UNCOMPRESSED DENSITY OF THE MOON, LUNAR MANTLE AND CORE. M. Szurgot, Lodz University of Technology, Center of Mathematics and Physics, Al. Politechniki 11, 90 924 Lodz, Poland (mszurgot@p.lodz.pl).

Introduction: Knowledge of densities, iron to silicon ratios, and mean atomic weights is important to characterize minerals and rocks, planets, moons, and asteroids. The aim of the paper was to apply relationship between density and *Fe/Si* ratio for extraterrestrial materials to verify Moon's uncompressed density, and *Fe/Si* atomic ratio. Literature data on chemical composition and density of the Moon [1-16] have been used to verify and apply *d(Fe/Si)* relationship, recently established for planetary materials, chondrules, chondrites, chondrules, planets, and asteroids by Szurgot [17].

Results and discussion: Recently relationships between mean atomic weight *Amean* and density *d* of meteorites, planets, moon, and asteroids have been established [18-21]. They are expressed by the equations:

$$Amean = (7.51 \pm 0.13)\cdot d - (2.74 \pm 0.55), \quad (1)$$

$$d = (0.133 \pm 0.002)\cdot Amean + (0.37 \pm 0.07), \quad (2)$$

where $d(g/cm^3)$ is a planetary uncompressed density, or grain density of meteorites [18-21]. Using eq. (2) we can predict *d*, if *Amean* is known. Values of RMSE: 0.54 for eq. (1), and 0.07 for eq. (2).

Another important relationship is between *Amean* and *Fe/Si* atomic ratio, valid also for chondrules:

$$Amean = (5.72 \pm 0.13)\cdot Fe/Si + (20.25 \pm 0.54), \quad (3)$$

for which RMSE = 0.12 [18-21]. Equations (2) and (3) suggest that there exists a relationship between density *d* and *Fe/Si* atomic ratio.

The *d(Fe/Si)* relationship for extraterrestrial matter has been discovered by the author, and verified for Mars, Venus, Earth, Moon, and OC chondrites [17]. The *d(Fe/Si)* dependence is presented in Fig. 1, and is expressed by the equation [17]:

$$d = (0.765 \pm 0.046)\cdot Fe/Si + (3.11 \pm 0.03). \quad (4)$$

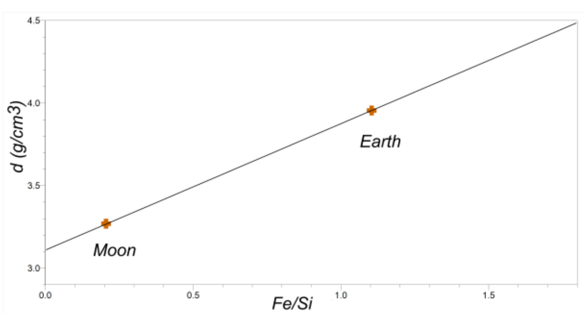

Fig. 1 Relationship between *d* and *Fe/Si* atomic ratio (eq. (4)). It is seen that Earth's data: $d = 3.955$ g/cm^3 [10,12], and $Fe/Si = 1.104$ [14]), and Moon's data: $d = 3.27$ g/cm^3 [10,12], and $Fe/Si = 0.205$ [1] verify *d(Fe/Si)* relationship.

Author's data reveal that *d(Fe/Si)* relationship is valid not only for rocky planets, asteroids, moons, OC, and EC chondrites, but also for ferromagnesian chondrules.

Figure 1 shows that Moon's and Earth's *Fe/Si* atomic ratios, and uncompressed densities much perfectly the relationship. For example, literature data indicate uncompressed density $d = 3.27$ g/cm^3 for the Moon [10,12], and substituting *Fe/Si* values: 0.205 [1], and 0.213 [6] into eq. (4) predicts the same value $d = 3.27 \pm 0.04$ g/cm^3 for uncompressed density of Moon.

Table 1. Moon's *Fe/Si* atomic ratio, uncompressed density predicted by *d(Fe/Si)* dependence (eq. (4)), and atomic weight *Amean* for various Moon's models.

Moon	*Fe/Si*	*d(Fe/Si)* (g/cm^3)	*Amean*
TWM*	**0.205** [1]	**3.27**	21.52
BM 1#	0.296 [2]	3.34	22.44
BM 2	0.063 [3]	3.16	20.96
BM 3a	0.074 [3]	3.17	21.09
BM 3b	0.135 [3]	3.21	21.37
BM 4	0.301 [4,15]	3.34	22.09
Interior	0 [5]	3.11	21.61
Interior	**0.213** [6]	**3.27**	21.73
Mantle	0.186 [7]	3.25	21.31
Mantle+Crust	**0.181** [7]	**3.25**	21.29
LPUM##	**0.138** [8]	**3.22**	21.14
U. Mantle	0.157 [9]	3.23	21.80
L. Mantle	0.307 [9]	3.34	22.32
Mantle+Crust	0.193 [16]	3.26	21.75
Crust	0.119 [7]	3.20	20.93
H. Crust	**0.082** [10]	**3.17**	21.57
Range	**0 - 0.30**	**3.1 - 3.34**	**21 - 22.4**

*TWM = Taylor Whole Moon, #BM = Bulk Moon, LPUM## = Lunar Primitive Upper Mantle, U = upper, L. Mantle = Lower Mantle, H. Crust = Highland Crust.

