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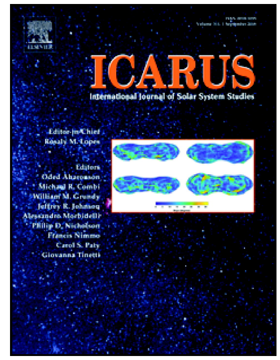

Comment on ‘A global system of furrows on Ganymede indicative of their creation in a single impact event’ by Hirata, N., Suetsugu, R. and Ohtsuki, K. (Icarus 352, 2020): Investigating the influence of the hypothesized ancient impactor on Ganymede's orbital eccentricity

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Comment on 'A global system of furrows on Ganymede indicative of their creation in a single impact event' by Hirata, N., Suetsugu, R. and Ohtsuki, K. (Icarus 352, 2020): Investigating the influence of the hypothesized ancient impactor on Ganymede's orbital eccentricity

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Abstract

The orbital eccentricity of a satellite may undergo significant alterations over time due to gravitational interactions with its parent planet and adjacent moons, as well as through other mechanisms, such impact by a sizable object. Ganymede is notably engaged in an orbital resonance with Io and Europa, where Ganymede completes one orbit around Jupiter for every two orbits of Europa and four orbits of Io. Nevertheless, Ganymede's free eccentricity component should have damped by the present time. It has been hypothesized that Ganymede was struck by a large impactor early in its history, generating sets of concentric furrows visible in its most ancient dark terrains (Hirata et al., 2020). In this study, we investigate the size of the impactor needed to pump Ganymede's free eccentricity up to its current value. Utilizing the constraints published on a hypothesized ancient impactor, we compare the calculated dimensions of the asteroidal or cometary impactor with the calculated requisite mass needed to excite Ganymede's orbital eccentricity. Given a head-on collision with no alteration in rotational dynamics and at a speed of 20 km/s, we deduce that pumping Ganymede's eccentricity to 0.0013 necessitates an impactor mass of 2.8274×10^{19} kg, aligning with the mass estimates for the theorized ancient impactor. As Ganymede's oldest dark terrains are believed to be about 4 Ga old, a more comprehensive analysis of the impactor's influence on Ganymede's orbital dynamics and possible effect on the resonance with Io and Europa is needed.

Keywords: Ganymede, impactor, tectonics, orbital eccentricity

1. Introduction

The orbital interaction between Io, Europa, and Ganymede forms a dynamic system which has a significant impact on the thermal history and tectonic evolution of these moons. The ice shell thicknesses of Europa and Ganymede as well as the thermal and mechanical properties of the ice are closely related to the thermal and stress conditions. The present orbital configuration of this trio of satellites is referred to as a Laplace resonance, characterized by an orbital period ratio of 1:2:4 for Ganymede, Europa, and Io, respectively. When an orbit experiences periodic perturbation such as a resonance, its eccentricity (e) includes a forced component ($e_{imposed}$) that arises exclusively from the characteristics of the perturbation. Additionally, the orbit can possess a free eccentricity (e_{free}) that is independent of the perturbation. The trio's orbital history and its possible effects on the eccentricity of Ganymede have been investigated in previous studies with two competing theories existing regarding the origins of the Laplacian resonance. The first theory, initially proposed by Greenberg (1981; 1982; 1987), suggests that the resonance is primordial. Greenberg outlined how tidal effects could have influenced the system's evolution from a state of deep resonance. More recently, Peale and Lee (2002) built upon Canup and Ward's (2002) model of satellite accretion to describe how the Laplacian resonance might have formed during the satellites' accretion phase. The alternative theory suggests that the Laplacian resonance emerged from tidal interactions. Initially, Yoder (1979), Yoder and Peale (1981), and Henrard (1983) examined analytically a scenario in which Io and Europa were first entrapped in a resonance before Ganymede was incorporated into the Laplacian resonance. Subsequently, Malhotra (1991) and Showman and Malhotra (1997) employed numerical simulations to develop models where Io, Europa, and Ganymede were involved in other three-satellite resonances that eventually dissolved, leading to the establishment of the current Laplacian resonance. Showman and Malhotra (1997) revealed that the Galilean moons might have been captured in three Laplace-like resonances for a duration ranging from 10 Ma to 1 Ga before reaching their present configuration. Some of these models account for a past higher eccentricity for Ganymede reaching values as high as e = ~0.07, potentially explaining episodes of heightened thermal activity, driving internal processes and leading to surface renewal and faulting. As a satellite's eccentricity rises, tidal heating intensifies, leading to the satellite's differentiation. However, according to Peale and Lee (2002), Ganymede's differentiation would have occurred during the accretion phase. In contrast, for a satellite that has already undergone differentiation, tidal heating acts to dampen its eccentricity. From this, we can conclude that such damping serves to hinder or postpone the satellite's escape from a resonance, contributing to the system's stability. Ganymede's free eccentricity (e_{free}) is rather large compared to the other satellites in the Laplacian resonance, and should have damped long before present time. However, past orbital resonances could have further pumped a free eccentricity along with the forced ($e_{imposed}$) component (Showman and Malhotra, 1997). The task of reconstructing and deriving insights from Ganymede's orbital history presents considerable challenges.

