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The Oort cloud as a remnant of the protosolar nebula

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Abstract. If comets are assumed to have been created in the cool, dense regions of interstellar clouds, then these macroscopic bodies have to take part in the collapse of a protostar cloud as bodies following the laws of mechanics, in contrast to the gas and microscopic dust, which follow the laws of hydrodynamics. Here we present evidence concerning the solar system comets: if the velocity distribution of comets before the collapse of protosolar cloud was similar to what it is now in the outer Oort cloud then the comets would have remained at large distances from the centre of the cloud. Hence, the comets in the solar Oort cloud may represent a remnant of the nebular stage of the solar system.

Key words: comets: general – solar system: formation – ISM: kinematics and dynamics

1. Introduction

The origin of the Oort cloud comets still remains an unanswered question, because all recent theories had serious shortcomings.

The most popular primordial theory at present, which assumes the creation of comets in the Uranus-Neptune region during planet formation, does not provide a sufficient source of energy to eject the cometary nuclei into the Oort cloud region. The initial Oort cloud cometary population exceeded at least 80 $M_\oplus$ (Earth masses) (Weissman 1990). Bailey (1994) estimated that the present cometary mass must be at least 380 $M_\oplus$, for which the upper limit of survival probability is 20%. That means the ejected mass of cometary population was several, if not many, times higher than the sum of masses of Uranus and Neptune, which were regarded as the main ejecting planets within the original concept.

Fernández (1997) tried to solve the problem of the energy needed to deliver the cometary nuclei into the Oort cloud; he assumed that a considerable fraction of the nuclei was ejected into the cloud not only by Uranus and Neptune, but by Jupiter and Saturn as well. In the classic scenario, the efficiency of the latter planets to place the nuclei into the cloud was too small, because they were very likely to overshoot the narrow energy range and eject the nuclei into interstellar space (the ratios of mass ejected to the comet cloud and interstellar space are only 0.03 for Jupiter and 0.16 for Saturn (Fernández 1985)). To remove this controversy, Fernández (1997) suggested an improved scenario in which the solar system forms within a dense galactic environment, perhaps a molecular cloud and/or an open cluster, which produces a more tightly bound comet reservoir. Due to their different birthplaces, the comets should exhibit a different physical-chemical nature. On this point, the new scenario still lacks observations in its favour, because some evidence has been found indicating that cometary nuclei were created in a cooler environment than the Jupiter-Saturn zone of protoplanetary dics. This was most recently documented by Bergin et al. (1999), who demonstrated that comets Halley and Hyakutake had to form at temperature 25 to 30 K, comet Hale-Bopp at 40 K.

The theories of interstellar origin cannot provide any suitable mechanism of capture of interstellar comets by the solar system (Valtonen & Innanen 1982; Torbett 1986). Moreover, these have been disregarded because of the density argument (e.g. Rickman & Huebner 1990).

Perhaps the only theory without any shortcoming is the theory of creation *in situ* published by Hills in 1982. He suggested that pressure due to the radiation from the Sun and neighbouring protostars may have forced the coagulation into comets of dust grains in collapsing layers of the protosun at distances from 1 to 5 thousand AU (astronomical units). However, if this mechanism is actually efficient in comet creation, then these would also have been coagulated, at an even higher rate, in molecular interstellar clouds during the passages of highly luminous stars through the dense cloud regions.

We know that there are many indications of similarities among cometary material and that of cool, dense interstellar clouds (e.g. Greenberg 1982, 1998; Clube & Napier 1985; Mumma et al. 1990; Delsemme 1991; Greenberg & Shalabiea 1994; Greenberg & Li 1998; Bergin et al. 1999). On the other hand, it can be regarded as proven that the comets have been bounded to the solar system over all its existence (all observed comets have been bounded to this system (Marsden et al. 1973)). Combining these facts and considering the previously mentioned shortcomings, it seems that molecular interstellar clouds are the most appropriate birth-place of comets. If this assumption is accepted, then the cometary nuclei also had to be present in the protosolar nebula before its collapse into the protosun and protoplanetary disc.

In this paper, we attempt to answer the question of whether the cometary nuclei remained at Oort cloud distances after the protosolar nebula collapse, in a more exact and complete way than in our previous studies (Neslušan 1994, 1999). We know the cometary nuclei had to take part in the collapse in a different way than the gaseous and dusty components of the nebula. The atoms and molecules lost their kinetic energy by the well-known mechanism suggested by Hayashi (see his review from 1966, e.g.), but this mechanism could not be efficient with such large bodies as cometary nuclei. If the nuclei were present in a cloud during its collapse, then these did move mechanically whilst the atoms and molecules followed the laws of hydrodynamics. Of course, the trajectories of the cometary nuclei would have been changed due to the change of gravitational potential, but that does not obviously imply their collapse into the protoplanetary disc. In other words, we suppose that the comets of our Oort cloud could represent a remnant of protosolar nebula from a stage before its collapse into the protosun and protoplanetary disc.

2. Cometary nuclei in the protosolar cloud

In this paper, we deal with the problem of how the comets present in the parent cloud of the solar system could remain at large heliocentric distances after the cloud collapse. However, we need to discuss the creation of cometary nuclei in the interstellar clouds as this is the rationale for our study.

The similarity of material in dense interstellar molecular clouds and cometary material, mentioned in Sect. 1, as well as the necessity of a relatively high abundance of dust in the star-forming regions (Lattanzio 1984; Delsemme 1991; Mouschovias 1996; Nakano et al. 1996) lead us to assume that molecular clouds are an appropriate birth-place of comets. The idea of interstellar cloud comet origin has already been proposed by several authors (omitting the theories which have been rejected, e.g. that by Lyttleton (1948), we can mention for example: Hasegawa (1976), Khanna & Sharma (1983), Yabushita (1985) or Greenberg (1998)). A particular argument in favour of this concept was given by Clube & Napier (1985). They noticed the results of previous studies (Cardelli & Bohm-Vitense 1982; Phillips et al. 1982; Mentese 1982; Tarafdar et al. 1983) viz. that the diffuse interstellar nebulae are deficient in almost all elements including most refractories (C, Mg, Fe, Ti) and volatiles (N, S, O, Ar) relative to solar abundances. It seems reasonable to suppose that the large gas phase depletions, which are difficult to reconcile simply with loss to grains (Greenberg 1974; Tinsley & Cameron 1974), are due to comet formation.

