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# Dynamical behavior of the Oort Cloud new comets in the planetary region
# 惑星領域に於けるオールト雲起源新彗星の力学的挙動

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**Abstract.** Nearly isotropic comets with very long orbital period are supposed to come from the Oort Cloud. Recent observational and theoretical studies have greatly unveiled the dynamical nature of this cloud and its evolutionally history, but many issues are yet to be known. Our goal is to precisely trace the dynamical evolution of the Oort Cloud new comets (OCNCs) produced in the evolving cloud, hopefully estimating the fraction of OCNCs embedded in the current populations of the small solar system bodies (SSSBs). We combine two models to follow the dynamical evolution of OCNCs beginning from their production until their ejection out of the solar system. The first model is a semi-analytical one about the OCNC production in an evolving comet cloud under the perturbation of the galactic tide and stellar encounters. The second model numerically deals with planetary perturbation over OCNCs' dynamics in planetary region. The main results of the present study are: (1) Typical dynamical lifetime of OCNCs in our models turned out to be $O(10^7)$ years. Once entering into the planetary region, most OCNCs stay there just for this timespan, then get ejected out of the solar system on hyperbolic orbits. (2) While the average orbital inclination of OCNCs is small, the so-called "planet barrier" works rather effectively, preventing some OCNCs from penetrating into the terrestrial planetary zone.

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**日文摘要**. オールト雲より飛来すると考えられている等方的な長周期彗星については観測的証拠が少なく、その力学的実体が定かでない。本研究では理論的な彗星雲の進化形成モデルを元にし、成長する彗星雲から落下する天体—新彗星—が惑星摂動下でどのように力学進化するのかを数値実験により確かめる。現時点までに以下の事柄が分かりつつある。(1) 惑星領域に突入した後のオールト雲起源新彗星の力学的寿命は $10^7$ 年の桁に留まる。その時間を経過すると大半の新彗星は惑星に散乱されて双曲化し、太陽系内には戻らない。(2) 新彗星が平面的に飛来する太陽系形成期にはいわゆる惑星バリアが有効に働く。これにより新彗星が地球型惑星領域まで浸透しない現象が発生し得る。

## 1. Introduction

In the middle of the past century, Jan Hendrik Oort predicted the existence of a vast comet cloud—currently called the "Oort Cloud"—having a shape of spherical shell stretching out to the farthest outskirt of the solar system, as far as thousands to ten thousands astronomical unit (Oort 1950). Oort's prediction was based on the nearly isotropic distribution of the long-periodic comets that were recognized at that time. Since then, numerous observational and theoretical studies have reinforced Oort's prediction on the existence of this comet cloud, but there is practically no discovery of any of such objects yet at the distance that Oort forecasted them to be.

Formation and evolution of the Oort Cloud is tightly connected with those of major planets. However, unlike the studies of the major planets which we have a large amount of observational evidence as for, studies of the Oort Cloud comets have been suffering from the lack of observational facts, mainly because their location is so far and the objects are so faint. The shortage of observational facts prevents our understanding of the Oort Cloud from becoming complete and certain. We have been working on the dynamical evolution of the Oort Cloud new comets (hereafter called "OCNCs") in the planetary region based on a modern dynamical model of the comet cloud formation. This article is a brief report on our work product as of today.

## 2. Dynamical models

Our study uses a combination of a pair of dynamical models. The first model is about an evolving Oort Cloud that produces OCNCs (Higuchi et al. 2006; 2007; Higuchi and Kokubo, submitted). This model initially starts from a planar planetesimal disk which evolves into a three-dimensional, nearly isotropic shape over a timespan of Gyr under the perturbation by galactic tide and stellar encounters. This model is largely analytical in order to reduce the amount of computation. The second model is about planetary perturbation given from the seven major planets (from Venus to Neptune) that works on OCNCs' dynamics in the planetary region. This model is purely numerical, and its framework is the same as that of our previous studies (Ito and Malhotra 2006, 2010). The second model receives OCNCs from the first model, and traces the orbital evolution of the comets up to 500 Myr until they get ejected out of the solar system by planetary scattering. The second model does not include galactic tide or stellar perturbation. For further reduction of computation amount, we assume that OCNCs go along their Keplerian orbits beyond $r = 800$au without any perturbations.

