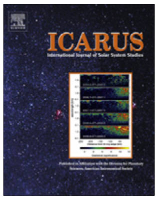
Icarus 223 (2013) 775–795

Contents lists available at SciVerse ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus



Black rain: The burial of the Galilean satellites in irregular satellite debris

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ARTICLE INFO

Article history:
Received 24 September 2012
Revised 9 January 2013
Accepted 9 January 2013
Available online 30 January 2013

Keywords:
Ganymede
Jupiter, Satellites
Irregular satellites
Callisto
Europa

ABSTRACT

Irregular satellites are dormant comet-like bodies that reside on distant prograde and retrograde orbits around the giant planets. They are likely to be captured objects. Dynamical modeling work indicates they may have been caught during a violent reshuffling of the giant planets ~4 Gy ago (Ga) as described by the so-called Nice model. According to this scenario, giant planet migration scattered tens of Earth masses of comet-like bodies throughout the Solar System, with some comets finding themselves near giant planets experiencing mutual encounters. In these cases, gravitational perturbations between the giant planets were often sufficient to capture the comet-like bodies onto irregular satellite-like orbits via three-body reactions. Modeling work suggests these events led to the capture of on the order of ~0.001 lunar masses of comet-like objects on isotropic orbits around the giant planets. Roughly half of the population was readily lost by interactions with the Kozai resonance. The remaining half found themselves on orbits consistent with the known irregular satellites. From there, the bodies experienced substantial collisional evolution, enough to grind themselves down to their current low-mass states.

Here we explore the fate of the putative irregular satellite debris in the Jupiter system. Pulverized by collisions, we hypothesize that the carbonaceous chondrite-like material was beaten into small enough particles that it could be driven toward Jupiter by Poynting–Robertson (P–R) drag forces. Assuming its mass distribution was dominated by $D > 50\ \mu\text{m}$ particles, we find that >40% ended up striking the Galilean satellites. The majority were swept up by Callisto, with a factor of 3–4 and 20–30 fewer particles reaching Ganymede and Europa/Io, respectively. Collision evolution models indicate most of this material arrived about 4 Ga, but some is still arriving today. We predict that Callisto, Ganymede, Europa, and Io were buried about 4 Ga by ~120–140 m, 25–30 m, 7–15 m, and 7–8 m of dark debris, respectively. The first two values are consistent with observations of the deepest dark lag deposits found on the most ancient terrains of Callisto and Ganymede. The rest of the debris was likely worked into the crusts of these worlds by geologic and impact processes. This suggests the debris is a plausible source of the dark lag material found in Europa's low-lying crevices. More speculatively, it is conceivable that the accreted dark particles were a significant source of organic material to Europa's subsurface ocean.

1. Introduction

Jupiter's satellites are often considered to be their own mini Solar System. The largest regular ones by far are the Galilean satellites, Io, Europa, Ganymede, and Callisto, which are comparable in size or larger than our Moon (Fig. 1). They reside near Jupiter's rotation equatorial plane on nearly-circular orbits that are 5.9, 9.4, 15, and 26.4 Jupiter radii from the center of Jupiter, respectively. Their compositions vary as well: Io is largely made of rock, while Europa, Ganymede, and Callisto are composed of ice and rock. The surfaces of the three outermost satellites are dominated by water ice.

If the Galilean satellites are the "planets" of this system, than the irregular satellites are its quasi-Oort cloud. These bodies reside on highly eccentric and inclined orbits (many retrograde) with semimajor axes that are nearly 300 Jupiter radii from Jupiter. The bodies even look like dormant comets, with spectroscopic properties similar to dark C-, D-, and P-type asteroids. For additional description of their properties, see the recent reviews by Jewitt and Haghighipour (2007) and Nicholson et al. (2008).

Along these lines, the proposed origins of the regular and irregular satellites are also different from one another. For example, one scenario suggests that the Galilean satellites formed over the first few My of Solar System history within a gas-starved disk that surrounded Jupiter during its final phase of accretion (e.g., Canup and Ward, 2009; Ogihara and Ida, 2012). The timing of irregular satellite capture, on the other hand, is more poorly understood; it could have been early or as late as several of hundreds of millions of

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http://dx.doi.org/10.1016/j.icarus.2013.01.008

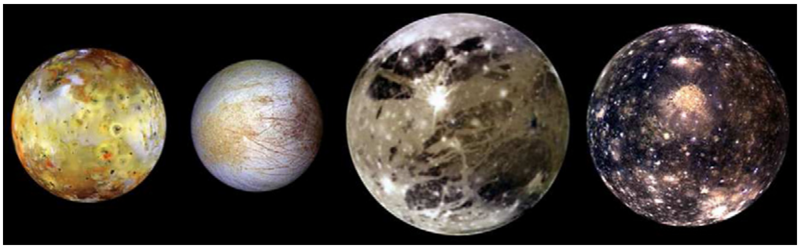

Fig. 1. The Galilean satellites, Io, Europa, Ganymede, and Callisto. They have radii of 1821.6, 1560.8, 2631.2, and 2410.3 km, respectively, and are 5.9, 9.4, 15, and 26.4 Jupiter radii from the center of Jupiter, respectively. Io is a volcanic body dominated by rock, and its surface is very young. The other Galilean moons are composed of rock and ice and have icy surfaces. Their surface ages increase sharply as one moves away from Jupiter. The color differences between these three moons are largely caused by the additional a dark material whose source is unknown. For each world, the regions with the most dark material are also those that are the most heavily cratered. The darkest regions on Ganymede, however, are not as dark as Callisto, even though the spatial density of craters in these regions may be comparable (e.g., Prockter et al., 1998; Schenk et al., 2004). The white spots on Ganymede and Callisto are craters, where bright ice has been dredged up as impact ejecta. This suggests the dark material is mainly a surface veneer. Image credit NASA/JPL/DLR, and courtesy of NASA/JPL-Caltech.

years after this time (e.g., Nesvorný et al., 2007; Bottke et al., 2012). This time gap, if true, could mean there were perhaps few or no irregular satellites present during the formative years of the Galilean satellites. It is also possible early irregulars captured by one mechanism were dynamically removed by a subsequent capture mechanism, say by late encounters between giant planets (Beaugé et al., 2002; Nesvorný et al., 2007). Regardless, this factor, as well as the large distances between the regular and irregular satellite systems, makes it easy to dismiss the irregular satellites as a population that can influence the nature of the Galilean satellites.