In spite of the fact that a number of interstellar theories have been published, we cannot disregard a certain weakness of this concept of comet origin: no specific physical mechanism of creation of cometary nuclei in an interstellar-cloud environment, even if relatively dense, has been suggested and worked out in detail. Nevertheless, new observational facts have recently revealed a variety of unexpected phenomena and structures in the interstellar clouds. As an example, we can mention the evaporating gaseous globules discovered few years ago in the Hubble Space Telescope WFCP2 images (Hestler et al. 1996). The discovery was made in the M16 nebula, which is the site of very active recent star formation. Such globules are overdense regions appropriate for a condensation of macroscopic bodies. The globules in M16 are very probably only a sample of these objects. They became visible due to the radiation of nearby O stars, which had disrupted the star formation. In the molecular clouds, we can expect a number of dark sites with relatively high density, which are similar to those in M16.

Another possibility of comet creation (already mentioned in Sect. 1) is provided by the mechanism suggested by Hills (1982). Not only the pressure due to radiation from the protosun and neighbouring protostars, but from any luminous star may have forced the coagulation into comets of the dust grains, if the star crosses a dense interstellar region. Let us assume a region of radius 10^5 AU. García-Sánchez et al. (1999) found that the rate of close approaches by star systems (single or multiple stars) within a distance D (in parsecs) from the Sun is given by $N = 3.5D^{2.12}$ Myr^{-1}. Applying this result to the assumed region, we can estimate a rate of passages through the region of about 750 star systems per Gyr. Some stars are luminous enough to form cometary nuclei along cylindric surfaces around their paths.

3. Description of the collapse of the protosolar nebula

To describe the motion of a cometary nucleus inside the collapsing protosolar nebula, we need to solve its equation of motion:

$$m\frac{d^2\boldsymbol{r}}{dt^2} = -G\frac{mM_r}{r^3}\boldsymbol{r}, \tag{1}$$

where m is mass of the nucleus, $\boldsymbol{r}$ is its radius vector, $d^2\boldsymbol{r}/dt^2$ is the second time derivative of this vector, G is gravitational constant, and M_r is mass inside the sphere of radius $r = |\boldsymbol{r}|$. To integrate this equation, we have to know mass M_r. This mass can be obtained from the equations describing the collapse of the nebula.

The collapse of a spherically symmetric, isothermal gaseous sphere has most recently and most completely been described by Whitworth & Summers (1985). They followed the previous work by Penston (1969), Larson (1969), Shu (1977), and Hunter (1977).

The equations describing the collapse can be written as:

$$\frac{\partial M_r}{\partial r} - 4\pi r^2\rho = 0, \tag{2}$$

$$\frac{\partial M_r}{\partial t} + 4\pi r^2\rho u = 0, \tag{3}$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial r} + \frac{GM_r}{r^2} + \frac{1}{\rho}\frac{\partial P}{\partial r} = 0, \tag{4}$$

$$P = a_o^2\rho, \tag{5}$$

where ρ is density of the gaseous sphere at distance r in time t, u is outward radial flow velocity, P is pressure, a_o is isothermal sound speed equal to $a_o = kT/\mu$, and k is Boltzmann's

constant. In agreement with other authors (e.g. Penston 1969; Larson 1969), we put the temperature of the gaseous sphere $T = 10$ K. The mean molecular weight, μ, of a typical molecular cloud is $\mu = m_H/(0.72/2 + 0.25/4)$ (m_H is the mass of a hydrogen atom), approximately.

Following Shu (1977), Whitworth & Summers re-wrote these equations with the help of the only dimensionless variable x defined by

$$r = xa_o t \tag{6}$$

and the dimensionless quantities w, y, z defined by

$$M_r = \frac{wa_o^3 t}{G}, \tag{7}$$

$$u = ya_o, \tag{8}$$

$$\rho = \frac{z}{4\pi G t^2}. \tag{9}$$

The new equations have the form

$$\frac{dy}{dx} = \frac{(x-y)^2 z - 2(x-y)/x}{(x-y)^2 - 1}, \tag{10}$$

$$\frac{dz}{dx} = \frac{(x-y)z^2 - 2(x-y)^2 z/x}{(x-y)^2 - 1}, \tag{11}$$

$$w = (x-y)zx^2. \tag{12}$$

Whitworth & Summers found a whole two-parameter continuum of solutions of equations describing the collapse. These solutions can be divided qualitatively, with respect to the initial density behaviour, into three groups representing: (i) a centrally rarefied cloud, (ii) a cloud with flat central density behaviour, (iii) a cloud with a centrally peaked density. Quantitatively, a given cloud can be characterized by the ratio of central and shock-front-(sonic point)-distance densities, z_c/z_s. According to Whitworth & Summers, an infinite number of types of density behaviour outside the shock front can occur for one given type of behaviour inside the front. We empirically find and utilize the fact that the appropriate numerical integration always results in the same behaviour outside the shock front (using whatever reasonable integration step), if the integration is performed from centre to edge of the cloud and no integration step starts exactly (or almost exactly) in the appropriate sonic point. (Such a start would be incorrect because the sonic point is a singular point.)

In nature, only centrally flat or mildly peaked clouds can be considered in the given context, because a collapse of a matter into a relatively rarefied space is improbable or, on the other hand, supposing a highly centrally peaked cloud, we would avoid the problem of how a denser region appears in a more or less uniform gaseous interstellar environment anyway.

It is clear that the model of a cloud with initially flat ($z_c/z_s = 1$) behaviour of density around the cloud centre (the solution found independently by Penston 1969 and Larson 1969) represents the first border of cloud models acceptable in the context of our problem. This model has already been considered in our first study (Neslušan 1999). As was demonstrated by Whitworth & Summers (1985, Table 1), there is no solution of Eqs. (10) and (11) in the range of z_c/z_s from 1.955 to 3755. Hence, the value $z_c/z_s = 1.955$ appears to be natural as the second border of acceptability. To avoid numerical difficulties in numerical integration at the true border, we assume value $z_c/z_s = 1.954$ as the border, in practice. Whilst the cloud model at the first border is characterized by the value x in sonic point $x_s = -3$, the model at the second border is characterized by $x_s = -2.339$.