Recently a series of detailed dynamical studies with similar scientific objects to ours were published (Fouchard et al. 2013; 2014a; 2014b). Our present study is an extension of our own independent project (Ito and Higuchi 2012; 2014a), and the dynamical models of ours and Fouchard's are rather different.

## 3. Major results

In what follows let us describe some of the major results that we have obtained so far in this project.

**Oort Cloud evolution.** Our first model tells us about the dynamical evolution of the Oort Cloud, which is typically exhibited in Figure 1. It is evident that the initially flat planetesimal disk at time $t = 0$ evolves into a 3-D, nearly isotropic comet cloud in the timescale of Gyr. Also note that the inner and the outer part of the Oort Cloud shows different evolutionary patterns: While the outer Oort Cloud (defined here as having the semimajor axis $a > 10,000$au) becomes almost isotropic at $t = 4.5$ Gyr, the inner Oort Cloud (defined as having $a \leq 10,000$au) still remain a 2-D, rather disk-like shape.

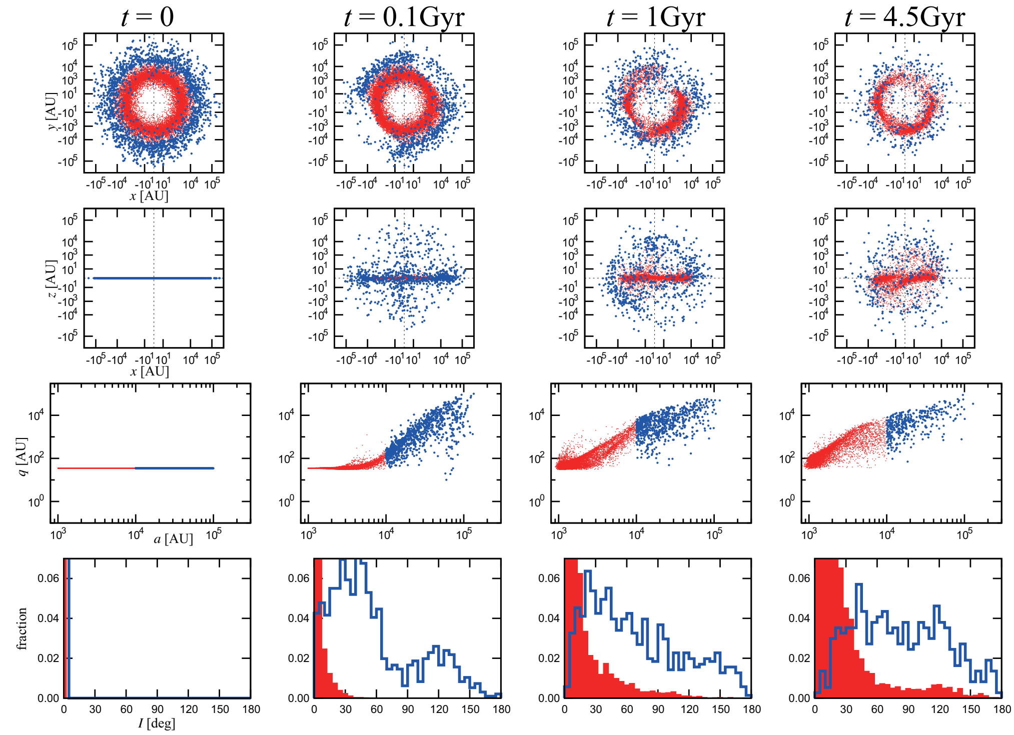


Figure 1. Example snapshots of the comet cloud evolution in our study using a star set that produced the initial condition IC1. From the left, each of the four-panel column indicates the status when time $t$ =0, 0.1, 1, and 4.5 Gyr. The top row: Distribution of the comet cloud objects seen from the north (along with the $z$-axis). The axis unit is au, but note that the distance is nonlinearly normalized by a power-law, $x^{0.2}$ or $y^{0.2}$. Also note that the objects with semimajor axis $a \leq 10,000$au are plotted in red, while other objects are plotted in blue with a slightly large radius. The second top row: Distribution of the comet cloud objects seen from the equator of the cloud (along with the $x$-$y$ plane). The third top row: Scatter plots of semimajor axis $a$ and perihelion distance $q$ of the cometary objects. The axe unit is au. The bottom row: Distribution of orbital inclination $I$ of the cometary objects. The unit of the horizontal axis is degree.

