MARS OBLIQUITY THROUGH DEEP TIME: NEW CONSTRAINTS FROM THE BOMBARDMENT COMPASS. Samuel J. Holo[1] (holo@uchicago.edu), Edwin S. Kite[1], and Stuart J. Robbins[2], [1] University of Chicago, [2] Southwest Research Institute.

Introduction: Mars' obliquity is currently ~25° but has changed dramatically over billions of years since solar system formation [1]. Further, the dynamics of Mars' obliquity are believed to be sensitive to orbital properties that vary chaotically on timescales < 100 Myr [2,3,4]. This provides a fundamental challenge for Martian climate scientists, as obliquity is a strong control on post-Noachian climate [5,6,7,8], but Mars' obliquity should have experienced no more than a few transitions between high and low values [9]. As a result, the effects of chaotic obliquity shifts (such as low-latitude snowmelt at high obliquities > 40°) do not "average out" over Mars' ~3.5 Gyr post-Noachian history. Many geologic methods have been proposed to vault this fundamental barrier of chaotic diffusion of the solar system and its effect on Mars' obliquity [e.g. 10,11,12], but all are indirect. Here, we describe a new direct method for constraining Mars' late-Hesperian-onward historical obliquity PDF (probability density function) using the "bombardment compass" provided by the orientations of elliptic craters [Figure 1, 13]. We showed that Mars' late-Hesperian-onward obliquity was lower than the central expectation in a simulation ensemble.

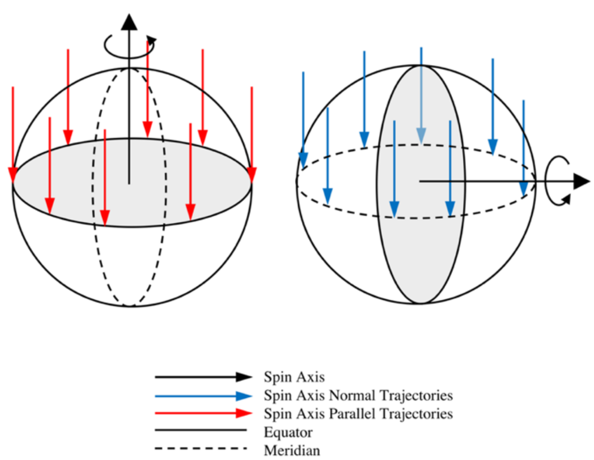

Figure 1. Schematic illustrating the basic principle in our model. Spin axis parallel impactors create N-S elliptic craters near the equator, while spin axis normal impactors produce elliptic craters that are E-W oriented at all latitudes except near the pole. The effects of gravity focusing are not shown here for simplicity.

Modeling Approach: The vast majority of craters on Mars are nearly circular, but impactors with small impact angles relative to the surface produce elliptic craters with major axes aligned with impactor velocity vector [14,15]. As a result, impactors that travel parallel to Mars' spin pole will create North-South oriented craters at the equator, and impactors that travel normal to the spin pole will create elliptic craters at all latitudes that are East-West oriented everywhere except near the pole (Figure 1). As the obliquity changes, the angles between impactors and the spin axis change, causing a change in predicted orientation of elliptic craters.

To simulate this fully, we developed a stochastically-driven forward model for the PDF of elliptic crater orientations on Mars that contains two major components: 1. An ensemble of equally likely Mars 3.5 Gyr obliquity PDF's from perturbed initial conditions [16] and 2. a long-term cratering model that, using a forward N-body simulation of representative Mars crossing asteroids, estimates the locations, sizes and orientations of elliptic impact craters as a function of obliquity. From this, we can generate ensembles of predicted elliptic crater populations under realistic obliquity and impactor conditions. Comparison of our model output with data enabled us to determine the most likely obliquity PDF's.

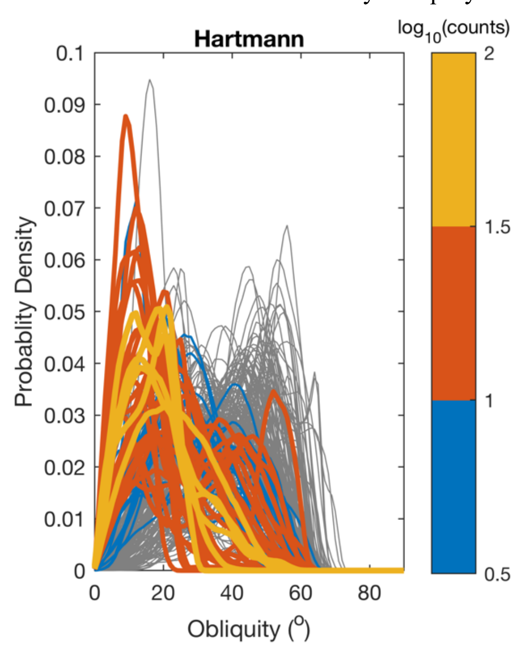

Figure 2. All 250 equally-likely obliquity PDF's in our ensemble, each colored by the number of times it provides the best fit to resampled data (tracks selected <3 times are shown in grey). The effect of chronology choice on these estimates is minimal.

