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Embedded star clusters and the formation of the Oort cloud
III. Evolution of the inner cloud during the Galactic phase

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Abstract

In a previous publication [Brasser, R., Duncan, M.J., Levison, H.F., 2006. Icarus 184, 59–82], models of the inner Oort cloud were built which included the effect of an embedded star cluster on cometary orbits about the Sun. The main conclusions of that paper were that the formation efficiency is about 10% and the median distance of the cloud to the Sun only depends on the mean density of gas and stars the Sun encountered. Here we report on the results of simulations which followed the ensuing dynamical evolution of these comet clouds in the current Galactic environment once the Sun left the embedded star cluster. The goal is to determine whether or not the dynamical influence of passing Galactic field stars and the Galactic tidal field is sufficient to replenish the current outer cloud (semi-major axis $a > 20{,}000$ AU) with enough material from the inner cloud ($a < 20{,}000$ AU). Since visible new comets come directly from the outer cloud, a mass estimate only exists for the latter, with a lower limit of 1 $M_\oplus$ [Francis, P.J., 2005. Astrophys. J. 635, 1348–1361]. Knowing the amount of expansion of the inner cloud may therefore yield an estimate of the mass of said (unseen) inner cloud. Our results indicate that typically only 10% of the comets from the inner cloud land in the outer cloud and are bound after 4.5 Gyr. If one assumes that in the extreme case all or the majority of the current population of the outer cloud has come from the inner cloud, then a typical value of the mass of the inner cloud is about 10 $M_\oplus$. The results of [Brasser, R., Duncan, M.J., Levison, H.F., 2006. Icarus 184, 59–82] showed that $\sim$10% of comets from the Jupiter–Saturn region were implanted in the inner Oort cloud, which implies an uncomfortably large value of about 100 $M_\oplus$ for the mass of solids in the primordial Jupiter–Saturn region. This extreme case might be remedied in two says: either the effect of Giant Molecular Cloud complexes on the inner Oort cloud must be much more severe than originally thought, or there was a two-stage formation process for the Oort cloud, in which the outer cloud was largely populated by comets scattered once the Sun had left its primordial birth cluster.

Keywords: Comets, dynamics; Orbits; Origin, Solar System; Trans-neptunian objects

1. Introduction

The idea of the Sun being surrounded by a reservoir of comets is not new (Oort, 1950). Neither is the idea that a significant fraction of this comet cloud resides in an unseen inner reservoir (Hills, 1981). Much research has been performed studying the formation and dynamics of the Sun's comet cloud. A few of these are listed here.

Dones et al. (2004) simulated the formation of this comet reservoir—called the Oort cloud—in the current Galactic environment using a model in which the Sun and giant planets were on their current orbits. They showed, among other things, that in their simplified model the amount of material ending up in the inner ($a \lesssim 20{,}000$ AU) and outer ($a \gtrsim 20{,}000$ AU) clouds are about equal. The total efficiency for implanting comets in the cloud at the end of the simulations is about 4%. Studies performed trying to form the inner comet cloud were done by Eggers (1999) and Fernández and Brunini (2000), simulating

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the environment while Sun was still in its putative birth cluster. Their results showed that the effect of passing stars was able to lift the pericenter of some of the comets under the control of Jupiter and Saturn before they could be ejected. In dense clusters this resulted in the formation of a tightly-bound comet cloud where the comets' orbits are of order 1000 AU—much smaller than those of Oort cloud comets seen today ($\sim$20,000 AU).

The most comprehensive study of Oort cloud formation while the Sun was in its birth cluster has been performed by Brasser et al. (2006)—who started with comets on low-eccentricity—cold—orbits in the Jupiter–Saturn region and let the comets evolve under the gravitational action of the Sun, planets and stars and gas of the cluster. Their results showed that the median distance of the comets' orbits scales as the inverse square-root of the mean density that the Sun encounters as it orbits the cluster center. Their efficiencies, which is the fraction of original material that ends up in the Oort cloud at the end of the simulation, were of order 10%.

In a second paper, Brasser et al. (2007) performed similar computations to those in Brasser et al. (2006) but added gas drag caused by the presence of the Sun's primordial disk. For gas densities typical of the minimum-mass solar nebula, this resulted in small comets ($r \lesssim 2$ km) being unable to reach the Oort cloud while the gas was present while larger bodies ($r \gtrsim$ 20 km) suffered very little drag and ended up on similar orbits to those of Brasser et al. (2006).

