1. EVOLUTION OF COMETARY ORBITS ON A COSMOGONIC TIME SCALE

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Abstract. A review of modern concepts of the evolution of cometary orbits for the time span of some million years is presented. These concepts are based on the hypothesis of the existence of the Oort cloud, the theory of diffusion developed by Shtejns, and the work by Kazimirchak-Polonskaya concerning the influence of the major planets in transforming cometary orbits. All these ideas are currently being developed with the aid of rigorous mathematical methods by cometary researchers in various parts of the world.

1. Celestial Mechanics and the Origin of Comets

Celestial mechanics is the branch of astronomy that is devoted to the investigation of the motions of the bodies of the solar system. There exists, however, one problem in celestial mechanics for the solution of which we have to go outside the solar system. This is the problem of the 'evolution of cometary orbits', it being the problem of the 'origin of comets' from a cosmogonical point of view.

The principal difficulty encountered in the solution of the problem is the relatively short 'orbital' life of the short-period comets, and this necessitates the solution of another problem, that of finding the source that replenishes these objects.

Three possible sources exist: (1) eruption processes occurring on the surfaces of the bodies of the solar system; (2) the outer region of the solar system, inaccessible to direct observation; and (3) interstellar space. We are therefore in a position to formulate three essentially different cosmogonical hypotheses on the origin of comets, and each of these points of view has its own ardent supporters.

The principles taken as the basis for cometary investigations at the Institute for Theoretical Astronomy are: the hypothesis on the existence of the Oort cloud, the problem of stellar perturbations, the 'diffusion theory' and the 'capture theory'.

All four stages may be investigated by the rigorous mathematical methods of celestial mechanics and, what is perhaps even more important, the major points of the theory can be compared with observations.

2. The Oort Cloud

The existence of the Oort cloud was assumed by many astronomers long before Oort discussed the matter in 1950. The Oort cloud is a natural consequence of several of the cosmogonic hypotheses on the origin of the solar system. The theory proposed by O. Schmidt provides a simple explanation for the formation of cometary nuclei at the periphery of the protoplanetary cloud (Levin, 1960, 1963). Oort's assumption that the cloud of cometary nuclei originated together with the asteroids as the result of the explosion of a major planet existing between Mars and Jupiter therefore

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becomes superfluous. This somewhat artificial supposition was indispensable when cometary nuclei were thought to be stony bodies. It became unnecessary after Whipple and Dubyago had formulated the icy model for a cometary nucleus. According to Oort the cometary cloud must contain about 10^{11} cometary nuclei moving in orbits of various inclinations and eccentricities. The semimajor axes of the orbits are confined within a distance of 30 000 to 100 000 AU (Oort, 1963), the maximum density being at about 50 000 AU from the Sun.

An estimate of the total mass of the cometary cloud is naturally rather unreliable. For cometary nuclei of mean mass 10^{15} g, the total mass is about 10^{26} g, or about 1/60 the mass of the Earth. At its formation, however, the mass of the cometary cloud could have been two orders of magnitude greater.

3. Stellar Perturbations

The Oort cloud is dynamically unstable, and individual stars often pass through it. As was shown by Chebotarev (1966), the motion of a comet (with eccentricity $e=0.6$) is only possible at distances of less than 80 000 AU from the Sun. The boundaries of the cometary cloud are therefore confined within the limits 60 000 to 100 000 AU. This result is in a good agreement with Oort's data, obtained by entirely different methods. Sekanina (1968a) extended the classical concept of the solar sphere of action (Chebotarev, 1963, 1964) for an n-body problem, where $n=43$ (the Sun and 42 stars situated in its vicinity). The mean radius of the sphere turned out to be 1.5 parsec, but local variations in the distribution of the stars caused a compression to 0.6 parsec (120 000 AU) in the direction of α Centauri. For this reason the outer regions of Oort's cometary cloud cannot be stable.

Finally, the problem of the boundaries of Oort's cloud has been studied by Antonov and Latyshev (1971). For the galactic potential they adopted the value obtained from observations ($F=M/r^{1.4}$) rather than the Newtonian potential $F=M/r^2$ used by Chebotarev.

In the investigation of the stability of the Oort cloud the irregular perturbations from individual stars must also be taken into consideration. Vsekhsvyatskij (1954) was the first to make a sufficiently accurate estimate of the number of stars systematically passing through the Oort cloud; see Table I. This table shows that during the lifetime of the solar system some 3000 stars at a distance of 50 000 AU

TABLE I

Frequency of stellar passages through the Oort cloud

Distance (AU)	Time (yr)
30 000	5 000 000
50 000	1 700 000
100 000	500 000
150 000	230 000
200 000	110 000

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and up to 20 000 stars at 150 000 AU might have passed through the cometary cloud. Vsekhsvyatskij concludes that the perturbations by these stars might destroy the cloud in a few million years. But Nezhinskij (1971) has shown that the half-life of the Oort cloud as a result of the cumulative effect of stellar perturbations is 1.1×10^9 yr. This is about one-fifth the lifetime of the solar system. This confirms that when the solar system was formed the mass of the cometary cloud must have been several times greater than the mass of the Earth.

