Planetary and Space Science 103 (2014) 82–95

Contents lists available at ScienceDirect

Planetary and Space Science

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

The primordial collisional history of Vesta: crater saturation, surface evolution and survival of the basaltic crust

D. Turrini*

Istituto di Astrofisica e Planetologia Spaziali INAF-IAPS, Via del Fosso del Cavaliere 100, 00133 Rome, Italy

ARTICLE INFO

Article history:
Received 24 December 2012
Received in revised form
28 August 2013
Accepted 4 September 2013
Available online 14 September 2013

Keywords:
Vesta
Impacts
Asteroids
Surface evolution
Jupiter
Solar System formation

ABSTRACT

The Dawn mission recently visited the asteroid 4 Vesta and the observations performed by the spacecraft revealed more pieces of the intriguing mosaic of its history. Among the first results obtained by the Dawn mission was the confirmation of the link between the howardite–eucrite–diogenite (HED) group of meteorites and Vesta. This link implies that Vesta was one of the first objects to form in the Solar System and that the differentiation of the asteroid likely completed before the formation of Jupiter. As a consequence, the bombardment triggered by the formation and migration of the giant planet, the Jovian Early Bombardment (JEB), contributed to the collisional evolution of the asteroid at a time where most of its interior was still molten. This work explores the implications of the JEB for the evolution of the primordial Vesta, in particular in terms of crater saturation, crustal excavation and surface erosion. Both scenarios assuming the planetesimals having formed in a quiescent or a turbulent nebula were explored and both primordial and collisionally evolved size–frequency distributions were considered. The results obtained indicate that, if the basaltic surface of Vesta was already formed, the JEB would saturate it with craters and could erode it to depths that vary from hundreds of meters to tens of kilometres. In the latter cases, the surface erosion caused by the JEB would be comparable with the thickness of the eucritic and diogenitic layers of Vesta. In the cases where the global surface erosion is limited, however, large impactors, if too abundant, can excavate the whole crust and extract significant quantities of material from the vestan mantle, incompatible with the present understanding of HED meteorites. This appears to be the case if the impacting planetesimals formed in a turbulent nebula and Jupiter migrated by 0.5 AU or more. Globally, the results obtained suggest that the scenarios where the planetesimal formed in a quiescent nebula and Jupiter underwent a modest migration (i.e. up to 0.5 AU) are the most consistent with our understanding of Vesta, even if the cases of planetesimals formed in a turbulent nebula with Jupiter undergoing limited (i.e. about 0.25 AU) or no migration cannot be ruled out. Recent results on the differentiation of the asteroid, however, raised the possibility that Vesta originally possessed a now-lost undifferentiated crust. In this case, the favoured scenarios would be those where the planetesimals formed in a quiescent nebula and Jupiter underwent a more significant migration (i.e. between 0.5 AU and 1 AU).

© 2013 Elsevier Ltd. All rights reserved.

1. Introduction

More than 40 years ago, the asteroid 4 Vesta was suggested, based on spectroscopic measurements, to be the parent body of the Howardite–Eucrite–Diogenite (HED in the following) class of meteorites (McCord et al., 1970). The Vesta–HED link was later supported by the observations of the Hubble Space Telescope (Gaffey, 1997; Binzel et al., 1997; Li et al., 2010) and was recently confirmed by the observations of the Dawn spacecraft (De Sanctis et al., 2012; Prettyman et al., 2012), which spent one year gathering data on the composition, morphology and gravity of the asteroid (Russell et al., 2012, 2013). The Vesta–HED link allows the use of the radiometric ages of HED meteorites to investigate the ancient past of the asteroid. As a consequence, based on the crystallization ages of the oldest eucrites (Bizzarro et al., 2005) and diogenites (Schiller et al., 2011) we know that Vesta formed and differentiated in the first 3 Ma of the Solar System's lifetime.

