ASTR630 Planetary Science: Final Project Abstract
Binary KBO Formation Through Graviational Instability

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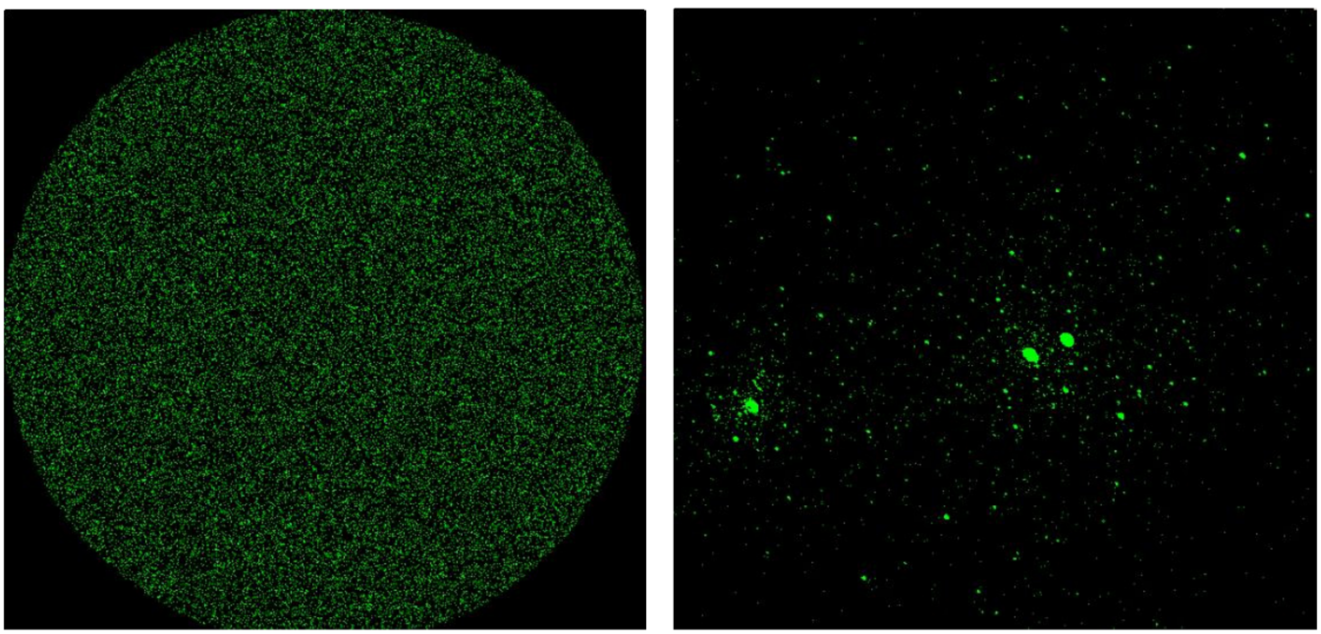
Kuiper Belt objects (KBOs) have been found in a very interesting and broad range of configurations of orbital parameters. Specifically, up to as many as 50% of KBOs form in binary or triplet systems (Noll et al. 2008a). Nesvorný et al. 2010 proposes a new method for the formation of KBO binary pairs that invovles direct gravitational collapse of over densities in the protoplanetary disk near or just after the gas has evacuated the disk ($\sim 10\,Myr$).

Work done by Johansen and Youdin et al. (2006 - 2009) has shown that overdensities, known as clumps, can form in a protoplanetary disks undergoing many instabilities; including Kelvin-Helmholtz, shearing and gravitional instabilities. The formation rate of these clumps has been found to be strongly dependent on circumsolar distance, gas density, sound speed and disk metallicity (Johansen et al. 2009; Youdin and Johansen et al. 2007; Johansen and Youdin et al. 2007). They explored a wide range of parameters to determine the frequency of clump formation and stability. Johansen et al. 2009 evolved systems with local disk metallicities of Z = 0.01, 0.02, 0.03 over 100 orbital periods to determine clump stability and formation rate. They formed clumps by starting with $\sim 1 - 10$ m sized objects and defined $Z = \rho_{pebbles}/\rho_{gas}$ as their independent paramter for comparisons.

Because the Johansen et al. papers were concerned with the larger structure of the disk, they did not follow through to the final graviational collapse, Nesvorný et al. 2010 studied simulations of the final gravitional collapse and planetesimal formation. Nesvorný et al. 2010 used PKDGRAV (Leinhardt & Richardson 2002) to investigate the late stages of the graviational collapse of a "swarm" of particles succombing to gravitional instabilities.



PKDGRAV simulation of a collapsing swarm into a triplet system similar to 1999 TC_{36} (Nesvorný 2008)

They find that a graviational instability driven collapse can produce a binary fraction in the Kupier Belt (KB) up to "100% for a wide range of initial conditions" (Nesvorný et al. 2010). They propose that gravitional instabilites (GI) allow for the Noll et al. 2008a estimate of a 50% binary KBO fraction in the KB today. With a range of total mass, initial angular momentum and particle radius, Nesvorný et al. 2010 simulated 240 different parameter combinations for 100 years with a 0.3 day time steps. They then categorized the results by comparing final eccentricity, inclination, separation radius and primary-to-secondary radii ratio. With the more interesting results, they evolved the systems for up 10,000 years to determine long-term evolution and stability conditions.

Alternatively, theories based around hierchical coagulation could produce similar results for the present KB. But, they require restrictive initial conditions on, or further evolution of the protoplanetary disk to form the observed rates of binary KBOs. These restrictions could be taken as constraints on the early conditions of the KB, but GI offers a second option with a different set of preconditions.

For example, many hierchical coagulation theories do not easily produce binary pairs with similar color or bulk density. Two or more solitary KBOs would not preferentially have similar compositions. As such, collisionally formed binary pairs more easily produce systems with varying bulk compositions and density (Goldreich et al. 2002).

Likewise, hierchical coagulation can form binary KBOs through two and three body interactions. But, the necessary rate of encounters to form the observed binary fraction of today's KB far exceeds the estimated size distribution of the early KB (Goldreich et al. 2002). Comparatively, the PKDGRAV simulations show that GI allows for the formation binary pairs in a variety of size distribution priors (Nesvorný et al. 2010).

Observationally, Benecchi et al. 2009 find that resolved KBO binaries tend to have "identical colors and bulk composition". The PKDGRAV simulations almost exclusive form binary pairs with indentical composition and colors to that of the initial swarm (Nesvorný et al. 2010). Further evolution does show collisions with other KBOs to form heterogenous binary pairs; but these interactions could more easily unbind the original pair (Petit & Mousis 2004).

The break down of GI for binary KBO formation is the inclination variation, initial mass and angular momentum limitations. The final inclination of KBO pairs from GI formation is strongly determined by the initial angular momentum of the swarm (Nesvorný et al. 2010). If the swarm is assumed to have similar angular momentum to the surrounding protoplanetary disk, then extreme inclinations, such as polar or retrograde binary orbits, would need to be formed through long-term evolution post-formation; which may be unlikely (Perets & Naoz 2009). Similarly, the initial mass for GI to form stable binary pairs is limited to that of an equivalent 100 - 250 km asteroid; scenarios above this limit have not been tested. Likewise, the initial angular momentum must have an upper bound equivalent to that for the swarm to orbit itself in circular orbits. Within these boundaries, the Nesvorný et al. 2010 simulations show that GI has the ability to form a wide range of fraction and size distribution for KBO binaries in the present KB.

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