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Considerations about the Equilibrium Shapes and Geology of TNOs

Hely C. Branco[1][2] & Felipe Braga-Ribas[1]

[1] Universidade Tecnológica Federal do Paraná - UTFPR | e-mail: `helycbranco@gmail.com`
[2] Universidade Federal do Paraná - UFPR

Abstract. Transneptunian Objects (TNOs), a class of small bodies of the Solar System, can be seen as spinning bodies under the influence of self-gravity, spin-related forces and tidal forces, classically considered to have fluid behaviour and, therefore, assume fluid equilibrium shapes. However, they are composed by geological materials that rarely behave as fluids; thus, the use of geological criteria to analyse the shapes assumed by these objects when in equilibrium, i.e. their equilibrium shape, is required. This work presents the main results and conclusions from the analysis of the equilibrium shapes of the TNOs Pluto, Haumea, Quaoar and 2003 VS_2, the centaurs Chariklo and 2002 GZ_{32}, and the asteroids Ceres, Vesta and Lutetia carried out through a two-year long masters project. Their shape (determined with high accuracy with stellar occultation data), rotation period and density (whenever available) were used to determine: i) if the object is in equilibrium; ii) if it presents fluid behaviour or if it has some type of internal resistance to deformation; and iii) the geological implications of this. In the absence of mass values, the method was used to infer the object's density. All objects were found to be in equilibrium, assuming shapes different from the ones assumed by a material with pure fluid behaviour (i.e. Maclaurin and Jacobi ellipsoids). It was shown that the material's behaviour is an indicative of the possible internal composition and structure of an object, what is somewhat related to geological processes that took and are taking place on it. The method has great scientific potential, allowing the understanding, at least in general terms, of the geological history and evolution of small bodies through the use of theoretical and analog models.

Resumo. Objetos Transnetunianos (TNOs), uma classe de corpos menores do Sistema Solar, podem ser vistos como objetos em rotação sob a influência de auto-gravidade, forças relacionadas à rotação e forças de maré, classicamente considerados com comportamento de fluido perfeito e, portanto, assumindo formas de equilíbrio para fluidos. Contudo, estes objetos são compostos por materiais geológicos que raramente comportam-se como fluidos; portanto, o uso de critérios geológicos para analisar suas formas de equilíbrio são necessárias. Este trabalho apresenta os principais resultados e conclusões da análise das formas de equilíbrio dos TNOs Plutão, Haumea, Quaoar e 2003 VS_2, os centauros Chariklo e 2002 GZ_{32}, e os asteróides Ceres, Vesta e Lutetia desenvolvidas ao longo de um projeto de mestrado. Suas formas (determinadas com grande acurácia através do uso de ocultações estelares), período de rotação e densidade (quando disponível) foram usadas para determinar: i) se o objeto está em equilíbrio; ii) se apresenta comportamento fluido ou se há algum tipo de resistência interna à deformação; e iii) as implicações geológicas disso. Na ausência de medidas de massa, o método foi usado para inferir a densidade média dos objetos. Verificou-se que todos os objetos analisados estão em equilíbrio, assumindo formas de equilíbrio diferentes das assumidas por um fluido perfeito (i.e. elipsóides de Maclaurin e Jacobi). Foi demonstrado que o comportamento dos materiais é um indicativo da possível composição e estrutura interna de um objeto, o que tem relação com processos geológicos atuais ou passados. O método usado tem grande potencial científico, permitindo a compreensão, ao menos em termos gerais, da história geológica e evolução de corpos menores através do uso de modelos análogos e teóricos para a interpretação dos resultados.

Keywords. Equilibrium shapes, Planetary Geology, Small Bodies of the Solar System

1. Introduction

The physical properties of small bodies (e.g. rotational period, density and shape) can be measured with high precision through the use of stellar occultation and other techniques (Braga-Ribas 2013, Rommel 2018). By implementing Holsapple's method (Holsapple 2004), these measurements can be used to evaluate an object's equilibrium state, giving insights regarding the material's behaviour, i.e. how close to a fluid it is; in the absence of an independent mass measurement, it also allows the estimation of its density with reasonable precision. When combined with other types of analysis, it can give constrains about the object's composition and internal structure (e.g. estimate of ϕ and likelihood of significant internal global porosity), allowing inferences regarding their geology.

2. Method

The method proposed by Holsapple (2004) correlates an object's three-dimensional shape, composition and spin velocity, allowing estimates of some physical properties such as density and composition. The scaled spin Ω is defined as:

$$\Omega = \sqrt{\frac{4\pi}{P^2\rho G}} \tag{1}$$

where ρ is the average density, P the period of rotation, and G the gravitational constant. The parameters α and β are related to the object's shape, defined as $\alpha = c/a$ and $\beta = b/a$, where a is the major, b the intermediate, and c the smaller semi-axis of a triaxial spheroid. These parameters are connected by the following equation:

$$\Omega^2 = \frac{2(\lambda_x A_x + \lambda_y \beta^2 A_y + \lambda_z \alpha^2 A_z)}{\lambda_x + \beta^2 \lambda_y} \tag{2}$$

where A_i are parameters related to equilibrium calculations and λ_i are related to the object's composition, assuming one of three values: 0, 1 and m. The last is defined as:

