A DOUBLE, OBLIQUE IMPACT ON MARS: ASTEROID OR MOONLET?

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Introduction: Based on counts of elliptical craters, Schultz and Lutz-Garihan [1] and Bottke et al. [2] came to differing conclusions regarding their provenance. Schultz and Lutz-Garihan concluded that Mars has an excess of elliptical craters, the result of impacts by a population of martian moonlets whose orbits tidally decayed. Phobos, which will also tidally decay and impact Mars, and Deimos which will not, were proposed to be remnant members of this population. In contrast, Bottke et al. concluded that no such excess of craters is present.

A feature identified by Gault and Wedekind [3], and included in both studies [1] and [2], presents a unique opportunity to investigate the properties and trajectory of the impactor that formed it, and therefore to determine what sort of object it was: an extra-martian asteroid or a moonlet. It is a double impact crater (Fig. 1) with the smaller crater (2.0 x 3.0 km) lying 12.5 km directly up-range of the larger one (7.5 x 10.0 km).

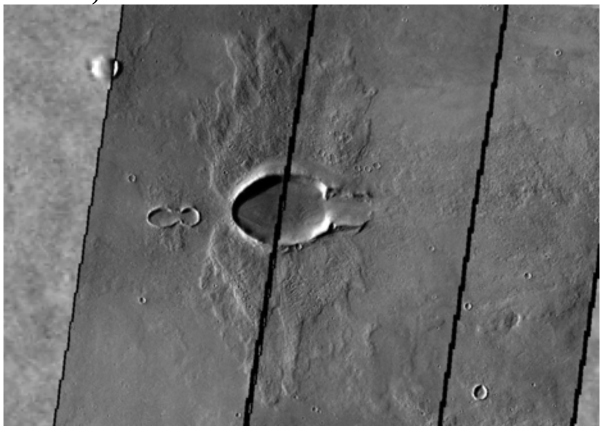

Figure 1: A large (7.5 x 10.0 km) elliptical crater with a smaller elliptical crater (2.0 x 3.0 km) lying 12.5 km directly uprange (to the left). 'Butterfly' pattern ejecta occur around both craters. (Mosaic of THEMIS daytime IR images).

Methods: An atmospheric entry and passage model [4,5] was used to try to reproduce the impact that formed the feature in question. Experiments by Gault and Wedekind [3] and work by Herrick and Hessen [6] indicate that these craters were formed by impactors incident at less than 10° above horizontal. Impact energies were estmated using 'equivalent' crater diameters given by $D = (ab)^{1/2}$, where a and b are the major and minor axes of the crater, and the simple impact energy (KE) vs. diameter relation $KE = KE_0 \times (D/D_0)^{1/3}$, where KE_0 and D_0 are reference values of KE and D (see ref. [4]).

The craters' separation and relative positions provide further constraints on the impact event. Their alignment, with the smaller crater lying uprange, implies that they were formed when a single object separated into two un-equal fragments high in the atmosphere, and the fragments were then separated by differential aerodynamic drag deceleration. It is unlikely that the fragments separated before atmospheric entry (e.g. via tidal effects) or that aerodynamic side-forces (e.g. 'lift') played a significant role, since either of these would usually result in randomly positioned craters, not ones aligned in the direction of flight, smaller one uprange.

The question is, what sort of impactor and trajectory can account for both the separation of the two craters and for their very shallow impact angles, a martian moonlet or an extra-martian asteroid? Clearly, to form the observed features, the impactor must have entered atmosphere at a fairly shallow angle in either case. But a moonlet in a decaying circular orbit would enter atmosphere at ~3.5 km/s (circular velocity at 100 km altitude), while an incident asteroid must be going least 5 km/s (escape velocity at 100 km), two very different events.

Implementation. Pairs of simulated 'test impactors', each pair representing an unfragmented impactor, were started from an altitude of 100 km (~9 martian atmospheric scale heights; considered the 'top of the atmosphere' herein) and velocities of 3.5 and 5.0 km/s. They were launched at trajectory angles of 0-14° below horizontal and followed until they either impacted the surface or left the atmosphere. This procedure was repeated for atmospheres of 6 and 60 mbar of surface pressure. The test objects' masses were chosen so that the initial kinetic energy of each is the same as its impact energy, as calculated from the crater dimensions. Note that implicit in this choice is the assumption that the initial and impact energies are approximately the same; the validity of this assumption was verified for each trial.

Generally, other parameters were chosen to favor the separation of the fragments. For example, impactor density was given a value of 1800 kg/m^3 (similar to Phobos and Diemos), and the lowest possible velocity for asteroid-like impactors (5 km/s) was used. Thus these results represent a limiting case, and other choices of these variables would result in smaller separations between craters.

Results: *Asteroid?* The combined effects of gravity and air drag only slightly deflect the paths of large (>1 MTon), fast (> 5 km/s) objects. Thus incoming extra-martian asteroids follow trajectories like I, II or IV on Fig. 2 upon encountering Mars. Such large asteroids (or fragments) *can* impact Mars at highly oblique angles (path II, Fig.2), but cannot explain the separation observed in the double crater. The shortness of the atmospheric flight path, together with the relatively high speeds of asteroids, make the atmospheric time-of-flight too short for the asteroid fragments to separate enough even to form individual craters, much less craters with the observed separation (Tables). Even for the 60 mbar atmosphere, the greatest separation of the impact points was ~3 km, which occurred for ~9°-10° entry. Thus a Mars-incident asteroid cannot reasonably account for the observed double crater under the atmospheric conditions studied here. Further, but preliminary, investigation indicates that crater separations of more than ~12 km only occur if the atmospheric density is at least several hundred mbar.

