The Preliminary Investigation of Impact Craters on Asteroid (4) Vesta

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Abstract

One of the most common geologic features across the solar system are impact craters. With the use of the Dawn spacecraft's Framing Camera it was revealed that (4) Vesta's surface is dominated by impact craters of all sizes. The crater's morphological and morphometric characteristics can provide insight into the target properties of Vesta which make them a prime target for this study. A preliminary database consisting of craters found in the south polar region (88.15°S - 80.05 °S) has been developed. These craters have crater diameters (D) ≥ 0.5 km and have been recorded over all longitudes at Vesta's south pole. This preliminary investigation is part of a larger study to analyze craters with D ≥ 0.5 km over the entire surface of Vesta to further understand its target properties and compare these data with those observed for the dwarf planet Ceres. Various interior morphologies, such as central peaks and central pits, were choosen for this dataset as they can provide insight into the crustal strength of a body. Additionally, the data collected for these impact craters consist of the center latitude and longitude, crater diameter (km), crater preservation state, ejecta morphologies, central peak diameter (km) and height (km), central pit diameter (km) and depth (km), if applicable, and crater depth and crater rim height (km) utilizing both topography models. Upon initial analysis, 115 craters have been reported at the south polar region of Vesta and show similarities to what is expected for other rocky bodies with the exception of the ejecta mobility ratio which is lower than expected. Further investigation into all craters across the surface is still ongoing.

Keywords: Craters, Vesta, Asteroid, Impact Craters, Planetary Geology

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La investigación preliminar de los cráteres de impacto en el asteroide (4) Actas de la Conferencia de Vesta

Resumen

Una de las características geológicas más comunes en todo el sistema solar son los cráteres de impacto. Con el uso de la cámara de encuadre de la nave espacial Dawn, se reveló que (4) la superficie de Vesta está dominada por cráteres de impacto de todos los tamaños. Las características morfológicas y morfométricas del cráter pueden proporcionar información sobre las propiedades objetivo de Vesta, lo que los convierte en un objetivo principal para este estudio. Se ha desarrollado una base de datos preliminar que consiste en cráteres encontrados en la región polar sur (88,15 ° S - 80,05 ° S). Estos cráteres tienen diámetros de cráter (D) ≥ 0,5 km y se han registrado en todas las longitudes en el polo sur de Vesta. Esta investigación preliminar es parte de un estudio más amplio para analizar cráteres con D ≥ 0,5 km en toda la superficie de Vesta para comprender mejor sus propiedades objetivo y comparar estos datos con los observados para el planeta enano Ceres. Se seleccionaron diversas morfologías interiores, como picos y fosas centrales, para este conjunto de datos, ya que permiten comprender la resistencia de la corteza de un cuerpo. Además, los datos recopilados para estos cráteres de impacto incluyen la latitud y longitud del centro, el diámetro del cráter (km), el estado de conservación del cráter, las morfologías de la eyección, el diámetro y la altura del pico central (km), el diámetro y la profundidad de la fosa central (km), si corresponde, y la profundidad y la altura del borde del cráter (km), utilizando ambos modelos topográficos. Tras un análisis inicial, se han reportado 115 cráteres en la región polar sur de Vesta, que muestran similitudes con lo esperado para otros cuerpos rocosos, con la excepción de la tasa de movilidad de la eyección, que es menor de lo esperado. Se continúa investigando la totalidad de los cráteres en la superficie.

Palabras clave: Cráteres, Vesta, asteroide, cráteres de impacto, geología planetaria

灶神星撞击坑会议记录的初步调查

摘要

撞击坑是整个太阳系最常见的地质特征之一。通过使用“黎

明”号航天器的取景相机，我们发现灶神星表面主要由各种大小的撞击坑组成。陨石坑的形态和形态测量特征能为灶神星的目标特性提供见解，这使其成为本研究的主要目标。已经开发了一个初步数据库，其中包含在南极地区(88.15°S - 80.05°S)发现的陨石坑。这些陨石坑的直径(D)≥0.5公里，并已记录在灶神星南极的所有经度上。本篇初步调查是一项更大规模研究的一部分，以分析灶神星整个表面D ≥0.5公里的陨石坑，以期进一步了解其目标特性，并将这些数据与矮行星谷神星的观测数据进行比较。该数据集选择了各种内部形态，例如中央峰和中央坑，因为它们能为天体的地壳强度提供信息。此外，利用两种地形模型收集的这些撞击坑数据包括中心纬度和经度、陨石坑直径（公里）、陨石坑保存状态、喷出物形态、中央峰直径（公里）和高度（公里）、中央坑直径（公里）和深度（公里）（如果适用），以及陨石坑深度和陨石坑边缘高度（公里）。经初步分析，灶神星南极地区已报告有115个陨石坑，与其他岩石天体的预期情况相似，但喷出物流动性比率低于预期。对整个表面所有陨石坑的进一步调查仍在进行中。

