THE ELLIPTICAL CRATER POPULATIONS ON THE MOON, MARS, AND VENUS. T. Glotch, *Colgate University, Hamilton, NY 13346, USA,(tglotch@center.colgate.edu)*, W. Bottke, *CRSR, Cornell University, Ithaca, NY 14853, USA*, S. Love, *NASA-JSC, Mail Code CB, Houston TX 77058, USA*, D. Tytell, *Caltech, M/S 170-25, Pasadena, CA 91125, USA*.

Introduction

Asteroids or comets striking a planetary surface at very shallow angles produce elliptical-shaped craters. According to laboratory impact experiments, where aluminum or pyrex spheres were shot at 6.4 km s^{-1} into sand [1], less than 1% of projectiles with isotropic impact trajectories create elliptical craters. This empirically-derived result, however, disagrees with surveys of the elliptical crater population on Mars, which indicate that approximately 5% of all craters larger than several km in diameter are elliptical in shape [2, 3]. Several scenarios to explain this discrepancy have been proposed (e.g., a ''special'' population of low-angle impactors; [2]; a new derivation of the threshold angle needed to estimate elliptical crater formation; [3]). Unfortunately, without any data from the other terrestrial planets, it is impossible to determine whether this fraction of elliptical craters is typical or anomalous.

To resolve this issue, we surveyed the non-crater-saturated regions of the Lunar Mare and the entire surface of Venus for elliptical craters (i.e., craters with major-to-minor axis ratios ≥ 1.2). Our results, completed over the summer as a Spacegrant student project, show that Venus and the Moon also have approximately 5% elliptical craters. Our procedure, results, and an explanation for these outcomes are presented below.

Survey of Elliptical Craters on the Lunar Mare

We started our crater survey in the Lunar maria located on the near side of the Moon. These regions comprise nearly 15% of the Moon's total surface area. Since the maria were still being covered by flood basalts after the Late Heavy Bombardment, impact craters larger than a few km tend to be distinct and relatively unmodified by other impact craters. We limited our survey to craters which were several km in diameter or larger, mainly to avoid biasing our sample with secondaries. Craters in obvious rays, in nearby but non-mare terrain, and those which had been deformed by impacts or basaltic flooding were excluded.

Regions investigated included Mare Tranquillitatis, Mare Nectaris, Mare Vaporum, Mare Nubium, the east half of Mare Serenitatis, the west half of Mare Humorum, and parts of Oceanus Procellarum. For the latter site, areas in the immediate vicinity of craters Copernicus and Kepler were excluded. More precisely, we studied Lunar Orbiter IV images 53, 54, 60, 61, 66, 72, 73, 77, 78, 85, 86, 90, 97, 113, 114, 120, 121, 126, 133, 138, 144, 149, 150, 156, 157, 162, and 169. Crater lengths and widths were measured using the NIH Image software package. 932 craters were measured in all, with the smallest being 2.3 km and the largest being 89 km. The mean crater size measured was 6.9 ± 7.1 km, indicating we found lots of small craters but only a few big ones.

We found that 50 of the 932 craters (5.4%) were elliptical, nearly the same fraction measured on Mars. This fraction does not change significantly with size; craters larger than 20 km in diameter produce nearly the same percentage of elliptical craters. The maximum ellipticity found among the 50 craters is 2.23, while the mean was 1.42 ± 0.23.

Survey of Elliptical Craters on Venus

We also performed a preliminary survey of the elliptical craters on Venus. This crater record is more difficult to interpret, since Venus's dense atmosphere causes some projectiles to break-up prior to impact. Factors such as the projectile's size, trajectory, velocity, composition, and internal structure determine whether the body can stay together long enough to form a ''standard'' crater or whether it disrupts and disperses, producing a irregular-shaped crater, a crater field, or no crater at all. Thus, we expect to see fewer ''big'' elongated craters than ''small'' ones, since big asteroids and comets are the least likely to suffer significant deformation in Venus's atmosphere.

For our survey, we used crater images produced using Magellan's synthetic aperture radar. The coordinates of Venusian craters can now be found on-line at the USGS [4]. Unfortunately for our purposes, Magellan CD images have been mapped using a sinusoidal projection, which keeps areas true but distorts features far from the central meridian. Mapping the images using a Mercator projection, which distorts areas but keeps shapes more-or-less true, was too labor-intensive and time-consuming for our available work time. Thus, to make the project more manageable, we broke our survey into two parts:

(i) We measured the elongation of 854 sinusoidally-projected Venusian craters, excluding those which were either highly degraded or clearly produced by multiple impacts. The smallest measured crater was $D = 1.7$ km, while the largest was $D = 268.7$ km. Our goal was to filter out most of the circular or nearly-circular craters from the database; we consider it unlikely that many elongated craters distorted by a sinusoidal projection were turned into nearly circular craters. Our results showed that 185 of the 854 (22%) sinusoidally-projected craters had major-to-minor axis ratios ≥ 1.2 This fraction drops to 14% (43 out of 303) for craters with diameters $D \geq 20$ km and then stays more-or-less constant for larger values of D. We interpret this to mean that aerodynamic break-up does not affect final crater shape of most $D \geq 20$ km craters.

(ii) We used Magellan image headers and IDL software to calculate true distances between the sinusoidally-projected elongated craters found in (i). This step was time-consuming enough that we were only able to re-measure 75 of the 185 craters before the summer ended. The 75 craters had D between 7.0 and 72.5 km. Of this set, we determined that only 23 were actually elliptical (about 30%). The maximum ellipticity of the 23 craters was 1.51, while the mean was 1.27 ± 0.085.

