

## Polycyclic aromatic hydrocarbons in asteroid 2008 TC<sub>3</sub>: Dispersion of organic compounds inside asteroids

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**Abstract**—Ureilites are carbon-bearing ultramafic rocks characterized by partial melt depletion and a violent disruption resulting in graphitic carbon and diamonds. Among the predominantly polymict ureilite meteorites collected from the impact of asteroid 2008 TC<sub>3</sub> on October 7, 2008—the first time an asteroid was spotted in space and subsequently recovered in the form of meteorites—were many fresh-looking chondrites. Four were classified as EH6 (#16), H5 (sample #25), EL6 (#41), and L4 (#A100) chondrites. All are called “Almahata Sitta,” named after the nearby inhabited outpost of Station 6. Six hundred meteorites were collected, which show a wide range of densities, textures, reflection properties, and elemental compositions. In this study, we employ laser desorption laser ionization mass spectrometry to analyze the polycyclic aromatic hydrocarbon (PAH) contents of six meteorites from 2008 TC<sub>3</sub> that are ureilites (sample #1, #4, #7, #15, #27, and #47) and three anomalous fragments (sample #25, #16, and #41). Numerous organic compounds were detected with a PAH signature that has not been observed in the carbonaceous chondrites previously studied by our experimental apparatus. Specifically, the Almahata Sitta spectra lack the diversity of alkylation series of parent PAHs commonly observed in Murchison and other carbonaceous chondrites. Spatial mappings of aromatic species across the surface of a fragment of sample #4 are presented including detection of what appears to be the aromatic amino acid tyrosine. Potential sources of terrestrial organic contamination are discussed and ruled out as a source of our observations. Meteorites #25 and #16 are found to have the same distribution of PAHs as the Almahata Sitta meteorites. Other chondrites have much different organic fingerprints. We conclude that both an H5 and E chondrite were included in asteroid 2008 TC<sub>3</sub> as foreign clasts and that organic compounds contained in ureilites can spread into other parts of an asteroid.

### INTRODUCTION

Meteorites almost always arrive on Earth as “dead letters,” that is, with no return addresses. It is through great detective work that, only in a few cases, can we suspect where they come from. One example is the howardites, eucrites, and diogenites (HED) meteorites that are thought to originate from the Vesta asteroid family. A rare exception occurred on October 7, 2008,

when asteroid 2008 TC<sub>3</sub> entered the Earth’s atmosphere above the Nubian Desert in northern Sudan. More than 600 meteorites survived on the ground, now called Almahata Sitta, and were recovered 2 months later by a team of students and staff of the University of Khartoum (Jenniskens et al. 2009). The asteroid was detected before impact by the Catalina Sky Survey Telescope on October 6, 2008. The collected meteorites were found to have oxygen isotopes and rare earth

elemental abundances that classified this meteorite as a ureilite. The meteorites contained aggregates of carbonaceous material as large as 0.5 mm in diameter, mostly in highly graphitized form, making this meteorite a candidate for organic analysis (Jenniskens et al. 2009).

These freshly fallen samples are of special interest because other known ureilites are contaminated by terrestrial organic matter. This has complicated the interpretation of the chemical and physical processes that occurred in these unique meteorites. All ureilites are thought to originate from one (now broken) ureilite parent body, hiding somewhere in the asteroid belt as an asteroid family. Because of its volatility, the carbonaceous matter may leave a unique fingerprint on all diverse parts of these asteroids, providing clues to the origin and evolution of the protoplanet (for a review see Goodrich 1992; Mittlefehldt et al. 1998; Jenniskens et al. 2010; Herrin et al. 2010).

Until now, much of the investigation into organic species in meteorites has focused on carbonaceous chondrites (Sephton 2002; Plows et al. 2003; Elsila et al. 2005). Laser desorption laser ionization mass spectrometry (L<sup>2</sup>MS) (Zenobi et al. 1989; Kovalenko et al. 1990; Clemett and Zare 1997) has found a wealth of organic compounds in the Murchison and Allende meteorites, consisting predominantly of polycyclic aromatic hydrocarbons (PAHs) with numerous alkyl side groups.

