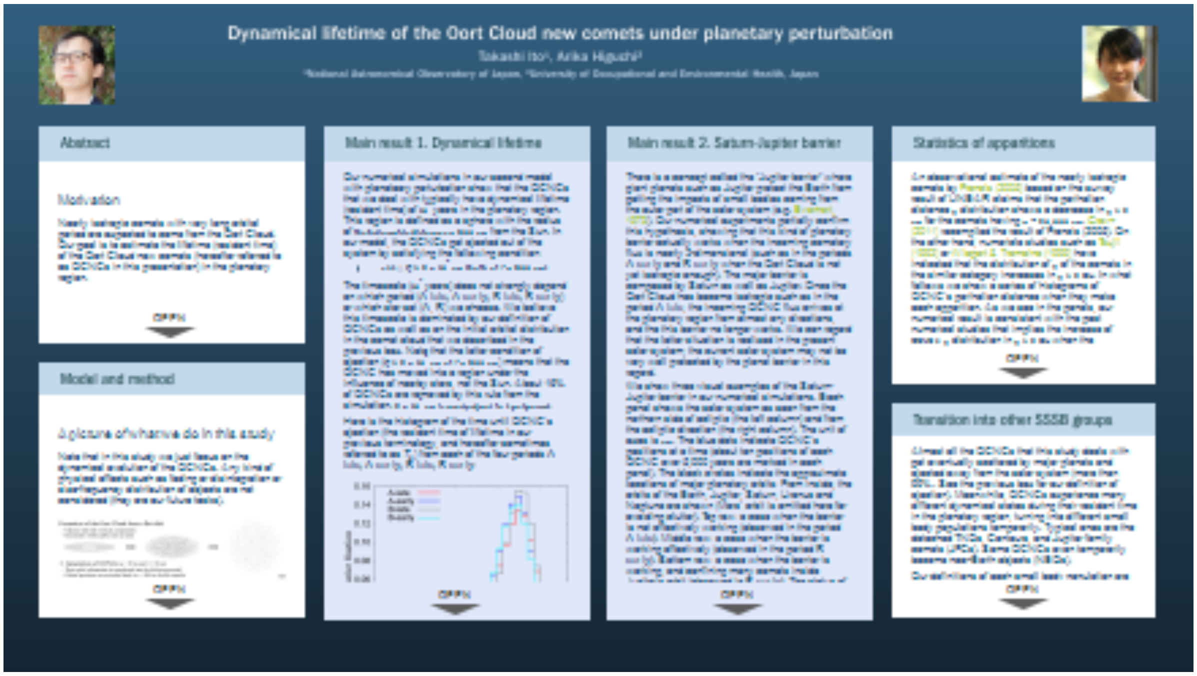
Dynamical lifetime of the Oort Cloud new comets under planetary perturbation



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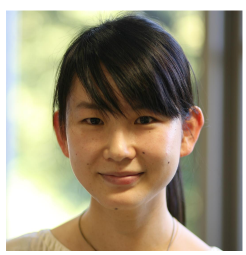

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ABSTRACT

Motivation

Nearly isotropic comets with very long orbital period are expected to come from the Oort Cloud. Our goal is to estimate the lifetime (resident time) of the Oort Cloud new comets (hereafter referred to as OCNCs in this presentation) in the planetary region.

Method

We combine two models to follow the dynamical evolution of OCNCs from their production in the Oort Cloud until their ejection out of the solar system. The first model is a semi-analytical one about the OCNC production in the evolving Oort Cloud under the perturbation by the galactic tide and stellar encounters of the nearby stars. The second model numerically deals with planetary perturbation over OCNCs' dynamics in planetary region.

Main results

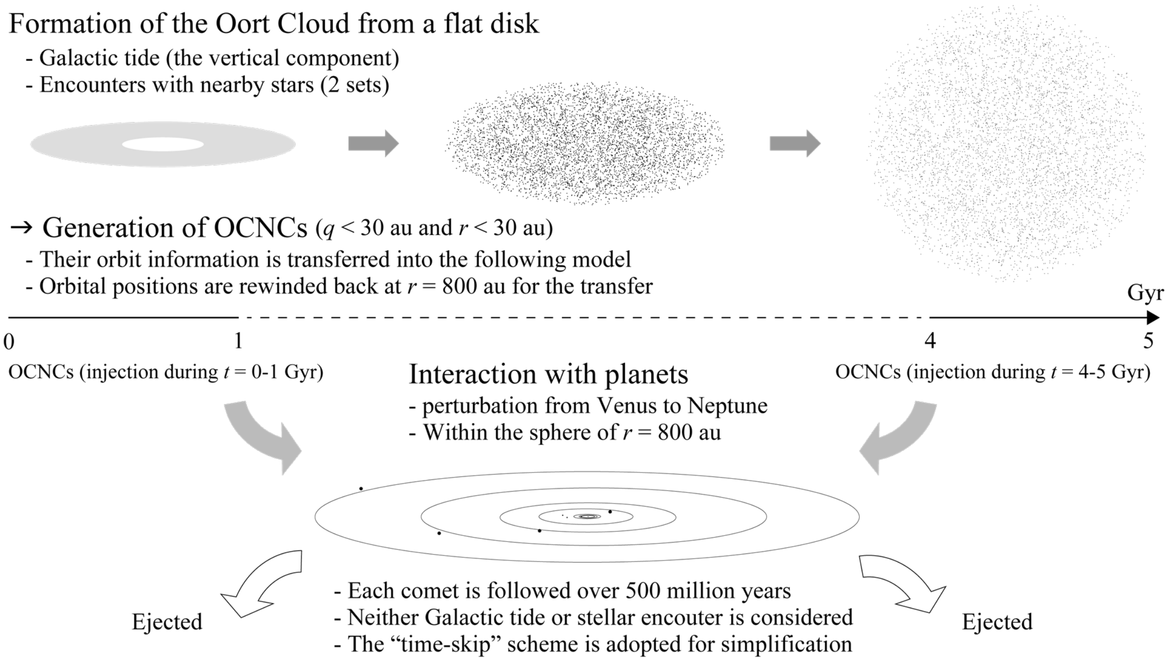
Although our study does not include any kind of physical effects such as fading or disintegration of comets yet, we made the following two findings:

1. Typical resident time of OCNCs in the planetary region is 10^7 years. Once entering into the planetary region, most OCNCs stay there for around this timespan, then get ejected out of the solar system on hyperbolic orbits.
2. When the initial orbital inclination of OCNCs is small, the so-called "planet barrier" works effectively, particularly "Saturn-Jupiter" barrier, preventing the OCNCs from penetrating into the terrestrial region.

MODEL AND METHOD

A picture of what we do in this study

Note that in this study we just focus on the dynamical evolution of the OCNCs. Any kind of physical effects such as fading or disintegration or size-frequency distribution of objects are not considered (they are our future tasks).

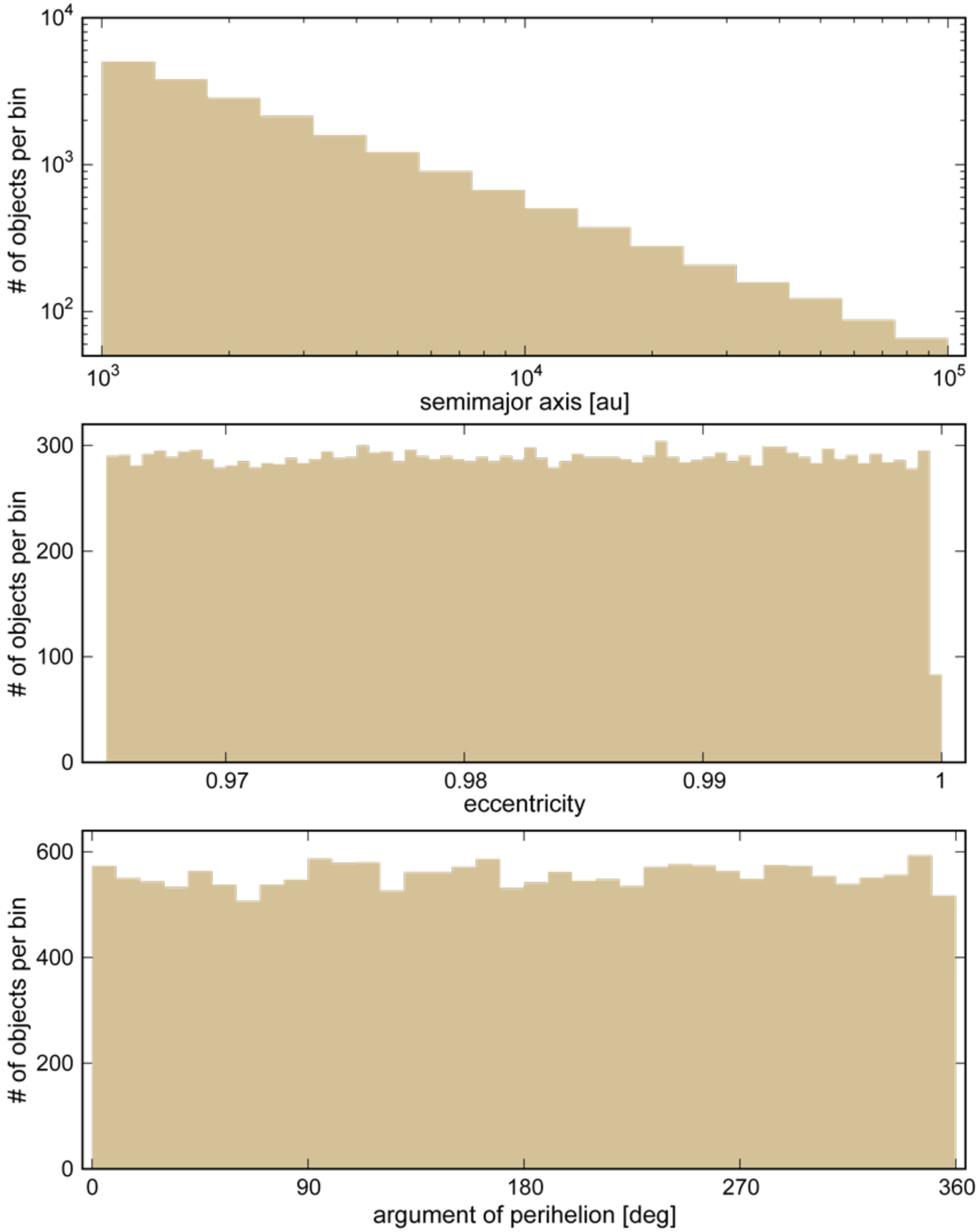


Evolution of comet cloud

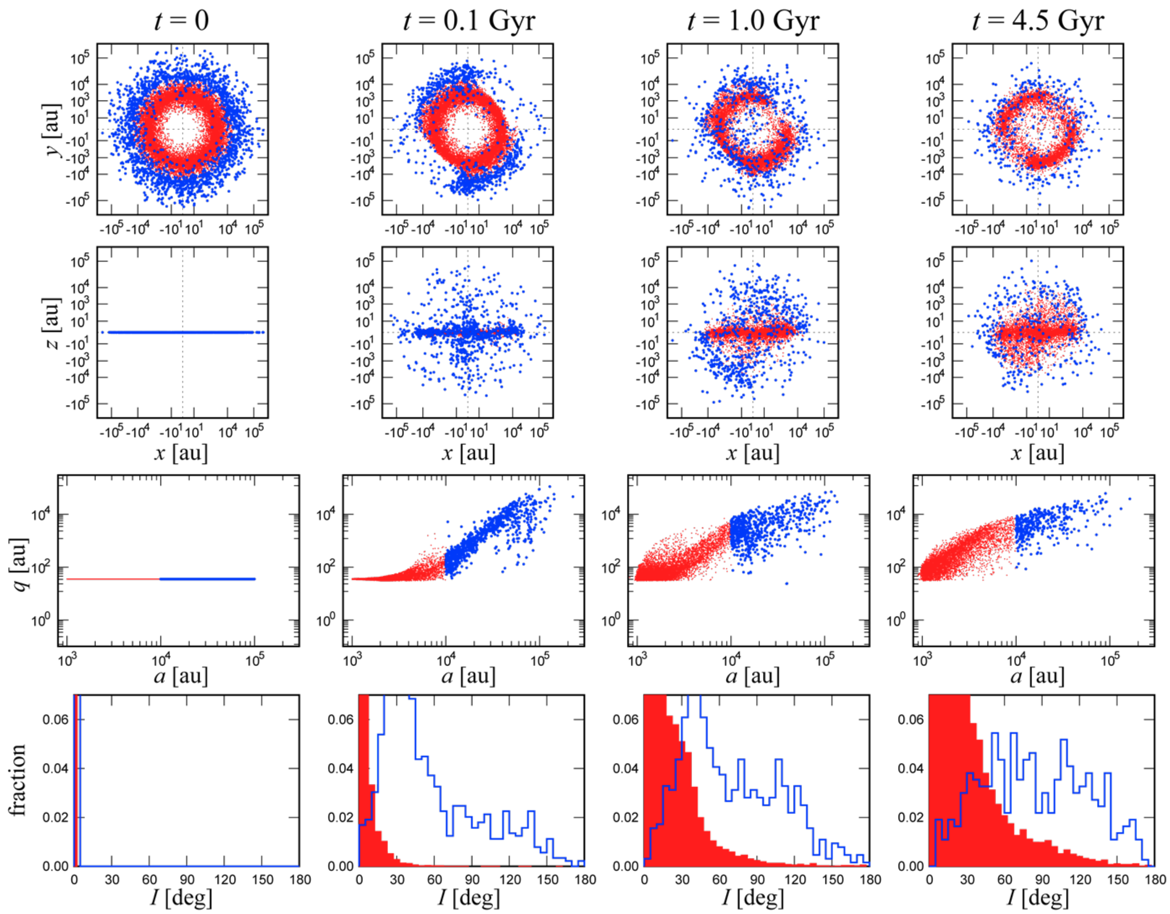
The first model to produce the Oort Cloud New Comets (OCNCs) is based on Higuchi et al. (2006 (https://ui.adsabs.harvard.edu /abs/2006AJ....131.1119H/abstract), 2007 (https://ui.adsabs.harvard.edu/abs/2007AJ....134.1693H/abstract), 2015 (https://ui.adsabs.harvard.edu/abs/2015AJ....150...26H/abstract)). This model semi-analytically calculates the dynamical evolution of a comet cloud located in the outmost skirt of the solar system under the perturbation by the galactic tide and stellar encounters by the nearby passing stars, eventually leading to the current Oort Cloud that continuously supplies OCNCs. In this model the initial condition of the comet cloud is a flat, 2-dimensional planetesimal disk created by the scatter from the major planets. This disk later evolves into 3-dimensional, nearly isotropic state over 0.1-1 Gyr timespan. The initial comet cloud has the following dynamical properties:

- semimajor axis a_0 = $[10^3, 10^5]$ au
- number distribution $\mathrm{d}N/\mathrm{d}a_0 \propto a^{-2}$
- eccentricity e_0 is randomly distributed between ~0.965 and 1
- perihelion distance q_0 = 35 au
- inclination with respect to ecliptic I_0 = 0
- argument of perihelion, longitude of ascending node, mean anomaly are all randomly distributed between 0 and 360 degrees.