In both models considered, the beginning of the nebula collapse is considered to be the moment when the mass inside the shock front just equals $1\ M_\odot$ ($M_\odot$ is solar mass). The radius of the spherical shock front is $R_o = GM_\odot/(2a_o^2)$ at that moment.

Unfortunately, the end of the collapse is not well defined. The collapse described with Eqs. (10) and (11) would continue during an infinite period. In nature, the real collapse of protosolar nebula was terminated by a wind of corpuscular particles and radiation emitted by the protosun as it came into being. Alternatively, the accretion of the protosun could be terminated by the disruption of the appropriate star forming environment by a nearby hot star (Hestler et al. 1996). Since no final evolution of the outer parts of the protosolar nebula has been exactly described, we considered it best to terminate our numerical integration for a given cometary nucleus, when it is located at such distance r from the centre, where $M_r = M_\odot$.

The rotation of the protosolar nebula is not considered because it is not significant during the period investigated. An additional orbital momentum coming from the rotation could only enlarge the final orbits, therefore neglecting the rotation does not act against the main goal of our endeavour.

We note that the motion of a nucleus inside the shock front can be described analytically, in the form of an infinite power series, for the flat density model (Neslušan 1997). The analytical solution can be utilized in checking the numerical integrability of the problem and can also accelerate the computations.

4. On the initial assumptions and numerical integration

Assuming the creation of cometary nuclei in molecular clouds, it seems to be reasonable to suppose that their number density in an element of volume is roughly linearly proportional to the density of cloud material in this volume.

The mathematical cloud model described by Eqs. (10) and (11) extends to an infinite radius. In practice, we need to constrain the size of the cloud, when we construct the initial distribution of the hypothetical nuclei: since we terminate the numerical integration of motion of a given nuclei when the nebular mass inside reaches $1\ M_\odot$ (see Sect. 3), we consequently perform the numerical integration only for those hypothetical nuclei that are inside the infalling shock front at the beginning of integration. To evaluate the possible influence of the nuclei outside the shock front on the resulting distribution, we construct one distribution containing only the nuclei initially inside of shock front and another distribution containing also the nuclei initially outside of this front, in which their resulting distribution is identical to their initial distribution (no integration of their motion is per-

formed). It is convenient to consider the nuclei outside the shock front up to a heliocentric distance at which their number density does not decrease below about one order of the number density at the distance of shock front in the collapse beginning, i.e. up to a distance, where $z/z_s = 0.1$ (in other words, up to $4.10\ R_o$ or $4.25\ R_o$ for the model with $z_c/z_s = 1$ or $z_c/z_s = 1.954$, respectively).

Concerning the velocity magnitudes, we assume a Maxwell-Boltzmann distribution with the most probable velocity v_P (the peak of the distribution).

Specifically, we assume, in the beginning of the collapse, that there are

$$\Delta^6 N = \frac{4C_n}{\sqrt{\pi} v_P^3} \frac{\rho_o}{\rho_{oc}} exp\left(-\frac{v_o^2}{v_P^2} - \frac{2GM_r}{v_P^2 r_o}\right) . \\ .v_o^2.cos\varphi.\Delta\vartheta.\Delta\varphi.\Delta v_o.\Delta V \quad (13)$$

hypothetical cometary nuclei in each element of volume, $\Delta V = r_o^2.cos\phi.\Delta\theta.\Delta\phi.\Delta r_o$, of the considered cloud, which move in the direction of a given elementary space angle, $cos\varphi.\Delta\vartheta.\Delta\varphi$, characterized by angles ϑ, φ, with the initial velocity ranging from $v_o - \Delta v_o/2$ to $v_o + \Delta v_o/2$. C_n is a constant proportional to the total number of cometary nuclei in the cloud, ρ_o and ρ_{oc} are the densities of material in the given element of volume and in the centre of the nebula, respectively.

Because of symmetries, we can analytically integrate through all the possible values θ, ϕ, and ϑ and thus simplify Eq. (13) resulting in

$$\Delta^3 N = \frac{32\pi^{3/2}}{v_P^3} C_n \frac{\rho_o}{\rho_{oc}} .exp\left(-\frac{v_o^2}{v_P^2} - \frac{2GM_r}{v_P^2 r_o}\right) . \\ .v_o^2.cos\varphi.\Delta\varphi.\Delta v_o.r_o^2.\Delta r_o. \quad (14)$$

In our particular case, we consider the grid points constructed putting $\Delta\varphi = 9°$, $\Delta v_o = 0.15 v_I$, and $\Delta r_o = 0.05 R_o$. The quantity $R_o = GM_\odot/(2a_o^2) = 1.26 \times 10^4$ AU is the radius of the shock front at the beginning of the collapse. The circular velocity at R_o at the beginning of the collapse, $v_I = \sqrt{GM_\odot/R_o} \doteq 266$ m s^{-1}, is chosen as a characteristic velocity scale. In the integration, the range of the individual variables is: $\varphi \in < -90°, +90° >$, $r_o \in < 0.05 R_o, 1 R_o >$, and $v_o \in < 0.15 v_I, 3.15 v_I >$ (the upper limit, $3.15 v_I$, was chosen to satisfy the requirement that the number of nuclei moving with this velocity has to be less than 10^{-4} of those moving with maximal velocity v_P, i.e. the number of nuclei above the limit is negligible).

The most probable velocity, v_P, is a free parameter in the integration. We perform a series of six integrations with v_P equal to 0.250, 0.375, 0.500, 0.625, 0.750, and 0.875 v_I.

The integration is performed using the Runge-Kutta method of numerical integration.

