On the fate of planetesimal discs in stellar clusters

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Abstract

We perform high-N, direct summation N-body simulations of the early phases of open cluster evolution. The stars in our clusters host populations of test particles arranged in Kuiper-belt style planetesimal discs. We evolve the clusters and debris discs simultaneously in one simulation, such that the exact cluster potential is known at each time-step, and no approximations are required to detemine the effect the cluster environment has on the planetesimals. We show that the early stages of evolution for Hyades-style clusters readily lead to the transfer of planetesimals between stars, free-floating planetesimals (such as A/2017 U1), and dynamically excited planetesimal discs. We also show that planetesimals captured from the stellar birth environment are not necessarily dynamically distinct from those native to a star. We discuss the implications of our results for both our own solar system and exoplanetary systems.

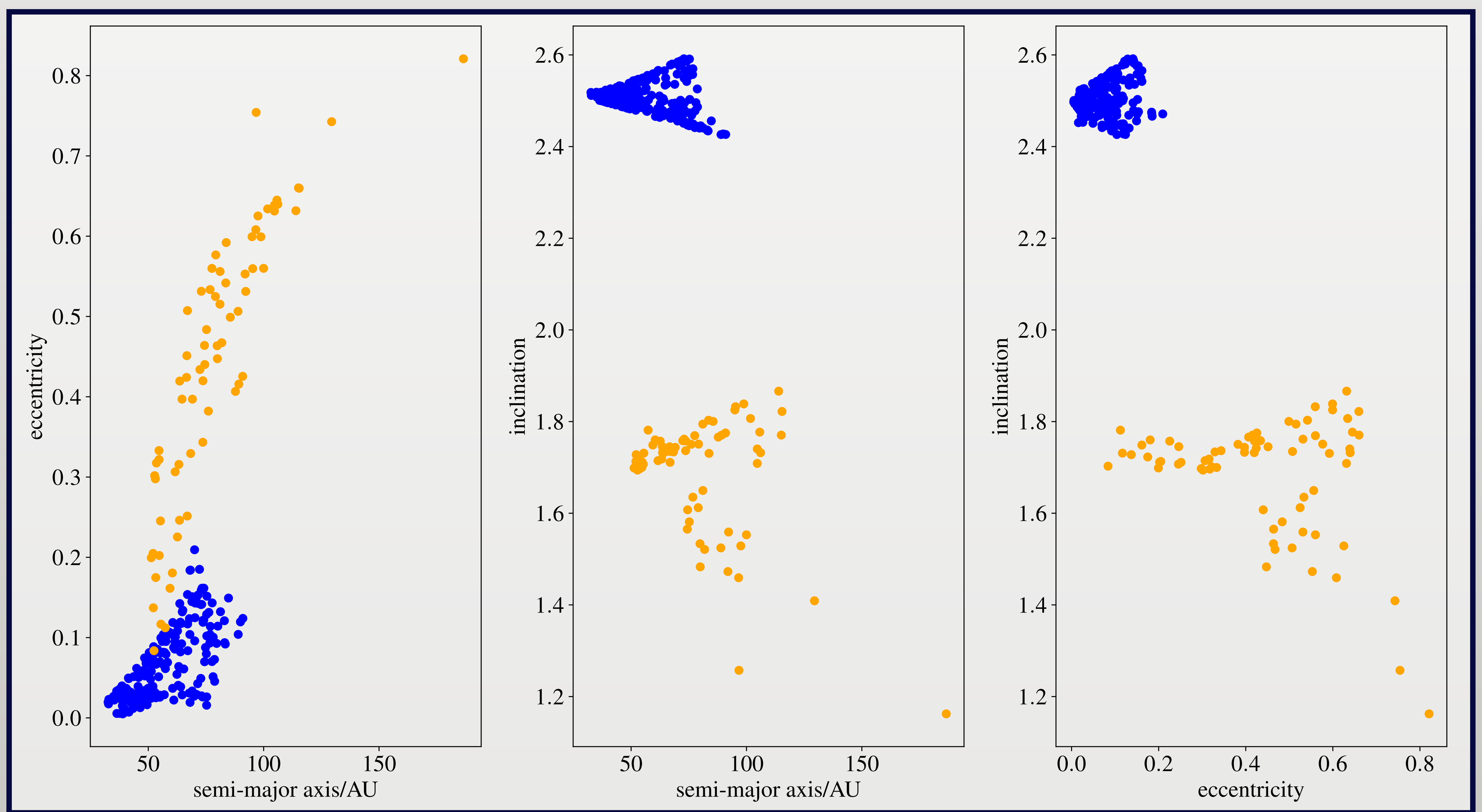

Figure 1 - Orbital elements of planetesimals surrounding a 0.66 M_{sun} star after 4.3Myr in an IC348-style cluster. Blue points show planetesimals native to the star, orange points show planetesimals captured from another star.

