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# Ray craters on Ganymede: Implications for cratering apex-antapex asymmetry and surface modification processes

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ABSTRACT

As the youngest features on Ganymede, ray craters are useful in revealing the sources of recent impactors and surface modification processes on the satellite. We examine craters with D > 10 km on Ganymede from images obtained by the Voyager and Galileo spacecraft to identify ray craters and study their spatial distributions. Furthermore, we carefully select images of appropriate solar and emission angles to obtain unbiased ray crater densities. As a result, we find that the density of large ray craters (D > 25 km) on the bright terrain exhibits an apex-antapex asymmetry, and its degree of asymmetry is much lower than the theoretical estimation for ecliptic comets. For large craters (D > 25 km), ecliptic comets ought to be less important than previously assumed, and a possible explanation is that nearly isotropic comets may play a more important role on Ganymede than previously thought. We also find that small ray craters (10 km < D < 25 km) on the bright terrain and ray craters (D > 10 km) on the dark terrain show no apex-antapex asymmetry. We interpret that the distribution difference between the terrain types comes from preferential thermal sublimation on the dark terrain, while the distribution difference between large and small ray craters suggests that rays of small craters are more readily erased by some surface modification processes, such as micrometeorite gardening.



## 1. Introduction

Ganymede, with a diameter of 5268 km, is the largest satellite in the solar system. Ganymede has a synchronous rotation with Jupiter and is in orbital resonance with both Europa and Io. Its relatively large density (1936 kg/m$^3$), the gravity data from the Galileo spacecraft, and the existence of an internal magnetic field indicate that Ganymede is highly differentiated, with an iron core, a silicate inner mantle, and an icy outer mantle (Anderson et al., 1996; Kivelson et al., 2002). In addition, the induced component of the magnetic field and its auroral ovals observed by the Hubble Space Telescope suggest a saline and electrically conductive subsurface ocean (e.g., Kivelson et al., 2002; Saur et al., 2015). The flybys of the Pioneer 10, Voyagers 1–2, and Galileo spacecraft revealed that the surface of Ganymede can be roughly classified into two types of terrains by albedo: the dark terrain, comprising 34–35% of the total area, is ancient and heavily-cratered, while the rest of Ganymede identified as the bright terrain, is a younger tectonized terrain, whose crater densities are 2 to 10 times less than those of the dark terrain (Gehrels, 1976; Smith et al., 1979a, b; Passey and Shoemaker, 1982; Shoemaker et al., 1982; Pappalardo et al., 2004).

Ray craters are ubiquitously found on Ganymede, as exhibited on the Moon, Mercury, Callisto, Dione, and many other solar-system solid bodies (e.g., Shoemaker, 1962; Gault et al., 1975; Shoemaker et al., 1982; Hirata and Miyamoto, 2016). Ray craters can be identified as craters surrounded by radial ejecta patterns with relatively higher albedo (Passey and Shoemaker, 1982; Shoemaker et al., 1982), though a few tens of craters on Ganymede have dark rays (Conca, 1982; Schenk and McKinnon, 1991). As on the Moon, ray craters on Ganymede are recognized to be the youngest features because they superimpose all terrain types and other craters (Shoemaker et al., 1982). In general, rays gradually fade out with time due to various surface modification processes, such as micrometeorite gardening, recrystallization, radiation darkening, and surface contamination (Smith et al., 1979a). Therefore, the distribution of ray craters is a good indicator for studying the sources of recent impactors and surface modification processes, which would contribute to the estimation of the surface ages and the understanding of the dynamic evolution of the outer solar system.

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Apex-antapex asymmetry of craters can provide insight into the origins of impactors. On a synchronously rotating satellite, heliocentric comets preferentially hit the leading hemisphere of the satellite, which would result in an apex-antapex asymmetry of crater density (Shoemaker and Wolfe, 1982; Horedt and Neukum, 1984). Heliocentric comets are further classified as ecliptic comets and nearly isotropic comets (NICs). A small encounter velocity (~5 km/s) for the case of ecliptic comets likely cause a relatively strong asymmetry, while a large encounter velocity (~20 km/s) for the case of NICs causes a relatively weak asymmetry. Schenk and Sobieszczyk (1999) and Zahnle et al. (2001) examined all the impact craters with diameters larger than 30 km on Ganymede and found that their density on the bright terrain decreases from the apex (the center of leading hemisphere) to antapex (the center of trailing hemisphere) of the motion, confirming that these craters are mainly caused by heliocentric comets. However, the degree of apex-antapex asymmetry is much lower than the theoretical estimation for ecliptic comets, which are favored as the dominant impactor source on Ganymede in their studies (Zahnle et al., 2001, 2003). Various possible reasons may lead to this inconsistency, such as crater saturation or periods of nonsynchronous rotation (Zahnle et al., 2001, 2003). The distribution of ray craters can test the theoretical degree of apex-antapex asymmetry and further constrain the recent impact flux because, being the youngest, they are less affected by the influence of the factors mentioned above.

