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New hints on Phobos collisional capture origin from Rosetta-OSIRIS observation

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Abstract. On 2007 February 24 and 25, the ESA *Rosetta* mission flew by the planet Mars during its complex interplanetary trajectory towards its main target: comet 67P/Churyumov-Gerasimenko. The geometry of this gravitational assist gave the chance to image Phobos before and after *Rosetta*-Mars closest approach (CA) from a distance range between 115 000 to 21 000 km. Different surface areas of Phobos were observed belonging to the leading and trailing hemisphere of the anti-Mars hemisphere of the satellite, and also a section of its sub-Mars hemisphere. We compared our spectra, obtained during the pre- and the post-CA, with the reflectance spectra of D-type asteroids, showing that Phobos near-ultraviolet, visible and near-infrared (263.5-992.0 nm) reflectivity is within the spectral dispersion of the D-type asteroids. We investigated then the possibility of a dynamical collisional capture of Phobos similar to the origin of the irregular satellites of the giants planets. The coupled observational and dynamical ones suggest an early capture of Phobos in the first 10-100 Ma of the lifetime of the Solar System, consistently with the results of previous studies of the orbital evolution of Phobos.

Key words. Phobos – Spectrophotometry – Collisional Capture – D-type Asteroid – OSIRIS

1. Introduction

Phobos is the subject of photometric and spectroscopic studies in the near-ultraviolet, visible and near-infrared range since more than 40 years.

It all started in 1972 with the NASA *Mariner 9* Phobos observation performed with the onboard UV spectrometer and with the NASA *Viking Lander II* camera which imaged Phobos in 1976. In 1989 it was the turn of the USSR *Phobos 2* spacecraft observation of

Phobos with the *Videospectrometric Camera*, the *Combined Radiometer and Photometer for Mars* and the *Imaging Spectrometer for Mars* (*VSK-KRFM-ISM*). The *Hubble Space Telescope* imaged Phobos in 1993 with the *Faint Object Spectrograph*, and then in 1997 with the *Wide Field Planetary Camera 2*. In 1997 Phobos was imaged with the NASA *Imager for Mars Pathfinder*. In 2004 the ESA *Mars Express* spacecraft performed a set of close encounters of the satellite which was observed through the *SPICAM* and *OMEGA* instruments. In 2007 it was the turn of the *CRISM* instrument onboard the NASA *Mars Reconnaissance Orbiter* and of the *OSIRIS*[1], instrument onboard the ESA *Rosetta* spacecraft, whose observation is the subject of this paper.

A detailed description of all previous observations performed from *Mariner 9* to *Mars Reconnaissance Orbiter* is presented in Pajola et al. (2012).

In the following work the OSIRIS Phobos data and their analysis are presented, together with its spectroscopic comparison with D-type asteroids. The final part is entirely dedicated to the origin of Phobos and its possible asteroidal collisional capture nature.

2. OSIRIS Phobos observation

2.1. Images description

On 2007 February 24 and 25, the *Rosetta* spacecraft flew-by the planet Mars (Pajola et al. 2012). The gravitational assist geometry foreseen for this swing-by provided the rare opportunity of observing Phobos and imaging it with different scales and phase angles.

The first image of each Phobos images set obtained from OSIRIS (Keller et al. 2006), is presented in Fig. 1. The bandpass filters which were used during the whole *Rosetta*-Mars fly-by are indicated in Table 1.

The filters used are optimized to study the mineralogical composition and the physical structure of the nucleus of comet 67P/Churyumov-Gerasimenko, the *Rosetta*

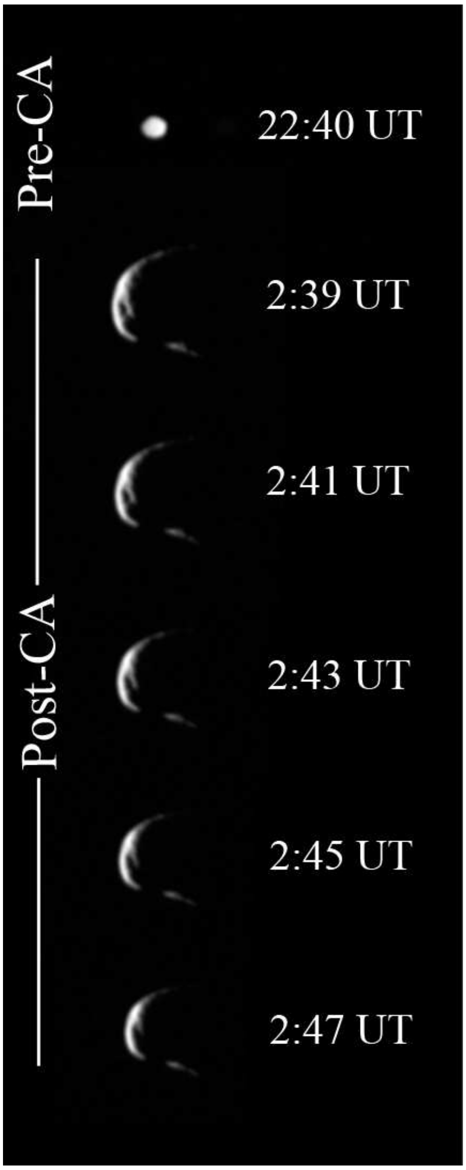

Fig. 1. OSIRIS Narrow Angle Camera (NAC) images of Phobos (taken at 650 nm) obtained on 2007 February 24 and 25, respectively. The upper image was obtained in the observation phase before *Rosetta*-Mars CA from a distance of 114 882 km with a scale of 2 166 m/px, while the lower five images were obtained after the *Rosetta*-Mars CA when OSIRIS pointed back towards Phobos. The distance of acquisition of these five images ranges between 20 786 km and 25 946 km at a correspondent scale range of 391 - 489 m/px.

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[1] Optical, Spectroscopic and Infrared Remote Imaging System.

Table 1. Filter number, central wavelength, full width to half maximum (FWHM) of each bandpass NAC filter used during the pre- and the post-Mars CA fly-by.

ID no.	Wavelength nm	FWHM nm	Observation Phase
F15	263.5	45.0	Pre - Post
F16	360.0	50.0	Pre - Post
F84	480.0	72.0	Pre
F24	480.5	73.0	Post
F83	535.0	60.0	Pre
F23	535.5	61.0	Post
F22	648.5	83.0	Post
F82	650.5	81.0	Pre
F87	700.5	21.0	Pre
F27	700.5	21.0	Post
F88	742.5	61.0	Pre
F28	743.0	62.0	Post
F58	790.5	23.0	Post
F51	804.5	39.0	Pre - Post
F41	882.5	65.0	Pre - Post
F61	932.0	40.0	Pre - Post
F71	992.0	44.0	Pre - Post

main target. Hence the use of these filters is also suitable to study the mineralogical composition of Phobos. In Keller et al. (2006) it is presented the description of all OSIRIS filters used in this specific work.

The OSIRIS pre-CA set was obtained on 2007 February 24 between 22:09:09 and 22:10:04 UT with a distance range of 114 882-114 467 km and a correspondent scale of 2 166-2 158 m/px. The phase angle of this set ranges between 18.89° and 18.95°. The observed area acquired in this set of eleven images goes from a longitude of 126°W to 286°W from pole to pole and coincides with the larger part of the Phobos anti-Mars hemisphere.

The OSIRIS five post-CA sets were obtained on 2007 February 25 from 02:39:11 to 02:47:37 UT with a distance range of 20 789-26 219 km and a correspondent scale range of 391-492 m/px. The phase angle of this set ranges between 136.80° and 139.62°. The imaged area acquired in this five sets goes from a longitude of 0°E to 43°E, from pole to pole, entirely belonging to the Phobos sub-Mars hemisphere.

2.2. Methodology

We performed a disc-integrated spectrophotometric analysis using the aperture photometry technique on the OSIRIS data reduced with the calibration pipeline presented in Magrin et al. (2012).

The flux coming from Phobos pre-Mars CA images was measured from an inner radius of 10 pixels centered on the target photocentre, while we computed the flux of the sky background from an annulus between 19 and 21 pixels far from the photocentre.

We used the same technique for the Phobos post-Mars CA data starting with an aperture radius of 35 pixels and evaluating the sky background from an annulus between 48 and 50 pixels centered on the Phobos photocentre for the first sets. In order to compute the Phobos flux from the last set we modified our aperture photometry parameters using an aperture photometry disk with a radius of 28 pixels and a sky background flux computed from an annulus between 32 and 34 pixels far from the target photocentre.

