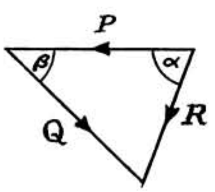
Martian impacts and the grooves of Phobos: implications for the evolution of Phobos' rotation axis

John B. Murray (Dept. of Earth Sciences, The Open University, Milton Keynes MK7 6AA, Buckinghamshire, England).
Jonathan C. Iliffe (Dept. of Photogrammetry & Surveying, University College London, U.K.).

Recent work has suggested that the grooves of Phobos might be explained as chains of coalesced secondary craters from impacts on Mars [1,2]. This work examined groove characteristics and orientations on Phobos, and showed that they were consistent with such a hypothesis. We have since looked at the 16 largest impact craters on Mars (i.e. all those greater than 200km diameter), and using standard gravitational models, have traced the paths of the ejecta from these impacts out to the orbit of Phobos. We have chosen large craters because Mars' atmosphere may have been denser than at present [3], which may have affected trajectories of ejecta from smaller impacts. Using a constant ejection angle, we show that the predicted lines of secondary craters on Phobos from these impacts can be made to match the orientations of most of the grooves on Phobos, simply by varying velocities of ejection at Mars.

Phobos' grooves can be divided into different families of different ages, each family consisting of secondary craters from a single impact on Mars. The velocity and direction of arrival of ejecta from a single Mars impact at Phobos are defined by the avoidance angle (= the minimum angle between Phobos' trailing apex and the fadeout point of the grooves of a given family), and the grooves' inclination to the orbital plane of Phobos, ∂ (where $-180° < \partial < 180°$). In tracing the path of the ejecta, it is easiest to begin with the impact on Phobos and work backwards in time. Fig. 1 shows the vector relationship between P, the motion of Phobos, R, the direction in which the ejecta approached Phobos, and Q, the vector of the ejecta direction in inertial space.



The angle $\alpha = 90°$ - avoidance angle

Fig.1

From this it is found that:

$$|Q|^2 = |P|^2 + |R|^2 - 2|P|.|R|.\cos\alpha$$

and
$$\sin\beta = \frac{|R|}{|Q|}.\sin\alpha$$

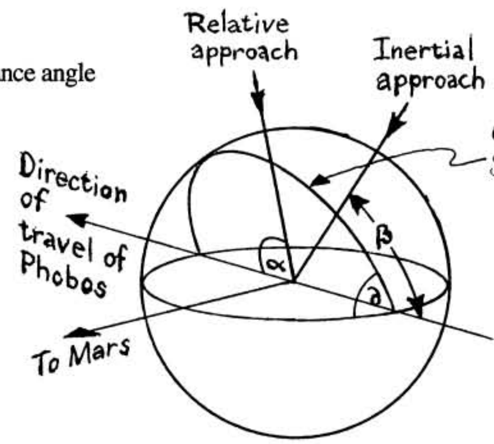


Fig.2. At Phobos

Since $|R|$ is unknown, a range of values is tried, which produces a range of values for $|Q|$ and β, the angle between the vector of motion of Phobos and the direction of ejecta motion. From these data, the angle γ between the direction to Mars and the ejecta direction is calculated as: $\cos\gamma = \sin\beta.\cos\partial$

It is then possible to compute the path of the ejecta using an eighth order Gauss-Jackson numerical integration, with a spherical approximation to the Martian gravity field.

In laboratory experiments, much of the ejecta from a hypervelocity impact is launched at an elevation angle of about 40° from the horizontal [4]. If we restrict the launch angle at Mars to 40°, then for those values of $|R|$ which trace back to this launch angle, the program computes θ, the areocencric angle between the direction of Phobos and the launch. The Mars latitude ϕ of the launch (= source crater) is then computed as:

$$\sin\phi = \frac{\sin\theta.\sin\beta.\sin\partial}{\sin\gamma}$$

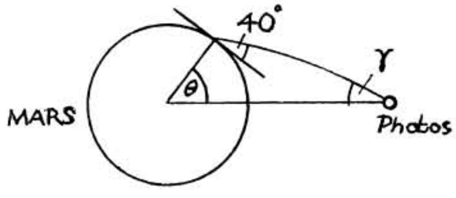


Fig. 3: Mars-Phobos in plane of ejecta trajectory

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It is not possible to give a longitude for the launch position because Mars is rotating relative to Phobos.

