THE ORIGIN OF PHOBOS GROOVES FROM EJECTA LAUNCHED FROM IMPACT CRATERS ON MARS: TESTS OF THE HYPOTHESIS.

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Introduction: The surface of the martian moon Phobos is characterized by parallel and intersecting rows of pits (grooves) that bear resemblance to secondary crater chains observed on planetary surfaces. Murray [1] has hypothesized that the main groove-forming process on Phobos is the intersection of Phobos with ejecta from primary impact events on Mars to produce chains of secondary craters. The hypothesis infers a pattern of parallel jets of ejecta, either fluidized or solidified, that break into equally-spaced fragments and disperse uniformly along trajectory during the flight from Mars to Phobos. At the moment of impact with Phobos the dispersed fragments emplace pits that are aligned along strike corresponding to the flight pattern of ejecta along trajectory. The aspects of the characteristics of grooves on Phobos cited by this hypothesis that might be explained by secondary ejecta include: their linearity, their parallelism, their planar orientation, their pitted nature, their change in character along strike, and a "zone of avoidance" where ejecta from Mars is predicted not to impact [1].

To test the hypothesis we plot Keplerian trajectories (true orbits and hyperbolic trajectories with periapsis and perifocal points located below the surface of Mars). From these precise trajectories we (1) set the fragment dispersion limits of ejecta patterns required to emplace the more typically well-organized parallel grooves observed in returned images from Phobos; (2) plot ranges of the ejecta flight durations from Mars to Phobos and map contours of exposure; (3) utilize the same contour map to observe trajectory-defined ejecta exposure shadows; (4) observe hemispheric exposure in response to shorter and longer durations of ejecta flight; (5) assess the viability of ejecta emplacing the large family of grooves covering most of the northern hemisphere of Phobos; and (6) plot the arrival of parallel lines of ejecta emplacing chains of pits at oblique incident angles.

Datasets and Analysis: We have compiled a dataset of approximately 5,000 trajectory solutions covering a comprehensive range of viable trajectories from Mars to Phobos in its current orbit. The present day orbit of Phobos represents the greatest historical extent of exposure to martian ejecta. Therefore our dataset inherently includes all surfaces of Phobos exposed to martian ejecta since the moon established its current tidal lock.

Hemispheric exposure centers are mapped onto a three dimensional model of Phobos for durations of flight of 0 to 45 minutes, 5 to 90 minutes and 5 to 180 minutes. From these centers, we observe the extent to which flight durations are associated with a drift in longitudinal exposure. We further plot contours defining the total exposure to ejecta to these ranges and inversely define exposure shadows.

We examine the consequences of test trajectories arriving at Phobos where slight differences in launch velocity and elevation (0.1 to 8.0 mm/s and 0.1 to 10.0 μR) result in a pattern of impact chain misalignment. From this pattern we set limits on the extent of allowable initial launch variations **(Fig 1)**. Beyond a lateral misalignment of 10%, pits appear to deviate noticeably. Where almost no grooves on Phobos reveal linear deviations along strike, we set a pass/fail limit of 10 meters of misalignment along-strike per 100-meters of groove width.

To test the viability of the northern family of grooves we select exposure hemispheres that reveal the most northerly centers of exposure (**Fig. 2**). The emplacement duration to form this northern family is predicted to be no more than nine seconds and therefore the entire family must fit within one complete hemisphere of exposure. Our flight simulations examine a typical ejecta launch elevation of 45° and also an extreme test case of 0° in order to model the greatest northerly exposure possible.

To assess the emplacement of oblique impacts of parallel ejecta columns, we simulate a set of parallel trajectories that arrive at Phobos in a range of ~30 to ~60 degrees from the vertical. At the interface of ejecta with Phobos we plot trajectory intersections onto a three dimensional model of Phobos in equal time units. We then observe the resulting pit pattern from a variety of view angles to assess the extent to which the pit pattern is affected by the irregularity of the local terrain and the small-body radius of Phobos.

Results and Discussion: The Murray hypothesis [1] infers individual fragments separating from monolithic or fluidized jets. Yet for typical trajectories the minimum rate of dispersion along-trajectory required for this process fully disrupts the pattern of flight. For this reason, the ejecta pattern must exit the primary crater with along- and across-trajectory spacing preset and each fragment in the flight pattern must adhere to its original grid position within a dispersion limit (typically < 1.0 mm/s of launch velocity and < 1.0 μR of launch elevation and azimuth). Each point within the pattern must remain referenced to a single datum point and must remain at its grid position within the pattern for up to three hours to expose the majority of Phobos. To maintain the required organization at impact, the longest duration flight patterns must launch with severely decreased dispersion-rate allowances. Furthermore, orbital adjustments are required during the flight to overcome the natural disrupting influence of independent Keplerian trajectories on grid patterns. There is no natural or human-engineered mechanism that can initialize and maintain the required flight parameters solely from the forces of an explosive event.

The Murray hypothesis predicts an absence of observed of grooves within a “zone of avoidance” at the trailing orbital apex of Phobos and proposes that this is due to a trajectory shadow where the zone is unexposed to secondary impacts from martian ejecta [1]. This alignment would only be the case if the motion of Phobos were to supply the *entirety* of velocity vectors. When we simulate the combined velocities of the orbital motion of Phobos *and* the motion of ejecta we observe a pattern-shift where the longitudinal exposure to secondary impacts and exposure shadowing trends to the east. As a consequence, ~50% of the observed "zone of avoidance" is clearly exposed to martian ejecta trajectories. Within contours that define the impact shadowing we also observe a significant quantity of groove pits. Therefore the "zone of exclusion" is unrelated to the exposure of Phobos to martian ejecta and remains a mystery.

