COMPELLING SCIENCE ENABLED BY GRAVITY INVESTIGATIONS AT MARS.

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Introduction: Geodesy is a powerful way to investigate a planet's formation, evolution, interior structure, and active processes. The power of geodesy is best demonstrated in the Earth-Moon system, where spacecraft missions like GRACE, LRO, and GRAIL have transformed geodesy from a purely geophysical tool into one that unlocks advances in geology, hydrology, climate change, and more. However, while geodetic measurements have flourished at the Earth and Moon, planetary geodesy has lagged behind (Fig. 1).

To address this issue, we are conducting a Keck Institute for Space Studies (KISS) study program [1] that identifies the transformative science that would be enabled by next-generation geodesy at other planetary bodies and the mission architectures needed to achieve that science. At the time of this writing, we have held one workshop focused on developing the most important scientific questions that could be addressed with geodesy beyond the Earth-Moon system. A second technology-focused workshop will be held in November 2021. Our study program discusses Mars, Venus, and Ocean Worlds and considers a variety of potential orbital, aerial, and landed assets.

Here, we focus on a subset of our study program that is relevant for this workshop: gravity science at Mars. Our group has identified a wealth of scientific questions that can be realistically addressed with this method if new geodetic data is acquired. In particular, we identified compelling science under two broad themes: climate and geodynamics. Below, we summarize the current state of gravity science from Mars, describe the compelling science under both themes that could be achieved with new gravity data at Mars, and discuss plausible mission architectures to obtain such data.

Current data: Our present knowledge of the Martian gravity field comes from Doppler tracking of individual orbital spacecraft, including the Mars Reconnaissance Orbiter, Mars Odyssey, and Mars Global Surveyor [2, 3]. The currently known gravity field has laterally variable uncertainty. It is accurate up to spherical harmonic degree ≈80 in the northern mid-latitudes and up to degree ≈100 at the south pole [2]. This field has proven valuable in, for example, inferring broad crustal thickness maps under assumptions of uniform density [4] or constraining the density of large polar deposits [5, 6]. However, the resolution and precision of the current field does not allow for many valuable analyses that could be done at Mars with realistically attainable gravity data. Below, we describe examples of such scientific investigations that address two broad questions: (1) What is the geodynamical history of Mars, and how and why does it differ from Earth's? (2) How do planetary climates respond to orbital forcing? This list is not exhaustive.

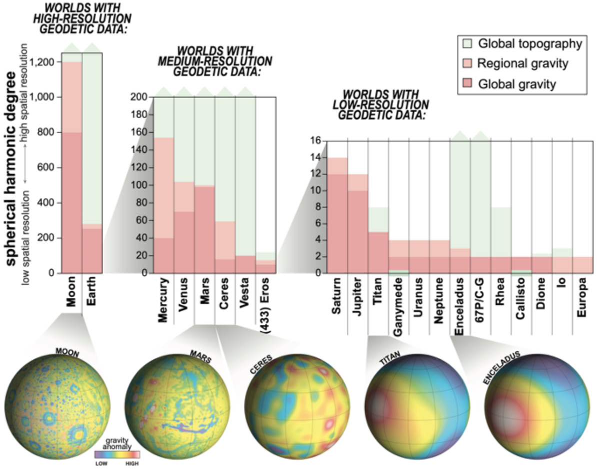

Figure 1: Current knowledge of gravity and topography across the Solar System from remote sensing spacecraft. Resolution in terms of the maximum spherical harmonic degree derived where signal is greater than uncertainty. Note change in vertical axis scale between the three plots.

Geodynamics: The global north-south dichotomy in topography, geology, and other datasets is the largest and most fundamental geophysical feature of Mars. Despite its profound importance in controlling planetary evolution, there is no consensus in how the dichotomy was formed [7]. Hypotheses for dichotomy formation include endogenic [e.g., 8, 9] and exogenic [e.g., 10, 11] processes, and combinations thereof [12]. A crustal thickness map derived under an assumption of uniform density shows global asymmetry [4]; a critical factor in testing dichotomy origin hypotheses is determining whether an asymmetry in crustal density instead is viable [13, 14]. A confident distinction between these possibilities is not currently possible, but would be if global gravity data were sufficiently precise to map Mars' crustal density independent of complicating effects from relief along the crust-mantle interface, as was done at the Moon with GRAIL data [15].

The Martian lithosphere records the history of the geodynamics of the planet. The history of the tectonic regime is debated [e.g., 16], and is inferred indirectly from, e.g., magmatic history [17]. Sufficiently precise gravity data would directly address this topic allowing for constraint of Mars' effective elastic thickness [e.g., 18]. New gravity data would be especially useful in determining elastic thickness at the time of loading of small-wavelength features and thus allow for reconstruction of the planet's thermal history.

A better understanding of Mars' thermal evolution and north-south dichotomy origin will also provide insights into the planet's magnetic field history and mechanisms of core dynamics [19]. Geodetic observations may additionally produce independent estimates of core size and composition that would complement those derived by the InSight mission [20].

Climate: On Earth, gravity has proved to be one of the most valuable datasets in study of climate. On Mars, this theme can only be touched on with current data, such as constraining density of polar deposits [5] or detecting seasonal volatile cycles [2]. A higher resolution static gravity field would allow for testing of the total water volumes present in the mid-latitudes, especially in areas where ice content is currently debated like Arcadia Planitia [21, 22] or the Medusa Fossae Formation [22, 23]. This investigation would have critical implications for human exploration [24].

A powerful dataset in studying Martian climate would be time-variable gravity. Time-variable gravity has allowed observation of ice sheet mass balance, hydrological cycles, and sea level change on Earth [25]. On Mars, data with sufficient precision and time baseline could be used analogously. Gravitational monitoring over multiple years could study sources and sinks of H_2O and CO_2, including quantifying interannual changes in polar cap mass balance and volatile loss from the planet. The dust cycle can also be studied; hypotheses on the initiation, evolution, and decay of dust storms can be tested, likely by observing the gravitational signature of related atmospheric effects rather than the direct mass of lofted dust.

Paths Forward: In November 2021, we are holding a KISS workshop with focus on identifying the mission architectures that could enable the gravity science described above. We are studying concepts that include spacecraft-to-spacecraft tracking, orbital gradiometry, small single spacecraft equipped with geodetic quality accelerometers (SmallSats), and regional gravimetry from aerial vehicles. At the Low-Cost Science Mission Concepts for Mars Exploration workshop, we will report the results of our November workshop. We will focus our report on identifying which of these architectures hold promise for compelling science return on the themes of geodynamics and/or climate at a cost of ~$300 million or less.

Next-generation geodesy at Mars may be accomplishable at low costs. While not all geodetic measurements or investigations are feasible at low costs, a certain subset is. For example, gravity science could be accomplished by Doppler measurements between small (potentially CubeSat class) radio beacons. These spacecraft could be placed on low-altitude orbits to fill in key data gaps that address some of the motivating science questions outlined above.

Low-cost geodesy is demonstrated by NASA's past missions, like GRAIL and LRO. GRAIL, a two-spacecraft geodesy mission to the Moon [26], has been the lowest-cost Discovery mission of the past 15 years (Phase A–E cost: ~$300M; with launch vehicle: $450M, for the primary phase)—far less than the cost of modern Discovery missions (e.g., Lucy, Psyche) [27].

Conclusion: Elevating gravity science at Mars to a level similar to that achieved in the Earth-Moon system will enable compelling research to address outstanding questions in Martian geodynamics and climate. Some subset of this science may be possible with relatively low-cost missions.

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