A remaining possibility is that an asteroid entering and passing through the atmosphere may theoretically emerge with its speed reduced below escape velocity (Fig. 3), and thus be 'captured' by Mars. Such an object will eventually re-encounter Mars' atmosphere at least once more, and eventually impact the surface on a path similar to III (Fig.2). However, calculations show that a single pass though even the 60 mbar atmosphere can only slow such a massive object (400-500 MTon) by a few m/s. Thus, to be captured, it would have to enter atmosphere at exactly the right angle and at almost exactly escape velocity. In the absence of a *much* denser, more extended atmosphere, this scenario is extremely unlikely.

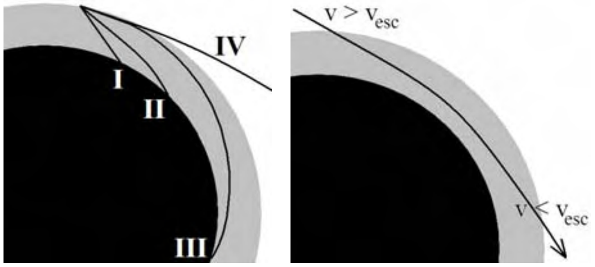

Fig. 2 (left): Trajectory types referred to in the text. I: direct impact, asteroid or moonlet; II: grazing impact, asteroid; III: grazing impact, moonlet; IV: 'skip-out', asteroid only. Fig. 3 (right): Illustration of an asteroid passing through Mars's atmosphere and being 'captured' via drag-deceleration. (Atmosphere is radially exaggerated in both.)

Moonlet? In contrast, the observed crater separation is relatively easy to explain if the impactor was a moonlet in a decaying orbit. Such an object would enter atmosphere nearly horizontally, at 3.5 km/s and follow a flight-path like III (Fig.2). In this case the long flight path allows ample time for the fragments to separate enough to form the double crater (Tables). In addition to being un-physical, steeper entry angles do not allow for enough crater separation. Trial runs at lower atmospheric pressures indicate that the 6 mbar atmosphere is the thinnest that can produce this double crater, even if the impactor is a moonlet.

Conclusions: Our results strongly suggest that only a moonlet-type object can reasonably explain this double oblique-impact feature, unless it was formed under an atmosphere of at least several hundred mbar.

If a moonlet, the impactor's composition was most probably carbonaceous/icy, since (1) Phobos and Deimos have such composition, and (2) denser compositions (e.g. stony, iron) would tend to reduce the differential deceleration between fragments. With a mass of ~1000 MTon (10^{12} kg) and a density of 1800 kg/m^{12} the moonlet would be ~1 km in diameter. It would have to encounter at least a 6 mbar martian atmosphere to account for the observed crater separation.

Fragment masses (MTon)	Velocity (km/s)	Angle (deg)	Impact Angle (deg)	Impact separation (km)
11.2 / 464.0	5.0	10	2.6 / 2.6	0.3
11.2 / 464.0	5.0	12	7.1 / 7.1	0.0
11.2 / 464.0	5.0	14	10.2/10.2	0.0
22.9 / 946.9	3.5	0	1.6 / 1.6	15.1
22.9 / 946.9	3.5	2	2.5 / 2.5	2.6
22.9 / 946.9	3.5	4	4.3 / 4.3	0.3
22.9 / 946.9	3.5	6	6.2 / 6.2	0.1

Tables 1 (above) and 2 (below): Selected results for asteroidal (light gray) and moonlet-type (dark gray) test impactors for 6 mbar (above) and 60 mbar (below) martian atmospheres.

Fragment masses (MTon)	Velocity (km/s)	Angle (deg)	Impact Angle (deg)	Impact separation (km)
11.2 / 464.0	5.0	10	2.7 / 2.6	3.2
11.2 / 464.0	5.0	12	7.2 / 7.1	0.2
11.2 / 464.0	5.0	14	10.2/10.2	0.0
22.9 / 946.9	3.5	0	2.3 / 1.8	97.6
22.9 / 946.9	3.5	2	2.9 / 2.6	22.7
22.9 / 946.9	3.5	4	4.4 / 4.3	3.4
22.9 / 946.9	3.5	6	6.3 / 6.2	0.8

References: [1] Schultz P.H. and Lutz-Garihan A.B. (1982), *JGR*, *87*, *Suppl*, A84-A96. [2] Bottke et al. (2000), *Icarus*, *145*, 108-121. [3] Gault D.E. and Wedekind J.A. (1978), *Proc. 9th LPSC*, 3843-3875. [4] Chappelow J.E. and Sharpton V.L. (2005) *Icarus*, *178*, 40-55. [5] Chappelow J.E. and Sharpton V.L. (2006) *Icarus*, *184*, 424-435. [6] Herrick R.R. and Hessen K.K. (2006) *MAPS*, *41*, 1483-1495.