The Evolution of the Outer Solar System During the Cluster Era

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Introduction

Stars typically form in clusters composed of ~ 100's stars, and such clusters can persist for up to 10^8 years or more. The Sun also likely formed in a cluster, and it is reasonable to ask whether perturbations from nearby cluster stars might have disturbed the outer Solar System.

The following describes Nbody simulations designed to assess whether passing cluster stars might disturb the orbits of the outer Solar System. In particular, Neptune's very circular orbit, as well as the existence of the Kuiper Belt, will be used to constrain the lifetime and density of the Sun's natal starcluster. This effort will also determine whether cluster perturbations might also explain some of the Belt's unusual orbital properties. Hopefully, these simulations will also provide new insight into the early history of the outer Solar System.

The Kuiper Belt

The Kuiper Belt is the swarm of comets that roam beyond Neptune's orbit. Figure 1 shows the orbits of the known KBOs, and these bodies preserve a record of past perturbations, mostly due to the giant planets. However, this Belt can also preserve a record of disturbances from stars that happen to pass sufficiently close (Ida *et al* 2000).

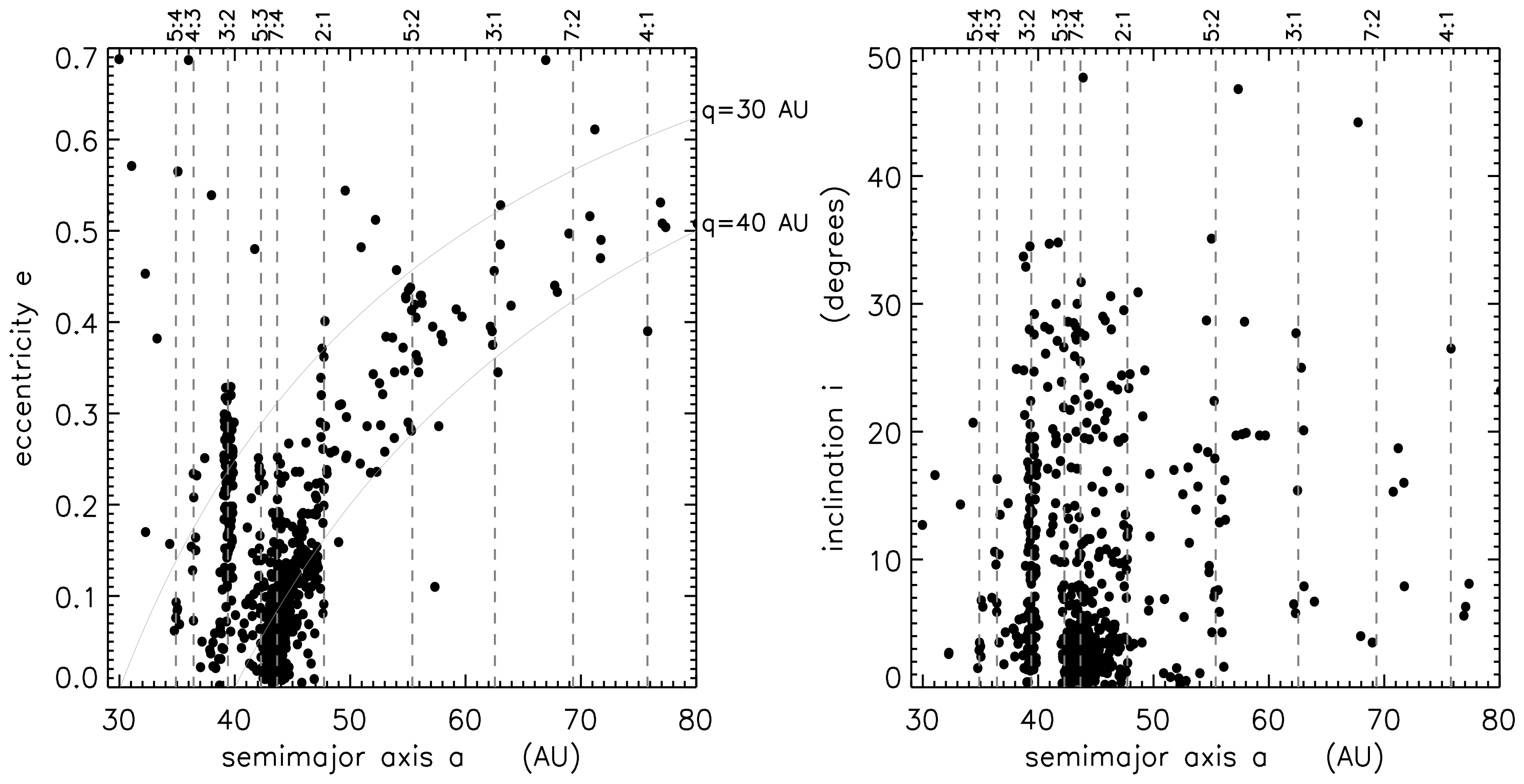

FIGURE 1: Left figure plots eccentricity e versus semimajor axis a for all KBOs observed for at least 2 oppositions. Dashed lines indicate mean motion resonances with Neptune, and grey curves indicate orbits having perihelia of $q = 30$ and $q = 40$ AU. Right figure plots the KBOs inclinations i versus a.

Figure 1 also reveals the Belt's distinct dynamical populations:

- **Main Belt (MB):** these low-eccentricity ($e \sim 0.1$) bodies live between Neptune's 3:2 and 2:1 resonances.
