UPPER LIMIT ON A PALEO-EQUATORIAL RIDGE FROM A TIDALLY-DISRUPTED MOON OF MARS. B. Fan [1] and E. S. Kite [2], [1] School of Yuanpei, Peking University, 5 Yiheyuan Road Haidian District, Beijing 100871 PRC (fanbowen@pku.edu.cn) , [2] Department of the Geophysical Sciences, University of Chicago, 5734 South Ellis Avenue, Chicago IL 60637 USA (kite@uchicago.edu).

Introduction: The larger Martian satellite, Phobos, is gradually evolving inwards towards Mars. Evolution studies suggest that in less than 70 Myr, the moon will be tidally torn apart. It was proposed that most of its mass will fall onto the Martian surface, leaving an equatorial ridge of debris [1], while the remaining mass will form a ring and accrete into a new satellite. This process occurs inside the synchronous orbit of Mars, which leads to an ongoing satellite-ring cycle [2] (see Figure 1). Thus, past moon disruption may have occurred and formed ridges.

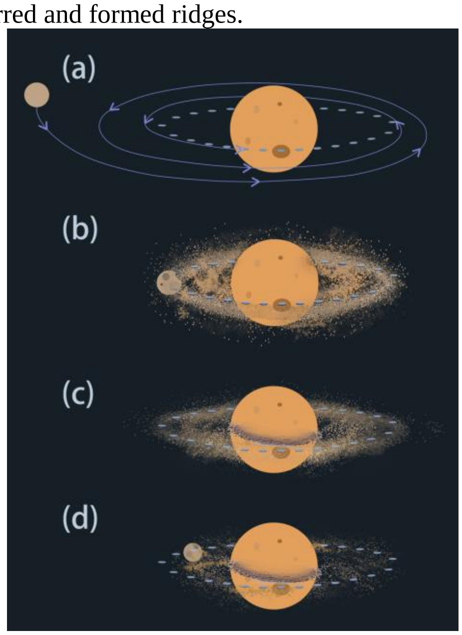

Fig. 1. An ongoing satellite-ring cycle (a) Inward evolution of Phobos (b) Phobos reaches the location of tidal breakup and break apart to form a new ring (c) Most of the ring's mass falls onto the equator, thus forming a ridge (d) The residue accreates into a new satellite.

However, no equatorial ridge-like feature was witnessed on any planets or moons in the solar system except Iapetus [3-4], Saturn's third-largest moon. Here we report our progress on a method to search for equatorial ridge by using Mars and Iapetus topography data and applying it to determine the limits of detection for an equatorial ridge on a terrestrial body like Mars.

Method: Mars and Iapetus topography data were obtained from Mars Orbiter Laser Altimeter (MOLA) and Cassini orbiter [5] separately. For Mars, geological units correspond to Amazonian, early Hesperian, volcanoes and Valles Marineris were masked out [6]. To include cases when the ridge lies on a slope, we detrended the 2D topography by subtracting a matrix derived from averaging data in radius ~2.5° range. Then we fit the 1D zonal mean height from 20° N to 20° S to a diffusion equation for stone ruins [7].

$$h = \frac{h_0}{2x_0}\left(erf\left(\frac{x+x_0}{\sqrt{4\kappa t}}\right) - \mathrm{erf}\left(\frac{x-x_0}{4\kappa t}\right)\right)$$

Where x_0 is the half-width, which was set to 10 km. The key parameters for fitting are initial height h_0 and diffusivity plus time κt. Goodness of fitting ω was defined as the size of fitted ridge over normalized error.

Upper Limit on an Equatorial Ridge: The Martian spin axis may have altered significantly during the past ages [8]. If any part of the predecessor moon had fallen onto Martian surface, then much or most of the debris should be near the paleo-equator. This is because the moon will contain some large-diameter particles that are too large to be easily shifted by the wind. We considered 32310 possibilities for the paleo-equator by multiplying the topography matrix by a rotational matrix, with rotated longitude $\Delta\theta$ ranging from -179° to 180° and rotated latitude $\Delta\varphi$ ranging from 1° to 90°. For each possibility we calculate goodness of fitting for the best fit, and if there was an equatorial ridge, then it would appear as a maximum on the ω-map like Figure 2.

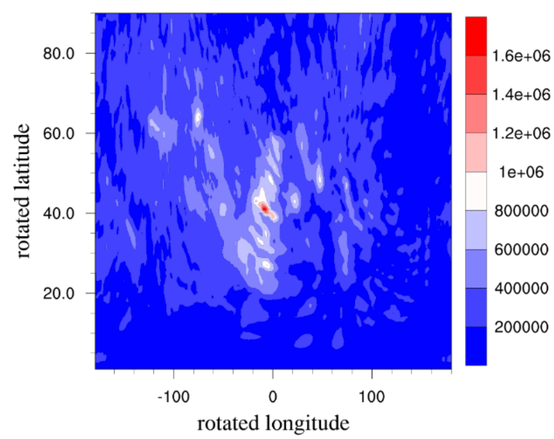

Fig. 2. Goodness of fitting for different paleo-equators. The best candidate for equatorial ridge lies in the central maximum in this map.

