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Ceres and the terrestrial planets impact cratering record

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ABSTRACT

Dwarf planet Ceres, the largest object in the Main Asteroid Belt, has a surface that exhibits a range of crater densities for a crater diameter range of 5–300 km. In all areas the shape of the craters' size-frequency distribution is very similar to those of the most ancient heavily cratered surfaces on the terrestrial planets. The most heavily cratered terrain on Ceres covers ~15% of its surface and has a crater density similar to the highest crater density on <1% of the lunar highlands. This region of higher crater density on Ceres probably records the high impact rate at early times and indicates that the other 85% of Ceres was partly resurfaced after the Late Heavy Bombardment (LHB) at ~4 Ga. The Ceres cratering record strongly indicates that the period of Late Heavy Bombardment originated from an impactor population whose size-frequency distribution resembles that of the Main Belt Asteroids.

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1. Introduction

Ceres is the largest object in the main asteroid belt, with an orbit near the center of the belt at a semi-major axis of 2.77 AU, a moderate eccentricity (e = 0.076) and inclination of 10.6° to the ecliptic. With a diameter of 945 km, it is much smaller than the Moon (3475 km) and only about the same size as the 950 km diameter lunar Orientale basin (Fig. 1). The NASA Dawn mission obtained high-resolution images, among other measurements, of Ceres.

A comparison of the cratering record on Ceres with the cratering record of the Moon and the terrestrial planets provides important new information on the origin of the impacting objects through time and the cratering process itself. Interpreting Ceres' cratering record is complicated by the evidence for cryovolcanic activity in the geologically recent past (Marchi et al., 2016; Krohn et al., 2016; Russell et al., 2016; De Sanctis, et al. 2016; Ruesch et al., 2016) involving hydrated salts resulting from global aqueous alteration of minerals on the surface, as well as by global relaxation of the surface at long-wavelengths (Fu et al., 2017). A recent study shows that water must be present in the regolith in order to account for the water in Ceres' exosphere (Landis et al., 2017).

2. Terrestrial planet cratering record

To facilitate comparison of Ceres' crater record with that of the Moon and terrestrial planets, this section provides a summary of the terrestrial planet cratering record with R plots of the crater and impactor size-frequency distributions taken from Strom et al. (2015). The crater size-frequency distributions in the inner solar system indicate that the Moon and terrestrial planets were impacted by two primary populations of objects (Fig. 2). Population 1 was due to the period of Late Heavy Bombardment (LHB) that began some time before ~4 Ga, peaked and declined rapidly over the next ~100–300 Myr (Tera et al., 1973, 1974; Ryder, 1990) and possibly much more slowly from about 3.8–3.7 Ga to ~2 Ga (Bottke et al., 2012; Morbidelli et al., 2012; Marchi et al., 2013). It produced heavily cratered surfaces with a complex, multi-sloped crater size-frequency distribution (Fig. 2). Population 2 dominated since about 3.8–3.7 Ga. It produced a crater size distribution characterized by a differential −3 single-slope power law for crater diameters up to at least 100 km (Fig. 2).

A comparison of impactor sizes derived from the cratering record compared to the size distribution of main belt asteroids indicates that Population 1 had a size-frequency distribution that resembles that of the present-day MBAs, whereas the size-frequency distribution of Population 2 projectiles resembles that of the present-day near-Earth objects (see Fig. 14 in Strom et al., 2015). Significantly, an observed systematic shift of the peak of the R plots of the crater SFDs found on the heavily cratered terrains of Mars, Moon and Mercury is consistent with that expected from the systematic difference in the average impact velocity of projectiles sourced from the main belt and hitting these three different bodies (see Fig. 15 in Strom et al., 2015).

Strom et al. (2005) suggested the simplest interpretation is that Population 1 were asteroids from the ancient main asteroid belt delivered from their source region into terrestrial planet-crossing

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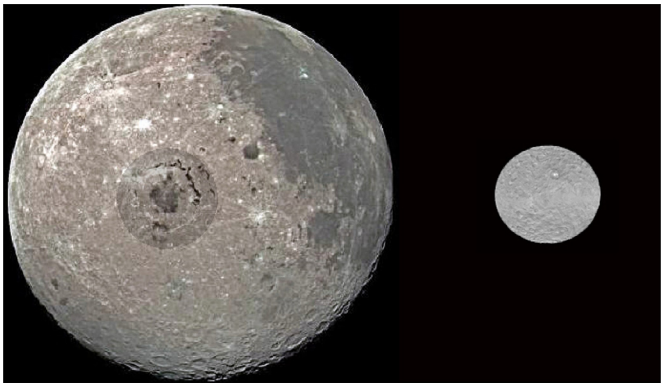

Fig. 1. Size comparison of the Moon (3476 km dia.) and Ceres (945 km dia.). Ceres is about the same diameter as the lunar Orientale basin shown by the shaded circle.