As we already mentioned (Sect. 3), no exact description of the end of the protosolar nebula collapse has been made, therefore we are compelled to terminate each integration prematurely: we terminate it when the mass contained within the interior of the sphere of radius equal to the distance of the nucleus from the centre the nebula reaches $1\ M_\odot$. A further collapse above this mass was improbable. It appears that a nucleus spirals toward the centre during the collapse. When the collapse is artificially turned into an expansion (changing the sign of time), then the nucleus begins to spiral outward. Taking this into account, the premature termination of the integration implies that our resulting orbits should be regarded as minimum-distance orbits.

Apart from the above termination, we also terminate the integration, when the nucleus approaches the centre of the nebula at a distance less than 100 AU. Such a nucleus is regarded as incorporated in the protoplanetary disc. Moreover, we check whether the nucleus enters a region having density higher than $\approx 10^{-10}$ kg m^{-3} (critical density at which the material begins to be heated (Gaustad 1963) and the model of collapse used becomes inadequate). Eventually we check that the force of drag in the cloud material decelerating the nucleus does not exceed 10^{-3} of the gravitational force assuming the minimum acceptable mean density of the cometary nucleus of 200 kg m^{-3} (Rickman 1987; Rickman et al. 1987), i.e. the maximum efficiency of drag deceleration. Such a deceleration could debase the result of given numerical integration. It appears that neither of these two latter cases occur at $r > 100$ AU.

5. Results and discussion

The distributions of perihelion distances, semi-major axes, and aphelion distances of the assumed grid of cometary orbits are displayed in Figs. 1, 2, and 3, respectively. Each figure consists of plots from (a) to (f), where each pair of adjoining plots show the corresponding distributions for two cloud models characterized by ratios z_c/z_s equal to 1 and 1.954 respectively, but with the same value of the peak velocity v_P, in the appropriate Maxwell-Boltzmann distribution of initial velocities of nuclei. Three such pairs of plots, for $v_P = 0.25$, 0.50, and 0.75 v_I, are given in each figure.

As stated in Sect. 4, the integration of motion of the hypothetical nuclei was also performed for the values of v_P equal to 0.375, 0.625, and 0.875 v_I. For all the values of v_P, some numerical characteristics are given in Table 1.

Hypothetical cometary nuclei inside the shock front were considered in the construction of the plots in Figs. 1–3. If analogous plots are constructed including also the nuclei outside the shock front (up to the distance where $z/z_s = 0.1$; see Sect. 4), we observe an insignificant shift of the bars to larger abscissa values (the abscissa values for the peaks of the distributions are given in Table 1). In the distribution of perihelion distances (Fig. 1), the behaviour is not truncated at $log(q) = 4.05$ for $v_P = 0.50$ and 0.75 v_I (plots from (c) to (f)), but has an exponential-like tail above $log(q) = 4.05$. Therefore, ignoring the external nuclei has no significant influence on the conclusion about the large heliocentric distances of these nuclei after the collapse.

Looking at the figures, it is clear that the nuclei remain at large heliocentric distances, if their initial velocity distribution lies within an appropriate range, i.e. if v_P is a value from a certain interval. More specifically, a very low number of nuclei

