Forging asteroid –– meteorite links

Ed Cloutis
University of Winnipeg

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Asteroid – meteorite links

- Why do we care? If we can determine asteroid composition, we can answer these questions:
  - What kinds of dynamical processes operated in the early solar system?
  - What kinds of heating processes operated in the early solar system?
  - What in situ resources are available on asteroids that could be economically exploited or used to facilitate extended human presence in space?
  - What kinds of impact hazards does the Earth face? Asteroid composition and structure will determine what impact mitigation strategies may be most effective.
Asteroid science milestones

- First asteroid discovered in 1801 (Ceres)
Asteroid science milestones

- The first indications that the asteroid belt may be geologically diverse came in the 1920s with the discovery of color differences between different asteroids (Bobrovnikoff 1929).
Asteroid science milestones

- The first and most strongly established mineralogical determination of asteroid surface composition and its meteorite association came about in 1970 for asteroid (4) Vesta (McCord et al. 1970).

Telescopic spectrum of Vesta vs. Nuevo Laredo eucrite
Asteroid science milestones

- The first large-scale taxonomic studies, whereby asteroids were categorized into different spectral or color groups, suggestive of both mineralogical diversity and compositional groupings emerged in the late 1970s – early 1980s (e.g., Bowell et al. 1978; Tholen 1984; Gradie and Tedesco 1982).
Asteroid science milestones

The ability to firmly constrain or establish surface mineralogy of spectrally-featured asteroids beginning in the 1970s and extending to more asteroids in the 1980s (e.g., Cruikshank and Hartmann 1984).
Asteroid science milestones

- Spectroscopic surveys of large numbers (hundreds) of asteroids beginning in the late 1970s (Zellner et al. 1985) and expanding during subsequent decades to include more asteroids and expanded wavelength coverage (e.g., Xu et al. 1995; Bus and Binzel 2002; Burbine and Binzel 2002; DeMeo et al. 2009.).
The discovery of mineralogical/spectral diversity across the surfaces of specific asteroids (e.g., Gaffey 1997) and within taxonomic groups (Gaffey et al. 1993), and the ability to derive or at least severely constrain surface mineralogy for spectrally-featured asteroids (1990s).
Asteroid science milestones

- Groundbased telescopic spectral analysis predicted LL ordinary chondrite composition of asteroid 25143 Itokawa (Binzel et al. 2001). Successful sample return by the Hyabusa mission gave ground truth confirmation of this (Nakamura et al. 2011).
Asteroid taxonomy

- We currently categorize asteroids on the basis of common characteristics, mostly reflectance spectra.
- Approximately 25 groups are commonly recognized.
Asteroid – meteorite linkages

- Some meteorites can be traced to specific regions in space or specific parent bodies. Sky scanning cameras can detect meteorites entering the Earth's atmosphere as fireballs and back calculate their orbits (e.g., Halliday et al. 1978; Bland et al. 2009). We were also fortunate recently to detect and study an asteroid prior to its encounter with Earth (2008 TC3) and recover pieces of the asteroid.
While Earth- and space-based investigations can help us constrain asteroid surface compositions, there is no substitute for having a sample of known provenance in hand. Recently we have directly sampled a comet (Brownlee et al. 2006), and a near-Earth asteroid (Itokawa). Future asteroid sample return missions are also scheduled for later this decade (OSIRIS-REx, Hayabusa-2).
Asteroid – meteorite linkages

- Compositional studies of meteorites indicate that they originate from at least many tens of distinct parent bodies. This assertion is based on many lines of evidence, including differences in oxygen isotopic composition, mineralogy/petrology, ages, and cosmochemical elemental abundances (Keil 2000).

(Adapted from Schröder et al., 2008, JGR, Fig. 3, doi: 10.1029/2007JE002990.)
Our meteorite collection is highly non-representative of the compositional diversity of the asteroid belt (Burbine et al. 2002; Vernazza et al. 2008).

There are a number of meteorite types which must have formed in association with other types which have not yet been found.

There are also a number of asteroids whose mineralogy is reasonably well understood, but for which we have no representatives in our meteorite collections (e.g., 44 Nysa, 349 Dembowska).

Complicating determinations of asteroid-meteorite links is the fact that the delivery of meteorites to Earth from the main asteroid belt is normally a multi-step process with various biases.
WAYS OF INVESTIGATING ASTEROIDS

- We have a multitude of ways of investigating asteroids and forging asteroid-meteorite connections. Each method has certain advantages and limitations and some can provide information on both physical properties and composition.

