The outer Oort Cloud formation: Simulation of the first Gyr evolution.

Giuseppe Leto, Marian Jakubík, Luboš Neslušan, Piotr A. Dybczyński, and Tomáš Paulech

***Abstract*—We used the GRID infrastructure to simulate the dynamical evolution of comets during the first Gyr of the Solar System life. The project is the result of a collaboration among Slovak, Polish and Italian researchers. The whole set of computation has been performed using the facilities made available through the Italian Virtual Organization (VO) belonging to the projects "TriGrid" and "PI2S2", which performed one fourth of the computing jobs. The Slovak and Polish members of the group contributed with the facilities of "VOCE", a central Europe VO, participating in "The EGEE Computing Grid Project". The model consists of 10038 test particles which represent the initial distribution of comets in the proto-planetary disc. The dynamical evolution of the particles/comets is followed taking into account the perturbations by four giant planets, Galactic tide, and stars having close approach to the Sun. The final product is the formation of a comet cloud in the outer region of the Solar System known as the Oort cloud. We show that the population of the outer Oort cloud reaches its maximum at about 210 Myr. Then, it decreases till an almost constant level, reached at about 500 Myr, which is followed by a very moderate population depletion.**

At 1 Gyr, the population decreases to about 40% of its maximum. The formation efficiency appears very low. Only about 0.29% of all considered particles reside in the outer Oort cloud at 1 Gyr. From about 50 Myr to the end of the simulation, the orbits are not distributed randomly, but high galactic inclinations of the orbital planes are strongly dominant.

***Index Terms*—Astronomy, Solar System, Simulation, GRID computing.**

I. Introduction

THE origin of comets and minor bodies of the Solar System (SS) has been and still is an unsolved puzzle. Oort (1950) [1] supported the idea of the existence of a distant cometary reservoir located far from the Sun but still gravitationally bound to the SS, the so called Oort Cloud (OC). He also suggested that comets formed in the proto-planetary disc (PPD) together with planets, and that after the formation a number of them were then scattered to large distance by the gravitational perturbation mainly due to giant planets. In particular it was pointed out that the outer ones (Uranus and Neptune) are responsible for the formation of the OC itself [2], [3] while the inner ones (Jupiter and Saturn) are responsible for the ejection of the comets out of the SS in a gravitationally unbound region [4].

G. Leto is with INAF Catania Astrophysical Observatory, Via Santa Sofia 78, I-95123 Catania, Italy, e-mail: giuseppe.leto@oact.inaf.it

M. Jakubík, and L. Neslušan are with Astronomical Institute, Slovak Academy of Sciences, 05960 Tatranska Lomnica, Slovakia, e-mail: mjakubik@ta3.sk, ne@ta3.sk

P. A. Dybczyński is with Astronomical Observatory of the A. Mickiewicz University, Sloneczna 36, 60-286 Poznan, Poland, e-mail: dybol@amu.edu.pl

T. Paulech is with Astronomical Institute, Slovak Academy of Sciences, Dubravska cesta 9, 84504 Bratislava, Slovakia, e-mail: astrotom@savba.sk

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The gravitational perturbation due to giant planets maintains the perihelion distance almost constant while increases the semi-major axis.

It is now largely accepted that relevant perturbation comes also from the so-called outer perturbers:

- The Galactic tide, that is the tidal force from the Galactic material, whose main signatures are a constant semi-major axis and increase/decrease of perihelion distance.
- Passing stars, the gravitational influence of near stellar passages

The recent cosmogony theories try to reconcile into a unified theory the Kuiper Belt (KB), Scattered Disc (SD), and Oort Cloud formation.

The OC is considered to be a possible source of long-period or nearly-isotropic comets observed in the zone of visibility, while the short-period or elliptic comets are related to the existence of the reservoirs of the KB and SD, situated beyond the orbit of Neptune.

In this work we are primarily interested in the formation of the OC and the genesis of the differentiation of the inner and outer part of OC.

II. Simulation of the Oort-cloud formation

Models of the Oort-cloud formation have been developed based on direct numerical integration, see [5] and [6], [7]. They account for the evolution of the PPD assuming that the giant planets were already formed and orbiting in the actual spatial position, that comets were present in the PPD as residua after the formation of planets, that close encounters with stars are the ones we estimate today. Since this kind of models need an enormous amount of computing time, they assume constrains either on the initial orbit or in the way the stars encounters are treated.

