Internal structure and physical properties of the Asteroid 2008 TC₃ inferred from a study of the Almahata Sitta meteorites

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The density measurements of Almahata Sitta ureilites reveal a bulk density of $\sim$3.1 g/cm$^3$. This value, together with the 2008 TC₃ 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 TC₃ 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 $\times$ 10$^3$ kg, which is lower than previously estimated. The presence of a non-ureilite 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.

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1. Introduction

On October 6, 2008 a small asteroid designated 2008 TC₃ 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 TC₃ impact (Bischoff et al., 2010; Kohout et al., 2010; Shaddad et al., 2010; Zolensky et al., 2010) revealing significant compositional heterogeneity of the 2008 TC₃ 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 TC₃.

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 $\sim$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 $\pm$0.1 cm$^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 $\pm$0.1 cm$^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.
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:

\[
m = \rho_B V = \rho_B p^{-3/2} \times 0.25 \text{ m}^3
\]

where \( \rho_B \) 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 \times 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 Churav’t, 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:

\[
m = (1 - P_{MA})\rho_B V = (1 - P_{MA})\rho_B p^{-3/2} \times 0.25 \text{ m}^3
\]

where \( P_{MA} \) is the macroporosity within the asteroid, \( \rho_B \) 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 filrated 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.
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 TC₃. 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 TC₃ is unknown. On the other hand the presence of a chondritic fraction on the surface of the 2008 TC₃ 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/cm³ 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 TC₃ decreases linearly with increasing macroporosity and thus will be most likely lower.

Our model of Asteroid 2008 TC₃ presented in Fig. 1 predicts lower mass estimates than previously reported values. Jenniskens et al. (2009) reported a mass of 83 ± 25 × 10³ kg (calculated from a density estimate 2.3 ± 0.2 g/cm³ 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 TC₃ (Fig. 1). However as Asteroid 2008 TC₃ 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 TC₃ should be lower than this estimate.

Borovička and Charvát (2009) reported a mass of 35–65 × 10³ 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 TC₃ 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 TC₃. Our calculations based on this albedo range leads to generally lower asteroid upper mass estimates, between 8 and 27 × 10³ 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 TC₃ 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 TC₃ was probably below 20 × 10³ kg, which is lower than previously proposed.

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