- **Resonant KBOs:** these objects inhabit mean-motion resonances with Neptune (3:2, 2:1, etc). Such bodies may have been parked at these resonances by a migrating Neptune (Malhotra 1995, Hahn & Malhotra 2005).
- **Scattered Disk Objects (SDOs):** these KBOs have perihelia $q \lesssim 40$ AU, and were likely tossed into these eccentric orbits by the giant planets (Duncan & Levison 1997).
- **Extended Scattered Disk Objects (ESDOs):** these distant objects have perihelia $q \gtrsim 40$ AU, and thus are decoupled from Neptune. Although rare, they are particularly interesting, since they hint at perturbations from other unseen objects, like for example other long-gone protoplanets (Gladman & Chan 2006).

However the following will show that ESDOs can also be produced by passing stars during the cluster era.

Simple Model of a Star Cluster

Our goal is to qualitatively assess the magnitude of the gravitational disturbances that cluster stars might exert on the recently-formed Solar System. Although a rigorous Nbody simulation of mutually interacting stars is planned, such simulations are very time consuming. However, quick results are readily obtained if we instead assume that the cluster stars are *non-interacting*, yet bound to the cluster by a simple spring force. This causes the stars to circulate on elliptical 2D orbits having random orientations that are also forced to precess over time. As Fig. 2 shows, this simple model of a star cluster causes each star to trace a 3D Lissajous figure over time.

Of course, a real cluster will shed mass over time as it ejects stars due to dynamical evaporation. To qualitatively mimic this effect in an admittedly crude way, the stars' masses are reduced over an exponential timescale τ_{evap}.