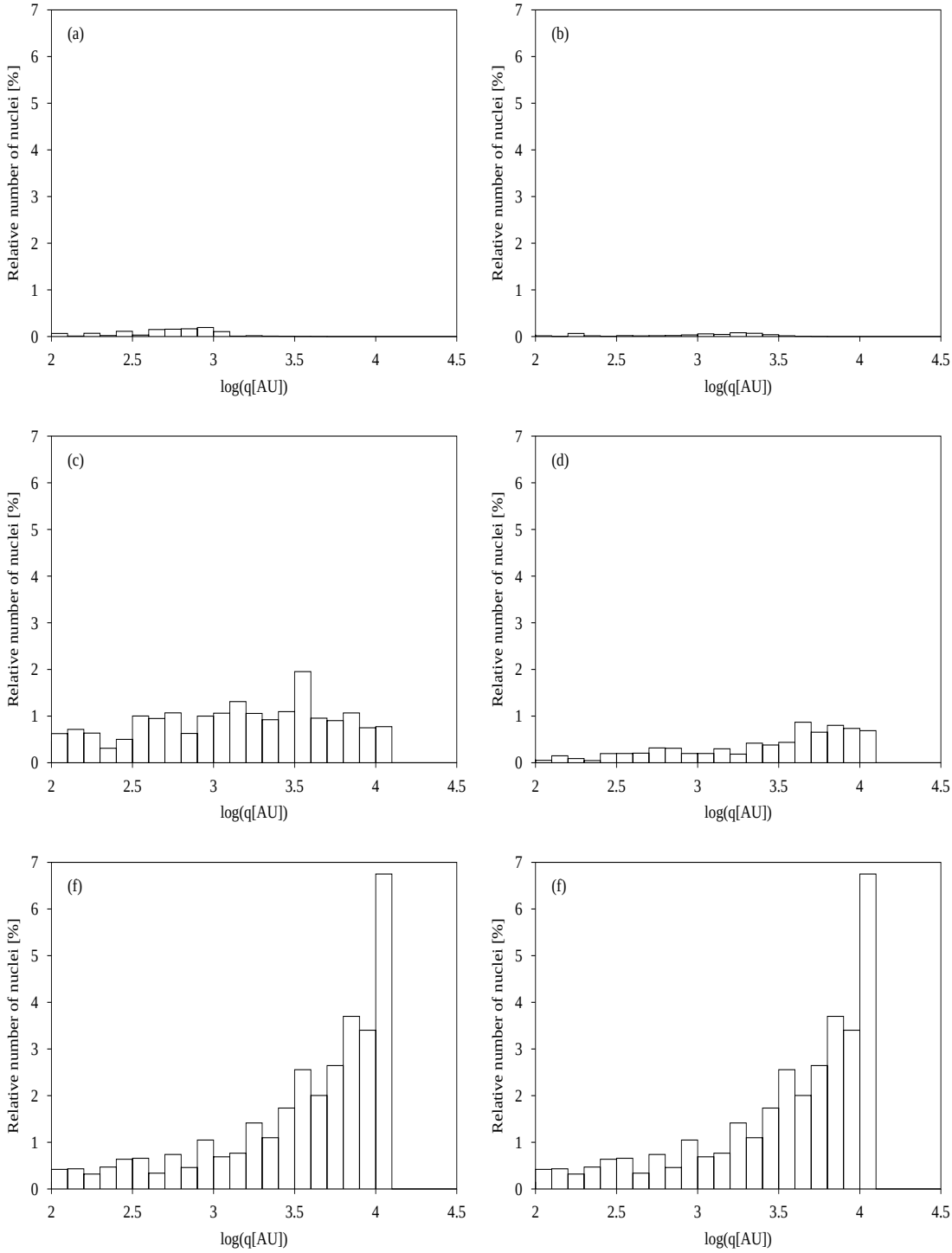

Fig. 1a–f. The distribution of perihelion distances, q, of the cometary nuclei sample considered. The left-hand plots (**a**, **c**, **e**) correspond to the model of protosolar cloud collapse with central and sonic-point initial density ratio, z_c/z_o, equal to 1, the right-hand plots (**b**, **d**, **f**) correspond to the model with $z_c/z_o = 1.954$. The first pair of plots (**a**, **b**) is constructed assuming the initial velocity distribution peak, v_P, equal to $0.25 v_I \doteq 66\ \mathrm{m\,s^{-1}}$, the second pair (**c**, **d**) for peak $v_P = 0.50 v_I \doteq 133\ \mathrm{m\,s^{-1}}$, and the third pair (**e**, **f**) for peak $v_P = 0.75 v_I \doteq 199\ \mathrm{m\,s^{-1}}$. The values in abscissa are expressed in common-logarithm scale.

remains at the large distances at $v_P \leq 0.25\ v_I$. On the other hand, the number of nuclei in a cometary cloud does not continue to increase if the peak exceeds the value of $\approx 0.75\, v_I$, because an increasingly significant fraction of the nuclei leaves the system along hyperbolic orbits (see Table 1).

We can assume that the nuclei gained their velocities mainly due to the gravitational perturbations by the protostars being

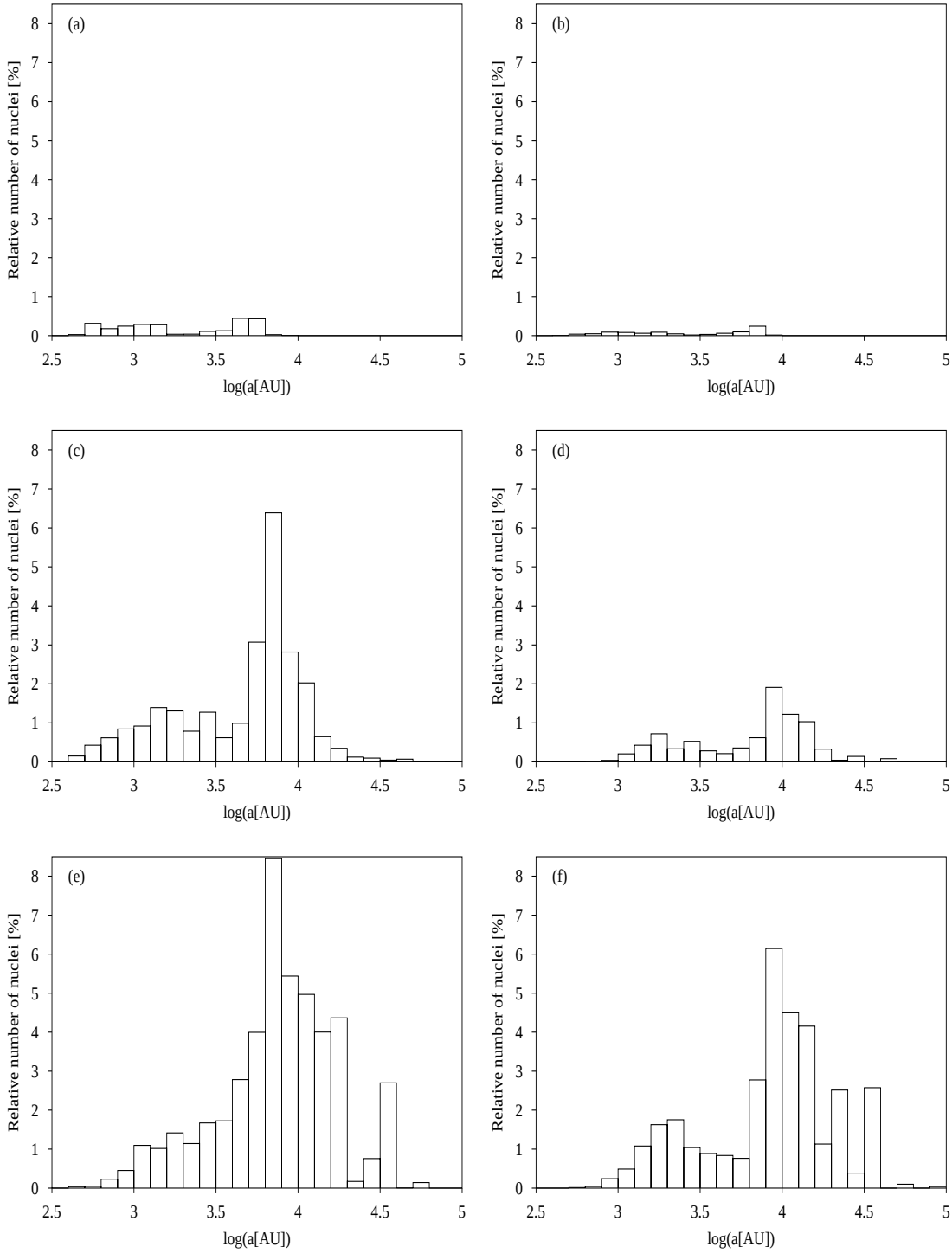

Fig. 2a–f. The distribution of semi-major axes, a, of the cometary nuclei sample considered. The distribution is constructed for the same models of cloud collapse and Maxwell-Boltzmann distributions of initial velocity as in Fig. 1.