Here are the histograms of the initial distribution of a_0, e_0 and argument of perihelion (the vertical value is not normalized):



The following figure shows four snapshots of the dynamical evolution of OCNCs generated from one of the star sets (the set **A** in what follows). The OCNCs with $a < 10{,}000$ au are denoted by red and those with $a > 10{,}000$ au are denoted in blue. We see that the outer part of the comet cloud (the blue dots) that are more subject to the galactic tide are pretty much isotropic around the time $t = 1$ Gyr, while the inner part (the red dots) remain largely flat.



Galactic tide and stellar encounters

The comet cloud mainly experiences two kinds of perturbations: the galactic tide and the encouters with the nearby stars. As for the galactic tide, we follow the theoretical model advocated in Heisler & Tremaine (1986) (https://ui.adsabs.harvard.edu /abs/1986Icar...65...13H/abstract) and implemented in Higuchi+ (2007) (https://ui.adsabs.harvard.edu/abs/2007AJ....134.1693H /abstract). The galactic plane is an infinitely extended plane, and we only consider the vertical component of the tide. This causes oscillation of eccentricity and inclination of the comets, while the semimajor axis remains constant in the doubly-averaged approximation.

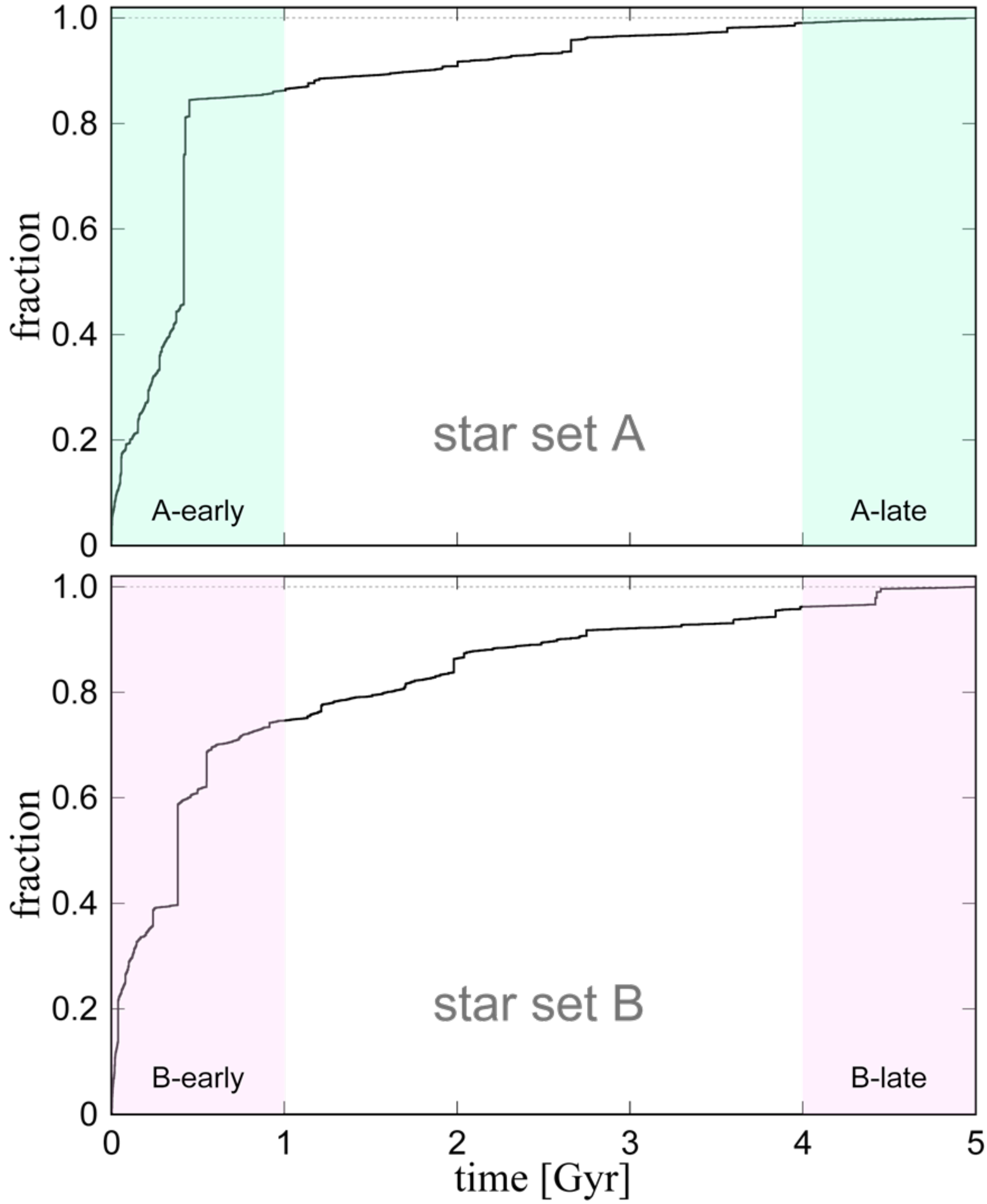
As for the effect of encounters of nearby stars, we adopt the impulse approximation (e.g. Rickman, 1976 (https://ui.adsabs.harvard.edu/abs/1976BAICz..27...92R/abstract)). This diffuses all the orbital elements, and causes ejection of some comets in the hyperbolic orbits ($e > 1$) directly from the cloud before they enter the planetary region as OCNCs. Here we do not consider GMC, and just consider stars. We keep the Sun at the same galactocentric distance. Also, we adopt the total density in the solar neighborhood ρ = 0.1 M_sun pc^(-3), and assume it as a constant.

Production of OCNCs

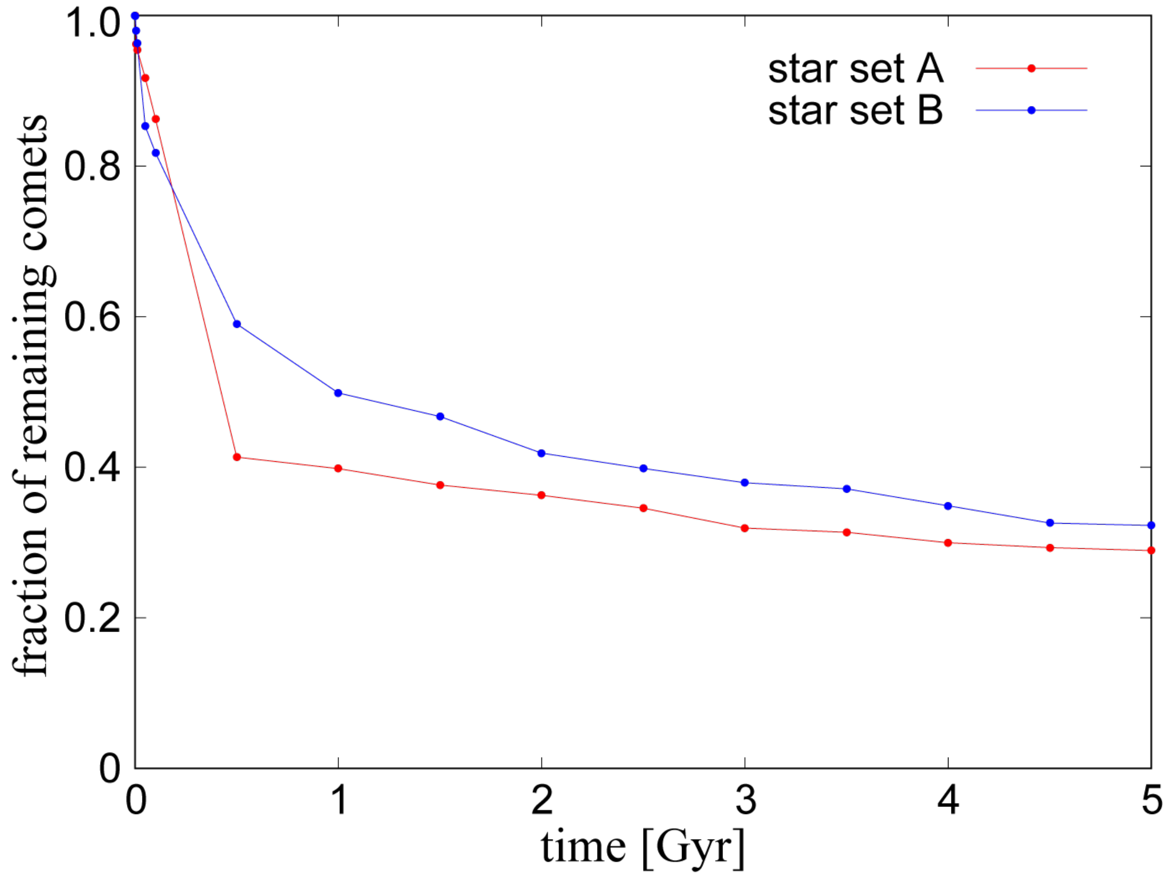
As stated above, a comet cloud that initially has a 2-dimensional shape evolves into a 3-dimensional shape under the galactic tide and the stellar encounters. The perturbations also produce a large number of small bodies with very small perihelion distance q, i.e. OCNCs. We define that an object in the comet cloud becomes an OCNC when it acquires the following orbital condition:

- Perihelion distance $q < 30$ au && Heliocentric distance $r < 30$ au

The following figure shows the timeline of the generation of OCNCs under two different star sets, **A** and **B**. The initial orbital configuration of the comet cloud is common to both.



As OCNCs get generated, the number of comets remaining in the original cloud decreases. The following panel shows the fraction of the remaining comets in the cloud and its time variation.

