Monthly Notices
of the
ROYAL ASTRONOMICAL SOCIETY

Mon. Not. R. Astron. Soc. **419,** 2315–2324 (2012) doi:10.1111/j.1365-2966.2011.19876.x

Rotational fission of trans-Neptunian objects: the case of Haumea

J. L. Ortiz,[1]⋆ A. Thirouin,[1] A. Campo Bagatin,[2,3] R. Duffard,[1] J. Licandro,[4]
D. C. Richardson,[5] P. Santos-Sanz,[1,6] N. Morales[1] and P. G. Benavidez[2,3]

[1] *Instituto de Astrofísica de Andalucía - CSIC, Apt 3004, 18008 Granada, Spain*
[2] *Departamento de Fisica, Ingenieria de Sistemas y teoria de la Señal, Universidad de Alicante, PO Box 99, 03080 Alicante, Spain*
[3] *Instituto de Física Aplicada a las Ciencias y la Tecnología, Universidad de Alicante, PO Box 99, 03080 Alicante, Spain*
[4] *Instituto de Astrofisica de Canarias, C/ Via Lactea sn La Laguna, Tenerife, Spain*
[5] *Department of Astronomy, University of Maryland, College Park, MD 20742-2421, USA*
[6] *Observatoire de Paris, LESIA-UMR CNRS 8109, 5 place Jules Janssen, F-92195 Meudon cedex, France*

Accepted 2011 September 22. Received 2011 September 19; in original form 2011 March 28

ABSTRACT

We present several lines of evidence, based on different kinds of observations, and we conclude that it is likely that rotational fission has occurred for a fraction of the known trans-Neptunian objects (TNOs). It is also likely that a number of binary systems have formed from that process in the trans-Neptunian belt. We show that Haumea is, potentially, an example of an object that has suffered rotational fission. Its current fast spin would be a slight evolution of a primordial fast spin, rather than the result of a catastrophic collision. This is because the percentage of objects rotating faster than 4 h would not be small in a Maxwellian distribution of spin rates, which fits the current TNO rotation data base. Besides, the specific total angular momentum of Haumea and its satellites falls close to that of the high-size-ratio asteroid binaries, which are thought to be the result of rotational fission or mass shedding. We also present *N*-body simulations of rotational fission applied to the case of Haumea. These show that this process is feasible; it might have generated satellites, and it might have even created a 'family' of bodies orbitally associated to Haumea. The orbitally associated bodies might come from the direct ejection of fragments, according to our simulations, or through the evolution of a proto-satellite formed during the fission event. The disruption of an escaped fragment after the fission might also create the orbitally related bodies. If any of these mechanisms are correct, other rotational fission families could be detectable in the trans-Neptunian belt in the future. Perhaps, TNO pairs might even be found (i.e. pairs of bodies sharing very similar orbital elements but not bound together).

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

1 INTRODUCTION

Our Solar system contains a large number of icy bodies beyond Neptune's orbit. These objects are collectively referred to as trans-Neptunian objects (TNOs), although they are also known as Edgeworth–Kuiper belt objects (EKBOs), or simply Kuiper belt objects (KBOs). These icy bodies are thought to be leftovers from the formation process of the Solar system and they are believed to contain the most pristine material of the Solar system beyond the ice line. They are also thought to be the source of short-period comets (Fernandez 1980), although many details of the mechanisms that bring the material from the trans-Neptunian region to the inner Solar system are still missing. A wealth of knowledge on the trans-Neptunian region has been accumulating since the discovery (Jewitt & Luu 1993) of the first TNO in 1992 (after Pluto and Charon). However, the study of TNOs is still a young field, and there are still many open questions.

A topic that has attracted particular interest within the science of TNOs is binarity. Binaries are a powerful means to study the trans-Neptunian belt because they can allow us to derive the masses and densities of their components (by assuming some mean albedo value). Also, TNO binaries appear to be quite common (Noll et al. 2008).

Several mechanisms of binary formation have been proposed for TNOs, most of which have been reviewed by Noll et al. (2008).

⋆E-mail: ortiz@iaa.es

There are also newer binary formation scenarios, such as direct collapse (Nesvorný, Youdin & Richardson 2010). However, rotational fission has not been particularly investigated in the case of TNOs. This mechanism is thought to be an important source of binaries in the near-Earth asteroid (NEA) population of objects (e.g. Walsh, Richardson & Michel 2008). The sizes and compositions of these objects are apparently very different from those of the much larger TNOs that we can currently observe. Although the preferred formation mechanisms of most of the binaries in the trans-Neptunian belt is the capture scenario (e.g. Noll et al. 2008), rotational fission might also provide a fraction of the observed high-mass-ratio binary systems, and other binaries with small specific angular momentum. It would be useful to know approximately what fraction should be expected. The study of rotational fission is important not only for binarity studies, but also for our general understanding of the trans-Neptunian belt.

In this paper, we present some evidence to show that the rotational fission of TNOs is a relevant mechanism, especially for large TNOs, and we study the case of Haumea in detail. Haumea (previously known as 2003 EL_{61}) is a good candidate to study because of its large size and fast spin (Rabinowitz et al. 2006). We also present numerical simulations of the spontaneous rotational fissions of large TNOs, which we apply to Haumea. In addition, we consider whether subcatastrophic collisions can induce the rotational breakup of primordial bodies that were already fast rotators, and we discuss the stability of the binary/multiple systems formed after rotational fissions.

2 OBSERVATIONAL CLUES FOR THE EXISTENCE OF ROTATIONALLY FISSIONED BODIES

After studying the rotational parameters of several TNOs, Ortiz et al. (2003) showed that a material strength of ∼1000 kPa is needed for TNOs to withstand shear fracturing and to remain intact. Therefore, objects having a smaller material strength than this value would not be intact – they would be damaged and would have fractures. We suspect that most TNOs have a material strength smaller than 1000 kPa (because the material strength of their relatives – the comets – is orders of magnitude smaller than this). Thus, we suspect that most of the TNOs are structurally damaged objects (i.e. partially or completely fractured bodies). Therefore, at least some TNOs might be able to break up easily as a result of rotation. Besides, the mass of 'large' TNOs would be sufficient to overcome rigid body forces and therefore these TNOs would be in hydrostatic equilibrium. The issue of how large these bodies must be in order to be in hydrostatic equilibrium is still unclear (Tancredi & Favre 2008; Duffard et al. 2009) because there are still a number of unknowns about the mechanical behaviour of the icy mixtures that form the TNOs. For these kinds of bodies, which are not dominated by rigid body forces, it might be interesting to study rotational fission from the perspective of the physics of fluid bodies.

From Maxwellian distribution fits to the observed rotation rates of TNOs (Duffard et al. 2009), it is immediately apparent that the spin distribution implies that ∼20 per cent of very fast rotating objects would not be able to remain in hydrostatic equilibrium for the typical densities of TNOs. Such densities are likely to be around 1000–1500 kg m^{-3}. Fig. 1 shows a Maxwellian distribution that fits the observed distribution of the known rotational periods of TNOs compiled in Duffard et al. (2009), with additional data from Thirouin et al. (in preparation). A Maxwellian distribution arises if the three components of the angular velocity are distributed according to a Gaussian with zero mean values and equal dispersions; such distributions have frequently been compared to histograms of the rotation rates of asteroids (Binzel et al. 1989).