Some 600 meteorites were collected from the debris of asteroid 2008 TC<sub>3</sub>, spread over a length of 29 km along the asteroid's ground trajectory (Shaddad et al. 2010). Over such a large surface area in a pristine desert, several meteorites would have fallen in the past, unrelated to Almahata Sitta. Indeed, several weathered meteorites were readily identified as having been there prior to the fall. Many anomalous samples (#25, #16, and #41), however, were surprisingly fresh-looking and Shaddad et al. (2010) estimate the nonureilites to be 20–30% of the total mass.

Among the anomalous meteorites, sample #25 was classified as an H5 chondrite by Zolensky of NASA Johnson Space Flight Center (Zolensky et al. 2009, 2010) and subsequently found to have the expected oxygen isotope composition of an H5 chondrite (Rumble et al. 2010). Similarly, three other samples were identified as an EH6 chondrite (#16), an EL6 chondrite (#41), and an L4 chondrite (#A100) (Zolensky et al. 2010). These fragments appeared freshly fallen and of about the same size as nearby meteorites of Almahata Sitta (Shaddad et al. 2010).

Here we report on a study of aromatic compounds found in nine fragments of Almahata Sitta, both ureilites and anomalous meteorites, as determined by

L<sup>2</sup>MS. L<sup>2</sup>MS couples subfemtomolar sensitivity, high selectivity for PAH detection and 50 μm spatial resolution of PAH composition on complex surfaces. This technique combines focused laser-assisted thermal desorption with resonance-enhanced laser multiphoton ionization to produce the high sensitivity, compound selectivity, and spatial resolution that is beyond the capabilities of many traditional analytical methods.

L<sup>2</sup>MS has been widely applied in the detection of aromatic organic species in both extraterrestrial and terrestrial samples including interplanetary dust particles (Clemett et al. 1993; Messenger et al. 1995), meteorites and comets (Zenobi et al. 1989; McKay et al. 1996; Spencer and Zare 2007; Hammond and Zare 2008), hydrocarbon-contaminated soils (Dale et al. 1993), and petroleum fractions (Pomerantz et al. 2008, 2009). L<sup>2</sup>MS is particularly well suited to analysis of samples for which organic contamination is an issue. Application of the technique requires minimal sample processing and handling, thus minimizing the risk of additional sample contamination. This technique has been previously used to assess terrestrial contamination of both meteorites (Plows et al. 2003) and Stardust mission aerogel capture media (Sandford et al. 2006; Spencer and Zare 2007). Additionally, owing to this technique's low detection limits and surface desorption, the required sample size is very small, and analysis leaves the bulk of the sample unaltered and available for further characterization.

Using L<sup>2</sup>MS, we present here analyses that include bulk PAH contents in crushed Almahata Sitta fragments, spatial mapping of the intensity of select PAHs and what appears to be the aromatic amino acid, tyrosine across the surface of a freshly fractured fragment of sample #4, and an analysis of potential terrestrial organic contamination from laboratory handling and storage. We find that the PAH signature of ureilites is distinctive and that some of the anomalous meteorites contain the same mixture of PAHs.

## EXPERIMENTAL TECHNIQUE

### Almahata Sitta Meteorite Sample Preparation

Nine meteorite samples were obtained from the University of Khartoum, Khartoum, Sudan. Of these samples, six were confirmed to be part of the asteroid 2008 TC<sub>3</sub> (sample #1, #4, #7, #15, #27, and #47), based on their common dark appearance and fresh fusion crust and their identification as ureilites (Jenniskens et al. 2009), while three samples (#25, #16, and #41) were of indefinite origin, because of their classification as chondrites. All nine samples were collected in aluminum foil and stored in foil and glass vials to

prevent organic contamination through contact with plastics. Additionally, two samples of desert sand were collected during the meteorite recovery to serve as contamination references for possible terrestrial aromatic compounds present in the Almahata Sitta strewn field.

