Icarus 212 (2011) 697–700

Contents lists available at ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

Internal structure and physical properties of the Asteroid 2008 TC_3 inferred from a study of the Almahata Sitta meteorites

T. Kohout [a,b,*], R. Kiuru [a], M. Montonen [a], P. Scheirich [c], D. Britt [d], R. Macke [d], G. Consolmagno [e]

[a] Department of Physics, University of Helsinki, P.O. Box 64, 00014 Helsinki University, Finland
[b] Institute of Geology, Academy of Sciences of the Czech Republic, Rozvojová 269, 16500 Prague 6, Czech Republic
[c] Astronomical Institute, Academy of Sciences of the Czech Republic, Fričova 1, 25165 Ondřejov, Czech Republic
[d] Department of Physics, University of Central Florida, P.O. Box 162385-2385, Orlando, 32816-2385 FL, USA
[e] Vatican Observatory, V-00120, Vatican City State

ARTICLE INFO

Article history:
Received 5 July 2010
Revised 26 January 2011
Accepted 29 January 2011

Keywords:
Asteroids
Meteorites
Near-Earth objects

ABSTRACT

The density measurements of Almahata Sitta ureilites reveal a bulk density of ~3.1 g/cm^3. This value, together with the 2008 TC_3 asteroid shape model and albedo, was used to estimate the asteroid's mass. Based on the study of recovered meteorites and atmospheric entry observations Asteroid 2008 TC_3 is compositionally heterogeneous and of low mechanical strength. Thus we consider the presence of significant macroporosity likely, lowering asteroid's bulk density compared to that of the Almahata Sitta ureilites. Most realistic albedos lie in a range of 0.09-0.2 and the presence of significant macroporosity leads to mass estimates below 20×10^3 kg, which is lower than previously estimated. The presence of a non-ureilitic fraction and space weathering may affect the albedo and also influence the mass estimates. However, from current data it is not possible to quantify this effect.

1. Introduction

On October 6, 2008 a small asteroid designated 2008 TC_3 was detected 20 h prior to its impact on Earth. This was the first Near-Earth Object (NEO) asteroid to be detected before its observed encounter with the terrestrial atmosphere and tracked to its subsequent recovery as a meteorite. The recovered meteorites were named "Almahata Sitta", meaning "Station 6" in Arabic, after a nearby inhabited outpost which served as the base camp of the subsequent meteorite recovery expeditions. Most of the recovered meteorites are classified as ureilites (Jenniskens et al., 2009). However, a significant number of pieces of various chondritic compositions have been found within the recovered meteorites which most likely also originated from the Asteroid 2008 TC_3 impact (Bischoff et al., 2010; Kohout et al., 2010; Shaddad et al., 2010; Zolensky et al., 2010) revealing significant compositional heterogeneity of the 2008 TC_3 asteroid.

This was the first time that meteorite physical properties could be compared directly to the properties derived from remote asteroid observations (Hiroi et al., 2010; Jenniskens et al., 2009). We have characterized these meteorites through the measurement of their bulk density and have set limits on the internal structure and mass of Asteroid 2008 TC_3.

* Corresponding author at: Department of Physics, University of Helsinki, P.O. Box 64, 00014 Helsinki University, Finland. Fax: +358 919151000.
E-mail address: tomas.kohout@helsinki.fi (T. Kohout).

0019-1035/$ - see front matter © 2011 Elsevier Inc. All rights reserved.
doi:10.1016/j.icarus.2011.01.037

2. Materials and methods

The Almahata Sitta meteorites that are the subject of this study were collected in Sudan and were provided for these measurements by the meteorite curators Muawia Shaddad and Peter Jenniskens. The list of the samples is provided in Table 1. The sample codes correspond to the catalogue in Shaddad et al. (2010).

Our density and porosity values were obtained using a well calibrated methodology which was also cross-checked among different laboratories. The samples were measured using a mobile laboratory described in Kohout et al. (2008). Bulk volume was determined using a modified Archimedean method (Consolmagno and Britt, 1998; Macke et al., 2010) incorporating glass beads ~0.75 mm in diameter. Alternatively filtrated desert sand of similar grain size was used during measurements done directly in Sudan. Ten sets of measurements per sample were done and each sample was measured independently by at least two operators. The method was thoroughly tested and calibrated prior the measurements using volume standards and the resolution was determined to be ±0.1 cm^3. In addition, the grain volume of one sample was measured using a Quantachrome Ultrapyc 1000 He pycnometer. The standard error of this device has been shown to be less than ±0.1 cm^3 (Macke et al., 2011).