Motivation

The majority of stars are thought to form in open clusters, loose groups which gradually disperse over a few 100 Myr. During their early lifetimes, these stars host potentially planet-forming discs of gas and dust, with lifetimes of approximately a few Myr. Interactions with these discs keep any planets or planetesimals embedded within them dynamically cold, whilst the high density of stars in a young custer core can have the opposite effect. Several recent studies have either inferred the presence of (see e.g., Zuckerman 2013) or directly detected (see e.g., Meibom et al. 2013) planets and debris discs in open clusters. Additionally, increasingly revealing studies of our own Kuiper belt show that it contains several populations of objects with drastically different orbital properties. This leads us to the question: what happens to Kuiper belt-style planetesimal discs a few Myr into the life of an open cluster, when the gas surrounding the stars has dispersed? In the period of time before this, the effect of the cluster is mitigated by damping from the gas, but any stellar interactions after the gas discs disperse will cause undamped changes to planetesimal orbits, leaving a signature in the disc for potentially several billion years. These signatures could then be observed, possibly in our own solar system.

The problem is challenging numerically due to the orders of magnitude difference in the dynamical time-scales between the cluster and the planetesimal discs. Previous work has largely focussed on integrating the satellites separately to that of the cluster (see e.g., Cai et al. 2017), or treating the planetary systems in a sub-grid fashion. Levison et al. (2010) performed a full integration of both planetesimals and a cluster itself to investigate Oort cloud formation, but considered only relatively small clusters and long-period, eccentric planetesimals. We perform direct simulations of Kuiper-style planetesimal belts orbiting open cluster stars, evolving both populations in one simulation. The idea is to understand the impact the cluster environment has on these young discs once the gas has dispersed.

Method

The enormous range of dynamical time-scales and high particle counts required to study this problem mean that some specialisation in the N-body method is required. We use a fast GPU implementation of the 4th order symplectic integrator "4A" (see e.g., Chin et al. 2005), selected for its excellent conservation properties. The time-step required for accurate integration of the system can change very rapidly and unexpectedly as stars approach each other and scatter planetesimals onto highly eccentric orbits. We have therefore developed a time-stepping algorithm based on Hairer et al. (2005) to adapt the time-step in a smooth and stable fashion, whilst keeping the adaptation time-reversible. Ensuring time-revesibility guarantees no secular growth of energy error which is vital for long period integrations.

We run a suite of N-body simulations of open clusters based on the initial conditions for the Hyades given in Ernst et al. (2011) and the observations of IC348 presented by Luhman et al. (2016). These models have 2250 and 440 stars respectively. We draw stellar velocities and positions from a Plummer (1911) sphere, using a Kroupa (2001) IMF for the stellar masses. Each star is surrounded by 100 (Hyades) or 200 (IC348) test particles, on initially circular, co-planar orbits. We aim to study the evolution of orbital elements of the planetesmal discs, as well as transfer of planetesimals between stars and their ejections.