All meteorite samples were attached to brass sample platters of 7 mm diameter using double-sided tape which contributes no background signal. For bulk organic component analysis, meteorite samples weighing approximately 3 mg were crushed between aluminum foil layers using a mortar and pestle. For spatial mapping of organic species across a sample surface, fresh fragments of each meteorite sample with diameter  $\leq 6$  mm were obtained using a chisel. Each analysis was performed on two fragments of each meteorite sample.

All chemicals used for calibration or sensitivity standards were obtained from Sigma-Aldrich. Investigations into possible sources of contamination were performed on glass microscope slide cover slips (VWR) which were heated under a halogen lamp for 72 h while in contact with potential sources of contamination. These potential contamination sources included: nitrile gloves (Fisherbrand), double-sided tape (Scotch 3M), plastic storage bags (Ziploc), aluminum foil (Fisherbrand), and the Almahata Sitta sample storage containers. Furthermore, samples of sand collected from the meteorite strewn field were analyzed to record the presence of any aromatic organic compounds that may have contaminated the meteorite.

### Two-Step L<sup>2</sup>MS Technique

The laser desorption laser ionization mass spectrometer (L<sup>2</sup>MS) has been described in detail elsewhere (Zenobi et al. 1989; Kovalenko et al. 1990; Clemett and Zare 1997). After introduction of each sample platter to the instrument via a vacuum interlock, the platter is positioned 2 mm below the mass spectrometer's ion extraction region, the instrument is evacuated to  $2 \times 10^{-7}$  torr, and the sample is allowed to outgas for 15–30 min to reduce observed background signal. Constituent molecules on the meteorite sample surface are desorbed by rapid heating (Cowin et al. 1978) via IR light from a pulsed CO<sub>2</sub> laser (Alltech AL 882 APS) focused by a Cassegrainian microscope objective (Ealing Optics, 15 $\times$ ). In order to avoid plasma formation and decomposition while desorbing only neutral species, the IR power used for desorption was approximately 100 mJ per pulse ( $5 \times 10^6$  mJ cm<sup>-2</sup>), which is below the plasma threshold.

After a time delay (10–50  $\mu$ s) during which the plume of desorbed neutral molecules forms in the extraction region, the output of a pulsed Nd:YAG laser

(Spectra Physics DCR11; 4th harmonic,  $\lambda = 266$  nm) is used to selectively ionize organic species containing a phenyl group moiety via (1 + 1) resonance enhanced multiphoton ionization (REMPI). Values of UV pulse energy for ionization are chosen to minimize fragmentation and maximize parent ion signal and typically range from 4 to 8 mJ per pulse (130–260 mJ cm<sup>-2</sup>). The resulting ions are injected into a reflectron time-of-flight mass spectrometer built using a modified Wiley-McLaren geometry (Wiley and McLaren 1955) after which the ions are detected using 20 cm<sup>2</sup> active area dual microchannel plates arranged in a chevron configuration. The detector output then passes through a fast preamplifier (Ortec 9326) and timing filter (Ortec 474) after which it is displayed on a digital oscilloscope (LeCroy 9450). The resulting signal is averaged within the oscilloscope for a series of 7–50 CO<sub>2</sub> laser shots and a computer is used to convert from time-of-flight to mass-to-charge ratio. This conversion is performed by use of two internal standards, toluene and toluene-*d*<sub>8</sub>, which are injected as gases into the sample chamber.

Spectra obtained from powdered meteorite samples to investigate bulk PAH compositions consist of averages of 50 mass spectra repeated with varying desorption (CO<sub>2</sub>) and ionization (Nd:YAG) laser powers as well as varying delay times. Spectra obtained for spatial mapping of selected PAHs across a meteorite sample surface consist of averages of seven spectra acquired using the IR and UV power and delay time settings producing the most intense spectra in the bulk analysis of each sample. Species maps were acquired along two perpendicular transects for each fragment.

## RESULTS

### Bulk PAH Compositional Analysis

Laser desorption laser ionization mass spectra for each of nine obtained meteorite samples as well as a sample of Murchison meteorite are plotted in Fig. 1. Several similarities and differences between Murchison, a chemically primitive CM2 carbonaceous chondrite, and Almahata Sitta are immediately obvious. Unlike Almahata Sitta, Murchison experienced extensive aqueous alteration of its parent body. All ureilite samples (e.g., #4, #27, and #47) showed a distinct pattern of mass to charge ratio (*m/z*) peaks. Individual samples show small but significant variations in the relative abundances of PAHs (see Table 1). Comparison of the Almahata Sitta spectra to those of the Murchison meteorite shows that the Almahata Sitta meteorite contains a much sparser array of aromatic organic species than the Murchison meteorite. Specifically, the

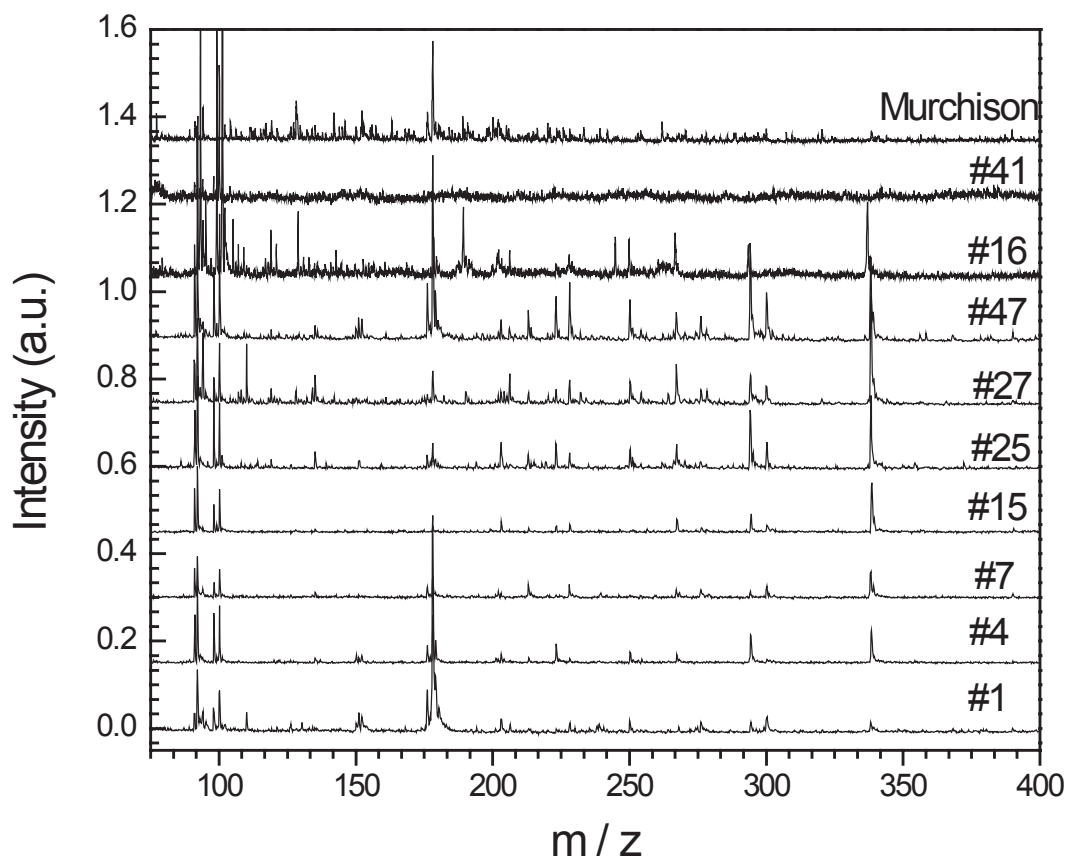


Fig. 1. Laser desorption laser ionization mass spectra of all nine samples obtained as well as a sample of the Murchison meteorite. All spectra were recorded using the same instrumental parameters, as described in the Experimental Technique section. A list of  $m/z$  values occurring in each sample can be found in Table 1.

Almahata Sitta spectra lack the diversity of alkylation series of parent PAHs commonly observed in Murchison and other carbonaceous chondrites (Elsila et al. 2005).

Within the Almahata Sitta samples analyzed, PAHs seem to be somewhat heterogeneously distributed. Some  $m/z$  ratios are commonly observed in samples including  $m/z$  178 (phenanthrene) and 202 (pyrene) among others while others such as  $m/z$  128 (naphthalene) are observed in only one Almahata Sitta sample (Fig. 1 and Table 1).

Surprisingly, as shown in Fig. 1 and Table 1, the spectrum of the nonureilite sample #25 shows a number of PAH peaks in common with the L<sup>2</sup>MS spectra of other Almahata Sitta samples, especially samples #27 and #47. Additionally, two samples determined to be E chondrites (#16 and #41) (Herrin et al. 2010) were studied. Sample #16 appears to have a PAH envelope very similar to that observed in spectra of ureilite samples (Fig. 1; Table 1). Sample #41, however, exhibits a spectrum free of aromatic compounds (Fig. 1), unlike those of other studied Almahata Sitta samples.

### Contamination Experiments

The series of peaks with  $m/z$  135, 223, 267, 294, and 338 (Fig. 1 and Table 1) have previously been observed in this laboratory during its participation in the Stardust mission organics preliminary examination team (PET) (Spencer and Zare 2007). We investigated whether these peaks might arise from contamination during sample preparation. Glass microscope cover slips were exposed to a variety of materials with which the Almahata Sitta meteorite samples may have come into contact. L<sup>2</sup>MS spectra of these cover slips revealed only low intensity peaks at  $m/z$  178 and 202 in the case of the plastic storage bag and no signal in the other cases. No peaks at the  $m/z$  ratios mentioned above were detected.

Two samples of Nubian Desert sand were studied that were handled in the same aluminum foil and containers as the meteorite samples. No aromatic compounds were detected (Fig. 2). This adds to the lack of organic compounds detected in sample #41. Thus, these peaks appear not to be the result of sample handling.

Table 1. Detected  $m/z$  values for nine meteorite samples. The sign “+” indicates the presence and the sign “-” indicates the absence of these peaks.

$m/z$	Ureilites						Anomalous meteorites		
	#1	#4	#7	#15	#27	#47	#25	#16	#41
110	+	-	-	-	+	+	-	+	-
120	-	-	-	-	+	+	+	+	-
128	-	-	-	-	+	-	-	+	-
135	-	-	-	-	+	+	+	-	-
152	+	+	-	-	-	+	+	-	-
178	+	+	+	+	+	+	+	+	-
192	-	-	-	-	+	-	-	+	-
202	+	+	+	+	+	+	+	+	-
206	+	-	-	-	+	+	-	+	-
212	+	+	+	+	+	+	+	-	-
223	-	+	-	+	+	+	+	+	-
228	+	+	+	+	+	+	+	+	-
234	-	-	-	-	+	-	-	-	-
250	+	+	-	-	+	+	+	+	-
267	-	+	+	+	+	+	+	+	-
276	+	-	+	+	+	+	+	-	-
278	+	-	-	-	+	+	+	-	-
294	+	+	+	+	+	+	+	+	-
300	+	-	+	+	+	+	+	-	-
338	+	+	+	+	+	+	+	+	-

Moreover, L<sup>2</sup>MS spectra were obtained along a set of perpendicular transects over the surface of a fragment of Almahata Sitta sample #4 with dimensions of approximately 6 mm by 3 mm (Fig. 3). Normalized intensities of coronene and phenanthrene signals are presented, which have been observed at intervals along the two transects. These  $m/z$  ratios (178 for phenanthrene and 300 for coronene) were chosen because they were detected in all analyzed Almahata Sitta samples and were considered to be ubiquitously present in the 2008 TC<sub>3</sub> asteroid. Additionally, choosing  $m/z$  ratios with strong intensities in sample #4 was a necessary choice due to the limited number of spectra that can be acquired and averaged for each location on the transect. L<sup>2</sup>MS is a surface technique and, if many spectra are obtained from one location on the sample surface, the PAHs in that area are quickly depleted, resulting in artificially low signal intensity.

The signals from these two PAHs are distributed randomly across the analyzed sample surface, exhibiting no trend of increasing or decreasing intensity when moving from the sample edge to the center. Similar random distributions are detected when analyzing other species along these transects not presented here, indicating that our measurements of coronene and phenanthrene are representative. A similar study of

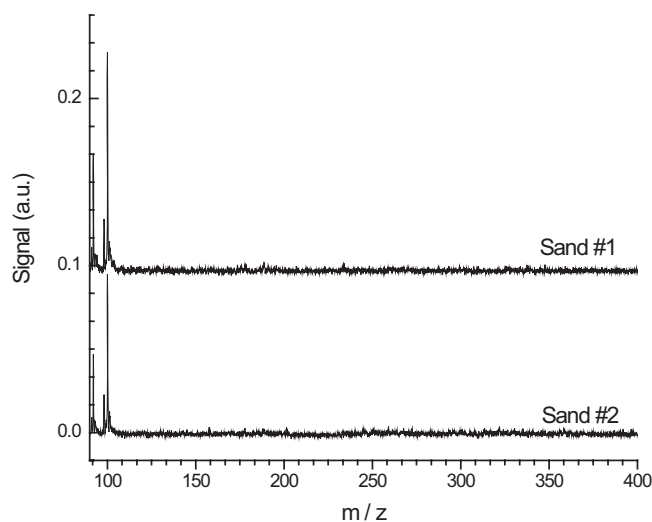


Fig. 2. Laser desorption laser ionization mass spectra of sand #1 and sand #2.

laboratory contamination was performed by Plows et al. 2003, in which a fragment of a meteorite was exposed to solid coronene in a laboratory setting and subsequently analyzed. This study showed a clear trend of decreasing coronene signal as detection moved to 80  $\mu\text{m}$  from the edge; no trend—increasing or decreasing—was detected in the center of the sample.

In addition to detecting PAHs, a peak at  $m/z$  181 was observed at four locations on the surface of Almahata Sitta sample #4 (Fig. 4). We suggest that this peak corresponds to tyrosine, an aromatic amino acid with mass 181, based on the observation of many amino acids in the chromatographic analysis of Almahata Sitta extracts (Glavin et al. 2010). An experiment to measure the L<sup>2</sup>MS sensitivity to tyrosine relative to coronene was performed in which equal masses of coronene and tyrosine were deposited on the sample platter and subjected to the same instrumental conditions used to detect  $m/z$  181 in sample #4. This experiment indicates that the L<sup>2</sup>MS technique is less sensitive to tyrosine than to PAHs.

## DISCUSSION

Laser desorption laser ionization mass spectra of the analyzed Almahata Sitta samples show some similarities in their aromatic organic species features to those observed in carbonaceous chondrites including the Murchison meteorite (Fig. 1). The absence of highly alkylated PAHs in the Almahata Sitta samples supports further the assertion that we have insignificant contamination by atmospheric pollutants. Such alkylated PAHs are widely considered to be constituents of pollution from incomplete combustion in industrial

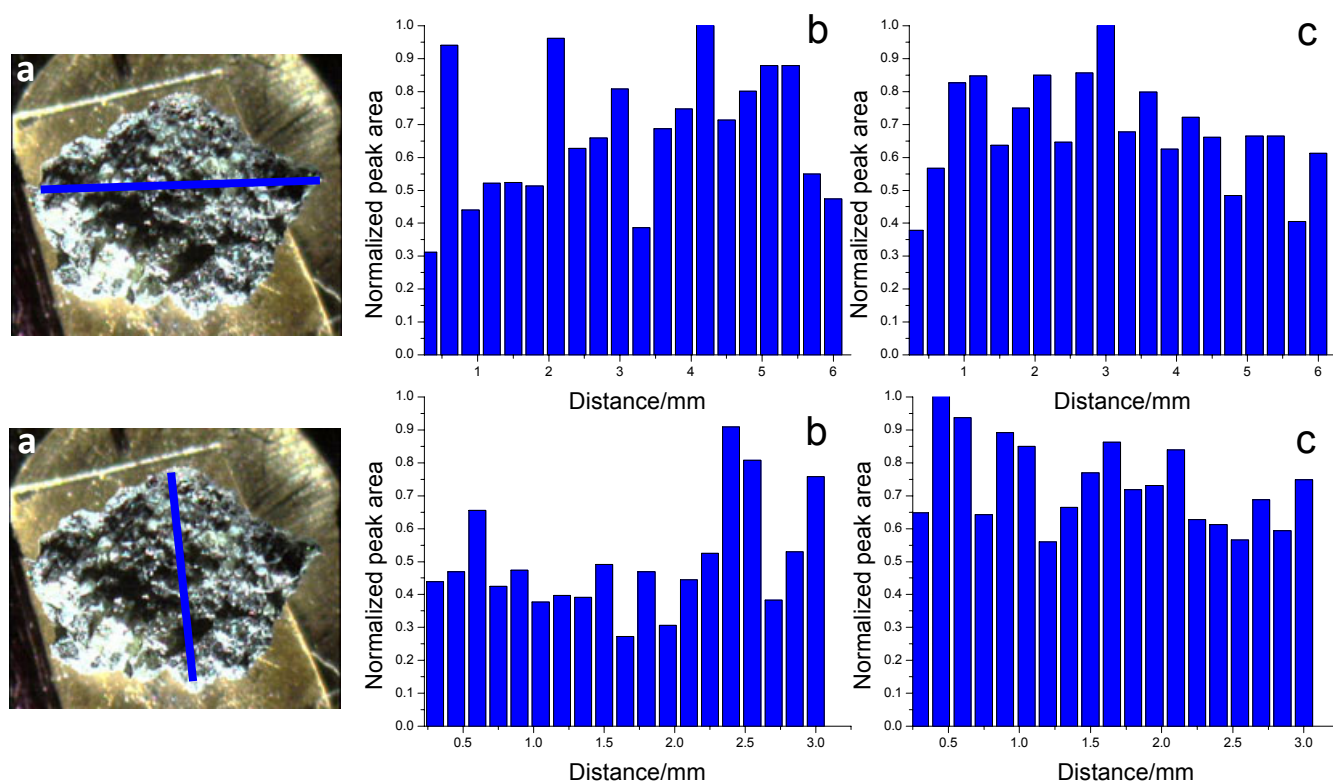


Fig. 3. Spatial map of coronene and phenanthrene across the surface of a fragment of sample #4. a) Transect paths across sample #4 fragment. b) Normalized intensity of coronene signal along transects indicated in (a). c) Normalized intensity of phenanthrene signal along transects indicated in (a).