Using this method, and allowing errors of up to 2° in latitude, we have found that 7 of the 16 largest craters on Mars could have been responsible for 7 individual groove families on Phobos. They are: 1. Isidis basin (1200 km diam.) 2. Schiaparelli (480 km diam.) 3. Huygens (470 km diam.) 4. Cassini (440 km diam.) 5. Antoniadi (400 km diam.) 6. Herschel (300 km diam.) 7. Schröter (280 km diam.) 8. Newcomb (230 km diam.) 9. Unnamed (220 km diam.). A further 2 Martian impacts could have produced groove families if we relax the restriction of an ejection angle of 40°, and allow angles less than this. They are: 10. Hellas (1950 km), and 11. Argyre (860 km). This may still be a realistic scenario, since ejecta thrown out from an impact in the first few moments of the excavation stage may be ejected at much lower angles to the horizontal [4].

However, so far we have assumed that Phobos' present orbit has been the same in the past, which observation since 1877 has shown to be untrue [5]. In this regard, the most interesting groove families are the 4 which cannot be tied to any point on Mars with Phobos in its present inclination, since they also imply that Phobos' orbit and spin axis has evolved with time. Phobos' present orbit is in Cassini state 2 [5,6], but it is possible that Phobos was in Cassini state 1 in the past, or with its spin axis highly inclined if it was captured.

If we postulate that having evolved a Cassini state 2 orbit, it retained for some time a spin axis orientation consistent with Cassini state 1, i.e. inclined at 25°(±10° approx. for precession) to the normal to its orbit plane, then the 4 remaining groove families can also have been secondary craters from earlier Mars impacts. However, with an inclined spin axis, we cannot assign these 4 groove families to single latitudes on Mars.

If we adopt this early spin axis tilt, then the observed distribution of grooves on Phobos can be matched closely, each groove family being assigned to actual craters on Mars. Figure 4 shows a preliminary model containing 15 groove families (=secondary crater alignments), 9 of which could have come from the Mars craters listed above with an ejection angle of 40°, 2 with an ejection angle of 29° - 35°, and 4 when Phobos' axis was tilted at 25° ±10° to Mars' equator. Groove *spacings* have been selected to roughly match those on Phobos.

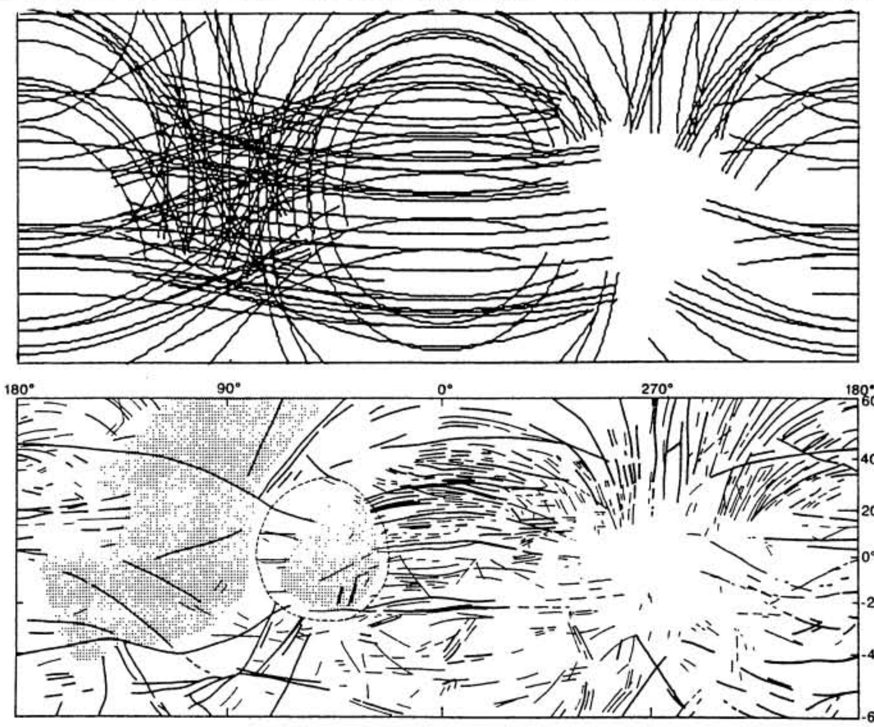

Fig. 4. Computed secondary crater orientation on Phobos from 15 impacts on Mars (top), and map of Phobos' grooves (bottom) from [7].

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