ASYMMETRIC DISTRIBUTION OF LUNAR IMPACT BASINS CAUSED BY VARIATIONS IN TARGET PROPERTIES. Katarina Miljkovic[1], Mark A. Wieczorek[1], Gareth S. Collins[2], Matthieu Laneuville[1], Gregory A. Neumann[3], H. Jay Melosh[4], Sean C. Solomon[5,6], Roger J. Phillips[7], David E. Smith[8], Maria T. Zuber[8]. [1]Univ. Paris Diderot, Sorbonne Paris Cité, Institut de Physique du Globe de Paris, 75013 Paris, France; [2]Dept. of Earth Sciences and Engineering, Imperial College London, SW7 2AZ, London, United Kingdom; [3]Solar System Exploration Division, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA; [4]Dept. of Earth and Atmospheric Sciences, Purdue University, West Lafayette, IN 47907, USA; [5]Department of Terrestrial Magnetism, Carnegie Institution of Washington, Washington, DC 20015, USA; [6]Lamont-Doherty Earth Observatory, Columbia University, Palisades, NY 10964, USA; [7]Planetary Science Directorate, Southwest Research Institute, Boulder, CO 80302, USA; [8]Dept. of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA 02139-4307, USA (miljkovic@ipgp.fr).

Summary: Crustal thickness maps of the Moon derived from NASA's Gravity Recovery and Interior Laboratory (GRAIL) mission have revealed more large impact basins on the nearside hemisphere of the Moon than on its farside. Numerical hydrocode modeling of the impact process shows that impacts on the hotter nearside hemisphere would have formed basins up to two times larger than similar impacts on the cooler farside hemisphere.

Introduction: The most relevant metric for the size of an impact basin is the diameter of its transient cavity, but this quantity is not easily estimated from surface measurements [1]. Most impact basins on the nearside hemisphere of the Moon have been filled by mare basalt deposits, hiding important morphological evidence of crater size. Other impact basins have multiple rings, and it is unclear which, if any, of these most closely approximates the transient cavity size. An alternative metric for the size of a basin is the diameter of the region of crustal thinning, D [2,3].

High-resolution gravity data obtained from the GRAIL mission [4] have provided global crustal thickness maps of the Moon [5]. Crustal thickness variations are dominated by basins with D>200 km, and these fall in the younger half of the total inventory of lunar basins [6,7]. In terms of age, the sole exception is the farside South Pole-Aitken basin, which is the oldest and largest impact structure on the Moon. We neglect it from further consideration as it formed during an earlier epoch than the other basins with clear crustal thickness signatures.

GRAIL data show that there are 12 basins with D>200 km on each hemisphere of the Moon (Fig. 1). However, when considering only the largest basins, the distribution is highly asymmetric. There are 8 basins on the nearside with D>320 km, but only one of this size (Orientale) is found on the farside, and this basin straddles the lunar limb. Simulations of the Moon's impact bombardment by near-Earth asteroids show that the difference in cratering rate between the near- and farside hemispheres should be less than 1% [6]. With a uniform cratering rate, there is less than a 2% probability that 8 basins with D>320 km would form on the nearside, and only one on the far side.

The Moon displays major geological differences between the near- and farside hemispheres. The lunar nearside is dominated by the compositionally unique Procellarum KREEP Terrane (PKT), which is enriched in heat-producing and incompatible elements [7]. Furthermore, more than 99% of the Moon's basaltic lavas by area are found on the nearside, which is plausibly a consequence at least in part of the high concentration of heat-producing elements found there [8]. Global crustal thickness models also show hemispherical differences, with the farside crust being on average more than 10 km thicker than the nearside [5]. From numerical simulations of the impact process, we show that hemispheric differences in crustal thickness and temperature are the cause of the Moon's asymmetric distribution of large impact basins.

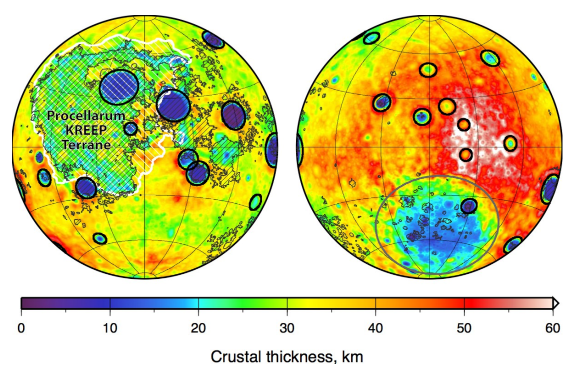

Fig. 1. GRAIL-derived crustal thickness map [5]. The PKT encompasses about 30% of the nearside hemisphere as defined by surface concentrations of thorium (white hatching) [7,9]. Mare basalts are also confined largely to the nearside hemisphere (black hatching). The 12 largest basins on the nearside are considerably larger than 12 largest basins on the farside.