However, no ridge was found from the Martian topography. Then we determined our sensitivity limit by adding an equatorial ridge to the real Mars. We considered 2 cases for the equatorial ridge. The first is like real Iapetus, which means the ridge only cover part of the longitude. In this case, the ridge can be mostly covered by lava, and we would never find it. The other is a ridge without longitudinal variation. This is possible because on Iapetus, there was probably no significant atmosphere when the ridge formed, so ring particles would be stopped only by hitting the surface. Because the surface changes during ridge formation, there is the possibility of positive feedbacks leading to longitudinal variation. On Mars however, the atmosphere can stop even quite big particles. This means that the infalling ring particles are not affected by the topography of the growing ridge, so the ridge should be longitudinally uniform. We performed "Mars + N*Iapetus ridge" for both cases with 10 randomly combined topography. As N decreases from a very large number (the ridge is very clear on the map), h_0 corresponding to the best fit of ridge decreases linearly while κt keeps a constant , meaning the fitting only shrink in size. But as N drops under a critical value N_c (~0.2), h_0 begins to decrease nonlinearly and κt rapidly grows to a high value meaning the fitting gradually transforms to a straight line and the ridge is too small to find (selected examples in Figure 3).

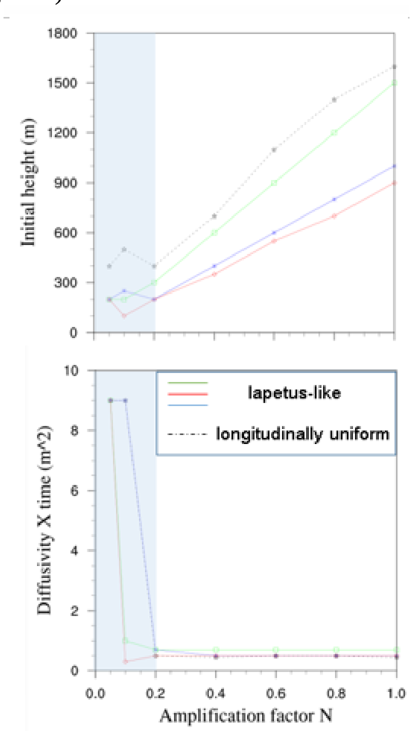

Fig. 3. Initial height and diffusivity-time product corresponding to the best fit (blue areas meaning the ridge can't be detected).

In our study, we define N_c to be the number at which the point corresponding "added ridge" drops out of first 3 maximum areas on ω-map. At $N=N_c$, the ridge is approximately 300m in height and 6° latitude wide, supposing the density of ridge equals 1860 kg/m^3 [1], the mass of ridge should be 5.7 x 10^{17} kg for the Iapetus-like case, or 2.1 x 10^{18} kg for the longitudinally uniform case.

Discussion: There are two factors to influence the order of upper limit of the ridge. The first is ridge type. For Iapetus-like ridge, the more ridge lies in geological young units like Northern lowland or Tharsis Montes, the greater the limit will be, and the harder we are able to find it. For longitudinally uniform case, the ridge can never be hiden, and the upper limit value is relatively stable for different ridge position. The second is the degree of detrending. If we detrend more thoroughly, there will be less information in data. For a detectable ridge, the critical height is 2~3 times the surrounding fluctuation (~100m), which is determined by the detrending disk radius. In most of our results, the radius is 2.5° . If we halve the disk radius, then the surrounding fluctuation will be ~50m, while the upper limit will decrease by a factor of 2. Though there is no strict constrain of the averaged disk size, an appropriate radius should be 1°~10°. A too big disk is ineffective for detrending, while a disk with radius less than 1° can erase the ridge even for real Iapetus.

In conclusion, the flexibility for our upper limit is no more than 1 order of magnitude. So the corresponding upper limit on moon radius should be no more than ~65km, which is 6 times greater than Phobos. Taken in this sense, if a satellite-ring cycle really happened in Martian history, in the manner proposed by [2], there should be a detectable ridge. However, we found noting in Martian topography detrended with disk radius = 1.25°, 2.5°. The possible explanations are (i) the disk radius for detection is too small for Mars topography, (ii) the ridge was totally degraded, (iii) the ridge is not longitudinally uniform, and it was covered by lava, (iv) there wasn't such a satellite-ring cycle as we expected.

Reference: [1] Benjamin A. Black, Tushar Mittal. (2015) *Nature Geoscience* 8(12), 913–917. [2] Andrew J. Hesselbrock, David A. Minton. (2017) *Nature Geoscience* 10(4), 266–269. [3] W.-H. Ip (2006) *Geophysical Research Letters* 33(16), L16203. [4] Andrew J. Dombard et al. (2012) *Journal of Geophysical Research* 117(E3), E03002 [5] P.M. Schenk (2010) *AAS-DPS meeting*, abstract 09.16 [6] Tanaka et al. (2014) *Geologic map of Mars: U.S. Geological Survey Scientific Investigations Map 3292*, scale 1:20,000,000, 43 p., *https://dx.doi.org/10.3133/sim3292*. [7] John Pelletier (2008) *Quantitative Modeling of Earth Surface Process* 2, 45. [8] Isamu Matsuyama et al. (2014) *Annual Review of Earth and Planetary Sciences* 42(1), 605-634.