formed in the neighbourhood of the protosun, in a common association. Unfortunately, it is difficult to appreciate the possible complex perturbations of motion of the nuclei from the beginning of their creation in an interstellar cloud to the beginning of the collapse of protosolar cloud. To give an order of magnitude estimate of the velocity dispersion, we adopt the concept of the birthplace of the solar system proposed by Fernández (1997). In this concept, the Sun formed within a molecular cloud and, perhaps, a star cluster. It is reasonable to assume that some stars of the cluster formed earlier and some later than the Sun. The stars which formed earlier influenced the motion of the nuclei in the birth cloud of solar system. Following Fernández, let us

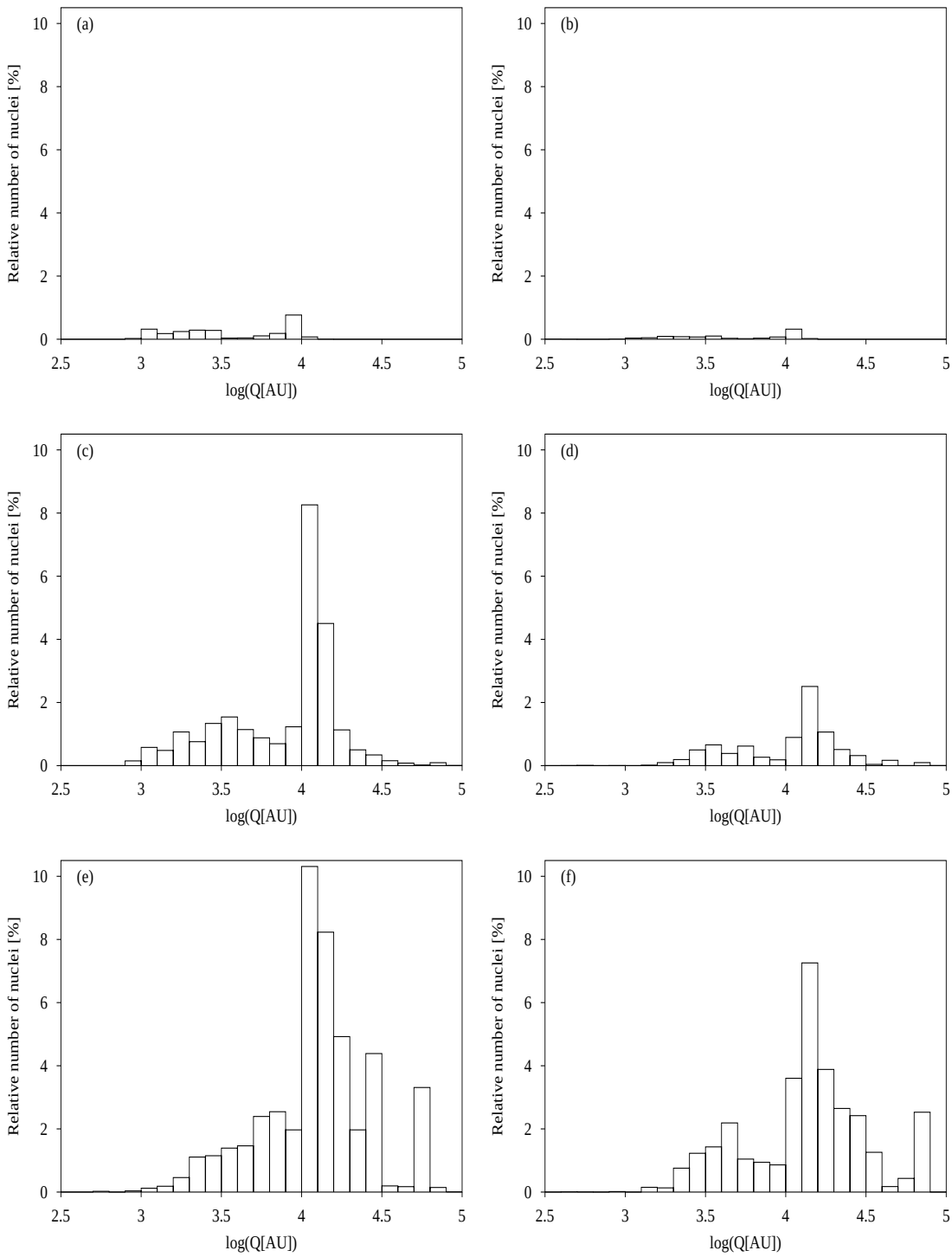

Fig. 3a–f. The distribution of aphelion distances, Q, of the cometary nuclei sample considered. The distribution is constructed for the same models of cloud collapse and Maxwell-Boltzmann distributions of initial velocity as in Fig. 1.

assume a cluster of stellar density $\approx$15 pc^{-3}, rms relative velocity $v_s \approx$1 km s^{-1}, and stellar flux in the protosolar nebula's neighbourhood $\approx$15 stars pc^{-2} Myr^{-1}. Then the mean separation between cluster stars is $< d > \approx 8.4 \times 10^4$ AU. The mean impulsive change in the comet's velocity relative to the centre of nebula is given by $< \Delta v_c > \approx 4GM_s r_c/(\pi v_s D_s^2)$. The mean mass of an approaching star, M_s, can roughly be assumed to be one solar mass. Before the protosolar nebula collapse, the highest number of cometary nuclei were at its border at distances $r_c \approx 1 \times 10^4$ AU. The typical minimum distance of the approaching star causing the impulse, D_s, can be identified approximately with the mean separation $< d >$. Thus, we obtain

Table 1. Some values characterizing the distributions of perihelion distances (q), semi-major axes (a), and aphelion distances (Q) of hypothetical cometary nuclei at the end of the protosolar cloud collapse for two models of the collapse and six Maxwell-Boltzmann distributions of the initial velocity of the nuclei. Each model is characterized by the ratio of central to sonic-point initial density ratio, z_c/z_s. A Maxwell-Boltzmann distribution of initial velocity with peak v_P is assumed. In the range of heliocentric distances from 10^2 to 10^5 AU considered for the numerical integration, the interval where the relative number of nuclei exceeds 1%, and the maximum of the appropriate distribution are given. (The appropriate values are expressed in common-logarithm scale as indicated in the first column in brackets.) Moreover, the relative number of nuclei having final perihelion distances less than 10^2 AU and the relative number of nuclei in hyperbolic orbits, for each model (in per cent unit) are given. We considered the distribution of only those cometary nuclei that were present inside the shock front at the beginning of the protosolar nebula collapse. Below each ordinary value, in parentheses, a corresponding value is given, if the nuclei outside the shock front are also included (see second paragraph of Sect. 4).