Masses were determined using a digital OHAUS Navigator balance with 0.1 g resolution. The balance was always calibrated prior the measurements using its internal calibration procedure.

Table 1
List of Almahata Sitta ureilites subjected to the bulk density measurements.

Meteorite	Mass (g)	Bulk density (g/cm^3)	Grain density (g/cm^3)	Porosity (%)
15	74.2	3.3	3.5	6
82	10.3	3.1		
S164	28.8	2.9		
S195	28.9	3.1		
S195A	24.9	3.2		
Almahata Sitta ureilite mean		3.1		

3. Density and porosity of the Almahata Sitta meteorites

The results of the measurements done on Almahata Sitta ureilites (Table 1) reveal that the bulk density of the individual pieces ranges from 2.9 to 3.3 g/m^3. Comparing the bulk density data to other ureilites, all but one of the measured Almahata Sitta bulk densities are slightly lower than the ureilite mean of 3.22 g/cm^3 reported in Macke et al. (2011).

In addition to these bulk densities, for our largest sample (Meteorite 13, mass 74.3 g, which is 44% of the total mass of material measured here) we were able to determine a grain density of 3.5 g/cm^3. Given its bulk density of 3.3 g/cm^3, the microporosity of this sample was 6%.

4. Limits on Asteroid 2008 TC_3 properties

Our next step is to use these measurements to place limits on the physical properties of Asteroid 2008 TC_3. First of all, for a homogeneous asteroid we note that the bulk density of the asteroid should not exceed that of the meteorites derived from that asteroid. Thus, the upper bulk density limit of the asteroid density is 3.1 g/m^3. This estimate already includes microporosity, which assumes that this porosity was characteristic of the asteroid material and not induced in its atmospheric entry. Given that most other achondrites and ordinary chondrites have a porosity less than 10% and, while not typical, many fresh fallen meteorites have been measured with very low microporosity (Consolmagno et al., 2008) even after surviving impact with the Earth, this assumption seems reasonable.

We can take this upper density limit to calculate the upper mass limit of the asteroid if we know the asteroid's volume. The only information we have about the size of the asteroid is the amount of light it reflected during observations of its passage en route to Earth. Thus, to estimate the volume of Asteroid 2008 TC_3 we must have some way to estimate its shape and albedo.

The shape was determined by Scheirich et al. (2010) by modeling the asteroid's light curve. The albedo is not known precisely, but several measurements have been done on Almahata Sitta ureilites. Jenniskens et al. (2009) report a value of 0.046 ± 0.005; however, they do not provide any details about their instrument setup or its calibration. Another measurement was reported by Hiroi et al. (2010) using the well calibrated RELAB instrumentation; their results show a higher albedo, in the range of 0.09–0.2, which is similar to other ureilites (Cloutis et al., 2010). Space weathering effects on ureilite albedos as well as the possible presence of a non-ureilitic surface fraction are sources of additional uncertainty in the 2008 TC_3 albedo.

We have calculated asteroid volumes V using the following equation derived from the shape model by Scheirich et al. (2010) giving the relation between the volume of Asteroid 2008 TC_3 and its albedo:

$$V = p^{-3/2} \times 0.25\ \mathrm{m}^3 \tag{1}$$

where p is the albedo and the term 0.25 m^3 is based on the asteroid's absolute magnitude and time-averaged effective diameter of the shape model (Scheirich et al., 2010).

The volume calculation was done with a range of albedos from 0.04 to 0.2 using Eq. (1) and the mass m was determined in the same albedo range using the following equation:

$$m = \rho_B V = \rho_B p^{-3/2} \times 0.25\ \mathrm{m}^3 \tag{2}$$

where ρ_B is mean bulk density of Almahata Sitta meteorites, p is albedo and the term 0.25 m^3 is explained in Eq. (1).

The theoretical albedo range of 0.04–0.2 in our calculation results in a volume range of 30–2.7 m^3 and, given our mean bulk density 3.1 g/cm^3 determined on Almahata Sitta ureilites, in an upper mass limit from 93 to 8×10^3 kg. The results are summarized in Fig. 1.

Another factor influencing the mass of an asteroid of a given volume is its macroporosity. We can deduce that the macroporosity of 2008 TC_3 must have been significant as the asteroid was observed to have low strength and disintegrated early on during its atmospheric entry (Jenniskens et al., 2009; Borovička and Charvát, 2009). However, it was not a completely strengthless body, given its high rotation rate with a period of 100 s (Scheirich et al., 2010). The body's strength may be not the result of a coherent structure, but could be also a product of inter-particle forces such as friction, van der Waals, and electrostatic forces (Scheeres et al., 2010).