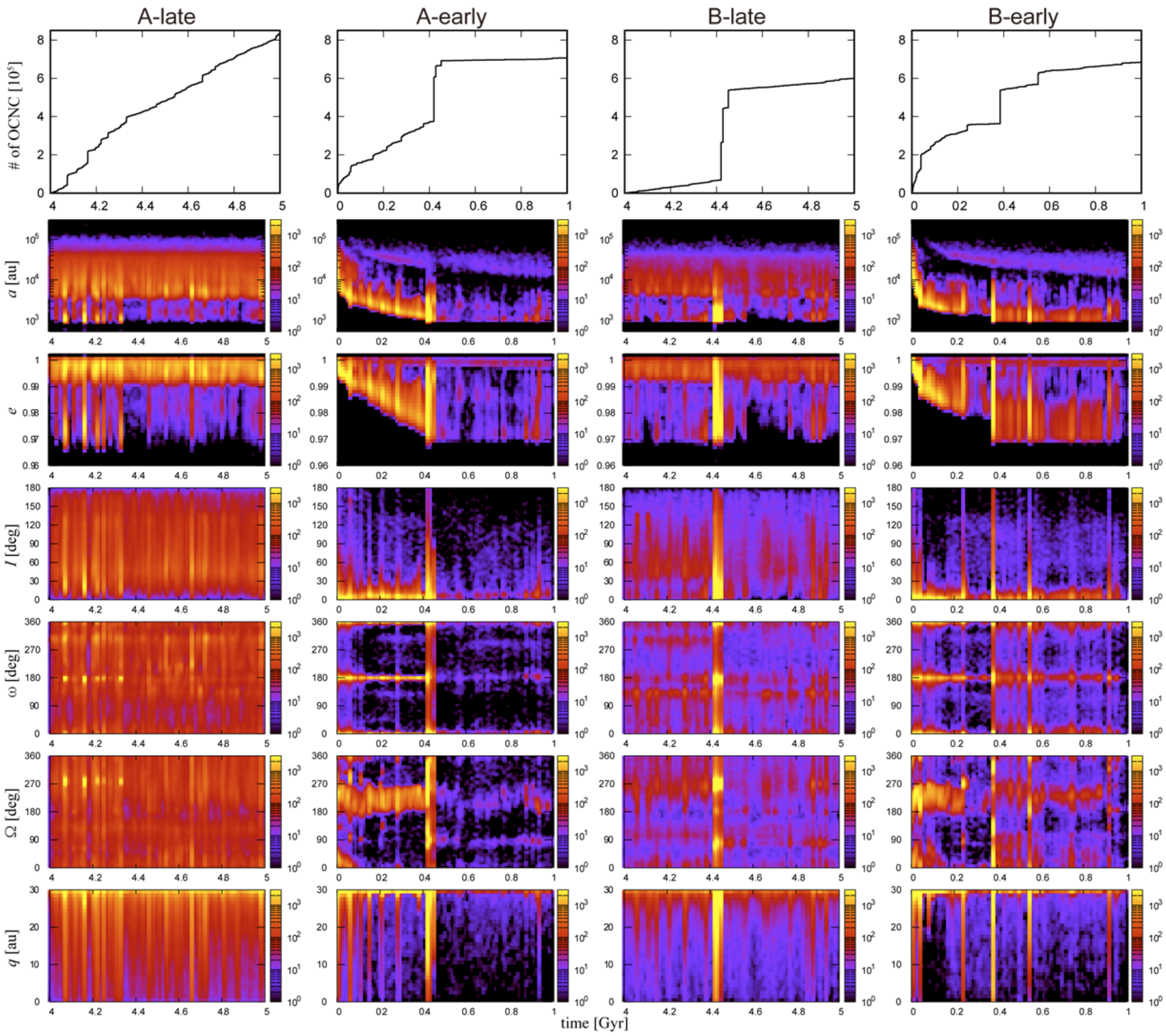


How the stellar encounters with the solar system in our model happen depends on what kind of random number set we use. We call this "star set". If we choose a different star set, statistics of the generated OCNCs get slightly different as shown in the above panel.

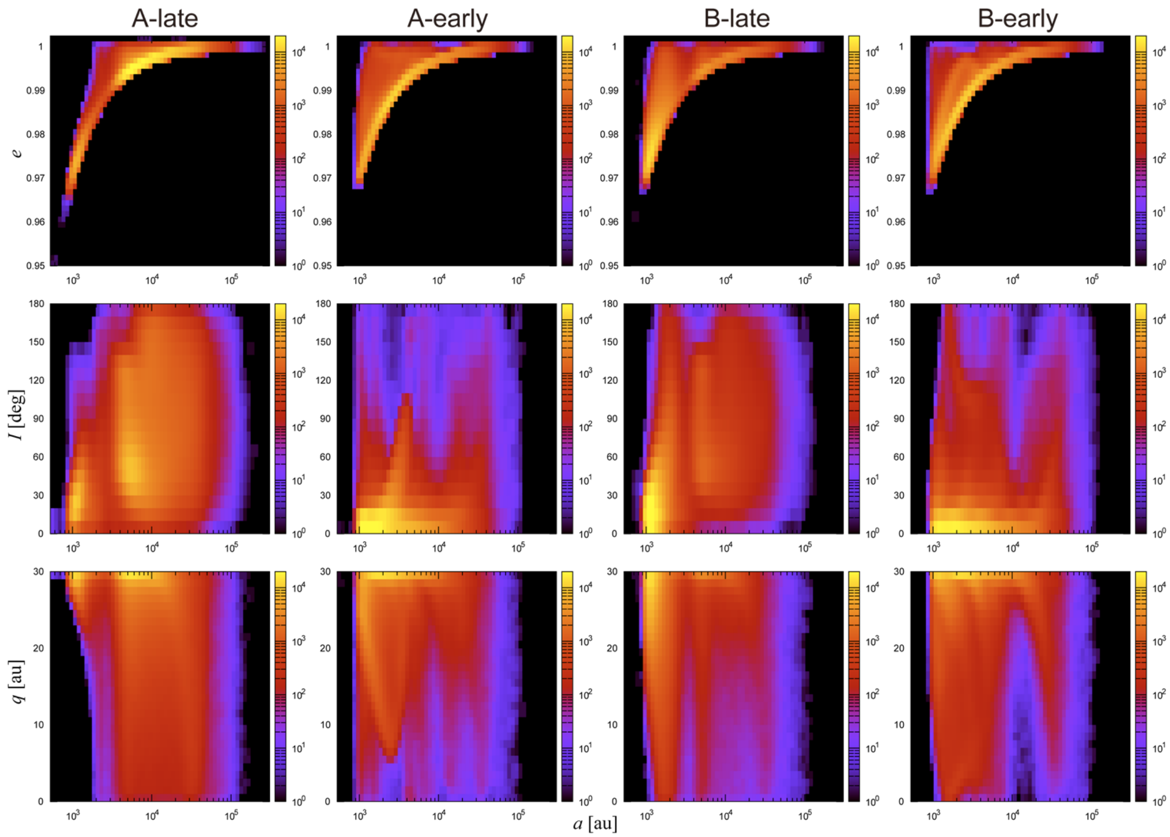
In our model we pick 6-8 x 10^5 OCNCs in each of the following 2 x 2 = 4 periods, and give them planetary perturbation within the planetary region:

- Periods **"A-late"** and **"B-late"** represent the late stage of the solar system history, time t = 4-5 Gyr. Durind this period OCNCs come from the dynamically evolved comet cloud, therefore the orbits of the incoming comets are distriuted nearly isotropically. Also, the incoming flux of the OCNCs is nearly stationary.
- Periods **"A-early"** and **"B-early"** represent the early stage of the solar system history, time t = 0-1 Gyr. During this period OCNCs come from the yet evolving comet cloud. Therefore the incoming OCNC flux is first confined in the 2-dimentional plane, and gradually getting 3-dimentional. The amount of flux is at first very large, and then rapidly decreases.

The following panels depict the production of OCNCs during each period. From the top, # of OCNCs, OCNCs' a, e, I, ω, Ω, q at their generation.



The following panels show the distribution of OCNC's initial orbital elements (e, q, I) at their generation and their dendence on the initial semimajor axis a (at their generation).

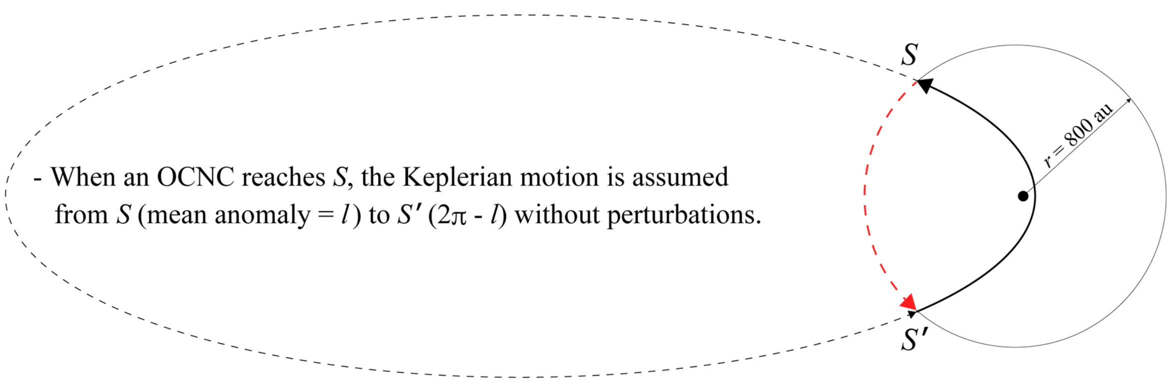


Planetary perturbation

Once a cometary object has been regarded as an OCNC through the definition we mentioned above, we remove it from the first model and put it into the second model that considers planetary perturbation. Calculation of this stage includes OCNCs, seven major planets from Venus to Neptune, and the Sun. We follow the dynamical evolution of the OCNCs for up to 500 Myr at most.

The "time-skip" scheme

To reduce computational amount, we assume that OCNCs that have reached $r = 800$ au follow the Keplerian motion in the farther part of their orbits. We call this the "time-skip" scheme. Validation of the scheme is important, and it will be presented in our forthcoming publications. However, our preliminary analysis indicates that this approximation does not significantly change our conclusion, but accelerating the calculation x10 to x100 times faster.



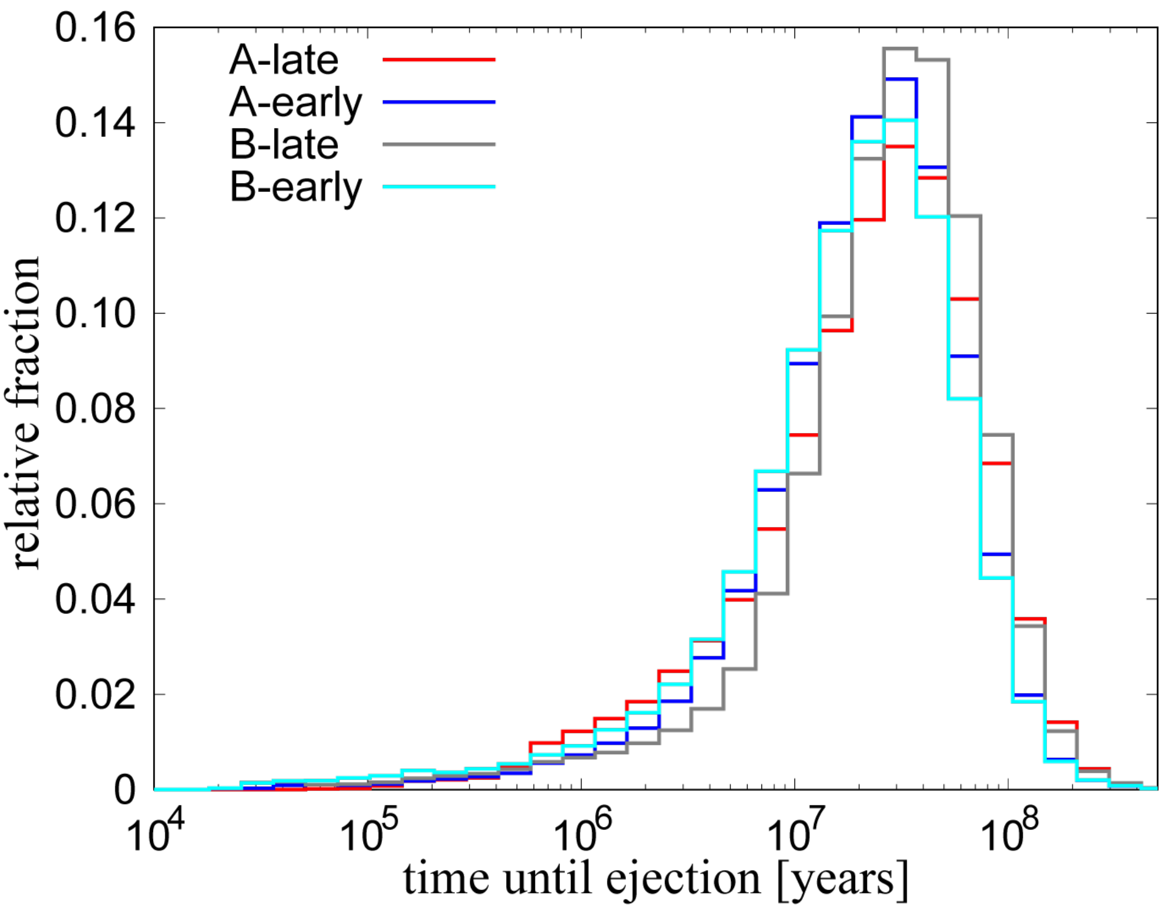
MAIN RESULT 1. DYNAMICAL LIFETIME

Our numerical simulations in our second model with planetaery perturbation show that the OCNCs that we deal with typically have dynamical lifetime (resident time) of 10^7 years in the planetary region. This region is defined as a sphere with the radius of the heliocentric distance r = 800 au from the Sun. In our model, the OCNCs get ejected out of the system by satisfying the following condition:

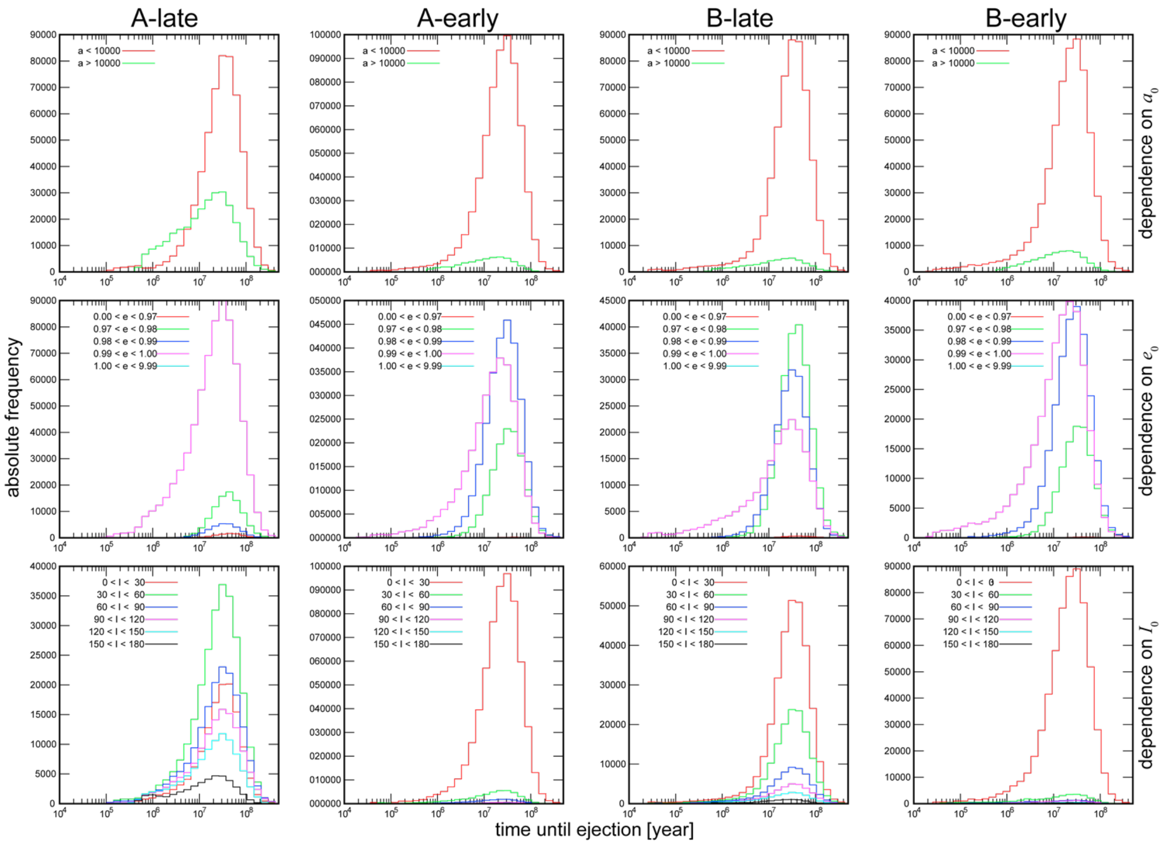
- $e > 1$ || $Q > 2 \times 10^5$ au (both at r = 800 au)

The timescale (10^7 years) does not strongly depend on which period (**A-late, A-early, B-late, B-early**) or which star set (**A**, **B**) we choose. We believe this timescale is dominated by our definition of OCNCs as well as on the initial orbital distribution in the comet cloud that we described in the previous box. Note that the latter condition of ejection ($Q > 2 \times 10^5$ au at r = 800 au) means that the OCNC has moved into a region under the influence of nearby stars, not the Sun. About 16% of OCNCs are removed by this rule from the simulation. 2×10^5 au is nearly equal to 1 pc (parsec).

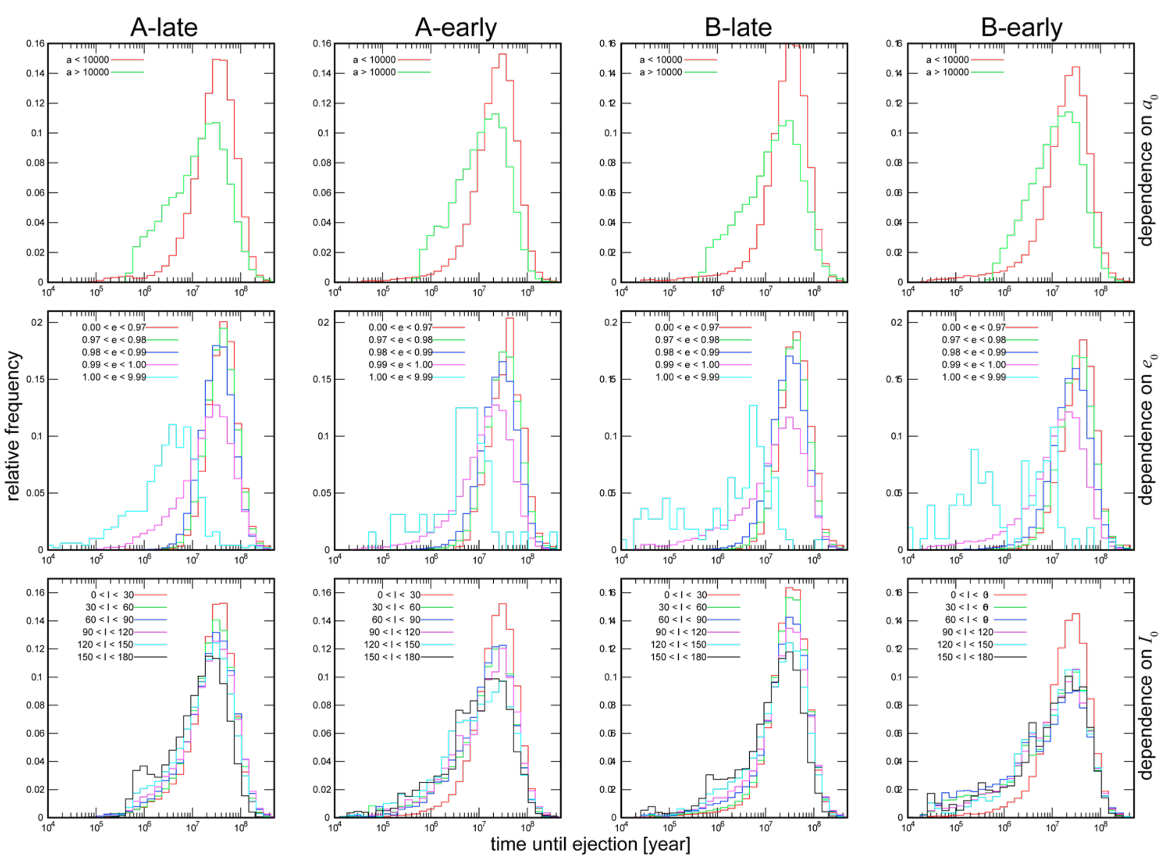
Here is the histogram of the time until OCNC's ejection (the resident time of lifetime in our previous terminology, and hereafter sometimes referred to as T_e) from each of the four periods **A-late, A-early, B-late, B-early**:



The following series of panels show more detailed dependence of the resident time T_e on OCNCs' initial orbital elements. The vertical axis is not normalized here. Note that the number of OCNCs with initial eccentricity larger than 1 is so small that we cannot recognize them in the following (not normalized) panels.



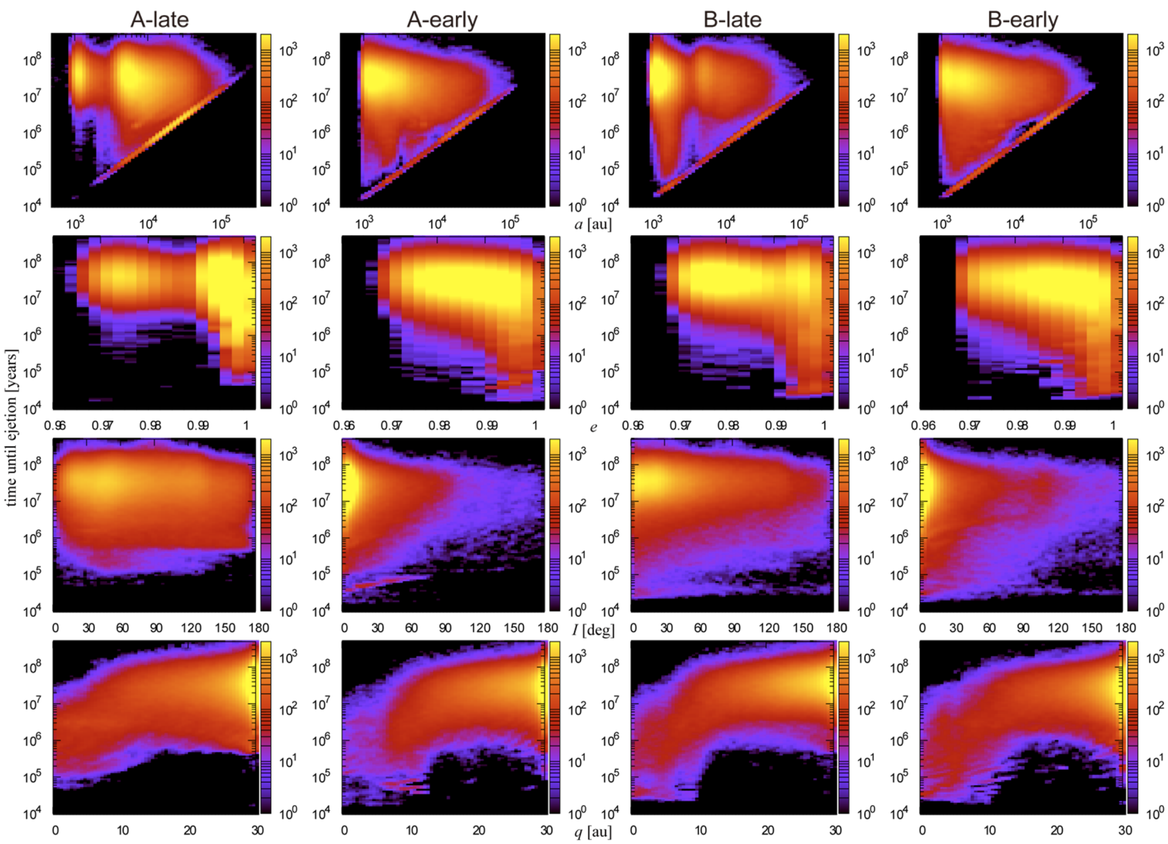
Here is another series of panels where the vertical axis values are normalized by the total number of the generated OCNCs in each period. Now the contribution of the hyperbolic objects are visible.



What we can observe from the above panels are as follows:

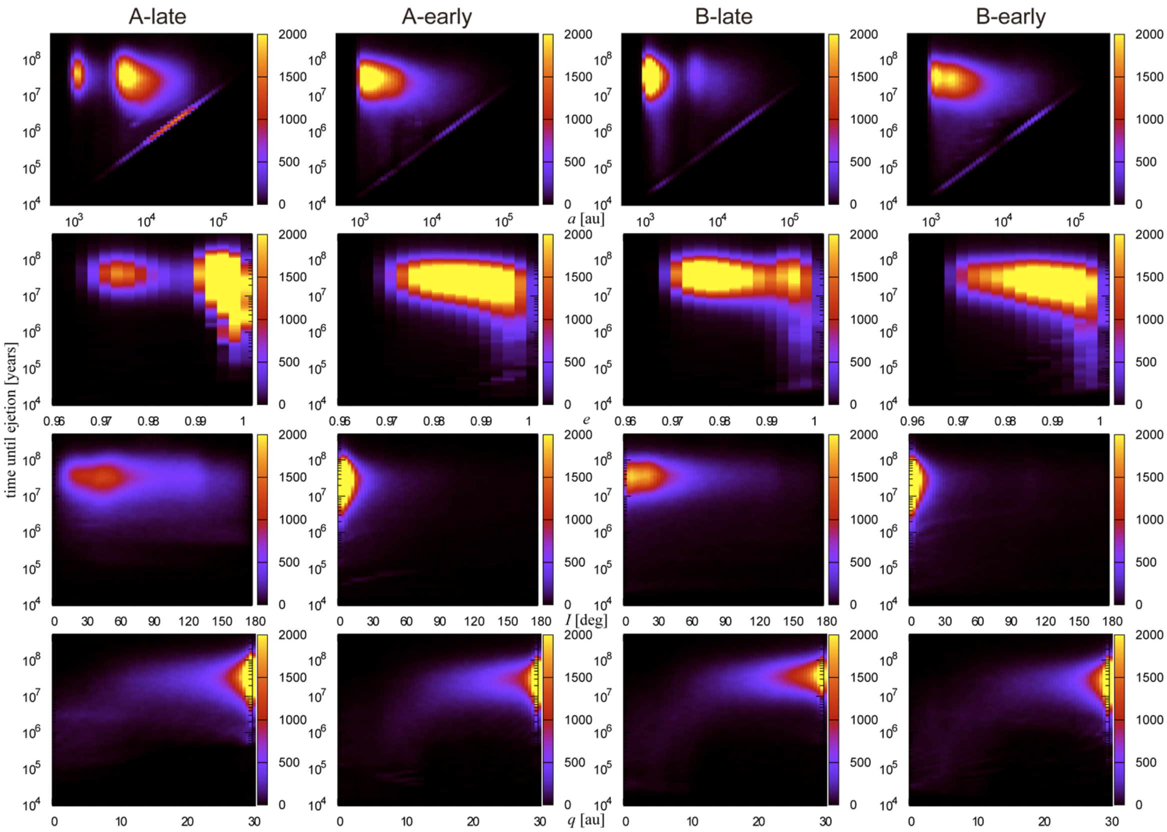
- The OCNCs that have large initial semimajor axis (a > 10,000 au) tend to have shorter T_e than those that have smaller initial semimajor axis. This is because the OCNCs with large initial semimajor axis generally have very large eccentricity by their definition, and thye are close to the state of ejection on a hyperbolic orbit from the beginning.
- The dependence of T_e on the initial eccentricy is weaker, except for the OCNCs with very large initial eccentricity (e > 0.99).
- The dependence of T_e on the initial inclination is not clear or very weak, if any.