This paper continues where Brasser et al. (2006) left off. Here some of the end results of Brasser et al. (2006) are taken and the orbits of comets that ended up in the inner Oort cloud are cloned and resumed under the action of the current Galactic tide and field stars for another 4.5 Gyr. The aim is to determine whether or not the perturbations of passing field stars are sufficient in power to expand a more tightly bound inner Oort cloud that replenishes the current population of the outer Oort cloud. The effect of Giant Molecular clouds is not included because their structures are not sufficiently known to allow detailed modeling. The addition of these clouds is reserved for later study. The model employed here, consisting of including Uranus, Neptune and passing field stars, should suffice as a first order approximation to the expansion problem.

This paper is divided as follows: Section 2 contains a summary of the main results of Brasser et al. (2006). Section 3 deals with some theoretical background and insights into the problem. In Section 4 the methods employed to perform the numerical simulations are described. Section 5 contains the results of the simulations. In Section 6 the conclusions and suggestions for future work are presented.

2. Summary of earlier work

Since this study is a continuation of Brasser et al. (2006), a short summary of its results is presented here.

In Brasser et al. (2006) it was decided to investigate the formation of a tightly-bound inner Oort cloud when the Sun was part of an embedded star cluster. This study was motivated by several events. First, there was the discovery of the object (90377) Sedna, whose orbital characteristics can only be explained by a stellar encounter (Morbidelli and Levison, 2004). Second, Oort cloud formation efficiency is very low (Dones et al., 2004), which may be increased if the Sun is in a denser environment. Earlier studies by Eggers (1999) and Fernández and Brunini (2000) were encouraging in that aspect. It was decided to build on the latter two studies to determine whether a dense cluster environment can increase Oort cloud formation efficiency and produce (90377) Sedna.

A simple model for the star cluster was constructed based on a Plummer potential (e.g., Binney and Tremaine, 1987). This potential has two free parameters: the Plummer radius of the cluster and the central density of the cluster. With a suitably-chosen IMF stars were generated in the Plummer model and the resulting embedded cluster was simulated for a few million years, which is the typical lifetime of such clusters (Lada and Lada, 2003). Encounters of solar-mass stars with other stars were recorded. These would be used later while simulating the formation of the comet clouds.

In total fifty numerical simulations forming the inner Oort cloud were performed: ten simulations per value of the central density of the cluster, ρ_0, to account for different solar orbits. The value of ρ_0 ranges from 100 to $10^6\ M_\odot\,\mathrm{pc}^{-3}$ in decade intervals. It turned out that the formation efficiency at the end of the simulation was fairly constant for $\rho_0 \in [10^2, 10^5]\ M_\odot\,\mathrm{pc}^{-3}$ and was in the range 8–15%, i.e., only 8 to 15% of the comets in the planetary region ended up in the cloud and were still bound at the end of the 3 Myr simulations. The clusters with the highest density proved to be too violent for an inner Oort cloud to form.

The simulations also showed that the position and extent of the cloud are virtually unaffected by the inclination between the Sun's orbit in the cluster and the Solar System plane. Instead, the median distance of a comet in the cloud turned out to be only a function of the mean density the Sun encountered during its orbit, $\langle\rho\rangle$, via $r_{50} \propto \langle\rho\rangle^{-1/2}$. Therefore, the value of r_{50} is also a function of ρ_0 because, on average, $\langle\rho\rangle \sim 0.15\rho_0$. It turned out that a minimum central density of $\rho_0 = 10^4\ M_\odot\,\mathrm{pc}^{-3}$ was needed to generate objects on Sedna-like orbits, with about 2% of objects in the cloud situated on such orbits.

In this paper, some of the inner Oort clouds from Brasser et al. (2006) are taken, the population is cloned by a factor of ten and the resulting cloud is simulated in the current Galactic environment under the action of the Sun, passing stars, Galactic tide and Uranus and Neptune. Since the size and position of the inner clouds depend on ρ_0, the results in this paper will be presented as a function of this parameter.

Before the simulations are discussed in detail, there are some theoretical considerations to bear in mind that are stated here first.

3. Theory

In this section some theoretical background information is presented and used as a basis for some predictions of the final outcome of this study. Numerical simulations, which need to confirm these results, are discussed later. First, the half-life of