EVIDENCE FOR A PRE-CALORIS SYNCHRONOUS ROTATION OF MERCURY.

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Summary. Impact craters should form with a nearly uniform rate across the surface of Mercury as a result of this planet's non-synchronous rotation. In contrast, we find that the distribution of ancient impact basins is decidedly non-uniform, with a dearth of basins being located in the direction of Mercury's intermediate principal moment of inertia. Both the magnitude and direction of this cratering asymmetry are shown to be consistent with Mercury having been in a state of synchronous rotation when the ancient basins formed. The impact event that formed the Caloris basin possesses the conditions required to increase the rotation rate of Mercury beyond synchronous, allowing subsequent capture into the presently observed 3/2 resonance.

Observations. The centers of the 23 recognized multiring impact basins, as determined by analyses of Mariner-10 images [1,2], are plotted in Figure 1 (red circles). The youngest (approximately 3.8 billion years old) and largest basin is Caloris, which is the westernmost basin in this figure. Since the relative age of the basin Beethoven is not known with certainty to be either younger or older than Caloris [1], this basin was not plotted, nor included in our analyses, even though its use would have strengthened our conclusions.

This image demonstrates that there is a clear deficit of ancient multiring basins centered around one of the intersections of the intermediate principal moment of inertia, B, with the surface (A<B<C). Indeed, no multiring basin centers are located within a circle of angular radius 45°, as shown by the dashed white circle. The locations of the seven pre-Calorian craters whose diameters are greater than 250 km (blue) [3] are also plotted, and the combined data set shows a similar lack of basins centered around the B axis. While the high solar incidence angles near the equator at 90° W could make the identification of basins more difficult here than elsewhere, we note that there is no apparent correlation between the number of craters with diameters smaller than 250 km [3] (most of which are probably younger than Caloris) and solar incidence angle.

The spatial distribution of impact basins on Mercury is quantified by assigning a unit vector to each basin and calculating the average resulting vector, **r** (see [4]). The probability that the observed value could have occurred by chance is determined by Monte Carlo simulations. Since the center of the Caloris basin does not lie on the imaged portion of Mercury as seen by Mariner 10, this basin was excluded from the statistical tests. For the case of a uniform cratering rate, we find that there is a probability of only 2.4% for the magnitude of **r** to be as small as observed. The observed value of **r** projected onto a unit vector coincident with the B axis on the Mariner-10 imaged portion of Mercury has a probability of only 4.5% of occurring by chance for a uniform cratering rate. Furthermore, the average angular distance between the observed basins and the B axis has a probability of only 3.1% to be as large as observed for a uniform cratering rate. Statistical tests that include the 7 pre-Calorian basins with diameters greater than 250 km yield similar results. The discovery of 5 or 6 additional basins near the equator at 90° W would be required to obtain the expected values of these statistics for a uniform cratering rate.

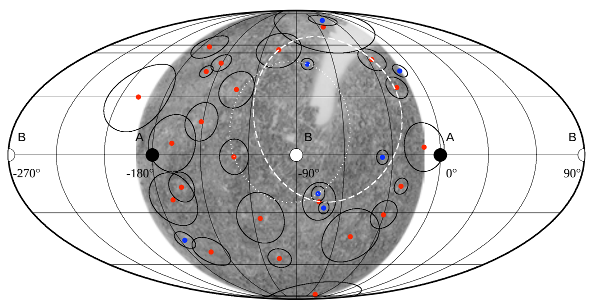

Figure 1. Locations of known impact basins on Mercury that are contemporary to, or older than, Caloris. Solid black and white circles mark the axes of the minimum, A, and intermediate, B, moments of inertia of Mercury, respectively.

Cratering rates on a synchronously locked planet. The trajectories of most asteroids and comets that intersect the orbit of Mercury do so at high angles, and geometric considerations imply that the highest impact rates should occur in the center of the daylit and unilluminated hemispheres. The Earth also exhibits this behavior, as is indicated by the radiants of sporadic meteors [5]. If Mercury was ever in a state of synchronous rotation, the axis of its minimum principal moment of inertia, A, would have been on average directed towards the Sun and the highest impact rates would thus have occurred near the subsolar (here defined as 0° longitude) and antisolar points. We calculate the expected cratering rates as a function of position on the surface of Mercury under the assumption of synchronous rotation. Impact probabilities of the planet-crossing objects with Mercury were first determined, the relative approach velocities and inclinations were then used to determine the impact coordinates on the planet, and scaling laws in the gravity regime were used to convert the distribution of projectile diameters into crater diameters [6]. Calculated cratering rates are plotted in Figure 2 for two different model populations of planet-crossing objects. One population is based on a calibration of orbital simulations to biassed observations [7], whereas the second is that of all known near-Earth objects with absolute magnitudes less than 18 [8].