- Sample return provides the capstone of our understanding of asteroid-meteorite connections (Binzel 2012).
WAYS OF INVESTIGATING ASTEROIDS: (1) PHYSICAL PROPERTIES

1. Gravitational interactions, whether involving larger asteroids, asteroids-planets, mutually gravitationally bound asteroids, or spacecraft-asteroid interactions, can reveal asteroid density most directly, and sometimes large-scale internal structures.
WAYS OF INVESTIGATING ASTEROIDS: (1) PHYSICAL PROPERTIES

- Stellar occultations by asteroids can be used to determine asteroid diameter/size.

Ceres

Pallas
WAYS OF INVESTIGATING ASTEROIDS: (1) PHYSICAL PROPERTIES

- Earth-based radar imaging of asteroids can be used to determine size and to place constraints on composition, particularly metal abundance, and surface features and roughness.

Arecibo radar image of asteroid Toutatis
WAYS OF INVESTIGATING ASTEROIDS: (1) PHYSICAL PROPERTIES

- Optical and radar polarimetry can be used to constrain surface texture at about the scale of the wavelength of energy used to make the observations.
WAYS OF INVESTIGATING ASTEROIDS:
(1) PHYSICAL PROPERTIES

- Rotational light curves provide information on asteroid shape, rotation rate, and pole orientation, constraints on their cohesive strength, and identify binaries or higher asteroids by mutual occultations.

Rotational light curve for asteroid 201 Penelope
WAYS OF INVESTIGATING ASTEROIDS: 
(1) PHYSICAL PROPERTIES

- Thermal infrared observations can be used to constrain surface temperature, thermophysical properties, regolith structure and porosity, composition. When combined with albedo, size can be determined.

Thermophysical model of asteroid 951 Gaspra
WAYS OF INVESTIGATING ASTEROIDS: (2) COMPOSITIONAL PROPERTIES

- Asteroid compositional determinations are also possible via multiple techniques.

Dark and bright terrains on Vesta
WAYS OF INVESTIGATING ASTEROIDS: (2) COMPOSITIONAL PROPERTIES

- Density determinations or constraints by gravitational interactions or radar observations. Such observations can be used, at a minimum, to eliminate certain classes of meteorites as being consistent with observations.
- For example, the determined density for asteroid Lutetia (3.4 ± 0.3 kg/m³), is inconsistent with many primitive chondrites (Pätzold et al. 2011). If further reasonable assumptions are made concerning macro and microporosity, compatible mineralogies or meteorite classes are further constrained.
WAYS OF INVESTIGATING ASTEROIDS: (2) COMPOSITIONAL PROPERTIES

- Radar reflectivity can be correlated with metal content. Again, with reasonable assumptions or observations concerning surface properties, asteroidal metal content can be constrained (Shepard et al. 2010).

Arecibo radar image of asteroid 1999 JM8
WAYS OF INVESTIGATING ASTEROIDS: (2) COMPOSITIONAL PROPERTIES

- Elemental analysis using gamma ray and neutron detection produced by cosmogenic nuclear reactions, solar X-ray induced fluorescence and scattering, and radioactive decay. The presence or absence of a number of elements can be determined using these techniques, which have different interaction depths (Prettyman et al. 2012; Trombka et al. 2000). Such data can be used to indicate similarities with specific meteorite classes or to infer or constrain near-surface mineralogy. These measurements must be made in space in proximity to a target asteroid.
WAYS OF INVESTIGATING ASTEROIDS: (2) COMPOSITIONAL PROPERTIES

- The presence of a magnetic field is detectable by spacecraft, and can be used to determine whether intact parent bodies (e.g., Vesta) or the parent body of an asteroid was differentiated and at one time possessed a magnetic dynamo.
WAYS OF INVESTIGATING ASTEROIDS: (2) COMPOSITIONAL PROPERTIES

- Optical polarimetry is sensitive to both surface microstructure and composition, and hence can be used to constrain surface mineralogy. This generally requires observations at multiple phase angles.
WAYS OF INVESTIGATING ASTEROIDS: (2) COMPOSITIONAL PROPERTIES

- Reflectance spectroscopy. Solar radiation reflected from an asteroid surface as a function of wavelength will depend on surface mineralogy. This most widely-used (the largest number of measured objects) technique can be done from Earth or in space and various analytical techniques can be applied to derive mineralogy from reflectance spectra.