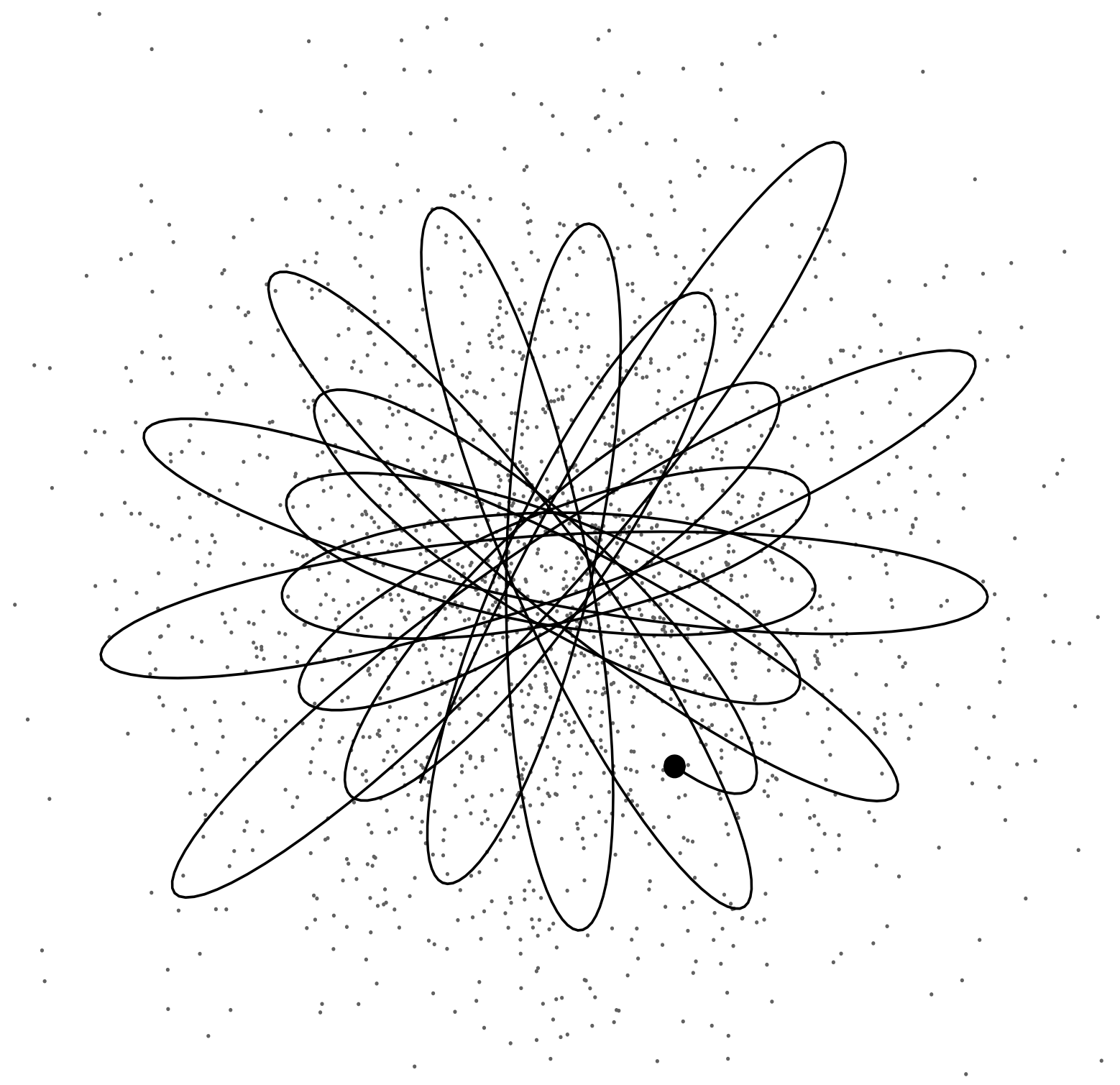

FIGURE 2: This snapshot shows stellar positions in a cluster composed of $N = 100$ stars, with the curve indicating one star's trajectory. Stars' velocities are assumed to be their virial velocity.

Simulating a Perturbed Solar System

The MERCURY Nbody integrator (Chambers 1999) is used to simulate the evolution of the four giant planets plus numerous test particles, with the code modified to account for the gravitational perturbations exerted by the cluster stars.

We are currently performing a grid of simulations, for clusters composed of $10 < N < 300$ stars inhabiting clusters of radii $0.1 < R < 3$ pc, which are comparable to observations of most young star-forming cluster (Clarke *et al* 2000). In these simulations, the cluster evaporation timescale is set to $\tau_{\text{evap}} = 10^8$ years.

Simulated outcomes are summarized in Fig. 3. A black X indicates that the outer Solar System was destroyed by the cluster stars, with the blue diamonds indicating that the outer Solar System was undisturbed. Red dots are the more interesting cases, with these simulations resulting in a disturbed outer Solar System that may, or may not, be consistent with observations of the Kuiper Belt.