Still, there are hints that the irregular satellites have affected the Galilean satellites in some fashion. Consider the following. The mean geometric albedos of Io, Europa, Ganymede, and Callisto are 0.62, 0.68, 0.44, and 0.19, respectively. These values decrease as one moves toward the irregular satellite region (Fig. 1). A closer look at Europa, Ganymede, and Callisto, as shown by a side-by-side comparison (Fig. 2) and high resolution images (Figs. 3–5, respectively), reveal that the dominant darkening agent appears to be deposits of small dark particles. Some of these particles are seen in the crevices of Europa's young surface, while more are seen in the heavily-cratered terrain of Ganymede. At Callisto, nearly all features appear to be blanketed by and/or are mixed with this dark material.

Interestingly, the reflectance spectrum of these terrains appears to be a combination of water–ice and a dark non-icy material that may be similar to carbonaceous chondrites (e.g., Moore et al., 2004; see also McKinnon and Parmentier, 1986). Some have argued that the dark non-icy component on their surfaces, as well as on many other giant planet satellites, appears to be spectroscopically similar to the irregular satellites (e.g., Cruikshank et al., 1983; Buratti and Mosher, 1991, 1995; Buratti et al., 2002; Tosi et al., 2010; Dalton et al., 2012).

This result prompted several groups to suggest that small debris from the irregular satellites might be the source of this material (e.g., Pollack et al., 1978; Johnson et al., 1983; Bell et al., 1985; McCord et al., 1998; see also McKinnon and Parmentier, 1986). We found this to be a highly intriguing scenario, particularly because it has such strong precedents. For example, many authors have suggested links between the small particles driven off of Saturn's moon Phoebe by collisions and the dark leading face of Iapetus (e.g., Soter, 1974; Burns et al., 1996; Verbiscer et al., 2009; Tosi et al., 2010; Tamayo et al., 2011). These particles would evolve inward toward Saturn by Poynting–Robertson (P–R) drag forces (e.g., Burns et al., 1979), with some landing on Iapetus.

To get substantial numbers of small particles, one needs to have two components: a sizable initial population, and lots of collisions. For the latter, we point out that observations of the heavily-cratered surface of Phoebe, its associated dust ring (Verbiscer et al., 2009), as well as the detection of irregular satellite families around many giant planets (e.g., Nesvorný et al., 2003, 2004; see

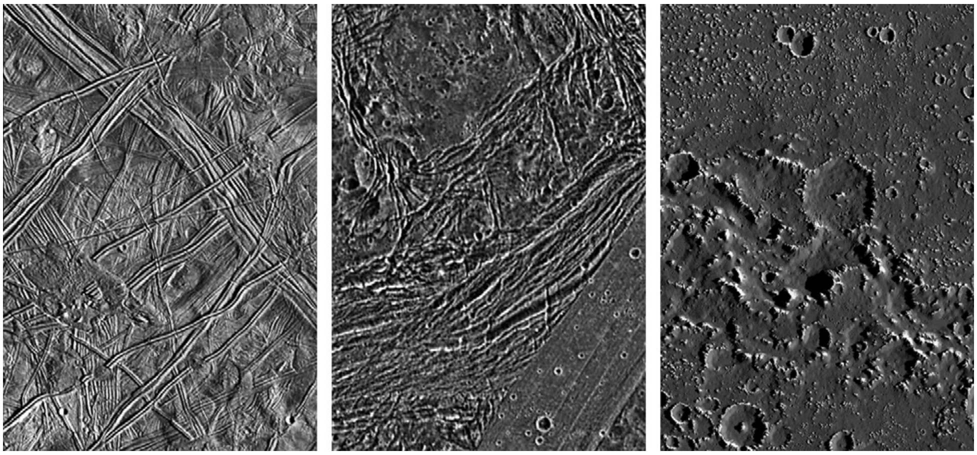

Fig. 2. The surfaces of Europa, Ganymede, and Callisto, scaled to the same resolution of 150 m per pixel. The Europa panel (left) was taken from the region around the Agave and Asterius dark lineaments. It shows few craters and numerous tectonic features. The Ganymede panel (center) was taken from Nicholson Regio. It contains several impact craters and a smaller greater degree of tectonic deformation. The surface is general darker than Europa. The Callisto panel (right) was taken from Asgard basin. It shows numerous impact craters and is covered by a dark layer of material. This layer covers the smaller craters in the image. The most heavily cratered terrains on Ganymede and Callisto are probably close to 4 Gy old, while those are Europa are perhaps less than 100 My old. The images were taken by the Solid State Imaging (SSI) system on NASA's Galileo spacecraft. North is up in all images. The spatial resolution of the original data was 180 m/pixel for Europa and Ganymede and 90 m/pixel for Callisto. Image credit NASA/JPL/DLR, and courtesy of NASA/JPL-Caltech.