Hot Idea April 30, 2010

Asteroid, Meteor, Meteorite

--- Detected in space less than a day before hitting Earth, the Almahata Sitta meteorite from asteroid 2008 TC_3 gives clues to the complex evolution of small asteroids.

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Almahata Sitta is the name identifying the collection of meteorite remnants of the first observed fall of a tracked asteroid, 2008 TC_3. Ground-based observatories, orbiting satellites, a pilot of a commercial airline flight, and eyewitnesses of the fireball in the Nubian Desert of northern Sudan all observed evidence of the spectacular events on October 6, 2008. The first meteorites were recovered two months later in Sudan by students and staff from the University of Khartoum (Sudan) led by Dr. Muawia Shaddad and further guided by Dr. Peter Jenniskens of the SETI Institute and NASA Ames Research Center (Mt. View, California). A session at the 41st Lunar and Planetary Science Conference held March 1-5, 2010 focused on ureilitic asteroids and insights from Almahata Sitta, and forms the basis for this article. Rather than discuss the results of each of the talks and posters presented at the conference, I highlight what makes the impact, recovery, and characterization of the ureilite meteorite fragments so outstanding. The complete listing of topics is available in the conference program (see reference link below).

Reference:

- Session at the (2010) 41st Lunar and Planetary Science Conference-- Ureilitic Asteroids: Insights from Almahata Sitta Full set of abstracts (pdf).
- Jenniskens, P. and 34 coauthors (2009) The Impact and Recovery of Asteroid 2008 TC_3. *Nature*, v. 458, doi: 10.1038/nature07920.

PSRDpresents: Asteroid, Meteor, Meteorite --Short Slide Summary (with accompanying notes).