In this paper we present a new and improved model for the formation of the OC. The initial situation can be described as follows: the giant planets (Jupiter, Saturn, Uranus, Neptune) are already formed with their current masses and located on their current orbits, we follow 10 038 Test Particles (TPs) representing the small objects present inside the proto-planetary disc in the range from 4 to 50 AU, the initial orbits are almost circular (eccentricity < 0.01) with small inclinations to the invariable plane (< 0.01 rad); the surface density profile is function of $r^{-3/2}$ (r heliocentric distance), see Fig.1.

We take into account two external perturbations:

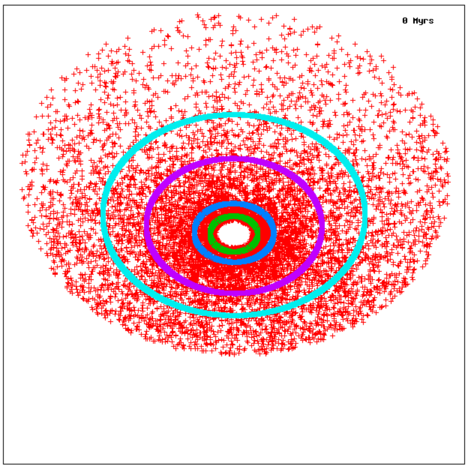


Fig. 1. The proto-planetary disk at the beginning of the simulation.

- Galactic tide perturbation: We assume that the density of solar neighborhood is $0.1\,M_\odot/pc^3$, and also that Oort's constants of galactic rotation A = -B = 13 km/s/kpc, that means we neglected differential rotation of Galaxy, see [8] for further details.
- Stellar perturbations: We assume realistic passages of 13 typical spectral types of stars; the model of the stellar passages was worked out within our previous work performed in the GRID. The number of possible encounters for each stellar type was calculated starting from the data available from the Hipparcos catalogue. The distance at which a star starts to significantly perturb a TP in its maximum considered distance (see next section) depends on the star's mass and heliocentric velocity. In our model we take into account this effect. In fact in our simulation a star is included as a perturber if its trajectory come closer than the calculated sphere of influence of the type at which the star belongs. This way also stellar encounters are described more realistically.

III. The Model

As already stated, we first take into account the perturbation due to the presence of giant planets. The numerical integration of orbits is performed by using the RADAU integrator [9] that is included in the MERCURY package developed by J. Chambers [10]. This package includes a sophisticated optimization of the integration time-steps, that enable a reduction of the computation time.

Stellar perturbations are calculated using the improved impulse approximation [11], [12]. We follow the small objects originated inside the PPD up to the distance of 10^5 Astronomical Unit (AU), as soon as they overcome this distance they are considered ejected. As a consequence, the model for stellar passages has been previously set and computed to identify the distance at which the 13 star types are able to induce a speed change of 0.02 m/s, that is about 5% variation of the velocity of comets being at the largest heliocentric distance at which they are still bound (10^5 AU). We have found that the most massive stars (B0 type) induce the 0.02 m/s speed

TABLE I
Parameters of the stars of 13 spectral types computed with our model of stellar passages.

i	S.T.	$M_{i;d}$ $[M_\odot]$	M_{*i} $[M_\odot]$	$M_{i;u}$ $[M_\odot]$	$r_{q,i}$ $[AU]$	N_{*i}
1	B0	7.8	13.2	18.6	1762957	334*
2	A0	2.14	2.4	2.66	809087	35
3	A5	1.72	1.86	2.00	724238	48
4	F0	1.45	1.55	1.65	669849	162
5	F5	1.22	1.32	1.42	625873	76
6	G0	1.06	1.12	1.18	584399	179
7	G5	0.91	0.98	1.05	553114	248
8	K0	0.76	0.82	0.88	514477	211
9	K5	0.61	0.68	0.75	477440	454
10	M0	0.44	0.52	0.60	430062	561
11	M5	0.11	0.27	0.43	337835	1714
12	WD	0.5	0.6	0.7	454544	347
13	gs.	2.0	2.2	2.4	778899	91