At the time Vesta was forming and differentiating, the Solar System was in the phase of its evolution known as the Solar Nebula (Coradini et al., 2011), i.e. it was a circumsolar disk of gas and dust where the first generations of planetary bodies were forming. The beginning of the Solar Nebula is generally assumed to coincide with the condensation of the oldest solids, the Ca–Al-rich inclusions (CAIs), about 4.568 Ga ago (Bouvier and Wadhwa, 2010). The duration of the Solar Nebula phase is indirectly constrained by observations of circumstellar disks, which indicate

---

* Tel.: +39 0649934414; fax: +39 0649934383.
E-mail address: diego.turrini@iaps.inaf.it

0032-0633/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.pss.2013.09.006

that the median lifetime is about 3 Ma with the range of observed values spanning between 1–10 Ma (Meyer, 2009). We know that the giant planets formed in the Solar Nebula, as the nebular gas supplied the material for the massive envelopes of Jupiter and Saturn and the limited ones of Uranus and Neptune. Theoretical (Bottke et al., 2005a,b) and observational (Scott, 2006) arguments suggest that Jupiter formed 3–5 Ma after the condensation of CAIs. As a consequence, the differentiation and the formation of the basaltic crust of Vesta predate the formation of Jupiter, plausibly the first giant planet to have formed (Coradini et al., 2011).

While we know that Vesta is differentiated and possesses an iron core (Russell et al., 2012, 2013), its internal structure is still a matter of debate. Depending on the initial composition of the asteroid, Ruzicka et al. (1997) estimated that the global thickness of the crust from which eucrites and diogenites originated should have ranged between 40 km and 80 km. More specifically, Ruzicka et al. (1997) report that the eucritic and diogenitic layers would have thickness of 26 km and 13 km respectively if Vesta had an initial composition similar to CI meteorites (i.e. olivine-rich). If the material initially composing Vesta was instead more similar to EH meteorites (i.e. olivine-poor), the thickness of the eucritic and diogenitic layers would respectively be 41 km and 42 km. However, McSween et al. (2013) argue that the latter case likely assumes an unrealistic initial composition of Vesta and favour the former scenario.

It is important to note that the ages of the oldest HED meteorites (Bizzarro et al., 2005; Schiller et al., 2011) indicate that eucritic and diogenitic material was already crystallizing at 3 Ma, but this does not necessarily imply that the whole basaltic crust of Vesta was completely solidified. Given the large range of temperatures over which silicates are partially molten (more than 400 K), it is more than likely that over a temporal window of at least a few Ma after the crystallization of the oldest samples the crust of Vesta still contained molten material. The results of thermal models (see e.g. Formisano et al., 2013 and references therein for previous works on the subject by other authors) and geophysical models (Tkalcec et al., 2013) point in this direction, indicating that between 3 Ma and 5 Ma from CAIs the thickness of the completely solidified crust could have gone from a minimum of 7 km (Formisano et al., 2013; Tkalcec et al., 2013, Supplementary Information) to about 30 km (Formisano et al., 2013).

As first pointed out by Davis et al. (1985), the survival of the basaltic crust of Vesta to the collisional evolution the asteroid underwent across the lifetime of the Solar System represents one of the stronger constraints to understand the past history of the asteroid belt. The present surface composition of Vesta observed by Dawn (De Sanctis et al., 2012; Prettyman et al., 2012) is globally consistent with howardites (breccias formed by a mixture of eucritic and diogenitic material), with regions more similar to eucrites and with an exposure of diogenitic material in the south polar basin RheaSilvia (De Sanctis et al., 2012; Prettyman et al., 2012; McSween et al., 2013). This implies that the surface erosion of Vesta should not exceed the values estimated by Ruzicka et al. (1997). The southern hemisphere of Vesta, however, was extensively excavated by the impacts that generated the RheaSilvia basin and the underlying Veneneia basin (Schenk and et al., 2012; Jutzi et al., 2013; McSween et al., 2013; Ivanov and Melosh, 2013). The global erosion experienced by the surface of Vesta from the formation of its basaltic crust to the formation of these two basins is therefore an important piece in the mosaic of the history of this body and the asteroid belt in general.