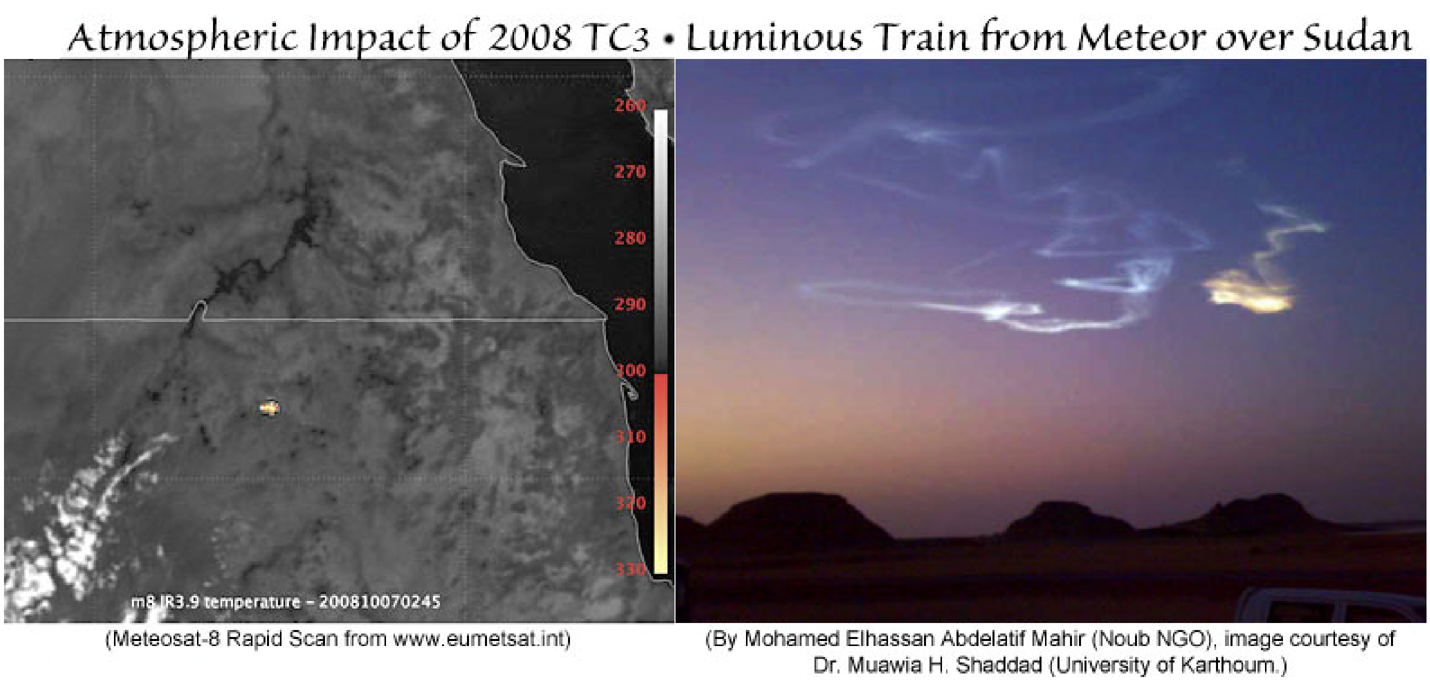
The Story of Asteroid 2008 TC_3

In the early morning of October 6, 2008 an asteroid close to Earth was detected by a Catalina Sky Survey (CSS) telescope at Mount Lemmon, Arizona. The CSS, begun in 1998, is the only near-Earth object survey covering both Northern and Southern hemispheres and obtains about 20 gigabytes of data with each of its three telescopes per night. Observers do near-real-time analysis of Earth-approaching objects, which was the case when CSS observer Richard Kowalski discovered the small (2-meter-diameter) object beyond the orbit of the Moon and moving toward Earth at 12 kilometers per second.

[Left] Telescope observatories at Mount Lemmon, Arizona. [Right] A series of discovery images of asteroid 2008 TC_3 taken at approximately 06:30 UTC on October 6, 2008 with the Catalina Sky Survey's 1.5-meter telescope at Mount Lemmon, Arizona. Credit: Richard Kowalski and Ed Beshore, Catalina Sky Survey. Click this image for a larger version.

The Catalina Sky Survey immediately alerted scientists at the Minor Planet Center in Cambridge, MA and NASA's Near Earth Object Program in Pasadena, CA. From the measured orbital parameters of the asteroid, the scientists calculated the asteroid would hit Earth's atmosphere over the Sudan within 19 hours. Though observatories around the world, both professional and amateur, rapidly supplied additional positional measurements, this asteroid posed no threat because of its small size. It was simply expected to disintegrate and burn up in the atmosphere. [Watch this video interview "Catalina Sky Survey Keeps an Eye on the Skies" from the University of Arizona News.]

As it entered Earth's atmosphere, the asteroid compressed and heated the air in front of it, heating itself and releasing a tremendous amount of light and energy. In those dark, wee hours of the morning on October 7, 2008 a KLM airlines pilot and co-pilot (who had received an alert about the incoming asteroid from the KLM dispatcher) were flying at an altitude of 10,700 meters over Chad and saw three or four short flashes of light beyond the horizon. Other reports of the asteroid's entry into the atmosphere came from U.S. satellites and infrasound signals from at least one ground station. A brief flash was even captured by an infrared channel on the weather satellite Meteosat-8. It disintegrated and exploded at an altitude of 37 kilometers. A high-altitude train of residual clouds lit up the early dawn sky.



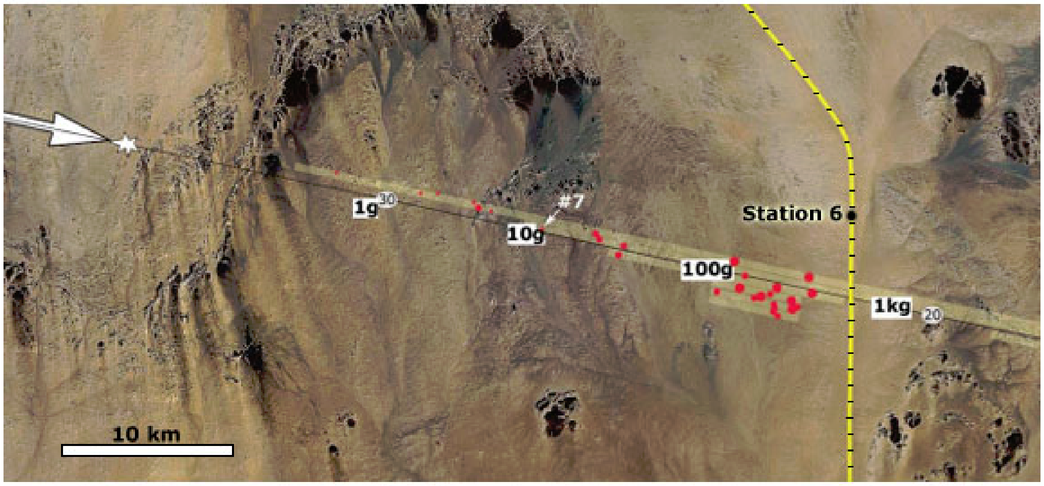
[Left] Infrared image obtained by the Meteosat-8 Satellite Rapid Scanning Service (5-minute interval) acquired October 7, 2008 at 02:45:47 UTC. The yellow and orange pixels in the center of the image show the impact of asteroid 2008 TC_3 in Earth's atmosphere over northern Sudan. Image courtesy of EUMETSAT. [Right] Photo taken from the ground of the high-altitude luminous train of residual clouds from the meteor.

The event was remarkable in itself because it was the first time an asteroid was detected and tracked in space before impacting Earth's atmosphere. Even more remarkable is the notion that pieces of this first observed fall of a tracked asteroid could be held in the palm of your hand.

Finding Fragments of Asteroid 2008 TC_3

The first field expedition to hunt for meteorites from asteroid 2008 TC_3 was organized on December 2-9, 2008 led by Dr. Muawia Shaddad (University of Khartoum, Sudan) and further guided by Dr. Peter Jenniskens (SETI Institute and NASA Ames Research Center, Mt. View, California). The location was Nahr an Nil in the Nubian Desert of Sudan. Students and staff from the university lined up, side by side along a kilometer line, to walk in a coordinated search along the projected ground path of the meteor. To the excitement of everyone, fifteen meteorites were found, totaling 563 grams. The closest recognizable location marker was the railroad's Station 6 located between Wadi Halfa and Abu Hamed. Almahata Sitta in Arabic means Station 6, and so the meteorite earned its name. Two additional searches organized by the University of Khartoum recovered more fragments, for a total number of 280 weighing 3.95 kilograms. The meteorites were found over an area of 28 x 5 kilometers.

Location of Meteorites Collected in December 2008



(From Jenniskens, *et al.* 2009, *Nature*, v. 458, p. 485-488.)

Overlain on this satellite image of the Nubian Desert of northern Sudan are the projected ground path of the meteor (white arrow and thin black line), foot search area (light yellow areas bordering the projected ground path), locations of collected meteorites (red circles, larger sizes signify larger meteorites), and railroad (striped yellow line).

Finding Fragments of Asteroid 2008 TC3 in the Nubian Desert

(Photos by Peter Jenniskens, SETI Institute. http://www.nasa.gov/topics/solarsystem/tc3)
Collage of pictures from the desert showing people in the expedition party finding fragments of the Almahata Sitta meteorite. These photographs and more in higher resolution are available here.

A Briefing on Ureilite Meteorites

Given that the recovered meteorites have been classified as a kind of ureilite, we will begin with a review of this meteorite group before looking at the specific characteristics of Almahata Sitta. Within the class of stony meteorites called achondrites is a group known as ureilites. The story of how they got their name is like any other--based on the location where the meteorite was found--but with a twist. Here is an excerpt from the book **Meteorites and Their Parent Planets** (Cambridge University Press, 1999) by Harry (Hap) Y. McSween, Jr.