Flights to the anti-Mars side of Phobos are proportionately fewer and longer in duration. East to west we would expect evidence of this in the form of increased dispersion of pits in chains, increasing disorganization of pit patterns and far fewer emplaced chains. This is not observed.

In an extreme test providing the most northerly exposure possible from a zero-degree launch elevation, we simulate a major basin-forming event [2] that inserts ejecta into a Phobos-crossing orbit beginning with a periapsis of 100 km. The northern hemisphere family of grooves does not fit within this or any other valid hemisphere of exposure.

Due to the irregularities of the local terrain of Phobos and the small-body radius of the moon, almost all lines of parallel ejecta would arrive at Phobos at oblique angles across strike. The emplaced grooves should show extensive local response to the irregularities of local terrain and the small-body radius of Phobos. In returned images we observe proportionately few examples of poor parallelism or localized emplacement irregularity.

Conclusions and Implications:

1. To emplace a family of grooves with virtually no defects, families of fragments (often thousands) must launch into pre-spaced grid patterns with essentially no observable disruption of the pattern during flights of up to three hours. Fragments must be nearly identical in diameter with no interlopers. Due to the natural perturbation geometries of ballistic formation flight, this is exceedingly implausible
2. Half of the areal region observed as a groove pit "zone of avoidance" is exposed to ejecta flight trajectories from the surface of Mars. The lack of grooves in this zone remains a mystery.
3. Groove pits from several families are observed within the trajectory-derived exposure shadow contour for flight durations of 5 to 180 minutes. This invalidates the related families of these groove pits.
4. East to west, longer flight durations should produce lower pit densities and reduced groove organization. This is not observed.
5. The northern family of grooves can not be emplaced by any valid trajectory. Further, the northern family leaks into the trajectory-defined exposure shadows for flight durations of 5 to 180 minutes.
6. Patterns of impactors would emplace chains of pits at oblique incident angles onto the irregular topography and small-body radius of Phobos. This should clearly disrupt patterns of linearity and parallelism. From almost all angles of view, this is rarely observed.

In summary, six major predictions of the Murray hypothesis (that many grooves are formed by intersection of ejecta from craters on Mars with Phobos) are not consistent with observations and models developed here.

References: [1] Murray, J. (2010) *The First Moscow Solar System Symposium*. [2] Schultz, P. & Crawford, D. (1990) *Abstracts of the Lunar and Planetary Science Conference* **18**:888. [3] Thomas, P. (1997) *NASA Planetary Data System*.

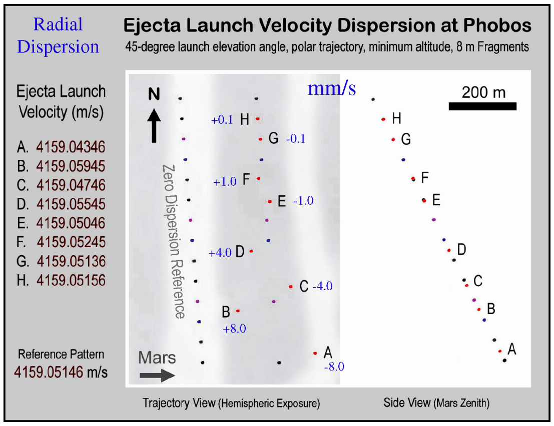

Figure 1: Test fragments are shown after a flight of 86 minutes just prior to impact with Phobos. Particles E and F (1.0 mm/s of launch velocity added and reduced) disperse across trajectory in excess of 10 m and would be observed as a linear defect when emplacing a groove of up to 100 m in width. Several thousand fragments must exit the primary crater in a pre-set flight formation targeted at Phobos with sequential launch velocities < 1.0 mm/s all referenced to a single datum with no observed interlopers or other deviations.

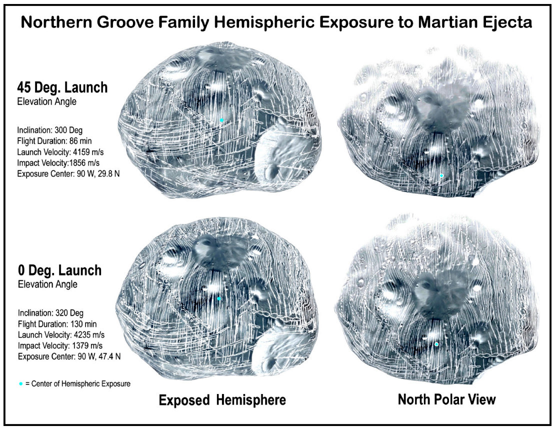

Figure 2: The views on the left show the hemispheres of exposure to martian ejecta for launch elevations of 45° and the unlikely example of a 0°. The launch velocity is optimized to expose the most northerly region of Phobos. The views on the right show the same exposure from above the north pole. Among our comprehensive set of ejecta flight trajectories, there is no trajectory that fully exposes the large northern hemisphere family of grooves.