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LETTER TO NATURE GEOSCIENCE

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Phobos and Deimos, the two small satellites of Mars, are thought either to be asteroids captured by the planet or to have formed in a disc of debris surrounding Mars following a giant impact[1-4]. Both scenarios, however, have been unable to account for the current Mars system[1-3,5-7]. Here we use numerical simulations to suggest that Phobos and Deimos accreted from the outer portion of a debris disc formed after a giant impact on Mars. Larger moons are formed from the denser inner disc and migrate outwards due to gravitational interactions with it. The resulting orbital resonances spread outwards and gather the dispersed debris, facilitating accretion into two satellites of sizes similar to Phobos and Deimos. The larger inner moons fall back to Mars after

about 5 million years due to the tidal pull of the planet, after which the two outer satellites evolve into Phobos- and Deimos-like orbits. Our results clarify why Mars has two small satellites instead of one large moon. Our model predicts that Phobos and Deimos are composed of a mixture of material from Mars and the impactor.

It was originally thought that Phobos and Deimos were asteroids captured by Mars[1,2]. This scenario explains their small size, irregular shape, cratered surface and presumed non-Martian composition but not their current near-circular, near-equatorial orbits[1-3]. Tidal dissipation rates inside Mars and the captured bodies are insufficient to change the orbits after capture into the present orbits of Phobos and Deimos, in particular the inclination from ecliptic to equatorial plane[1,3]. These orbits argue in favour of formation *in situ* around Mars[1-4], for example in an extended circum-Martian accretion disc of 10^{18} kg resulting from a giant collision, which could also be responsible for the spin rate of Mars[6]. The formation of satellites has been considered in a disc of identical mass lying inside the Roche limit[7] (at about 3 Mars radii), similar to the formation of the Earth-Moon system and of Saturn's small and mid-sized moons[8-9]. Moons with the mass of Phobos and Deimos can be formed at the Roche limit before migrating outwards, but they cannot cross the synchronous orbit at 6 Mars radii so that tidal forces cause them to rapidly fall back to the planet[7].

The huge impact that created the Borealis basin may have resulted in a more massive disc (~10^{20} kg)[5,10] extending beyond the current orbit of Deimos at 7 Mars radii[5]. The formation of satellites in such a disc has not yet been widely investigated, particularly in its outer part around the synchronous orbit. Taking into account the tidal effects in Mars and integrating a circular, equatorial orbit backwards from the present position of Phobos, it is found that 4.5 Gyr ago, this body must have been at about 5.7 Mars radii[1]. Over the same time, the orbit of Deimos hardly changed due to its much smaller mass[1]. The challenge for an accretion scenario in an extended disc is thus to form only two small bodies just below and slightly above the synchronous orbit.

Here we report the results of numerical simulations for successive stages following a giant impact. The first step is to describe the formation of the disc of debris and in particular to determine the distribution of mass inside. Our SPH simulations reproducing the calculations by Citron et al.[5] (see Methods) show that most of the mass is contained within the Roche limit for Mars: we refer to this region as the inner disc. The remaining material is distributed in an outer region extending beyond the synchronous orbit, which we will refer to as the outer disc. We found that at most 1% of the total mass resides in the outer disc (Fig. 1), represented in the SPH calculations by only a couple of particles. A precise estimate of the outer disc mass would however require computing power that is as yet unavailable. We therefore modelled the outer disc with a set of small bodies, hereafter called satellite-embryos, similar to embryos in planetary discs[11,12] (Supplementary Information, Section 1), assuming that the total mass beyond 4.2 Mars radii is equal to the combined mass of Phobos and Deimos. We first implemented an N-body code using a symplectic integrator to track the motion of these satellite-embryos[13] together with a very simple model in which accretion occurs if two bodies move within their mutual Hill radius, which is similar to their physical radius. We found that the satellite-embryos never accrete into two small bodies below and above the synchronous orbit, even after 50 Myr (*i.e.* > 10^9 orbits): the system is not dynamically excited enough to allow a sufficiently large number of close encounters between satellite-embryos.