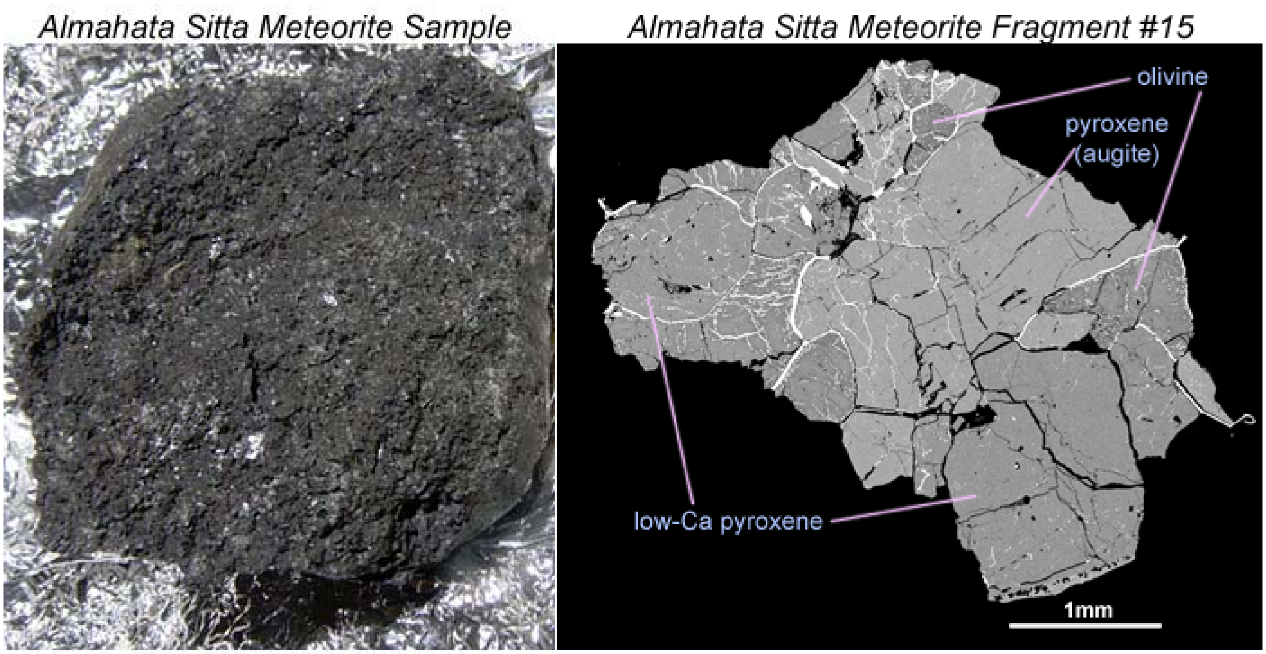
> "On a September morning in 1886, several meteorites fell near the village of Novo Urei in the Krasnoslobodsk district of Russia. This was a particularly interesting fall for several reasons. One of the stones was soon recovered by local peasants, whereupon it was broken apart and eaten. The motivation for this rather unusual action is not known, but this constituted an impressive feat from a dental perspective, because the meteorite contained numerous small diamonds."

Since Novo-Urei, 260 more ureilites have been identified [see the entire listing of ureilites in the Meteoritical Bulletin Database]. Ureilites are coarse-grained ultramafic achondrites chiefly made of olivine and pyroxene, plus tiny grains of graphite (a low-pressure form of carbon), diamond (a high-pressure form of carbon), minor iron-nickel metal, and other minor phases. Cosmochemists specializing in the study of ureilites have discovered that ureilites are igneous rocks with diverse oxygen isotopic compositions that signify incomplete melting of their parent asteroid. The working hypothesis is that ureilites are mantle material that may preserve a unique stage of early differentiation of a carbonaceous-chondrite-like parent asteroid. The diamond most likely came from the original graphite in the rock that was converted by high-pressure shock waves during large impact events on the parent asteroid.

The typical ureilites have nice igneous texture with olivine more abundant than pyroxene. But about 10% of ureilites are fragmental breccias from near the surface of the asteroid. They are mostly made of rock fragments from different parts of the ureilite parent asteroid with about 1% debris from other asteroids.