(From Clark et al., 2002: Asteroid Space Weathering and Regolith Evolution, in Asteroids III, p. 585-599.)
WAYS OF INVESTIGATING ASTEROIDS: (2) COMPOSITIONAL PROPERTIES

- Thermal emission spectroscopy. In the infrared, asteroids will emit radiation whose intensity as a function of wavelength will depend on temperature, mineralogy, and surface physical properties. Some asteroids that may be spectrally featureless in reflected light may have thermal emission features that can be used to constrain composition.
WAYS OF INVESTIGATING ASTEROIDS:
(2) COMPOSITIONAL PROPERTIES

- Direct imaging. Images acquired during spacecraft encounters and space-based telescopes such as Hubble can be used to detect color or albedo variations on an asteroid that could be indicative of compositional differences.
WAYS OF INVESTIGATING ASTEROIDS: (2) COMPOSITIONAL PROPERTIES

- Dynamical correlations. A direct correlation between orbital characteristics (such as high eccentricity and high inclination) and measured composition is found, for example in distinguishing which near-Earth asteroids may be extinct or dormant comets (Fernandez et al. 2005).
WAYS OF INVESTIGATING ASTEROIDS: (2) COMPOSITIONAL PROPERTIES

- As with the multiplicity of techniques that can be used to constrain physical properties, these observational techniques probe asteroids to different depths and at different spatial scales, providing complementary information to one another.
One issue that hampers our ability to link specific meteorites and asteroids is the lack of multi-technique observations of asteroids.

We are also seeing that as data quality improves and other kinds of observational data become available, traditional asteroid taxonomic classes may include mineralogically diverse bodies.
A further issue that complicates the forging of links is the dynamic nature of the asteroid belt. Once formed, asteroids do not serenely orbit the Sun, untouched. They are subject to impacts over a range of sizes and energies, orbital perturbations, solar wind and galactic cosmic ray bombardment, the vacuum of space, and temperature excursions.

Polymict breccias and the presence of xenoliths are the norm rather than the exception.
LINKING ASTEROIDS AND METEORITES

- The availability of meteorites and samples of known provenance (such as the Hayabusa samples from Itokawa and the Almahata Sitta meteorites from 2008 TC3) is proving to be an extremely valuable resource as we continue to forge asteroid-meteorite links.
- While Itokawa samples yielded a specifically predicted result (Binzel et al. 2001), the much more complex characteristics of the Almahata Sitta meteorite given cause for concern for the ways that telescopic data cannot possibly reveal the full complexity compared with equivalent data collected for meteorites in the laboratory.
- By combining asteroid observational data with models of asteroid orbital evolution and surface modification, and meteorite data such as ejection and exposure ages, we are beginning to fill in the details on how we can better reconcile asteroid and meteorite observations.
EXAMPLES OF DEVELOPED ASTEROID-METEORITE LINKS – VESTA AND HEDs

- One of the earliest asteroid-meteorite links was between (4) Vesta and howardite-eucrite-diogenite meteorites (McCord et al. 1970).
- Initially this circumstantial spectroscopic similarity was deemed dynamically dubious (Wetherill et al. 1987) owing to no plausible pathway from Vesta to the Earth.
- The discovery of the Vesta family (or “Vestoids”; Binzel and Xu 1993) extending from Vesta to resonance delivery zones solidified the link – a link that has stood the test of time and been confirmed by the \textit{in situ} results of the Dawn mission to this asteroid.
EXAMPLES OF DEVELOPED ASTEROID-METEORITE LINKS – ITOKAWA AND LL CHONDRITES

- The return of samples from Itokawa by the Hayabusa mission cemented the inferred relationship between Itokawa and LL chondrites predicted prior to that spacecraft’s launch.
OTHER ASTEROID – METEORITE LINKAGES

- More tenuous than the previous two examples:
  - E-asteroids and aubrites
  - A asteroids and pallasites/brachinites
  - D asteroids and Tagish Lake
  - K asteroids and CV chondrites

- Meteorite-asteroid links can be enhanced when observational data are combined with other lines of evidence, such as location of asteroids near "escape hatches" for delivery to Earth, clusters of meteorite exposure ages, and spectral uniqueness of parent bodies (e.g., Gaffey and Gilbert 1998).
“MISSING” METEORITES

- There are also abundant cases where asteroids exist for which no plausible meteorite analogues have been identified. This mostly includes a number of the low albedo, spectrally featureless asteroids, such as many subgroups of the C superclass.

- Some recently identified asteroids exhibit absorption features diagnostic of ferrous iron-bearing spinel, and while such minerals are present in a number of primitive carbonaceous chondrite meteorites, the inferred overall mineralogy of these asteroids is unlike any known meteorite (Sunshine et al. 2008).
Remnants of the building blocks or the terrestrial planets are likely still present in the asteroid belt. As knowledge of the compositional diversity of asteroids and compositional structure of the asteroid belt and near-Earth asteroids improves, we will be able to better address questions such as:

- Which models of solar system evolution are consistent with any compositional zonations (Walsh et al. 2011)?
- Could the main asteroid belt have provided all the building blocks for the formation of the terrestrial planets?
- