THE DENSITY / POROSITY OF ASTEROIDS. D.T. Britt[1], D.A. Kring[1], and J.F. Bell[2]. [1]Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ, 85721. [2]PGD/SOEST, University of Hawaii, Honolulu, HI 96822.

The discovery of Ida's companion Dactyl and the derivation of a density range for Ida from Dactyl's orbital parameters has stimulated much discussion on the density and porosity of asteroidal material. However, too often the discussions have floundered on hazy definitions of the terms and a lack of data on the ranges of densities/porosities found in meteorites, regoliths, and terrestrial materials. To further this discussion we will review the definitions for the critical terms, the density ranges of meteorite types, and the available data on porosity of common geological materials and meteorites before discussing the implications of density measurements of asteroids.

Definitions:.

Bulk Density **(ρ_b):** The mass of an object divided by its volume, including the volume of its pore spaces [1,2]. This is typically measured after drying in an oven at 105°C.

$$\rho_b = M_g / V_b$$

Grain Density **(ρ_g):** The mass of an object divided by the volume occupied by the mineral grains, excluding the volume of its pore spaces [2]. This is the average density of the solid portions of a rock and in the case of most of the measurements presented below, is determined using a gas-pycnometer.

$$\rho_g = M_g / V_g$$

Porosity **(η_t):** The percentage of the bulk volume of a rock that is occupied by interstices, whether isolated or connected [1,2]. Note that porosity can never be greater than 100%.

$$\eta_t = (1 - \rho_b / \rho_g) \times 100$$

Density / Porosity of Geological Materials and Meteorites: Shown in **Table 1** are the density ranges in g/cm^3 for the meteorite types from Wasson [3], except for the mesosiderite data which is from Buchwald [4]. In terms of the above definitions these should be taken as "grain density". There are only a limited number of meteoritic porosity measurements in the literature and we have listed those available in **Table 2** along with the porosity ranges for geologic materials of interest [2,3,5,6,7,8,9]. The Antarctic meteorites listed in **Table 2** were selected for their fresh appearance, lack of weathering rust, and lack of apparent large cracks to minimize the influence of secondary terrestrial weathering effects on density [6,7,8,9].

Discussion: From the data in **Table 2** it is clear that meteorites can have porosities up to 20-25%. This is well within the range of other types of coherent rock such as terrestrial sandstones that can maintain porosities of up to 30% under lithostatic pressures much greater than those attainable on asteroids. However, this does not define the range of possible asteroidal porosities. Meteorites are probably subject to strong selection factors that exclude both the weak porous material that cannot survive passage to the Earth's surface, and the stronger metal rich material that cannot be easily broken off their parent bodies for the trip to a Natural History Museum. Our sample of meteoritic porosities is probably limited largely to rocky material of moderate strength and almost certainly excludes materials of large porosities. From the lunar experience and impact modeling we should expect that many asteroids should have a low density regolith soil (lunar soil has porosities up to 45%) and a kilometers thick megaregolith with significant fracturing. Since meteorites would tend to break along lines of fractures and voids, measurements of meteoritic porosity miss a major source of asteroidal porosity, the large-scale fractures and voids produced by impacts into the megaregolith. There are surface features that have been interpreted as fracturing visible in the images of Phobos and Ida. The amount of impact-produced porosity that can be accommodated by a still-coherent body is unknown, but it is clear that some significant amount can be added to the small scale porosity seen in meteorites.

The density measurements of small bodies themselves point to a significant portion of pore space. The density of Phobos is now well known from the Russian Phobos mission and at 1.905 g/cm^3 is substantially less dense than the least dense meteorite. This bulk density would require porosities of 15% for a CI composition, 31% for a CM composition, or 45% for a CV/CO composition. For Ida, the range of densities suggested by the limits on the orbital parameters of Dactyl is 2.2 to 2.8 g/cm^3. If Ida is of ordinary chondrite composition, it would take porosities of between 15-42% to match the range of grain densities found in ordinary chondrites. In both cases the porosity range of the object is equal to or greatly exceeding the average porosity of the possible meteorite analogues. This suggests that meteoritic porosities should be treated as lower bounds for asteroidal porosities. In

DENSITY OF ASTEROIDS: Britt D.T. et al.