关键词：陨石坑，灶神星，小行星，撞击坑，行星地质学

Background

Vesta has long been of interest to the scientific community because of its geologic diversity of iron-rich and calcium-rich pyroxene observed in the western hemisphere and magnesium-rich and calcium-poor pyroxene observed in the eastern hemisphere (Binzel et al., 1997) as well as the possibility of its links to the Howardite, eucrite, and diogenite meteorites (Benzil and Xu, 1993). With further observations, Gaffey (1997) had proposed that impact craters would be the dominant geologic features across the surface of Vesta which would provide insight into the early solar system. It has been long suggested that Vesta is an object which formed during the early solar system similar to dwarf planet Ceres, and can provide significant clues into the early solar system and planet formation (Russell et al., 2004; Russell et al., 2012).

The Dawn mission, which orbited Vesta from July 2011 to September 2012, acquired global visible image datasets (Russell et al., 2012) using the Framing Camera (Sierks et al., 2011) during the High Altitude Mapping Orbit (HAMO) with a resolution of ~60 m/pixel (Roatsch et al., 2013; Nathues et al., 2015). During its flight, the Dawn spacecraft did confirm the initial reports by Gaffey (1997) that the surface of Vesta is dominated by impact craters of varying sizes (Marchi et al., 2012) which can provide insight into the formation and evolution of this body.

Several studies of impact craters on Vesta have shown a wide range of impact crater sizes and distributions across the surface (Marchi et al., 2012; Kneissl et al., 2011; Vincent et al., 2014; Liu et al., 2018). Vincent et al. (2014) investigated the depth-to-diameter relationship (d/D) for the impact craters on Vesta and reported that these values fell within the range seen for other rocky airless bodies in the solar system with variations seen depending on their geographic location. Vincent et al. (2014) also reported that the simple-to-complex transition diameter (Dsc), the diameter at which small simple bowl-shaped craters with simple crater morphologies transition into larger more complex craters displaying complex morphologies (Pike, 1977), was ~20 km for the strength-to gravity dominated regime and 38 km for the Dsc.

The goal of this study is to create a global dataset for impact craters on Vesta, identifying a number of morphometric and morphological properties to better understand Vesta's surface and subsurface composition. This will be done by investigating the crater ejecta and interior morphologies, the depth-diameter ratios (d/D) and the simple-to-complex transition diameter (Dsc) to provide insight into any crustal heterogeneity across the surface of Vesta. Findings from this study are reported at the preliminary stages of crater collection.

Methodology

The previous studies of impact craters on Vesta have only looked at craters within a specified size range (Marchi et al., 2012; Kneissl et al., 2011; Vincent et al., 2014). The first global database for Vesta was developed by Liu et al. (2018) containing 11,605 craters with diameters ≥ 0.7 km. That dataset included the longitude and latitude of the impact crater, crater diameter, crater depth, ellipticity and azimuth of the major axis, along with the d/D and the associated error measurements for each category. However, many additional important properties of the impact craters were not included in the Liu et al. (2018) study which prompted this study to compile a new crater dataset for Vesta containing craters with diameters ≥ 0.5 km.

Crater data were obtained using the Java Mission-planning and Analysis for Remote Sensing (JMARS) software (Gorelick et al., 2003) with the Framing Camera's HAMO global mosaic (Roatsch et al., 2013). Impact craters below the diameters ≥ 0.5 km were not reported in the dataset for the resolution of the global mosaic which made it difficult to clearly identify if these impact craters were primary or secondary craters. Secondary craters were not reported in this dataset. Crater diameters were assessed initially using the measuring tool found within JMARS to ensure a crater diameter was at or above the 0.5 km limit for the database. If the crater measurements were in agreement with the criteria set for the database, then the crater diameter, and the center latitude and center longitude of the crater were determined using the 3-point crater counting routine found within JMARS (Christensen et al., 2009; Wren et al., 2017). To develop a more robust crater database, similar methods and measurements were taken in the way reported in the Zeilnhofer & Barlow (2021) Ceres crater database. These measurements include a crater identification number (Crater ID), radius of the crater (Rc) in km, minor crater diameter (Minor D) in km only if the crater was elliptical in shape was a value reported, crater preservation scale (Pres) which ranged from 0.0-5.0 where 0.0 is a "ghost crater" and 5.0 is a fresh impact crater, ejecta morphology (Ejecta), if applicable, ejecta radius (Re) in km, ejecta mobility ratio (EM ratio) which was calculated using the formula EM = Re/Rc, two interior morphologies (Int 1 and Int 2), if applicable, peak diameter (Dpk) and peak height (Hpk) in km, if applicable, the peak diameter to crater diameter ratio (Dpk/Dc), if applicable, pit diameter (Dp) and pit depth (P d) in km, if applicable, the ratio of pit diameter to crater diameter (Dp/Dc), if applicable, rim height (rim) and crater depth (d) in km using both topography models. Comments were also included to show if a crater had a formally recognized name or if the crater was polygonal.