Ganymede's surface shows signs of shear deformation in all ages of terrains and large-scale feature offsets in intermediate aged units, which are inferred to be caused by tidal stress (e.g., Murchie and Head, 1988; Collins et al., 1998; Pappalardo et al., 1998; 2004; Patel et al., 1999; Pappalardo and Collins, 2005; Cameron et al., 2018; 2019; 2020; Burkhard et al., 2023). As Ganymede rotates synchronously in its orbit around Jupiter, the tidal bulge it experiences changes in size because of the orbit's eccentricity (Bills, 2005; Wahr et al., 2009). However, in order to promote shear displacement on Ganymede, only heightened stress values due to a combination of diurnal tidal stresses and non-synchronous rotation (Cameron et al., 2019) or a higher value of eccentricity in the satellite's past, such as e = 0.02-0.05 compared to the present e = 0.0013 (Cameron et al., 2020; Burkhard et al., 2023), would be sufficient to induce strike-slip faulting.

Approximately 34% of Ganymede's surface is covered by dark terrains, which represent the satellite's geologically oldest features (Passey and Shoemaker, 1982; Pappalardo et al., 2004). One of Ganymede's most prominent surface features is a concentric network of furrows located in these oldest dark terrains, which are crosscut by craters exceeding a diameter of 10 km. This dates these troughs as the oldest surface features on Ganymede (Passey and Shoemaker, 1982; Pappalardo et al., 2004). Hirata et al. (2020) reanalyzed the distribution of these furrows using both Voyager and Galileo imagery, and showed that this network is not just in a hemispherical scale as previously assumed (Schenk and McKinnon, 1987; Zuber and Parmentier, 1984) but on a global scale. It was therefore hypothesized that a single large impactor with an estimated radius of 150 km is responsible for the creation of these furrows (Hirata et al., 2020). This approximation includes some uncertainty; however, such an impactor size would be consistent with the properties of the furrow network that is centered at the anti-Jovian longitude (180ºW). Hirata et al. (2020) predict that consequently, there should be a positive gravity anomaly around 20ºS, 180ºW with a radius of ~1000 km, which could be tested by ESA's Jupiter Icy Moons Explorer (JUICE) mission and NASA's Europa Clipper mission.

In this short exploratory study, we revisit the methods of Showman and Malhotra (1997) and compute the dimensions of an impactor required to pump Ganymede's orbital eccentricity. By applying the constraints from the hypothesized impactor of Hirata et al. (2020), we assess the necessary mass of an asteroidal or cometary impactor that would excite Ganymede's orbital eccentricity to match current values and show consistency with Hirata et al.'s hypothesis.

2. Methods and results

We consider the ancient impactor as hypothesized by Hirata et al. (2020) to calculate the mass and radius of a cometary or asteroidal impactor necessary to excite Ganymede's orbital total eccentricity (e) assuming an initial state of zero. For this, we utilize the equation previously employed by Showman and Malhotra (1997), which assumes that the impactor strikes Ganymede in an inertial reference frame with Jupiter at its center at an angle θ tangent to Ganymede's orbit in a head-on collision, striking through Ganymede's center of mass with no change to its rotational state. Consequently, the eccentricity after an impact is calculated as

$$e^2 = \left(\frac{m_i}{M_G}\right)^2 \left[4 + \frac{v_i^2}{v_G^2}\left(1 + 3cos^2\theta\right) - 8\frac{v_i^2}{v_G^2}cos\theta\right]$$

where M_G and v_G are Ganymede's mass (1.4819×10^{23} kg) and orbital velocity, and m_i and v_i are the impactor mass and speed. We considered Ganymede's speed relative to Jupiter as

$$v_G = \sqrt{\frac{GM_J}{r}}$$

where G is the gravitational constant, M_J the mass of Jupiter and r Ganymede's semi-major axis. Given the scenario's specifics of the impactor striking on the anti-Jovian longitude 180ºW (Hirata et al., 2020), the impact angle θ would effectively be 180º considering the direction towards Jupiter as 0º.

We calculated possible impactors with a fixed speed of 20 km/s (Zahnle et al., 2003) but with varying densities to illustrate impactor compositions and radii needed to meet the mass required to excite Ganymede's eccentricity to the threshold value of e = 0.0015 (Fig. 1). Large impactors from the outer Solar System do not necessarily have to be made up purely of ice, but can have a higher density with a mixture of silicate materials and nickel-iron (Carry, 2012). An asteroidal or cometary impactor consisting of mixed water ice could have a density of 1000 kg/m^3, while an impactor containing metal alloys could range in values of >3000 kg/m^3. In order to excite Ganymede's eccentricity to its current value of e = 0.0013, a mass of 2.8274×10^{19} kg is needed, which corresponds to an impactor with a radius of 150 km and density of 2000 kg/m^3 as modeled by Hirata et al. (2020). To excite the eccentricity to a value of e = 0.0015, an impactor with a density of 3000 kg/m^3 would require a radius of ~138 km, while an impactor with density of 1000 kg/m^3 would need a radius of ~200 km.

