MODELING THE EFFECT OF OBLIQUITY ON MARS ELLIPTICAL CRATER ORIENTATIONS.

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Introduction: Obliquity is a strong control on post-Noachian Martian climate [1]. However, Martian obliquity is chaotic and dynamical models produce a wide range of instantaneous and long-term average values [2]. Here, we model the effect of Mars mean obliquity on the distribution of fresh elliptic crater orientations. To achieve this we used an N-body simulation to estimate the time-averaged distribution of asteroid close encounter inclinations and speeds. These close encounters seeded an analytic forward model of asteroid trajectories that tracked impact orientations and angles. Preliminary comparison of model output and elliptic crater orientation data from the Robbins database [3] suggest that mean Mars obliquity after the Mars impactor population stabilized was low, < ~30°.

Close Encounter Simulation: We started with the Minor Planet Center database of asteroid orbital elements and selected Mars crossing objects defined as having perihelion distance less than $a \times (1 + e)$ and aphelion distance greater than $a \times (1 - e)$ where a = 1.52AU is the semi-major axis of Mars and e = 0.15 was chosen to include the entire range of Mars eccentricities observed in our simulations. We also required that the objects have magnitude less than 14 to ensure population completeness and more than one opposition to ensure accuracy of orbital elements. Using the *Mercury* N-body hybrid symplectic code [4], we integrated the solar system forward 10Myr with these objects as massless test particles. Each instance of a test particle passing within 1 Hill radius of Mars was counted as a close encounter, and from these close encounters we obtained a distribution of impactor speeds and inclinations relative to Mars's orbital plane (Figure1).

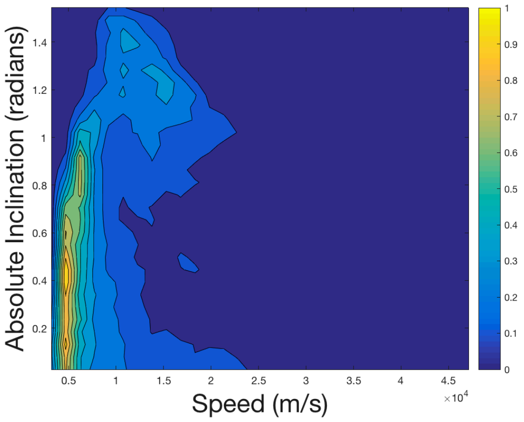

Figure 1. Relative frequency of 30x30 binned close encounter speeds and absolute inclinations.

Impact Model: From each of the ~43,000 close encounters, we constructed 100 impacts following a method similar to [5]. In particular, for each inclination-speed pair we randomly generate impact parameters and arguments uniformly in the disk where hyperbolic orbits with focus at Mars' center of mass are guaranteed to impact Mars. The trajectories of the hyperbolic orbits were solved analytically, the precessional season of the axial tilt (i.e. the angle between the axes of rotation for inclination and obliquity) was sampled uniformly from [0, 2π], and obliquity was varied as a free parameter from 0 to 90°. The set of impacts with impact angle (relative to the planet's surface) in the bottom 5% were assumed to produce elliptic craters. Model outputs show that the most abundant crater orientation shifts from North-South to East-West as obliquity increases.

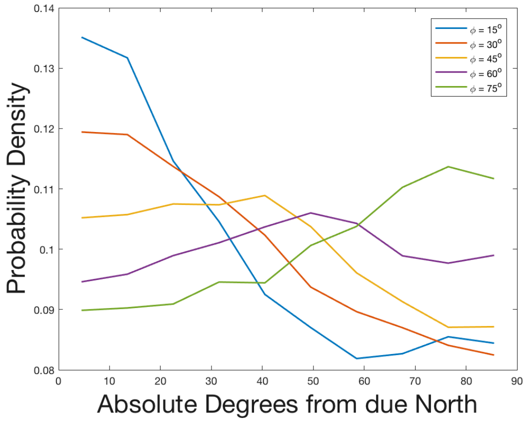

Figure 2. Probability density of elliptic crater orientations predicted by our forward model.