The resulting reflectance plots are presented in Fig. 2 where we compared our results with the Tagish Lake meteorite reflectance spectrum and the Bus D mean type of the Bus asteroid taxonomy. As a comparison we also plotted our resulting spectra with some D-Type asteroids presented in Lazzarin et al. (1995), Bus et al. (2002a,b) and Jewitt et al. (1990).

2.3. Results and discussion

As it is possible to see from Fig. 2, our reflectance spectra are well within the spread of the reflectance of other reported D-type asteroids. We decided to plot the spectra of the D-type asteroids 336 Lacadiera (Bus et al. 2002a,b), the Trojans 624 Hektor and 884 Priamus (Jewitt et al. 1990) and 1167 Dubiago (Lazzarin et al. 1995), because they well represent a set of different D-type slopes.

Our spectra suggest a surface mineralogical composition typical of outer belt asteroids like D-type asteroids and Trojans.

We also compared our results with the Tagish Lake meteorite, being a D-type spectral

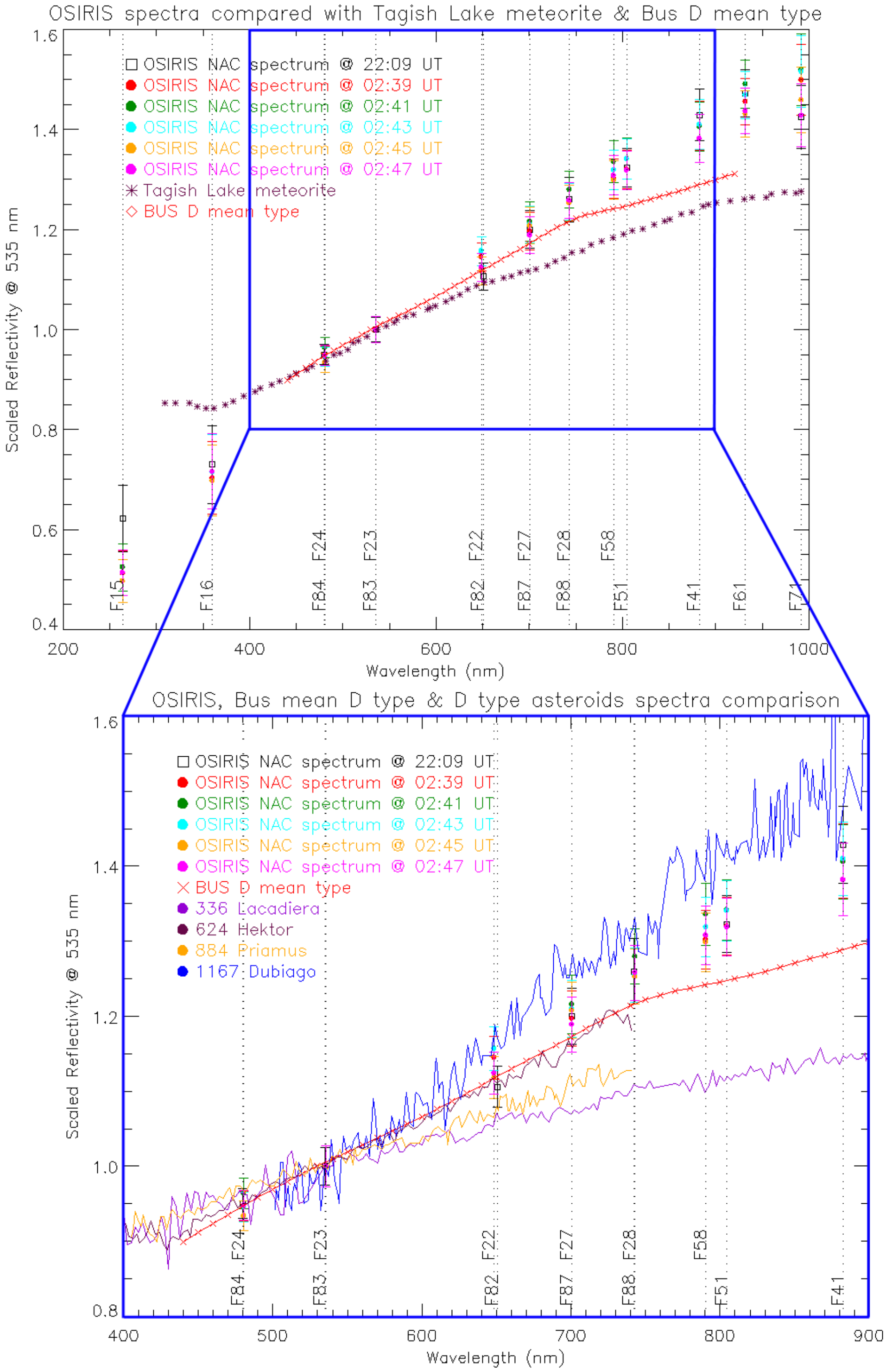

Fig. 2. OSIRIS-NAC spectra obtained during the pre- and the post-CA. In the upper image we compared our results with the Tagish Lake meteorite reflectance spectrum (Hiroi et al. 2001) and with the Bus D mean type of the Bus asteroid taxonomy Bus et al. (2002a,b). In the lower image we compared our results with some D-Type asteroids presented in Bus et al. (2002a,b), Jewitt et al. (1990) and Lazzarin et al. (1995). The different filters used in the pre- and post-CA are also indicated.

behaviour meteorite (Hiroi et al. 2001). Our spectra is slightly redder than the Tagish lake reflectivity, but it is consistent with its spectral behaviour.

3. Phobos as a collisional captured D-type asteroid: the dynamical model

After we derived from OSIRIS observations that Phobos can have an outer belt D-type asteroidal origin, we managed to explore in detail the possibility of the capture of Phobos in the aftermath of a collision between two asteroidal bodies occurring within the sphere of influence of Mars and to attempt to constrain the timing of such event.

3.1. Methodology

The idea of the collisional capture origin to explain the existence of the families of irregular satellites of Jupiter was first presented by Colombo et al. (1971). It was used by Turrini et al. (2009) to study the capture of irregular satellites of Saturn presenting the change in velocity $\delta \boldsymbol{v}$ needed to capture the satellite Phoebe. We adopted this scenario to calculate the possible heliocentric orbits of the putative parent body of Phobos and the conditions for its capture by using the MSSCC (Modelling Software for Satellite Collisional Capture) code developed by Turrini et al. (2009).