Parameters for types from B0 to M5 on the main sequence in the H-R diagram, for white dwarfs (WD), and giants (gs.) are listed. These representative stellar spectral types were first selected by [13]. The other symbols in the heading: M_{*i} − typical mass, $M_{i;d}$ and $M_{i;u}$ − the lower and upper limits of M_{*i} dispersion, $r_{q,i}$ − the heliocentric distance of the most distant passage, N_{*i} − the number of stars with the perihelion distance within $r_{q,i}$ passing the solar system during 100 Myrs (number of considered stars of i-th type);
* for the first spectral type, the period of 1 Gyr is considered.

change as soon as it reaches a distance of about 2×10^6 AU that is 10 times the value obtained in the case of the less massive stars (M5 type). The 13 heliocentric distance values calculated for the different star types are tabulated in Tab.I. A star is considered as perturber and enters the model only if and when it reaches the tabulated heliocentric distance at which it is able to significantly perturb the comets of the model. We also calculated the trajectories and the probability of such encounters during the first Gyr of the evolution of the PPD. The simulation of the encounters inside the model is made by introducing the incoming stars at random time.

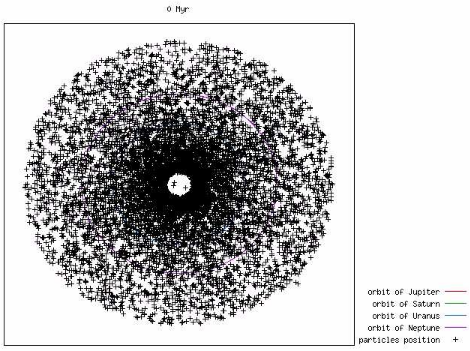
IV. Grid Usage

We used the GRID facilities to compute our model of the first Gyr evolution of the proto-planetary disk of the Solar System.

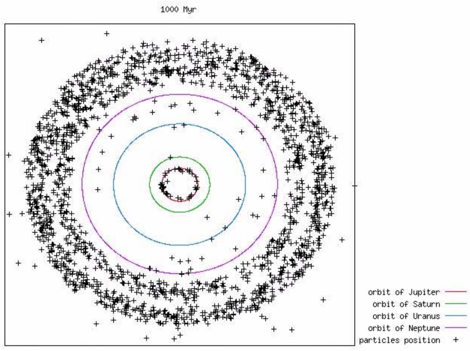
To prepare all input data for the main model we had to calculate in advance a model for the stellar passages that includes the computation of 401400 different trajectories. This high number of trajectories is the results of the possible combination of initial parameters for the trajectories and the effective number of stars of the 13 different types calculated on the basis of real observations collected by the satellite Hipparcos. The statistical results to apply to the model of evolution of the PPD are shown in Tab.I.

We found that the integration of a single stellar trajectory lasted about 6 minutes, in average, when a 2.8 GHz processor was used. This single processor would have run 1672.5 days (4.6 years) to complete all integrations. Such an extensive computation requires a huge computational capacity. To perform it, we used the GRID virtual organization VOCE for central Europe, and Cometa PI2S2 facilities for south Europe.

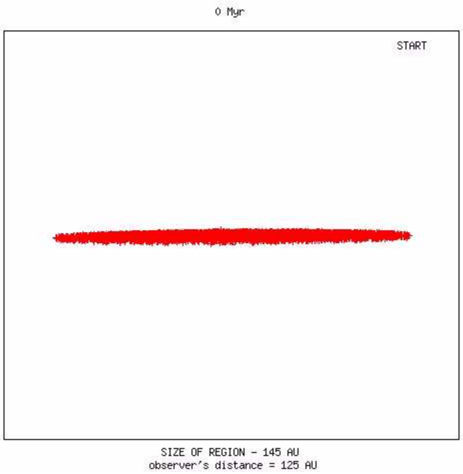
The integration of a single stellar trajectory was regarded as a single computer job. However, it appeared that the sequential