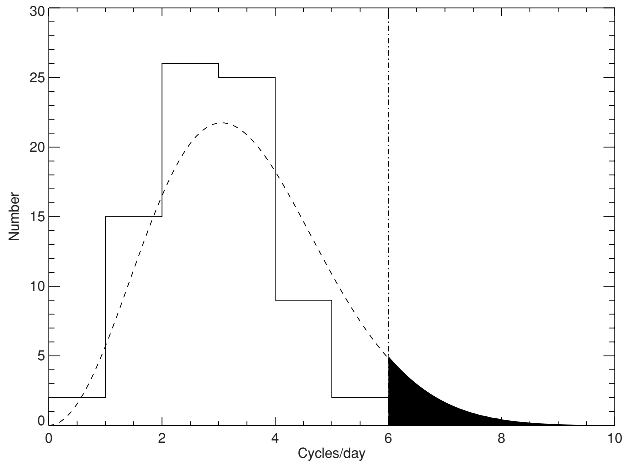

Figure 1. The Maxwellian distribution that fits the observational data base on rotation rates, taken from Duffard et al. (2009) plus recent results from Thirouin et al. (in preparation). The black shaded area under the curve indicates the percentage of objects that should spin faster than 4 h (six cycles per day). Such an area is not a very small fraction of the total area.

The spin frequency distribution we see today is the evolution of the primordial one. The primordial spin distribution changed as a result of frequent collisions in the early ages of the Kuiper belt. At that epoch, the trans-Neptunian belt was very massive and the collisional evolution was intense (Davis & Farinella 1997; Benavidez & Campo Bagatin 2009). Because collisions can spin up or spin down the bodies, the final distribution of rotations can include a fraction of objects spinning faster than the average initial spin frequency. We believe that a fraction of the objects that underwent net spin-up ended up suffering rotational fissions because they reached their critical rotation speeds.

The shaded area in Fig. 1 indicates the percentage of objects with a spin faster than ∼4 h, which is expected from our Maxwellian fit. Specifically, in Duffard et al. (2009), we show that ∼15 per cent of the objects cannot be equilibrium figures for a typical density of 1500 kg m^{-3}, whereas the percentage rises to 25 per cent for a density of 1000 kg m^{-3} (see fig. 6 of Duffard et al. 2009). In other words, around ∼20 per cent of the objects would have suffered fission as a result of rotation. Furthermore, there is additional observational evidence to suggest the existence of a spin barrier of around 3.9–4 h in the observational data (e.g. Duffard et al. 2009; Thirouin et al. 2010) below which no TNOs are found. This possibly indicates that the bodies predicted in the Maxwellian distribution below ∼4 h have already broken up.

It can be argued that we do not see objects spinning faster than ∼4 h simply because they could not form in the accretion phase. However, our view is that these objects did not form, but the objects that formed from the accretion phase suffered an intense collisional environment, which accelerated some of them and slowed down others. Those TNOs that suffered spin-up to a significant degree would undergo a significant mass loss if their critical rotation periods were reached. As already stated, we do know that there was an intense collisional evolution in the early phases of the Kuiper belt, and thus we think that the spins were significantly altered in this phase. From this point of view, most of the rotational fissions would have taken place in the first Gyr after the formation of the Solar system, when collisions were more frequent.

After a fission, at least part of the material ejected from the parent body can form a satellite. In the case of asteroids, it is well known that the formation of a satellite is one of the outcomes of rotational fission. Similarly, binary or multiple systems might be, or might have been, common within the trans-Neptunian region. Nevertheless, if they are as old as a few Gyr, the effects of dynamical interactions and subtle collisions could have destroyed a large fraction of binary and multiple systems.

Since our previous paper (Ortiz et al. 2003), we have been expecting to find fast rotators in the TNO population, which would allow us to study these mechanisms in detail. Haumea, formerly known as (136108) 2003 EL_{61}, turned out to be an excellent candidate for this. Its very fast rotation (e.g. Rabinowitz et al. 2006) could perhaps make it a typical case of a rotational fission, and the existence of small satellites also argues in favour of the object being the remnant of a rotational fission process. Thus, we have chosen this object as the best case to study.

There are other observations that might indicate the existence of TNO binaries originating from rotational breakup. One of these cases could be the Orcus system. The specific total angular momentum of the system is very close to that of an object that has the same size and mass but is spinning near its critical spin rate. The details of the study of Orcus and other useful data are presented in Ortiz et al. (2011). Regarding the NEA population, a similar argument was made to point out that the mechanism of rotational disruption appears to be the formation scenario for many binaries (Pravec et al. 2006).

3 THE CASE OF HAUMEA

2003 EL_{61} (Haumea) is a dwarf planet with a tri-axial shape (2000 × 1500 × 1000 km^3), a mass of 4.006×10^{21} kg (Ragozzine & Brown 2009) and a short spin period of 3.92 h. Two satellites, Hi'iaka and Namaka, are orbiting Haumea at 49 880 ± 198 km and 25 657 ± 91 km, respectively, and have mass ratios relative to Haumea of 1/200 and ~1/2000, respectively (Ragozzine & Brown 2009). A group of TNOs has been dynamically associated to this system and is frequently called Haumea's 'family'. This term has been imported from the study of the asteroid belt, where it refers to groups of objects that are very close in the proper-elements space and that comply with suitable tests to establish their clustering.

It has been hypothesized that Haumea is a fast spinning object as a result of a catastrophic collision that would have spun up the body and would have, at the same time, also created its two satellites and a collisional family (Brown et al. 2007). However, the claim that a catastrophic collision would have resulted in a large body spinning quickly and, by serendipity, near its rotational breakup limit is not supported by analytical or numerical works. In fact, there is evidence to the contrary. Takeda & Ohtsuki (2009) studied the rotation end state of rubble-pile asteroids after collisions of different sorts, by means of *N*-body numerical simulations. They showed that after catastrophic collisions in a wide range of geometries, the largest remaining body always rotated slower than it did prior to catastrophic collisions.

If these results for rubble piles are applicable to bodies in hydrostatic equilibrium, the fast rotation rate of Haumea would not appear to be the result of a catastrophic collision. It would be difficult to imagine that Haumea had ever been rotating faster than today. In fact, the required density and material strength – in the fluid approximation – would have to be even higher than its highest estimated density of around 2700 kg m^{-3} (Rabinowitz et al. 2006), a much higher density than that of Pluto. Therefore, it seems more plausible that Haumea has been a fast spinning object ever since its formation.

Besides, using the collisional and dynamical evolution model of Campo Bagatin & Benavidez (in preparation, hereafter CB2011), the probability of a catastrophic collision for a very large object such as Haumea is less than 7×10^{-6} (CB2011).

It is necessary to come up with very artificial mechanisms, such as the collision of two scattered disc objects resulting in a classical belt object, to obtain a small chance of a catastrophic event (Levison et al. 2008). Besides, the alleged collisional 'family' of Haumea has estimated dispersion velocities that are not consistent with those implied by the proposed collision.