**Dynamical lifetime of OCNCs.** The evolution of the comet cloud is inevitably accompanied by the production of a large number of OCNCs. Eventually nearly half of the entire comet cloud objects fall into the planetary region as OCNCs. In our numerical experiments using the second model including the planetary perturbation, we selected three different pe-

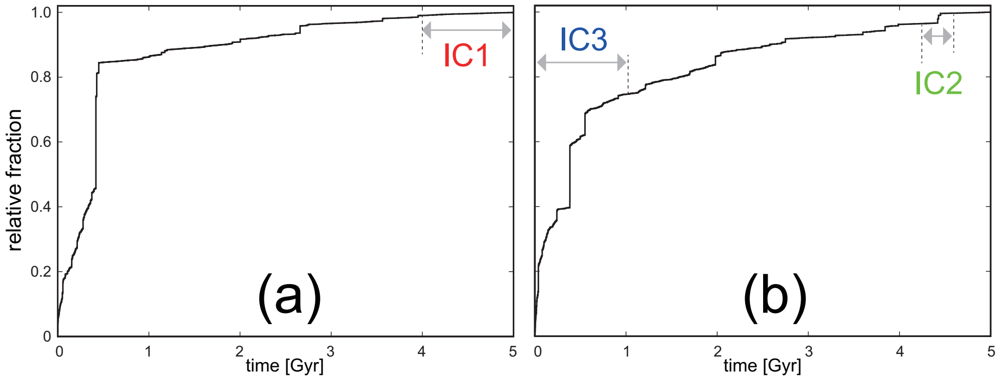


Figure 2. Production rate of OCNCs from the comet cloud obtained by using two different star sets. The three different initial conditions are: IC1 that denotes the period from $t = 4$–$5$ Gyr in (a), IC2 that denotes the period from $t = 4.41$–$4.46$ Gyr in (b), and IC3 that denotes the period from $t = 0$–$1$ Gyr in (b).

riods as initial conditions (Figure 2). IC1: the period $t = 4$–$5$ Gyr when the outer comet cloud is almost in an isotropic shape with a nearly constant supply of OCNCs. IC2: the period $t = 4.41$–$4.46$ Gyr when a few extensive OCNC production occurred resulting as comet showers. IC3: the period $t = 0$–$1$ Gyr while the comet cloud is still nearly planar with a high OCNC production rate. In our numerical calculations an OCNC is defined as being ejected out of the system when either of the conditions, (i) $r > 800$au and $e > 1$, or (ii) its aphelion distance $Q > 2 \times 10^5$au, is satisfied. As a result, it turned out that most of the OCNCs get scattered away by the four giant planets with a typical timespan of $O(10^7)$ years (Figure 3(a)). This timescale is roughly consistent with an analytical estimate described in Tremaine (1993). Also, this timescale does not strongly dependent on which period we choose, as the range of OCNC's semimajor axe of each IC is similar to each other (Figure 1, the third row).

For confirming the accuracy of our assumption, we separately evaluated the ignored effect of galactic tide that OCNCs would receive during the $r > 800$au region using an analytical function that reproduces the galactic tidal force employed in the first model. This inspection yielded a result that the galactic tide would play just a minor role in this region even if it ever works, largely justifying our assumption that OCNCs' motion is a pure Keplerian in $r > 800$au (Ito and Higuchi 2014b).

**OCNC encounters with major planets.** To get an estimate as to which planet has the largest dynamical influence on the fate of OCNCs, we calculated the number of planetary encounters defined by OCNC's close approaches within 500 × scatter radius of planets. The scatter radius, $r_\mathrm{s} = Gm/v_\mathrm{rel}^2$ (where $m$ is the mass of a planet and $v_\mathrm{rel}$ is the relative velocity between the planet and an OCNC), is a distance when a massless body's orbit gets bent ninety degrees by planetary scattering (Battin 1987). The resulting statistics revealed that Jupiter and Saturn play a dominant role on scattering OCNCs away from the system on hyperbolic orbits. [no figure for this result in this article.]

**Saturn–Jupiter barrier.** There has been a concept called the "Jupiter barrier" where giant planets such as Jupiter protect the Earth from cometary bombardments (*e.g.* Everhart 1973; Wetherill 1994). Our study partially validates this hypothesis, indicating that the planetary barrier actually works when incoming OCNC flux is nearly planar as in IC3 (Figure 3(b)). The main barrier is composed by Saturn with an aid by Jupiter, making OCNCs' perihelia stick around Saturn's orbit. Therefore we might want to call this barrier as the "Saturn–Jupiter" barrier. This must have been the situation in the early solar system, and we may say that the early Earth was protected from cometary bombardment by Saturn and Jupiter to some extent. Once the comet cloud has become isotropic as in IC1, OCNCs can come from almost any directions, and the barrier no longer works as effectively as before. This is the situation going on in the current solar system. Figure 3(b) indicates that the Saturn–Jupiter barrier worked most effectively in IC2. This is because most of the major cometary showers produced in IC2 happened to be along the ecliptic plane. This is just a coincident, but as a result many "showering" OCNCs were blocked by the Saturn–Jupiter barrier quite effectively.

## 4. Concluding remark

In this short report we have described the current status of our series of studies on the dynamical evolution of OCNCs. Some of them may have a profound influence on the studies of the SSSB origin and evolution. We have many more issues to mention, discuss and analyze among the result of our analytical and numerical calculations, such as the number and the distribution of OCNCs' apparition and perihelion passages, contribution of OCNCs to each of the SSSB groups, detailed analysis of the cometary showers happened in IC2, dynamical characteristics of survivors over 500

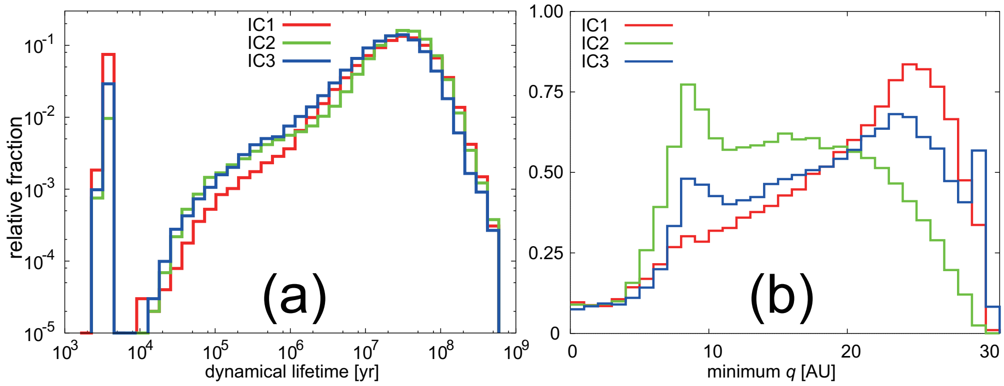


Figure 3. (a) Distribution of dynamical lifetime of OCNCs. Note that there is an isolated peaks in the $O(10^3)$-year bins. This is due to a group of OCNCs that were ejected jut after the first apparition (= perihelion passage) in our model, which is a sort of model artifact. (b) Distribution of the minimum perihelion distance that each of the OCNCs has experienced during its lifetime.

Myr in our numerical integrations, and comparison of our calculation result with the current observational evidence in the solar system. We will make detailed reports on these issues as our forthcoming publications.

## References

Battin, R. H., 1987, *An Introduction to the Mathematics and Methods of Astrodynamics,* AIAA, New York

Everhart, E., 1973, *Astron. J.* **78**, 329

Forchard, M., 2013, *Icarus* **222**, 20

Forchard, M., 2014a, *Icarus* **231**, 110

Forchard, M., 2014b, *Icarus* **231**, 99

Higuchi, A., 2006, *Astron. J.* **131** 1119

Higuchi, A., 2007, *Astron. J.* **134** 1693

Higuchi, A. & Kokubo, E. *Astron. J.* submitted

Ito, T. & Higuchi, A. 2012, *LPI Contribution* **1667** 6209

Ito, T. & Higuchi, A. 2014a, ACM2014 (Asteroids, Comets, and Meteors) abstract

Ito, T. & Higuchi, A. 2014b, JSPS2014 fall meeting abstract (Tohoku University, text in Japanese)

Ito, T. & Malhotra, R. 2006, *Adv. Space Res.* **38**, 817
Ito, T. & Malhotra, R. 2010, *Astron. Astrophys.* **519**, A63
Tremaine, S. 1993, *ASP Conference Series* **36**, 335
Wetherill, G. W. 1994 *Astrophys. Space Sci.* **212**, 23