The Density, Porosity, and Magnetic Susceptibility of Martian Meteorites as Constraints on Gravity Models

Walter S. Kiefer[1], Robert J. Macke[2], Daniel T. Britt[3], Anthony J. Irving[4], and Guy J. Consolmagno[2], [1]Lunar and Planetary Institute, 3600 Bay Area Blvd., Houston TX 77058, kiefer@lpi.usra.edu , [2]Vatican Observatory, V-00120 Vatican City State, [3]Dept. of Physics, University of Central Florida, Orlando FL, [4]Dept. of Earth and Space Sciences, University of Washington, Seattle WA.

Introduction

Gravity observations currently provide our primary tool for understanding lateral variability in the structure of the crust and mantle of Mars. Accurate gravity models require the use of densities and porosities for geologically appropriate compositions. On the Moon, a compilation of density and porosity measurements of both Apollo samples and lunar meteorites [1] has been an important contribution to recent studies of lunar gravity data [2, 3]. In a similar manner, previous studies of martian meteorites [4-6] have contributed to gravity modeling of volcanos and the global crustal structure of Mars [7, 8]. In this work, we report recent measurements of the density, porosity, and magnetic susceptibility of seven martian meteorites, made in the NASA Johnson Space Center Antarctic Meteorite Lab and at the Vatican Observatory. These samples include the first ever physical properties measurements of three classes of martian meteorites: orthopyroxenites, poikolitic shergottites, and mafic regolith breccias. The expanded density and porosity data set will improve our ability to develop future gravity models of martian volcanic and tectonic features and of crustal structure.

Methods

We measured both the bulk density, ρ_{bulk}, and the grain density, ρ_{grain}. The bulk density is based on the entire volume of the sample, including any pore space. The grain density is based solely on the solid material, excluding the pore space. Bulk density is important for calculation of gravity anomalies, and grain density is used for studying systematic trends in density as a function of rock composition. Porosity is calculated as $P=1- (\rho_{bulk} / \rho_{grain})$. Bulk volume is measured by immersion in glass beads, approximating an Archimedean fluid. Grain volume is measured by ideal gas pycnometry [9-11]. These measurements are fast, non-destructive and non-contaminating. Errors are determined by repeated measurements of each sample and are typically 10-20 kg m^{-3} (< 0.6%) for grain density provided that the sample mass exceeds 10 gm. The plagioclase that was originally present in these rocks has typically been converted to maskelynite due to shock. However, the grain densities of anorthite and maskelynite are similar, resulting in little change to the overall meteorite density. Due to equipment difficulty with the pycnometer, we were not able to measure grain densities of the Antarctic meteorite samples at the Johnson Space Center in October 2013. We plan to complete these measurements in spring 2014. Until these data are available, we use the normative mineral density (as discussed in [1]) as a proxy for the grain density in order to estimate the porosity of these samples.

We measured magnetic susceptibility with a ZH-Instruments SM-30 meter and the volumetric correction of [12]. The susceptibility results are reported in log units and provide a rapid means of assessing the presence of phases such as magnetite or metal [13].

Results: Orthopyroxenite ALH 84001

Allan Hills (ALH) 84001 is an igneous cumulate rock with ~95% orthopyroxene. Due to its age of more than 4 Ga [14], it has experienced an extensive deformation history, including at least four shock metamorphic events, a period of thermal metamorphism, and low-temperature chemical alteration [15].

Sample 84001,55 (11.86 gm) has a measured bulk density of 3080±70 kg m^{-3}. The normative mineral density of 3390 kg m^{-3} leads to an estimated porosity of 9.1 %. The magnetic susceptibility is 2.54±0.08. These are the first reported physical properties measurements for this unique martian sample.

Poikolitic Shergottites

The poikolitic shergottites (formerly lherzolititic shergottites [16, 17]) contain large pyroxene crystals, possibly implying slow cooling at depth, and their textures may be consistent with formation in a buried magma chamber. Thus, they are potential analogs for the high density material that produces gravity anomalies at martian volcanos such as Syrtis Major, Apollinaris Patera, and Tyrrhena Patera [7].

We measured two poikolitic shergottites, ALH 77005 and Roberts Massif (RBT) 04261 [18, 19]. Both samples consist primarily of olivine, pyroxene and maskelynite, but differ in the relative mineral proportions. ALH 77005 is relatively richer in olivine and depleted in maskelynite relative to RBT 04261. ALH 77005,1 (14.2 gm) has a bulk density of 3050±60 kg m^{-3}, an inferred porosity of 10.6%, and a magnetic susceptibility of 3.54±0.08. RBT 04261,13 (7.0 gm) has a bulk density of 3080±140 kg m^{-3}, an inferred porosity of 9.1%, and a magnetic susceptibility of 2.87±0.08. These results are the first density and porosity measurements for poikolitic shergottites.

Olivine-phyric Shergottite EET 79001

Olivine-phyric shergottites consist primarily of coarse grained olivine and orthopyroxene, set in a matrix of fine grained pigeonite and maskelynite [20]. The known olivine-phyric shergottites show significant variations in the relative abundances of olivine and pyroxene, which is likely related to addition of variable amounts of cumulate olivine during crystallization [21]. From the perspective of gravity modeling, these variations in composition correspond to potential differences in density, so it is desirable to measure densities for the full range of compositions.