After the formation of Jupiter and Saturn, the asteroid belt underwent a rapid process of depletion due to the interplay between the orbital resonances created by the two giant planets and the gravitational perturbations of the planetary embryos in the inner Solar System (see Coradini et al., 2011; O'Brien and Sykes, 2011 and references therein). Following this phase of depletion, the population of the asteroid belt decreased by about two orders of magnitude (see Coradini et al., 2011; O'Brien and Sykes, 2011 and references therein). Bottke et al. (2005a,b) investigated the collisional evolution of the asteroid belt from the beginning of this depletion process to present time and found that it is globally consistent with the survival of the basaltic crust of Vesta. In these studies, the authors did not account for the effects of cratering erosion but focus on those of catastrophic disruption. According to Davis et al. (1979), if the primordial population of the asteroid belt was very steep, cratering erosion would contribute to the global collisional evolution of the asteroid belt and dominate that of small bodies with negligible gravity. Even in this case, however, the asteroid belt would naturally evolve to a more relaxed state where cratering erosion is not important in less than 10^8 years (Davis et al., 1979), i.e. on a timescale much shorter than the one considered by Bottke et al. (2005a,b).

A temporal interval not covered by the studies of Bottke et al. (2005a,b) is the one going from the beginning of the formation of Jupiter to the end of that of Saturn. The formation of Jupiter has been shown by different authors (Safronov, 1972; Weidenschilling, 1975; Weidenschilling et al., 2001; Turrini et al., 2011, 2012) to trigger a sudden spike in the flux of impactors in the early history of the Solar System. This event, named the Jovian Early Bombardment (Turrini et al., 2011, 2012, JEB in the following), is caused by the scattering of ice-rich planetesimals from the outer Solar System due to the gravitational perturbation of the giant planet (Safronov, 1972; Weidenschilling, 1975; Weidenschilling et al., 2001; Turrini et al., 2011, 2012) and by the appearance of the Jovian mean motion resonances in the asteroid belt, in particular the 3:1 and 2:1 resonances (Weidenschilling et al., 2001; Turrini et al., 2011, 2012). The duration of the JEB is limited to about 1 Ma (Weidenschilling, 1975; Turrini et al., 2011, 2012), with the bulk of the impacts taking place in the first $3\text{–}5\times10^5$ years (Turrini et al., 2011). The flux of impactors due to the Jovian resonances is the dominant one in the inner Solar System (Turrini et al., 2011) and is the one shaping the early collisional evolution of the asteroid belt (Turrini et al., 2011, 2012).

Turrini et al. (2011) estimated the fluxes of impactors coming from the outer Solar System and from the Jovian resonances during the JEB, the crater populations they produce and the probability of Vesta being destroyed during the bombardment using different size–frequency distributions (SFDs in the following) of the impactors. Their results showed that the probability of Vesta undergoing a catastrophic impact is negligible, but suggested that cratering erosion could play an unexpectedly significant role due to the higher, pre-depletion population of planetesimals inhabiting the asteroid belt at the time. Turrini et al. (2012) further investigated the subject of asteroidal erosion during the JEB and, using a more detailed physical description of the mass loss processes, showed that cratering erosion indeed played a much more relevant role than catastrophic disruption in determining the fate of primordial asteroids. Turrini et al. (2012) showed that cratering erosion is a function of the extent of Jupiter's migration and of the position of the target body in the asteroid belt. Depending on the considered scenario and SFD of the impactors, planetesimals the size of Vesta could lose from a few times 1% to a few times 10% of their original mass (Turrini et al., 2012).

This work will discuss the primordial surface evolution of Vesta due to the JEB and extend the analysis of the results described in Turrini et al. (2011), by reprocessing them with an updated version of the collisional model first applied in Turrini et al. (2012) and by putting them in the context of the most updated understanding of the geophysical state of Vesta at that time. Together with the SFDs

Download English Version:

https://daneshyari.com/en/article/8143429

Download Persian Version:

https://daneshyari.com/article/8143429

Daneshyari.com