Excitation can however be provided by inner moons spawned at the Roche limit as the inner disc spreads viscously outwards[7]. Using a 1D hydrodynamical model[8], we found that for a disc containing 5x10^{20} kg of material, the most massive moon formed is about 10^{19} kg (Fig. 2). Angular momentum exchange between the disc and moons, occuring at the Lindblad resonances in the disc, results in a rapid expansion of their orbits[7,8,14]. The moons reach their maximum distance from Mars when their 2:1 mean-motion resonance (MMR) encounters the edge of the inner disc, resulting in a maximum semi-major axis of about 4.4 Mars radii reached after 3,400 years.

The dynamics of a massive inner moon migrating outwards was included in the N-body code in order to investigate how its presence modifies the accretion of the satellite-embryos. To improve the description of the accretion process, two-body collisions are treated as inelastic, but the possibility that one or both bodies break up is neglected (see Methods). We find that capture of satellite-embryos in MMRs with the inner moon plays a critical role in facilitating accretion in the outer disc. The 2:1 and 3:2 resonances are located at 1.59 and 1.31 times the distance of the inner moon from Mars (Fig. 3), thus their locations sweep outwards as the moon migrates. These resonances excite the orbit of the satellite-embryos, favouring close encounters and hence accretion. Embryos that are trapped by the resonances migrate outwards with them, meeting and accreting with other embryos to form larger bodies (Fig. 3 and Supplementary animations). They may however be pulled off-resonance during accretion events, and trapped again later by the same or a different MMR. After a few thousand years, the system is eventually left with only two outer satellites, one on each side of the synchronous orbit. The outermost satellite generally results from the mutual accretion of satellite-embryos initially placed well beyond the 2:1 resonance.

In most cases, the mass of this satellite is less than that of the innermost one, which has accreted more satellite-embryos during the MMR capture process (Fig. 3).

Out of 288 simulations with various initial conditions (Supplementary Information, Section 2), 91 runs (31.6%) yielded a single, more massive satellite below the synchronous orbit and a single, less massive satellite above it. In 11 cases, the masses of the innermost and outermost satellites lie within 5% and 30% of the mass of Phobos and Deimos respectively. In 4 cases, the orbits of the two satellites are very close to those expected for Phobos and Deimos 4 Gyr ago. In the other cases, the satellites are slightly closer to Mars; the more massive satellite can have as little as 60% of the mass of Phobos while the smaller satellite can have up to four times the mass of Deimos (Fig. SI3 in the Supplementary Information, Section 2). In other simulations with more relaxed constraints on the range of initial eccentricities and inclinations, between one third and half of the runs yielded similar results. The eccentricity of the outermost satellite however tends to be larger and is difficult to reconcile with today's value after 4 Gyr of tidal damping. It is however a reasonable hypothesis that the particles in the disc are smaller than a few hundred meters in size, which argues in favour of an initially less-excited disc (Supplementary Information, Section 3). Eventually the inner disc is emptied, its content having either fallen back to Mars or having been pushed across the Roche limit. The tidal pull of Mars then prevails, causing the large inner moon to fall back to Mars after about 5 Myr.

Our N-body simulations involve about 110 satellite-embryos initially distributed between 4.2 and 7 Mars radii, with a mutual separation of 10 Hill radii and a size between 1 and 4 km (See Methods). For smaller and more numerous initial bodies, we have found that MMR with the inner moon triggers accretion as efficiently as for larger satellite-embryos, and the results are therefore similar (see

Supplementary animations for a run with a mutual separation of two Hill radii, corresponding to ten times more satellite-embryos). This demonstrates the robustness of the MMR mechanism in accreting all material in the outer disc.

Tidal effects can modify the orbits of the satellites, eventually bringing them closer to those of Phobos and Deimos. Analysis of long-term tidal evolution (See Methods) shows that the orbit of Deimos can be reached after 4 Gyr, provided the tidal dissipation factor in the satellites is between 10^{-5} and 10^{-4}. Phobos' orbit requires a lower tidal dissipation factor (less than 6×10^{-7}), which seems difficult to reconcile with formation at close distance in the same accretion disc. Resonances with Mars' orbit and spin can however lead to sudden increases in Phobos' eccentricity[15], so that higher tidal dissipation factors, consistent with those for Deimos, are required to allow Phobos to reach its current orbit after 4 Gyr (Supplementary Information, Section 4).