During Voyager-era investigations, many bright ray craters on Ganymede were identified (Smith et al., 1979a, b) with a higher concentration on the bright terrain than the dark terrain. Squyres (1980) ascribed the concentration to greater crustal ice content on the bright terrain than on the dark terrain. Passey and Shoemaker (1982) identified 84 bright ray craters with D > 30 km, and found that the density of bright ray craters has a tendency to increase with the distance from the apex of motion for 30°–150° (0°–20° and 160°–180° are not covered by Voyager images), which is inconsistent with the theoretical estimation for heliocentric comets. Therefore, they argued that micrometeorite gardening and/or surface contamination are dominant ray erasure processes. Also, they proposed that sublimation was likely to play a role because bright rays appear to be fainter at lower latitudes and the bright terrain has a 40% higher density of ray craters than the dark terrain. In addition, some latitudinal-dependent surface modifications (e.g., sublimation and sputtering) are accepted to be dominant on Ganymede (Pappalardo et al., 2004) and responsible for the distribution of dark ray craters (Schenk and McKinnon, 1991).

However, the density distribution proposed by Passey and Shoemaker (1982) were based on an insufficient coverage of Voyager images near the apex and antapex regions. Moreover, although the identification of crater rays is highly sensitive to solar illumination, we would like to note that previous studies do not take this effect into account. Also, Voyager-based classification of terrain types has been significantly modified since the release of Galileo images (e.g., Collins et al., 2013). For these reasons, we scrutinize Galileo images along with Voyager images and carefully exclude the possible biases caused by solar incidence and emission angles, which could provide a more accurate measurement of ray craters on Ganymede.

In this study, the spatial distribution of ray craters is examined in terms of (1) the difference between the bright and dark terrains, (2) the relationship with the distance from the apex of motion, and (3) latitudinal dependence. All of these factors lead to an improved understanding of the processes forming and modifying ray craters on Ganymede, as we discussed above.

## 2. Data and method

The Voyager 1 spacecraft obtained images of the subjovian hemisphere of Ganymede at a resolution of up to 1.0 km/pixel, and the Voyager 2 obtained images of the anti-jovian hemisphere at a resolution of up to 500 m/pixel (Pappalardo et al., 2004). The Galileo spacecraft performed six close encounters to Ganymede, and it obtained numerous images at moderate resolution (~ 0.8–3.6 km/pixel) and limited small regions at higher resolution (Pappalardo et al., 2004). These images are available via the Planetary Data System from NASA. A combination of Voyager 1 and 2 and Galileo images were used to produce a global mosaic of Ganymede, which has a spatial resolution of 1.0 km/pixel and is available via the U. S. Geological Survey (2003).

In this study, we use (1) 244 Imaging Science Subsystem (ISS) images obtained by the Voyager spacecraft, (2) 52 Solid State Imager (SSI) images obtained by the Galileo spacecraft (Supplementary Table S1), and (3) the global image mosaic of Ganymede. To measure the diameters and locations of impact craters, we use the global mosaic and ArcGIS software with the CraterTools add-in to measure the crater diameters. Additionally, we measure the surface area of each Study Area using ArcGIS. This software determines the center and diameter of a crater from the user's selection of three points along the crater rim crest.

Identification of ray craters is based on their circular raised rims accompanying relatively brighter filaments and/or continuous ejecta deposits, extending radially from the center of the craters longer than one diameter from their rims (Fig. 1). We investigate these features using raw images, rather than the global mosaic. We identify rays only by using the raw images because the global mosaic includes images at low sun (solar incidence angles are close to horizontal to the surface) or large emission angles. This is important because the ray systems can be difficult to identify with images of high solar incident angles (say > 70°), and surface features such as craters are barely seen at large emission angles (say > 85°). Therefore, we study ray craters by using images of solar incidence angles smaller than 70° and emission angles smaller than 85°. We ignore catena (i.e., chain of craters (Schenk et al., 2004)) with rays in this study.

We define four Study Areas (SA1–SA4) to obtain unbiased ray crater densities, based on resolution (Res), emission angle (E), and solar incidence angle (SI): (SA1) Res ≤ 1.0 km/pixel, E < 85°, and SI < 70°; (SA2) Res ≤ 2.0 km/pixel, E < 85°, and SI < 70°; (SA3) Res ≤ 2.5 km/pixel, E < 85°, and SI < 70°; and (SA4) Res ≤ 4.0 km/pixel, E < 85°, and SI < 70°. These are delineated in Figs. 2 and 3a, noting that SA1 is included within SA2, SA2 within SA3, and SA3 within SA4. The latitudinal ranges 70°N–90°N and 70°S–90°S can hardly be studied because the obliquity of the Jupiter system with respect to the Sun is nearly equal to 0°. Each study area enables the reliable identification of craters with diameters of D > 10 km for SA1, D > 15 km for SA2, D > 20 km for SA3, and D > 25 km for SA4. To calculate both the emission and solar incidence angle of each image, we calibrate the raw image using the ISIS3 (Integrated Software for Imagers and Spectrometers) software produced by the U. S. Geological Survey. For comparison with the identified bright ray craters in our study, we also measured all craters (i.e., impact craters including ray craters but excluding catena, palimpsests, penepalimpsets, and basins) with D > 10 km for images Res ≤ 4.0 km/pixel (Fig. 3b). Following Collins et al. (2013), we classify the dark terrain as including the dark materials unit and the dark parts of the reticulate material unit, and the bright terrain as including the light material unit and the light parts of the reticulate material unit.

## 3. Results

We identify a total of 202 ray craters with diameters larger than 10 km (Fig. 3a), along with 5335 all craters in total with diameters larger than 10 km (Fig. 3b) on Ganymede. Their locations and sizes are detailed in Supplementary Tables S2 and S3, and their distribu-