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Dynamical evolution of comets during the first Gyr of the Solar System life

A grid computed model

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Abstract. We used the GRID infrastructure to develop a new and improved model of the dynamical evolution of comets during the first Gyr of the Solar System life. The project is a collaboration among Slovak, Polish and Italian researchers. Computations are performed by using the facilities of "Cometa" Virtual Organization (VO) for the Italian part of the GRID, and "VOCE", a central Europe VO which belongs to the "The EGEE Computing Grid Project". The model consists of 10,038 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 a close approach with 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.

Key words. Comets: general – Kuiper Belt – Oort Cloud

1. Introduction

The origin of comets and minor bodies of the Solar System (SS) has been and still is an unsolved puzzle. Oort (1950) 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). In his hypothesis, comets formed in the proto-planetary disc (PPD) together with planets and after their formation, a number of them were scattered to large distances by gravitational perturbations mainly due to giant planets. In particular, Uranus and Neptune were responsible for the formation of the OC itself while Jupiter and Saturn were responsible for the ejection of the comets out of the SS in a gravitationally unbound region (Safronov 1972; Fernandez 1985). The gravitational perturbations by giant planets typically maintain the perihelion distance almost constant while

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increase the semi-major axis. It is now largely accepted that relevant perturbations come also from the so-called outer perturbers:

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

The recent research attempts try to bring a unified cosmogonical theory of the planetary, 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 ecliptic comets are related to the existence of the reservoirs of the KB and SD, situated beyond the orbit of Neptune. Here we present a new/improved model for the formation of the OC and its properties at the age of 1 Gyr which can be compared with observations.

2. The Oort-Cloud formation model

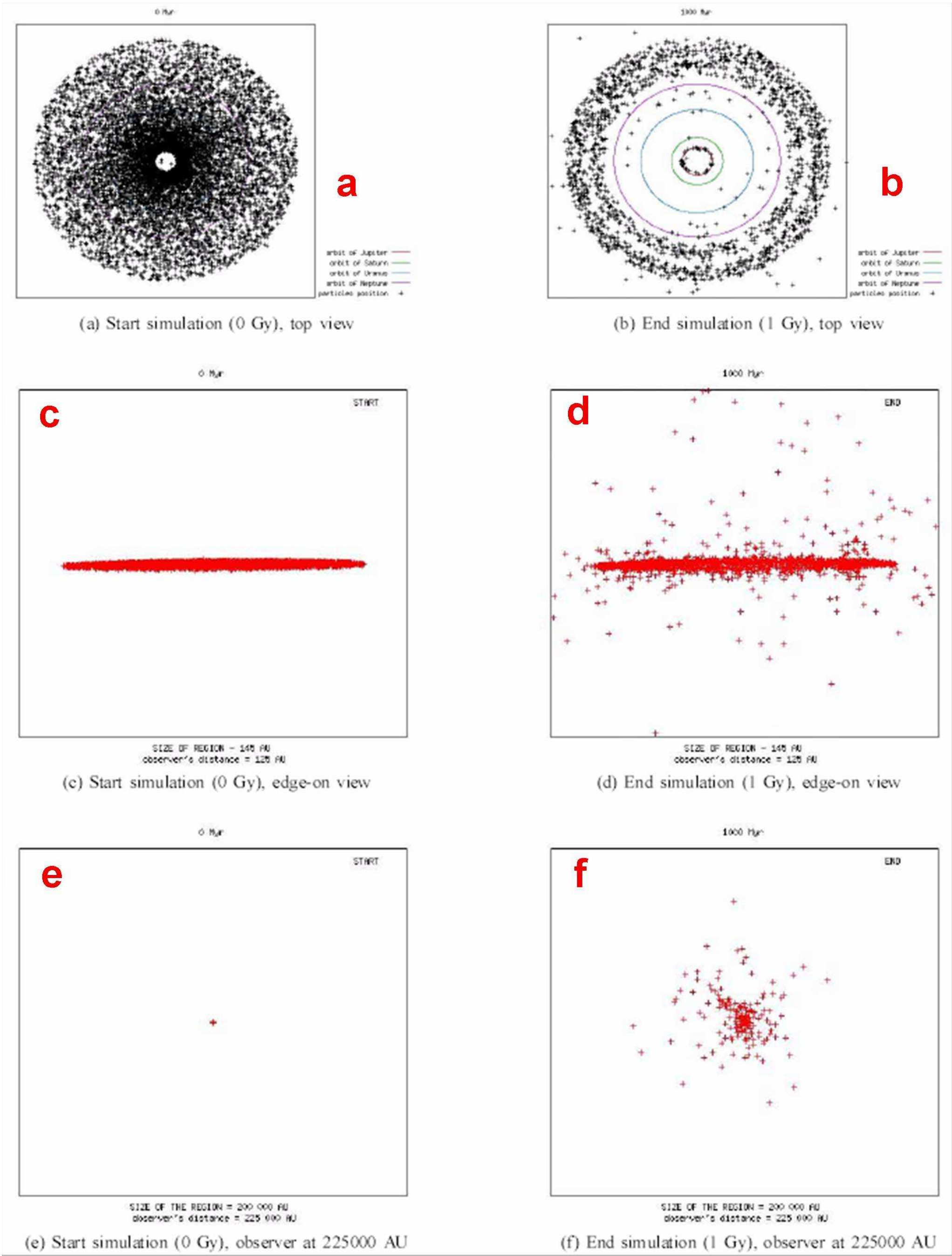
The simulation starts after the giant planets (Jupiter, Saturn, Uranus, Neptune) are formed, they have their current masses and are already settled in their current orbits. 10,038 Test Particles (TPs) represent the small objects inside the PPD from 4 up to 50 Astronomical Units (AU). TPs orbits are almost circular with a small inclination with respect to the ecliptic; the surface density profile is a function of $r^{-3/2}$ (r heliocentric distance), see Fig. a. In addition to the giant planets perturbation, we also take into account two external perturbations:

- Galactic tide: We assume that the density of the solar neighborhood is 0.1 $M_{\odot}/pc^3$ and also that Oort's constants of the galactic rotation A = -B = 13 km/s/kpc, that means we neglected the differential rotation of Galaxy (see Levison (2001) for further details).
- Stellar encounters: We assume realistic passages of 13 different star types; the model of the stellar passages was worked out previously also using the GRID. The number of possible encounters for each stellar type was calculated starting from the real data available from Hipparcos catalogue. The distance at which a star starts to significantly perturb a TP located at its maximum considered distance depends on the star's mass and heliocentric velocity, in our model we take into account this effect.

We follow the small objects originated inside the PPD up to the distance of 10^5 AU. Within our work, we worked out the model of stellar passages for the numerical integration of each individual star as well as the simple model, when the impulse approximation (Öpik, 1932) or its improved version (Dybczyński, 1994) of stellar perturbations was used. In the models, both well-known distributions of the frequency of passages and star-Sun minimum-proximity distance had to be simultaneously satisfied. In the first model, the consistency between these distributions was found by integrating the motion of stars on 401,400 alternative trajectories and selecting the trajectories with the appropriate minimum-proximity distance. In the second, simple model, only the position and velocity vectors of a given star at the moment of its minimum approach to the Sun were required, therefore the consistency was easy to be found. When considering the stellar perturbations, it is necessary to determine the sphere of influence within which the perturbations are significant. For each of the 13 spectral types, we calculated the minimum-proximity distance, from which the star induces a change of 5% in the speed of a comet at the maximum considered heliocentric distance of 100,000 AU. The simulation of the encounters inside the main model is made by introducing incoming stars at random t.

2.1. Results

After 1 Gyr, giant planets ejected the major number of planetesimals from the PPD into the interstellar space; meanwhile, a significative number of planetesimals still remains bound



(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. 1. Simulation results .

at large heliocentric distance, where they form the cometary cloud (OC) (see Fig.d,f).

A detailed analysis of the data also demonstrates 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 forms during the outer OC formation.
- The Galactic tide is the dominant outer perturber of 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 (Fig.b). Our simulation reveals some new facts and also raises new questions; here we report 2 of them:
- The efficiency of the OC formation, especially its outer part, is much smaller than the previous works predicted (only 0.3% of TPs are in the outer OC after the first Gyr)
- We also found that the OC sub-population of objects coming from the Jupiter-Saturn region is not negligible, but reaches about one third of that from Uranus or Neptune region. So, there is quite a high probability to observe an OC comet formed in the hotter, Jupiter-Saturn, region. In the light of this fact, the composition of comet C/1999 S4 (LINEAR), corresponding with the Jupiter-Saturn formation region (Boehnhardt 2001; Mumma 2001), does not seem to be surprising any longer.

2.2. Grid usage

The model for the stellar passages includes the computing of 401,400 different trajectories, using a single CPU we would need 4.6 years to complete all integrations. To complete the main model a single 2.8-GHz CPU would have to work 21 years. The use of the GRID allowed us to complete the whole computation in 5 months, more than 40 times faster.

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