The crater preservation scale utilized was the same as the Ceres crater database where the values were interpreted by looking at craters of similar sizes and identifying if the crater depths, crater rims, and degradation from one another (Zeilnhofer & Barlow, 2021). The ejecta morphology was noted to be continuous ejecta blankets and if an ejecta blanket was not present the word "No" was place in the column. The ejecta radius was measured three times out from the crater rim to the end of the ejecta and averaged together. The interior morphologies investigated include floor deposits, central peaks, central pits, summit pits, and wall terraces. If a crater displayed any of these morphological features, they were placed in the Int 1 or Int 2 column. If no morphology was present, then "No" was placed in the column. The central peak diameter and the central pit diameter were measured at the base of each morphology three times and an average was calculated while the heights and depths were measured once across each feature. The crater rim height and crater depth were also measured three times across the crater and out to ~2 crater radii to account for the varying topography of Vesta's surface. These values reported in the database are averages of the three profiles for crater rim height and crater depth. Both topography models were used since the mean spheroid model depicts Vesta as a perfect spheroid and the oblate spheroid model depicts Vesta as an oblate spheroid which helps to preserve local topography differences.

Preliminary Results and Analysis

The preliminary crater database contains 115 craters which are located from 88.15°S - 80.05 °S on Vesta. The crater diameters measured from 0.51 km to 5.74 km with more impact craters favoring the smaller crater diameters as seen in Figure 1. These impact craters also were found in a range of crater preservation classes from 1.0-5.0 where no impact crater was reported to be a "ghost crater" (preservation class 0.0). This could be a result of resolution.

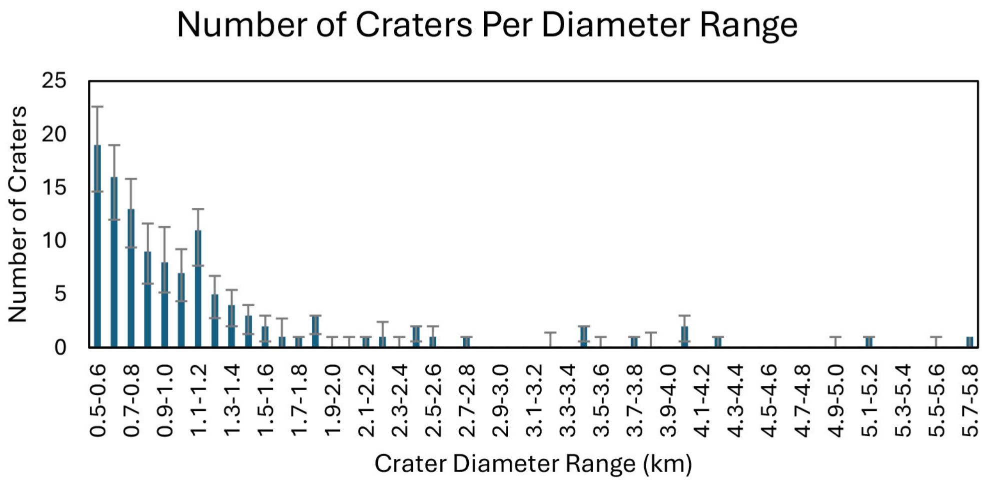

Figure 1. *Number of Impact Craters per Crater Diameter*

Note: Number of impact craters per 0.1 km found across the south pole of Vesta. Poisson error bars are calculated.

Additionally, the crater ejecta morphologies were reported for 26 impact craters which is ~ 22.6% of the total. The ejecta morphologies reported are continuous ejecta blankets which are similar to those found on rocky bodies such as the Moon and Mercury (Barlow, 2015). Craters which displayed a visible ejecta blanket had diameters between 0.53 km and 3.79 km, with 16 of the ejecta blankets being reported around craters with diameters >1.0 km. The ejecta mobility ratio (EM = Re/Rc) was calculated for the 26 craters (Figure 2). These values help to provide insight into how the material flows across the surface and can be compared to other solar system bodies which display ejecta blankets. The EM ratio ranged from 0.977 – 6.15 with an average value of ~ 2.50. This value is much lower than the expected value for ejecta blankets found on the lunar highlands with values reported to be ~10.0 (Boyce et al., 2010) and slightly higher than what was reported for dwarf planet Ceres at ~1.5 (Zeilnhofer & Barlow, 2021). Further investigation of these values shows that they are similar to the average value of 2.35 for layered ejecta blankets found in the solar system, but higher than the EM ratio for layered ejecta on Mars (~1.5) and Ganymede (0.7-1.1) (Boyce et al., 2010). The difference in these values may be a result of the gravitational differences found for each of these planetary bodies.