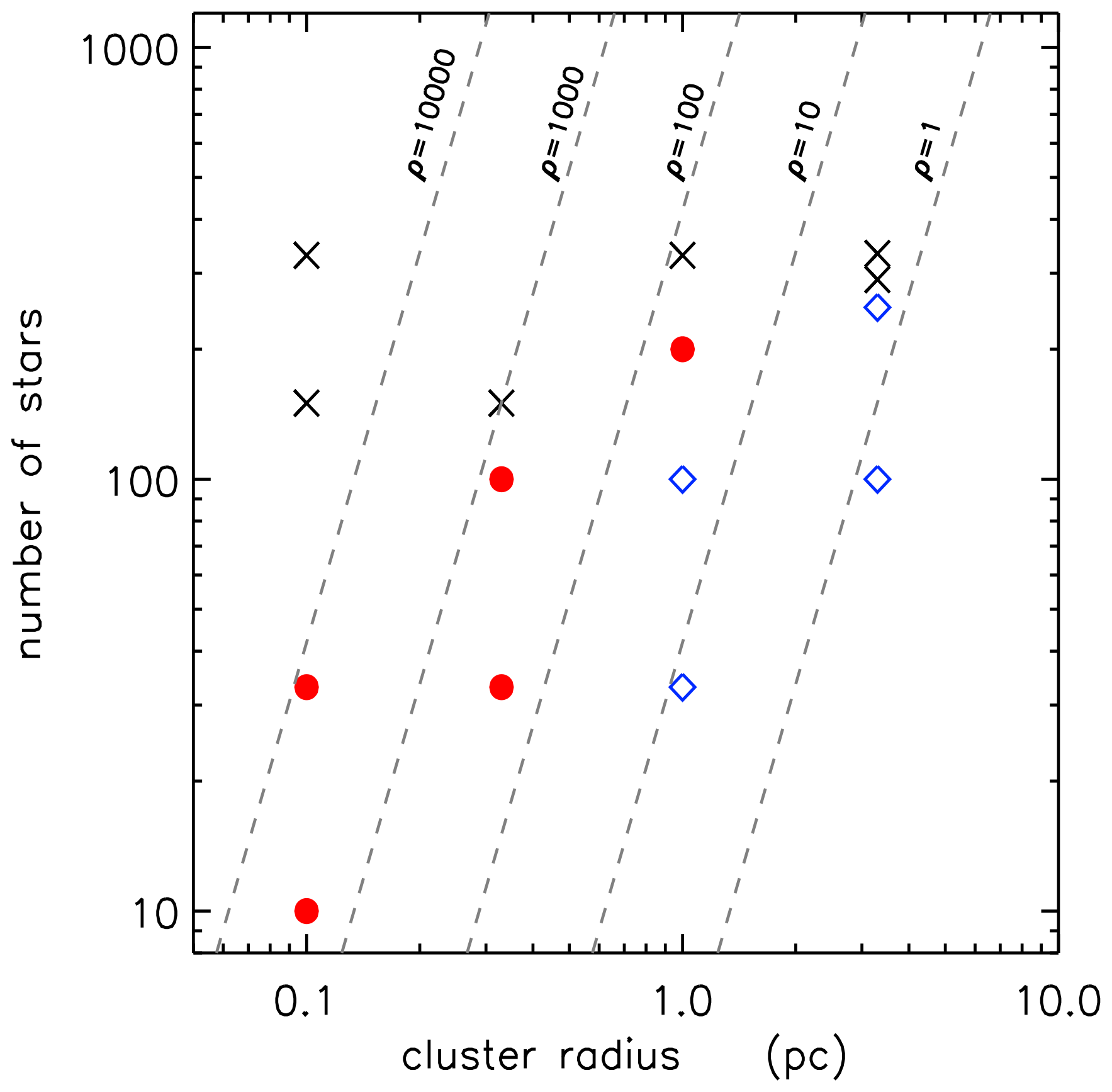

FIGURE 3: Symbols show the simulations performed to date. A black X indicates that the outer Solar System was destroyed by the cluster perturbations, while a blue diamond indicates that the outer Solar System was undisturbed. Red dots represent simulations where the outer Solar System was disturbed in ways that may, or may not, be consistent with the observed Kuiper Belt. Dashed lines are curves of constant cluster density, in units of stars/pc^3.

