Planetary and Space Science 103 (2014) 104–130

Contents lists available at ScienceDirect

Planetary and Space Science

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

The cratering record, chronology and surface ages of (4) Vesta in comparison to smaller asteroids and the ages of HED meteorites

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ARTICLE INFO

Article history:
Received 31 December 2012
Received in revised form
1 April 2014
Accepted 5 April 2014
Available online 18 April 2014

Keywords:
Vesta
Crater retention ages
Cratering chronology
Crater scaling
Rheasilvia
Veneneia

ABSTRACT

We derived model functions for the crater production size-frequency distribution and chronology of the asteroids 951 Gaspra, 243 Ida, 21 Lutetia and 4 Vesta, based on a lunar-like crater production function and a lunar-like chronology with a smooth exponential decay in impact rate for the first ~1 Ga of Solar System history. For Gaspra, Ida and Lutetia we find surface ages roughly in agreement with published data. Using the same approach for Vesta leads to results with high correlation to Ar–Ar reset ages of HED meteorites, for which a strong dynamical and spectroscopic connection to Vesta has been found. In contrast to recently published young formation ages of the Rheasilvia and Veneneia basins of about 1 and 2 Ga, respectively, we find for Rheasilvia a formation age of 3.5 ± 0.1 Ga and for the Veneneia formation a lower limit of 3.7 ± 0.1 Ga. For comparison we also give surface model ages for a preliminary version of a chronology (pers. comm. D.P. O'Brien) based on the Late Heavy Bombardment theory. Error bars presented in our work stem only from statistical analysis of measured crater distributions and do not include the uncertainty of the used chronology model.

1. Introduction

The asteroid Main Belt is most likely the chief source region of impacting projectiles in the inner Solar System (Neukum, 1984; Neukum and Ivanov, 1994; Neukum et al., 2001; Hiesinger et al., 2002; O'Brien and Greenberg, 2005; Strom et al., 2005; Ivanov, 2008; Massironi et al., 2009). As asteroids are believed to be the remains of the main building blocks at least of the inner major planets (Weidenschilling, 1974, 1976, 1977; Spaute et al., 1991; Inaba et al., 2003; Guillot and Gautier, 2007; Raymond et al., 2009; Weidenschilling, 2011) and thus also of the Earth (Alexander et al., 2012), it is of great interest for a number of planet and Solar System-related science topics to understand the diversity, nature and interaction of these bodies in a region, probably very similar to the very early Solar System. For this reason the first spacecraft dedicated to investigating an asteroid was christened "Dawn" (Russell et al., 2012). The Dawn mission will also investigate the only dwarf planet in the asteroid Main Belt, 1 Ceres (Russell et al., 2007; Russell and Raymond, 2011). Previous spacecraft had only investigated asteroidal bodies much smaller than Vesta (Table 1).

In this work we will review earlier work on asteroidal surface ages (Chapman et al., 1996a; Chapman et al., 1996b; Marchi et al.,

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http://dx.doi.org/10.1016/j.pss.2014.04.004
0032-0633/

Table 1
List of asteroid fly-bys by spacecraft other than Dawn. Phobos is known as a satellite of Mars but shares many similarities with primitive asteroids (e.g. Jones et al., 1990).

Listed no.	Name	s/c	Min. distance [km]	Date
5535	Annefrank	Stardust	3079	02.11.2002
132,524	APL	New Horizons	101,867	13.06.2006
9969	Braille	Deep Space 1	26	29.07.1999
433	Eros	NEAR Shoemaker	Landed	12.02.2001
951	Gaspra	Galileo	1600	29.10.1991
243	Ida	Galileo	2390	28.06.1993
25,143	Itokawa	Hayabusa	Landed	20./25.11.2005
21	Lutetia	Rosetta	3170	10.07.2010
2685	Masursky	Cassini	1,600,000	23.01.2000
253	Mathilde	NEAR Shoemaker	1212	27.06.1997
2867	Steins	Rosetta	800	05.09.2008
–	Phobos (may be captured)	Mariner 9, Viking 1, Mars Global Surveyor, Mars Express, Mars Reconnaissance Orbiter	45	29.12.2013 (Mars Express)

2012b) in order to compare the crater distributions and chronologies of small Main Belt asteroids such as 243 Ida, 951 Gaspra and 21 Lutetia with the much larger asteroid 4 Vesta. We will derive a chronology for each of these bodies and characterize the main features of their impact histories. Data on the smaller asteroids is predominantly presented in the supplementary online material of this paper.