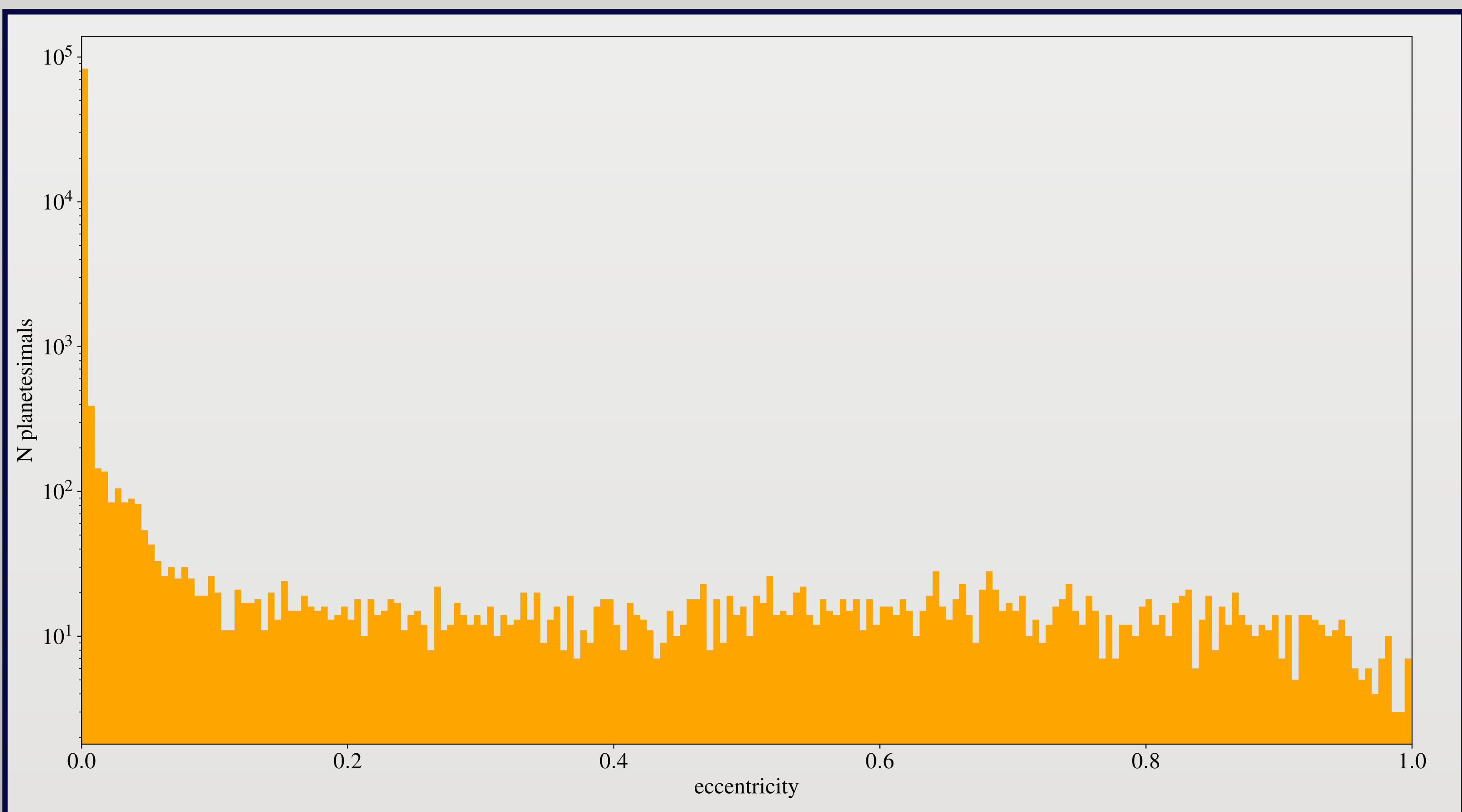

Figure 2 - Eccentricity distribution of all bound planetesimals within IC348 after 4.3Myr. The vast majority remain on almost-circular orbits, but a significant number are also pushed onto eccentric orbits by interactions with the cluster.

Results & Conclusion

Figures 1 and 2 show results taken from a simulation of IC348, with planetesimals given initial periods between 30 and 1000 years. Fig. 1 is an excellent example of planetesimals being captured from another star, forming a dynamically distinct population - though we note that captured planetesimals are not always dynamically distinct. The other star involved in this interaction lost 75% of its disc, with many planetesimals becoming free-floating and some ending up loosely bound to much more distant stars, suggested as a possible avenue for Oort cloud formation by Levison et al. (2010). The interaction also pumps the eccentricity of the original planetesimals in the system up as high as 0.2. Fig. 2 shows that while most planetesimals in the cluster remain on roughly circular orbits, cluster interactions can introduce a large variation in eccentrcities. Futher to this, we see a significant quantity of ejections cluster-wide. In one of our realisations of IC348, 0.9% of all planetesimals are ejected, which has implications for the origins of free-floating comets such as 'Oumuamua.

We find that interactions between stars in young stellar clusters can significantly impact even initially tight, dynamically-cold planetesimal discs. This can lead to significant mass transfer between stars, and generate large numbers of free-floating planetesimals .

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