MARS CRUSTAL MAGNETISM: LESSONS LEARNED FROM ORBIT AND ON THE GROUND.

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Overview: After several Mars flybys by the Mariner spacecraft in the 1960s, Mars Global Surveyor (MGS) was the first spacecraft to orbit Mars equipped with a magnetometer. It enabled the discovery of crustal magnetic fields that result from rocks magnetized in an ancient dynamo field [1]. MGS was in orbit from 1997-2006 providing the starting point for crustal field studies. The crustal magnetization was acquired at the time of a core dynamo, either by cooling of intruded or extruded igneous rocks (thermal remanence), chemical alteration induced by water, or possibly shock effects (impacts). Thus, Mars’s magnetic field provides a window into the planet’s interior and evolution, allowing us to address questions regarding the characteristics and distribution of magnetic carriers, and the evolution and timing of the ancient dynamo field.

Currently operating missions have provided additional magnetic field information from orbit and, for the first time, the surface. With the arrival of the Mars Atmosphere and Volatile EvolutioN spacecraft (MAVEN) in 2014 [2], MGS data have been supplemented by new orbital measurements. InSight landed in November 2018 and the InSight Fluxgate (IGF) magnetometer represents the first magnetic observatory on the surface of a planet other than the Earth [3].

Here we provide a short overview of advances made in mapping the martian crustal magnetic field since 2014. We highlight some of the new crustal field information from orbital data and review recent local and global crustal field modeling efforts. We discuss the crustal field observed at the surface and compare those observations with orbit-based predictions.

Orbit-Derived Crustal Field Information: MGS and MAVEN magnetometer measurements provide the basis for what we have learned about global magnetism on Mars. Because MGS spent almost 7 years at 400 km in a 2 am / pm orbit, the multiple repeat measurements allow for an excellent description of the crustal field at that altitude. Lower altitude measurements providing smaller wavelength information were sparse and mostly collected during the day-time. These are non-ideal for crustal field modeling because external fields of ionospheric and interplanetary magnetic field origin are substantial on the dayside [4,5]. MAVEN’s elliptical orbit with a nominal periapsis at ~135 km and some even lower (~110 km) altitude measurements during nine ~5 day deep dip campaigns, provides dense night-time coverage below 400 km and therefore complements the MGS data set.

Additional signal in the data: Figure 1 highlights some of the additional signal as compared with the MGS data, especially small wavelengths that are better resolved at lower altitudes. Most can be found in the areas of strong magnetizations, Terra Cimmeria and Terra Sirenum, but also in other locations such as Arabia Terra or the northern hemisphere. We note that additional low altitude MAVEN data down to ~120 km from the aerobreaking campaign in spring 2019 provides excellent coverage particularly around the equator and in the southern hemisphere; this is in addition to what is shown in Figure 1.

Small wavelengths and therefore higher resolution globally is an important contribution when comparing geological surface features with magnetic signatures. Past studies have relied on the best possible resolution available at the time to analyze the magnetic field e.g., associated with impact craters [6,7] or volcanoes [8,9]. The age of magnetized features can constrain the timing and longevity of the ancient dynamo.

Crustal Magnetic Field Models: Crustal magnetic field models are a useful tool that allow data from different altitudes and locations to be consolidated to predict the field at specific altitudes including the surface. MGS-based models such as the one shown in Fig. 1a [10] and others e.g., 11,12 were mainly based on 400 km altitude data. Lower altitude day-time observations were partially available, but despite careful selection or weighting of data, clear identification and treatment of external field signals in these low altitude observations remains challenging. The inclusion of low altitude MAVEN night-time data and the development of solar activity proxies to identify quiet data have enabled a new generation of high-fidelity local [13,15] and global [14,15] crustal field models. Local field models have been a useful tool to model the InSight Landing Site [13] and to aid in the selection of the Mars 2020 Landing Site [16]. A new generation of
global models is also underway. For example, a companion paper [17] describes one such model using Equivalent Source Dipoles, a further model using spherical harmonics is being developed based on [10].

Orbital measurements and resulting crustal field models provide a comprehensive picture of the global magnetic field, although currently limited to wavelengths greater than ~120 km. Magnetic fields of smaller spatial wavelengths superposed on such regional scale fields might lead to actual surface fields of stronger or weaker amplitude.

**Surface Measurements:** Since December 2018, the IFG instrument on InSight has been returning magnetic field data taken on the martian surface. Because no dedicated magnetic cleanliness program was employed, the measurements contain signals of both martian and spacecraft origins. However, multiple ways of getting an estimate of the crustal magnetic field at the Landing Site are suggested in a companion abstract [18].

A preliminary comparison of orbital and surface data indicates larger amplitudes at the surface compared with model predictions. If the signal is indeed of crustal origin, it suggests contributions from wavelengths <~100 km.

**Conclusion:** Recent advances in the understanding of planetary magnetism has been greatly aided by the science return of the magnetometers on MAVEN and InSight. Concurrent measurements in orbit and at the surface allow for refinement of our understanding of crustal magnetism as well as external magnetic fields including ionospheric signals. Such time-varying fields provide foundation for magnetic sounding of the planetary interior [18]. The return of martian samples to Earth, the next major step towards understanding martian crustal evolution and magnetism, is envisioned for future missions including Mars 2020 and a follow-on sample retrieval mission.


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**Fig. 1:** (a) The crustal field model after [10] predicted at 400 km with the star indicating the InSight Landing Site. The B\textsubscript{r} difference of this crustal magnetic field model and MAVEN night-time data up to November 2018 (data-model) for altitudes of (b) ~400 km and (c) ~150 km.