$v_P[v_I]$	0.250	0.375	0.500	0.625	0.750	0.875
Cloud model with $z_c/z_s = 1$:						
q: number above 1%	$no\,interval$	3.0–3.1	2.5–3.9	2.7–4.1	2.6–4.1	2.2–4.1
$[log(q_d) - log(q_u)]$	$(no\,interval)$	(3.0–3.1)	(2.5–3.9)	(2.6–4.1)	(2.6–4.2)	(2.6–4.2)
q: maximum number	2.95	3.05	3.55	4.05	4.05	4.05
$[log(q_{max})]$	(2.95)	(3.05)	(3.55)	(4.05)	(4.05)	(4.05)
a: number above 1%	$no\,interval$	3.6–3.9	3.1–4.1	3.2–4.5	3.0–4.6	3.1–5.0
$[log(a_d) - log(a_u)]$	$(no\,interval)$	(3.6–3.9)	(3.1–4.1)	(3.2–4.5)	(3.2–4.6)	(3.3–5.0)
a: maximum number	3.65	3.75	3.85	3.85	3.85	3.85
$[log(a_{max})]$	(3.65)	(3.75)	(3.85)	(3.85)	(3.85)	(4.05)
Q: number above 1%	$no\,interval$	3.9–4.1	3.2–4.3	3.5–4.7	3.3–4.8	3.4–4.7
$[log(Q_d) - log(Q_u)]$	$(no\,interval)$	(3.9–4.1)	(3.2–4.3)	(3.5–4.7)	(3.5–4.8)	(3.5–4.8)
Q: maximum number	3.95	4.05	4.05	4.05	4.05	4.05
$[log(Q_{max})]$	(3.95)	(4.05)	(4.05)	(4.15)	(4.15)	(4.15)
number with q $<$ 100 AU	98.9	91.7	80.6	66.7	50.6	36.5
[%]	(98.9)	(91.7)	(79.9)	(62.5)	(42.3)	(26.0)
number of hyperbolic orbits	0.0	0.0	0.1	1.2	4.7	12.1
[%]	(0.0)	(0.0)	(0.1)	(1.4)	(6.2)	(16.5)
Cloud model with $z_c/z_s = 1.954$:						
q: number above 1%	$no\,interval$	$no\,interval$	2.5–3.9	2.9–4.1	2.9–4.1	2.9–4.1
$[log(q_d) - log(q_u)]$	$(no\,interval)$	$(no\,interval)$	(2.5–3.9)	(2.7–4.1)	(2.7–4.2)	(2.9–4.3)
q: maximum number	3.25	3.35	3.55	4.05	4.05	4.05
$[log(q_{max})]$	(3.25)	(3.35)	(3.55)	(4.05)	(4.05)	(4.05)
a: number above 1%	$no\,interval$	3.8–3.9	3.0–4.1	3.1–4.5	3.1–4.6	3.2–4.5
$[log(a_d) - log(a_u)]$	$(no\,interval)$	(3.8–4.0)	(3.1–4.1)	(3.1–4.5)	(3.2–4.6)	(3.3–4.7)
a: maximum number	3.85	3.85	3.85	3.85	3.95	4.05
$[log(a_{max})]$	(3.85)	(3.85)	(3.85)	(3.95)	(3.95)	(4.05)
Q: number above 1%	$no\,interval$	4.0–4.2	3.2–4.3	3.4–4.8	3.4–4.9	3.4–4.7
$[log(Q_d) - log(Q_u)]$	$(no\,interval)$	(4.0–4.2)	(3.2–4.3)	(3.4–4.8)	(3.5–4.9)	(3.5–4.9)
Q: maximum number	4.05	4.05	4.05	4.15	4.15	4.15
$[log(Q_{max})]$	(4.05)	(4.05)	(4.05)	(4.15)	(4.15)	(4.25)
number with q $<$ 100 AU	99.5	94.7	80.6	69.5	63.0	48.0
[%]	(99.5)	(94.5)	(79.9)	(60.6)	(47.4)	(30.2)
number of hyperbolic orbits	0.0	0.0	0.1	1.3	4.7	12.5
[%]	(0.0)	(0.0)	(0.1)	(1.7)	(7.1)	(18.3)

a one-impulse velocity change $< \Delta v_c > \approx 1.6$ m s^{-1} (0.006 v_I). Assuming the stellar flux ≈15 stars pc^{-2} Myr^{-1}, we find that ≈8 stars cross the circular area of radius $< d >$ per 1 Myr. According to Fernández, the nebular galactic environment in which the solar system formed could have persisted for at most a few 10^7 years. If the Sun formed as one of the last stars of the cluster, then the nuclei in the protosolar nebula could have been exposed to ≈(8 Myr^{-1})×(a few 10^7years), i.e. roughly a hundred individual impulses. That means that the velocity dispersion from the mean approaches of cluster stars could have been expected to be from about 1.6 to 160 m s^{-1} (0.006 to 0.6 v_I).

Fernández moreover assumed a few very close stellar approaches. Such an approach of a star to the protosolar nebula

could last $\approx 3 \times 10^7$ years, with $D_s \approx 6.9 \times 10^3$ AU. In this case, the order of one-impulse velocity change can be estimated to be 2×10^2 m s^{-1} (0.9 v_I). Both the above estimates imply that the velocities of cometary nuclei in the birth cloud of the solar system could actually be dispersed to the expected magnitude by the neighbouring stars.