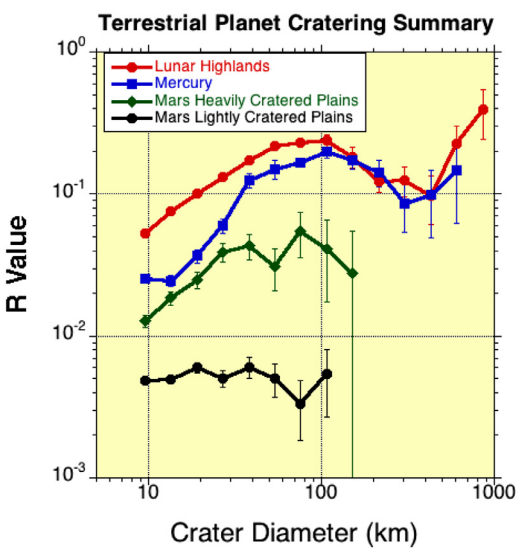

Fig. 2. These *R* plots summarize the inner solar system cratering record for crater sizes in the range of about 10 km to about 1000 km. They show two distinctly different crater populations. The curves above an *R* value of about 0.01 have a complex shape characteristic of Population 1, and the lower curve (Mars Lightly Cratered Plains) has a nearly horizontal straight line shape characteristic of Population 2. Other lightly cratered regions of the Moon, Venus and Mercury have similar curves. The paucity of Mercury craters below about 35 km is due to intercrater plains formation. Also the upturn in the curve at 10 km diameter is due to secondaries. (See Strom et al., 2015 for additional details.).

orbits, possibly by means of gravitational resonance sweeping during orbit migration of the giant outer planets. This caused the period of Late Heavy Bombardment (LHB). Similar results were obtained by comparing the crater SFD on most ancient lunar terrains with those somewhat younger of Nectarian-era (Marchi et al., 2012). This scenario of the origin of the LHB impactors from the main asteroid belt is additionally supported by numerical simulations of planetesimal-driven late migration of the giant planets (Gomes et al., 2005; Bottke et al., 2012), as well as the signatures of that migration on the orbital distribution in the present-day asteroid belt (Minton and Malhotra, 2009), although the precise timing of this event remains debated (Zellner, 2017; Nesvorny et al., 2017). The mechanism of gravitational resonance sweeping would be insensitive to the size and mass of the asteroids, hence would produce projectiles having the same size distribution as that of the asteroid belt itself.

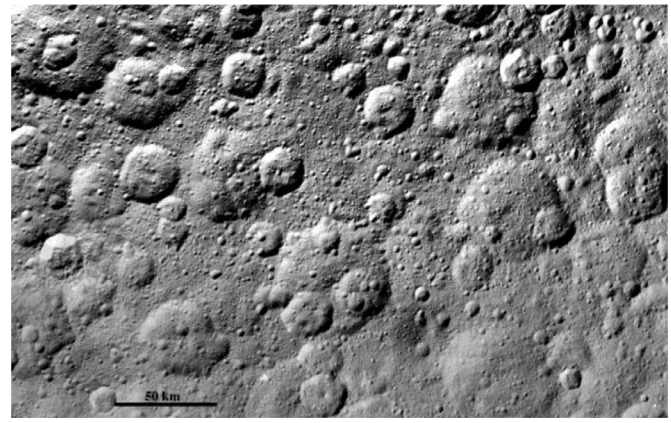

Fig. 3. Photomosaic of a portion of the heavily cratered area on Ceres. The region shown here is centered on 43°N and 315°E. The scale bar is 50 km.

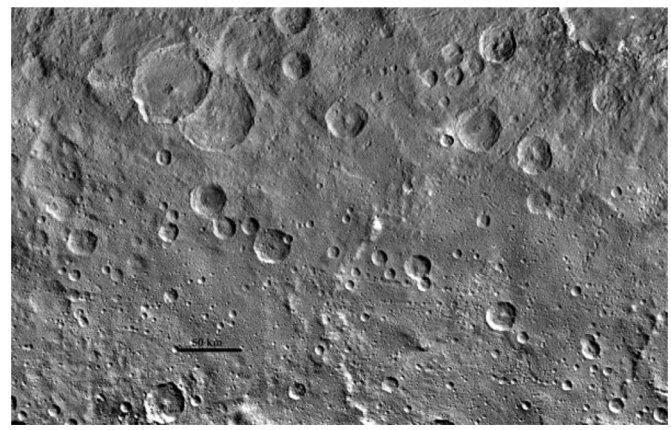

Fig. 4. Photomosaic of a portion of the lightly cratered area on Ceres. The region shown here is centered on 0°N and 108°E. The large partial crater rim on the right has been almost obliterated by resurfacing. The scale bar is 50 km.

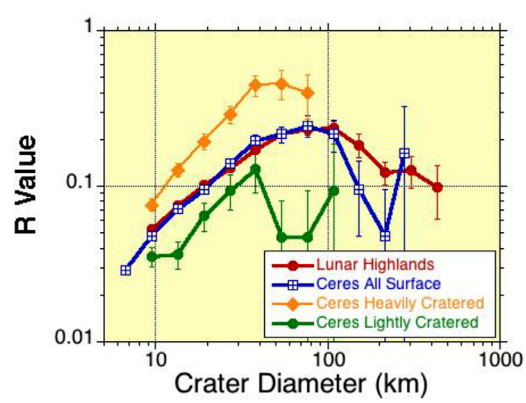

Fig. 5. R plots of the lunar heavily cratered highlands (red) compared to the heavily cratered (orange) terrain, the entire surface (blue), and the lightly cratered (green) terrain of Ceres. See text for interpretations. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3. The Ceres cratering record

The cratering record on Ceres in the size range 5–100 km has a crater size-frequency distribution that is very similar to the heavily cratered surfaces of the Moon, Mars, and Mercury. However, the crater density varies in certain areas of the asteroid. Fig. 3 shows an area that has a very high density of craters while Fig. 4 shows an area that is relatively lightly cratered. Fig. 5 is R plots of heavily cratered (orange), lightly cratered (green) and total surface (blue)

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