**DISTINGUISHING DIFFERENTIATED DARK ASTEROIDS FROM PRIMITIVE DARK ASTEROIDS: CLUES AND CAUTIONS FROM ASTEROID 2008 TC$_3$ AND THE ALMAHATA SITTA METEORITE.** C. A. Goodrich[1], M.E. Zolensky[2], A.M. Fioretti[3], M.H. Shaddad[4], H. Downes[5], T. Hiroi[6], I. Kohl[7], E.D. Young[7], N.T. Kita[8], V.E. Hamilton[9], M. Riebe[10], H. Busemann[10], R.J. Macke[11], M. Fries[2], M. Sanborn[12], Q-Z. Yin[12], D.K. Ross[13], P. Jenniskens[14]. [1]Lunar and Planetary Institute, USRA, Houston TX 77058 USA (goodrich@lpi.usra.edu); [2]ARES, NASA-JSC, Houston TX USA; [3]CNR, Padova Italy; [4]Univ. Khartoum, Khartoum Sudan; [5]Birkbeck Univ. London, London UK; [6]Brown Univ., Providence, RI USA; [7]UCLA, Los Angeles, CA USA; [8]Univ. Wisconsin, Madison, WI USA; [9]SwRI, Boulder, CO USA; [10]ETH, Zürich Switzerland; [11]Specola Vaticana, Vatican City State; [12]UC Davis, Davis, CA USA; [13]Jacobs-JETS, NASA-JSC, Houston TX USA; [14]SETI, Mountain View, CA USA.

**Introduction:** Asteroid 2008 TC$_3$ was the first near-Earth object to be detected and studied in space before it hit the Earth [1-6]. More than 700 cm-sized (~0.2-400 g) stones were recovered from the predicted fall area and named the Almahata Sitta (AhS) meteorite [7]. AhS is the first meteorite observed to originate from a spectrally classified asteroid. It provides an unprecedented opportunity to correlate spectral, compositional, and physical properties of a meteorite with those of the asteroid from which it was derived.

The reflectance spectrum of 2008 TC$_3$ was measured in the 0.5-1 µm range [4] and most closely matches F-type asteroids [8]. The average F-type albedo of 0.046 [9] is consistent with independent estimates of the asteroid's size [4]. F-type asteroids belong to the C complex of dark asteroids commonly identified with carbonaceous chondrites (CC) [8-11]. If Almahata Sitta had not been recovered, 2008 TC$_3$ would have been assumed to be a CC-type asteroid.

However, AhS turned out to be a unique and complex meteorite. The AhS stones are diverse, with ~70-80% of those studied so far being various types of ureilites (achondrites from the mantle of a differentiated asteroid), and 20-30% being various types of chondrites (mainly enstatite-, ordinary- and Rumuruti-types) [12-14]. Based on the apparent dominance of ureilites, AhS was classified as an anomalous polymict ureilite [4]. It has been inferred that 2008 TC$_3$ was a loosely-consolidated, heterogeneous breccia that disintegrated in the atmosphere, with its clasts landing on Earth separately and most of its mass lost [4,13]. Determining its structure and composition has been hindered so far because none of the studied AhS stones showed contacts between ureilitic and chondritic lithologies.

We have now discovered AhS 91A and AhS 671, the first AhS stones to show contacts between ureilitic and chondritic materials and provide direct information about the structure and composition of asteroid 2008 TC$_3$. Combined petrologic, geochemical, physical, and spectroscopic studies of these stones [14] provide clues and cautions to distinguishing differentiated dark asteroids from primitive dark asteroids in remote spectroscopy.

**The First AhS Stones Showing Contacts Between Ureilitic and Chondritic Lithologies:** AhS 91A and AhS 671 are friable breccias, dominated volumetrically by hydrous CC-like (C1) material which encloses rounded to angular clasts (<10 µm to 3 mm) of olivine, pyroxenes, plagioclase, graphite, and metal-sulfide, as well as chondrules (~130-600 µm) and chondrule fragments. The C1 material consists of fine-grained phyllosilicates (serpentine and saponite) and amorphous material, magnetite, bruennerite, dolomite, fayalitic olivine (Fo 28-42), an unidentified Ca-rich silicate phase, Fe,Ni sulfides, and minor Ca-phosphate and ilmenite. It has similarities to CI1, but the Ca-rich silicate (dehydrated saponite + CaO?) is unique and may indicate post-aqueous alteration thermal metamorphism. Its bulk oxygen isotope composition ($\delta^{18}O = 13.53‰$, $\delta^{17}O = 8.93‰$) is unlike that of any known CC. Its Cr isotope composition is also unique, with the highest $\varepsilon^{54}Cr$ of any known solar system material.

The clasts and chondrules do not belong to the C1 lithology. The olivine (Fo 75-88), pyroxenes (pigeonite of Wo ~10 and orthopyroxene of Wo ~4.6), plagioclase, graphite, and some metal-sulfide are unquestionably ureilitic, based on mineral compositions, textures, and oxygen isotope compositions, and represent at least six distinct ureilitic lithologies. The chondrules are probably derived from type 3 OC and/or CC, based on mineral and oxygen isotope compositions. Some of the metal-sulfide clasts are derived from EC.

AhS 91A and AhS 671 are plausible representatives of the 99% of the mass of asteroid 2008 TC$_3$ that was lost. The bulk density of AhS 91A (2.35 ± 0.05 g/cm$^3$) is lower than densities of other AhS stones and closer to estimates for the asteroid (~1.7-2.2 g/cm$^3$) [15]. Its porosity (36%) is higher than porosities of other AhS stones, but near the low end of estimates for the asteroid (33-50%), consistent with significant macroporosity [15]. They contain most previously known AhS stone types but, importantly, are dominated by hydrous CC, rather than ureilitic, material.