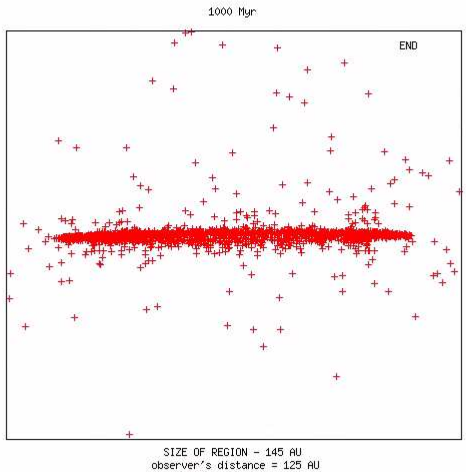
(a) Start simulation (0 Gy), top view



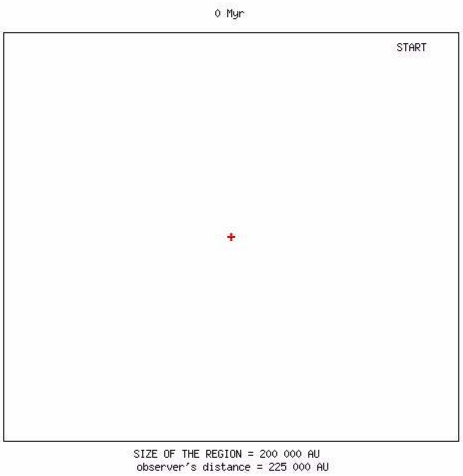
(b) End simulation (1 Gy), top view



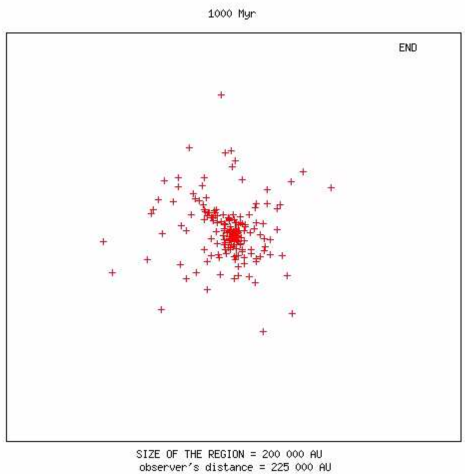
(c) Start simulation (0 Gy), edge-on view



(d) End simulation (1 Gy), edge-on view



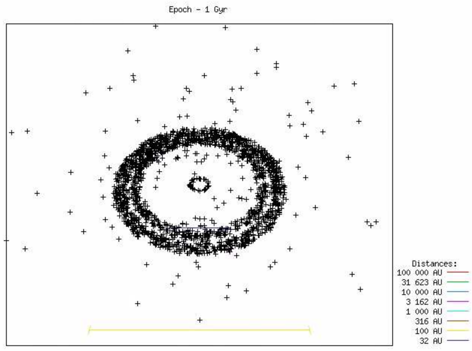
(e) Start simulation (0 Gy), observer at 225000 AU



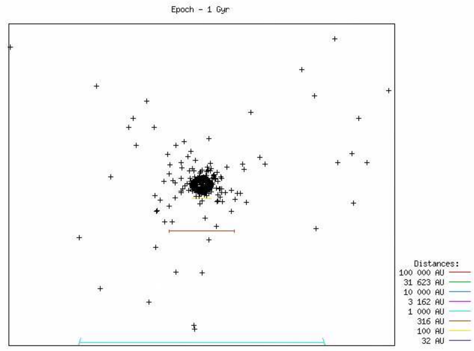
(f) End simulation (1 Gy), observer at 225000 AU

Fig. 2. Simulation results

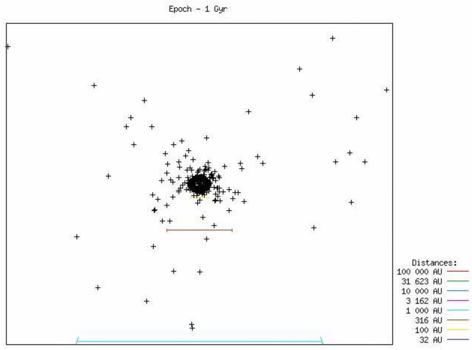
submissions of a lot of relatively short jobs overloaded the "resource broker" (RB) and distribution of the jobs among the available GRID processors became a "bottle-neck" of the computing. The character of our tasks enabled a linking of the individual jobs. To eliminate the drawback of the overloaded RB, we used a more sophisticated script developed by J. Astaloš from the Enabling-Grids-for-E-sciencE supporting team. This script managed the integration of 29 trajectories in the first step or 61 trajectories in the second step to be regarded, by the system, as a single job. This way of submission represented a reduction of the number of jobs of about a factor of 90. Moreover, a new approach to the submission was chosen. A bulk of the linked jobs was emplaced on the "storage element" (SE). After the emplacement, we started the new script on the "user interface" (UI), which controlled another script on a given "computing element" (CE). The script on