Method: The iSALE-2D [10,11] hydrocode is a multi-material and multi-rheology finite difference shock physics code for simulating impact processes. An infinite halfspace target mesh in 2D was divided into crust and mantle layers, represented by basaltic and dunite rock analogues, respectively. For material parameters, we used equation of state tables generated using ANEOS equation of state and strength and failure models for basalt and dunite [12,13]. The pre-impact crustal thickness was H=30 km (corresponding to the nearside) or H=60 km (corresponding to the farside). Impactors ranged from 15 to 90 km in diameter and the impact speed was 10 km/s or 17 km/s.

The three-dimensional thermo-chemical code GAIA [14] was used to simulate the Moon's thermal evolution under the assumption that a strong concentration of heat-producing elements exists in the PKT. Thermal profiles beneath the cold highlands and hot PKT during the time of basin formation were then used as input to the iSALE impact simulation. The thermal profiles beneath the PKT are considerably hotter (approaching the solidus) than on the farside.

Results: The process of transient cavity collapse into a final basin-size crater is not solely governed by surface gravitational acceleration, but also the yield strength. When shear stresses are larger than the yield strength, the material deforms permanently [1]. The material strength also decreases with increasing temperature. Our results show that the different thermal profiles beneath the near and far side hemispheres have important effects during the crater collapse and modification stages (as observed in [15]). For the same impact conditions, the diameter of the region of crustal thinning in a hot target on the nearside is found to be nearly twice as large as a similar impact on the cooler farside crust (Fig. 2). The effects of crustal thickness variations are smaller than thermal variations but not negligible. The crustal thinning diameter is slightly larger in thinner crusts.

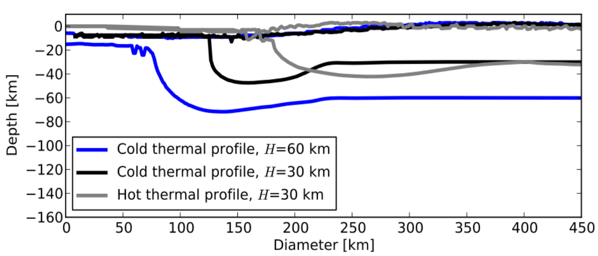

Fig. 2. Final depth of the crust-mantle interface formed by a 45-km-diameter impactor at 17 km/s in a cold and thick crust representative of the farside highlands (blue), a cold and thin crust (black), and a hot and thin crust representative of the nearside PKT (grey).

We ran over 60 iSALE simulations in which we varied impactor size and velocity, crustal thickness, and thermal profile. From these results, a functional dependence between crater diameter D in a cold, thick, farside highlands crust and a hot, thin, nearside PKT crust was determined. From these relations, the sizes of the basins on the nearside were adjusted to give an estimate of their size as if they were to had formed on a target with properties similar to those on the farside (Fig. 3). Once the nearside basins are normalized for the effects of target temperature and crustal thickness, the size distributions of the near- and farside basins are found to be comparable.

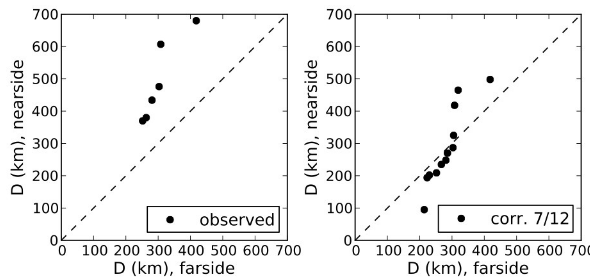

Fig. 3. Diameter of the n^{th} largest basin on the nearside plotted versus the diameter of the n^{th} largest basin on the farside for the 12 largest basins. The observed distribution is offset from the 1:1 line as a result of the larger nearside basin diameters (left). After normalizing the sizes of nearside basins that lie within and close to the PKT to the sizes for a farside target, the distributions are more similar.

Conclusions: The thermal regime of the Moon's nearside hemisphere is highly atypical in comparison to other planetary bodies, and the size distribution of impact basins found there is thus not representative of either the Moon as a whole or the other planets in general. The concept of a late heavy bombardment [16, 17] is based on the ages of nearside impact basins that are either within or adjacent to the PKT. The magnitude of the impact bombardment at that time has thus likely been overestimated. Studies of the early impact flux in the inner solar system that are based on the record of lunar basins may warrant revision.

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