However it should be noted that the cluster evaporation time really varies as $\tau_{\text{evap}} \propto \sqrt{NR^3}/\ln N$ (Binney & Tremaine 1987), yet these simulations used a fixed $\tau_{\text{evap}} = 10^8$ years. So expect the above outcomes to change when we perform more realistic simulations of a star cluster.

Endstates

The following shows a few endstates for simulations of the four giant planets plus 200 massless particles initially distributed in circular, coplanar orbits over $15 < a < 100$ AU and evolved until the cluster has evaporated. Note that although the Main Belt appears truncated at $a \simeq 45$ AU (Trujillo & Brown 2001; see also Fig. 1), these simulations allow for a much larger initial Solar System, in order to determine whether passing stars might truncate the Belt's outer edge.

Figure 4 shows results for a particularly interesting simulation of a Solar System that is perturbed by $N = 10$ stars packed into a small, dense cluster of radius $R = 0.1$ pc. Although the particles' eccentricities are largely unaffected by the cluster, the small bodies' inclinations are strongly perturbed at $a \simeq 55$ and $a \simeq 85$ AU. The cause for this structure is not yet clear, but we wonder whether this might be due to passing stars introducing new secular resonances into the system.

The high inclinations seen in Fig. 4 also suggests the possibility that the Main Belt might *not* be truncated at $a \simeq 45$ AU, as is indicated by Fig. 1. Note that most KBOs are discovered by astronomers who survey near the ecliptic. But if passing stars instead excited distant KBOs to higher inclinations, like that seen in Fig. 4, then such objects become much less likely to be detected, which could then result in an *apparent* outer edge in the Main Belt that might not be real.

