Icarus 226 (2013) 865–884

Contents lists available at SciVerse ScienceDirect

Icarus

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

Secondary craters from large impacts on Europa and Ganymede: Ejecta size–velocity distributions on icy worlds, and the scaling of ejected blocks

Kelsi N. Singer *, William B. McKinnon, L.T. Nowicki

Department of Earth and Planetary Sciences and McDonnell Center for the Space Sciences, Washington University in St. Louis, 1 Brookings Dr., Saint Louis, MO 63130, USA

ARTICLE INFO

Article history:
Received 4 March 2013
Revised 27 June 2013
Accepted 29 June 2013
Available online 12 July 2013

Keywords:
Europa
Ganymede
Impact processes
Cratering
Satellites, Surfaces

ABSTRACT

We have mapped fields of secondary craters around three large primary craters on Europa and Ganymede and estimated the size and velocity of the fragments that formed the secondaries using updated scaling equations for ice impacts. We characterize the upper envelope of the fragment size–velocity distribution to obtain a function for the largest fragments at a given ejection velocity. Power-law velocity exponents found in our study of icy satellite secondary fields are compared to the exponents found for similar studies of mercurian, lunar, and martian craters; for all but basin-scale impacts, fragment size decreases more slowly with increasing ejection velocity than on rocky bodies. Spallation theory provides estimates of the size of ejected spall plates at a given velocity, but this theory predicts fragments considerably smaller than are necessary to form most of our observed secondaries. In general, ejecta fragment sizes scale with primary crater diameter and decrease with increasing ejection velocity, v_{ej}, by $1/v_{ej}$ or greater, and point-source scaling implies a relation between the two. The largest crater represented in any of these studies, Gilgamesh on Ganymede, exhibits a relatively steep velocity dependence. Extrapolating the results to the escape speed for each icy moon yields the size of the largest fragment that could later re-impact to form a so-called sesquinary crater, either on the parent moon or a neighboring satellite. We find that craters above 2 km in diameter on Europa and Ganymede are unlikely to be sesquinaries.

1. Introduction

The relationship between the size and velocity of fragments ejected during large cratering events on icy satellites is poorly known. Yet knowledge of the size–velocity distribution (SVD) of ejected fragments is critical to understanding the contribution of ejecta to the overall population of small craters (e.g., Zahnle et al., 2008; Bierhaus et al., 2012) and thus to the paramount issue of age dating by means of crater counts (e.g., Bierhaus et al., 2005; McEwen and Bierhaus, 2006). Although ejecta characterizations from laboratory experiments, explosion craters, and theoretical models are available and helpful, empirical studies of ejecta size–velocity distributions specifically for icy surfaces are sparse. Only one (preliminary) study has previously mapped and determined the SVD for such secondaries, from the crater Pwyll on Europa (Alpert and Melosh, 1999). Here we extend an analysis (first presented in Singer et al., 2011) to three other large primaries on Europa and Ganymede, including the largest preserved multiringed impacts on these satellites. We also compare these results to similar studies performed for rocky bodies: Mercury, the Moon, and Mars (Vickery, 1986, 1987; Hirase et al., 2004; Hirata and Nakamura, 2006). Characterizing the fragment-size velocity dependence also complements work on other aspects of ejecta-velocity relationships, such as the relationship between ejection velocity and ejection position, the mass of material ejected at a given velocity, and the number of fragments ejected at a given velocity (Alvarellos et al., 2002; McEwen and Bierhaus, 2006; Housen and Holsapple, 2011; Bierhaus et al., 2012; and references therein).

We consider ejecta fragments that form traditional secondaries, and in addition extrapolate to fragments ejected at a moon's escape velocity, which could re-impact the parent moon or another body, forming so-called sesquinary craters (Zahnle et al., 2008). Secondary craters have been demonstrated to be extensive, as revealed most directly in cases where much of the secondary field related to a given primary can be reliably mapped (e.g., Zunil on Mars; McEwen et al., 2005). On Europa secondaries could constitute as much as 95% of craters smaller than 1 km in diameter (Bierhaus et al., 2005). The extensive presence of secondaries has

* Corresponding author. Address: Washington University in St. Louis, Department of Earth and Planetary Sciences and McDonnell Center for the Space Sciences, Campus Box 1169, 1 Brookings Dr., St. Louis, MO 63130-4862, USA. Fax: +1 (314) 935 7361.

E-mail addresses: ksinger@levee.wustl.edu (K.N. Singer), mckinnon@wustl.edu (W.B. McKinnon).

0019-1035/$ - see front matter © 2013 Elsevier Inc. All rights reserved.
http://dx.doi.org/10.1016/j.icarus.2013.06.034

been cited as a problem for calculating surface ages based on counting small craters and mistakenly assuming they are formed by asteroidal or cometary impactors (Bierhaus et al., 2005, 2009; McEwen and Bierhaus, 2006). Sesquinaries are an additional, conflating, contribution to the population of small craters. Sesquinaries (and distant secondaries) can be located at any distance from the primary crater, and are less likely to have any morphology or geometric associations indicating they are not primary (e.g., forming clusters or radial chains).

Sesquinaries can also travel between neighboring satellites, although the majority of fragments are predicted to re-impact their parent moon (e.g., Alvarellos et al., 2002, 2005). Thus, ejecta from large impacts have been noted as a potential source of planetocentric impactors in satellites systems. Heliocentric projectiles should preferentially impact the leading hemisphere of a prograde, synchronous satellite, while planetocentric debris should impact more isotropically. Jovian satellite crater populations do not exhibit strong apex–antapex asymmetries (e.g., Zahnle et al., 2001; Schenk et al., 2004), motivating consideration of sesquinaries as important contributors to the cratering rates.