We can use the values from (ii) to scale our elongated crater results from (i): $(185/854) \times (23/75) = 6.6\%$ elongated craters over all sizes, while $(43/303) \times (23/75) = 4.4\%$ elongated craters for $D > 20$ km. The latter value is more appropriate for comparisons with the other terrestrial planet crater populations, and we find it a good match with the $\sim 5\%$ elliptical crater fraction found on Mars and the Moon.

Interpretation of Elliptical Crater Results

The fact that Venus, Mars, and the Moon all share roughly the same fraction of elliptical craters make it unlikely that a ''special'' population of low-angle impactors is landing on any given surface. Instead, we believe this common outcome can be explained by revising estimates of the threshold incidence angle necessary to produce elliptical craters.

It has been pointed out by [3] that that hyper-velocity impact experiments into sand [1] and aluminum [5, 6] targets create elliptical craters at different critical angles to the horizontal; sand produces them at 4.75°, while aluminum produces them at 25°. This indicates that the critical angle steepens as target strength increases, calling into question the dependance on cm-scale laboratory sand targets as an analog for km-scale planetary surfaces. Unfortunately, no oblique angle impact experiments (that we are aware of) have been attempted for rocky targets. It is also unclear whether such experiments are even germane to craters forming in the gravity-scaling regime. Given these limitations, [3] did the best they could with the data they had. Fitting a power-law to the two available pairs of data for crater-to-projectile diameter ratio and threshold angle for elliptical crater production: (4.7, 25°) for aluminum targets and (61, 4.75°) for sand targets, they estimated that the critical angle for making elliptical craters on various planetary surfaces was:

$$\theta_{crit} = 68.1^\circ \left(\frac{D_c}{D_p}\right)^{-0.648} . \qquad (1)$$

where D_c is the crater diameter produced by a projectile D_p on a given planetary surface. Using pi-scaling laws, we can put numbers into this equation. Using km-sized projectiles, D_c/D_p for Venus, Mars, and the Moon is approximately 13, 15, and 16, respectively, which makes $\theta_{crit} = 13^\circ, 12^\circ$, and 11°, respectively. Assuming the canonical $\sin^2\theta$ probability distribution for random impact angles, we predict that between 4-5% of craters on these planets should be elliptical. This result compares favorably with the $\sim 5\%$ elliptical craters found in our various surveys.

Conclusions

We have determined that the elliptical crater fraction on Venus and the Moon is $\sim$ 5%, the same fraction found on Mars. Interpolating between impact experiment data produced in sand and aluminum, we derived new elliptical crater threshold angles for Venus, Mars, and the Moon, all which matched observations within uncertainty given an randomly flying projectile population. Thus, we conclude that the proportion of elliptical craters on the terrestrial planets is a natural by-product of projectiles striking at random angles, and that no additional formation mechanisms are needed.

References

[1] Gault, D.E., and J. A. Wedekind. (1978) *Proc. Lunar. Sci. Conf.* 9, 3843. [2] Schultz, P. H., and A. B. Lutz-Garihan. (1982) *J. Geophys. Res.* 87, A84. [3] Tytell, D, S. G. Love, and W. Bottke (1999) Submitted to *Icarus*. [4] URL: http://wwwflag.wr.usgs.gov/USGSFlag/Space/venus/ [5] Christiansen E. L., E. D., Cytowski, and J. Ortega. (1993) *Int. J. Impact Eng.* 14, 157. [6] Burchell, M. J., and N. G. Mackay (1998) *J. Geophys. Res.* 103, 22,761.

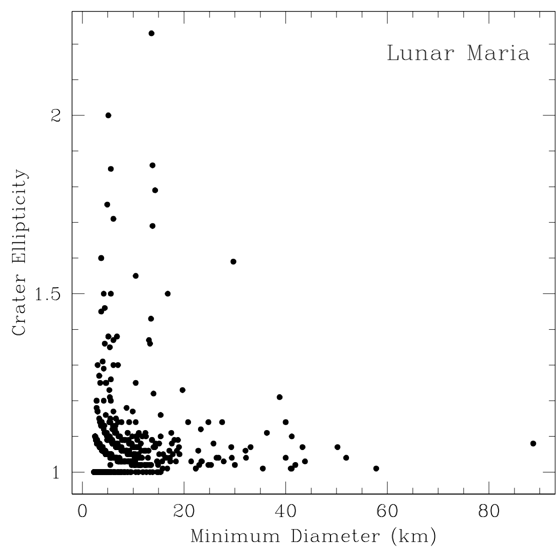

Figure 1. Lunar maria craters. Minimum crater diameter (km) plotted against ellipticity (ratio of maximum-to-minimum crater diameter) for 932 craters. Note that only the ones with ellipticities ≥ 1.2 are considered elliptical craters.

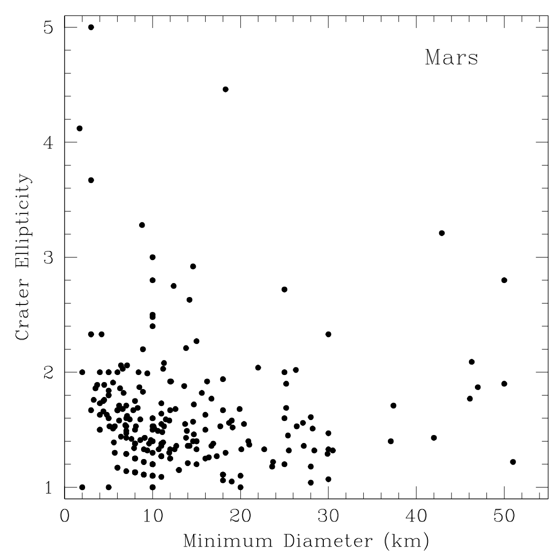

Figure 2. Martian elliptical craters reported by [3]. 255 craters are shown. Note that no ''standard'' craters are shown here, unlike Fig. 1.