Characteristics of Almahata Sitta Meteorite

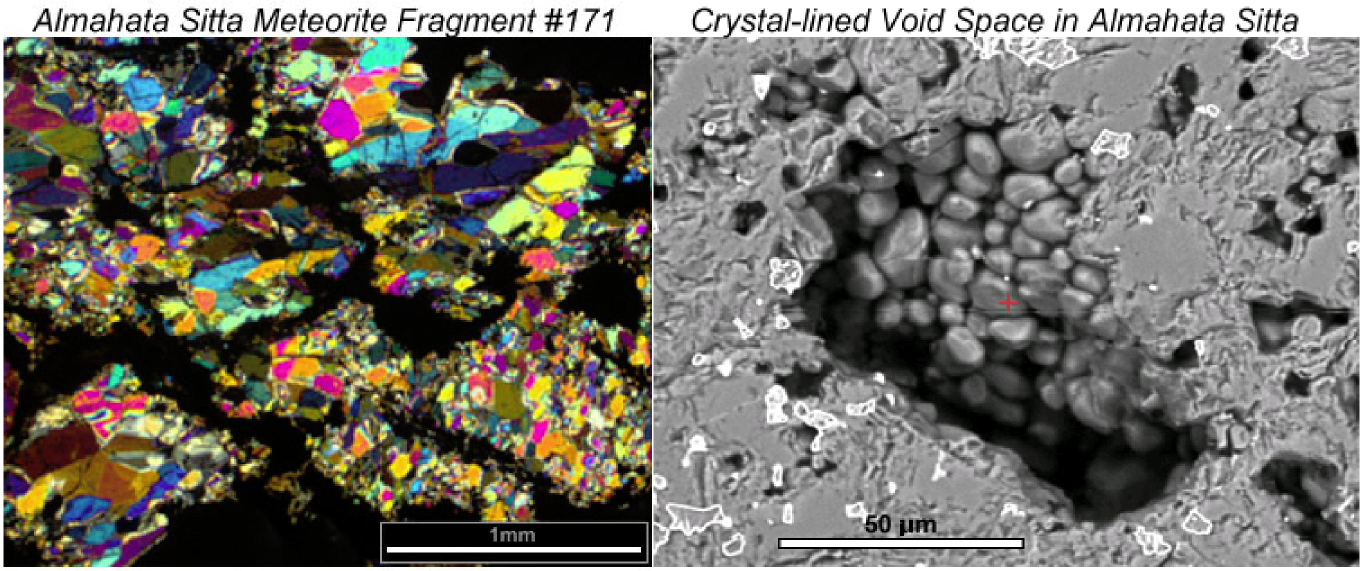
The analyses so far, and the reports from the 2010 Lunar and Planetary Science Conference, identify Almahata Sitta as a remarkable ureilite fragmental breccia of subrounded mineral fragments (commonly milimeter-scale), olivine aggregates, pyroxene aggregates, and aggregates of carbonaceous material, in a matrix of ureilitic material [Data link from the Meteoritical Bulletin]. The carbon is mostly crystalline graphite, but diamond aggregates, up to several micrometers across, have been reported within graphite grains. The term anomalous is applied to this meteorite and refers to its unusual or distinctive textures, namely the large size of carbonaceous aggregates, high porosity, and the overall fine-grained texture of so many of the fragments. The boundaries between clasts are commonly separated by mixtures of carbon-phase+metal+sulfide and/or void space. The void spaces seem to be places where mineral grains were not completely welded together and some voids have crystalline linings. What makes Almahata Sitta even more unique is that it contains dozens of different lithologies making it a spectacular breccia of achondritic and chondritic materials. [For another example of an extraordinary meteorite breccia see **PSRD** article: Kaidun--A Meteorite with Everything but the Kitchen Sink.]



(Peter Jenniskens, SETI Institute. http://www.nasa.gov/topics/solarsystem/tc3)

(Adapted from a slide courtesy of Jason Herrin, NASA Johnson Space Center, cross ref. Herrin *et al.*, 2010, *LPSC*, abstract #1095.)

