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The effect of orbital evolution on the Haumea (2003 EL_{61}) collisional family

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ABSTRACT

The Haumea family is currently the only identified collisional family in the Kuiper belt. We numerically simulate the long-term dynamical evolution of the family to estimate a lower limit of the family's age and to assess how the population of the family and its dynamical clustering are preserved over Gyr timescales. We find that the family is not younger than 100 Myr, and its age is at least 1 Gyr with 95% confidence. We find that for initial velocity dispersions of 50–400 m s^{-1}, approximately 20–45% of the family members are lost to close encounters with Neptune after 3.5 Gyr of orbital evolution. We apply these loss rates to two proposed models for the formation of the Haumea family, a graze-and-merge type collision between two similarly sized, differentiated KBOs or the collisional disruption of a satellite orbiting Haumea. For the graze-and-merge collision model, we calculate that >85% of the expected mass in surviving family members within 150 m s^{-1} of the collision has been identified, but that one to two times the mass of the known family members remains to be identified at larger velocities. For the satellite-break-up model, we estimate that the currently identified family members account for ~50% of the expected mass of the family. Taking observational incompleteness into account, the observed number of Haumea family members is consistent with either formation scenario at the 1σ level, however both models predict more objects at larger relative velocities (>150 m s^{-1}) than have been identified.

1. Introduction

The Haumea (2003 EL_{61}) collisional family was discovered by Brown et al. (2007) who noted that Haumea and five other Kuiper belt objects (KBOs) shared a spectral feature that is indicative of nearly pure water ice on the surfaces of the bodies. These six KBOs, along with four additional family members identified by Schaller and Brown (2008), Snodgrass et al. (2010), and Ragozzine and Brown (2007), can all be dynamically linked to Haumea, and there do not appear to be any dynamically unrelated KBOs that share this spectral feature. Aside from being spectrally linked to these other KBOs, Haumea itself shows signs of its collisional past. Despite having a nearly pure water ice surface, Haumea's density is ~2.6 g cm^{-3} (Rabinowitz et al., 2006), which is higher than expected for typical assumed ice/rock ratios in the Kuiper belt (Brown, 2008); one way to achieve this higher density is to have a catastrophic collision between a differentiated proto-Haumea and another KBO in which proto-Haumea loses a substantial fraction of its water ice mantle (Brown et al., 2007). This scenario is supported by the presence of at least two water ice satellites (Barkume et al., 2006; Ragozzine and Brown, 2009). Haumea also has an elongated shape and a very short spin period of ~4 h that is unlikely to be primordial (Rabinowitz et al., 2006; Lacerda and Jewitt, 2007).

Ragozzine and Brown (2007) examined the dynamical connections between the identified Haumea family members. These connections are made by first estimating the orbit of the center of mass of the colliding bodies, and then estimating the ejection velocities of each family member relative to the collision's center of mass. The ejection velocity is given by

$$\Delta\vec{v} = \vec{v} - \vec{v}_{cm} \quad (1)$$

where $\vec{v}_{cm}$ is the estimated collision's center-of-mass velocity. Because Haumea is by far the largest remnant from the collision, its orbit immediately after the collision should have nearly coincided with the center-of-mass orbit. However, Haumea is currently located at the boundary of the 12:7 mean motion resonance (MMR) with Neptune; over long timescales, the chaotic zone of this resonance causes a random walk of the proper elements such that Haumea's current orbit may be significantly distant from its post-collision orbit. Ragozzine and Brown (2007) estimate the center-of-mass collision orbit by minimizing the sum of the relative speeds of all family members, assuming that Haumea's semimajor axis and its Tisserand parameter with respect to Neptune are both conserved during its chaotic evolution; they then use Haumea's present distance from the collision's center-of-mass orbit, together with a calculation of its chaotic diffusion rate, to estimate the age of the collisional family to be 3.5 ± 2 Gyr. Given the exceedingly low collision probabilities for objects large enough to form the Haumea family in the current Kuiper belt, the family is likely to be old.

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However, the family probably cannot have formed in the primordial, much more massive Kuiper belt, because whatever caused the mass of the Kuiper belt to be depleted (by an estimated 2 or 3 orders of magnitude) would have also destroyed the dynamical coherence of the family (Levison et al., 2008). The high inclination ($\sim$27°) of the family also argues against a primordial origin, because such large inclinations are probably products of the excitation and mass depletion of the Kuiper belt. Thus, it appears that the Haumea family-forming collision occurred near the end of the primordial, high-mass phase of the Kuiper belt.

Several of the largest KBOs show evidence of their collisional past (see review by Brown (2008)), but the Haumea family is the only collisional family that has been identified in the Kuiper belt. The dynamical connections between the members of the family allow us to place some constraints on the type of collision that formed the family and also constrain the age of the family as being old, but probably not primordial. These characteristics make the Haumea family an excellent probe of the collisional environment in the Kuiper belt following the excitation and mass depletion event; understanding the type of collision that created the family (especially the relative sizes and speeds of the impactor and target) would provide valuable insight into the size and orbital distribution of the Kuiper belt at the time of the collision (see discussions of this in Marcus et al. (2011) and Levison et al. (2008)).

Proposed models for the formation of the Haumea family have attempted to reproduce the family's relatively small velocity dispersion ($\sim$150 m s^{-1}) and to explain the compositional and orbital characteristics of the family. However, the orbits of the family members have been sculpted by several gigayears of dynamical evolution. In this paper we use numerical simulations to determine how this orbital evolution affects the dynamical coherence of the family. In Section 2, we determine the loss rates for the family, which depend on the initial velocity dispersion from the collision, and we determine how the velocity dispersion of the surviving family members is altered over time; from these simulations, we also obtain a hard lower limit for the age of the family. In Section 3, we apply these results to the family-formation models of Leinhardt et al. (2010) (a graze-and-merge type collision between two similarly sized, differentiated KBOs) and Schlichting and Sari (2009) (the collisional disruption of a satellite orbiting Haumea), and we compare the predictions from these two formation models to the current observations of the family. Section 4 provides a summary of our results and conclusions.

2. Orbital evolution of the Haumea family

Even though the identified Haumea family members (see Table 1) have a fairly low velocity dispersion ($\Delta v \sim 150$ m s^{-1}), their proper orbital elements span a relatively large range in semimajor axis, a, and eccentricity, e, (a range that is typical of classical KBOs), and they have atypically large inclinations, i, of $\sim$27°. Using the data for their best-fit orbits,[1] we did a 10 Myr numerical simulation to obtain the average values of a, e, and i for each family member over that time span, and we calculated the corresponding values of Δv (Eq. (1)) relative to the center-of-mass collision orbit determined by Ragozzine and Brown (2007); these are listed in Table 1 for the family members identified by Brown et al. (2007), Schaller and Brown (2008), Ragozzine and Brown (2007), and Snodgrass et al. (2010). Below, we examine the orbital distribution of the known family members to refine the center-of-mass orbit in light of the additional identified family members since Ragozzine and Brown (2007). We use the results of long-term numerical simulations to estimate how much the family's orbits have evolved since its formation, and we obtain a hard lower limit on the age of the family.

2.1. Collision center-of-mass orbit and a lower limit on the family's age

We use the average values of a, e, and i for the nine identified family members (Table 1) to re-calculate the center-of-mass collision orbit using the method described by Ragozzine and Brown (2007): we minimize the sum of Δv for the nine family members while fixing the semimajor axis of the center-of-mass orbit at that of Haumea's current orbit, allowing its eccentricity and inclination to vary such that Haumea's current Tisserand parameter with respect to Neptune ($T_N = 2.83$) is maintained, and allowing the mean anomaly, M, and the argument of pericenter, ω, to vary freely; the longitude of ascending node, Ω, is ignorable as it does not affect the distribution of Δv. Fig. 1 shows the results of this calculation for a range of eccentricity and inclination combinations of the collision center-of-mass orbit. The lower limit of the shaded region in the figure is the value of the family's average Δv found by selecting values of the mean anomaly and argument of pericenter that minimize Δv; the shaded area shows the range in Δv obtained by allowing ω to vary, but still selecting the value of M that minimizes Δv for each value of ω. Parameters along the lower boundary of the shaded regions represent collisions occurring very near to the ecliptic plane, while parameters along the upper boundary represent collisions at the extreme, off-ecliptic points in the orbit ($\sim$15–20 AU above the ecliptic plane). The difference in average Δv for the different values of ω is a factor of $\sim$2, as noted by Ragozzine and Brown (2007); this increase in average Δv for off-ecliptic collision points is due to the fact that producing the observed family's spread in inclination requires a larger Δv at these locations. Because collisions near the ecliptic are much more probable than off-ecliptic collisions, we choose the center-of-mass orbit that minimizes the lower portion of the filled curve in Fig. 1. The result is $(a, e, i, \omega, M) = (43.1$ AU, 0.124, 28.2°, 270°, 76°). This is very similar to the collision center-of-mass orbit determined by Ragozzine and Brown (2007): $(a, e, i, \omega, M) = (43.1$ AU, 0.118, 28.2°, 270.8°, 75.7°), indicating that the newer family members do not significantly affect the estimate of the collision center-of-mass orbit. The small difference in the eccentricity does not much affect the values of Δv for the family members (both values of Δv are listed in Table 1) because the calculated Δv is a fairly flat function of eccentricity within $\pm\sim 10\%$ of its minimum.

In the above calculations, as in Ragozzine and Brown (2007), we assumed a constant semimajor axis and conservation of the Tisserand parameter during the chaotic evolution of Haumea's orbit. To test the validity of this assumption, we performed numerical simulations of resonant diffusion within the 12:7 MMR, and we find that Haumea's Tisserand parameter can vary by ±0.5%. This is a small variation, but it does affect the allowable combinations of e and i for the best-fit center-of-mass orbit. We performed the minimization of the sum of Δv for the identified family members while allowing e and i to vary independently, and we find a slightly revised best-fit center-of-mass orbit: $(a, e, i, \omega, M) = (43.1$ AU, 0.124, 27.3°, 276°, 70°). This orbit has a Tisserand parameter $T_N = 2.84$, which is within the range of T_N found in our numerical simulations. If we additionally relax the constraints to allow the semimajor axis of the orbit to vary by ±0.15 AU (the approximate range of variation in the 12:7 MMR), we find very similar results: $(a, e, i, \omega, M) = (43.1 \pm 0.15$ AU, 0.121, 27.3°, 278°, 68°). These alternate minimum Δv center-of-mass orbit fits give us an estimate of the uncertainties in the orbital parameters:

$$(a, e, i, \omega, M)_{cm} = (43.1\text{ AU},\ 0.115{-}0.132,\ 27{-}28.3^\circ,\ 270{-}278^\circ,\ 68{-}76^\circ).$$

[1] Orbit information was taken from the AstDyS website (http://hamilton.dm.unipi.it/astdys).