Model-Data Comparison: To compare our model outputs with data, we use a corrected version of the Robbins crater database [17] that contains accurate ellipticity and orientation (long-axis azimuth) measurements. After vetting the dataset for acceptably low inter-analyst variability on ellipticity and orientation measurements [13], we restricted the elliptic crater populations to those found on late-Hesperian and younger terrains as mapped in [18]. We then carried out a Monte Carlo procedure that generates predicted elliptic crater orientation populations and accounts for latitude- and diameter-dependent geographic masking of elliptical craters, as well as uncertainty in the age of each elliptical crater (underlying unit age constrains only maximum age). We compared the generated predictions to the observed data and computed the relative likelihood of each ~3.5 Gyr obliquity PDF from our perturbed ensemble (Figure 2).

We found a few obliquity PDF's were strongly favored and that many never provide a good fit to the observed orientation distribution (Figure 2). Weighting each PDF by their computed likelihoods allows us to construct posterior distributions on parameters like the mean obliquity (Figure 3) and the fraction of time spent at high obliquity (Figure 3).

Conclusions: Our novel elliptic crater "bombardment compass" technique allowed us to determine which possible Mars ~3.5 Gyr obliquity PDF's are most likely to reproduce observed orientation data. We found that obliquity was lower than expected, limiting the potential for (among other things) Amazonian low-latitude snowmelt.

What's Next: The "bombardment compass" technique may have the ability to detect true polar wander by searching for degree-2, order-2 twists in preferred long-axis orientation that cannot be explained by geographic masking alone.

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References: [1] Ward 1973 *Science* [2] Touma+ 1993 *Science* [3] Laskar+ 1993 *Nature* [4] Brasser+ 2011 *Icarus* [5] Jakosky+ 1985 *Nature* [6] Mellon+ 1995 *JGR* [7] Head+ 2003 *Nature* [8] Mischna+ 2013 *JGR* [9] Li+ 2014 *ApJ* [10] Fassett+ 2014 *Geology* [11] Ma+ 2017 *Nature* [12] Kent+ 2018 *PNAS* [13] Holo+ 2018 *EPSL* [14] Bottke+ 2000 *Icarus* [15] Collins+ 2011 *EPSL* [16] Kite+ 2015 *Icarus* [17] Robbins+ 2012 *JGR* [18] Tanaka+ 2014 *USGS Map*.

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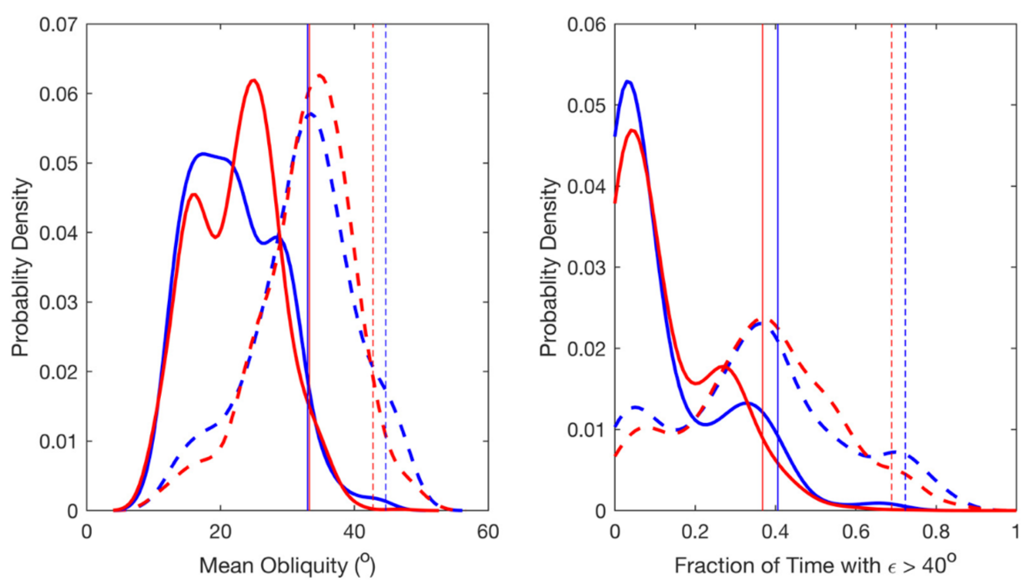

Figure 3. Smoothed prior (dashed) and posterior (solid) PDF's for mean obliquity (left) and fraction of the ~3.5 Gyr history spend at high values (right). Hartmann chronology-based estimates are in blue, and Neukum estimates are in red. Vertical lines represent 95th percentile locations.