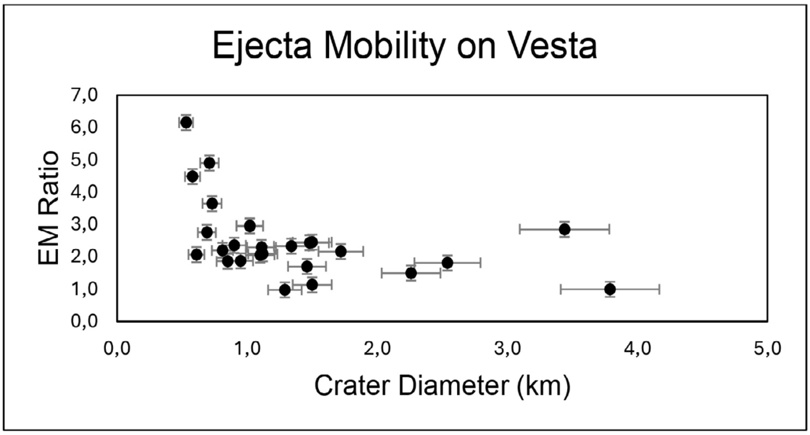

Figure 2. *EM Ratio for Vesta*

Note: The EM ratio with respect to crater diameter for 26 impact craters on Vesta. Standard error bars are calculated.

There were 16 fresh impact craters (Preservation 5.0) reported on Vesta. These craters have depth values ranging from 0.12-0.59 km, for the mean spheroid model, and 0.08-0.49 km, for the oblate spheroid model. The average depth for the mean spheroid and oblate spheroid models is 0.22 km and 0.18 km, respectively. To fully understand the surface properties of Vesta, the depth-diameter ratio (d/D) was calculated for the 16 preservation 5.0 craters (Figure 3). These values ranged from 0.17-1.01 for the mean spheroid model and 0.14-0.84 for the oblate spheroid model. These values are consistent with the 0.05-0.35 reported by Vincent et al. (2014), but higher than the average reported value of 0.065 for craters > 40 km (Liu et al., 2018).

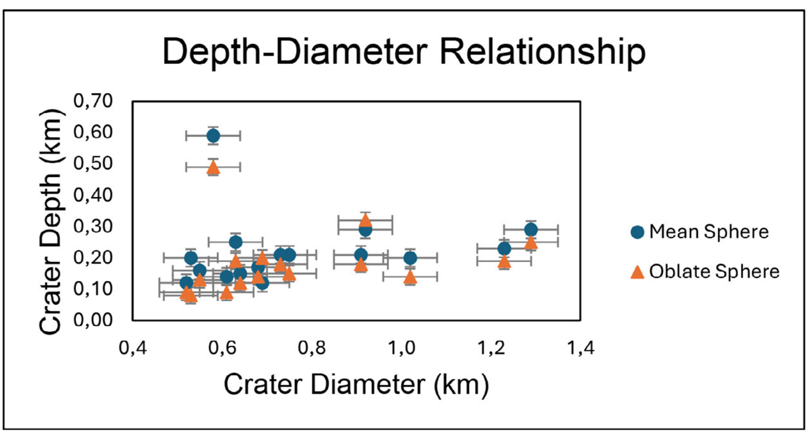

Figure 3. *Depth-Diameter Ratio for Fresh Impact Craters on Vesta*

Note: The depth-diameter relationship for the 16 fresh impact craters on Vesta. The blue circles are the mean spheroid model, and the orange triangles are the oblate spheroid model. Standard error bars are calculated.

Initial Conclusions and Future Work

Based on the initial findings of the 115 impact craters at the south pole of Vesta, it can be inferred that Vesta is showing similarities to other rocky bodies based on the d/D values of ~0.2 and the presence of continuous ejecta blankets. The EM ratio, however, is different than what would be expected for a rocky body such as the lunar highlands but is still within the range of what we see for other solar system bodies such as Mars and Ceres. The difference in values could be due to the lower gravity on Vesta compared to the other bodies as well as the smaller sample size. Further investigation of impact craters across the surface will be ongoing with hopes of understanding some of the values reported here. Additional data collection on the interior morphologies, such as central peaks and central pits, along with polygonal impact craters will provide better insight into the crustal heterogeneity of Vesta.

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