Validation of Elliptic Crater Data: The Robbins Mars crater database [3] contains measurements of crater ellipticities and major axis orientations obtained from fitting ellipses to points traced around crater rims. To validate this data, we retraced a random sample of elliptic craters from [3] spanning all ellipticities greater than 1.1 and major axes greater than 1km and performed the direct ellipse fitting procedure from [6] that was used in [3]. When retracing craters, we displayed only the reported centers and not the best fit circles to avoid biasing our traced rim locations. Filtering out highly degraded craters (degradation state ≤2 in [3]) and crater-matching blunders, agreement between our measurements and measurements in [3] of ellipticity and orientation is good (Figure 3).

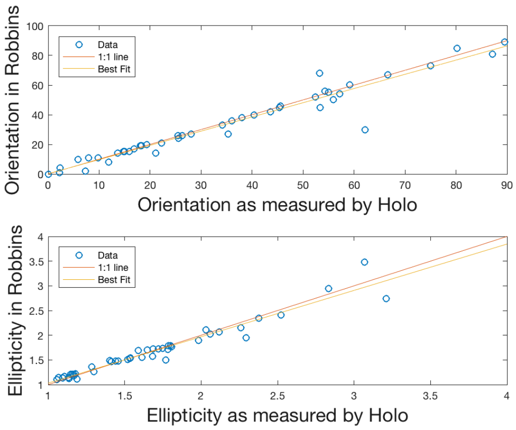

Figure 3. Inter-analyst comparison of ellipticity and orientation measurements. The red lines show a perfect 1:1 correspondence and the yellow lines the best fit linear relationships

Preliminary Model-Data Comparison: Considering fresh craters (degradation state ≥3) with major axis greater than 10km and ellipticities greater than 1.1, we see that most craters are oriented in the North-South direction (Figure 4). This is consistent with a low obliquity in our model predictions. Minimizing the chi-squared statistic between our model distribution and the Robbins distribution indicate a best-fit long-term mean obliquity of ~5^o (Figure 4).

Discussion and Future Work: In our model-data comparison, we included only relatively fresh craters with degradation state ≥3. Degradation state is a proxy for individual crater age, and thus this filter was chosen to remove ancient craters from the target sample. Our estimate of the impactor population on Mars is seeded from modern observations of asteroids and thus cannot be representative of the chaotic early solar system. Recent work in [7] suggests that solar system stabilization occurred ~3.5Gyr ago. We plan to include a more quantitative estimate of crater degradation in future analyses.

The distribution of close encounters are limited to objects with magnitude less than 14, where the cumulative number of objects deviates from a power law (following the method in [8]), to ensure completion of the population. However, if there is an albedo bias with asteroid inclination, we may be biasing the contribution of different inclination groups to the crater record. Comparison with NEOWISE [9] data should allow us to estimate the magnitude of this albedo bias.

Our inter-analyst comparison of ellipticity and orientation showed generally good agreement, which allowed us to take a simple data-cut for our model-data comparison. However, we plan to perform more rigorous tests of the relative contribution of systematic and random error. This will allow us to carefully decide which craters to accept as elliptical.

The current model assumes a single obliquity value for every impact seeded from the close encounters. We hope that with bootstrapping over the dataset we will be able to invert higher-order information about the obliquity probability distribution function.

Preliminary model fits suggest that Mars obliquity since solar system stabilization was often low (Figure 4). At high obliquities (> ~40^o), seasonal melting is more likely to occur, even at low latitudes, while at low obliquities, atmospheric collapse could occur [1,10,11]. Thus, our results may have implications for the frequency and duration of periods during which liquid water was stable at the Martian surface and could potentially produce runoff.

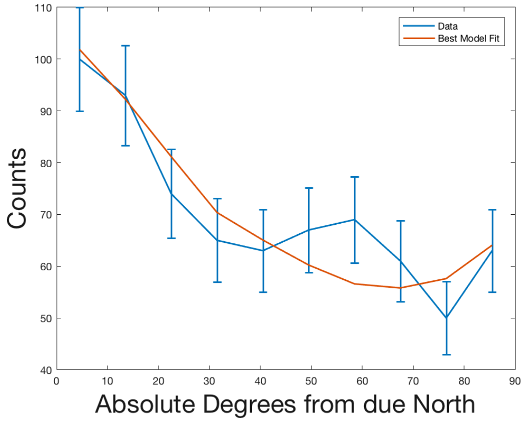

Figure 4. Histogram of elliptic crater orientations for all craters with ellipticity > 1.1, major axis > 10km, and deg ≥ 3. Error bars reflect sqrt(N) shot-noise estimates. Best fit obliquity is 5^o.

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