Our results provide, for the first time, a working dynamical framework for the formation of two satellites orbiting Mars from an accretion disc generated by a giant collision that occurred in the early history of the planet, such as the one thought to have formed the Borealis basin[10]. At least one large inner moon with a mass of about 10^{19} kg is required to produce two satellites similar in mass to Phobos and Deimos. In addition, these satellites are expected to retain a significant amount of porosity since they have been formed by accretion of smaller debris[16]. The recent and precise estimation of the masses of Phobos and Deimos has confirmed a low bulk density (lower than 2 g/cm^3), which can be interpreted as a significant amount of porosity in their interior[3,17]. The SPH simulations also show that the disc of debris can retain significant amounts of material from the impactor (around half of its mass, Fig. 1). The possibility that non-Martian material can be included in the disc could reconcile the giant collision scenario with the primitive composition of the Martian satellites suggested by remote sensing observations of their surfaces[18]. These measurements are however highly ambiguous when interpreted in terms of composition and are only representative of the surface, not of the bulk composition of the bodies[3,19]. Our scenario provides further motivation for a sample return mission to the Martian satellites.

Our study shows that the Phobos and Deimos system may represent a new kind of giant impact outcome, different from the Earth-Moon or Pluto-Charon system, arising from the relative position of the Roche limit (about 3 planet radii) compared to the synchronous orbit. For fast rotators, such as the proto-Earth, the synchronous orbit is well inside the Roche limit, resulting in the tidal survival of the largest moons produced by the inner portion of the disc. In the case of Mars, the synchronous orbit is much further out than the Roche limit, so that all moons formed in the massive inner portion of the disc fall back to Mars. Only the light and widespread outer debris survive and finally accrete if sufficient excitation is provided, for example by orbital resonance-enhanced accretion as demonstrated here. This is further evidence that processes for satellite formation are as diverse as the satellites in the solar system themselves.

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Author Contribution:

P.R. and S.C developed the proposed scenario for the formation of Phobos and Deimos. S.C. also ran the 1D-model of massive moon formation at the Roche limit. K.M.D. and M. T.-D. built and ran the N-body code for accretion of small debris in the outer part of the disc. A.T. computed the mass repartition of debris and produced the supplementary animations. A.T. and S.T. built and ran models of tidal evolution of the orbit of the two satellites after their formation. R.H. ran the SPH code of post-impact accretion-disc formation provided by H.G.

Competing financial interest:

The authors have no competing financial interest.

Figures:

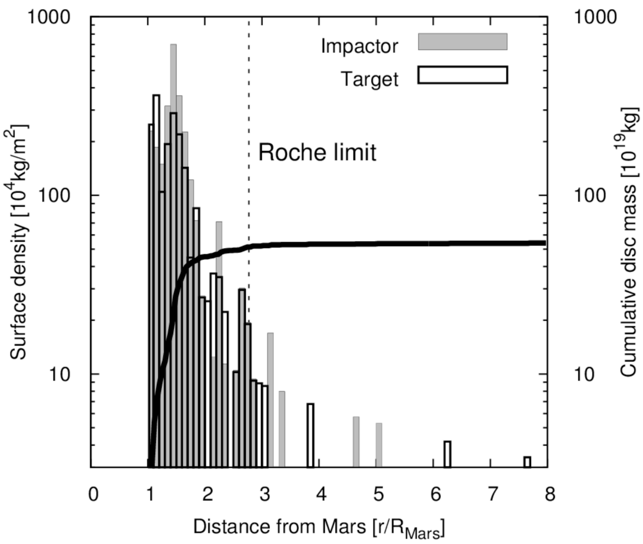

Figure 1: Mass distribution in the disc formed after the giant impact as obtained in our reproduction of SPH simulations[5]. Columns represent the surface density of the accretion disc as a function of the distance from Mars, while the thick curve corresponds to its cumulative mass. The grey bins correspond to impactor material, the white bins to target material. Most of the disc mass is below the Roche limit (dotted line), while the most distant fragments are located beyond the synchronous orbit. The simulation also shows that 43% of the disc mass comes from Mars and the rest from the impactor.