The specific parameters used to explore the capture of Phobos with MSSCC are presented in Pajola et al. (2012). We used sampling steps of 5° for the $\delta \boldsymbol{v}_i$ vectors in the $x - y$ plane and in the z direction and again 5° for the mean anomalies of Phobos and Mars: with this setup, the MSSCC code explores about 8.5×10^6 possible configurations. The mass, semimajor axis, eccentricity and inclination respect to the ecliptic plane of Mars and the mass and inclination respect to the ecliptic plane of Phobos have been obtained from the Horizons system of the NASA Jet Propulsion Laboratory [2]. The post-capture semimajor axis of Phobos has been assumed equal to the synchronous orbital radius of Mars ($a = 1.3656 \times 10^{-4}$ AU) while the post-capture eccentricity of Phobos varied in the range $0.2 - 0.8$.

3.2. Results and discussion

The results we obtained with the MSSCC software are shown in Fig. 3. The different colors identify, in the [a–e] and [a–i] plane, the orbital parameters of the potential parent bodies of Phobos for different values of the $\delta \boldsymbol{v}$ required to obtain fragments in planetocentric orbits with an eccentricity of 0.2. The $\delta \boldsymbol{v}$ presented goes from 0.6 km/s up to 10 km/s with a step of 1 km/s from 1 to 10 km/s. The same color code is used to show the orbital parameters of the potential parent bodies of Phobos required to obtain fragments in planetocentric orbits with an eccentricity of 0.5 and with an eccentricity of 0.8.

The comparison of these three different plots shows that the higher the post-capture eccentricity is, the higher is the maximum pre-capture semimajor axis of the possible parent body of Phobos for a given value of $\delta \boldsymbol{v}$.

If we now assume that the asteroids presently populating the asteroid belt did not migrate from their formation regions by more than 0.5 AU throughout their histories (O'Brien et al. 2007), the bulk of D-type asteroids should have populated the orbital region comprised between $3-5$ AU. If the parent body of Phobos was a D-type, in order to be captured by Mars it should have been injected on a high-eccentricity orbit and then it should have lost between 4 and 6 km/s of its orbital velocity due to the collision for the capture to occur. The aforementioned extreme collision implies that the parent body of Phobos and the planetesimals against which it impacted had a high relative velocity and the most likely scenario to supply the high change in velocity needed is that the parent body of Phobos impacted against a planetesimal on a Mars-like orbit.

The realistic probability for such a capture event to occur need contemporary a large number of planetesimals in the orbital region of Mars against which the parent body of Phobos could impact and a large flux of D-type aster-

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[2] `http://ssd.jpl.nasa.gov/?horizons`

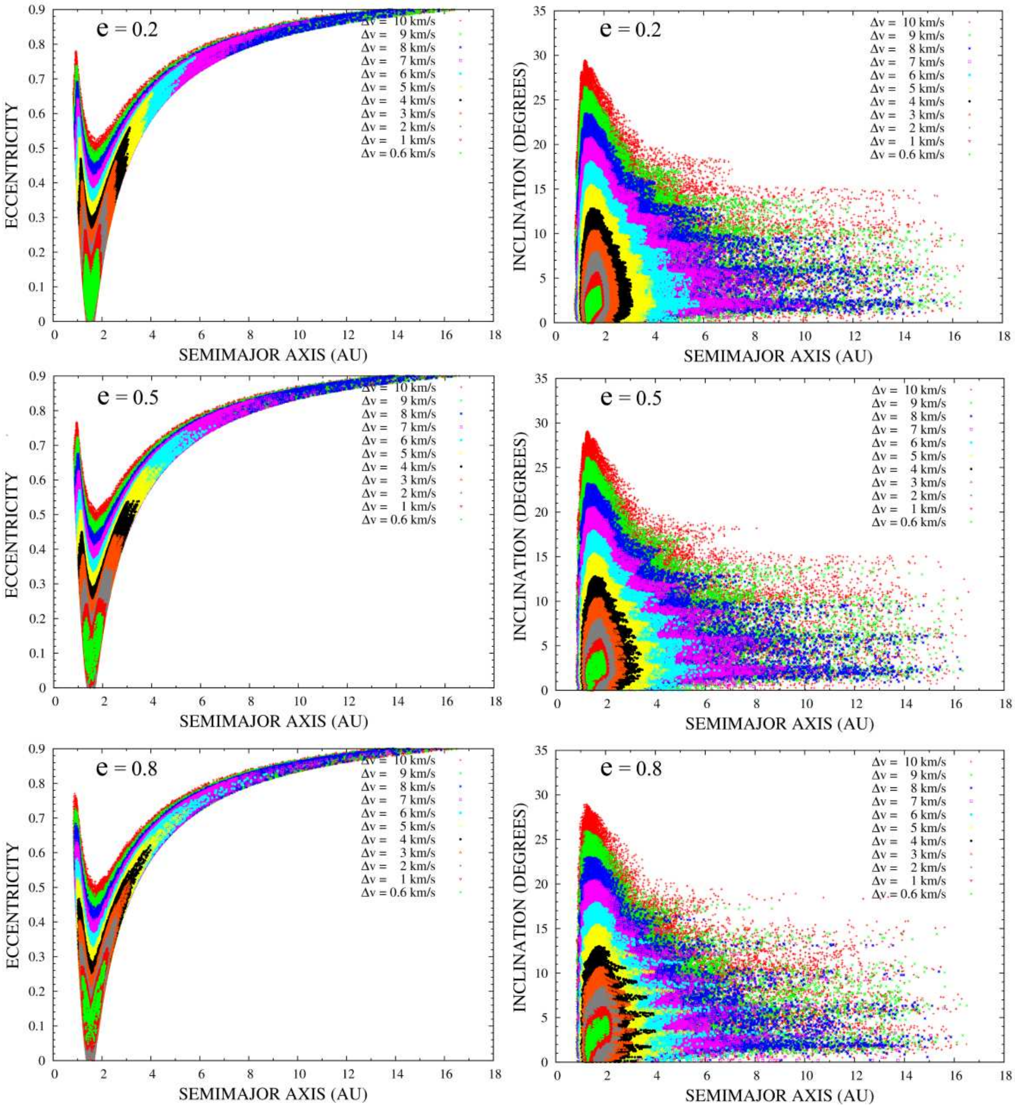

Fig. 3. Possible heliocentric orbits of the parent body of Phobos projected in the $a - e$ plane (top panel) and in the $a - i$ plane (bottom panel). The various colors identify the value of δv required to capture Phobos on a primordial orbit with planetocentric semimajor axis $a = 1.3656 \times 10^{-4}$ AU (*i.e.* the synchronous orbital radius), inclination $i = 27.72°$ (*i.e.* the present-day inclination respect to the ecliptic plane) and eccentricity of $e = 0.2$, $e = 0.5$ and $e = 0.8$.

oids ejected from the asteroid belt and injected in the inner Solar System on high eccentricity orbits.