addition, this cautions against using bulk density as a diagnostic parameter for the interpretation of asteroidal mineralogy. In the case of Ida other possible meteoritic analogues such as lodranites, acapulcoites, and primitive achondrites have roughly the same grain density as ordinary chondrites. In the extreme case a pallasite with a grain density of 4.3 g/cm^3 would require only 35% porosity to fall into the upper bound of Ida's density range. The only density value that would be somewhat diagnostic is one that puts an asteroid out of the range of chondrites of low porosity, such as a density of >4 g/cm^3. This value suggests a greater than chondritic metal fraction which would imply significant melting and differentiation. Our conclusion is that because of large unknowns in the porosity of rocky asteroids, density by itself cannot be a diagnostic parameter of asteroidal mineralogy.

Table 1

Group	Density	Group	Density	Group	Density	Group	Density
E4	3.6-3.8	LL	3.4-3.5	Aub	3.2	How	3.2-3.3
E6	3.5-3.7	CV/CO	3.3-3.6	Dio	3.3-3.4	Mes	4.85
H	3.6-3.8	CM	2.6-2.9	Ure	ca. 3.3	Pal	4.3-5.8
L	3.5-3.6	CI	2.2-2.3	Euc	3.1-3.2	IIA, IIIA	7.8-8.0

Table 2

Item	Bulk Density	Grain Density	Porosity %	Item	Bulk Density	Grain Density	Porosity %
Basalt	2.75		1	Y-74191 (L3)	3.23	3.6	10.3
Sandstone	2.1-2.5		5-30	Krymka (L3)			6.7
Shale	1.9-2.4		7-25	Barrata (L4)			0.7
Basaltic Pumice (Scoria)			up to 95	Saratov (L4)			18.3
Lunar Soil	0.9-1.1		45	Bjurbole (L4)			16.7
Phobos	1.905 ±0.053		?	Y-75097 (L4)	3.28	3.65	10.1
Olivine		3.27-4.37		Arapahoe (L5)	3.52	3.61	2.5
Mokoia (CM)			24.2	Elenovka (L5)			10.5
Allende (CV3)	2.75	3.43	19.8	Farmington (L5)	3.4	3.59	5.3
Monroe (H4)	3.58	3.8	5.8	ALH-78103 (L6)	3.23	3.73	13.4
Forest Vale (H4)			18.1	ALH-78251 (L6)	3.33	3.73	13.2
Y-74156 (H4)	3.45	3.8	9.2	MET-78003 (L6)	3.33	3.61	7.8
Y-74647 (H4-5)	3.49	3.83	8.9	Mount Browne (L6)			6.8
ALH-77294 (H5)	3.35	3.84	13.8	ALH-77231 (L6)	3.07	3.58	14.2
ALH-77288 (H5)	3.69	3.77	2.1	Kunashak (L6)	3.41	3.59	5
Wellman (H5)	3.58	3.82	6.3	Bruderheim (l6)	3.31	3.6	8.1
Gilgoin Station (H5)	3.61	3.81	5.2	New Concord (L6)	3.27	3.6	9.2
Zhovtnevyi (H5)			13.1	Leedey (L6)	3.25	3.63	10.5
Gladstone (H6)	3.56	3.75	5.1	Cumberland Falls (Aub)			4.3
Stannern (Euc)			14.8	Pesyanoe (Aub)			15.1

References: [1] Bates R.L. and Jackson J.A. eds (1987) *Glossary of Geology*. [2] Johnson G.R. and Olhoeft G.R. (1988) In: Carmichael R.S. ed, *CRC Handbook of Physical Properties of Rocks*, Vol. III, Ch1. [3] Wasson J.T. (1974) *Meteorites*. [4] Buchwald V.F. (1975) *Handbook of Iron Meteorites*. [5] Parker S.P. ed (1991) *McGraw-Hill Encyclopedia of the Geological Sciences* 2nd Ed. [6] Hamano Y. and Yomogida K. (1982) *Proc. 7th Symp. Antartic Met.*, 281. [7] Yomogida K. and Matsui T. (1981) *Proc. 6th Symp. Antartic Met.*, 384. [8] Yomogida K. and Matsui T. (1982) *Proc. 7th Symp. Antartic Met.*, 308. [9] Yomogida K. and Matsui T. (1983) *JGR 88*, 9513.