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Invited Review

The Almahata Sitta polymict breccia and the late accretion of asteroid 2008 TC_3

Marian Horstmann*, Addi Bischoff

Institut für Planetologie, Westfälische Wilhelms-Universität Münster, Wilhelm-Klemm-Str. 10, 48149 Münster, Germany

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ABSTRACT

On October 7, 2008, a small asteroid named 2008 TC_3 was detected in space about 19 h prior to its impact on Earth. Numerous world-wide observations of the object while still in space allowed a very precise determination of its impact area: the Nubian Desert of northern Sudan, Africa. The asteroid had a pre-atmospheric diameter of ~4 m; its weight is reported with values between ~8 and 83 t, and the bulk density with ~2–3 g/cm^3, translating into a bulk porosity in the range of ~20–50%. Several dedicated field campaigns in the predicted strewn field resulted in the recovery of more than 700 (monolithological) meteorite fragments with a total weight of ~10.5 kg. These meteorites were collectively named "Almahata Sitta", after the nearby train station 6, and initially classified as an anomalous polymict ureilite. Further work, however, showed that Almahata Sitta is not only a ureilite but a complex polymict breccia containing chemically and texturally highly variable meteorite fragments, including different ureilites, a ureilite-related andesite, metal-sulfide assemblages related to ureilites, and various chondrite classes (enstatite, ordinary, carbonaceous, Rumuruti-like). It was shown that that chondrites and ureilites derive from one parent body, i.e., asteroid 2008 TC_3, making this object, in combination with the remotely sensed physical parameters, a loosely aggregated, rubble-pile-like object. Detailed examinations have been conducted and mineral-chemical data for 110 samples have been collected, but more work on the remaining samples is mandatory.

Detailed study of Almahata Sitta allows insights into the formation and evolution of ureilites and their parent body. These results support the catastrophic impact disruption of the ureilite parent body and re-accretion of the dispersed ureilitic material into second generation ureilite asteroids. Almahata Sitta shows that different chondritic materials were present in the region of re-accretion and mixed into the newly formed rubble-pile-like asteroid. Asteroid 2008 TC_3 was part of a late-formed ureilitic second generation body in the main belt and was liberated ~20 Ma ago, finally moving into Earth-crossing orbits that ultimately led to its impact on Earth. The abundant samples of Almahata Sitta, fragments of Asteroid 2008 TC_3, allow study of not only different types of meteorites, but offer the unique opportunity to gain further insights into processes in the asteroid belt of our Solar System such as migration, collision, mixing, and (re-)accretion of asteroidal bodies. Beyond that, this event has the potential to further the understanding of the meteorite–asteroid links, which is a major goal of meteorite science.

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* Corresponding author. Tel.: +49 251 8336377; fax: +49 251 8336301.
E-mail address: marianhorstmann@uni-muenster.de (M. Horstmann).

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1. Introduction

Asteroids are generally accepted to be the parent bodies of the majority of meteorites in the world's meteorite collections. Establishing and understanding the link between meteorites available for study on Earth and their asteroidal parent bodies is one of the major goals of meteorite science. However, this is quite challenging and has, except for the Itokawa S-type asteroid and the LL ordinary chondrites via the Hayabusa space craft (Nakamura et al., 2011), not been successfully demonstrated by direct sampling of asteroidal material. Further albeit weaker links of meteorite classes and asteroids have been based on spectroscopic observations (e.g., Burbine et al., 2002). The Dawn mission was designed to further elucidate the proposed link between the largest achondrite group of HED (howardites, eucrites, diogenites) meteorites and asteroid 4 Vesta (e.g., McSween et al., 2010).

In October 2008, a one-of-a-kind event allowed for the first time the study of an asteroid in space that subsequently impacted Earth and allowed collection of numerous meteorite fragments, enabling a direct comparison of the asteroids properties obtained via remote sensing and detailed petrographic and mineral-chemical aspect of its meteorite remnants: On October 6th, 2008, Richard Kowalski at the automated Catalina Sky Survey telescope at Mt. Lemmon Observatory (Arizona) detected a small asteroidal body at 06:39 UTC (Kowalski, 2008; Yeomans, 2008; McGaha et al., 2008; Chesley et al., 2008). The object was designated asteroid 2008 TC_3. Subsequent orbital calculations predicted an impact on Earth in the Nubian Desert of northern Sudan about 19 h after the discovery (McGaha et al., 2008; Jenniskens et al., 2009a,b; Table 1).

After its impact, field campaigns organized by Peter Jenniskens and Muawia Shaddad (supported by staff from the University of Khartoum) and further independent search activities resulted in the collection of several hundred small meteorite fragments that were collectively named the Almahata Sitta meteorite, which is the Arabic translation for the nearby train station 6 (e.g., Goodrich et al., 2014; Jenniskens et al., 2009a,b; Bischoff et al., 2010b; Shaddad et al., 2010). To date more than 700 specimens with a total weight of roughly 10 kg have been collected, 25 of which (number refers only to those for which mineral-chemical data are available) were studied in a consortium led by P. Jenniskens. Fragments of about 80 different meteorites were investigated independently in cooperations organized by the Institut für Planetologie, Münster. A small number of additional samples were examined by other institutions. Overall, petrographic and mineral-chemical data have been collected for 110 samples (Table 2).

The Almahata Sitta meteorite, originally classified as a anomalous polymict ureilite (Jenniskens et al., 2009b), soon turned out to be a complex polymict breccia consisting of various ureilites and chondrites showing a broad range of textures, mineral abundances and compositions (Bischoff et al., 2010a,b). Combined with remote sensing data, these results made asteroid 2008 TC_3 a prime example of a rubble pile asteroid, although the different lithologies appear to be weakly welded together (Popova et al., 2011, and below). This is different from the classical case of a rubble pile, in

Table 1
Orbital parameters of asteroid 2008 TC_3 used to calculate the approach path. For details see Jenniskens et al. (2009b).

Symbol	Parameter	Value
α	Semimajor axis	1.308201 ± 0.000009 AU
q	Perihelion distance	0.899957 ± 0.000002 AU
ω	Argument of perihelion	$234.44897 \pm 0.00008^\circ$
Ω	Longitude of ascending node	$194.101138 \pm 0.000002^\circ$
i	Inclination	$2.54220 \pm 0.00004^\circ$
T_p	Perihelion time	2008 November 20.3989 ± 0.0001 UT