For an illustration of a possible real value of peak v_P, it might be worthwhile, in this context, to mention the fact that stellar random perturbations of orbits in the outer Oort cloud have scattered the near-aphelion velocities by 121 m s^{-1} during the last 4.5 billion years (Delsemme 1985). If the original mean near-aphelion velocity (before the scattering) was negligible in comparison with the latter (the Gauss distribution velocity can be identified with the Maxwell one), then the value found by Delsemme corresponds to $v_P = \sqrt{2} \times 121$ m s^{-1} $= 171$ m s^{-1} ($0.644\, v_I$). We have to emphasize the indicative character of this illustration, however, because it is necessary to realize that the value 171 m s^{-1} is related to the nuclei in the outer Oort cloud accelerated by stellar perturbations during a long period, whilst v_P is related to the entire cometary spherical halo and initial velocity distribution.

Duncan et al. (1987) showed that the semi-major axes of comets in the inner Oort cloud ranged from about 3.10^3 to 2.10^4 AU (from 3.5 to 4.3 in common-logarithm scale). The axes longer than a few thousand astronomical units are necessary the Oort cloud perturbers could move the nuclei to the dynamically active outer cloud. Our integration of cometary orbits shows that the distribution of semi-major axes follows the requirement by Duncan et al., if v_P is equal or higher than about $0.375\, v_I$ (and does not considerably exceed v_I, of course).

If $v_P > 0.375\, v_I$, then roughly 20% to 50% of the cometary nuclei, being in the protosolar nebula before its collapse, remained in the Oort cloud after the collapse (the complement of the relative numbers of comets with $q < 100\, AU$ and those having hyperbolic orbits – see Table 1). So, the number of comets in the nebula before the collapse was a factor of from 2 to 5 higher than that in the Oort cloud after the collapse. If the initial number of Oort cloud comets is known, then we can estimate the total number as well as the average number density of comets in the nebula before the collapse. If we suppose an initial total number of cometary nuclei in the Oort cloud of order 10^{12}, then the initial number of these nuclei in the nebula is of order 10^{12} to 10^{13}, what corresponds with an average number density of order 10^0 to 10^1 nuclei per AU^3.

Figs. 1 to 3 give the appropriate distributions of the entire Oort cloud comet population in the beginning of the existence of the solar system. A majority of comets represents the inner cloud. As a consequence of the cloud perturbers (stars and massive interstellar clouds randomly passing the solar system, galactic disc and nucleus), the comets from the inner cloud have been pumped up to the outer cloud to form it during the entire subsequent period. This scenario of replenishment of the outer cloud presented by Duncan et al. (1987) is also assumed in our concept.

After the formation of the Oort cloud, the formation of the solar system continued with the creation of the protosun and planetesimals in the protoplanetary disc. If we suppose a total number of cometary nuclei in the inner Oort cloud of order 10^{12} at the end of our integration (at the beginning of planet formation), then a significant number of these nuclei approached the centre of the system to nearer than 100 AU (see Table 1), and they can be assumed to have become part of the protoplanetary disc due to the drag of the disc material.

Since these nuclei ended up in a relatively dense region, they had to be altered in interactions with surrounding material. In this context, it is worthwhile to mention the conclusion by Delsemme (1991) on the probable origin of two populations of comets of different symmetry (the Oort cloud and the Kuiper-Edgeworth belt). We state that the comet-like bodies of Kuiper-Edgeworth belt cannot be regarded as bodies identical to the common comets because of their different birth-place on the outskirts of the protoplanetary disc. However, we can expect an essential similarity in the composition of both groups because of the identity of their original material and the similarity of creation conditions.

As can be seen in Table 1, the number of nuclei with $q < 100$ AU was about the same order as the number of nuclei in the Oort cloud. In other words, there were at least 10^{12} cometary nuclei, in the protoplanetary disc at the beginning of the accretion process, which should have accelerated the accretion.

In the suggested comet origin scenario, we do not need to tune initial conditions of planet and comet origin theories. For example, the theory of planet formation by Greenberg et al. (1984) results in planetesimals in order of 100–300 km in diameter in the Uranus-Neptune zone. However, this size interval does not correspond to the observed range of diameters of cometary nuclei, which are usually 2 orders of magnitude lower.

No comet on a clearly interstellar trajectory has been observed passing through the region of planets. This fact constrains the number density of comets in interstellar space. Weissman (1990) estimated this density taking into account the primordial theory scenario of ejection of comets from the Uranus-Neptune region (it is estimated that between 3 and 50 times as many comets are ejected by protoplanets as are placed in the Oort cloud) and obtained a value which exceeds the upper limit by about 1.3 to 23 times. Looking at Table 1, the amount of nuclei escaping into interstellar space along hyperbolic orbits does not exceed about 20% (in fact it is probably less than about 7%). This amount is much lower than that yielded by the primordial theory. Hence, the estimate of the space density of interstellar comets should considerably be reduced.

6. Conclusion

Assuming the creation of cometary nuclei in cool, dense, molecular interstellar clouds, we modelled their dynamical evolution in the collapsing protosolar nebula. We demonstrated that a significant number of cometary nuclei remained at large heliocentric distances at the end of the collapse, if the peak of supposed Maxwell-Boltzmann distribution of the initial velocities of the nuclei was not lower than about 100 m s^{-1} (and not higher than

a few hundreds of meters per second; an excess of this upper limit was improbable and was not looked for). We assumed that the neighbouring protostars, forming together with the protosun in a common association, scattered the velocities of cometary nuclei, therefore the cloud of comets at large heliocentric distances could actually be a *remnant* from the era when the protosolar nebula started its collapse or, maybe, even from an era of interstellar cloud - a birth cloud of the protosolar nebula. Unfortunately, it is impossible to make a reliable quantitative estimate of the the peak of velocity distribution.

In spite of this uncertainty, there is a chance to prove the theory with the help of future analysis of some of its consequences. For example, it sets up new initial conditions at the accretion of planets and reduces the estimated number of interstellar comets. Thus, it may provide a new way how to solve or to avoid some problems that have occurred in the theories of comet as well as planet origin.

In contrast with the primordial theory assuming the creation of comets within planet formation, the suggested theory assumes the creation of comets earlier, already within star formation or even before it. If the theory is proved, it will be possible, studying the Oort cloud comets, to improve the model of protosolar nebula collapse (to determine free parameters of this process) and, furthermore, to gain some new details on the early stage of protosun formation.

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