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Comets in star clusters: I. Dynamics of free-floating comets

Qi Shu[1,2⋆], M.B.N. Kouwenhoven[4], Rainer Spurzem[1,3,5]
[1] *Kavli Institute for Astronomy and Astrophysics, Peking University, Yiheyuan Lu 5, Haidian Qu, 100871, Beijing, China*
[2] *Department of Astronomy, School of Physics, Peking University, Yiheyuan Lu 5, Haidian Qu, 100871, Beijing, China*
[3] *National Astronomical Observatories and Key Laboratory of Computational Astrophysics, Chinese Academy of Sciences, 20A Datun Rd., Chaoyang District, 100012, Beijing, China*
[4] *Department of Mathematical Sciences, Xi'an Jiaotong-Liverpool University, 111 Ren'ai Road, Suzhou Dushu Lake Science and Education Innovation District, Suzhou Industrial Park, Suzhou 215123, P.R. China*
[5] *Astronomisches Rechen-Institut, Zentrum für Astronomie, University of Heidelberg, Mönchhofstrasse 12-14, 69120, Heidelberg, Germany*

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ABSTRACT
The Sun's Oort Cloud contains trillions of comets in weakly bound, highly eccentric orbits. Most stars are formed in star clusters, where comets are easily removed from their host stars. We carry out numerical simulations to investigate the dynamical evolution of comet populations in star clusters.

Key words: minor planets, asteroids: general – planetary systems – planet-disc interactions – methods: numerical – planets and satellites: dynamical evolution and stability – protoplanetary discs

1 INTRODUCTION

The outer Oort Cloud in our Solar system contains roughly 5×10^{11} comets with absolute magnitudes $H < 17$ (Francis 2005). These comets are thought to have originated during the planet formation process, when many planetesimals collided with the newly-formed planets and the Sun, but many others got ejected to the outer fringes of the Solar system. Some obtained a velocity beyond the local escape velocity and became free-floating comets in the Galactic field, while others obtained highly-eccentric orbits in the Oort cloud. Given the ubiquity of exoplanets in the Galactic field, it is not unreasonable that a similar process has also occurred during the formation of other stars, and that our Galaxy is filled with Oort clouds and free-floating comets. In fact, several authors claimed to have found evidence for so-called exocomets in system such as β Pictoris (e.g., Welsh & Montgomery 2016, and references therein) and KIC 8462852 (e.g., Bodman & Quillen 2016; **?**, and references therein)

The vast majority of young stars are found in or near star forming regions that contain hundreds to millions of stars. These star forming regions either disperse within several tens of millions of years, while others remain bound and become the open clusters and globular clusters that we know today (e.g., de Grijs & Parmentier 2007). Isotope studies of meteorites even suggest that our own Sun was once part of a star cluster that has long dispersed. Given that most stars are formed in crowded stellar environment, it is worthwhile to investigate what happens to the comet populations belonging to stars in these environments.

During the planet formation process, a large number of comets is ejected from their host star systems after scattering events with (proto-)planets. In a star cluster environment, close encounters between comet-hosting stars and other cluster members can also result in the ejection of comets. These two processes are responsible for the injection of large numbers of comets into the star cluster (e.g., Brasser & Schwamb 2015). These comets remain part of the star clusters until they escape from the cluster through ejection or evaporation. In some cases, these comets may be captured by other stars in or near the cluster. The balance between the injection and escape of comets into/from the cluster determines the total number of free-floating comets at a certain time in a star cluster.

All presently-known comets come almost certainly from the outskirts of our solar system (Dones et al. 2015). The most likely interstellar comet (i.e., a comet originating from outside our solar system is C/2007 W1 (Boattini), which has a derived velocity-at-infinity of 0.2 $\mathrm{km\,s^{-1}}$ (Dybczyński & Królikowska 2015). However, given that the velocity dispersion in the Galactic field is two orders of magnitude larger than this value, the reconstructed orbit of C/2007 W1 is more likely the result of gravitational perturbations by other bodies. Moreover, due to the large velocity dispersion in the Galactic field, our Solar system is unlikely to capture free-floating comets from the field. Currently, Comet

⋆ E-mail:shuqi@pku.edu.cn

96P/Machholz is the best candidate for comets with interstellar origin, (Schleicher 2008) because of its high eccentricity and inclination as well as different composition than other comets.

The situation is different in star cluster. In star clusters, many comets are expected to be liberated from their host star. The origin of free-floating comets is two-fold: (1) comets that are ejected from their host star systems, for example as a result of a dynamical interaction with planet, and (2) comets that are removed from their host star following a close encounter with another star cluster member. In the clusters, all stars and most free-floating comets ejected from their host stars have similar velocities. As a result, free-floating comets can remain bound to the star cluster for many dynamical times, and the capture probabilities are non-negligible.