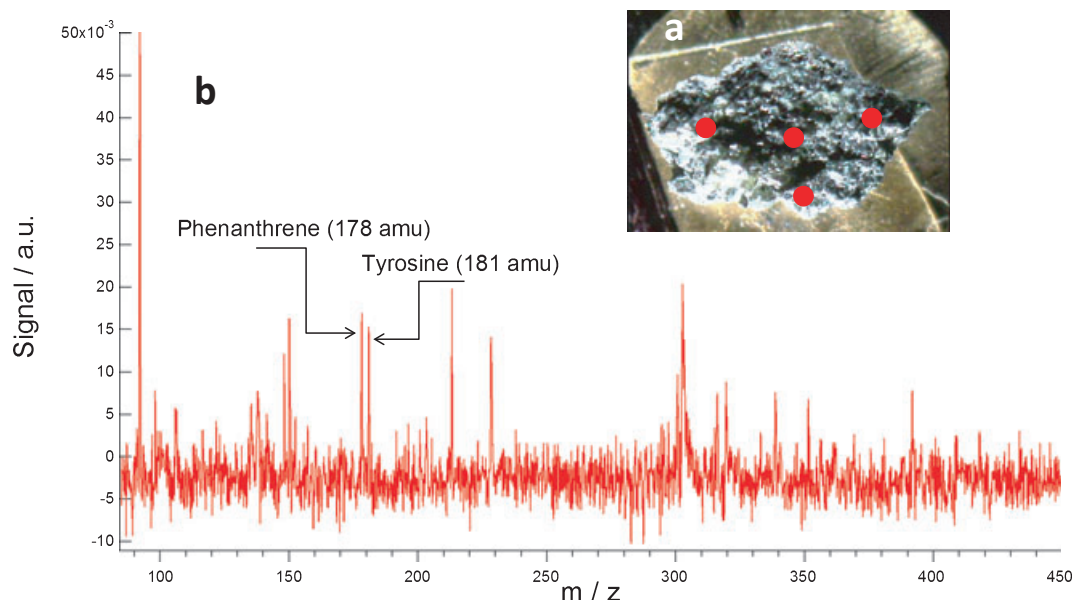


Fig. 4. Detection of  $m/z$  181 (tyrosine) from Almahata Sitta sample #4. a) Approximate locations of detection of  $m/z$  181. b) Sample spectrum showing peak at  $m/z$  181, which is tentatively identified as the amino acid tyrosine.

plants, especially in the Northern Hemisphere (Kawamura et al. 1994; Gingrich and Diamond 2001). In addition, the organics-free spectra of Nubian Desert sand samples and other laboratory materials support the conclusion that meteorite fragments were not exposed to terrestrial organics contamination. Study of relevant laboratory materials revealed only low intensity peaks at  $m/z$  178 and 202 which are observed at much higher intensity from the meteorite fragments themselves, indicating that, while a small portion may be contamination, the bulk of these signals represent species native to the meteorite. Based on this exclusion of terrestrial contamination as the source of PAHs in Almahata Sitta and the observation of relatively high PAH signal intensity, we conclude that these species are native to the asteroid at the time of impact.

The fact that samples #25 and 16 have the same PAH signature as other samples of Almahata Sitta, after excluding a variety of possible terrestrial contamination sources, strongly suggests that samples #25 and #16 belonged to asteroid 2008 TC<sub>3</sub> at the time of atmospheric entry. This result implies that the PAHs in ureilites can spread throughout an asteroid body. The clasts of ureilitic material are found in much smaller units than the approximately 10 m sized fragments which originally were released from the parent body. The ureilites underwent a dramatic reduction in size by numerous violent collisions with other asteroids (Herrin et al. 2010). During the reaccretion of these fragments, foreign chondritic material was mixed in. In subsequent collisions, the asteroids may have been heated to sufficient degree to enable the dispersion of the organic compounds in the ureilite material and thus contaminate the foreign chondritic clasts.

The lack of organic aromatic species in sample #41 invites two speculations as to the origin of this sample. One is that the porosity of #41 prevents the diffusion of PAHs into this sample. The other is that this meteorite originated from an unrelated meteorite fall.

## CONCLUSION

Based on the PAH signature, we conclude that ureilites contain a distinctive range of PAHs and other aromatic compounds. For the sensitive L<sup>2</sup>MS technique—approximately 1 attomole—the freshly fallen Almahata Sitta ureilites are rich in a limited number of PAHs without alkyl side chains. Identification of most of these compounds awaits analysis with a higher  $m/z$  resolution. Other organic compounds may remain undetected because the selectivity of (1 + 1) REMPI for PAHs and other aromatic species blinds us to the presence of compounds such as straight-chain alkanes and nonaromatic amino acids.

The ureilite fragments of 2008 TC<sub>3</sub> did not experience heating above PAH destruction temperatures—several hundred degrees Celsius—during atmospheric entry and catastrophic disruption.

The observed PAH compounds were formed prior to atmospheric entry, but presumably after the catastrophic event that disrupted the ureilite parent body, when temperatures increased to well above the PAH destruction temperature. It is likely that the distinctive set of PAHs were created in subsequent collisions after the pieces of this parent body reassembled into asteroids. Later collisions may have heated the organic matter again, volatilizing the PAHs, and allowing them to spread to any newly aggregated foreign parts, such as samples #25 and #16. The PAH profile identifies both fragments as part of 2008 TC<sub>3</sub> before it impacted Earth's atmosphere.

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