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On the genesis of the Haumea system

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ABSTRACT

The scenarios proposed in the literature for the genesis of the system formed by the dwarf planet 136108 Haumea, its two satellites and a group of some 10 bodies (the family) with semimajor axes, eccentricities and inclinations close to Haumea's values, are analysed against collisional, physical, dynamical and statistical arguments in order to assess their likelihood. All scenarios based on collisional events are reviewed under physical arguments and the corresponding formation probabilities in a collisional environment are evaluated according to the collisional evolution model ALICANDEP. An alternative mechanism is proposed based on the potential possibility of (quasi-) independent origin of the family with respect to Haumea and its satellites. As a general conclusion the formation of the Haumea system is a low-probability event in the currently assumed frame for the evolution of the outer Solar system. However, it is possible that current knowledge is missing some key element in the whole story that may contribute to increase the odds for the formation of such a system.

Key words: Kuiper belt objects: individual: Haumea – minor planets, asteroids: individual: Haumea – planets and satellites: individual: Haumea.

1 INTRODUCTION

Our Solar system contains a large number of icy bodies beyond Neptune's orbit, in the so-called Edgeworth–Kuiper belt (EKB), collectively named as trans-Neptunian objects (TNOs). These icy bodies are thought to be the leftovers from the process of formation of the outer Solar system. They are also shown to be the source of the short-period comets (Fernandez 1980). A wealth of knowledge on the trans-Neptunian region has accumulated since the discovery of the first TNO in 1992 (after Pluto and Charon), but there are still many open questions in the study of TNOs.

Besides Pluto, three large TNOs about the size – or slightly smaller – than Pluto were discovered in the last decade and have been included in the class of *dwarf planets*. 13199 Eris, 136472 Makemake and 136108 Haumea. All these bodies have one or more known satellites, and only Haumea has been associated with a group of objects with similar orbital elements and spectral features. This has brought interest to understand the mechanism that produced such a system.

Haumea has a 3-axial shape with sizes estimated as about $1900 \times 1 \times 1000$ km, a mass of 4.006×10^{21} kg and a short spin period of 3.92 h (Rabinowitz et al. 2006; Lacerda, Jewitt & Peixinho 2008; Thirouin et al. 2010; Santos et al. 2012; Lockwood, Brown & Stansberry 2014). From that available data and the assumption that Haumea has a fluid equilibrium shape, it has been argued (Rabinowitz et al. 2008) that its density should be in the 2.6–3.3 g cm^{-3} range, much higher than Pluto's. On the other hand, Holsapple (2007) suggests that Haumea instead may not have assumed a fluid shape due to its own internal shear stresses. As a consequence, its mass density could be considerably lower, and the object might be consequently larger than estimated. Its two satellites, Hi'iaka and Namaka, are orbiting Haumea at 49 880 ± 198 km and 25 657 ± 91 km and have mass ratios of approximately 1/20 and 1/200, respectively (Ragozzine & Brown 2009). The group of TNOs that has been dynamically associated with this system – and frequently called the Haumea's 'family' – is made of about 10 candidate members (Brown et al. 2007; Ragozzine & Brown 2007; Schaller & Brown 2008; Snodgrass et al. 2010; Trujillo, Sheppard & Schaller 2011). We prefer to quote the term *family* in this context as this has been imported from the asteroid belt, where it refers to groups of objects that are very close in the *proper elements* space and overcome suitable tests to establish their clustering. Unfortunately, one of the main requirements for a group of objects to be classified as a dynamical family is not fulfilled in the case of the Haumea system. Namely, the dispersion velocity of the candidate members must be much smaller than their Keplerian velocity, a circumstance that does not apply in this case, where they are

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comparable. As we have not observed any other such clustering in the trans-Neptunian region, one may agree to release the latter condition and – for analogy – accept to use the same terminology as in the asteroid belt, being aware of the difference. Besides having close proper elements, all the system components are characterized by clear crystalline water ice spectroscopic features. That is one of the pieces of supported evidence for a common origin. Their spread in inclination and eccentricity is interpreted as compatible with dispersion velocities around 140 m s^{-1}. Interestingly enough, the only member out of this clustering is Haumea itself, with a dispersion velocity of some 400 m s^{-1} with respect to the centre of the region of the orbital elements space about which the group is spread. A tempting explanation for that was given by Brown et al. (2007) in terms of the 12:7 mean motion resonance with Neptune that might be able to perturb the eccentricity of Haumea.

1.1 ALICANDEP

The Nice model (Levison et al. 2008b) simulates the dynamical evolution of the outer Solar system since the epoch when dust and gas had been eliminated from the region. It is based on the idea that the gas giants formed much closer together, surrounded by a disc of planetesimals stretching between 16 and 30 au. Due to interactions with the planetesimal disc, Saturn, Neptune and Uranus migrated outwards and Jupiter migrated slightly inwards. After some ∼600 to 800 Myr, Jupiter and Saturn crossed their 2:1 mean motion resonance and the system became temporarily destabilized, affecting the orbital elements of the outer planets. As Neptune moved out into the trans-Neptunian region, its secular resonances excited the orbits of many of the TNOs (Gomes et al. 2005). After that, Neptune has continued to erode the trans-Neptunian region by gravitational scattering (Holman & Wisdom 1993; Duncan & Levison 1997). The Nice model offers an explanation to the Late Heavy Bombardment (LHB) and to the main features of the current dynamical structure observed in the trans-Neptunian region.

It indeed has to be acknowledged that the Nice model is not the definitive explanation to all currently observable features in the trans-Neptunian region. Other scenarios have been proposed to explain specific aspects, but we assumed the Nice model scheme as the most detailed model that includes the main phases that any evolutionary scenario of the outer Solar system has to take into account. These are a compact and dynamically cold phase, an excitation phase, a major depletion and a long time evolution in a dynamically stable environment. Therefore, most of the statistical calculations in this work apply strictly only under the Nice model assumptions, even if important exceptions in boundary conditions have been introduced in the study. No major changes – as for collisional evolution outcome and related probabilities is concerned – are expected when changing the details of that general scheme.

In the following text – and for the sake of brevity – the term 'LHB phase' is used simply to indicate the instability phase in which major dynamical depletion took place, without specific reference to the exact explanation introduced by the Nice model itself.

This general scheme cannot be ignored in the interpretation of the events that occurred in the EKB history. Campo Bagatin & Benavidez (2012) developed ALICANDEP (Asteroid-Like Collisional ANd Dynamical Evolution Package), a numerical model of collisional evolution that includes statistical elimination of objects by dynamical effects within the frame of a disc migrating and gradually dynamically exciting, as well as the dynamical migration of objects between regions. ALICANDEP manages to match current observables fairly well and it finds high probabilities for the collision that formed the Pluto–Charon system. Therefore, we chose this package as a reliable tool to estimate the likelihood of the collisional scenarios for the formation of the Haumea system proposed in the literature

Table 1. Two different sets of boundary conditions (Model A and Model B) are used in the numerical simulations. q_1 and q_2 are the slope indices of the differential size distributions for bodies smaller and larger than 100 km in the dynamical zone where the Haumea system is; M_i is the initial mass of the whole TN region (in Earth masses), and Δt is the interval corresponding to the beginning and the end of the instability phase (shortly labelled as LHB phase), in millions of years.

Boundary cond.	($q1$, $q2$)	M_i˜(M_E)	Δt˜(Myr)
Model A	(3;6)	86–110	500–600
	(3;6)	86–110	600–700
	(3;6)	86–110	500–550
	(3;6)	86–110	200–300
Model B	(–;6)	34	500–600
	(–;6)	34	600–700
	(–;6)	34	500–550
	(–;6)	34	200–300

The boundary conditions under which we run our analysis are based on those specified in Campo Bagatin & Benavidez (2012). They are varied within a wide range of reasonable values according to current cosmogonic understanding of the outer Solar system. In general, we consider a broken power-law differential size distribution of the belt: $\mathrm{d}N = C \cdot D^{-q}\mathrm{d}D$, where N is the number of objects, D the size of bodies, $q = q_1$ the slope for objects smaller than a transition size (typically 100 km), $q = q_2$ the slope for larger objects and C is a constant. Model A considers an initial power law for small objects (see Table 1), while Model B stands for the extreme conditions of having no initial mass in that size range. In this work, we actually explored boundary conditions beyond the optimal ones for a 'pure' Nice model as described in Campo Bagatin & Benavidez (2012). We mention other modifications explored in boundary conditions for the present study. (a) Apart from considering no mass under 100 km in Model B, instead of a very shallow slope, −0.5, as in Campo Bagatin & Benavidez (2012), we included the cases for which (b) the slope of the initial differential size distribution of objects in the dynamical zone to which Haumea belongs has been smoothed out in the differential distribution from $q_2 = -7$ to -6. In this way, we widen the range of initial conditions still within plausible values and increase the probabilities for the different proposed mechanisms. (c) The instability phase starts at 500 Myr (instead of 600 Myr), and we considered the cases for which (d) we reduced to 50 Myr (instead of 100 Myr) the duration of that phase. (e) Finally, in order to dramatically change the situation with respect to the Nice model boundary conditions, we run the cases for which the beginning of the instability phase is set to 200 Myr.

These modifications in boundary conditions still had to grossly accomplish with the minimum required mass predicted by the Nice model at the end of the instability phase and with most of the current observables. As a consequence of the changes in boundary conditions, the initial mass of the system was tuned accordingly with respect to what shown in Campo Bagatin & Benavidez (2012). The initial mass interval reported in Table 1 corresponds to the range that has been investigated in order to match these conditions and necessarily differs from the optimal cases found in that former paper.

Due to the analogies with the case of asteroid families, a number of scenarios involving high-energy collisional mechanisms have been proposed to explain the existence of the Haumea's system. In the following sections, we analyse the likelihood of such scenarios and propose an alternative mechanism for its formation, which we check statistically as well.

2 THE PROPOSED FORMATION MECHANISMS

Most of the formation mechanisms proposed in the literature are based on the hypothesis that a collision between similar-sized objects at high relative velocities occurred. No assumption is generally made on the spin state of the parent body and its final – anomalously fast – spin rate, with the exception of Ortiz et al. (2012). The existence of the two satellites and that of the 'family' are sometimes claimed to be explained by each process. Nevertheless, none of these characteristics are modelled with sufficient detail to produce the observed features, for instance, none of the schemes reproduces both satellites on stable orbits. However, the different proposed mechanisms have opened an interesting discussion on the genesis of the Haumea system. Each scenario is relevant as it raises important questions about the physics of the event, its dynamical evolution and its likelihood in the frame of an evolving EKB. All provided probabilities are calculated for the dynamical zone where Haumea and the family currently are, namely the main classical belt of TNOs. Table 3 summarizes the statistical results.

2.1 Single catastrophic collision (Brown et al. 2007)

Brown et al. (2007) have hypothesized that Haumea was originated by a collision between two bodies of radii 830 and 500 km at relative velocities around 3 km s^{-1}. A fast spinning object (Haumea), the satellites and the 'family' should have been produced as a result of such a catastrophic collision. However, the claim that a catastrophic collision would have resulted in a large body spinning close to its rotational breakup limit is not justified. The displacement in the orbital elements space of Haumea and satellites with respect to the rest of the group may be explained by the circumstance that Haumea fell into the 12 : 7 mean motion resonance with Neptune, raising its eccentricity enough to produce the observed offset. However, that explanation was successful in about 10 per cent of their numerical simulations. It is also suggested that the collision is relatively recent, due to the clear detection of water ice on all member candidates of the 'family', with no surfaces apparently affected by space weathering and darkening. Some serious concerns about the physical, dynamical and statistical likelihood of such a scenario arise.

Takeda & Ohtsuki (2009) studied the rotation end state of gravitational aggregate asteroids after collisions of different kinds, by means of N-body numerical simulations, and showed that after catastrophic collisions in a wide range of geometries, the largest remaining body always rotated at a slower rate than prior to catastrophic collisions. Moreover, Takeda & Ohtsuki (2007) showed that in moderately damaging impact events (not catastrophic) the largest remnant acquires a significant amount of spin angular momentum. They stressed that – in order for angular momentum to be transferred to the spin of the largest fragment – the collision had to be much less disruptive. If these results for gravitational aggregates are applicable to a general case, the fast rotation rate of Haumea would not appear to be the result of a catastrophic collision. Given that Haumea is currently on the edge of hydrostatic rotational instability, it is unlikely that its parent body were rotating even faster at the moment of collision. Otherwise, the required density and material strength – in the fluid approximation – would have been even higher than the highest density currently estimated.

Moreover, Leinhardt, Richardson & Quinn (2000) and Leinhardt & Richardson (2002) show that an elongated shape is not characteristic of the remnants of disruptive collisions, and Leinhardt & Stewart (2009) showed by means of high-resolution smoothed particle hydrodynamics (SPH) code numerical simulations that the suggested collisional event has insufficient energy and momentum coupling between projectile and target to produce a fast spinning primary.

Furthermore, the alleged collisional 'family' of Haumea has estimated dispersion velocities that are not consistent with those characteristic of catastrophic collisions between bodies of the suggested sizes. Typical escape velocities in this case are of the order of 700–900 m s^{-1} (depending on the spin state and size of the parent body), much larger than the estimated dispersion velocities for the members of the group.

On the other hand, the statistical likelihood of a catastrophic collision for a very large object like Haumea is very small. We run ALICANDEP looking for the probabilities for such a catastrophic event, and the best estimation was less than 2×10^{-4} over the age of the Solar system (see Table 3), variable depending on the phase in the outer Solar system evolution in which it happened. The largest probability is obtained during and after the LHB phase in the extreme case the original mass in the region was between 86 and 110M_{E} and the LHB period was reduced to about 50 Myr, but this kind of scenario does not fit the current estimated constraints suggested by the Nice model and the observational findings by the Canada–France Ecliptic Plane Survey (CFEPS; Petit et al. 2011). Before the LHB phase, the mass density of the primordial belt was 100 times the mass of the present belt, but mutual relative velocities were too small to produce such catastrophic events and the probability turns out to be negligible in this pre-LHB era. One has to come up with very artificial mechanisms such as the collision of two scattered disc objects, resulting in a classical belt, to get a larger but still small chance of a catastrophic event (Levison et al. 2008b) during the LHB phase. In this case, the 'family' should still overcome the rest of the LHB period, characterized by intense collisional and dynamical activity potentially destroying most of the generated family members.

2.2 Catastrophic collision and shattering of a satellite

2.2.1 *Schlichting & Sari (2009)*

A smart collisional formation scenario was introduced by Schlichting & Sari (2009, S09). They propose a formation mechanism in three phases. The first phase requires a collision between two bodies of the size of those proposed by Brown et al. (2007), but within a primordial region. The impact would have then occurred in the sub-Hill velocity regime, that is indeed below 1 km s^{-1}, in this case. The collision would form one or more satellites, one of them with a radius of 260 km and a fast spinning Haumea. After that, the satellite(s) would undergo tidal dissipation of orbit(s), and finally the (larger) satellite would be hit by a projectile of radius 20–70 km so that ejection velocities of the fragments are compatible with the dispersion velocity observed for the 'family'. The two known satellites would also form in the process. This is indeed a very interesting mechanism as a whole, even if it also meets difficulties.

From a physical point of view, the initial collision would happen in a sub-sonic velocity regime, and great uncertainties in the collisional physics for objects thousands of km in size arise. It is not clear that the formation of an elongated primary and a satellite would be straightforward, nor the amount of damage and ejected mass is predicted by any theory or model in that regime. The claim that such a collision would produce a fast spinning Haumea is not further supported either and finds the objections pointed out in the case of the Brown et al. (2007) mechanism. Moreover, it is well known that tidal dissipation and orbit separation in the primary-satellite system formed by a collision work against very fast spin in the primary due to loss in spin angular momentum in favour of orbital angular momentum.

ALICANDEP computes the statistical probability of both collisions. It is necessary to consider the probability on a proto-Haumea, combined with the shattering probability on the satellite formed by the former collision. In the case of the collision on the proto-Haumea, the probability is in the 0.04–0.08 range. In the case of the satellite, the probability of a shattering collision on an object of its size was close to 1 at that time. The latter has to be combined with the $1/N$ odds ($N \sim 10^5$ is the number of objects of that size before the LHB phase) that the shattered object is the very outcome of the former collision on the proto-Haumea. The resulting probability turns out to be of the order 10^{-6}, if the formation mechanism took place before the LHB phase (see Table 3). However, the LHB phase depleted the former population of objects by about 99 per cent, which means that – in order to observe the current family – the original family should have had 100 times more objects. Therefore, the corresponding proto-satellite should have been 100 times more massive in order to survive the LHB phase to the current observable mass. That means that it should have been of the same order of Haumea itself, changing substantially the needed original collision to a much larger one and dropping the overall probability to nil.

Nevertheless, both collisions may have happened during the LHB phase, when the number density was still high but decreasing and relative velocities were increasing due to the excitation of eccentricities and inclinations, or even after. In this case, the probability of the primary impact to happen is in the range $0.3–1 \times 10^{-3}$ (during the LHB phase) to $0.1–0.5 \times 10^{-4}$ (after the LHB phase). One or more shattering events on objects larger than some 400 km diameter are expected to happen in the main classical belt with a Poisson probability of 0.48–0.63, as calculated by ALICANDEP so that the existence of such a family is predicted by the model. Again, this probability has to be combined with the probability that the mentioned shattering event happens right on the proto-satellite of Haumea. At the beginning of the LHB phase, some 10^5 400-m objects were present, they were reduced to 800 at its end and this population did not change substantially afterwards. The total probability for this mechanism in this phase is then of the order of 10^{-7}, as reported in Table 3.

2.2.2 *Ćuk, Ragozzine & Nesvorný (2013)*

A thorough analysis of the dynamics of the Haumea's satellites is described in Ćuk et al. (2013). From that analysis, the authors derive implications on the origin of the moons and the family itself and conclude – on one hand – that the family-forming event took place after the end of planetary migration, in the current planetary configuration. On the other hand, they find that the scenario based on the disruption of a proto-satellite is well supported if the current orbits of Hi'iaka and Namaka are retrograde with respect to Haumea's rotation.

This is not a brand new formation mechanism of the Haumea system, but rather a modification of that proposed by Schlichting & Sari (2009). It indeed is an important result as it provides a stringent criterion to rule out – or rather confirm – this as a suitable mechanism of formation. In fact, it may add likelihood to it, were the retrograde condition for the satellites be confirmed by observations of the system, in particular the determination of the direction of rotation of Haumea.

However, from a probabilistic point of view, it does not provide any improvement to the low odds of the whole scenario. On the contrary, the requirement that the family-forming collision should have happened after the end of the dynamical depletion phase confines the probability to the lower estimate reported in Table 3 for the 'post-LHB' phase in the S09 scenario ($0.1–0.6 \times 10^{-7}$).

2.3 Graze-and-merge collision (Leinhardt, Marcus & Stewart 2010)

Leinhardt, Marcus & Stewart (2010) carefully analyse the outcomes of coupled SPH–N-body simulations of collisions showing that it is necessary to claim for a grazing impact in order to achieve the necessary angular momentum of the Haumea's system. Their study is the most detailed available attempt to thoroughly reproduce the system and comes to the conclusion that a grazing collision, with impact parameter of 0.6–0.65 and relative velocity around 800–900 m s^{-1}, between two equal-sized bodies of radius ∼650 km, would produce a secondary merging collision with enough energy and angular momentum to disperse part of its mass into orbit and unbound, leaving a rotating primary with similar characteristics to Haumea. They also provide a size distribution of the escaping fragments forming the synthetic family, that is hardly comparable to the members of the observed group due to uncertainties in their albedos and thence, sizes.

Beyond the obvious caveats in extrapolating specific, parameter-dependent, SPH–N-body simulations to the real world, it has to be said that the model is reasonably successful as far as the physics is concerned. Nevertheless, the authors do not provide details about the mass and number of created satellites and rather quote a total orbiting mass of $0.01M_{\mathrm{lr}}$ (M_{lr} is the mass of the largest remnant in the collision), which is five times smaller than the satellite Hi'iaka's only mass, while their eccentricity looks very high ('below' 0.9) for the orbiting mass to be stable on the long term.

The main concern with this interesting scenario is about the very small probability to happen when analysed by ALICANDEP. Were the formation happened before the LHB phase, the probability for a collision with the required conditions is below 5 per cent. The total mass found in the simulations for the produced fragments is about 0.06 the mass of the largest remnant, of which they estimate that only 35–60 per cent would have the required velocity dispersion. This implies a total mass of the order of 20 times larger than the mass currently estimated for the 'family'. Instead of being a problem, that may turn into the right direction; in fact, when the system underwent the LHB phase, 99 per cent was quickly swept away by dynamical interactions.

A probability of $0.1–0.2 \times 10^{-2}$ is finally estimated by ALICANDEP for the collision to happen during the LHB phase, decreasing by two orders of magnitude after the LHB phase itself (see Table 3).

2.4 Collision-induced rotational fission (Ortiz et al. 2012)

Ortiz et al. (2012) introduced the idea that Haumea's parent body may have partially been a pre-shattered body – at least at its external layers – at the time when the system formed and show pieces of evidence for a rotational fission induced by a relatively low energetic collision that triggered the process.

A proto-Haumea body with a shattered mantle might have been rotating at spin rates close to disruption and eventually impacted by a much smaller body, around 1/50–1/20 the mass of the parent, that easily provoked rotational fission by stripping part of its mantle and formed a satellite.

It is easy to show that a collision by a 300–500 km size body, at typical classical disc relative velocities ($\leq 1\,\mathrm{km\,s^{-1}}$), off-axis along the target's equatorial plane, would provide enough angular momentum to trigger instability – and therefore fission – on the proto-Haumea body (Ortiz et al. 2012). This is true for a generic triaxial ellipsoid with axial ratios close to those estimated for Haumea and mass equal to that of the whole Haumea system (e.g. 4.1×10^{21} kg), rotating around its minimum inertia axis at 90 per cent its critical angular momentum.

The satellite-forming event may be able *per se* to produce fragments with a dispersion velocity of the order of that observed for the members of the dynamical group of Haumea, and even a secondary satellite, as recently shown by numerical experiments. This scenario is discussed in Ortiz et al. (2012), and a quantitative thorough study of these mechanisms is presented by means of *N*-body-based numerical simulations.

This mechanism has been able to provide most of the characteristics of the system but the exact mass ratio of Hi'iaka to Haumea nor the existence of Namaka (which is not created in any of the rest of proposed scenarios either). These dispersion velocities and the offset of Haumea in the orbital elements space are reasonably justified. The odds for such event are high (3 to 7 events) if we consider the pre-LHB period, but the same concerns about the survival of the family arise as in the other described scenarios. Nevertheless, we find a 10–20 per cent probability for such an event to happen during the LHB phase of evolution under ALICANDEP statistical analysis (see Table 3), that is significantly higher than found in previously discussed scenarios. The formation probability is also larger – even if still small – than for the rest of scenarios in the case of a post-LHB phase event (0.06–0.36×10^{-2}).

3 INDEPENDENT ORIGIN OF HAUMEA AND THE FAMILY

In addition to the serious statistical and physical difficulties of the current collisional scenarios for the formation of the Haumea system, just described, dynamical issues on the dispersion velocities of the family members (Volk & Malhotra 2012) encouraged us to look for alternative mechanisms of formation.

The formation of Haumea and its satellites and that of the family itself may not be necessary linked. The events that formed them may have involved two independent parent bodies on two independent – but close – orbits and happened at different epochs. The fact that we are observing the Haumea triple system and the family relatively close to each other in the orbital elements space (a, e, i) does not mean that they originated in the same event. In fact, as pointed out in Ragozzine & Brown (2009), 'Unfortunately, after a relatively short time, the coherence of the original orbital angles is lost, and at the present epoch only the proper semimajor axes, proper eccentricities, and proper inclinations are known'. Their following discussion justifies the coherence for members of the family, not for Haumea.

How could that happen? Let us take two distinct bodies: a proto-Haumea and a proto-family parent body. They may have had close orbital elements (a, e, i) even in the past, but they may have had different longitudes of the ascending node, Ω, that implies laying on different planes and/or different arguments of pericentre, ω, which means an orbit rotated with respect to the other (even in the case of being almost on the same plane, that is having similar Ω). Moreover, orbital elements $(a, e, i, \omega, \Omega)$ are a geometrical description and location of orbits, and even in the extreme case that the two parent bodies had very similar values for all orbital elements, still they might have been physically in very different positions. In fact, to determine the position of a celestial body on an orbit at a given time, a sixth orbital element is needed, namely the time (or the argument) of its passage at pericentre.

Table 2. Members of the Haumea family.

Asteroid		H	Diameter (km)
(55636)	2002 TX$_{300}$	3.20	325
(145453)	2005 RR$_{43}$	4.00	224
(120178)	2003 OP$_{32}$	3.95	230
	2009 YE$_7$	4.40	187
(19308)	1996 TO$_{66}$	4.50	178
(308193)	2005 CB$_{79}$	4.70	163
(24835)	1995 SM$_{55}$	4.80	155
	2003 UZ$_{117}$	5.30	123
	2003 SQ$_{317}$	6.30	78
(86047)	1999 OY$_3$	6.74	64

An alternative scenario is then possible. At some time, a collisional event triggering fission originated Haumea and its satellites, and some time before or after that event, a catastrophic collision on a parent body smaller than 500 km, in a different place, originated the family. In this case, even if they currently have retained similar orbital elements (a, e, i), the two groups of objects may have never been close in physical space because they may had different orbital elements Ω and ω. In this case, no common origin is required.

However, both Haumea and the family happen to have spectra showing water ice on their surfaces. This is clearly playing against the formation mechanism proposed in these lines, as very few objects in the EKB show similar features. Nevertheless, Trujillo et al. (2011) find significant unambiguous spectral differences between Haumea and the family members, characterized by the former having less water absorption ($J - \mathrm{H_2O} = -0.85 \pm 0.04$) than the latter ($J - \mathrm{H_2O} = -1.5 \pm 0.1$). A simple explanation for that is that they generated from different parent bodies. They are not the only TNOs showing water ice spectral feature, in fact Charon – Pluto's moon – has strong water ice features as well, even if in different amounts. Besides, the number of relatively large TNOs for which spectra are available is a small fraction of the number of objects in the region, and the discovery of a population of TNOs with similar characteristics cannot be ruled out.

The proposed scenario has the advantage of not needing unlikely mechanisms to explain – at the same time – both the presence of Haumea's satellites and an offset dynamical group of objects. On one hand, Haumea would just be an example of a multiple system in the trans-Neptunian region and – on the other hand – the family would just be the first one observed among TNOs; therefore, it should rather be referred to as the family of its brightest member (instead of the *Haumea family*).

The size of the parent body of the family can be estimated from its current known members. 10 known family members taken from Snodgrass et al. (2010) and Trujillo et al. (2011) are listed in Table 2. Their absolute magnitudes are taken from the JPL HORIZONS online Solar system data (http://ssd.jpl.nasa.gov/?horizons), and the diameters were estimated assuming that all the objects have an albedo of 0.88, which is the value found by Elliot et al. (2010) for (55636) 2002 TX_{300}. The sum of the volumes of all these objects provides an estimation of 430 km for the minimum diameter of the family parent body. Campo Bagatin & Benavidez (2012) and Marcus et al. (2011) find that this is right in the upper limit for likely shattering of large bodies in the EKB. ALICANDEP predicts the existence of at most one single family with such a large parent body, after the LHB period. Therefore, this could be the only dynamical family in the EKB with large enough members to be detected.

Observations of the bodies in the orbital elements space where the group of Haumea has been found are still needed in order to better characterize the number of its potential members. Also, a better estimate of their albedos and sizes is necessary so that the current mass of the family can be better estimated and probabilities of formation improved.

Since these objects have a youthful appearance due to their high albedo, it is possible that the family were created by a relatively recent collision. Their parent body could have had a highly irradiated surface with an albedo lower than that observed for the family members. Then, assuming an albedo of the family parent body of the order of the average albedo observed for hot classical objects ($p_v = 0.11 \pm 0.04$; Vilenius et al. 2012), the absolute magnitude of this body should have been $H = 4.80$–5.00. This assumption is supported by at least one object in the trans-Neptunian belt with a high fraction of water ice and a moderate albedo: (208996) 2003 AZ_{84} is a resonant object with a fraction of water ice of 0.42 ± 0.06, according to its spectrum (Fornasier et al. 2004), and an albedo of 0.123 ± 0.043 (Stansberry et al. 2008).

One crucial point in the validity of this scenario is to estimate the probability that the centres of mass of the two systems that feature today close semimajor axes, eccentricities and inclinations were completely independent objects in the past trans-Neptunian belt, with different values for the rest of their orbital elements. In order to do that, a distance between those two hypothetical bodies has to be defined in a suitable metric and a probability of finding the current distance has to be worked out.

The standard metric proposed is similar to that introduced by Zappalà et al. (1990, 1994, 1995) to search for asteroid families using the hierarchical clustering method, with the difference that in our case it is not necessary to express the distance in velocity units. In this metric, the distance is defined as $d = [k_a((a_1 - a_0)/\langle a\rangle)^2 + k_b(e_1 - e_0)^2 + k_c(\sin i_1 - \sin i_0)^2]^{1/2}$, where a, e and i are orbital elements of two objects, $\langle a\rangle$ is the average semimajor axis and $k_a = 5/4$, $k_b = 2$, $k_c = 2$ are constants. An alternative constant set, for example $k_a = 1/2$, $k_b = 3/4$ and $k_c = 4$ (Zappalà et al. 1990), produce similar results.

Using this metric, the distance between Haumea ($a = 43.00$ au; $e = 0.197$; $i = 28.2$ deg) and the barycentre of the family members ($a = 43.35$ au; $e = 0.126$; $i = 27.7$ deg; Lykawka et al. 2012) is $D = 0.1014$.

Therefore, the probability of finding two objects with $H \leq 4.8$–5.0 within such metric distance can be found by computing the ratio between the number of pairs of objects with distance $d \leq D$ and the total number of pairs of same size range in the population. The population of objects near Haumea was simulated using the synthetic model of the CFEPS (Petit et al. 2011), and the results are shown in Fig. 1. According to these results, the probability of finding an object with enough mass to have formed the family at a distance $D = 0.1014$ from Haumea is between 0.015 and 0.025. This calculation is made assuming the current number density of objects in the EKB and is valid for the post-LHB phase. In order to get a probability estimation for the LHB phase, we point out that the calculation of probability scales according to the product of the number of objects of each size. The change in number of objects was due to dynamic perturbations, then the number distribution simply scales like the mass and typical numbers in the considered region scale a factor of 40–50 at the considered sizes. Therefore, the probability of finding two objects within the defined metric distance scales as a factor of ~2000. That implies that – on one hand – the calculated probabilities would have been higher by about 2000 during the early LHB phase, when the number of objects was some 40–50 times larger than today. Now, that probability needs to be combined with the average Poisson probability of shattering collisions on ~430 km size objects, the size of the parent body of the family. This is calculated by ALICANDEP, resulting to be 0.40 over the whole age of the Solar system and a 0.30 probability is found after the LHB phase. In addition, the probability that the shattered object is the very object that was at the right metric distance calculated above is $1/N$, where N is the number of existing bodies of that size. In this case, $N \sim 500$–1000 in the present belt, while $N \sim 2$–4×10^4 at the beginning of the LHB phase. Therefore, the combined probability of the whole scenario is in the 0.1–0.3×10^{-3} range during the LHB phase and smaller than 0.15×10^{-4} in the post-LHB phase. These probabilities are of the same order as those found in the Leinhardt et al. (2010) scenario during or after the LHB case, and significantly smaller than those found in the case of Ortiz et al. (2012).

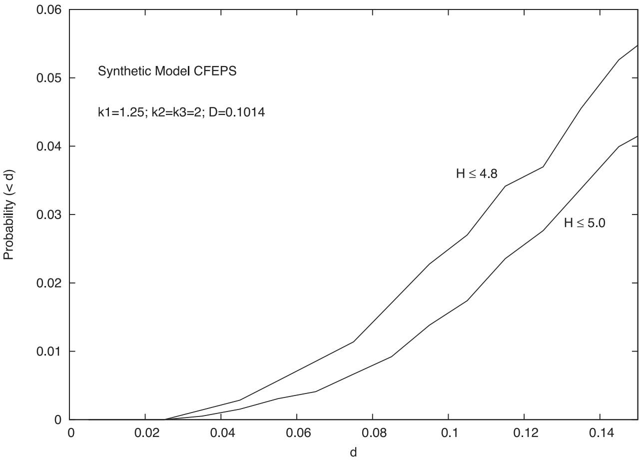

Figure 1. Probability of finding two objects with $H \leq 5.0$ and $H \leq 4.8$ at a distance less than d using the synthetic model of the CFEPS as population in the neighbourhood of Haumea.

However, this probability should be weighed against the odds of having both objects belonging to a very similar spectral type with common water features. Unfortunately, nothing is known about the true abundances of such types among TNOs. Future knowledge will make it possible to find an estimation of the abundance of such objects and thence combine probabilities accordingly. However, as a reasonable estimation, the probabilities in this case should be reduced by about one order of magnitude, based on available – though loose – estimations of the likelihood of the existence of a population of icy bodies (Barkume, Brown & Schaller 2008).

3.1 'Quasi-independent' origin of Haumea and the family

We outline here an example of the possible alternative mechanisms that may be figured out assuming an independent origin. It is beyond

Table 3. Probabilities of the scenarios discussed in the text, according to different dynamical evolution phases. Namely, pre-LHB refers to the period preceding the instability phase; LHB to the instability phase itself, post-LHB to the period from the end of the stability phase to the present. Different scenarios are identified by 'B07' (Brown et al. 2007), 'S09' (Schlichting & Sari 2009), 'L10' (Leinhardt et al. 2010), 'O12' (Ortiz et al. 2012) and 'IO' (independent origin, in this work).

Phase	B07	S09	L10	O12	IO
Pre-LHB	$<10^{-9}$	$(0.1–1) \times 10^{-6}$	$(0.16–0.46) \times 10^{-1}$	3–7	N/A
LHB	$(0.06–0.21) \times 10^{-5}$	$(0.3–1) \times 10^{-7}$	$(0.11–0.22) \times 10^{-2}$	0.10–0.20	[a]$(0.1–0.3) \times 10^{-3}$
Post-LHB	$(0.09–0.15) \times 10^{-4}$	$(0.12–0.63) \times 10^{-7}$	$(0.05–0.74) \times 10^{-4}$	$(0.06–0.36) \times 10^{-2}$	[a]$(0.04–0.15) \times 10^{-4}$

Note. [a]In the case of the 'purely independent' (IO) scenario, this probability should be weighed by the spectral abundance of objects showing water features, roughly estimated as 0.1.

the scope of the present work to thoroughly examine this scenario as ad hoc numerical simulations should be carried out to suitably explore the parameter space.

Nesvorný, Youdin & Richardson (2010) examined the possibility that TNO binaries formed during gravitational collapse when the excess of angular momentum prevented the agglomeration of available mass into a solitary object. This apparently took place during the coagulation growth of bodies in the early EKB. This process may lead to a variety of outcomes, as was shown by numerical simulations in the mentioned paper and in Tanga et al. (2009), not all of them necessarily leading to binary formation. We outline here that an excess of angular momentum may generate two bodies with total positive energy, that is an unbound system. In this way, a population of pairs of objects with common origin may have formed. In the very case of Haumea, one of the bodies may – or may not – retain mass to form satellites, and the other one would have run away from the largest one and could eventually be shattered at any later time. That would naturally explain the offset in orbital elements between Haumea and the family itself, and it would also naturally explain the fast rotation period of Haumea. This scenario is a way in between the 'independent origin' proposed in this paper and the pure rotational fission scenario in Ortiz et al. (2012): even a small collision (one of the mechanisms put forward in that paper) would not be required to trigger fission, which occurred simply because the collapsing cloud had too much angular momentum for a single body to withstand it. The Haumea system would be the only one of the 'pairs' formed in the accretion phase whose secondary components were shattered at some point.

In this case, the probability of formation can be estimated from that calculated for the 'independent origin' scenario. Here it is not necessary to combine the probability with the whole population of 400 km bodies, as there is nothing special in any of the two parent bodies and we would just be observing the only system for which a collision on the secondary body took place. In addition, there would be no need to weigh this probability against any given spectral abundance. In fact, the two parent bodies would both come from the same region and share very similar chemical composition. Therefore, the probabilities would be significantly larger and would be at least 40 per cent by the end of the LHB phase and somewhat larger ($0.2–1.5 \times 10^{-2}$) than those found in the case of Ortiz et al. (2012) in the post-LHB period. Nevertheless, despite promising statistical estimates of collisions, we do not include this scenario among the ones listed in Table 3, as it needs a dedicated study to model and assess the conditions under which it would be likely also from a physical point of view.