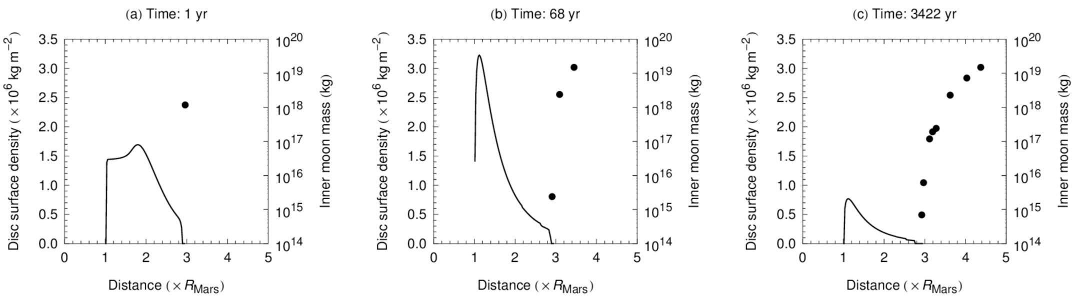

Figure 2: Formation of moons from the inner disc below the Roche limit. (a-c) Time evolution of the surface density of the inner disc (solid line) and the masses of the moon (solid black circles) as a function of the distance from Mars. (a) After only 1 year, disc material crosses the Roche limit (at about 3 Mars radii) and conglomerates into moons. (b) In less than one century a few moons are produced and migrate outwards due to the gravitational interactions with the disc. (c) The most massive moon reaches the maximal distance of about 4.4 Mars radii after 3,400 years.

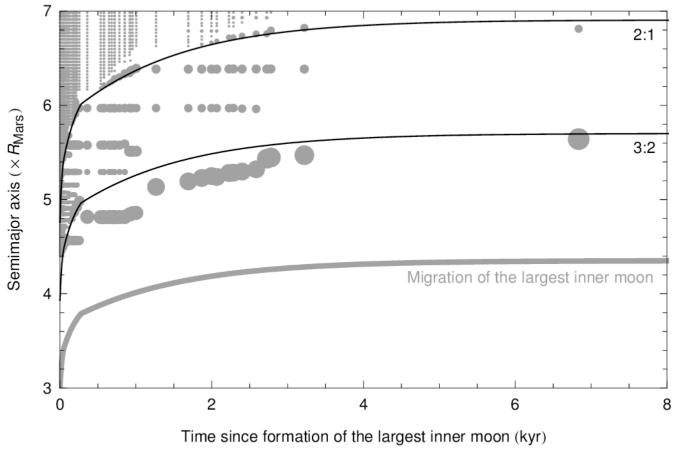

Figure 3: Typical evolution of the outer disc since the inner moon's formation, resulting in satellites similar to Phobos and Deimos. Satellite-embryos of mass ~1% that of Phobos are initially between 4.4 and 7 Mars radii. The thick line represents the outwards migration of the inner moon from the Roche limit. The thin lines are the positions of MMRs following the migration. The size of the circles is proportional to the mass of the body. The two final satellites have masses 0.999 and 1.005 times those of Phobos and Deimos, respectively. Animated versions of this figure are provided as supplementary material.

Methods

Simulation of post-impact accretion-disc formation:

In a recent study[5], Citron et al. performed Smoothed Particle Hydrodynamics (SPH) simulations to study the formation of a disc of debris after a giant impact on Mars. Some information, such as the surface density, the pressure/temperature profile of the disc and the amount of impactor material incorporated in the disc was however not given. We have therefore repeated their calculations using the same computer code[20] and initial conditions in order to obtain this information.

SPH simulation is a Lagrangian method[21] in which hydrodynamic equations are solved by considering averaged values of particles through kernel-weighted summation. Pressure is calculated using the Tillotson equation of state[22] as a function of internal energy and density. For the artificial viscosity, a Von Neumann Richtmyer-type viscosity[22,23] is used with parameters α=1.5 and β=3.0.