$$m = \frac{1 + sin\phi}{1 - sin\phi} \tag{3}$$

Table 1. Physical parameters used for the equilibrium shape analysis

object	semi-axis			α	β	P(h)	ρ (kg/m^3)	calculated ρ (kg/m^3)	ϕ(°)
	a	b	c						
Quaoar	581^{+12}_{-8} (3)	581^{+12}_{-8} (3)	529^{+6}_{-20} (3)	$0.9110^{+0.0234}_{-0.0526}$	1	8.839±0.002 (3)	1990±460 (3)	$\sim1600^{+1650}_{-650}$	~0
Haumea	1161±30 (15)	852±8 (15)	513±16 (15)	$0.442^{+0.016}_{-0.017}$	0.734	3.915341±0.000005 (20)	1885±80 (15)	1900^{+410}_{-250}	<5
2003 VS$_2$	313±7.1 (1)	$265^{+8.8}_{-0.8}$ (1)	$247.3^{+26.6}_{-43.6}$ (1)	$0.788^{+0.085}_{-0.139}$	0.846	7.4175285±0.00001 (1)	∗	$\sim1050^{+410}_{-220}$	<5
2002 GZ$_{32}$	172.5 (21)	152.5 (21)	70 (21)	0.4058	0.8841	5.80±0.03 (7)	1160-1520 (7)	~770±110	<5
Chariklo$_m$	143^{+3}_{-6} (13)	143^{+3}_{-6} (13)	96^{+14}_{-4} (13)	$0.6713^{+0.0583}_{-0.0412}$	1	7.0040±7.0040(13)	970^{+300}_{-180} (13)	⋆	⋆
Chariklo$_j$	157±4 (13)	139±4 (13)	89±1 (13)	$0.5478^{+0.0208}_{-0.0198}$	0.8854		796^{+2}_{-4} (13)	~600	~0
Chariklo$_t$	148^{+6}_{-4} (13)	132^{+6}_{-5} (13)	102^{+10}_{-8} (13)	$0.6892^{+0.0858}_{-0.0788}$	0.8919		∗	$\sim800^{+320}_{-180}$	<5
Pluto	1188.2±3.0 (14)	1188.2±3.0 (14)	1189±4.0 (14)	0.999±0.001	1	6.3871 (22)	1854±11 (14)	~1850±1000	~0
Ceres	483.1±0.2 (16)	481.0±0.2 (16)	445.9±0.2 (16)	0.9230±0.0008	1	9.07417±0.000002 (6)	2161±8 (16)	~1650	~0
Lutetia	60.5±1 (5)	50.5±1 (5)	37.5±13 (5)	$0.6198^{+0.0678}_{-0.0626}$	0.83	8.168270±0.000001 (4)	3400±300 (17)	$\sim4800^{+5200}_{-2800}$	5-15
Vesta	286.3±0.1 (19)	278.6±0.1 (19)	223.2±0.1 (19)	0.7796±0.0006	0.97	8.168270±0.000001 (8)	3800±600 (12)	$\sim720^{+4250}_{-290}$	<5

∗ not available in the literature ⋆ not calculated small numbers in parenteses point to the references

where ρ is the angle of internal friction, related to the object's composition.

Through the use of these equations, it is possible to construct Ω vs. α graphs for certain shape families, expressed by the algebraic relationship between α and β. Thee situations were explored: i) oblate spheroids, with $\beta = 1$; ii) prolate spheroids, with $\beta = \alpha$; and iii) triaxial spheroids, with $\beta = n\sqrt{\alpha}$. In order to apply this method, it is necessary that the object's three-dimensional shape and spin velocity are known with high accuracy. In addition to that, if the object's mass is also known, the method can be used to verify if the object is in equilibrium, resulting in considerations regarding its composition and internal structure based on ϕ estimates.

If the mass is unknown, as is the case for most small bodies, the method can be used to estimate it, given that some constrains related to its composition can be made; e.g. if it is a TNO, it can be assumed that it is composed by ice and rock, with ϕ between 0 and 5° (Durham al. et 2012, ElShafie et al. 2012).

3. Results & Conclusions

Analysis were made for the TNOs Pluto, Haumea, Quaoar and 2003 VS_2, the centaurs Chariklo and 2002 GZ_{32}, and the asteroids Ceres, Vesta and Lutetia (Table 1). For the objects whose mass is known, the two types of analysis were carried out, resulting in fairly similar density estimates. For the objects with unknown mass, the method was used to estimate their density. Pluto and Ceres were chosen as controls, as both have been visited by space probes and have well known mass and shape. Vesta and Lutetia were chosen to assess the method's limits, i.e. if it is applicable for small rocky objects.

The equilibrium analysis indicated that the studied objects are in equilibrium, in most cases with behaviour considerable similar to a perfect fluid. This divergency is small, characterising studies considering a pure fluid behaviour as good first approximations. It was also shown that the material's behaviour has a significant impact on the object's shape, resulting in equilibrium shapes different than Maclaurin and Jacobi ellipsoids.

Mass estimates require additional assumptions. For icy oblate spheroids, it is necessary to assume global fluid behaviour ($\phi = 0°$) in order to obtain reasonable density estimates; for triaxial icy objects, an assumption of $0° \leq \phi \leq 5°$ is needed.

Quaoar's density was obtained under the assumption that is behaves like a fluid and, therefore, assumes a Maclaurin ellipsoid shape; the calculated points fall on the Maclaurin ellipsoid line, validating the method. Haumea was shown to be a triaxial ellipsoid in equilibrium, with fluid or almost-fluid behaviour and equilibrium shape different from a Jacobi ellipsoid. The analysis for 2003 VS_2 and 2002 GZ_{32} assumed fluid behaviour ($\phi = 0°$) for the average (blue point) and extreme (limits of the error bars) values of density, resulting in densities of $\sim 1050^{+410}_{-220}$ and $\sim 770 \pm 110\ kg/m^3$ respectively. Results for Vesta and Lutetia require further refinement.

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