This paper describes our empirical study of secondary craters and ejecta fragment SVDs as follows. In Section 2 we acquaint the reader with the characteristics of the three primary craters and their secondary fields, and outline our mapping procedures. The derivation of secondary fragment size and velocity is explained in Section 3, along with our justification for carrying out this part of the analysis in the gravity regime. In Section 4 we present the results of fitting the upper envelope of the size–velocity distributions, compare the fits between the three primaries studied here, and attempt some general scalings. The discussion in Section 5 extends this comparison to similar studies on other bodies and to theoretical models related to crater ejecta processes, especially spallation. We then consider the implications of our results for sesquinaries on the icy satellites. Final remarks are given in Section 6, and point-source ejecta block scaling relations are developed in the Appendix.

2. Sites and mapping methods

We mapped secondary populations around three primary craters: Tyre on Europa, and Achelous and Gilgamesh on Ganymede. Mapping was limited by availability of high-resolution imagery from the Galileo and Voyager 2 missions. We also describe a previous mapping of secondaries around Europa's conspicuous bright-rayed crater Pwyll (Alpert and Melosh, 1999) as an additional example. A summary of measured and estimated characteristics of the primary craters (calculations described in Section 3) and the number of secondaries mapped per scene, noting the largest secondary diameter, are given in Table 1.

Secondary crater diameters and distances from the primary were measured geodesically in ArcGIS. There are several instances of clustered secondaries and secondaries arranged linearly. Where it was possible to distinguish individual craters they were mapped as such. The main secondary field was assumed to begin at some radial distance outside of the continuous ejecta blanket, which was usually quite obvious. Small craters inside of this boundary were excluded from the datasets below. In some cases craters were also excluded if they were noticeably different from the majority of the surrounding secondaries in terms of size or morphology (though we recognize that rejecting outliers carries a risk of rejecting signal that has distinguished itself from "noise"). In general small primaries tend to be more perfectly bowl-shaped with sharper, more pronounced rims than secondaries. If these distinctions were made, they are noted below for each location.

2.1. Tyre – Europa

Europa provides a unique case study for investigating secondary cratering processes. Europa's young, relatively uncratered surface is ideal for mapping secondaries from a given large primary; contamination from other small primaries or for that matter secondaries from other craters is minimal (Bierhaus et al., 2005, 2009; Zahnle et al., 2008; Bierhaus and Schenk, 2010). At ~38 km in equivalent diameter, with concentric furrows extending out to ~175 km in diameter, Tyre is the largest impact basin on Europa (Fig. 1). Equivalent diameter is determined from scaling ejecta deposits to rim locations for other large craters on icy bodies (Schenk and Ridolfi, 2002; Schenk and Turtle, 2009). The secondary field around Tyre is well defined; however, mapping is limited by the Galileo imagery extent to a radial distance of 100–300 km from the equivalent rim location. This limits the range of fragment velocities we can model (described below). The main mosaic has a resolution of 170 m px^{-1}, but there is also a smaller high resolution image sequence (~30 m px^{-1}) in the southeastern portion of the secondary field, which was useful for counting smaller craters and examining secondary morphology. Tyre's ejecta distribution is also somewhat asymmetrical, with more secondaries towards the western side.

We mapped 1165 secondaries on the field overall, with diameters ranging from 0.5 to 2.8 km. Undoubtedly other, smaller secondaries exist,[1] but given the practicalities of distinguishing between craters and other topographic relief on Europa (chaos or otherwise tectonized terrain), we were not aiming to measure all of the smallest "specks" that could be secondary craters. For our purposes we are primarily concerned with the largest craters at a given distance, as will be further explored below.

The higher resolution, ~30-m px^{-1} inset was also mapped (Fig. 2). In this mosaic, the background confusion from albedo patterns (concentrations of dark material in crater floors), lineaments, chaos, and general surface roughness becomes a factor along with resolution in identifying the smallest craters. Specifically, the incidence and phase angles were low (~30° and ~3°, respectively), and not in themselves ideal for mapping based on topography. Still, approximately 375 craters were identified in this scene alone, confirming secondary craters that were mapped at lower resolution and also revealing many smaller craters (some of which could be background). The smallest feature positively identifiable as a crater is ~180 m, or about 6 pixels across, which is close to what would be expected as a practical resolution limit. We note that in none of our study areas was image resolution sufficient to identify ejecta blocks on secondary crater rims, which have been argued by Bart and Melosh (2007) as a potential means of distinguishing primary from secondary craters.

2.2. Achelous – Ganymede

Achelous is a 35-km diameter, relatively fresh crater observed by Galileo at low Sun angles (Fig. 3) and at a similar spatial resolution to Tyre (180 m px^{-1}). We mapped 630 secondaries in this scene, in the diameter range of 0.7–2.7 km. Achelous has a distinct ejecta pedestal and visible tongues of ejecta. Another somewhat older crater of similar size, Gula, lies to its north. In addition to Gula's overall more degraded appearance, its ejecta blanket appears to be overprinted on the eastern and possibly southern sides by later tectonized (grooved) terrain. There are several identifiable small craters in Gula's floor, whereas none are identifiable within Achelous. It is possible some small craters mapped in this scene

[1] Our mapping is independent of the Tyre secondaries mapped by Bierhaus and Schenk (2010) for other purposes.