Following Citron et al.[5], it is assumed that Mars is differentiated with a basalt mantle and an iron core. The core-to-mantle mass ratio is 0.3 with a total mass of $6.0\text{x}10^{23}$ kg. The impactor is taken to be an undifferentiated basalt sphere of mass $1.68\text{x}10^{22}$ kg. The total number of SPH particles in the simulation is $3\text{x}10^5$. The impact angle is 45 degrees and the impact velocity is 1.4 times the mutual escape velocity of these bodies.

The results of our simulation agree with those of Citron et al.[5] They also show that most of the disc mass is below the Roche limit and only a few particles are located beyond Deimos' orbit at 7 Mars radii (see Fig. 1). The outer extended disc however contains too few SPH particles to accurately resolve its mass distribution.

This problem cannot be overcome by simply increasing the number of SPH particles due to the limitation in current computational resources.

<u>*Distribution of satellite-embryos in the outer disc:*</u>

As current SPH simulations do not have sufficient resolution, we could not reliably determine the mass distribution of small debris in the outer disc. Irrespective of whether the outer disc is made of satellite-embryos or unaccreted debris after the impact, MMRs with the inner moons push the material outwards and hence stimulate accretions. We therefore assumed a distribution of satellite-embryos in the outer disc similar to the runaway growth of planetesimals in planetary discs[11,12]. These embryos are initially separated by about 10 times their Hill radii as follows[13]:

$$a_{i+1}=a_i+10\left(\frac{M_{i+1}+M_i}{3M_p}\right)^{\frac{1}{3}}\left(\frac{M_{i+1}a_{i+1}+M_i a_i}{M_{i+1}+M_i}\right) \qquad (1)$$

where M_p is the mass of the planet, a_i and M_i are the distance from Mars and the mass of the i^{th} embryo respectively. This mass is assumed to be the isolation mass[24]:

$$M_i=\frac{\left(20\pi a_i^2\sigma(a_i)\right)^{\frac{3}{2}}}{\left(3M_p\right)^{\frac{1}{2}}} \qquad (2)$$

where $\sigma(a_i)$ is the disc surface density at distance a_i from Mars. A good approximation to the surface density profile of a planetary accretion disc is given by:

$$\sigma(a_i)=\sigma_0 a_i^q \qquad (3)$$

with $-5 < q < -0.5$. The surface density is used to derive the isolation mass or embryo mass profile versus the distance from Mars. The σ_0 factor in Eq. 3 is adjusted so that the total mass of the satellite-embryos is equal to the combined mass of Phobos and Deimos ($1.15\text{x}10^{16}$ kg).

N-body simulation of accretions in the outer disc:

The Hamilton equations of motion of all the bodies (Mars, the large inner moons and the satellite-embryos) between collisional events are solved using a symplectic integrator[25]. Such numerical methods are well known for their ability to integrate Hamiltonian systems over very long time spans while preserving the total angular momentum. We chose the higher, 6th-order symplectic integrator SI6A[25] as the number of force function evaluations remains manageable. The inner moon is subjected to an additional force of the form $\alpha\ \exp(-\beta t)v$, where v is the moon's velocity and the parameters α and β are chosen in order to reproduce the time dependence of its semi-major axis given by the 1D hydrodynamic model[8]. Its mass is also increased during the propagation to take into account accretion with other less massive moons spawned from the inner disc at the Roche limit.

The collisions are treated as inelastic by using normal and tangential coefficients of restitution, ε_n and ε_t: if two bodies i and j of mass m_i and m_j moving with velocities v_i and v_j approach each other to within their mutual Hill radius, a post-impact or rebound velocity v' is calculated as:

$$v_n' = -\varepsilon_n v_n \qquad (4)$$

$$v_t' = \varepsilon_t v_t \qquad (5)$$

where $\boldsymbol{v}_n$, $\boldsymbol{v}_t$ are respectively the normal and tangential components of the impact velocity. If the rebound velocity is less than the escape velocity for the two bodies, accretion is assumed to occur: the two colliding bodies are replaced by a body of mass equal to the sum of their masses and whose position and velocity are those of their centre of mass. If the rebound velocity is greater than the escape velocity, the two bodies separate with velocities:

$$v_i' = v_{cm} + m_j v' \qquad (6)$$

$$v_j' = v_{cm} - m_i v' \qquad (7)$$

where v_{cm} is the velocity of their centre of mass. The two separating bodies are tracked over the next few time steps until they move beyond their mutual Hill radius. If they encounter each other again at a later time, this is considered to be a new collision.