The upper mass estimates presented by the most upper curve in Fig. 1 assume no macroporosity and include only the microporosity incorporated in the bulk density of the Almahata Sitta ureilites. The addition of macroporosity within Asteroid 2008 TC_3 would lower its bulk density, resulting in a lower mass. The mass of Asteroid 2008 TC_3 can be then expressed as follows:

$$m = (1 - P_{MA})\rho_B V = (1 - P_{MA})\rho_B p^{-3/2} \times 0.25\ \mathrm{m}^3 \tag{3}$$

where P_{MA} is the macroporosity within the asteroid, ρ_B is mean bulk density of Almahata Sitta meteorites, p is the albedo and the term 0.25 m^3 is explained in Eq. (1).

In Fig. 1 we show the calculated effect of macroporosity in a range of 0–50% on the mass of the 2008 TC_3 asteroid.

5. Discussion

Our Almahata Sitta ureilite bulk densities are in general higher than the values presented in Jenniskens et al. (2009) or Shaddad et al. (2010). While their values were important first estimates, we cannot verify them. It is possible that the use of unfiltered desert sand and uncalibrated methodology does not produce the high-precision results that have been shown for well-calibrated glass beads or filtrated desert sand of similar grain size. In our modeling we rely on our new data obtained using a methodology established in previous studies.

The estimation of Asteroid 2008 TC_3's bulk density and mass is a difficult task due to the uncertainty in its albedo as well as its possible content of non-ureilitic material. Based on our meteorite measurements, the upper bound bulk density limit is 3.1 g/cm^3, i.e. the average bulk density of Almahata Sitta ureilites. This value could be slightly increased given the reported presence of a denser chondritic fraction, if the fraction is substantial. No quantitative estimate of this fraction can be made based on the present level of mineralogical data because only a few dozen of all the recovered Almahata Sitta meteorites (of over 600 individuals) have been classified so far. However, the major fraction seems to resemble ureilite lithologies (Shaddad et al., 2010) and thus we use the Almahata Sitta ureilite bulk density as a base value.

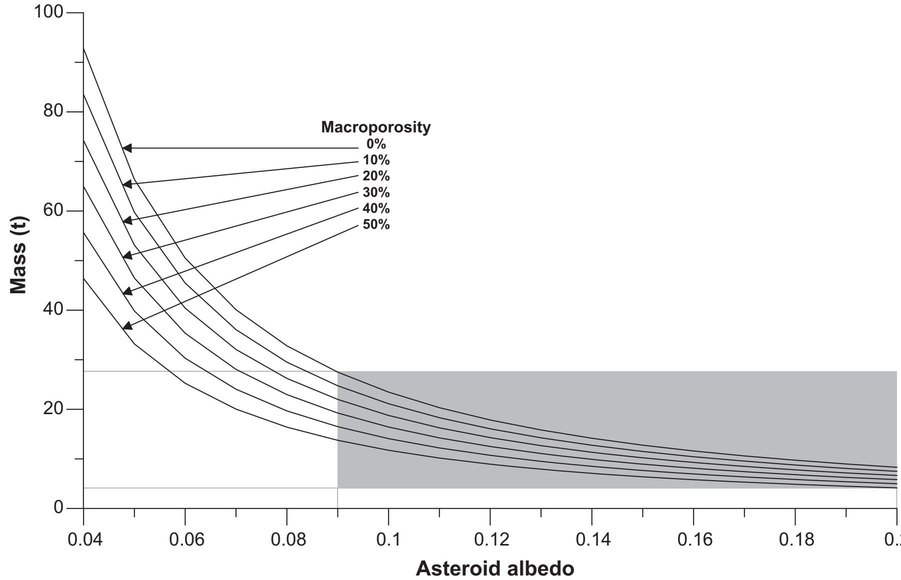

Fig. 1. Mass of the 2008 TC_3 asteroid as function of its albedo and macroporosity. The mass was calculated from an asteroid volume and empirically determined average Almahata Sitta ureilite bulk density 3.1 g/cm^3. The volume is a function of albedo and was derived from the shape model of Scheirich et al. (2010). The different lines demonstrate the effect of increasing macroporosity. For a certain albedo (and volume) the total asteroid mass decreases linearly with increasing macroporosity. The albedo range determined on Almahata Sitta ureilites by Hiroi et al. (2010) and corresponding mass range is highlighted by a gray box. Note that the ureilites include additional microporosity.

