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The unusually frail asteroid 2008 TC3

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Abstract. The first asteroid to be discovered in space and subsequently observed to impact Earth, asteroid 2008 TC3, exploded at a high 37 km altitude and stopped ablating at 32 km. This would classify the fireball as of Ceplecha's PE-criterion IIIb/a, meaning "cometary" in nature. In this case, the structural weakness may have come from pores found in some of the recovered meteorites, called *"Almahata Sitta"* (= Station 6 in Arabic). The explosion turned most of the asteroid mass to dust and vapor, only a tiny fraction shattered into macroscopic meteorites, the heaviest of which was 283 gram. Other similarly frail asteroids may be related to main belt comets.

Keywords. Meteoroids, comets, asteroids

1. Introduction

On October 6, 2008, a small 3-4 meter sized asteroid was discovered by the Catalina Sky Survey program at Mount Lemmon (Kowalski *et al.* 2008). The asteroid, designated 2008 TC3, turned out to be on a collision course with Earth. Some 570 astrometric positions were determined, from which the impact trajectory was calculated (Chesley 2008). One 0.55–1.0 μm reflection spectrum was measured (flat in the visual with a weak 0.9 μm pyroxene band), which suggested the asteroid was of "C", "B", or "F" taxonomic class (Jenniskens *et al.* 2009, for a popular account see Kwok 2009).

The impact occurred 20 hours later over the Nubian Desert of northern Sudan. It was seen by KLM pilot Ron de Poorter, as well as by thousands of Sudanese along the river Nile awake for Morning Prayer. US government satellites detected the fireball first at 65 km, penetrating down to 37 km where the object exploded in three bright flares. From METEOSAT 8 images, it was deduced that fragmentation may have started with a small flare around 53 km (Borovicka & Charvat 2009). Two bright flares occurred with peak brightness of -18.8 magn. at 45 km and -19.7 magn. at 37.5 km. After this, the fireball penetrated for another second to end in a final weaker flare at $\sim$32.7 km. Two dust clouds of silicate smoke were deposited around 44 and 36 km, with a total mass of about 3,100$\pm$600 kg. More mass was likely lost in the form of larger and colder grains than seen by METEOSAT 8. From the fireball brightness, the initial mass of 2008 TC3 was estimated between 35,000–65,000 kg (Borovicka & Charvat 2009, Jenniskens *et al.* 2009).

The fireball PE-criterion, which uses the fireball's observed end height of about 32 km, velocity (12.4 km/s), ass and entry angle (20^o) as a proxy for estimating its physical structure, would make this a IIIb/a-type, normally associated with cometary debris (Ceplecha *et al.* 1998). Of course, cometary debris is known to disrupt at even lower pressures

Figure 1. Search strategy for finding fragments of 2008 TC3 in the Nubian Desert of northern Sudan: students of the University of Khartoum comb the desert gravel.

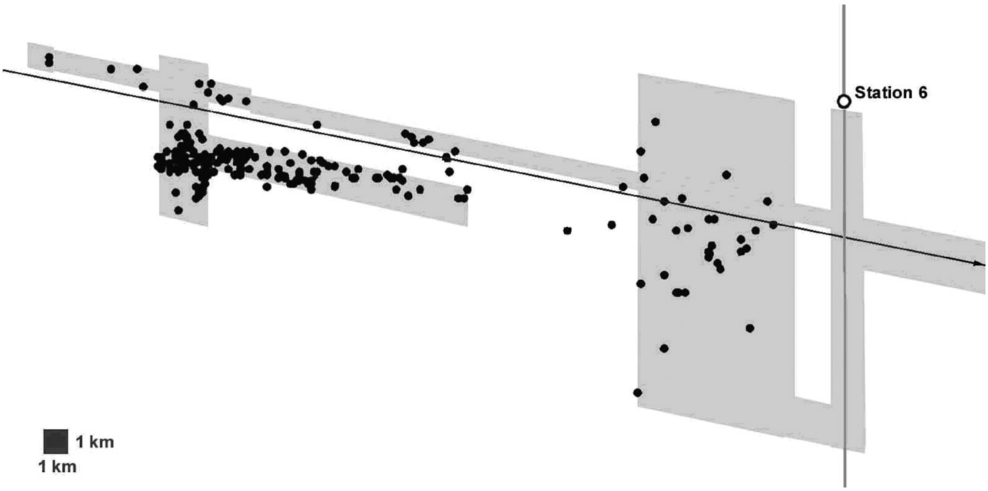

Figure 2. The distribution of recovered fragments relative to the calculated impact trajectory of asteroid 2008 TC3 (arrow pointing right) and the location of Station 6 (on the north-south railroad from Wadi Halfa to Abu Hamad). Gray areas were searched.

(< 0.1 MPa) than that at which 2008 TC3 disrupted (0.1–0.2 MPa), but ordinary chondrites are expected to break at around 5 Mpa ($\sim$ 25 km altitude). It is clear that this asteroid must have had a low cohesive strength or that it was exposed to unusually high thermal or mechanical stresses between 65 and 37 km.

For two months, the explosion of the asteroid in the atmosphere appeared to be the final word on the 2008 TC3 story. No meteorite had ever been recovered from a fireball ending this high in the atmosphere. In early December 2008, however, a search by students and staff of the University of Khartoum succeeded in recovering 15 meteorites along the calculated approach path. To find small fragments in a gravelly desert, a search strategy was adopted whereby the desert floor was combed by foot (Fig. 1). In subsequent searches in late December, and in February/March 2009, the total number of recovered meteorites rose to about 300, with a total mass of some 5 kg (Fig. 2). The largest recovered meteorite was 283 gr (#27, Fig. 3).

The meteorite strewnfield is unusual too, in that the meteorites are spread over a much larger area around the impact trajectory than commonly found. The strewnfield covered an area of at least 29 x 8 km (Fig. 2). We now understand that this was because of the

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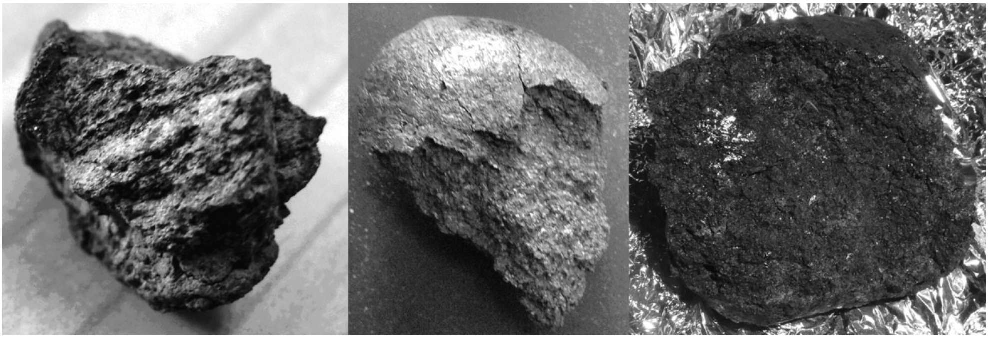

Figure 3. Examples of recovered meteorites (#1, 4, and 27) showing a wide array of textures and albedoes.

high explosion altitude, so that the asteroid had not yet significantly slowed down at the time of breakup. The range of recovered fragments is also larger than in most other falls, with many fragments 1 cm or smaller in diameter.

The meteorites are of a type called "anomalous polymict ureilite", a non-basaltic type of achondrite (Figure 3). A large range of textures and albedoes were found, with some meteorites more rich in pyroxene than others, some even showing pyroxene-rich layers (Fig. 3). The material is anomalous because of the abundant presence of pores and high δ^{17}O in some of the meteorites, and a large concentration of highly sintered organic matter. The organic matter is mostly graphitized, with small amounts of nano-diamonds, PAHs, and even amino acids. The pores are present in interconnected sheets and appear to form the outlines of partially sintered grains (Zolensky *et al.* 2010).

Most meteorites were dark, with an albedo of 0.046 ± 0.005 for the darkest components and values of 0.08–0.15 for lighter parts (Jenniskens *et al.* 2009). Combined with the measured absolute brightness of the asteroid, this would give a volume of $\leqslant 2.8 \pm 6$ m^3, or a bulk density of $\geqslant 1.8 \pm 0.6$ g/cm^3 (Scheirich *et al.* 2010).

The meteorite bulk density was measured by using fine sand to determine the volume displacement (Shaddad *et al.* 2010). Care was taken to shake the sand just enough so it settled into a rigid mass. From this, we have a significant range of densities for individual meteorites (Fig. 4). The mean value is 2.8 g/cm^3, with a significant variation in the range of 1.7 to 3.3 g/cm^3. These values are preliminary, while methods are being pursued to obtain better values.

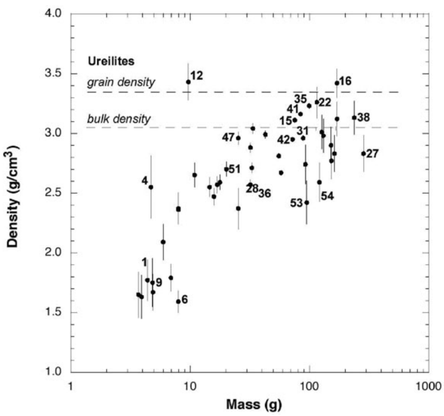

Figure 4. Measured mean densities of Almahata Sitta as a function of mass.

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Other ureilites have a bulk density of 3.05 ± 0.22 g/cm^3 and a micro-porosity of 9%, assuming an average ureilite grain density of 3.35 g/cm^3 (Britt & Consolmagno 2003). Many larger masses of Almahata Sitta have similar bulk density. Indeed, many show the large olivine crystals and same $\delta^{17}O/\delta^{18}O$ ratios typical of known ureilites. On the other hand, some have significantly lower density, with porosities in the range of 20–50%. Similar high porosities are found in carbonaceous chondrites, but here the presence of large olivine crystals and partially sintered grains produces a particularly fragile material.

The shape of 2008 TC3, too, may have played a role. Inversion of the asteroid's light curve implies a shape like a loaf of bread with one large flat surface (Scheirich *et al.* 2010). Entry modeling shows that the asteroid re-oriented with this flat side forward between 65–37 km, which can cause high mechanical stresses (Bent *et al.* 2010).

Based on the astronomical spectrum and the reflection properties of the meteorites, the asteroid is now classified as of taxonomic class "F", or possibly "B" (Jenniskens *et al.* 2009). Many "B"-class asteroids, have hydrated minerals, not found in Almahata Sitta. One such "B"-class asteroid is 3200 Phaeton, parent body of the Geminid meteor shower, now linked to the Pallas family of "F" and "B" class asteroids (Jenniskens *et al.* 2010). Hence, it is possible that some asteroids, notably F- and B-class asteroids, are so frail that they resemble cometary matter in the event of a collision, possibly leading to main belt comets (Hsieh & Jewitt 2006).

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