Elephant Moraine (EET) 79001 includes several distinct lithologies. Our sample is from Lithology A, the olivine-phyric part of the meteorite. EET 79001,299 (12.6 gm) has a bulk density of 2940±60 kg m^{-3}, an inferred porosity of 11.4 %, and a magnetic susceptibility of 2.59±0.09.

Nakhlite MIL 090032

Miller Range (MIL) 090032 is paired with MIL 03346, a nakhlite that consists primarily of cumulus clinopyroxene [22]. Prior measurements of the type specimen, Nakhla [6], were used as a modeling constraint in a gravity model of the Syrtis Major volcano [7]. MIL 090032,46 (12.1 gm) has a bulk density of 2980±60 kg m^{-3}, an inferred porosity of 10.8 %, and a magnetic susceptibility of 3.75±0.09. These results are consistent with previously reported values [5, 13].

Breccia

Northwest Africa (NWA) 7034 and paired samples are complex regolithic breccias, consisting primarily of clasts of hypabyssal igneous lithologies, feldspars, pyroxene, and magnetite [23-25]. The high concentrations of meteoritic siderophiles suggest formation as a regolith breccia [24].

We measured 3 stones totaling 810 gm that we judge to be paired with NWA 7034. The grain density is 3160±20 kg m^{-3}, the bulk density is 2900±40 kg m^{-3}, the porosity is 7.4±1.5%, and the magnetic susceptibility is 4.43 ±0.08. These are the first reported physical properties measurements for this unique martian sample.

Basaltic Shergottite

Basaltic shergottites have a broad range of mineral compositions and Mg-numbers, both of which can result in significant variability in density. It is important to measure samples that reflect the full range of compositions and thus densities; at present, only three such samples have been measured [5].

NWA 6963 is a basaltic shergottite consisting of about 60% pyroxene and 35% maskelynite [26]. This pyroxene content is in the mid-range of the measured basaltic shergottites. We measured a grain density of 3400±10 kg m^{-3} and a magnetic susceptibility of 3.21±0.08 on a 435 gm paired stone found in the same strewn field as NWA 6963.

Comparison with Lunar Basalts

The porosities inferred here, 7.4-11.4 %, are somewhat larger than those measured for lunar mare basalts (2-10%, [1, 27]). This may reflect the higher specific energy that is required to eject material from the martian surface, where the surface gravitational acceleration is 2.3 times the lunar value. The range of magnetic susceptibilities, 2.54-4.43, is larger than the typical lunar basalt range of 2.7-3.2, although one lunar basalt with metallic iron has a magnetic susceptibility of 3.94 [28]. The high magnetic susceptibility of the breccias is consistent with the high abundance of magnetite and maghemite [23-25].

Acknowledgements: This work was supported by NASA grant NNX12AH93G.

References [1] Kiefer et al., *Geophys. Res. Lett.* 39, 2012GL051319, 2012. [2] Wieczorek et al., *Science* 339, 671-675, 2013. [3] Kiefer, *JGR Planets* 118, 733-745, 2013. [4] Britt and Consolmagno, *Meteoritics Planet. Sci.* 38, 1161-1180, 2003. [5] Macke et al., *Meteoritics Planet. Sci.* 46, 311-326, 2011. [6] Britt et al., *Met. Soc.* 75, abstract 5250, 2012. [7] Kiefer, *Earth Planet. Sci. Lett.* 222, 349-361, 2004. [8] Neumann et al., *JGR Planets* 109, 2004JE002262, 2004. [9] Consolmagno et al., *Chemie der Erde* 68, 1-29, 2008. [10] Macke et al., *Planet. Space Sci.* 58, 421-426, 2010. [11] Macke et al., *LPSC* 43, abstract 1398, 2013. [12] Gattacceca et al., *Geophys. J. Int.* 158, 42-49, 2004. [13] Rochette et al., *Meteoritics Planet. Sci.* 44, 405-427, 2009. [14] Lapen et al., *Science* 328, 347-351, 2010. [15] Treiman, *Meteoritics Planet. Sci.* 33, 753-764, 1998. [16] Nyquist et al., *Geochim. Cosmochim. Acta* 73, 4288-4309, 2009. [17] Walton et al., *Meteoritics Planet. Sci.* 47, 1449-1474, 2012. [18] McSween et al., *Earth Planet Sci. Lett.* 45, 275-284, 1979. [19] Usui et al., *Geochim. Cosmochim. Acta* 74, 7283-7306, 2010. [20] Goodrich , *Geochim. Cosmochim. Acta* 67, 3735-3771, 2003. [21] Filiberto and Dasgupta, *Earth Planet. Sci. Lett.* 304, 527-537, 2011. [22] Day et al., *Meteoritics Planet Sci.* 41, 581-606, 2006. [23]Agee et al., *Science* 339, 780-785, 2013. [24] Humayan et al., *Nature* 503, 513-516, 2013. [25] Wittmann et al., *Met. Soc.* 76, abstract 5272, 2013. [26] Wilson et al., *LPSC* 43, abstract 1696, 2012. [27] Kiefer et al., *LPSC* 43, abstract 1642, 2012. [28] Macke et al., *LPSC* 45, this conference.