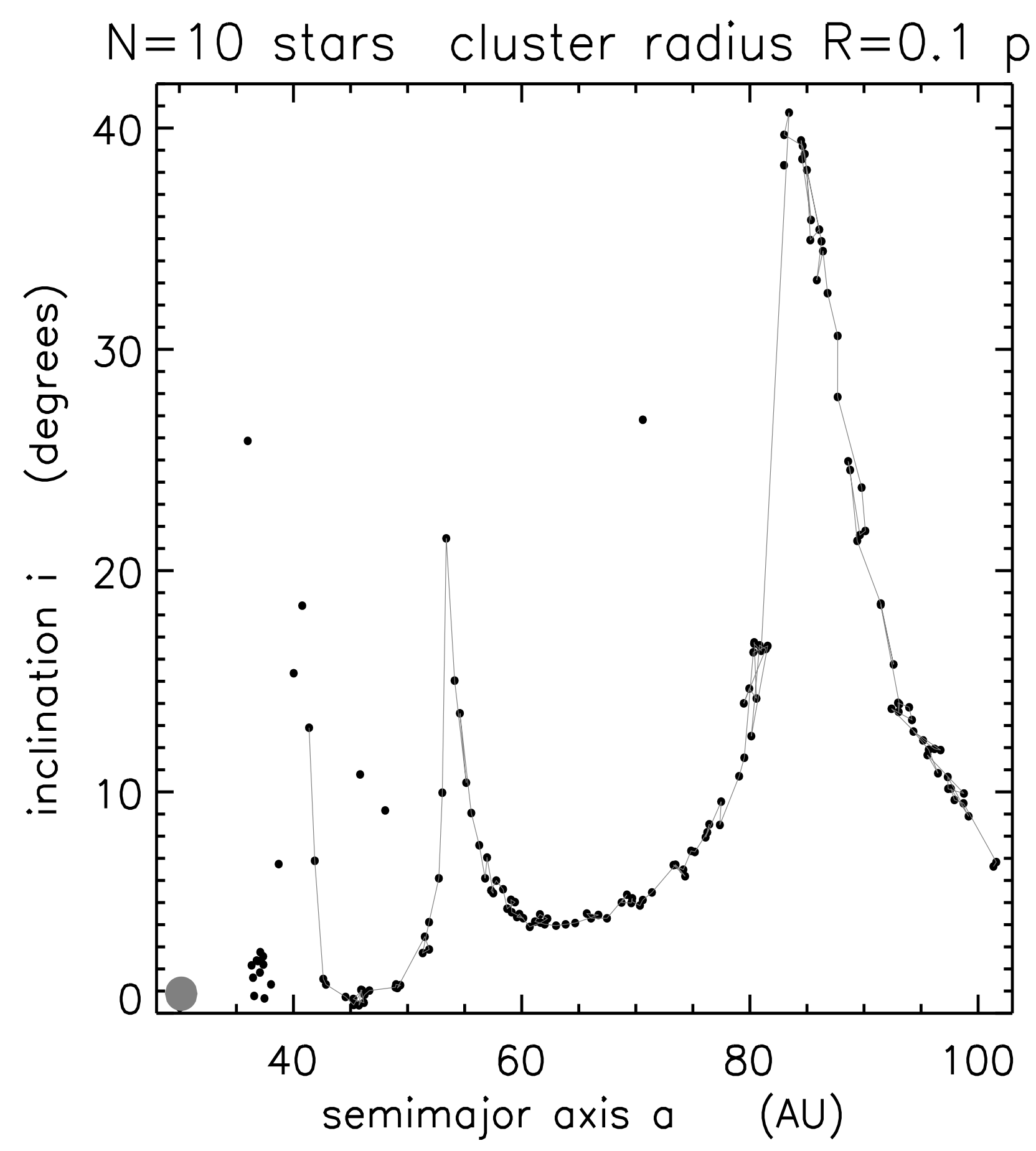

FIGURE 4: This figure plots the inclinations i versus semimajor axes a for a system composed of the four giant planets + 200 particles distributed over $15 < a < 100$ AU and evolved for 3×10^8 years while perturbed by $N = 10$ stars in a cluster of radius $R = 0.1$ pc. Although this system's eccentricities are hardly disturbed by the cluster stars, the particles inclinations are strongly disturbed.

Figure 5 show another interesting endstate, with this Solar System perturbed by a cluster that is three times more dense with stars. This simulation shows that passing stars can 'demote' eccentric scattered KBOs to lower-eccentricity orbits, past the $q = 40$ AU threshold. This figure also shows that cluster stars can 'promote' distant KBOs from circular to eccentric orbits. Now recall that the region beyond Neptune's 2:1 resonance that is below the $q = 40$ AU curve is the domain of the Extended Scattered Disk (ESD, see Fig. 1), so this simulation shows that passing cluster stars might be responsible for the formation of the ESD. Similar outcomes can also be seen in simulations by Fernández & Brunini (2000).