Star cluster members occasionally pair up and form new binary systems. Such newly-formed systems are often transient (e.g., Moeckel & Clarke 2011), but several several may survive for much longer times, in particular when they remain in the outskirts of the star cluster or when they have escaped (Kouwenhoven et al. 2010). Free-floating planets are also captured (Perets & Kouwenhoven 2012), which is particular interest to us, as our free-floating comets can be considered as test particles. Unlike multi-planet systems, multi-comet systems do not suffer from strong scattering effects. Re-captured multi-comet systems can thus survive for long periods of time in star clusters.

Spurzem et al. (2009) investigated the instabilities of planetary systems in star clusters, and the ejection process of planets from their host system. Wang et al. (2015) studied the survival rate of these ejected free-floating planets (FFPs). In this paper, We will consider the free-floating comets born in the cluster field and study their dynamical evolution and captured possibility.

This article is organised as follows. In §2 we describe our numerical method and initial conditions. We discuss the evolution of the star clusters and the free-floating comet populations in §3. Finally, we summarise our results and discuss the implications of our findings in §4.

2 METHODOLOGY AND INITIAL CONDITIONS

2.1 Numerical method

Simulations are run using a new version of `NBODY6++GPU` (Wang et al. 2015) which is adjusted to suit the purpose of our simulations. Stellar evolution and binary evolution are implemented following the prescriptions of Cambridge stellar evolution package and the improvements (Eggleton et al. 1989; Hurley et al. 2000, 2005; Belczynski et al. 2007).

We have adjusted the `NBODY6++GPU` package to be able to integrate large numbers of comets. The mass of comets is ten times orders of magnitude smaller than that of stars, and the comets can therefore be safely treated as test particles. Star-comet binaries are excluded from KS scheme. When calculated the gravitational interaction from other particles to a certain star, comets are ignored. As comets can be safely treated as massless particles, the choice for total number of comets, $N_{\rm c}$ will not affect our results, other than statistically. The results can be easily scaled up to realistic values of $N_{\rm c}$.

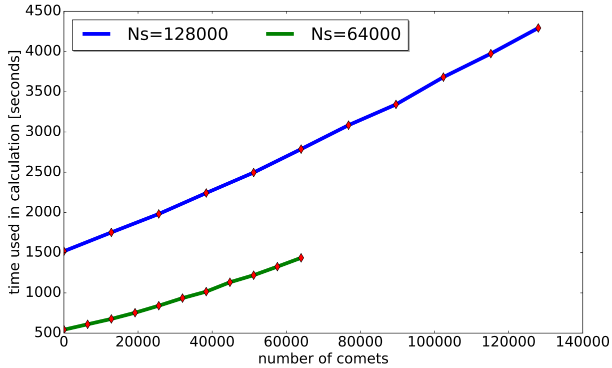

Figure 1. Time used in the 10 N-body unit test simulations with same number of single star 64k/128k, but different number of free-floating comets from 0 to 64k/128k.

Binary systems, which can be either star-star or star-comet systems. We do not consider comet-comet binaries, as these do not occur when considering massless particles. For each pair of bodies in the system we mutual binding energy. If this mutual binding energy is negative (i.e., we have identified a candidate binary), we proceed as follows: (1) if both bodies have mass, then they only form a bound binary if they are each other's mutual nearest neighbours with mass;, and (2) if only one body has mass, then the two bodies only form a binary if the body with mass is the nearest body with mass of the massless particle. We then obtain the orbital elements of each binary. We consider only binaries with semi-major axes less than one parsec, which corresponds to the stability limit in the Galactic field.

Comparing with the code used in (Wang et al. 2015), the new code has better performance when more massless particles is added. Because we disable the interaction between massless particle, the time consuming is roughly $\alpha N_{star}^2 + \beta N_{comet} N_{star}$, if we fix N_{star}, time consuming increased linearly with N_{comet}. The real simulation time used is shown as Figure 1.

Our simulations are carried out on a workstation with an Intel CPU (i7-5960X CPU @ 3.00GHz) and one/two NVIDA GPU cards (GeForce GTX 980 Ti).

2.2 Initial conditions

We evolve star cluster models that correspond to large open clusters or small globular clusters. Our initial conditions are summarised in Table 1. The positions and velocities of all stars are drawn from the Plummer (1911) model in virial equilibrium with a virial radius of $r_{\rm vir} = 5 \sim 20$ pc. Stellar masses are drawn from the Kroupa (2001) initial mass function (IMF) in the range $0.08 \sim 100 M_{\odot}$. We do not include primordial binaries, nor do we include primordial mass segregation. One of the $v^2 \sim r$ plots can be seen in Figure 2. The tidal force is currently disabled.

The population of $N_{\rm c}$ free-floating planets is constructed independently of that of the stars. Their positions are drawn from the Plummer (1911) model with a virial radius identical to that of the stellar mass distribution. Their velocity distribution is also constructed from the Plummer

Table 1. Initial conditions for our default model.

Quantity	Value
Number of stars	12800
Stellar IMF	Kroupa(2001), 0.08-100 solar masses
Virial radius	$r_{\rm vir} = 20$ pc
Dynamical model	Plummer (1911)
Stellar evolution	Enable mass loss
Tidal field	no tidal force
Comet mass	Test particles
Comet-to-star-ratio	$\mathcal{R} = N_{\rm c}/N = 1$
Comet spatial distribution	Statistically identical to stars
Comet velocity distributions	$Q = 0.5$ (in virial equilibrium with stars)

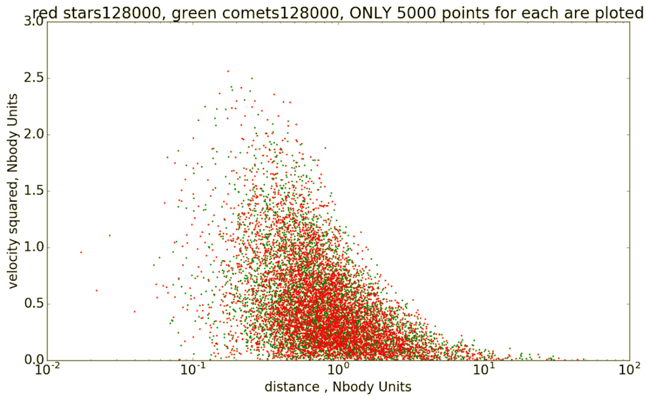

Figure 2. The velocity and distance distribution of particle in the simulation, $N_s = N_c = 128$k, Q = 0.5.

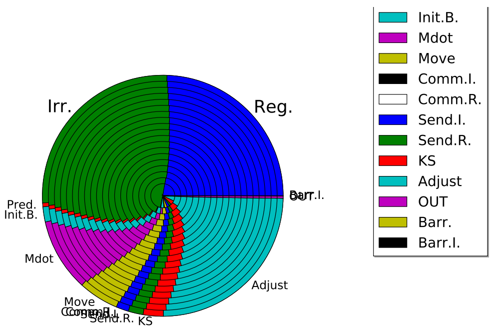

Figure 3. Calculation time costed in different processes.

(1911) model with $Q = 0.5$. The model is integrated for 70000 N-body time units.

3 NUMERICAL RESULTS

We have carried out some long simulations as shown in Table 2.

A reasonable calculation cost distribution of simulation should be like Figure 3. This figure shows the distribution of calculation time cost in the simulation A5. The time for irregular and regular force calculation always dominate at the beginning, while the time for adjust process keep growing as simulation goes.

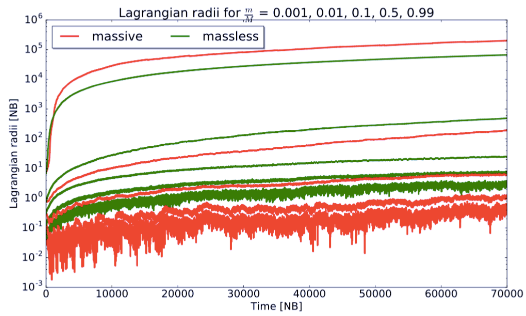

Figure 4. Lagrangian radii for all particles, considering the tiny small mass of massless particles, it is also Lagrangian radii for all stars.

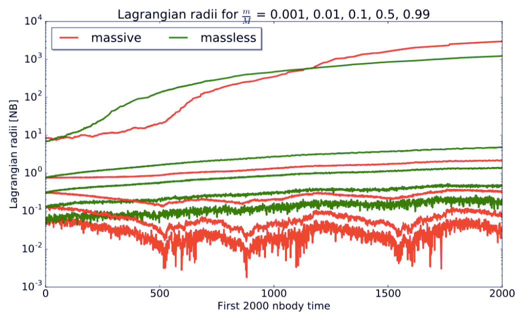

Figure 5. Only show the first 2000 N-body time.

3.1 Star cluster evolution

We calculate the time-dependent Lagrangian radii for both the stellar population and for the cometary population. At the begging of the simulation, the massive particles go through a gravitational resonance around the cluster centre while the massless particles do not, see figure 5. Only the massive particles can have the three-body close encounter and then be ejected from the cluster centre, so at the late time, the same mass ratio Lagrangian radii lines for the massive particles are clearly higher than that of massless particles, shown as figure 4.

Figure 6 shows how the average mass of particles change

Table 2. The long simulation details. N_s number of stars, N_c number of comets, $B\%$ primordial star-star binaries fraction,$b\%$ primordial star-comet binaries fraction, NBt simulated N-body time, T_{cal} real time used for calculation in unit of seconds.

