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 (≈ 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 $(a, e, i, \omega, M) = (42.1 \, AU, 0.118, 28.2^\circ, 270.8^\circ, 75.7^\circ)$; they then estimate the age of the family to be $3.5 \pm 2 \, Gyr$ 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 $\Delta v$ (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 $\Delta v$ 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 $\Delta v$. 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 $\Delta v$. Ragozzine & Brown (2007) outline a procedure to estimate $\Delta v$ using only an object’s proper $a - e - i$ and the collision location (information about the other orbital elements $(\Omega, \omega, M)$ 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 $\Delta v$ 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 esti-
mate of the uncertainty of the known family members’
calculated values of \(\Delta v.\)

![Figure 1: Fraction of family members remaining vs. time for different values of \(\Delta v.\)](image)

![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 \(\Delta v\) distri-
bution from their collision simulations (see their Fig-
ure 3) as well as an estimated mass for the collisional
family, \(\sim 0.07\) Haumea masses \((M_H).\) Using their
distribution of \(\Delta v\) 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 re-
main ing 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 col-
lisional family with \(\Delta v \sim 200 \, ms^{-1}\) and a mass of
\(\sim 0.05 M_H.\) Assuming a uniform \(\Delta v\) 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 esti-
mated 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 origi-
nal 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 \(\Delta v.\)
Some of the discrepancy between the models and the
observations is likely due to observational incomple-
teness, but some of the missing mass could be hidden
in the form of KBOs that lack the water ice spectral fea-
ture, as suggested by Cook et al. (2011) [2].

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