Stellar perturbations on the motions of comets can be considered in two ways:

(1) with the star fixed relative to the Sun and moving comet (Fesenkov, 1951; Shtejns, 1955; Makover, 1964); or

(2) with the comet fixed relative to the Sun and moving star (Shtejns and Sture, 1962).

Since the velocity of the comet ($v = 0.2$ km s^{-1}) at the periphery of the solar system is two orders less than the velocity of the passing star ($V = 20$ km s^{-1}), we might assume that the second method is the more realistic. Sekanina (1968b), however, has shown that both dynamical arrangements yield statistically identical results, namely, small changes in semimajor axis and large changes in perihelion distance. Only very close stellar encounters (within 1000 AU) are capable of appreciably changing the character of the cometary orbit within the Oort cloud. As a result of those large perturbations some of the cometary nuclei are forced into orbits with perihelion distances less than the radius of Jupiter's orbit, and the comets may thus become observable from the Earth.

4. The Theory of Diffusion

When a comet from the Oort cloud passes into the region of the major planets the perturbations by the stars become less important than those by the planets. As a result of the planetary perturbations the semimajor axis of the orbit may decrease, or the comet may be ejected outside the solar system into interstellar space. The accumulation of small planetary perturbations is random and requires the application of nonclassical methods of celestial mechanics. Actually, only the semimajor axes are involved in this diffusion (Shtejns, 1964, 1965). Shtejns has formulated three laws of diffusion:

(1) cometary orbits with small semimajor axes also have small inclinations (Oort was the first to state this law);

(2) Orbits with large perihelion distances have on the average small eccentricities;

(3) The number of 'new' comets, i.e., those approaching the Sun for the first time, increases with decreasing perihelion distance. For instance, at perihelion distance $q = 1$ AU about 30% of the comets are 'new', while at $q = 4.5$ AU only 3 to 5% are 'new'.

The laws of diffusion have been checked by Shtejns and Kronkalne (1964) on 20 000 fictitious comets.

5. The Theory of Capture

The theory of capture in its classical form was advanced by Laplace in 1796. He

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thought that comets entered the solar system from interstellar space and that some of them could be captured by the planets if a sufficiently close approach occurred, i.e., the parabolic orbit would be transformed into an ellipse. This theory gained wide popularity in the last quarter of the nineteenth century, following the classical work by Tisserand, Schulhof, H. A. Newton, Callandreau, and others. They demonstrated that such a 'capture' could take place for a comet passing through Jupiter's sphere of action. However, the low probability of this was found to be in serious disagreement with the observations, and the idea was untenable for other reasons too, such as the absence of short-period comets with retrograde orbits.

Only recently has the evolution of orbits of comets that entered the inner planetary system been fully understood (Kazimirchak-Polonskaya, 1967a, 1967b, 1968; Belyaev, 1967a, 1967b). As a rule, a comet approaching the Sun has already passed through the solar system a number of times before, and in accordance with the theory of diffusion it cannot have a parabolic orbit with an arbitrary inclination to the ecliptic plane. By studying the motions of a number of comets over the interval 1660–2060 Kazimirchak-Polonskaya has obtained for the first time a real picture of the evolution of cometary orbits within the orbit of Pluto. This appears to be a remarkable confirmation of the modern concept of the capture theory.

6. Comparison with Observations

The main difficulty in conclusively proving the capture theory is that no comets have been observed with perihelion distances greater than 4 to 5 AU. Table II lists those with the largest perihelion distances.

TABLE II

The comets with the largest perihelion distances

Comet	q (AU)	Comet	q (AU)
1957 IV	5.5	1925 VI	4.2
1948 III	4.7	1942 VIII	4.1
1954 V	4.5	1956 I	4.1
1957 VI	4.4	1729	4.1
1959 X	4.3	1936 I	4.0

A comet becomes accessible to observation only after it approaches inside the orbit of Jupiter. When comparing theory with observations some caution is necessary because it is impossible to detect, not only the comets within the Oort cloud, but also the great majority of comets inside Pluto's orbit.

It is an observational fact, however, that the aphelia of the vast majority of comets lie at distances exceeding 20 000 AU. It may be inferred that a cometary cloud exists at the periphery of the solar system. The density of the cloud is uncertain. It is probable that the cometary cloud is supplemented by so-called 'interstellar' comets that might have originated in the vicinity of other stars and were ejected afterwards into interstellar space (Sekanina, 1968b).

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It is important to stress here that we do not know anything about the existence of major planets outside Pluto's orbit (Chebotarev, 1972), and any such planets would play an important role in the evolution of cometary orbits.

7. Conclusions

Modern celestial mechanics allows us to outline certain aspects of the theory of the origin of comets. The Oort cloud, situated at the periphery of the solar system, provides a constant supply of observable comets. The evolution of cometary orbits is determined by perturbations from the stars and planets. Because of the perturbations many comets are ejected outside the solar system while others remain forever the 'prisoners' of the major planets.

The problem of the genetic relationship between comets and minor planets involves the physical structure of cometary nuclei. We are of opinion that comets and minor planets are objects of absolutely different types. The minor planets are the debris of parental protoplanets that originated between the orbits of Jupiter and Mars at the formation of the solar system. There are difficulties, however, in the classification of some objects (e.g., Hidalgo).

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