Another source of error is the uncertainty in the asteroid's average albedo. The mean *F*-class asteroid albedo reported in Warner et al. (2009) is around 0.05. However, this value is the average F-class albedo and does not include 2008 TC_3. As discussed in the previous section the most reliable albedo measurements of ureilites, including Almahata Sitta samples, as published by Hiroi et al. (2010), vary between 0.09 and 0.2. The value of the actual asteroidal albedo may be decreased compared to the fresh meteorite material of the same body due to space weathering of the surface (Clark et al., 2002), but the extent of space weathering of Asteroid 2008 TC_3 is unknown. On the other hand the presence of a chondritic fraction on the surface of the 2008 TC_3 asteroid may slightly increase its overall albedo.

Thus, in our study we covered the whole range between 0.04 and 0.2 and calculated the asteroid mass as a function of albedo. The values given a bulk density of 3.1 g/cm^3 and zero macroporosity are upper limits of the asteroid mass and are represented by the most upper curve in Fig. 1. Subsequently as shown in Fig. 1 the effect of macroporosity on asteroid mass is evaluated and the mass of Asteroid 2008 TC_3 decreases linearly with increasing macroporosity and thus will be most likely lower.

Our model of Asteroid 2008 TC_3 presented in Fig. 1 predicts lower mass estimates than previously reported values. Jenniskens et al. (2009) reported a mass of $83 \pm 25 \times 10^3$ kg (calculated from a density estimate 2.3 ± 0.2 g/cm^3 for a spherical asteroid of albedo 0.046 ± 0.005, resulting in a diameter of 4.1 ± 0.3 m). Based on our modeling we note that such a high mass is possible only for albedos of 0.05 or lower and no macroporosity within Asteroid 2008 TC_3 (Fig. 1). However as Asteroid 2008 TC_3 is compositionally heterogeneous and probably of low mechanical strength we consider it very likely that the asteroid contains significant macroporosity, around 50% or higher as also suggested by Borovička and Charvát (2009) or Welten et al. (2010). Thus we conclude that the bulk density and mass of Asteroid 2008 TC_3 should be lower than this estimate.

Borovička and Charvát (2009) reported a mass of 35–65×10^3 kg based on Meteosat observations of the asteroid entry. Their large range of values is mainly due to the uncertainty in the luminous efficiency coefficient of 2008 TC_3 during its luminous entry. Our modeling allows a mass in this range for an albedo range of 0.08–0.05 but the presence of macroporosity in order of several tens of percent is possible only in the case of an albedo close to 0.05 (Fig. 1). However if the albedo is higher and/or the macroporosity is closer to 50% as discussed above and as is also typical of many dark asteroids, then this mass estimate would be too large.

As the albedo range of 0.09–0.2 reported in Hiroi et al. (2010) is measured on well calibrated equipment and consistent with other ureilites, we conclude this albedo is probably to be preferred as our choice for the albedo of 2008 TC_3. Our calculations based on this albedo range leads to generally lower asteroid upper mass estimates, between 8 and 27×10^3 kg as highlighted by the gray box and lines in Fig. 1. This estimate should be taken as the asteroid upper mass limit as it can be further decreased by presence of macroporosity.

6. Conclusions

Given that the 2008 TC_3 asteroid is compositionally heterogeneous and of low mechanical strength we consider the presence of significant macroporosity to be very likely. Most realistic ureilite (including Almahata Sitta) albedos are in the range of 0.09–0.2. Such an albedo and the presence of significant macroporosity around 50% leads us to estimate that the mass of Asteroid 2008 TC_3 was probably below 20×10^3 kg, which is lower than previously proposed.

Acknowledgments

We would like to thank the Väisälän Foundation and University of Helsinki for research and travel funding, and to meteorite curators Muawia Shaddad and Peter Jenniskens providing us with an access to the Almahata Sitta meteorite material. Institute of Geology is supported by Academy of Sciences of the Czech Republic Research Plan AV0Z 30130516.

References

Bischoff, A., Horstmann, M., Pack, A., Laubenstein, M., Haberer, S., 2010. Asteroid 2008 TC3 – Almahata Sitta: A spectacular breccia containing many different ureilitic and chondritic lithologies. Meteorit. Planet. Sci. 45, 1638–1656. doi:10.1111/j.1945-5100.2010.01108.x.

Borovička, J., Charvát, Z., 2009. Meteosat observation of the atmospheric entry of 2008 TC_3 over Sudan and the associated dust cloud. Astron. Astrophys. 507, 1015–1022. doi:10.1051/0004-6361/200912639.

Clark, B.E., Hapke, B., Pieters, C., Britt, D., 2002. Asteroid space weathering and regolith evolution. In: Bottke, W.F., Jr., Cellino, A., Paolicchi, P., Binzel, R.P. (Eds.), Asteroids III. Univ. Arizona Press, pp. 585–599.

Cloutis, E., Hudon, P., Romanek, C.S., Bishop, J.L., Reddy, V., Gaffey, M.J., et al., 2010. Spectral reflectance properties of ureilites. Meteorit. Planet. Sci. 45, 1668–1694. doi:10.1111/j.1945-5100.2010.01065.x.

Consolmagno, G.J., Britt, D.T., 1998. The density and porosity of meteorites from the Vatican collection. Meteorit. Planet. Sci. 33, 1231–1241. doi:10.1111/j.1945-5100.1998.tb01308.x.

Consolmagno, G., Britt, D., Macke, R., 2008. The significance of meteorite density and porosity. Chem. Erde 68, 1–29. doi:10.1016/j.chemer.2008.01.003.

Hiroi, T., Jenniskens, P., Bishop, J.L., Shatir, T.S.M., Kudoma, A.M., Shaddad, M.H., 2010. Bidirectional visible–NIR and biconical FT-IRreflectance spectra of Almahata Sitta meteorite samples. Meteorit. Planet. Sci. 45, 1836–1845. doi:10.1111/j.1945-5100.2010.01097.x.

Jenniskens, P., Shaddad, M.H., Numan, D., Elsir, S., Kudoda, A.M., Zolensky, M.E., et al., 2009. The impact and recovery of Asteroid 2008 TC_3. Nature 458, 485–488. doi:10.1038/nature07920.

Kohout, T., Kletetschka, G., Elbra, T., Adachi, T., Mikula, V., Pesonen, L.J., et al., 2008. Physical properties of meteorites – Applications in space missions to asteroids. Meteorit. Planet. Sci. 43, 1009–1020. doi:10.1111/j.1945-5100.2008.tb00689.x.

Kohout, T., Jenniskens, P., Shaddad, M.H., Haloda, J., 2010. Inhomogeneity of the 2008 TC_3 asteroid (Almahata Sitta meteorites) revealed through magnetic susceptibility measurement. Meteorit. Planet. Sci. 45, 1778–1788. doi:10.1111/j.1945-5100.2010.01110.x.

Macke, R.J., Britt, D.T., Consolmagno, G.J., 2010. Analysis of systematic error in "bead method" measurements of meteorite bulk volume and density. Planet. Space Sci. 58, 421–426. doi:10.1016/j.pss.2009.11.006.

Macke, R., Britt, D., Consolmagno, G., 2011. Density, porosity and magnetic susceptibility of achondritic meteorites, Meteorit. Planet. Sci. 46, in press. doi:10.1111/j.1945-5100.2010.01155.x.

Scheeres, D., Hartzell, C.M., Sanchez, P., Swif, M., 2010. Scaling forces to asteroid surfaces: The role of cohesion. Icarus 210, 968–984. doi:10.1016/j.icarus.2010.07.009.

Scheirich, P., Ďurech, J., Pravec, P., Kozubal, M., Dantowitz, R., Kaasalainen, M., et al., 2010. The shape and rotation of Asteroid 2008 TC_3. Meteorit. Planet. Sci. 45, 1804–1811. doi:10.1111/j.1945-5100.2010.01146.x.

Shaddad, M.H., Jenniskens, P., Kudoda, A.M., Numan, D., Elsir, S., Riyad, I.F., et al., 2010. The recovery of Asteroid 2008 TC_3. Meteorit. Planet. Sci. 45, 1557–1589. doi:10.1111/j.1945-5100.2010.01116.x.

Warner, B.D., Harris, A.W., Pravec, P., 2009. The asteroid lightcurve database. Icarus 202, 134–146. doi:10.1016/j.icarus.2009.02.003.

Welten, K.C., Meier, M.M.M., Caffee, M.W., Nishiizumi, K., Wieler, R., Jenniskens, P., et al., 2010. Cosmogenic nuclides in Almahata Sitta ureilites: Cosmic-ray exposure age, preatmospheric mass and bulk density of Asteroid 2008 TC_3. Meteorit. Planet. Sci. 45, 1728–1742. doi:10.1111/j.1945-5100.2010.01106.x.

Zolensky, M., Herrin, J., Mikouchi, T., Ohsumi, K., Friedrich, J., Steele, et al., 2010. Mineralogy and petrography of the Almahata Sitta ureilite. Meteorit. Planet. Sci. 45, 1618–1637. doi:10.1111/j.1945-5100.2010.01128.x.