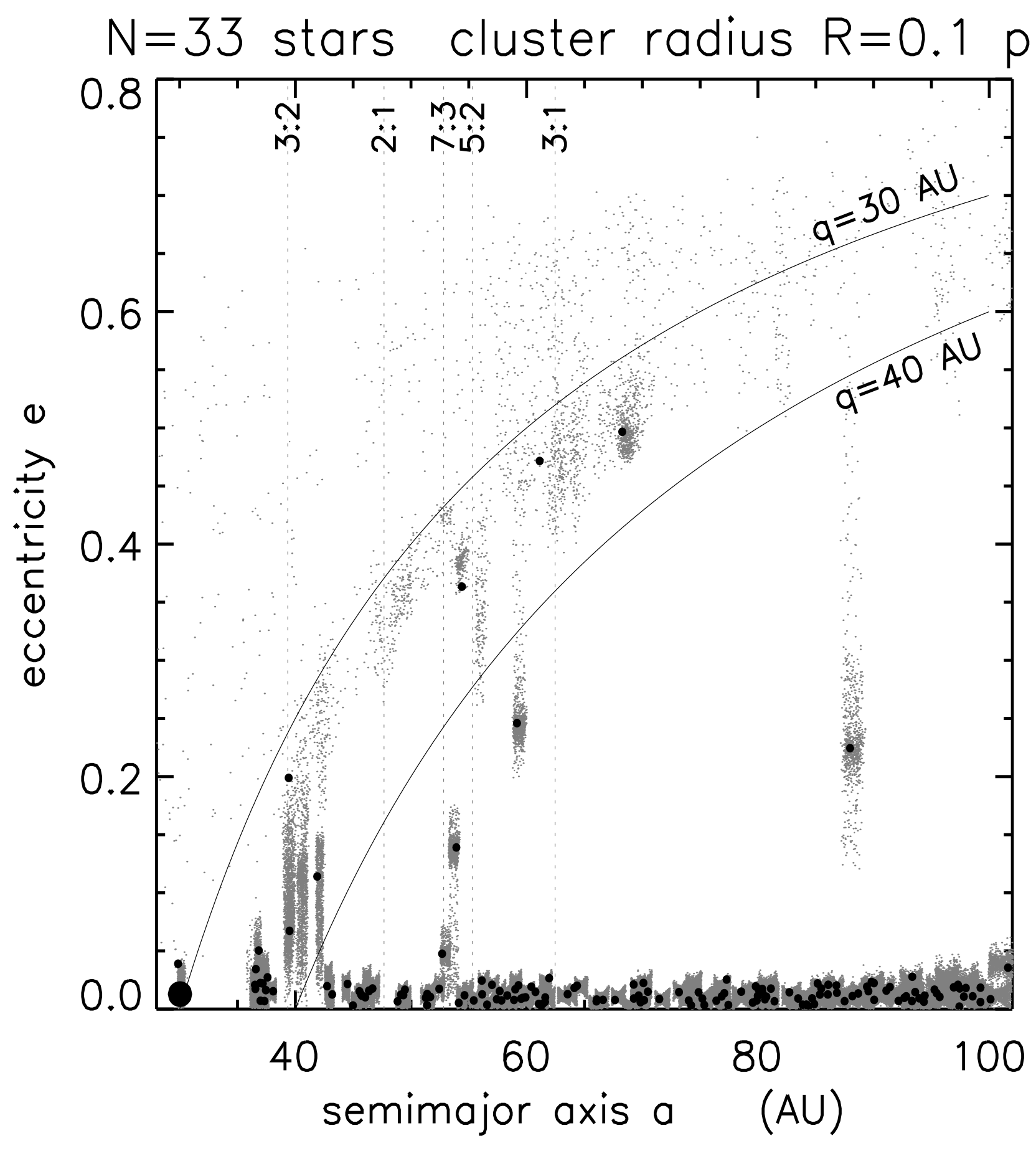

FIGURE 5: Eccentricities e are plotted versus a for this system of giant planets + 200 particles evolved for 3×10^8 years while perturbed by $N = 33$ stars in a cluster of radius $R = 0.1$ pc. Grey dots indicate the surviving particles' time-history.

Main Findings

- Passing stars can disturb (or destroy) the outer Solar System while the Sun was still embedded in its natal star cluster (see Fig. 3).
- Under certain circumstances, cluster stars can dramatically alter inclinations in the outer Solar System (see Fig. 4).
  - indeed, this inclination-pumping by passing stars can make distant Main Belt KBOs more difficult to detect, perhaps resulting in an apparent edge at $a \simeq 45$ AU that might not be real.
- passing stars can also 'demote' Scattered Disk Objects into the Extended Scattered Disk, as well as 'promote' circular KBOs into the ESD (see Fig. 5).

Next Steps

- A real Nbody integrator will be used to evolve a cluster's mutually interacting stars. Such simulations will allow the cluster to evaporate in a much more realistic fashion. Note that the main deficiency of the current model is in fact our crude treatment of cluster evaporation.
- We will also investigate the cause of the interesting dynamical structure seen in Figs. 4 and 5. New resonances are suspected, but the details are unclear.
- Also include the Galactic tide in this model, and then monitor the Oort Cloud, to see whether cluster stars might also disturb or destroy this comet cloud.

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