paper presented at the European Workshop on Planetary Sciences, organised by the Laboratorio di Astrofisica Spaziale di Frascati, and held between April 23–27, 1979, at the Accademia Nazionale del Lincei in Rome, Italy.
the formation of a silicate crust overlying the interior ice, while alternative fates would be complete evaporation or splitting. Evidently an estimate of the fraction of the burnt-out comets which survive as sizeable asteroidal bodies is an important piece of information. It does not uniquely discriminate between the different models of the cometary nucleus, but at least it provides an upper limit for the fraction of the comet nuclei which contain sizeable asteroidal cores.

Such an estimate was derived by Opik (1963). However, it depends heavily upon several unsafe assumptions about comet P/Encke. This comet is assumed to be physically similar to other short-period comets in spite of its peculiar orbit with a very small aphelion distance. It is also assumed to be the only comet which could develop into an Apollo asteroid, thanks to this peculiar orbit which saves it from close encounters with Jupiter. Thirdly, the occurrence of an Encke-like orbit among the short-period comets at any particular time is assumed to be a probable event.

In this paper we derive an upper limit for the fraction of ‘asteroidal survivors’ among the extinct comets by a different method, where all the Jupiter family comets (aphelion distances $4 \text{ AU} < Q < 8 \text{ AU}$) can be considered as possible sources of Apollo or Amor asteroids. The basic assumptions are the following. The active comets of the Jupiter family form a population which is maintained in a steady state by a balance between the deactivation processes (sink) and captures from nearby orbits with larger perihelion distances by Jovian perturbations (source). In a similar way the extinct comets – i.e., the results of the deactivations, whatever they may look like – form a population which is also kept in a steady state. The source of extinct comets is the same as the above mentioned sink for the active comets, while the sink of extinct comets is provided by Jovian perturbations expelling the objects into long-period orbits and eventually out of the solar system.

These steady-state assumptions are natural because of the very short time-scales required for all the transfer processes ($10^3$–$10^4$ years). Hence we may imagine a quasi-constant number of both active and extinct comets in Mars-crossing orbits of the Jupiter family. Close encounters with the terrestrial planets may transfer members of this constant reservoir into orbits with smaller aphelion distances ($Q \leq 4.2 \text{ AU}$) after which the major Jovian perturbations would be effectively ‘switched off’. In this essential process of reduction of the aphelion distance the non-gravitational forces influencing the active comets are also likely to play an important rôle.

We have estimated the steady-state number of extinct comets in the Mars-crossing Jupiter family by means of Monte Carlo simulations of the orbital evolution under the influence of Jovian perturbations. The principles of this method were described by Rickman and Vaghi (1976): a population of fictitious comets is allowed to perform a random walk in a certain domain of the $(Q, q)$-plane. The steps $(\Delta Q, \Delta q)$ are chosen from a precalculated sample of Jovian perturbations, and the population is kept at a constant size by a detailed balance between disappearances, corresponding to the limited observable lifetimes, and infeeds of new comets into a particular ‘source region’ of the $(Q, q)$-plane.

In a recent paper (Froeschlè and Rickman, 1979) we have developed and improved the simulation technique and attained a substantial improvement of the dynamical information