Vesta is the chief source for basaltic HED (Howardite – Eucrite – Diogenite) meteorites (McCord et al., 1970; Binzel and Xu, 1993; Moskovitz et al., 2008, 2010; McSween et al., 2011), although there is evidence for more sources of basaltic meteorites than just Vesta (Moskovitz et al., 2008; Roig et al., 2008; Scott et al., 2009). While earlier investigations of the cratering age of asteroids could not be cross-checked with meteorites for several reasons, radiometric ages of HED meteorites (e.g. Bogard and Garrison, 2003; Bogard, 2011) could be used to validate cratering chronology models of Vesta and thus, will have immediate consequences for earlier cratering age determinations of asteroids. These results will also have profound implications for understanding the dynamics and collisional history of the early inner Solar System. In general HED meteorites provide ground truth data for calibration and validity checks on Dawn science data.

2. Methodology

In order to derive absolute surface ages for asteroidal bodies, we measure crater frequencies and fit a crater production function to our measurements. From the fitted production function we determine the frequency of craters above a standard diameter, 1 km. Knowing the frequency of craters ≥ 1 km, we then use a chronology function to convert the measured crater frequency into a surface model age.

This technique is described in a number of papers (e.g. Neukum and Hiller, 1981; Neukum, 1984; Neukum and Ivanov, 1994; Michael and Neukum, 2010). For the calculation of surface ages, we use the "craterstats" software (Michael and Neukum, 2010). This software also allows for the determination of ages of partially resurfaced areas, for example by ejecta blanketing or seismic shaking.

Errors of Surface Model Ages: Errors given with model ages are derived from the size of the counting area and the number of craters used to fit the production function to the measured crater distribution. Due to the non-linear characteristics of the chronology functions for ages >3 Ga, errors show some asymmetric characteristic (Michael and Neukum, 2010). Error bars for individual crater size bins in a crater plot represent the 1σ standard deviation for the respective crater size bins (Crater Analysis Techniques Working Group et al., 1979). Such error bars are based on the number of craters within the individual crater bins. Thus, a bin with only one or a few craters has large error bars, while a bin with many craters has small error bars. The quoted errors give no measure of the likelihood of the used chronology model, the systematic errors of which could be much larger. Despite this, the ages may be interpreted in a relative sense with a level of confidence reflected by the quoted errors.

Coordinate System: The maps presented use the 'Claudia' system, which is the same system used in all publications of the Dawn results to date (Russell et al., 2012). The Planetary Data System provides data at different systems that follows IAU coordinate system recommendations (Archinal et al., 2011). The IAU longitudes are offset from the Claudia system by an addition of 150°.

Terminology: we use the term "lunar-like" to describe a chronology model which is scaled from the lunar model, but not to suggest that the Vesta chronology is the same as that of the Moon.

2.1. Crater counting

Crater counting is commonly performed on near spherical bodies such as the Moon, Mars, Mercury, Venus and the larger satellites of the giant planets in the outer Solar System. For this task we use the mapping software ArcGIS (ESRI) and the CraterTools plug-in (Kneissl et al., 2011), which simplifies crater counting. CraterTools allows for measuring crater size-frequency distributions on planetary surfaces independently of image and data frame map projections. All crater counts are performed by experienced human crater counters and cross checked by at least one other experienced crater counter. However, there are a number of specific sources of error, which are difficult to quantify such as the effect of solar illumination angles, photometric characteristics of images, and other similar factors. In addition, there is some variability in the identification of craters by different individuals. Each measurement is complemented with crater maps in the supplementary online material (SOM) chapter 1 (Ida, Gaspra and Lutetia; also measurement description) and chapter 2 (Vesta). We present our crater statistics following Crater Analysis Techniques Working Group et al. (1979), although we use a higher resolution pseudo-log binning with 18 intervals per decade (Neukum, 1984).

Due to the irregular shape of asteroids, data projection on a sphere introduces a source of error in spatial measurements. Therefore, we corrected our measurements gathered from projected imaging data according to a digital elevation model as described by Kneissl et al. (2014).

With increasing body size more ejecta are expected to be retained on the target body. On large asteroids ($\varnothing > \sim 100$ km) with low to moderate porosity the surface gravity is sufficient to form well identifiable impact ejecta blankets (Housen and Holsapple, 2011,