EVOLUTION OF THE OORT CLOUD ANGULAR MOMENTUM:
NUMERICAL SIMULATION

ALEXANDER LOPATNIKOV, LEONID MAROCHNIK, LEV MUKHIN,
ROALD SAGDEEV, DANIEL USIKOV, and GEORGY ZASLAVSKY

Space Research Institute, Academy of Science of the USSR, Moscow, U.S.S.R.

(Received 8 February, 1991)

Abstract. This paper considers the evolution of a flat swarm of cometary bodies (under the effect of the
passage of stars), initially moving in one direction along the circular orbits with radii
1.4 \times 10^4 < r < 2 \times 10^4 \text{ AU} and along elliptic orbits with semi-major axes
5 \times 10^3 < a < 1 \times 10^4 \text{ AU} and
with perihelia within 50 < q < 100 \text{ AU}. Numerical simulation shows that the original flat belt of comets is
thermalizing. Its root-mean-square $z$-coordinate grows with $r$. A cometary cloud forms with a dense flattened
inner core and a rarefied halo (the Oort cloud proper). The value $\beta = N_{\text{core}}/N_{\text{halo}}$ varies within a wide range
(up to the order of magnitude) depending on the model used ($N_{\text{core}}$ and $N_{\text{halo}}$ are the numbers of comets
in the core and the halo, respectively).

The hypothesis of a massive Oort cloud (Marochnik et al., 1988) implies that the Oort cloud should have
a large angular momentum. This paper employs numerical simulation to calculate Oort cloud models to
which the initially flat located at the periphery of the solar nebula rotating cometary swarms is evolving in
time. The loss of the initial angular momentum over the time of the Oort cloud evolution is not large.

1. Introduction

The concept of a large-scale structure of the solar system is consisting of the Sun, nine
planets and their satellites underwent a change in 1950, when Oort (1950) showed that
a giant cloud of comets is located at the periphery of the solar system (Oort cloud). From
the flux of observed comets the number of comets in the cloud was estimated as
$N_0 \approx 2 \times 10^{11}$. Semi-major axes of the orbits of the comets belonging to the cloud,
according to Oort's estimate, should be within the $4 \times 10^4 < a < 2 \times 10^5 \text{ AU}$ interval.
Now this interval is estimated as $2$ to $3 \times 10^4 < a < 5$ to $10 \times 10^4 \text{ AU}$ (see, e.g.,
Marochnik et al., 1989a; and the references quoted therein).

The preliminary estimate of the Oort cloud mass was made under the assumption that
the nuclei of all comets are spheres with a mean radius of the order of $R = 1 \text{ km}$ and
density $\rho = 1 \text{ g cm}^{-3}$. Hence, the mass of the Oort cloud is $M_0 = 0.1 \text{ M}_\odot$ (Oort, 1950).
Thus the cometary cloud filling the periphery of the solar system seemed to be dynamically weightless, not affecting the distribution of mass and angular momentum in it.

With time, however, estimates of the Oort cloud mass become larger. The most
detailed investigation of the mass spectrum of the comets populating the Oort cloud was
made by Weissman (1983). He relied on the Everhart (1967) intrinsic function which
takes into consideration the effects of observational selection, and estimated the mass
of the Oort cloud as $M_0 = 1.9 \text{ M}_\odot$. Here the average density of the cometary nucleus
was assumed equal to $\rho = 1 \text{ g cm}^{-3}$, its albedo $A = 0.6$, the number of comets of the

Oort cloud is \( N_0 = 1.2 \) to \( 2 \times 10^{12} \). The spectrum-averaged mass of the nucleus of the typical comet was then estimated as \( \langle M \rangle = 7.3 \times 10^{15} \text{ g} \) and its radius is \( R = 1.2 \text{ km} \).

As Hughes (1988) noted, the data by Everhart (1967) are obviously subject to the effects of observational selection. If we use the data by Hughes (1988) not corrected for the effect of observational selection, then the analysis of the mass spectrum of long-period comets yields the estimate \( M_0 = 4 M_\odot \) (Marochnik et al., 1989a, b) where again \( A = 0.6 \) was assumed. With an accuracy up to the factor of \( \sim 2 \) this result coincides with the preliminary estimate Weissman (1983) made, that is, the same order of magnitude is obtained for \( M_0 \).

Along with this, if we assume that the average albedo of long-period comets \( A_{LP} \) should be close to that of short-period comets \( A_{SP} \), then we get a markedly larger estimate of the mass of the Oort cloud. It was Weissman (1986a) who first mentioned that, he assumed, \( A_{LP} = A_{SP} = 0.05 \) and got \( M_0 \cong 25 M_\odot \). A similar estimate made by Marochnik et al. (1989a) was \( M_0 \cong 100 M_\odot \) for \( A_{LP} = A_{SP} = A_H = 0.04 \) where \( A_H \) is the \textit{in situ} measured albedo for P/Halley.

Note that there are also physical arguments supporting the assumption of similar \( A_{LP} \) and \( A_{SP} \) values. The low albedo is implied by the formation of a thin layer of dark material on the surface of the comet's nucleus. The data of lab experiments on low-temperature ice which obtains \( \text{H}_2\text{O}, \text{CH}_4 \) and organic compounds and are irradiated with high-energy protons demonstrate that black graphite-like materials forms (Strazzula, 1986).

As Weissman (1986b) mentioned, the effect of galactic cosmic rays on cometary nuclei within the Oort cloud (till before they appear in the planetary system) should lead – for the reason indicated above – to the formation of a sufficiently thick crust made of a dark graphite-like polymer which acts as a 'cometary glue' fastening the surface of the nucleus against sublimation.

Because of the low thermal conductivity of such a polymeric layer the low albedo of the surface of cometary nuclei may be provided by a layer only several cm thick. The low volatility of this layer and its 'gluey' properties will preserve this layer even if the comet changes its orbit for a short-period one.

At present it is considered probable that the canonical Oort cloud is only a halo surrounding a dense inner cometary core with the outer boundary corresponding to the semi-major axis \( a_c = 2 \) to \( 3 \times 10^4 \text{ AU} \) (Hills, 1981; Heisler and Tremaine, 1986). This core is a source replenishing comets into the halo when the latter is being depleted when the solar system approaches nearby passing stars and giant molecular clouds in the Galaxy (GMC) and because of the tidal force of the Galaxy. Sometimes this inner cloud is called the Hills cloud. The outer boundary of the Hills cloud is identified unambiguously enough, as Hills (1981) showed, since comets with large semi-major axes \( a < a_c \) do not fill the loss cone in the velocity space, which supplies them into the region of the planetary system where they are observed. According to Hills, the value \( a_c \) depends, but weakly on the parameters that enter the formula for \( a_c \) (exponent \( \frac{2}{3} \)), so that its value is determined confidently enough. Along with this taking into account the tidal effect of the vertical gravitational force of the galaxy fields the estimate \( a_c \cong 3 \times 10^4 \text{ AU} \), according to Heisler and Tremaine (1986).