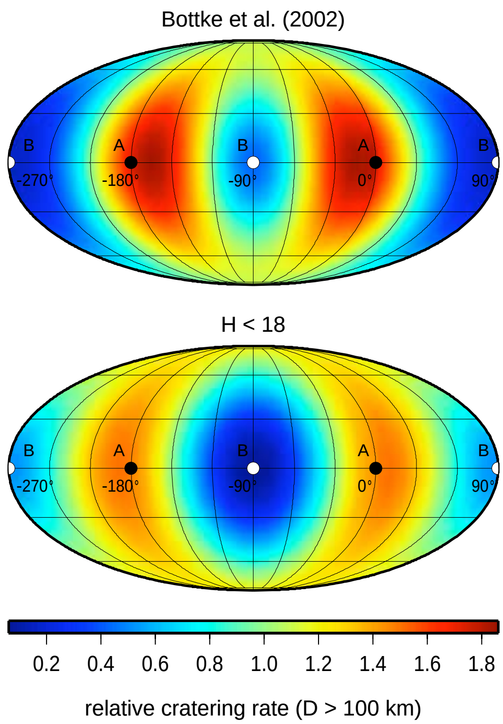

Figure 2. Predicted impact cratering rate normalized to the average value for craters greater than 100 km in diameter using two model populations of the planet-crossing objects. 0° longitude corresponds to the average subsolar point.

The two model populations of planet-crossing objects both predict that the average cratering rate should have varied systematically across the surface by a factor of about ten. The lowest predicted cratering rates are found to be located near the equator at 90° W and 90° E longitude, which is in qualitative agreement with the distribution of ancient basins. The expected distribution of 22 impact basins on the Mariner-10 imaged hemisphere of Mercury, formed from the model cratering rates, is quantified using Monte Carlo modeling. Since the cartographic 0° longitude is defined to coincide with one of the two intersections of the minimum principal moment of inertia with the surface, and since the choice between these two points is arbitrary, we test two cases for each model. In case 1, 0° cartographic longitude coincides with the average subsolar point for synchronous rotation, whereas for case 2, 180° cartographic longitude coincides with this point. We find that while the observed statistics are inconsistent with a spatially uniform cratering rate, all four cases that assume synchronous rotation fit the observations considerably better. Indeed, one case of each model yields results that are nearly identical to the observations.

From synchronous to 3/2. The distribution of ancient impact basins on Mercury is consistent with this planet having been in a state of synchronous rotation up until at least the formation of the Caloris basin, and a mechanism is required to subsequently place Mercury into the presently observed 3/2 spin-orbit resonance. Even though variations in the orbital eccentricity can not destabilize synchronous rotation [9], impulses from large impact events can. One possibility is that an impact event could have imparted enough angular momentum to have instantaneously increased the spin rate beyond that of the 3/2 resonance. Capture could then have occurred as tides reduced the spin rate. A second possibility is that the impulse imparted by an impact event could have unlocked the planet from synchronous rotation [4,10,11] and that the spin rate was then tidally accelerated to the 3/2 resonance whenever the eccentricity remained above the critical value of 0.285 for a few million years [9].

We have calculated that an impact event forming a basin between about 650 and 1100 km would be required to increase the spin rate of Mercury directly from synchronous rotation to that of the 3/2 resonance. With a diameter of about 1550 km, the Caloris basin would have been the last impact event capable of performing such a direct transfer. For the second scenario, we find that an impact event forming a crater with a diameter between about 275 and 450 km would have been sufficient to unlock Mercury from synchronous rotation. However, there are only a few impact basins younger than Caloris that are larger than these diameters, and the impact geometry of about half of these would have acted to decrease the rotation rate of Mercury.

References: [1] P Spudis, J Guest, Mercury, Univ. Arizona Press, 118–164, 1988; [2] P Spudis, The geology of multi-ring impact basins, 1993; [3] USGS, planetarynames.wr.usgs.gov; [4] M Wieczorek, M Le Feuvre, Icarus, in press; [5] M Campbell-Brown, Icarus 196, 144, 2008; [6] M Le Feuvre, M Wieczorek, Icarus 197, 291, 2008; [7] W Bottke et al., Icarus 156, 399, 2002; [8] Lowell Observatory, ftp://ftp.lowell.edu/pub/elgb/astorb.html; [9] A Correia, J Laskar, Nature 429, 848, 2004; [10] HJ Melosh, EPSL, 26, 353, 1975; [11] J Lissauer, JGR, 90, 11289, 1985.