For *Fe/Si* ratio established for the upper mantle (0.138) eq. (4) predicts 3.22 g/cm^3, the same value which was recently given for the lunar mantle [11].

Predicted density for lunar crust (3.17 g/cm^3) is, however too high. Lower bound (3.11 g/cm^3) indicated for density by eq. (4) is too high for crustal materials, and recent GRAIL data reveal crustal density as low as

2.55 g/cm^3 [11], that is even lower than the previous estimations for the lunar crust 2.8 - 2.9 g/cm^3.

Various Moon's models lead to the range of uncompressed values: 3.11 – 3.34 g/cm^3 for Moon (Table 1). This means that *d(Fe/Si)* relationship (eq. (4)) holds well for the Moon**.** Equation (4) and Table 1 data indicate that relative error in *d* determination is of the order of 1 - 2%.

There exists the inter-dependence between density and *Fe/Si* ratio expressed by *Fe/Si(d)* relation. It is described by the equation:

$$Fe/Si = (d - 3.11)/0.765, \quad (5)$$

for which expected error is *Δ(Fe/Si)* ≈ 0.02 for Earth's *Fe/Si* ratio: 1.10, and 0.004 for Moon's *Fe/Si* ratio: 0.20. Using eq. (5) we can predict *Fe/Si* atomic ratio, if *d* is known. Equation (5) predicts *Fe/Si* = 0.209 ± 0.004 for the Moon's uncompressed density *d* = 3.27 g/cm^3 (Table 2). Relative error is of order of 2%.

Table 2. Uncompressed density of Moon, and *Fe/Si* atomic ratios predicted by *Fe/Si(d)* dependence (eq. (5)).

d(g/cm^3) /[reference]	*(Fe/Si)(d)*	*Fe/Si* /[reference]
3.27 [10]	**0.209** ±0.004	**0.205** [1]
3.27 [10]	**0.209** ± 0.004	**0.213** [6]

Various Moon's models lead to various values of elemental abundance of the Moon, and as a result they predict various values of *Fe/Si* ratio, various values of mean atomic weight, and various values of uncompressed density of the Moon. Moon's *Fe/Si* ratio is in the range of 0–0.30, predicted density *d* is in the range: 3.11 - 3.34, and Moon's range of *Amean* is: 21.0 – 22.4 [18] (Table 1).

Data presented in Tables 1 and 2 show that eq. (4) for *Fe/Si* = 0.209 ± 0.004 gives the best value for uncompressed density of Moon: *d* = 3.27 ± 0.04 g/cm^3. For this value of *Fe/Si* ratio we get *Amean(Fe/Si)* = 21.4 ± 0.1, i.e. 2% lower value *Amean* than that resulted from the Moon's bulk composition.

Table 3. Moon's mean atomic weight *Amean*, uncompressed density *d* (g/cm^3) resulted from *d(Amean)* dependence (eq. (2)), and *Fe/Si* ratio predicted by *Fe/Si(d)* dependence (eq. (5)).

	Amean [18]	*d(Amean)*	*Fe/Si(d)*
Moon	**21.8** ± 0.4	**3.27** ±0.04	**0.21** ± 0.05
Mantle +Crust	**21.5** ± 0.4	**3.23** ±0.05	**0.16** ± 006
Core	**50.3** ± 3.7	**7.06** ±0.49*	**5.2** ± 0.5#

**d(Amean)* range: 6.57-7.55 (g/cm^3), #*Fe/Si(d)* range:4.7-5.7. For *Fe/Si* = 5.7 eq. (1) gives *d* = 7.47 g/cm^3, and for *Amean* = 54 eq. (2) gives *d* = 7.55 g/cm^3 for the lunar core.

Author's recent data indicate that the whole Moon bulk composition leads to *Amean* = 21.8 ± 0.4 [18]. Lunar core *Amean* = 50.3 ± 3.7, mantle *Amean* = 21.9 ± 0.4, crust *Amean* = 21.7 ± 0.4, and bulk silicates of mantle and crust *Amean* = 21.5 ± 0.4 [18].

Table 4. Lunar mean atomic weight *Amean*, *Fe/Si* atomic ratio, and uncompressed density *d*.

Amean	*Fe/Si*	*d(Fe/Si)*	*d(g/cm^3)*
21.8±0.4	**0.21**±0.05	**3.27**± 0.04	**3.27** [10,12]

Table 3 presents data on predicted values of uncompressed density of Moon's bulk silicates and Moon's core by *d(Amean)* (eq. (2)) dependence. Is is seen that uncompressed density of Moon's silicates is 3.23 g/cm^3, and lunar core: 7.06 g/cm^3, and 7.55 g/cm^3, for mean density, and upper limit of density, respectively. Data collected in Table 4 show values of Moon's mean atomic weight *Amean*, *Fe/Si* ratio, and uncompressed density *d*, verified in this paper.

Conclusions: Dependence between density and *Fe/Si* atomic ratio *d(Fe/Si)* predicts precisely uncompressed density of the Earth, and the Moon, and leads to reliable values for uncompressed density of lunar mantle+crust, and lunar core. *Fe/Si* ratios are predicted by *Fe/Si(density)* relation. Moon's mean atomic weight, uncompressed density, and *Fe/Si* atomic ratio have been verified.

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