4 SUMMARY AND CONCLUSIONS

We have analysed the collisional mechanisms proposed in the literature for the formation of the Haumea system, trying to assess their likelihood on the basis of physical, dynamical and statistical considerations, and we put forward a different genesis for Haumea and its satellites and for the family. The probabilities of different scenarios – during different dynamical phases in the frame of the Nice model collisional evolution and beyond – are calculated and summarized in Table 3.

From our analysis, serious doubts arise about an origin based on a single high-velocity catastrophic collision, as proposed by Brown et al. (2007) – even including the improvements introduced by Levison et al. (2008a) – due to its difficulties on physical and statistical grounds.

The scenario proposed by Schlichting & Sari (2009, S09) is a multi-collision mechanism that does not appear to be very likely from our analysis either; nevertheless it is particularly interesting as it introduces the idea that a secondary collision on a previously formed proto-satellite may be the key to the formation of the system itself. Ćuk et al. (2013) introduce modifications to this scenario that do not significantly affect the calculated probabilities.

The problem is fairly well studied by Leinhardt et al. (2010, L10) from a physical point of view, even if their scenario finds troubles on a dynamical ground and the only statistical odds (with probability smaller than <5 per cent) to have taken place before the LHB instability phase, making it however very unlikely to get intact to present times.

An improvement in the understanding of the formation process is found in Ortiz et al. (2012) that argue on the possibility of formation by an induced fission on a parent body with a fragmented mantle. This mechanism has the advantage to be two orders of magnitude more likely than other mechanisms, when considered from the point of view of the dynamical and collisional evolution of the outer Solar system, reaching a 20 per cent during the LHB phase.

In this work, we introduce the simple idea that Haumea and its satellites might have formed independently from the rest of the so-called family members. In fact, initial coherence of orbital elements (a, e, i) for the whole system does not grant any coherence for the rest of orbital elements, that is necessary to state a common origin. The formation of the family on its own could be explained by a catastrophic collision on an object of the order of 430 km, happened in a different epoch with respect to the event that generated the triple system of Haumea and satellites. Our simulations show that the end of the LHB phase is the best candidate period for that event. Unfortunately, the common spectral features of Haumea and the family members lower the probability of such a scenario by an unknown factor due to poor knowledge of relative spectral abundances in the EKB. In fact, this scenario requires a population of objects with water ice features that – even if it cannot be ruled out – has not yet been discovered, but it has been grossly estimated as not larger than 10 per cent of the overall populations.

Instead, having the two parent bodies originated as an unbound system during gravitational collapse at the time the coagulation growth of bodies was taking place in the early EKB (quasi-independent origin) would provide a common chemical origin and probabilities at least of the order of those found in the Ortiz et al. (2012) scenario. This has to be further explored and modelled to be assessed as a likely mechanism though.

We mean to point out that an independent origin is another low-probability event as are most of the multi-collisional scenarios proposed to date.

The previous sections have shown that most of the proposed scenarios for the formation of the Haumea system seem to have small probabilities to happen. The best case – from a statistical point of view – has a probability smaller than 20 per cent to happen during the LHB phase, with the trouble to survive intact until now, and a probability below 10^{-2} after the LHB period. It is obvious that a small-probability event may indeed happen in nature, but it is certainly disappointing that our analysis gives such small odds provided it provides good matches to current observables in the trans-Neptunian region and – for instance – gives very reasonable probabilities (close to 1) for the formation of the Pluto–Charon system (Campo Bagatin & Benavidez 2012).

We explored the cases in which the boundary conditions of the evolution are dramatically changed with respect with a 'pure' Nice model case. In particular, introducing an early beginning of the instability phase does not improve the probabilities found; on the contrary, as dynamical depletion starts early, the odds for collisions decrease.

The existence of the Haumea system is observational evidence that is predicted with relatively low probabilities according to the current understanding of collisional and dynamical evolution of the EKB. Even when the boundary conditions of the dynamical and collisional evolution are varied inside wide ranges (as explained in Section 1.1), the probabilities calculated by ALICANDEP do not increase substantially. The changes in boundary conditions influenced the outcome of the evolution model still into the uncertainties of the populations predicted by the CFEPS survey for TNOs and still roughly met the current observables in the TNO region. No substantial changes in the collisional probabilities arose. It is worth pointing out that these modifications go beyond the limitations of the Nice model itself and the results show that the collisional evolution is not very sensitive – in terms of overall collisional probabilities – to such changes in boundary conditions. That supports the idea that we should not expect major changes in collisional probabilities within a general picture of a period of strong dynamical excitation following a densely packed low-velocity regime and preceding a long stationary period, whatever the very details of the model are.

These arguments may lead to two alternative conclusions: either the current dynamical or collisional understanding of the evolution of the EKB – and its modelling – has to be deeply revised, or the Haumea system is just a low-probability outcome occurred in the history of the outer Solar system. Further investigation of the family members and the discovery of more water ice features in isolated bodies in the EKB may contribute to improve our understanding of the puzzling system of the dwarf planet Haumea, which – in turn – will provide important clues on interesting features of that region of the Solar system.

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