Another collisional scenario has been put forward by Schlichting & Sari (2009) to explain Haumea's 'family'. They propose the formation of a large satellite in an initial subsonic speed impact. The satellite would subsequently be destroyed by a second collision, and this process would form the current two satellites together with the 'family' itself. The potential weaknesses of this model are the uncertainties in the collisional physics at subsonic speeds for objects thousands of km in size and the low probabilities (<0.3 per cent) for the overall process to take place (CB2011). Finally, in the time-span required for the second collision, the tidal interaction between the former satellite and Haumea would have slowed down Haumea's spin, so that its current fast rotation could not be explained.

The probability for the grazing collision scenario described in Leinhardt, Marcus & Stewart (2010) to occur is less than 0.01 per cent after the late heavy bombardment (LHB) period and less than 0.1 per cent before its end (CB2011). As with the other scenarios, using this scenario, it is also difficult to explain the survival of the 'family' after the onset of the LHB phase some 4 Gyr ago (CB2011). In this phase, according to the Nice model (Gomes et al. 2005; Morbidelli et al. 2005; Tsiganis et al. 2005), the mass of the region was reduced to, at most, 5 per cent of the starting mass by dynamical effects. This means that the current mass of the family should be at least 20 times larger, implying that there was a larger parent body and that the system was created by an even more unlikely event. The stability of the satellites in this phase clearly cannot be taken for granted either.

Because there are difficulties with all the proposed scenarios, it seems natural to explore a different scenario to explain Haumea's remarkable properties. Rotational fission appears as a natural alternative process. Here, we propose that Haumea's parent body (which we call proto-Haumea) was born already rotating fast and that it subsequently suffered a rotational fission, which perhaps created its satellites and might have provided the mass of Haumea's 'family'. In order to cause the spin-up of an isolated rotating system, additional angular momentum must be provided by an external cause. In the NEA case, a torque resulting from the Yarkovsky–O'Keefe–Radzievskii–Paddack (YORP) effect causes the spin-up. We do not know the exact reasons for spin-up in the trans-Neptunian region. Rotational fission could be induced by a subcatastrophic collision (these events were not at all unlikely, contrary to the catastrophic collision scenario), providing enough angular momentum to trigger the process. A moderately disruptive (non-catastrophic) collision might have transferred the slight amount of angular momentum needed to trigger a rotational fission. Takeda & Ohtsuki (2007) have shown from numerical simulations that, in moderately disruptive impact events, 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 slightly disruptive, not catastrophic.

It is straightforward to show that for a generic triaxial ellipsoid with size and mass close to those estimated for Haumea, rotating close to its critical angular momentum, a cratering collision with a body with a size of 300–500 km at typical classical disc relative velocities ($\leq$1 km s^{-1}), off-axis along the target's equatorial plane, would provide enough angular momentum to trigger instability, and therefore mass loss, on the proto-Haumea body. This type of collision was statistically relatively common ($\sim$1 per cent) in the past, especially in the early Solar system up to the end of the LHB phase, when hundreds to thousands of Pluto-sized objects still dwelled in the disc.

As described in Section 2, from the Maxwellian distribution that best fits the current data base on TNO rotations, we find that the percentage of objects that should have ended up with rotation rates below 4 h is not small (see Fig. 1). Thus, we expect that many TNOs acquired a 'high' rotation rate.

3.1 Haumea's satellites: specific angular momentum

The specific angular momenta (H) of the systems formed respectively by Haumea + Namaka and Haumea + Hi'iaka are both around 0.3 (see Fig. 2), while the scaled spin rate (Ω') is around 0.6. We computed H (equation 1) according to Descamps & Marchis (2008) and Ω' (equation 5) according to Chandrasekhar (1987). Specifically,

$$H = \frac{q}{(1+q)^{13/6}}\sqrt{\frac{a(1-e^2)}{R_\mathrm{p}}} + \frac{2}{5}\frac{\lambda_\mathrm{p}}{(1+q)^{5/3}}\Omega + \frac{2}{5}\lambda_\mathrm{s}\frac{q^{5/3}}{(1+q)^{7/6}}\left(\frac{R_\mathrm{p}}{a}\right)^{3/2}, \quad (1)$$

where q is the secondary-to-primary mass ratio, a is the semimajor axis, e is the eccentricity and R_p is the primary radius. The Ω parameter is the normalized spin rate, expressed as

$$\Omega = \frac{\omega_\mathrm{p}}{\omega_\mathrm{c}}, \quad (2)$$

where ω_p is the primary rotation rate and ω_c is the critical spin rate for a spherical body:

$$\omega_\mathrm{c} = \sqrt{\frac{GM_\mathrm{p}}{R_\mathrm{p}^3}}. \quad (3)$$

Here, G is the gravitational constant and M_p is the mass of the primary. Assuming a triaxial primary with semi-axes as $a_o > a_1 > a_2$, the λ_p shape parameter is

$$\lambda_\mathrm{p} = \frac{1+\beta^2}{2(\alpha\beta)^{2/3}} \quad (4)$$

where $\alpha = a_2/a_0$ and $\beta = a_1/a_0$.

In this paper, we consider the satellites to be spherical bodies, so λ_s=1.

Finally,

$$\Omega' = \frac{\Omega}{\sqrt{\pi G \rho}}, \quad (5)$$

where ρ is the density of the object.

The specific angular momenta and scaled spin rates of the systems formed by Haumea + Hiiaka and Haumea + Namaka fall within the 'high-size-ratio binaries' circle in fig. 1 of Descamps & Marchis (2008). They studied the binaries in the asteroid population (near-Earth, main belt and Jupiter trojan asteroids) and they came to the conclusion that these systems very likely arise from rotational fission or mass shedding. Therefore, Haumea's system falls into that same class of binaries, supporting the idea that the system might come from a fission process rather than a catastrophic collision.

Pravec et al. (2006) have also pointed out that the specific angular momentum of most asynchronous binary systems in the NEA population is similar (within 20 per cent uncertainty) and close to the angular momentum of a sphere with the same total mass (and density) rotating at the breakup limit. This suggested to them that binaries were created by mechanisms related to rotation close to the critical limit for break up.

In the next section, we turn to numerical simulations of the rotational fission of a fast-spinning body gently spun up until it breaks up. We also simulate a final rotational disruption triggered by a small impact.

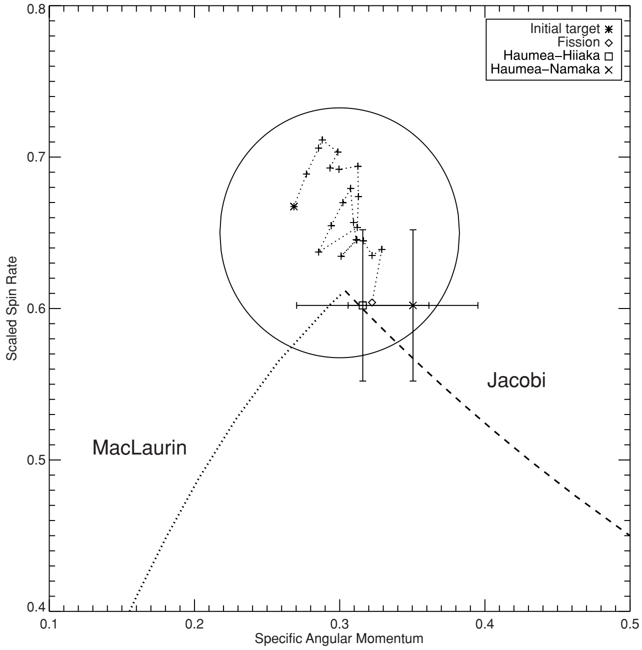

Figure 2. Scaled spin rate versus specific angular momentum of the systems formed by Haumea + Namaka and Haumea + Hi'iaka (asterisk and square symbols, respectively). Each cross represents a small increase of angular momentum in a synthetic body, as described in Section 3.2. The diamond symbol indicates the point where the proto-Haumea underwent fission. The proto-Haumea underwent fission near the Jacobi–MacLaurin transition point in the zone of high-size-ratio binaries, as shown by the circle (Descamps & Marchis 2008).

3.2 Numerical simulations of rotational fissions

In order to carry out our fission simulations, we have assumed that at least some of the TNOs are gravitational aggregates. Housen (2009) performed laboratory experiments showing that N collisions (each with energy Q_S^*/N, i.e. 1/Nth the threshold specific energy for the fragmentation of the target) cause the same amount of structural damage, into the target itself, as a single collision at Q_S^*. Therefore, N subcatastrophic collisions can finally shatter a large target without ejecting mass and producing a cohesionless structure, which is similar, in many respects, to a gravitational aggregate.

A gravitational aggregate behaves almost like a fluid when it comes to rotation. The situation is not exactly the same because of the presence of some shear strength (Holsapple 2008), and it can be numerically handled with the help of a suitable N-body code (Tanga et al. 2009). Therefore, by studying the rotational fission of gravitational aggregates, we can also obtain an approximation of the behaviour of rotating objects in hydrostatic equilibrium, which, by definition, are dwarf planets. In other words, we do not expect TNOs larger than 1000 km to be gravitational aggregates, as their interiors are very likely in hydrostatic equilibrium. However, the shape they adopt and their general response to rotation can be approximated with the structure of a gravitational aggregate.

In order to study the possibility of forming binary systems by having large gravitational aggregates undergo rotational fission, we performed numerical simulations of the processes using the PKDGRAV *N*-body code (Richardson et al. 2000, 2009; Stadel 2001). This code has the advantage of performing both the numerical integration of mutual gravitational interactions between the mass components (considered as hard spheres) of a given gravitational aggregate, and the calculation of the collisional interactions between any pair of such components. Gravitational aggregates have shear strength, because of the finite particle sizes and the confining pressure of gravity. This is automatically taken into account by PKDGRAV. However, shear stress (resistance to sliding) is not included in the code, but the instantaneous rotation of components is considered whenever a collision occurs. It is straightforward to show that the work necessary to move a cubic mass across one of the faces of an equal-mass cube, in the presence of friction, is only 28 per cent larger than the work necessary to rotate a sphere (with the same volume as the cube) over a quarter of the surface of an equal-mass sphere. So, the code is underestimating surface friction in this case. Nevertheless, if the calculation is made considering cubes and spheres with equal surfaces (instead of volumes), the equivalent work is 17 per cent smaller in the case of the sliding cubes than in the case of the rotating spheres, and now the code is overestimating surface friction. In any case, as the true situation inside a gravitational body involves both dissipative sliding and rotation of irregularly shaped components, and as the two calculated effects are of the same order, it can be assumed that the code accounts for surface friction to some extent.

Coming to the numerical simulations that have been performed, the first step of the process is the generation of a fast-spinning object with a total mass of around 4.5×10^{21} kg. Such a gravitationally held object has comparable mass and size to Haumea, with a mass some 10 per cent larger in order to account for mass loss as the system is formed. The proto-Haumea body is generated by means of a coagulation method starting from a spinning nebula of 1000 equal-sized particles, which generates a stochastic pile of spheres with no preferential geometrical structure (Tanga et al. 2009). The physical characteristics of a typical proto-Haumea body generated in this way are listed in Table 1.

Table 1. Physical characteristics of target 1 (the proto-Haumea generated for the simulations of the pure rotational fission scenario, S1). Target 2 is the body created after the twentieth spin-up of scenario S1. Target 2 is used in the collisionally induced rotational fission (scenarios S2 and S3). Target 3 is the target used for the S4 scenario. The physical properties of the projectile used for simulations S2, S3 and S4 are also listed. N is the number of particles, a_1, a_2 and a_3 are the semi-axes of the body, ρ_b is the initial bulk density and T_0 is the initial rotation period.

Object	N	Mass (kg)	a_1, a_2, a_3 (km)	ρ_b (g cm^{-3})	T_0 (h)
Target 1	866	4.48×10^{21}	$1362 \times 744 \times 513$	2.1	3.98
Target 2	797	4.12×10^{21}	$1620 \times 611 \times 483$	2.1	4.52
Target 3	846	4.38×10^{21}	$1355 \times 641 \times 506$	2.4	3.64
Projectile	183	1.92×10^{20}	$349 \times 338 \times 294$	1.3	No rotation

The scenarios mentioned in Section 2 for the formation of a primary and a satellite were studied by using four sets of simulations, as follows.

S1. In the sequences of gentle spin-ups of the parent body, 21 small increments of angular momentum were performed until fission occurred. The object is allowed enough time to adjust itself to the corresponding equilibrium figure of rotation between successive increments of angular momentum. This technique is used in order to look for the object's disruption limit in a very smooth way, avoiding sharp accelerations to the body's rotation.

S2. These simulations are induced rotational fissions, which are equivalent to S1 until the twentieth spin-up step is done. This was done to simulate a situation in which a proto-Haumea is originally rotating fast when, at some point, a low-energy collisional event occurs. The last step is performed by means of a collision that provides enough angular momentum to trigger fission. The relative speed of the collision is 1 km s^{-1}, the average impact speed in most of the main classical belt of TNOs. This simulation is performed in order to answer the straightforward question that can arise after S1: why should a 2000-km-sized body increase its own angular momentum at some point? In the asteroid belt, the YORP effect is able to spin up bodies up to a few km in size, and close encounters with planets might also have a similar effect on NEAs. Nevertheless, no effect like the YORP effect is available for a body of Haumea's size and at heliocentric distances of the order of 40 au, and planetary close encounters are not likely in the trans-Neptunian region. Comets can speed up their rotations from the torques created by sublimating material on their surfaces. However, this effect will also be too small for TNOs, which are considerably larger than usual comets. The most likely process capable of triggering the fission of a TNO that is already spinning fast seems to be a collision.

S3. This is a faster collision than in S2, which provides more angular momentum than is strictly needed for a fission. The collision is performed at 3 km s^{-1}. The relative speeds that have been tested are close to, or even above, the limit for sound speed in the target body. In a homogeneous body, simulations of hypervelocity collisions must include the damage produced by the propagation of the shock wave into the body structure, as in smoothed particle hydrodynamics (SPH) simulations. Nevertheless, this consideration does not invalidate our technique because we are dealing with bodies that have, at least, a crust of heavily fragmented material. In such environments, the shock wave is rapidly extinguished (Asphaug 1999). The damage is limited to the collisional area, where part of the energy is dissipated and the rest of the energy is available for dissipative collisions and rotations to occur between the fragments forming the outer structure of the body itself.

S4. This fourth scenario corresponds to simulations in which a different target is impacted by the projectile at 3 km s^{-1}. Except for the target, this scenario is the same as S3. In S4, the target has a different number of particles and rotation period, compared to S2 and S3. The characteristics of this target and those of S2 and S3 are listed in Table 1.

Dozens of simulations were performed within each of the four scenarios. Fission easily results in the formation of a pair of objects with positive total energy, or in the formation of a bound system (binary) in S1 and S2. For any set of simulations, a representative sample of boundary conditions is chosen here for description (Table 2). In the case of S3, the production of a bound system is restricted to a narrow range of boundary conditions.

Table 2. Some results of the simulations. M_p and M_e are the masses of the primary and the mass ejected from the system, respectively. $M_\mathrm{s}/M_\mathrm{p}$ is the mass ratio of the binary system (the mass of the satellite divided by mass of the primary). T is the rotation period of the primary. $\langle V_\mathrm{d} \rangle$ is the average speed of the ejected free particles with respect to the centre of mass, of the ejected pairs of particles and of the ejected rubble piles, respectively.

Simulation	M_p ($\times 10^{21}$ kg)	T (h)	$M_\mathrm{s}/M_\mathrm{p}$	M_e ($\times 10^{20}$ kg)	$\langle V_\mathrm{d} \rangle$ (m s^{-1})
S1	3.922	3.698	0.113	3.620	303, 429, 318
S2	4.302	3.823	0.113	1.327	490, 0^a, 0^a
S3	3.460	3.375	0.237	0.576	1296, 0^a, 0^a
S4	4.160	3.632	0.017	3.398	1912, 1009, 330

[a] In these simulations, no groups of two particles or rubble piles were formed.

In Fig. 2, we plot the scaled spin rate versus the specific angular momentum for the 21 steps of S1. As can be seen in the plot, the proto-Haumea fission is near the Jacobi–MacLaurin transition point. Animations showing the four fission scenarios are presented as on-line material. In Fig. 3, we show the speed distributions of the ejected material in the four different scenarios. In all cases, the fragments escaping from the system immediately after rotational fission have average speeds of 0.3, 0.5, 1.3 and 1.9 km s^{-1} for scenarios S1, S2, S3 and S4, respectively. However, the distribution of ejection speeds is very broad (see Fig. 3). In Fig. 4, we show snapshots of the simulations.

In many simulated cases, a large-enough body is formed from the ejecta of the parent body and remains in orbit around the primary for the full length of the numerical integration (several days). By a 'large-enough body', we mean an object with the total mass of the 'family' and the satellites. The stability of the binary systems formed has not been studied numerically with PKDGRAV because the long-term evolution is very CPU-intensive. However, it can be analysed theoretically and by using other methods (see Section 4).

4 RESULTS AND DISCUSSION

From the reported numerical simulations and from other considerations, we suggest that the fission mechanism for the formation of large complex systems of TNOs, such as Haumea, seems to be preferable (from a statistical point of view), rather than catastrophic collisions between large primitive bodies.

It must be pointed out that using a very large gravitational aggregate to describe Haumea is a considerable simplification because Haumea could be a differentiated body (McKinnon et al. 2008) with, at least, a fluid-like interior. Nevertheless, gravitational aggregates behave almost like fluids, regarding the shape they adopt as a response to rotation. They even break up near the theoretical limit for a fluid (as shown in Fig. 2). Hence, the simulations presented in this paper retain the basic physics of rotational fission, even for large bodies such as Haumea.

We now examine whether the mechanism of rotational fission can alone reproduce all the observables of the Haumea system (Section 4.1). In Sections 4.2– 4.4, we speculate whether three other related mechanisms could also explain the observables. The main observables are the existence of satellites, the fast Haumea spin and the existence of a 'family' with a 140 m s^{-1} dispersion speed.

4.1 Rotational fission alone

By rotational fission, we mean any of the S1, S2, S3 and S4 scenarios mentioned in Section 3.2, that is, pure rotational fission (S1), regardless of its cause, or collisionally induced rotational fission (S2–S4).

Even though the numerical simulations form satellites of various sizes together with a fast-spinning Haumea, which are two of the main observables, the formation of a family also has to be explained. Looking at the distribution of speeds (Fig. 3 and Table 2), it would seem that the family is not formed because the average ejection speeds in scenarios S1, S2, S3 and S4 are much higher than 140 m s^{-1}. However, it must be pointed out that Haumea itself requires a dispersion speed of 400 m s^{-1}, whereas the rest of the members of the family cluster around a dispersion speed of 140 m s^{-1} (Brown et al. 2007). Therefore, the fragments ejected from Haumea need an offset speed of $\sim$ 300–500 m s^{-1} with respect to Haumea itself.

In this regard, let us point out that the ejected fragments in our simulations have a net predominant direction. By taking the average of the velocity vectors (at infinity with respect to the centre of mass of the system) of all the ejected fragments, we obtain a vector of components (13, 22, 0 m s^{-1}) with a modulus of 25.2 m s^{-1} and a standard deviation of 328 m s^{-1} in scenario S1. For scenario S2, we obtain (-447, -189, -34.5 m s^{-1}) with a modulus of 487 m s^{-1} and a standard deviation of the speed around this direction of 314 m s^{-1}. For scenario S3, the mean velocity vector is (-934, 442, 200 m s^{-1}) with a modulus of 1050 m s^{-1} and a standard deviation of 1250 m s^{-1}. For scenario S4, we obtain (-1730, 263, 11 m s^{-1}) and a modulus of 1750 m s^{-1} with a standard deviation of 1131 m s^{-1}.

Because Haumea has an offset speed of 400 m s^{-1} with respect to the other members of the 'family' (Brown et al. 2007) and because this offset speed can be reproduced with the S2 scenario, we think that this scenario is our best approximation to explain the formation of the Haumea system. However, the dispersion speed of 328 m s^{-1} of the fragments is still a factor of 2.3 higher than necessary. We should note that the 400 m s^{-1} offset of Haumea, because of its displacement in eccentricity from the rest of the family, might be explained by Haumea's chaotic diffusion within the 12: 7 mean-motion resonance with Neptune, which can change Haumea's eccentricity to its current value (Brown et al. 2007). In our model, this difference in eccentricity can be explained if the material is ejected in the orbital plane. In this case, the orbits of the ejected fragments will have a very different eccentricity with respect to the progenitor, but not a significantly different inclination. If the spin axis of proto-Haumea was perpendicular (or nearly perpendicular) to its orbital plane, the ejection of the fragments would be in the orbital plane. Thus, we would expect a small spread in inclinations and a larger separation in eccentricity with respect to the progenitor. So, we do not need to invoke chaotic resonance diffusion to explain the different eccentricity of Haumea from the rest of the family members.

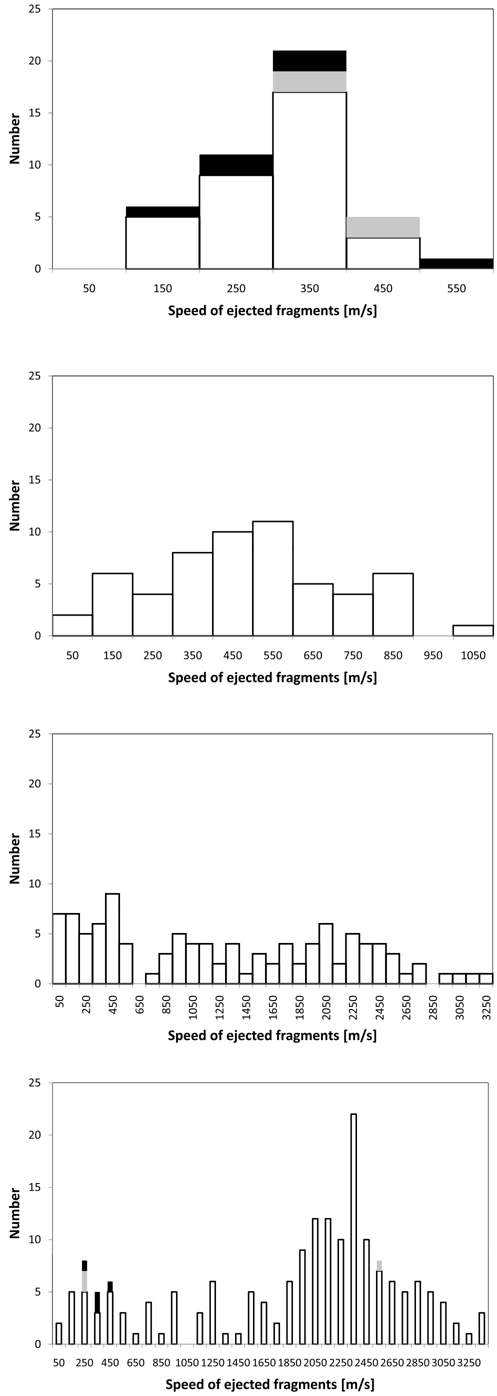

Figure 3. Histograms showing the number of ejected fragments as a function of speed with respect to the centre of mass in simulations S1 (upper plot), S2 (second plot), S3 (third plot) and S4 (bottom plot). The grey bars in the upper plot correspond to groups of two particles and the black bars correspond to ejected rubble piles (i.e. a group of three or more particles). Simulations S2 and S3 did not produce any groups with two or more particles. Movies of these simulations are presented in the Supporting Information section (online only). S1 corresponds to pure rotational fission whereas S2, S3 and S4 correspond to collisionally induced rotational fission with impact speeds of 1000, 3000 and 3000 m s^{-1}, respectively (see Section 3).

In summary, scenario S2 is qualitatively consistent with the observables and quantitatively very close to the exact values of the observables. A slightly smaller impact speed below 1000 m s^{-1} might provide a more precise offset speed and the dispersion speed observed in the Haumea system. With respect to the other family members, the offset in Haumea's eccentricity but not in inclination is a consequence of the fission occurring close to the orbital plane. The family members are part of the ejected components from the parent body. This circumstance is likely because large bodies, in many cases, have small obliquities.

Our simulations can form a large satellite (see Table 2) and a family, but a second small satellite is obtained only in some cases (i.e. in scenarios S1 and S2). In addition to this difficulty, the dynamical coherence of the family (its velocity dispersion) would have been destroyed if the collision that induced the fission took place when the Kuiper belt was more massive.

Although the induced rotational fission is our preferred mechanism to explain the main features of the Haumea system, in the following subsections we explore other dynamical mechanisms, which might also place the shed material in heliocentric orbits sufficiently grouped in orbital parameter space to form the 'family' and simultaneously to meet the other observables.

4.2 Rotational fission plus collision on the proto-satellite

A catastrophic collision on a large proto-satellite (some 500 km in diameter) formed after the fission can be an alternative mechanism to generate a 'family' with the observed dispersion speed. At the same time, it could also generate the satellites. This collision would not require very large impacting bodies, and thus it would be reasonably likely. In fact, the size distribution of TNOs is steep in the required size range [$N(D, D \pm \mathrm{d}D)\,\mathrm{d}N \propto D^{-b}\,\mathrm{d}D$, with $b > 4$] and the probability of a shattering event on a 500-km-sized body, within an even rarefied (i.e. the post-LHB phase) classical disc is at least four orders of magnitude larger than that of having a catastrophic collision between two bodies each of about 1000 km in size. Specific simulations are currently underway, in which the fissioned satellite is impacted and a system with the current characteristics of the Haumea system is obtained. However, such a study is beyond the scope of this paper, which is focused on the fission process itself.

This scenario meets similar problems as the scenario proposed by Schlichting & Sari (2009) and pointed out in Section 3. Besides, the time-span between the formation by fission and the required impact event might be enough to slow down Haumea's rotation through the tidal interaction of the satellite. Angular momentum conservation implies that the orbital momentum gained by the satellite is obtained from the rotation of the primary, and therefore the primary must slow down. Because Haumea's rotation is still very fast, the scenario of a collision on the proto-satellite requires an impact shortly after the fission event (so that the tidal effect does not have time to slow down Haumea), which is less likely.

4.3 Rotational fission followed by secondary fission of the proto-satellite

Jacobson & Scheeres (2010a) have recently proposed that low-mass-ratio binary asteroids resulting from fissions are generally unstable, but that stable cases arise when the satellite suffers spin-up through tidal interactions with the primary and finally undergoes a rotational fission itself, with the dispersal of part of the mass of the system. Thus, the same mechanism might be applicable to

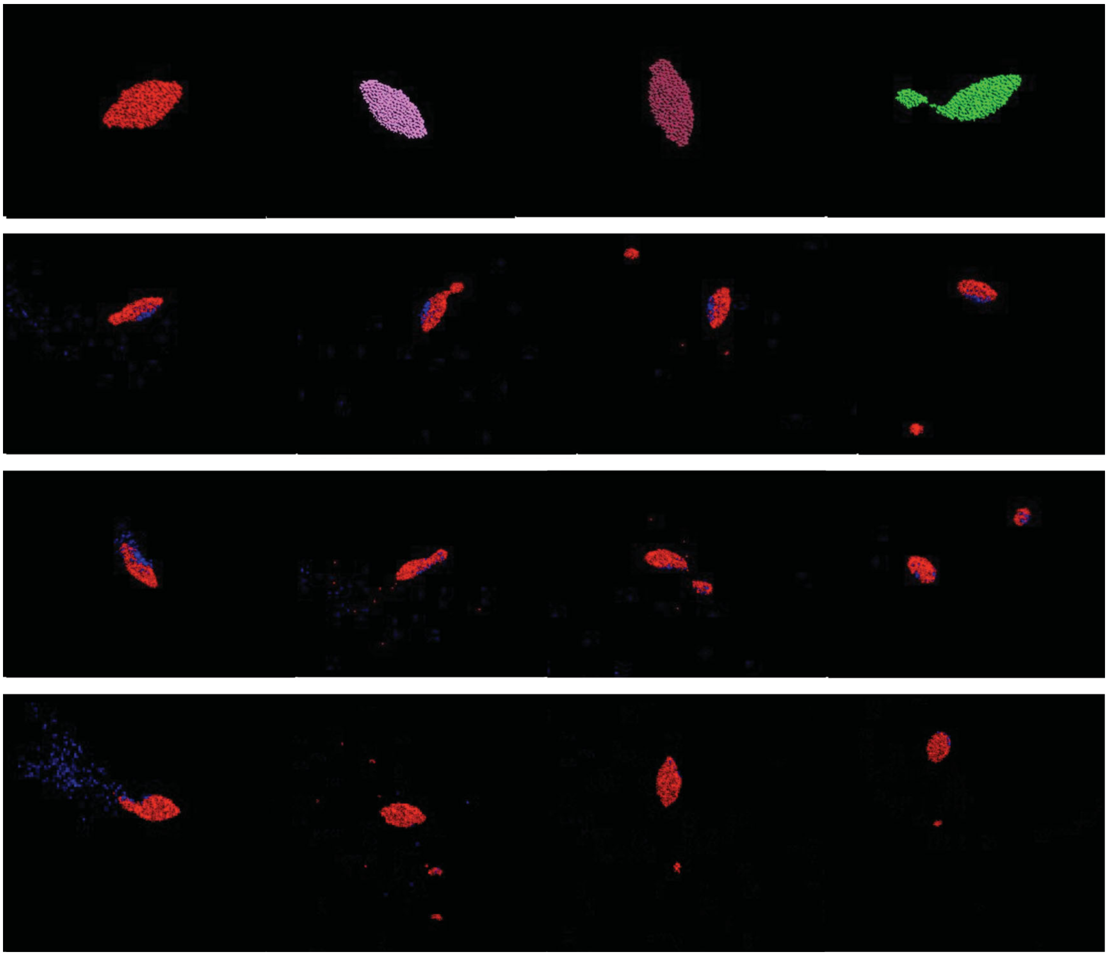

Figure 4. Snapshots of the different simulations. The top row is the rotational fission scenario, showing the different steps of the process in Fig. 2. Different colours are used every time the object is spun-up (from left to right), following the same colour coding as in the onlinefission1.avi movie in the Supporting Information. The middle row is the S2 scenario, showing the collision at 1 km s^{-1}. As can be seen, some of the projectile material ends up in the crust of the large body, covering a non-negligible area of the body. This might perhaps account for the existence of a dark albedo area on Haumea (Lacerda, Jewitt & Peixinho 2008). The third row is the S3 scenario, showing the collision at 3 km s^{-1}. The bottom row is the S4 scenario, in which a lower-mass satellite is created, compared to S3. In the S2, S3 and S4 scenarios, the projectile particles are depicted in blue.

TNOs and could explain the existence of a group of bodies with orbital elements related to those of Haumea (with small dispersion speeds). This scenario does not require collisions. If the mechanism of rotational fission of the secondary mentioned in Jacobson & Scheeres (2010a) is not rare, rotational fission families might be found around other large TNOs. Jacobson & Scheeres (2010a) point out that the spin-up of the satellite and its fission can only take place in systems with satellite-to-primary mass ratios smaller than 0.2.

Therefore, if the formation of the Haumea ‘family’ was the result of a secondary fission (the fission of the proto-satellite), the mass of the ‘family’ and the current satellites must be smaller than 0.2 times that of Haumea. This appears to be the case. In fact, summing up the mass of all the members of the ‘family’ – computed by assuming an average albedo of 0.6 and a density of 2000 kg m^{-3} – we obtain a mass that is just a few per cent of that of Haumea, of the same order of the mass of the known satellites. The uncertainty in mass comes primarily from the albedo uncertainty. However, because all the objects clearly contain water ice in large amounts, they are believed to be at least as reflective as Haumea, so albedos even higher than 0.6 would apply. Recent and accurate measurements of the albedo of one of the ‘family’ members resulted in a value of $0.88^{+0.15}_{-0.06}$, according to Elliot et al. (2010). Therefore, the total mass of the family might be even smaller than a few per cent of that of Haumea. The low-mass ratio is a further clue in favour of the fission mechanism.

4.4 Rotational fission, formation of a pair and disruption of the small member of the pair

An interesting mechanism for the formation of TNO systems arises as a by-product of our numerical simulations of the Haumea system. In some cases, the proto-Haumea fission results in the formation of a TNO pair, with a secondary typically of the order of some 200–500 km.

Referring to the NEA population and the main asteroid belt, the existence of asteroid pairs (pairs of asteroids with similar orbits but not bound together; Vokrouhlický & Nesvorný 2008) has been explained as arising from rotational fissions. Using the dynamical simulations of the evolution of fissioned bodies, Jacobson & Scheeres (2010b) have pointed out that systems with satellite-to-primary mass ratios larger than 0.2 always evolve to synchronous binaries, whereas asynchronous binaries, multiple systems and asteroid pairs can only form if their mass ratios are smaller than 0.2. Using a large observational data set, Pravec et al. (2010) have shown that asteroid pairs are indeed formed by the rotational fission of a parent contact binary into a proto-binary, which subsequently disrupts under its own internal dynamics soon after formation. This is found only for mass ratios smaller than 0.2, as expected from the theory. These results, together with our numerical simulations, suggest that pairs might have been formed in the trans-Neptunian region.

It has been shown that the primaries of the asteroid pairs have larger light-curve amplitudes than the primaries of binary asteroids with similar mass ratios. This probably indicates that the elongated shapes of primaries play a significant role in destabilizing the system and ejecting the satellite (Pravec et al. 2010). For systems with a primary having the characteristics of Haumea, the formation of a pair then seems plausible.

According to Jacobson & Scheeres (2010b), the time-span in which a binary system ejects its satellite is usually very short. Therefore, the tidal interaction would not slow down the primary significantly and it might still be observed in a high rotation state.

Once a TNO pair is formed, the secondary can subsequently undergo a disruptive collision or a secondary rotational fission, so that a group of bodies can be created. These objects would share very similar orbital parameters to those of the primary and they would look like its collisional ‘family’. Actually, the secondary would be their parent body rather than the primary itself. The velocity dispersion of the fragments ejected in the collision would indeed be close to the typical escape speeds from a 500-km-sized body, as in the case of the Haumea ‘family’ (140 m s^{-1}). According to our simulations of spontaneous or induced fissions, most of the fragments that escape shortly after have relative speeds with respect to the primary of around 400–500 m s^{-1}, in the range of the offset speed of Haumea with respect to the other ‘family’ members (∼400 m s^{-1}). Fig. 3 shows many fragments with escaping speeds in the required range.

A disruptive collision on a small object (the secondary of the pair) is likely enough, so this scenario is plausible to explain a group of bodies with similar orbital parameters to that of the primary, as in the case of Haumea. Nevertheless, this ‘family’ formation scenario faces some difficulties in the case of the Haumea system. In fact, although the existence of two satellites is not straightforward to explain, this would not be impossible. For example, a multiple or triple system might have formed soon after fission, so that the system ejected one of its satellites and retained the two currently satellites of Haumea. Simulations of the S1 series show that this is possible. Jacobson & Scheeres (2010a) have pointed out that a fraction of low-mass-ratio proto-binaries can evolve to multiple systems, which might eject one of their members.

Also, the interaction of a third body with the proto-binary formed in the fission process might result in the ejection of the proto-satellite from the system at a small relative speed with respect to Haumea. In this case, the mass ratio would have to be no smaller than 0.2. As explained above, if the ejected body underwent a catastrophic disruption, the generated fragments would likely share similar orbital parameters to those of Haumea. Petit & Mousis (2004) studied the interactions of binaries with third bodies in order to estimate the stability and persistence of primordial binaries. They found that these interactions were frequent early on in the Solar system and that a large fraction of binaries were destroyed. Therefore, such a mechanism might also have taken place for a young binary Haumea.

In summary, a mechanism that might account for all the observables would require that the proto-Haumea underwent fission and formed a stable low-mass-ratio triple system (which is one of the outcomes of the evolution of rotational fission of proto-binaries within the formalism of Jacobson & Scheeres 2010a,b). This would explain the presence of the satellites Hi’iaka and Namaka. At the same time, some of the ejected mass should have the correct dispersion velocity to form the observed ‘family’ or should be clustered into a single escaping body, which should ultimately undergo a catastrophic disruption, forming the ‘family’ itself.

4.5 Future prospects

Can we find more ‘families’ similar to that of Haumea for other known objects? Observationally, first we should try to find fast-rotating ‘large’ TNOs with large light-curve amplitudes and then we should look for objects with similar orbital elements. However, among potentially large TNOs, the only other fast-spinning object is (120178) 2003 OP_{32} (Rabinowitz et al. 2008; Thirouin et al. 2010), which belongs to the Haumea ‘family’ itself. Other fast rotators in the period range of ∼4 h might be identified in the future. Nevertheless, the tidal interaction of a former satellite could have slowed down the spin of potentially good candidates, and therefore current very fast spins might not necessarily be a constraint. Varuna, the most elongated object among the large TNOs, might be an interesting case of a primary slightly slowed down. Unfortunately, there is currently no indication that it has orbitally related objects. If a ‘family’ were related to Varuna (whose magnitude in V is ∼ 20), the members would be at least two to three magnitudes fainter than Varuna itself and the census of TNOs down to magnitude 23 is far from complete.

It could be possible that the Haumea system is the only system to have been found because it is one of the brightest TNOs and its ‘family’ members were detectable by telescopic surveys.

A possible test for the relevance of the proposed fission mechanisms can be derived by considering the resulting binary fraction. If all the rotationally disrupted objects formed stable satellite systems after rotational breakup, we should expect of the order of 20 per cent of binaries for a nominal bulk density of 1300 kg m^{-3}, as discussed in Section 2. The fraction of stable binary systems could be considerably lower than 50 per cent, because their stability depends critically on the mass ratio of the system (Jacobson & Scheeres 2010b). Bearing in mind that mass ratios larger than 0.2 form stable systems (Jacobson & Scheeres 2010b), an average of ∼50 per cent of the fissioned bodies might be stable, and most of these should already be synchronous binaries. Thus, around 10 per cent of the large TNOs could be binaries formed by rotational fission. This fraction could be lower if third-body interactions occurred frequently in the young trans-Neptunian belt. Collisional evolution models, which take into account changes in rotation rates and are able to keep track of the surviving binary systems, would be needed to assess the fraction of binaries currently expected.

Concerning the possibility of finding ‘TNO pairs’, note that the orbital elements of most TNOs are more uncertain than those of main belt asteroids. Therefore, searches for TNO pairs are more difficult. Moreover, there are only around 1400 known TNOs. This is too small a sample when compared to the around 5×10^5 known asteroids, among which only ∼60 pairs were found (Vokrouhlický & Nesvorný 2008). Besides, the small mass ratio implies that many TNO pairs could remain undetected because one of the members is too faint. Another difficulty resides in the fact that a large fraction of the pairs might have formed a few Gyr ago. Therefore, they would be more difficult to identify than in the asteroid belt, where pairs are much younger than 1 Gyr. Nevertheless, we can perhaps limit the search by following Pravec et al. (2010), who showed that the primaries of asteroid pairs have larger light-curve amplitudes than the primaries of binary systems with similar mass ratios. If this were applicable to TNOs, the best candidates for the primaries of TNO pairs are those with high light-curve amplitudes, such as Varuna, Haumea and a few others.

5 SUMMARY AND CONCLUSIONS

We have presented evidence that indicates that rotational fission of TNOs might be a mechanism that has affected a fraction of the TNO population. Binaries could have formed in this way in the trans-Neptunian region. Also, 'TNO pairs' – and even triple systems – might exist as a result of rotational fission. Binaries, pairs and triple systems are the typical outcomes of rotational fission in the asteroid population, depending on the mass ratio of the proto-binaries formed. The indications for fissions in the trans-Neptunian region come from various observations and also from numerical simulations of the process. Haumea is a particularly good candidate, which might have suffered a rotational fission because of its fast spin rate and other remarkable features. The satellites of Haumea might have been formed as a result of the fission itself. The 'family' of bodies orbitally related to Haumea might derive from the ejected fragments after the fission (as we have shown with our S1 simulations). They could also be a result of the evolution of a proto-satellite in the proto-binary after the fission, or might even arise from the disruption of an escaped fragment or an escaped satellite. We show that the fission process has a larger probability of occurring than the high-energy collisional scenarios that have been proposed in the literature to explain the existence of satellites and bodies orbitally related to Haumea. Therefore, we propose that the fission mechanism is a more natural scenario and can generally explain most of the features of the Haumea system. Future studies of high-mass-ratio binaries in the trans-Neptunian belt could provide more detail about the scenario of rotational fission. Also, the existence of 'TNO pairs', or future discoveries of other groups of dynamically related objects, might shed more light on the rotational fission of TNOs.

ACKNOWLEDGMENTS

This research was partially supported by Spanish grants AYA2008-06202-C03-01, AYA-06202-C03-02, AYA2008-06202-C03-03, P07-FQM-02998 and European FEDER funds. RD acknowledges financial support from the MICINN (contract Ramón y Cajal). DCR acknowledges support from the National Aeronautics and Space Administration under grant No. NNX08AM39G issued through the Office of Space Science. PGB took part in this research during her stay at the Southwest Research Institute (Boulder, CO, USA) with support from the Ministerio de Ciencia e Innovación (Spain). We thank Seth Jacobson and Daniel Scheeres for sharing with us their manuscript, while it was in preparation.

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Movie files. Animations showing the four fission scenarios.

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