ID	N_s	N_c	$B\%$	$b\%$	NBt	T_{cal}
A5	12.8k	12.8k	0	0	70000	100350
E2	12.8k	12.8k	10	0	70000	180370

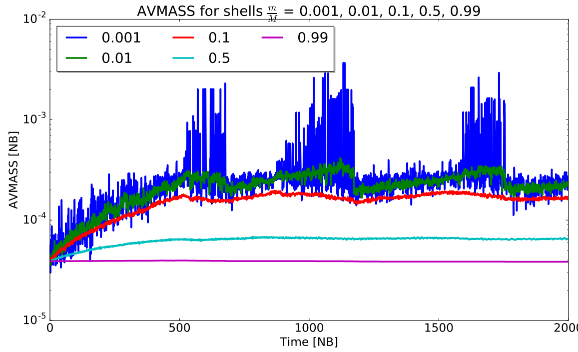

Figure 6. Average mass of all particles in different Lagrangian radii shells.

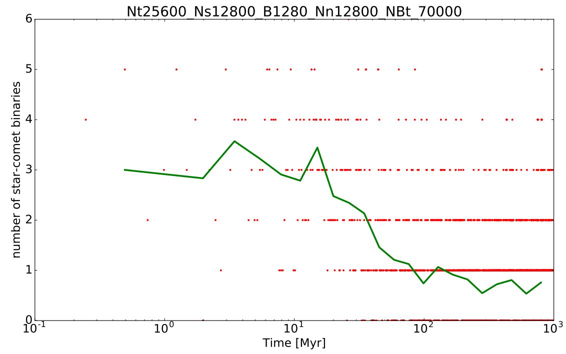

Figure 8. Number evolution of star-comet binaries. The simulation starts with 12.8k stars with 10% primordial binaries and 12.8k free-floating comets.

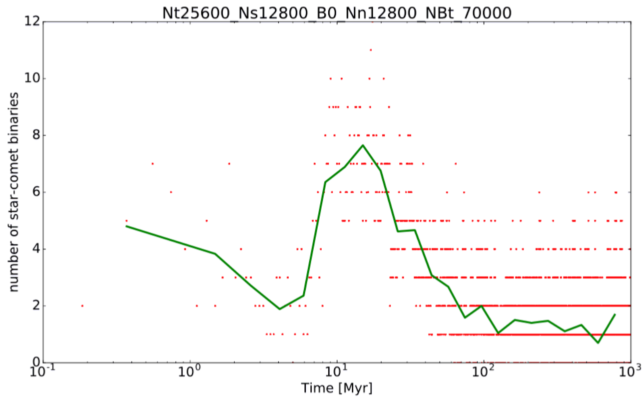

Figure 7. Number evolution of star-comet binaries. The simulation starts with 12.8k single stars and 12.8k free-floating comets.

with time in these Lagrangian radii shells. The average mass in the core region can be as high as ten times of that in the outside regoin.

3.2 Captured of comets

While most free-floating comets escaping, a small fraction is captured by free-floating stars. Only single digit free-floating comets are captured by a certain star at a solar age, see as figure 7. Increasing the primodial star binaries fraction will not give significant difference, see figure 8

We can estimate the probability of capturing comets for a single star by counting the number of single stars, single comets and star-comet binaries, $p = \frac{N_{s-c}}{N_{star}N_{comet}}$. From simulation we have $N_{star} = N_{comet}$ =12.8k and $< N_{s-c} >\sim 1$, so $p \sim 10^{-8}$.

Considering the total mass of Oort Cloud comets is about 5 Earth masses (Morbidelli 2005), we expect total mass of free-floating comets in the embedded cluster(where the Sun was originally born) is around 10^3 solar masses. The current micro-lensing observations are sensitive to object mass down to earth mass, the observation of cometary object in star cluster is still too difficult in the near future.

4 CONCLUSIONS

In this work we have considered the dynamical evolution of comets in star clusters. To simulate such system, we developed a new version of N-body code. We found the different dynamical evolution behavior of free-floating comets than that of stars in the cluster. We expect several thousands solar masses equivalent free-floating comets in the embedded star cluster. We still need more simulations and observations to give preciser results. In our next paper (Shu et al., in prep.) we will study the more realistic situation in which planets are initialised on circumstellar orbits.

We have also ignored the presence of planetary companions. Although modelling of multi-planet systems is difficult (Hao et al. 2013; Shara et al. 2016), it is possible in the AMUSE software environment (see Portegies Zwart et al. 2013; Pelupessy et al. 2013; Cai et al. 2016) or by sequentially integrating the stellar and planetary components (Cai et al. 2015). Moreover, it is a necessary step for obtaining a full understanding of comet populations in star clusters, in particular for understanding the transfer of material between planetary systems through comet-planet collisions.

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