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Long-term dynamical stability of the Haumea (2003 EL_{61}) collisional family

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Abstract

The Haumea family is so far the only identified collisional family in the Kuiper belt [1]. The formation of the family occurred at least 1 Gyr ago, but it most likely occurred in the primordial Kuiper belt as collision probabilities are exceedingly low in the current Kuiper belt [4]. Here we examine the long-term dynamical evolution of hypothetical family members to assess how the dynamical coherence (velocity dispersion) and number of members within the family are preserved over Gyr timescales. We find that for initial velocity dispersions of $150 - 400\ ms^{-1}$, approximately $20 - 45\%$ of the family members will be lost to close encounters with Neptune after 3.5 Gyr of orbital evolution. The remaining members' orbital elements diffuse over short timescales ($\sim$ 10 Myr) to produce $50 - 100\ ms^{-1}$ scatter in their velocities relative to the collision's center-of-mass orbit; family members that become trapped in mean motion resonances (MMRs) with Neptune diffuse even further from the original orbit.

1. Introduction

The Haumea collisional family was identified by the observation of a common deep spectral feature caused by water ice [1]. Based on the velocity dispersion of the identified family members, Ragozzine & Brown (2007) [4] estimate the center-of-mass orbit for the collision that formed the family to be $(a, e, i, \omega, M) = (42.1\ \text{AU}, 0.118, 28.2°, 270.8°, 75.7°)$; they then estimate the age of the family to be 3.5 ± 2 Gyr based on the time it takes the largest fragment (Haumea) to diffuse from the center-of-mass orbit to its current location via the 12:7 MMR with Neptune.

There are several models for the formation of the Haumea family [2, 3, 5]; one observed property that must be explained is the family's relatively small velocity dispersion of $\sim 150\ ms^{-1}$. Here we focus on the models of Leinhardt et al. (2010) [3] (the creation of the family via a graze and merge type collision between two similarly sized, differentiated KBOs) and Schlichting & Sari (2009) [5] (family members are created via the collisional disruption of a satellite orbiting Haumea) to determine how 3.5 Gyr of dynamical evolution affects the models' predicted velocity dispersion and total mass of the family members relative to Haumea.

2. Numerical Integrations of Hypothetical Family Members

We performed long-term numerical integrations of test particles representing family members with values of Δv (where $\Delta v = |\vec{v} - \vec{v}_{cm}|$ at the collision location) from $150 - 400\ ms^{-1}$ (in increments of $50\ ms^{-1}$). Test particles were generated by isotropically adding Δv to the collision center-of-mass orbit determined by Ragozzine & Brown (2007). The test particles were integrated forward in time for 4 Gyr under the gravitational influence of the sun and the four outer planets. Any particle that had a close encounter with Neptune was removed from the family. Figure 1 shows the fraction of test particles remaining as a function of time for the various values of Δv. Figure 2 shows snapshots of the proper eccentricity and semimajor axis distribution for $\Delta v = 150\ ms^{-1}$ at $t = 0$ and 3.5 Gyr later.

Many of the unstable test particles start out at semimajor axes near various MMRs with Neptune. Some of the stable particles undergo large changes in eccentricity due to these resonances, increasing their velocity dispersion relative to the center-of-mass collision orbit. Even the non-resonant test particles undergo large enough changes in $a, e,$ and i to significantly change their apparent Δv. Ragozzine & Brown (2007) outline a procedure to estimate Δv using only an object's proper $a - e - i$ and the collision location (information about the other orbital elements (Ω, ω, M) at the time of the collision is rapidly lost due to orbital precession); applying this procedure to our test particles, we find that the estimated values of Δv tend to be evenly spread within $\sim \pm 50 - 100\ ms^{-1}$ of the known initial value. The amount of scatter induced by the dynamical evolution of a, e, and i is a useful estimate of the uncertainty of the known family members' calculated values of Δv.

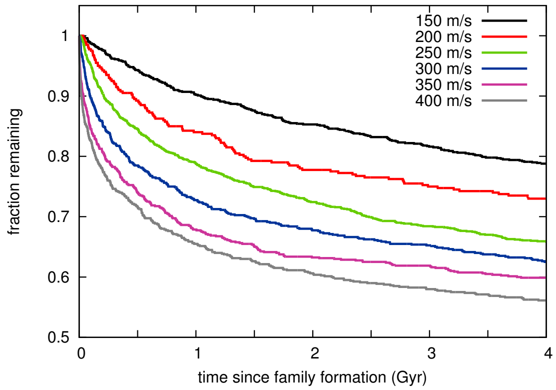

Figure 1: Fraction of family members remaining vs. time for different values of Δv.

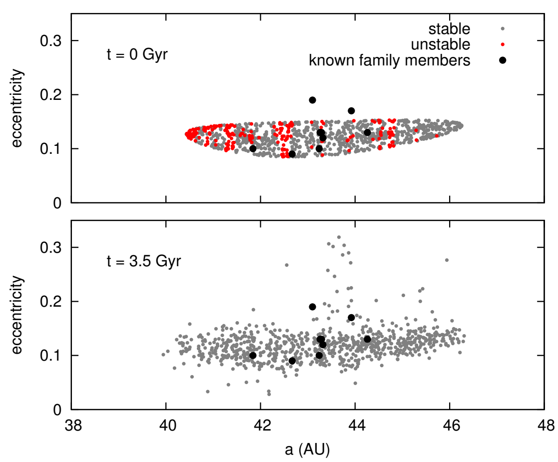

Figure 2: Eccentricity vs. semimajor axis for test particles with an isotropic $\Delta v = 150\ ms^{-1}$ at $t = 0$ and at $t = 3.5\ Gyr$. Gray indicates stability over 4 Gyr, red particles have close encounters with Neptune.

3. Discussion

We can apply these simulation results to the models of Leinhardt et al. (2010) and Schlichting & Sari (2009). Leinhardt et al. (2010) report a cumulative Δv distribution from their collision simulations (see their Figure 3) as well as an estimated mass for the collisional family, ~ 0.07 Haumea masses (M_H). Using their distribution of Δv and the loss rates determined from our simulations we find that $\sim 80\%$ ($\sim 0.056\ M_H$) of the family members created in the collision survive to 3.5 Gyr (the nominal age of the family). Of the remaining family members, $\sim 40\%$ ($\sim 0.024\ M_H$) have an original $\Delta v < 150\ ms^{-1}$. The formation scenario outlined in Schlichting & Sari (2009) produces a collisional family with $\Delta v \sim 200\ ms^{-1}$ and a mass of $\sim 0.05\ M_H$. Assuming a uniform Δv and the loss rate from our simulations, the mass of the collisional family members after 3.5 Gyr should be $\sim 0.036\ M_H$.

For comparison to both these models, the estimated mass of all the observed family members (plus Haumea's satellites) is $\sim 0.017 M_H$ [2], and all the known family members are consistent with $\Delta v < 150\ ms^{-1}$ [4]. Compared to Schlichting & Sari's (2009) model, these results indicate that we have observed $\sim 50\%$ of the collisional family. Assuming the model of Leinhardt et al. (2010), we have observed 70% of the family members within $\sim 150\ ms^{-1}$ of the original collision, but $\sim 0.036\ M_H$ (about twice the mass of the known family members) of material associated with the family remains to be observed at larger Δv. Some of the discrepancy between the models and the observations is likely due to observational incompleteness, but some of the missing mass could be hidden in the form of KBOs that lack the water ice spectral feature, as suggested by Cook et al. (2011) [2].

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