To satisfy the first condition, the capture should have taken place before or while the terrestrial planets were forming and before the dynamical depletion of the orbital region comprised between Mars and the asteroid belt took place (Weidenschilling et al. 1977; Wetherill et al. 1992). This means that we are assuming that the capture took place during the first 100 Ma of the life of the Solar System. In order to satisfy the second condition, the capture should have taken place either at the time of the formation of the giant planets or during the depletion of the asteroid belt. Both the latter cases are plausible since meteoritic data suggest that Mars completed its accretion in 2 – 6 Ma (see *e.g.* Dauphas et al. 2011), thus likely before or contemporary to the formation of the giant planets and the dispersal of the nebular gas.

Both the first and the second conditions we need to satisfy in order to have a reasonable chance to collisionally capture Phobos, pointing toward an early capture of the satellite. After the first 10 Ma of the life of the Solar System, in fact, the population of the asteroid belt would be depleted by about one order of magnitude with respect to its original value and the inner Solar System would be devoid of planetesimals by about the same factor (O'Brien et al. 2007). After 100 Ma, the depletion of the asteroid belt and the Martian orbital region would decrease the population of planetesimals by about another order of magnitude (O'Brien et al. 2007), lacking both possible parent bodies of Phobos to inject on Mars-crossing orbits and impactors on Mars-like orbits for the collisional capture to have reasonable chances to occur.

4. Summary and conclusions

On 24 and 25 of February 2007 the OSIRIS NAC camera took seventy multiband images of Phobos covering a wavelength range from 263.5 to 992.0 nm.

The OSIRIS NAC spectrophotometric sets have been divided into two sections: the pre-Mars CA data obtained between 22:09:09 and 22:10:04 UT, on 24 February 2007 and the post-Mars CA data obtained between 02:39:11 and 02:47.37 UT, on 25 February 2007.

We performed a disk-integrated spectrophotometric analysis of the Martian satellite both in the pre- and post-Mars CA. During the pre-Mars CA observation we covered an area of Phobos which goes from 126°W to 286°W in longitude and from 90°S to 87°N in latitude. In the post-Mars CA observation we imaged an area which goes from 0° to 43° E, entirely belonging to the sub-Mars hemisphere/redder unit never studied in multi-wavelength before.

We compared our reflectance spectra, both pre- and post-CA, with Tagish Lake meteorite, which presents a slightly lower spectral slope with respect to OSIRIS data, and with the Bus D mean type of the Bus asteroid taxonomy. Comparing our results with other D-type asteroids it resulted that our spectra of Phobos are redder than the mean D-type, but within the behavior of the spectra of other D-types and Trojans.

In order to verify whether the parent body of Phobos could have originally been a D-type asteroid as the OSIRIS data suggest, we built an updated scenario for the capture of Phobos based on the collisional mechanism first proposed for the irregular satellites of the giant planets.

We showed that D-type asteroids ejected from the asteroid belt could be captured by Mars after a collision with planetesimals in the Martian orbital region. This scenario temporally locate the capture event somewhere in the first 10 – 100 Ma of the lifetime of the Solar System, consistently with the results of previous studies of the orbital evolution of Phobos.

The above mentioned results give mineralogical and dynamical costraints regarding Phobos asteroidal collisional capture birth. Our hints can be considered as a reference for future Phobos surface studies dedicated to understand its origin. In the next 15 years two Phobos space missions are foreseen: the repurposed Roscosmos *Phobos-Grunt* mission, and the ESA 2022 *Phootprint* Phobos sample return mission. The ESA *Phootprint* mission has not been officially selected yet, but it will be probably an ESA-Roscosmos joint project, belonging to the European Robotic Exploration Programme (EREP), which will follow the *ExoMars* mission and which will finally address Phobos striking question related to its intriguing origin.

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