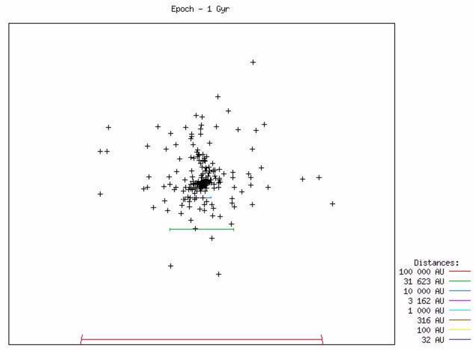
(a) View from 100 AU



(b) View from 1.000 AU



(c) View from 10.000 AU



(d) View from 100.000 AU

Fig. 3. Simulation results, end of the simulation (1 Gy)

the CE run till the entire bulk of jobs, with inputs stored on the SE, was completed. In this way, only a single submission was needed for all jobs in the given bulk enabling a light administration of the entire set of jobs.

The main model was then prepared for the run. It was divided in 240 individual and mutually independent tasks, so that groups of 60 tasks could be separately run by every single collaborator. Each task was submitted to GRID assuming its running on a single CPU (theoretically: 240 tasks = 240 CPUs). Each task was performed as a sequence of many runs; a single run was designed to last about 2 days and provided the result for a 50-Myr period of the 1000-Myr simulation. We estimate that a single 2.8-GHz CPU would have to work approximately 21 years to complete all the computation. All the simulation has been actually completed after approximately 5 months, i.e. it was completed more than 40 times faster!

V. Results

Our simulation provides results confirming the following already well-known facts:

Giant planets ejected a large number of planetesimals from the proto-planetary disc to the large heliocentric distances, where these ejectas formed the cometary cloud, whereby many more planetesimals were ejected into the interstellar space see Fig.2, 3.

A detailed analysis of the data demonstrate also that:

- Galactic tide enlarges the perihelion distance of cometary orbits outside the gravitational influence of the planets, therefore the comets might survive in stable orbits at large heliocentric distances.
- The inner OC was also formed during the outer OC formation.
- The Galactic tide is the dominant outer perturber of the objects in the outer OC.
- Although the Galactic tide and passing stars have continuously eroded the outer OC, the erosion has been slow enough to allow the survival of a significant fraction of comets in the outer OC till the present.
- Many bodies in our simulation survive in the region beyond 35 AU, which is related to the KB and SD, in agreement with observations.

Our simulation reveals some new facts and also opens few new questions:

- The efficiency of the OC formation, especially its outer part, is much smaller than predicted in the previous works (only 0.3% of TPs are in the outer OC after the first Gyr).
- The population of the inner OC is questionable, because the results from various simulations are quantitatively different.
- In our simulation, the population of the outer OC reached its maximum at the 210 Myrs (in contrast to about 600 Myrs reported by [7]).
- A relatively significant part of the outer OC originates from the Jupiter-Saturn region.
- The directional distribution of the outer-OC orbits is not random, but the high Galactic inclinations are relatively

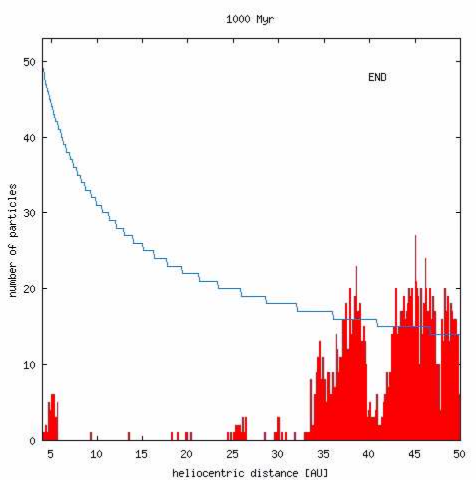


Fig. 4. Initial distribution of objects along the PPD (exponential curve), final distribution of residual objects (histogram).

more abundant.

- A significant part of the outer-OC population came from the heliocentric distance of about 42.25 AU (corresponding with the 5:3 mean-motion resonance with Neptune) see Fig.4; previous results implied that the region beyond about 35 AU is dynamically inactive.

We also found that the OC sub-population of objects coming from the Jupiter-Saturn region is only about one third (one half) that from Uranus or Neptune region, that implies a quite high probability to observe an OC comet formed in the hotter, Jupiter-Saturn region of the PPD see Fig.5. In the light of this knowledge, the composition of comet C/1999 S4 (LINEAR), corresponding with the Jupiter-Saturn formation region [14], [15], does not longer seem to be surprising.

VI. Conclusion

We have developed a new model for the evolution of the Solar System proto-planetary disc that describes the evolution of the system during its first Gyr life. That model implement realistic features like Galactic tide and stellar passages that are accounted for by means of algorithms based on real observational data.

We have found a general agreement with previous developed models on the general behavior of the depletion of the disc and the formation of the outer OC. We also found that the Kuiper Belt region remains populated and that an inner OC is formed. The model reveals also insights that can give solution to standing problems such as the composition of the comet C/1999 S4 (LINEAR). In fact we demonstrated that a significant part of objects in the OC come from the inner part of the Solar System, that is the Jupiter-Saturn region.

The use of the GRID facilities, in particular PI2S2-Cometa and VOCE virtual organizations, was fundamental for the development of the entire project. In few months, including all the necessary dead-time to develop and test the model, we were able to complete the first run of the model. We evaluated that using a single, even the fastest, workstation we would take more than 20 years to reach the same result.

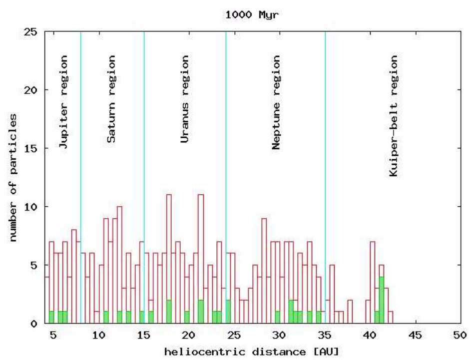


Fig. 5. Source region of objects appearing in the OC at some time during the simulation (empty bars), distribution for the objects present in the OC at the end of the simulation (full bars).

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Giuseppe Leto (1961) received his degree in Physics and Ph.D. at Catania University, Italy in 1990 and 1995 respectively. Giuseppe Leto was researcher of the “Istituto di Radioastronomia” of the Italian National Research Council from 1994 till 1999 when he became researcher of the Catania Astrophysical Observatory. Giuseppe Leto has worked on physico-chemical effects induced by fast ion and photons colliding with solids (frozen gases, organic materials) with specific astronomical applications on Solar System objects and interstellar medium. He is today deputy of the Observing Station of the Catania Astrophysical Observatory on mount Etna, Sicily.

Marian Jakubík (1978) received his master degree in Physics and Ph.D. in Astronomy at the Commenius University in Bratislava, Slovakia in 2001 and 2005, respectively. Having finished these studies, he became a research assistant of the Department of Interplanetary Matter at the Astronomical Institute Slovak Academy of Sciences, Tatranska Lomnica, Slovakia. Professionally, he is interested in origin and dynamical evolution of the Solar System, dynamics of its small bodies and related cosmogonical problems.

Luboš Neslušan (1960) received his Ms. degree in astronomy and astrophysics at the Commenius University, Bratislava, in 1984, and subsequent PhD degree at the Astronomical Institute of the Slovak Academy of Science (SAS) in 1996. After a compulsory military service, popularizing astronomy, and being programmer of microprocessor systems for an industrial company (all 1984-1989), he started to work at the Astronomical Institute of SAS in 1989. He has worked in positions of observer, research assistant/PhD student, and senior researcher. A year (2000/2001), he stayed at the Queen Mary College of the University of London. In the research, he deals with the dynamics of small bodies in the solar system, mainly in concern of the cosmogony of their reservoirs.

Piotr A. Dybczyński (1957) graduated in physics and astronomy in 1980, Ph.D thesis (1991) on the stellar perturbations of the Oort cloud. Works as an researcher and teacher at the A. Mickiewicz University, Pozna, Poland. Main interests: Oort cloud formation and evolution, the origin of long period comets, cometary dynamics. Teaching: small bodies in the Solar System, numerical computer programming.

Tomáš Paulech (1975) works as researcher at the Astonomical Institute, Slovak Academy of Sciences. He received degree and Ph.D. at Commenius University in Bratislava, Slovakia in 1998 and 2005 respectively. His work mainly concerns comets with focus on evolution of fine dust structures in cometary coma.