3. Discussion and conclusions

It was previously estimated that a comet striking Ganymede should have a mass of ~10^{20} kg in order to increase the eccentricity to the current value (Showman and Malhotra, 1997). Therefore, it was concluded that Ganymede's eccentricity could not have been produced by an impactor since the largest recent impactor basin on Ganymede's surface is Gilgamesh, which is too small. It is assumed that large impact basins such as Gilgamesh are concurrent with the large lunar basins Orientale and Imbrium, dating to 3.8 billion years ago (Neukum, 1997; Neukum et al., 1999; 2001). Newer Galileo-based crater counts on the floor and ejecta of Gilgamesh and revised observational estimates of the number of comets near Earth suggest that Gilgamesh is much younger, dating around 700 Ma (Zahnle et al., 2003). However, an eccentricity increase created by such an impactor would have damped long before present time, since the tidal damping time for Ganymede is estimated to be 10^8 years (Showman and Malhotra, 1997). However, Ganymede could have experienced orbital resonances after a more ancient and larger impact basin formation that further pumped its free eccentricity component, since resonances modeled could only excite Ganymede's eccentricity to half the current value. Nevertheless, it was mentioned that unpublished exploratory resonance model runs suggest that paths may exist that allow for larger free eccentricity values, and that the current free eccentricity value is therefore a remnant of an ancient resonance passage (Showman and Malhotra, 1997).

Our calculations show that a mass of 3.35×10^{19} kg is needed to excite Ganymede's eccentricity from zero to a value of e = 0.0015. Hypothetically, it is also possible that an impactor could have further excited an already existing eccentricity if we do not assume the initial free eccentricity to be zero. Given that Ganymede's darkest terrains are estimated to be around 4 Ga old, there is a need for a deeper investigation into how the impactor might have affected Ganymede's orbital behavior and its potential impact on the resonance dynamics with Io and Europa. New data from NASA's Juno mission, as well as future observations by ESA's Jupiter Icy Moons Explorer (JUICE) mission and NASA's Europa Clipper mission, will enhance our comprehension of Ganymede's history and improve resolution of terrain studies for feature and age analysis.

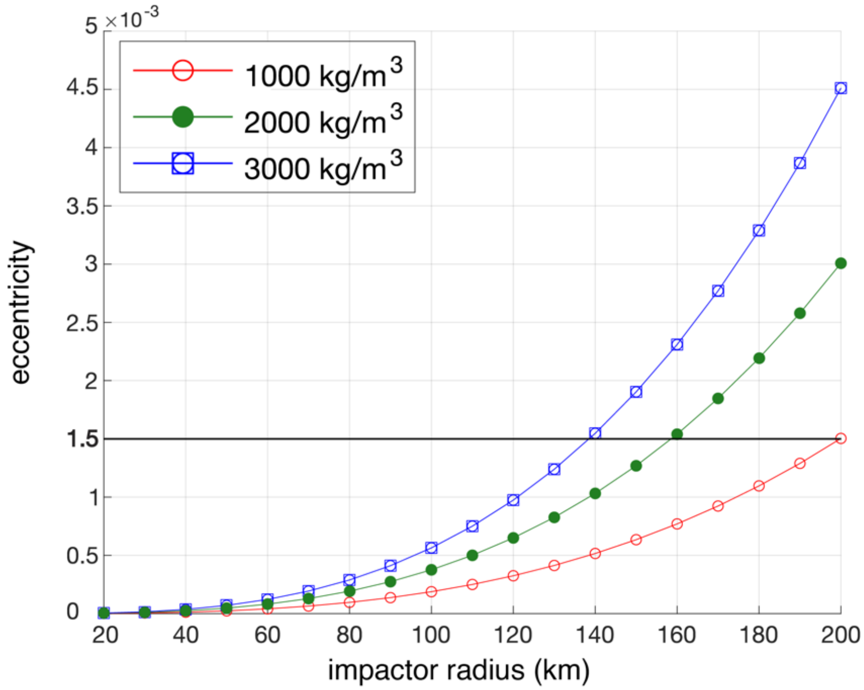

Figure 1. Calculated orbital eccentricity values and radii of possible impactors at a fixed impact velocity of 20 km/s plotted with varying densities: 1000 kg/m^3 analogous to an asteroidal or cometary impactor consisting of mixed water ice, 2000 kg/m^3 as used in models by Hirata et al. (2020), and 3000 kg/m^3 representative of basalt or mixed metal alloy. Ganymede's present eccentricity value depicted as black line at 0.0015.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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