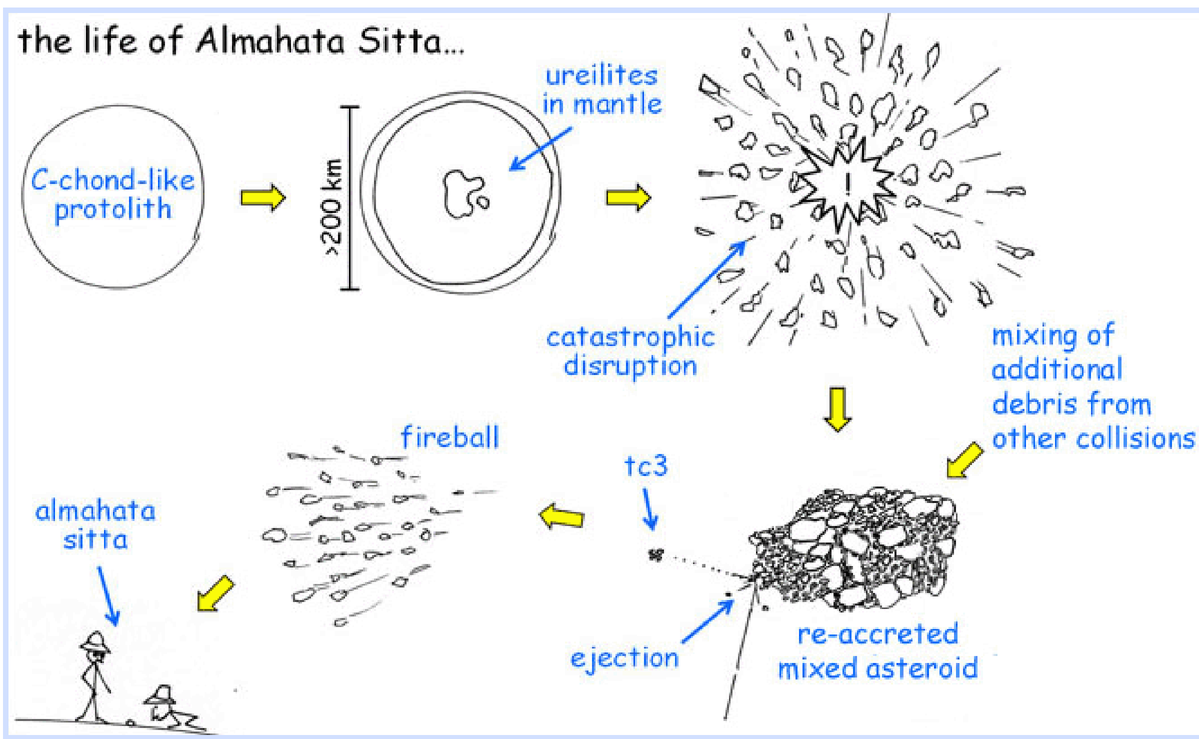
[Left] This fist-sized sample of the Almahata Sitta ureilite meteorite was photographed in the field on a piece of aluminum foil on the second day of the search expedition in the Nubian Desert (December 7, 2008). [Right] Backscattered electron image of an Almahata Sitta ureilite meteorite fragment showing olivine and pyroxene. The white lines are iron metal.



(From Bischoff *et al.*, 2010, *LPSC*, abstract #1763.) (From Zolensky *et al.*, 2010, *LPSC*, abstract #2306.)

[Left] Photomicrograph in cross-polarized light of a coarse-grained Almahata Sitta ureilite meteorite. Major minerals are olivine and low-calcium pyroxene. [Right] Backscattered electron image of an Almahata Sitta meteorite fragment with a void space lined by olivine and pyroxene.

In addition to the different coarse-grained and fine-grained ureilite meteorite fragments, researchers at LPSC also reported on the other kinds of lithologies found in the Almahata Sitta samples. They have found enstatite chondrites (of different kinds; for those of you who need to know: at least EL3, EL3/4, EL4/5, EL5, EL6), H-group ordinary chondrites, and several unique meteorite fragments having, so far, unknown textures and mineralogies. Researchers have also found aromatic hydrocarbons and amino acids (formed by nonbiologic processes, such as the Fischer-Tropsch reaction). From the titles of the presentations at LPSC it's obvious that this meteorite is spurring further research into the fine details of ureilite breccias and asteroid 2008 TC_3 including mineralogy, density, thermal history, magnetism, and geologic evolution.



(Adapted from a slide courtesy of Jason Herrin, NASA Johnson Space Center, cross ref. Herrin *et al.*, 2010, *LPSC*, abstract #1095.)

This illustration shows a possible story of the origin of the Almahata Sitta meteorites, adapted from the LPSC presentation by Jason Herrin (NASA Johnson Space Center) and colleagues. Follow the arrows clockwise from the upper left. Researchers propose that the story begins with a carbonaceous-chondrite-like parent body that was heated and partially melted. This hot body was smashed to smithereens by a major impact and the wreckage cooled and was mixed with debris from other asteroidal collisions. The re-accreted debris assembled into a rubble pile of all sorts of materials, with a regolith accumulated on its surface. Further impacts ejected debris off this rubble pile, sending our asteroid 2008 TC_3 careening through space and eventually through Earth's atmosphere where it broke apart and scattered itself in the Nubian Desert.

Learning More About Ureilites

The tremendous interest in, and motivation behind the work on, Almahata Sitta stems from the important fact that researchers know exactly what asteroid these remnants came from. This event has provided cosmochemists and astronomers new views into the composition and structure of asteroids. For instance, although ureilite meteorites were thought initially to be derived from a S-class asteroid, asteroid 2008 TC$_3$ is regarded as a F-class asteroid based on visible and near-infrared reflectance spectra. F-class objects are found mainly in the asteroid belt at about 2.45 AU and research on the isotopic compositions in the meteorite set a cosmic-ray exposure age of approximately 15 million years. That number represents the length of time asteroid 2008 TC$_3$ was hurling through space to Earth. But where exactly did asteroid 2008 TC$_3$ originate? The Almahata Sitta meteorite is so different from other ureilite breccias that researchers are trying to figure out if it was blasted from deep within the rubble-pile parent body or from the regolith where they think the other breccias came from.

The fascinating details of the ureilites and their parent asteroid (or asteroids) are the subject of much current work and researchers are making a coordinated effort to learn all they can from Almahata Sitta/asteroid 2008 TC$_3$. A consortium has been organized to analyze Almahata Sitta meteorite samples. And another group of research teams is coordinating their analyses of the orbit, spectroscopy, and impact trajectory of asteroid 2008 TC$_3$.

In addition to the session at LPSC, a topical session on the impact and recovery of asteroid 2008 TC$_3$ was held in October 2009 (the one-year anniversary of the fall) at the 41st annual meeting of the Division for Planetary Sciences of the American Astronomical Society. Researchers will discuss more results at Meteoroids 2010--an international conference on minor bodies in the Solar System, on May 24-28, 2010. Still in the works are the detailed papers planned for publication in an upcoming special issue devoted to Almahata Sitta/asteroid 2008 TC$_3$ in *Meteoritics and Planetary Science*, the journal of the Meteoritical Society, which should help satisfy your curiosity about this asteroid, meteor, meteorite.

Additional Resources

LINKS OPEN IN A NEW WINDOW.

- **PSRDpresents:** Asteroid, Meteor, Meteorite --Short Slide Summary (with accompanying notes).

- Goodrich, C. A., Scott, E. R. D., and Fioretti, A. M. (2004) Ureilitic Breccias: Clues to the Petrologic Structure and Impact Disruption of the Ureilite Parent Asteroid. *Chemie der Erde*, v. 64, p. 283-327, doi:10.1016/j.chemer.2004.08.001. [NASA ADS entry]
- Jenniskens, P., Shaddad, M. H., Numan, D., Elsir, S., Kudoda, A. M., Zolensky, M. E., Le, L., Robinson, G. A., Friedrich, J. M., Rumble, D., Steele, A., Chesley, S. R., Fitzsimmons, A., Duddy, S., Hsieh, H. H., Ramsay, G., Brown, P. G., Edwards, W. N., Tagliaferri, E., Boslough, M. B., Spalding, R. E., Dantowitz, R., Kozubal, M., Pravec, P., Borovicka, J., Charvat, Z., Vaubaillon, J., Kuiper, J., Albers, J., Bishop, J. L., Mancinelli, R. L., Sandford, S. A., Milam, S. N., Nuevo, M., and Worden, S. P. (2009) The Impact and Recovery of Asteroid 2008 TC$_3$. *Nature*, v. 458, doi: 10.1038/nature07920. [NASA ADS entry]
- Lunar and Planetary Science Conference (2010) Ureilitic Asteroids: Insights from Almahata Sitta Full set of abstracts (pdf).
- Martel, L. M. V. (October, 2009) Kaidun--A Meteorite with Everything but the Kitchen Sink. *Planetary Science Research Discoveries*. http://www.psrd.hawaii.edu/Oct09/Kaidun_meteorite.html.
- Meteoroids 2010--An International Conference on Minor Bodies in the Solar System (May 24-28, 2010) http://www.cora.nwra.com/Meteoroids2010/
- NASA Solar System News: The Impact and Recovery of Asteroid 2008 TC3, with high-resolution images.
- The night 2008 TC3 was Discovered. A time-lapse sequence of photographs of the telescope and night sky: Catalina Sky Survey's 1.5-meter telescope at Mount Lemmon, Arizona by Richard Kowalski (Full Moon Photography).

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