Reflectance spectra of AhS 91A are dark (reflectance ~0.04-0.05) and relatively featureless in VNIR, with an ~2.7 µm absorption band due to $OH^-$ in phyllosilicates, similar to ungrouped C2 (Fig. 1a). They are much closer to the spectrum of 2008 $TC_3$ than spectra of other AhS stones measured so far (Fig. 1b). Spectral modeling, using mixtures of VNIR reflectance spectra of AhS stones to fit the F-type spectrum of the asteroid (Fig. 2), suggests that 2008 $TC_3$ could have consisted of up to 79% AhS 91A-like (i.e., hydrous CC) material, with the remainder being mostly ureilitic, and <10% all other meteorite types. If this is the case, 2008 $TC_3$ could have had a 2.7 µm absorption band.

**Discussion:** [13] suggested that 2008 $TC_3$ was a piece of regolith from a ureilitic asteroid. [14] suggested that AhS 91A/671 represented a volume of such regolith dominated by a CC-like impactor, as has been suggested for dark regions on Vesta and Psyche [16,17]. However, based on current knowledge, it is also possible that 2008 $TC_3$ originated from a CC-like asteroid that had acquired minor foreign ureilitic (and other types of) materials. For several reasons (see also [19]), ureilitic regolith may be difficult to distinguish from hydrous CC material in remote spectra. A 2.7 µm absorption band may not imply a primitive asteroid.

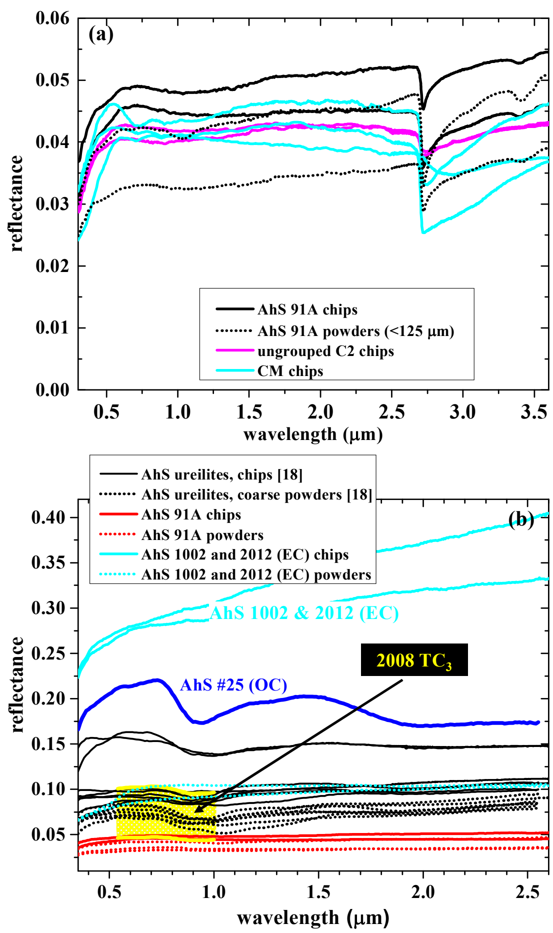


**Fig. 1.** (a) Reflectance spectra of AhS 91A chips and powders [14]. (b) Reflectance spectra of various AhS stones [14,18] compared with the spectrum of 2008 $TC_3$ at a range (yellow region) of albedo estimates [4,18].

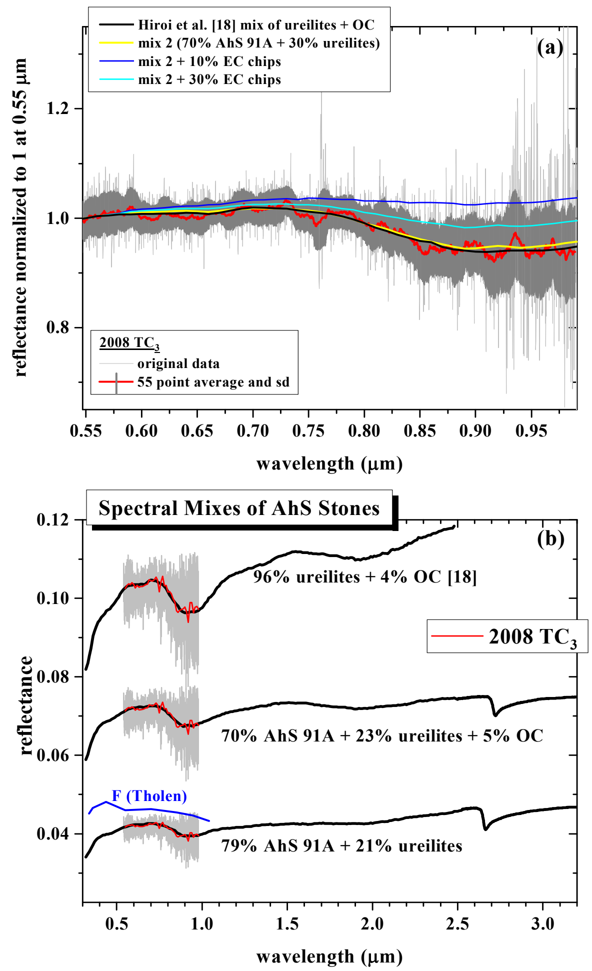


**Fig. 2.** (a) Results of spectral modeling, comparing mixes of various AhS stones with spectrum of 2008 $TC_3$. Within the uncertainty of the asteroid, mixes dominated by the CC lithology AhS 91A give matches comparable to those dominated by ureilites. (b) Similar comparison, showing that mixes dominated by AhS 91A fit the albedo of the asteroid better than mixes dominated by ureilites.

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