If at time t the two bodies are found within their mutual Hill radius but are separating rather than approaching, and not being tracked after a collision, the code returns to the previous time and reduces the time step until it finds a time at which the two bodies are approaching each other. The execution then continues as described above. After the collision, the time step is reset to its initial value.

One caveat with this approach is the possibility that collisions may occur at sufficiently high speed to cause shattering and dispersal of the fragments, which may change the dynamics of the system and compete against accretion. To the best of our knowledge no simple model or scaling laws yet exist that could be easily implemented within our approach. However, as impact velocities are much lower than typical orbital velocities (about 1,600 m/s at 6 Mars radii), any fragments formed will tend to stay in similar orbits and rapidly recollide. Since energy is lost during each collision, fragments can then recombine within a few orbits. Indeed, in our simulations we have observed similar behaviour after inelastic collisions not resulting in accretion.

In our calculations, the shortest orbit period is 8.5 hours, corresponding to that of the inner moon at 3 Mars radii. The integration time step is chosen as 15 minutes, and is reduced by a factor 10 when the distance between any pair of bodies becomes less than three times their mutual Hill radius. When this condition is no longer met, the time step is set back to 15 minutes. This strategy lengthens the calculations but increases the chance of detecting close encounters. Changing the time step in the symplectic integrator code amounts to changing the integration Hamiltonian and hence violating the conservation of angular momentum and energy of the system characterizing the method. We have verified that the loss of symplecticity remains completely negligible. The algorithm was further modified in order to reproduce the migration of the inner moon due to the gravitational torque exerted by the inner disc. The numerical results of our code were validated by comparing them with those of the Radau integrator[26] which is valid for a non-conservative system but computationally more costly.

Tidal orbital evolution of Phobos and Deimos-like satellites:

The tidal orbital evolution of Phobos and Deimos-like satellites formed in the outer disc is modelled as the variations of their semi-major axis a and eccentricity e under the effect of tidal dissipation in Mars and in the satellite by integrating the following equations[9,27]: for a satellite orbiting above the synchronous limit,

$$\frac{da}{dt}=\frac{3k_{2p}MG^{\frac{1}{2}}R_p^5}{Q_pM_p^{\frac{1}{2}}a^{\frac{11}{2}}}\left[1+\frac{51e^2}{4}\right]-\frac{21k_2nM_pR^5}{QMa^4}e^2 \qquad (8)$$

$$\frac{de}{dt}=\frac{57k_{2p}nMR_p^5}{8Q_pM_pa^5}e-\frac{21k_2nM_pR^5}{2QMa^5}e \qquad (9)$$

for a satellite orbiting below the synchronous limit,

$$\frac{da}{dt}=\frac{-3k_{2p}MG^{\frac{1}{2}}R_p^5}{Q_pM_p^{\frac{1}{2}}a^{\frac{11}{2}}}\left[1+\frac{51e^2}{4}\right]-\frac{21k_2nM_pR^5}{QMa^4}e^2 \qquad (10)$$

$$\frac{de}{dt}=\frac{-57k_{2p}nMR_p^5}{8Q_pM_pa^5}e-\frac{21k_2nM_pR^5}{2QMa^5}e \qquad (11)$$

where k_{2p}, Q_p, M_p, R_p, are respectively the tidal Love number, the tidal quality factor, the mass of Mars and the radius of Mars, k_2, Q, M, R, are those of the satellite, n is the satellite orbital frequency, and G is the universal gravitational constant.

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Code availability. The codes are not available.

Data availability. The authors declare that all data supporting the findings of this study are available within the article and its supplementary information files

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