The following color maps show the frequency distribution of T_e and its dependence on OCNC's initial orbital elements, a, e, I, q. The color scale is logarithmic.

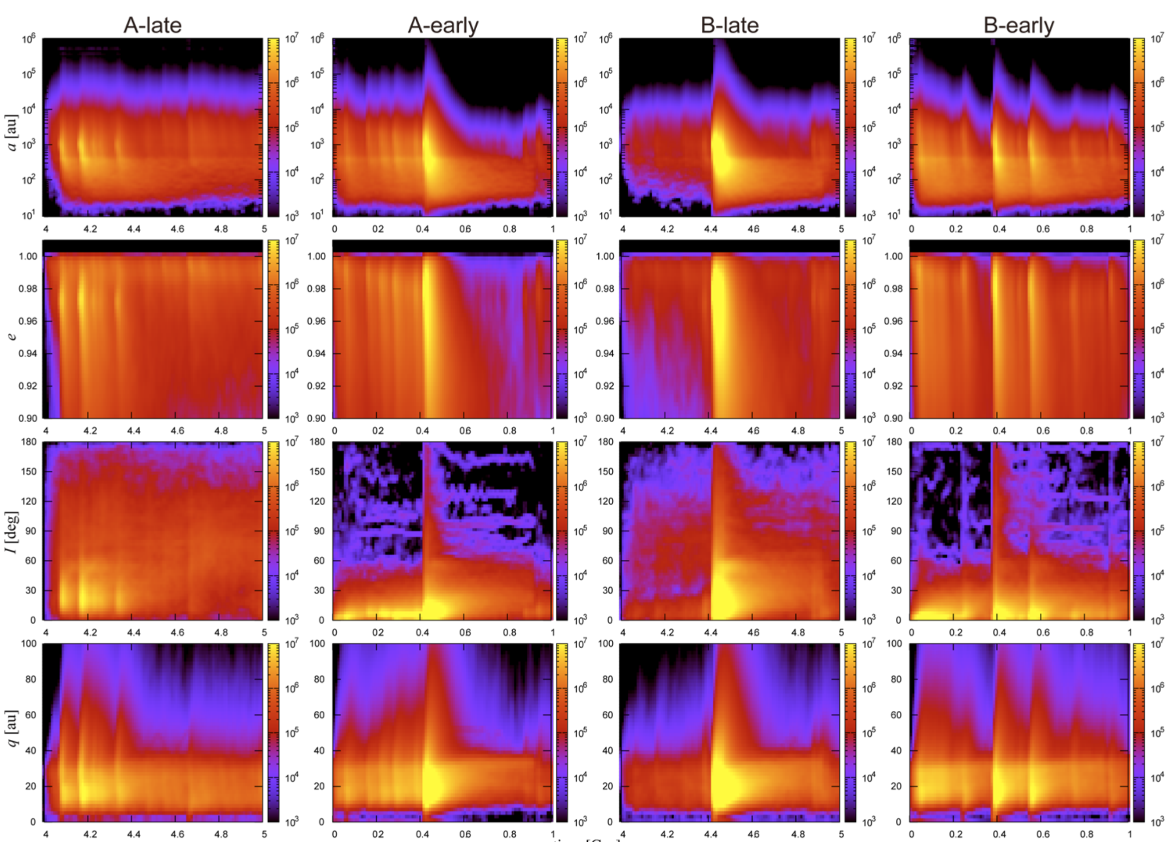


The sharp boundaries seen in the bottom left to the top right of the four panels on the top row are due to the way we calculate T_e. We reckon this time from the aphelion of each OCNCs. Therefore the minimum of T_e of an OCNC takes place when the OCNC gets ejected just after its first apparition. In this case $T_{e,\min} = P/2 \propto a^{1.5}$, which forms the sharp boundary seen in the top-row panels for (a, T_e). Since the initial eccentricity distribution of the comet cloud is close to unity, non-negligible fraction of the OCNCs (~10%) are near this border, and get ejected out of the system after their first apparition. This may be regarded as a kind of model artifact, and we are going to rectify it in the future.

For reference, the linear color scale version of the panelsares here:



Over the timespan of the numerical integration (5 million years at most), OCNC's orbital elements change, and new OCNCs are always supplied from the comet cloud (i.e. from the calculation result of the first model). Here is a set of color diagrams that visualizes the collective orbital evolution of OCNCs:

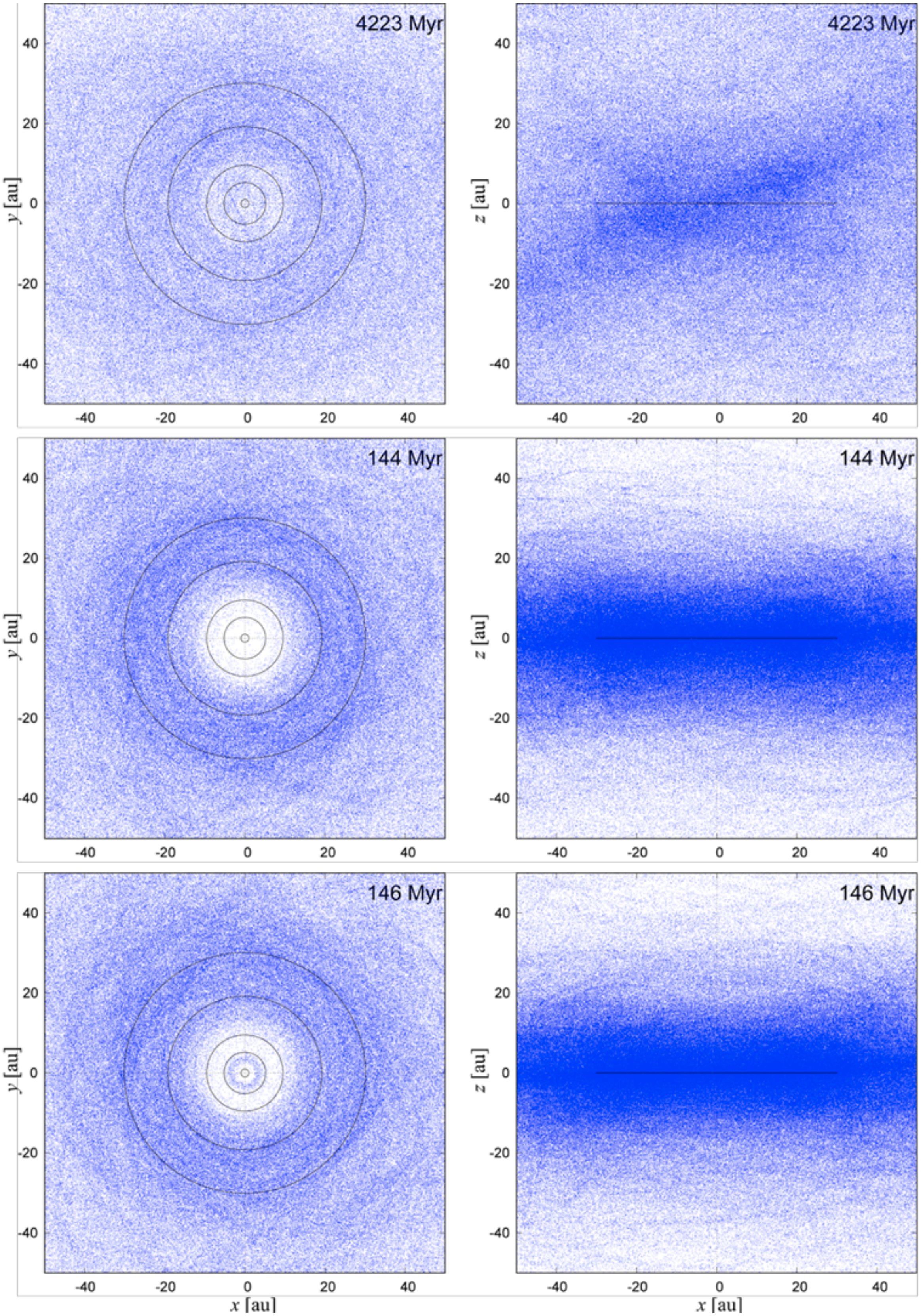


In the above panels we see sharp increases of the OCNC flux at many occasions. They represent the outcome of strong comet showers invoked by very close encounters of nearby stars. In particular, the comet shower that happend at t ~ 4.4 Gyr in the period **B-late** is impressive, thinking about the fact that this kind of shower can principally happen in our present solar sytem.

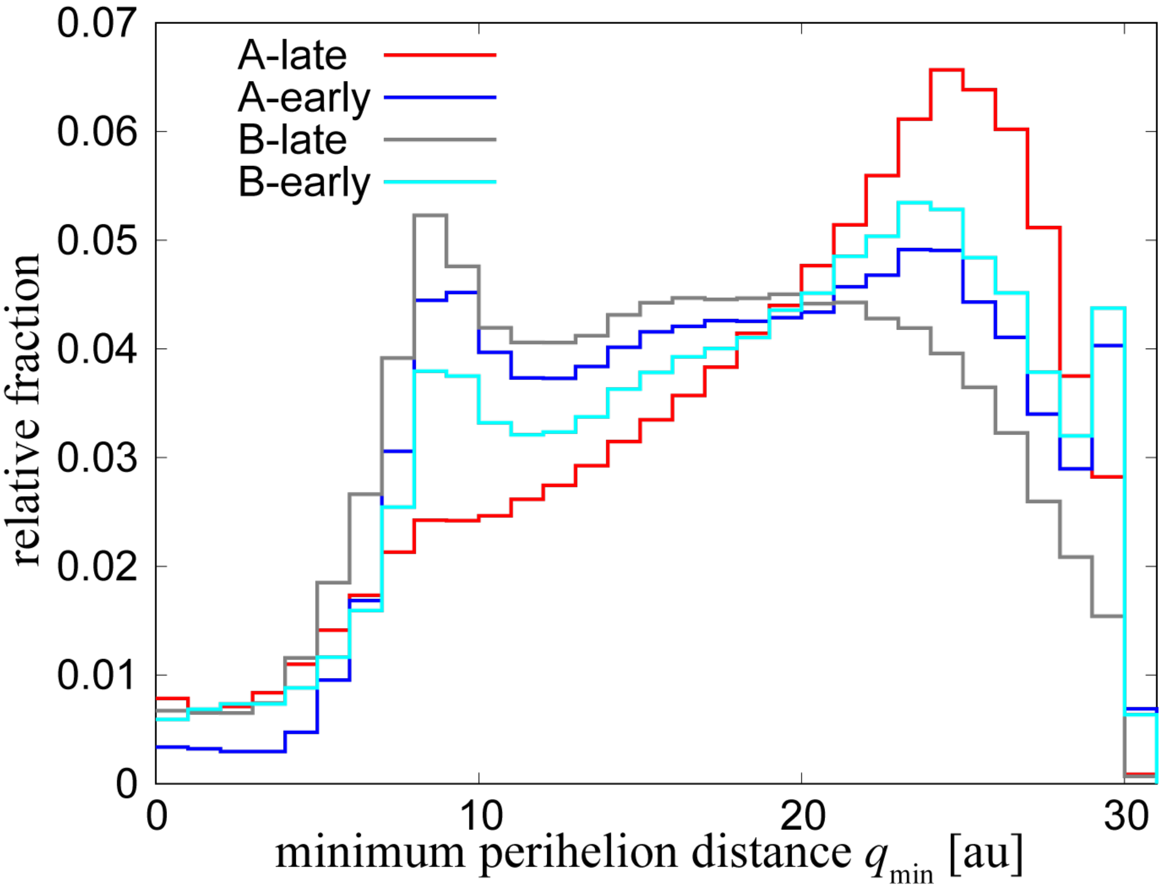
MAIN RESULT 2. SATURN-JUPITER BARRIER

There is a concept called the "Jupiter barrier" where giant planets such as Jupiter protect the Earth from getting the impacts of small bodies coming from the outer part of the solar system (e.g. Everhart, 1973 (https://ui.adsabs.harvard.edu /abs/1973AJ.....78..329E/abstract)). Our numerical experiments partially confirm this hypothesis, showing that this kind of planetary barrier actually works when the incoming cometary flux is nearly 2-dimensional (such as in the periods **A-early** and **B-early** when the Oort Cloud is not yet isotropic enough). The major barrier is composed by Saturn as well as Jupiter. Once the Oort Cloud has become isotropic such as in the period **A-late**, the incoming OCNC flux arrives at the planetary region from almost any directions, and the this barrier no longer works. We can regard that the latter situation is realized in the present solar system; the current solar system may not be very well protected by the planet barrier in this regard.

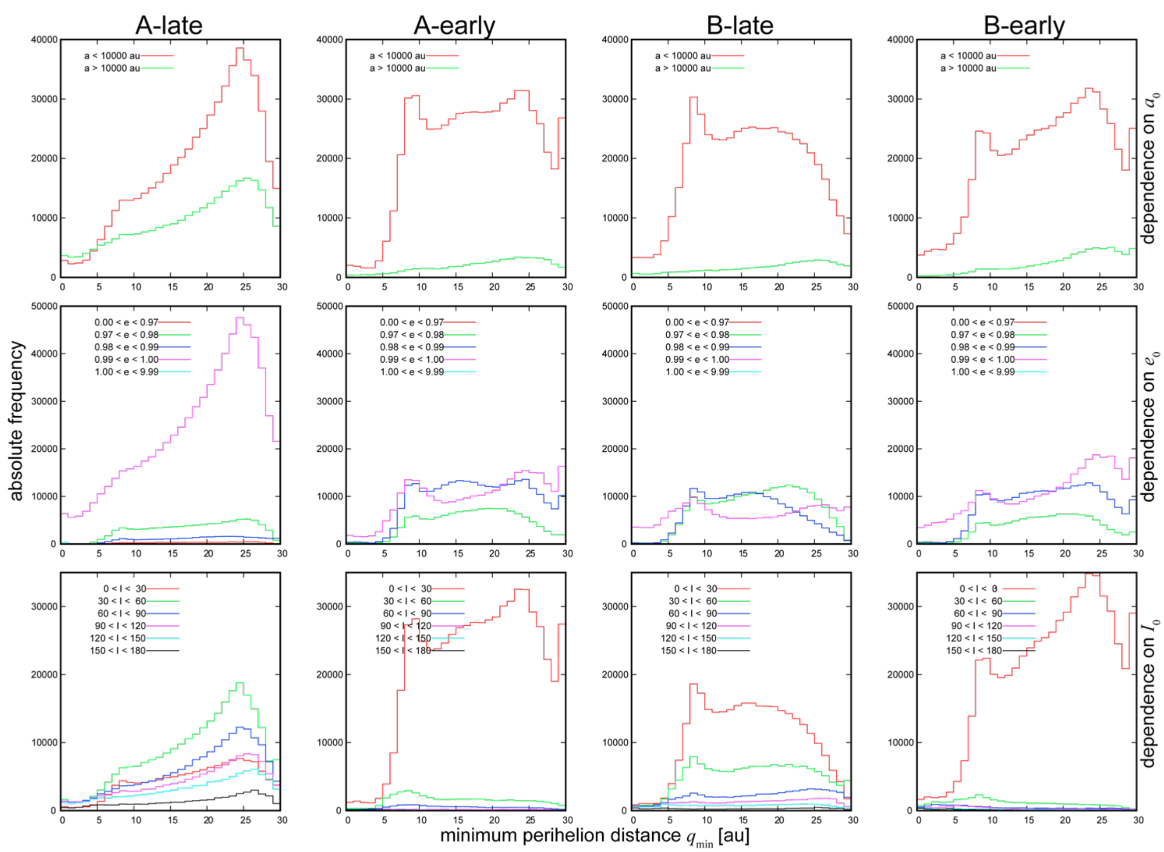
We show three visual examples of the Saturn-Jupiter barrier in our numerical simulations. Each panel shows the solar system as seen from the northern side of ecliptic (the left column) and from the ecliptic direction (the right column). The unit of axes is au. The blue dots indicate OCNC's positions at a time (about ten positions of each OCNC over 5,000 years are marked in each panel). The black circles indicate the approximate locations of major planetary orbits: From inside, the orbits of the Earth, Jupiter, Saturn, Uranus and Neptune are shown (Mars' orbit is omitted here for avoiding clutter). Top row: a case when the barrier is not effectively working (observed in the period **A-late)**. Middle row: a case when the barrier is working effectively (observed in the period **B-early)**. Bottom row: a case when the barrier is working, and confining many comets inside Jupiter's orbit (observed in **B-early)**. The status of the bottom panels continued for a couple of thousand years. The model time for each snapshot is decribed at the top right of each panel in the unit of million years.



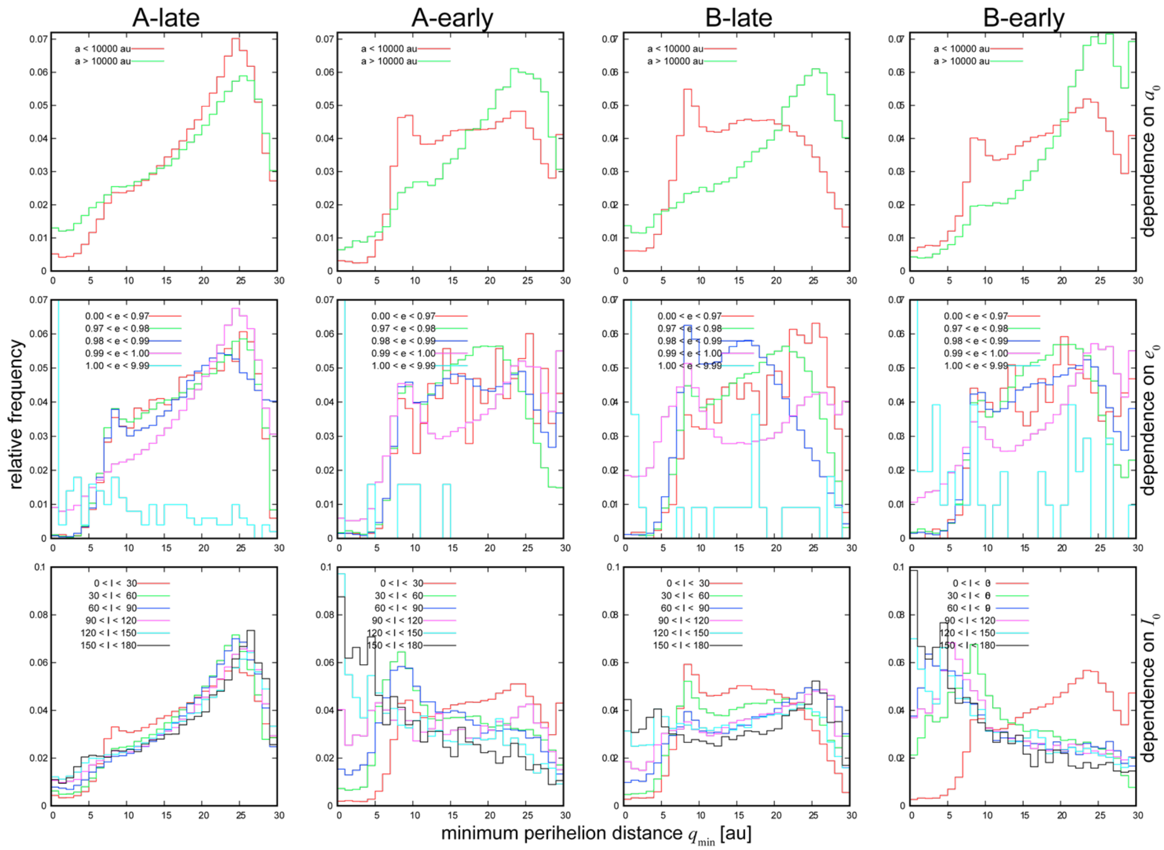
How effective the barrier works depends on the initial orbital elements of the incoming OCNCs. The following figure shows the frequency distribution of OCNC's $q_{\rm min}$ that is normalized by the total number of OCNCs in each period. We can see local maxima between Jupiter's and Saturn's orbits ($5 < q < 10$ au) in the results obtained in the periods **A-early, B-late, B-early**. The result obtained in the period **A-late** does not exhibit a strong local maximum probably because the incoming OCNC flux is nearly istropic in this case and they do not strongly interact with major planets orbiting near ecliptic.



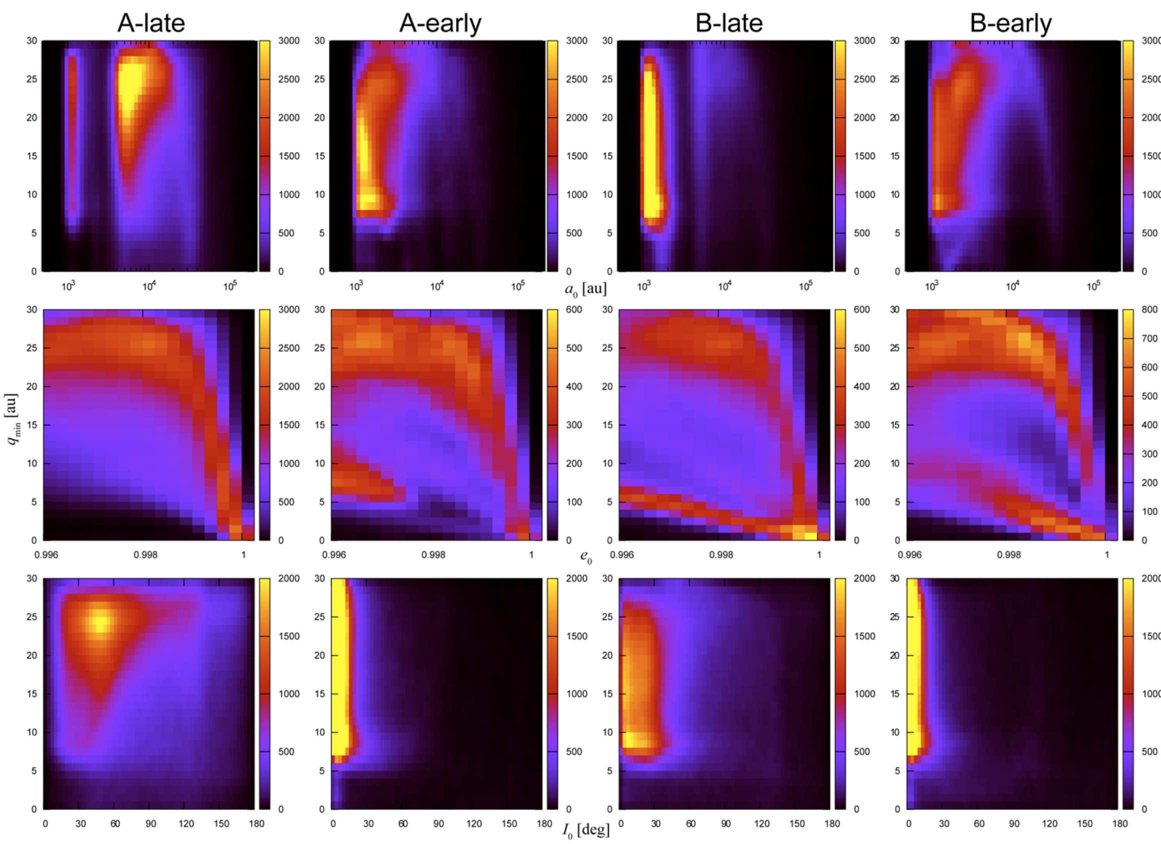
The following panels show the dependence of the $q_{\min}$ distribution on OCNC's initial orbital elements. The vertical axis is not normalized. Note that the number of OCNCs with initial eccentricity larger than 1 is so small that we cannot recognize them in the following (not normalized) panels.



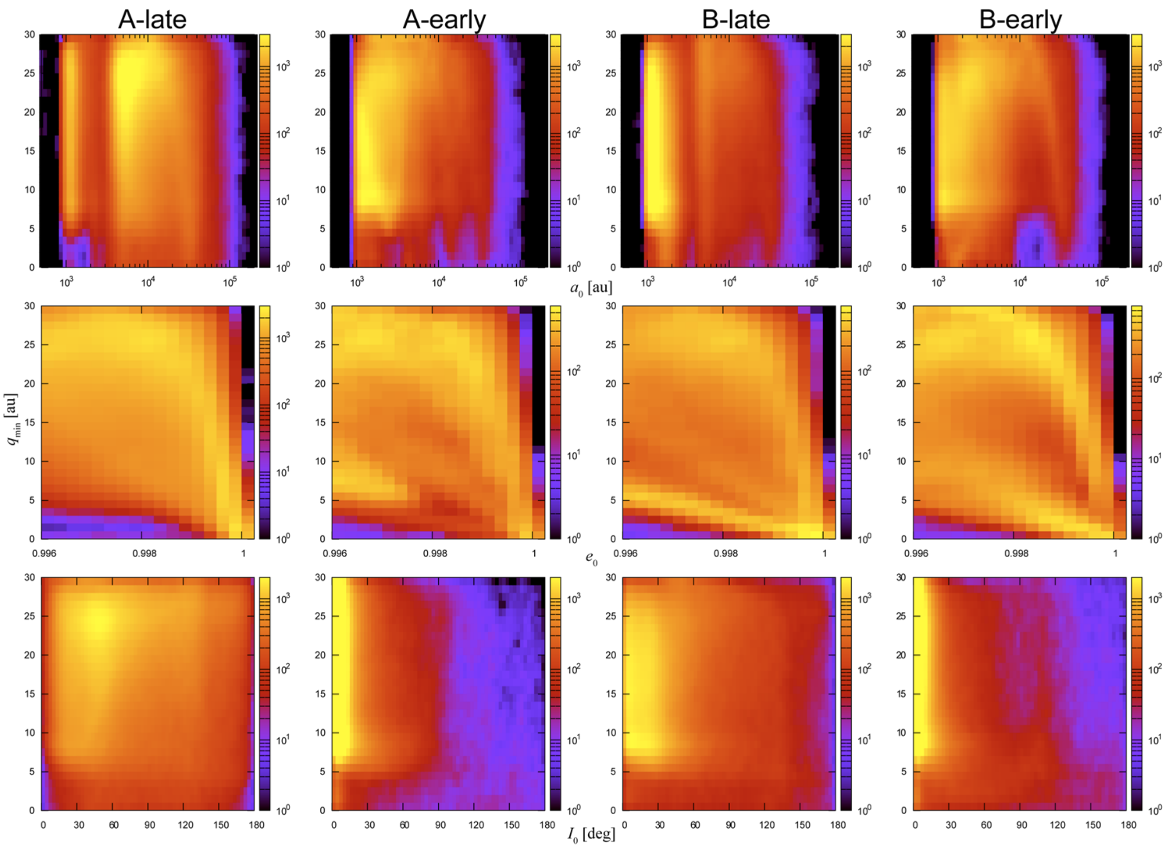
If we normalize the vertical axis by the total number of OCNCs generated in each period, we have another version of the panels as follows. Now the contribution of the $e > 1$ objects is visible:



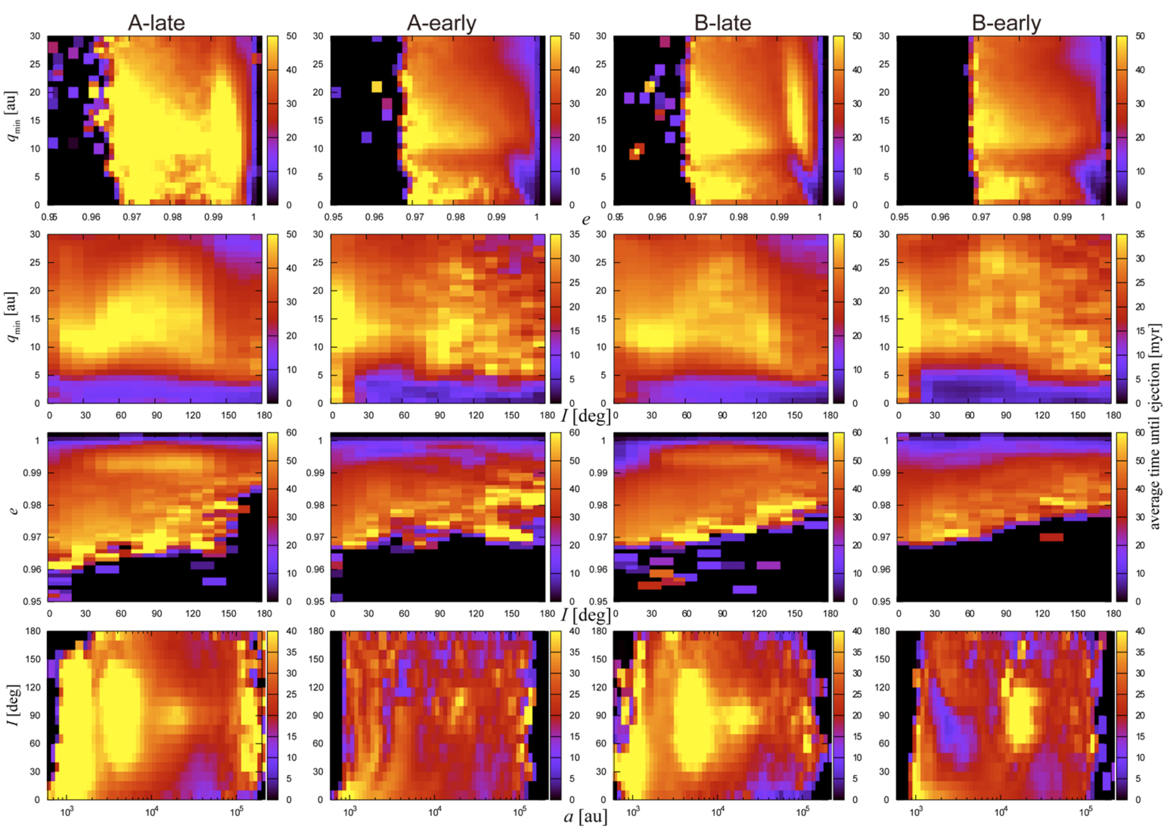
We made a series of color diagrams showing the frequency distribion in phase space of $q_{\min}$ and the initial orbital elements. Here is the version with the linear-scale colorbars:



Here is another version with the logarithmic-scale colorbars:



Here we show the dependence of the average time until ejection (= the average resident time of OCNCs in the planetary region) that we discussed on the left column on the some initial orbital elements and $q_{\rm min}$.



We may want to say the following things from the above panels:

1. The top row: Dependence of the average resident time T_e on the initial eccentricity and q_{min} . We do not see particularly significant features.
2. The second top row: Dependence of the average T_e on the initial inclination and q_{min}. In the region of small q_{min}, it may seem that the retrograde OCNCs (I > 90 deg) have slightly longer averaged T_e than the prograde ones (I < 90 deg). This means that the retrograde objects possess stronger stability than the prograde ones in this region, but the difference is not large.
3. The third row: Dependence of the average T_e on the initial inclination and the initial eccentricity. We find that the retrograde OCNCs have larger ececntricity than the prograde ones. This means that the retrograde objects tend to go inside the planetary region more deeply than the prograde objects do. Also, in the region of larger eccentricity, it seems that the retrograde objects show longer T_e. But again the trend is subtle, and the difference between the retrograde objects and the prograde objects in these panels is not much.
4. The bottom row: Dependence of the average T_e on the initial semmajor axis and the initial inclination. We do not see particularly significant features.

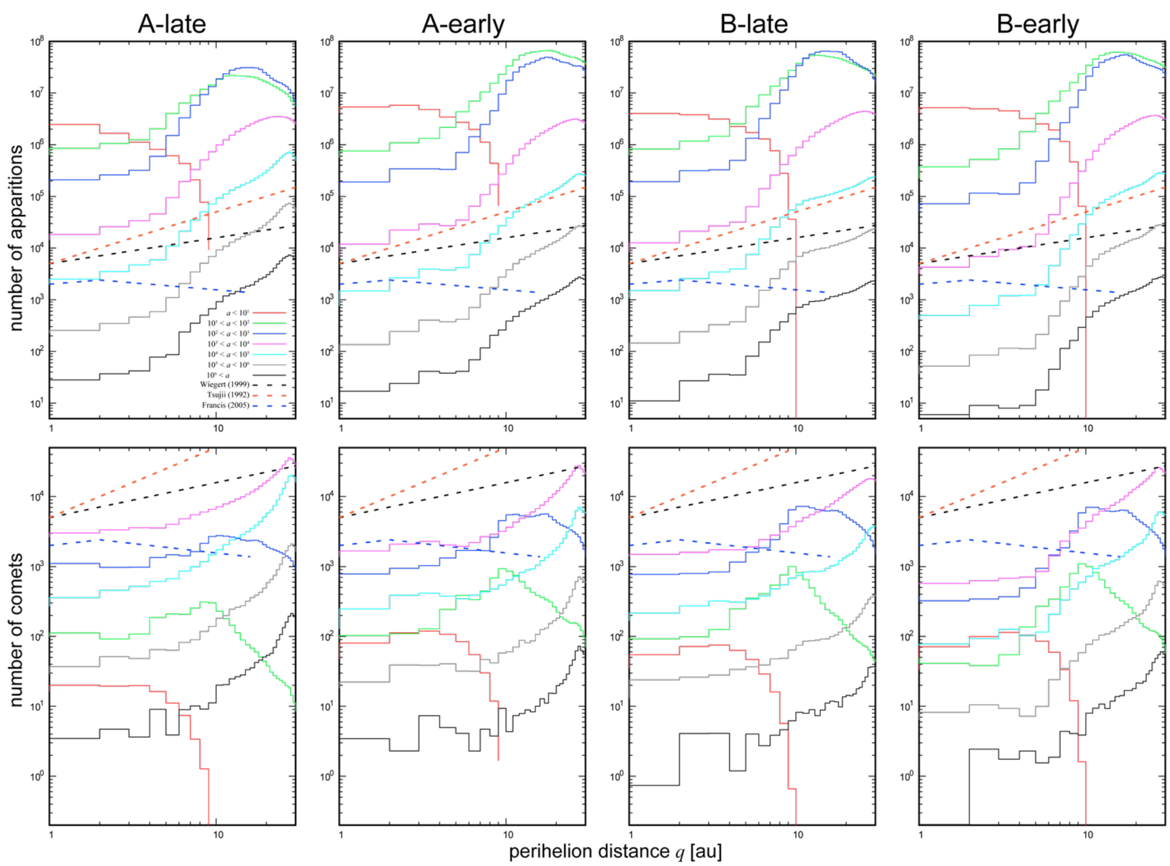
As the summary of this section, let us itimeze what we observe from the above panels:

- In the result obtained in the period **A-early, B-late, B-early**, there is a clear dependence of q_{min} on OCNC's initial orbital inclination. The Saturn-Jupiter barrier seems to work effectively when the initial inclination of OCNCs is small. This is typically seen in the periods **A-early** and **B-early** when the comet cloud is still nearly flat. In the period **B-late** when a very strong comet show happened in the ecliptic direction, we can also see this trend.
- It is also clear that the OCNCs with retrograde orbital motion (I > 90 deg) penetarete much more deeply into the planetary region than those have prograde ones (I < 90 deg). This is presumably consistent with previous studies of the three-body problem (e.g. Harrington, 1972 (https://ui.adsabs.harvard.edu/abs/1972CeMec...6..322H/abstract); Harrington 1975 (https://ui.adsabs.harvard.edu/abs/1975AJ.....80.1081H/abstract); Donnison & Mikulskis, 1994 (https://ui.adsabs.harvard.edu/abs/1994MNRAS.266...25D/abstract)) that showed the greater stability of the retrograde orbital motion than the prograde one. Even when their orbits are close to ecliptic (such as 150 < I < 180 deg), close encounters of the retrograde OCNCs with major planets generally continue for much shorter time than those of the prograde OCNCs due to their larger relative velocity. This effect reduces the influence of the planetary encounter on the dynamical evolution of retrograde OCNCs, and compromises the barriering effect of the major planets.
- We find another trend: the smaller the initial eccentricity of OCNCs is, the more effectively the barrier works. This seems common to all the periods. This is also probably due to the large relative velocity between the OCNCs and the major planets.
- It seems that the smaller the initial semimajor axis of OCNCs is, the more effectively the barrier works. This is probably because, as we mentioned earlier, the OCNCs with smaller initial semimajor axis have smaller eccentricity due to our definition of OCNC.
- In the period **A-late**, it seems that q_{min} does not depend on OCNC's initial orbital inclination much. We guess this is because most of the incoming OCNCs in this period have large initial eccentricity, and their interaction with the major planets is not so strong.

STATISTICS OF APPARITIONS

An observational estimate of the nearly isotropic comets by Francis (2005) (https://ui.adsabs.harvard.edu/abs/2005ApJ...635.1348F) based on the survey result of LINEAR claims that the perihelion distance q distribution shows a decrease in $q > 2$ au for the comets having $a = 20{,}000$ au. Grav+ (2011) (https://ui.adsabs.harvard.edu/abs/2011PASP..123..423G/abstract) recompiled the result of Francis (2005). On the other hand, numericla studies such as Tsujii (1992) (https://ui.adsabs.harvard.edu/abs/1992CeMDA..54..271T/abstract) or Wiegert & Tremaine (1999) (https://ui.adsabs.harvard.edu/abs/1999Icar..137...84W/abstract) have indicated that the distribution of q of the comets in the similar category increases in $q > 2$ au. In what follows we show a series of histograms of OCNC's perihelion distance when they make each apparition. As we see in the panels, our numerical result is consistent with the past numerical studies that implies the increase of OCNC's q distribution in $q > 2$ au when the semimajor axis is larger than 1,000 au or larger.

In the panels on the top row in what follows, we treat an apparition of a comet as one record. If a comet makes 1,000 apparitions over its resident time (T_e) in our model, the total number of the record in the top three panels would be 1,000. On the other hand in the panels on the bottom row, we normalize the number of apparitions of each comet as unity. This means if a comet makes n = 1,000 apparitions over its lifetime with different semimajor axis (such as 100 apparitions with $a < 100$ au and 900 apparitions with $a > 100$ au), we normalize the number of apparitions by n: i.e., 0.1 with $a < 100$ au and 0.9 with $a > 100$ au. Thus the total number of vertical values in the bottom row panels is equivalent to the total number of OCNCs treated in each period.



We will further investigate our own numerical results, and compare them with what Silsbee & Tremaine (2016) (https://ui.adsabs.harvard.edu/abs/2016AJ....152..103S/abstract) and Vokrouhlicky et al. (2019) (https://ui.adsabs.harvard.edu/abs/2019AJ....157..181V/abstract) recently obtained in their simulations. The analysis result will be presented in our forthcoming publications.

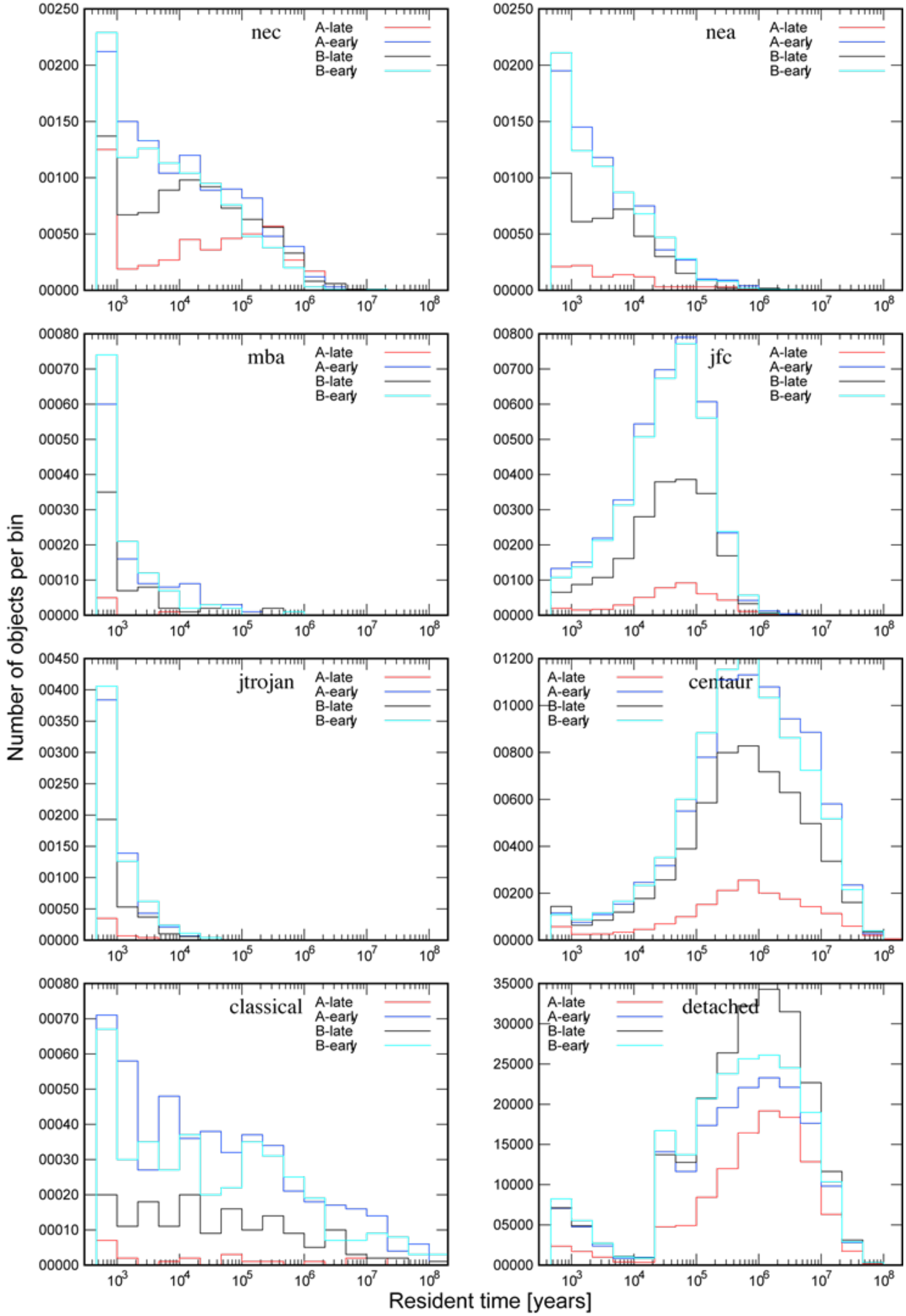
TRANSITION INTO OTHER SSSB GROUPS

Almost all the OCNCs that this study deals with get eventually scattered by major planets and ejected away from the solar system (more than 99%. See the previous box for our definition of ejection). Meanwhile, OCNCs experience many different dynamical states during their resident time in the planetary region, turning into different small body populations temporarily. Typical ones are the detached TNOs, Centaurs, and Jupiter family comets (JFCs). Some OCNCs even temporarily become near-Earth objects (NEOs).

Our definitions of each small body population are as follows. Some of them may be different from the conventional definitions in the past literature:

- NEC (near-Earth comets): q < 1.3 au && P < 200 years
- NEA ("extended" near-Earth asteroids): q < 1.3 au && a < 3.5 au
- MBA (main belt asteroids): 2.1 < a < 3.5 au && e < 0.35
- JFC (Jupiter family comets): 2 < T_J < 3.0 && a <= 10 au
- Jupiter Trojans: 5.05 < a < 5.35 au && e < 0.2 && I < 40 deg
- Centaurs: (T_J >= 3.05 || q >= 7.35 au) && a_{Jupiter} < a < a_{Neptune}
- Classical TNOs: (T_J >= 3.05 || q >= 7.35 au) && 39.4 < a < 47.8 au && e < 0.240 && I < 35 deg
- Detached TNOs: (T_J >= 3.05 || q >= 7.35 au) && a < 2000 au && e > 0.24 && q > 35 au

Let us show a series of histograms for the resident time distribution of the OCNCs in the orbital space of the small body populations described above.



As expected, not a lot of OCNCs experience the state of MBAs or Jupiter Trojans which have moderate to small eccentricity. But many OCNCs experience the state of Jupiter family comets (JFCs). A small but non-negligible fraction of OCNCs experience the state of near-Earth objects. The number of OCNCs that experience the state of Centaurs, the classical TNOs, and the detached TNOs is large, and we can conjecture the transition of this kind has been common in the solar system history.

Added on October 29, 2020

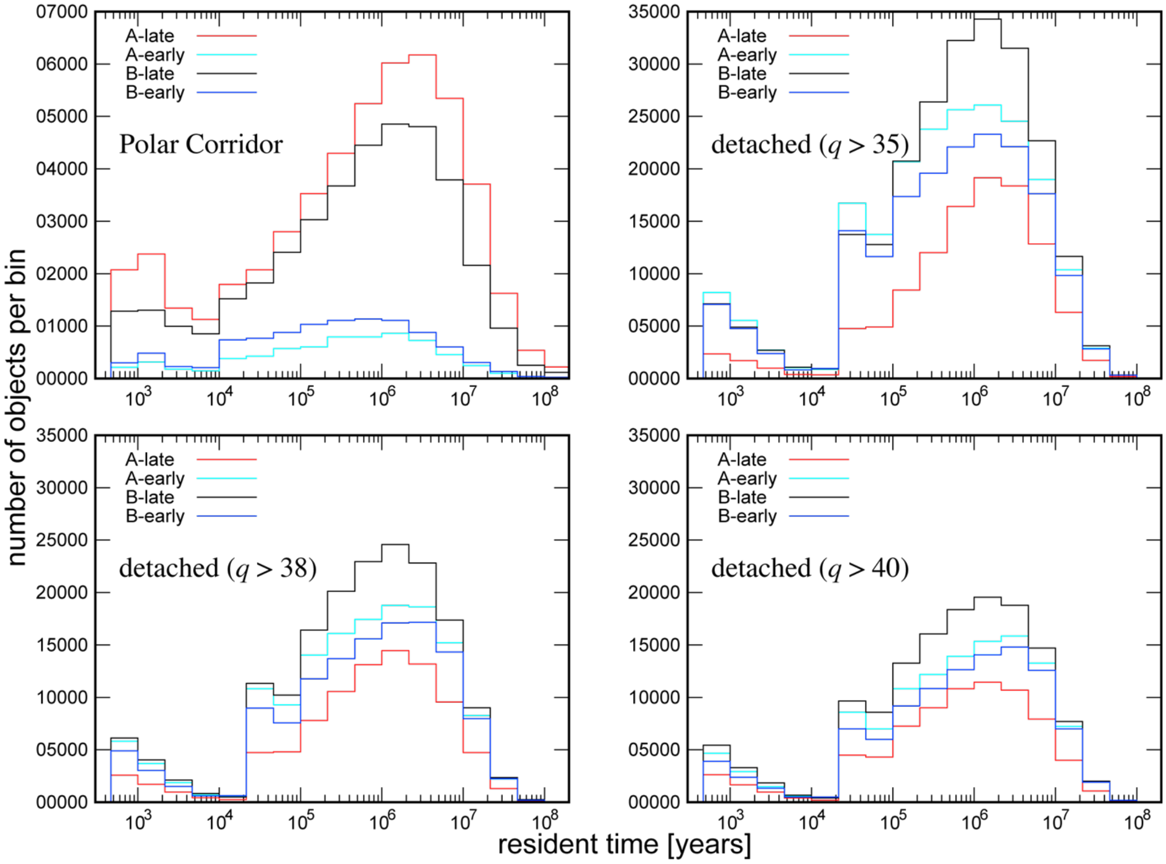
On the DPS Slack Channel (`#304` "beyond the classical kuiper belt") we received the following set of questions from Dr. Brett Gladman:

1. Does your study show supply into the so-called 'Polar Corridor' (Namouni and Moraias 2018, MNRAS, 477, 117 (https://ui.adsabs.harvard.edu/abs/2018MNRAS.477L.117N/abstract)) of $30 < a < 1000$ au, i = 60-120 deg, from the Oort cloud?
2. I think using a $q > 35$ au 'box' for the Detached population includes in great majority actively scattering objects; by what factor do your significant detached numbers drop if you restrict that to $q > 38$ au and also $q > 40$ au?"

Our answers to the above questions are as follows, respectively.

1. Yes, our numerical result shows non-negligible supply of the objects staying in the "Polar Corridor". Their integrated resident probability seems larger than that of Centaurs (in particular when the comet cloud is already isotropic).
2. By restricting the box to $q > 38$ au, the number seems to drop by a factor or ~2/3 of the $q > 35$ au case. By setting $q > 40$ au, the factor seems ~1/2 of the $q > 35$ au case.

Here we have attached a supplemetary figure with four panels which shows the resident time of OCNCs that experienced the state of PCOs (Polar Corridor Objects, $30 < a < 1000$ au && $60 < I < 120$ deg) and the detached TNOs with different perihelion distance criteria ($q > 35$ au, $q > 38$ au, $q > 38$ au). The periods when the comet cloud is nearly isotropic (**A-late** and **B-late**) yield more PCOs than other periods, which seems reasonable considering their definition of inclination ($60 < I < 120$ deg).



[Added on November 1, 2020]

On the DPS Slack Channel (`#304` "beyond the classical kuiper belt") we received the following set of questions from Dr. Adam Battle and Dr. Neal Turner. We will copy the questions and our replies as follows with some edit on the original Slack chats.

(Adam Battle asked) You mention the dynamical lifetime of Oort Cloud New Comets is 10^7 yrs once they are in the planetary region. How does this compare to the expected frequency of OCNC entering the planetary region?

(Our reply) I do not exactly know how I can answer to your question as to how we should compare the resident timescale of the

OCNCs in the planetary region (10^7 years) to the expected frequency of OCNCs entering the planetary region. But let me list some numbers that might partly answer to them: Very roughly speaking, in our comet cloud model, ~40% of the objects that compose the initial comet cloud are directly scattered out of the solar system by stellar encounters before coming into the planetary region. ~55% of the objects remain in the comet cloud for more than 5 billion years. The rest, ~5% (or less) of the objects, can fall into the planetary region and become new comets (we are re-working on this number again to get it more precise). However, please note that these probabilities can vary much depending on the definition of the new comets (in our case q < 30 au at r = 800 au) and the initial distribution of the cometary objects.

(Adam Battle asked) Yes, that was great! The ~5% of objects actually falling into the planetary region is the number I couldn't wrap my head around.

(Our reply) We will investigate on the probability in our forthcoming publication (which we will submit within a couple of months) in more detail. It can never be larger than order O(1%), and could be much smaller than ~5%. Please stay tuned. However, as I wrote above, please note that this probability can vary much depending on the definition of the OCNCs (new comets) and the initial distribution of the cometary objects at time = 0. We will also work on the dependence of the probability on these initial conditions.

(Neal Turner asked) What does this suggest about the number of comets in the Oort Cloud today, when considering the rate at which new comets are observed?

(Neal Turner asked) Is it feasible to estimate the fraction of current Jupiter-Family comets that originated from the Oort Cloud?

(Our reply) (As for your first question) Assuming that this probability (here after we call it p) is accurately estimated, and assuming that the observational detection of the Oort Cloud new comets up to a certain size (or magnitude) is completed, principally we can estimate the number of objects up to this size in the Oort Cloud. But things are not so simple. First, the current observational detection of these objects is not complete at all, and the number of the "observable" Oort Cloud comets is limited. Second, our current model just deals with the simple dynamics of point masses, not considering any physical effects such as comet's fading or disintegration near the Sun, or their size-frequency distribution. These factors can become big complications when we try to compare our model results and the actual observational results.
Anyway, we will work on these issues as well as on the more accurate estimate/dependence of the probability p on the initial comet cloud conditions, and summarize them in our forthcoming publication.
(As for your second question about the Jupiter-family comets), yes, it is feasible I think. Of course we would need to make the observational detection of JFCs as complete as possible.

ABSTRACT

We describe the result of our numerical simulations that trace the dynamical evolution of the Oort Cloud new comets that fall down to the planetary region. These comets approach the planetary region (such as inside Neptune's orbit) through the galactic tide and encounter with nearby stars, stay in the planetary region for a while, and eventually get scattered away. We combine two dynamical models (analytic and numerical) to follow the dynamical paths of the comets that leave the Oort Cloud during two different periods: One is the 1 billion years that include the present time when the outer comet cloud is likely nearly isotropic, and the other is the 1 billion years in the early solar system presumably with the comet cloud confined in a flat disk. Here are two major conclusions derived from our numerical result: (1) Typical dynamical lifetime of the comets is O(10^7) years. After traversing the planetary region for this timespan, most of the comets get scattered and ejected out of the system. (2) When orbital inclination of the comets is small, the so-called planet barrier works effectively, preventing the comets from penetrating into the terrestrial planetary region. Transition probabilities of the comets into other minor body populations, such as Centaurs or Jupiter-family comets, are also discussed.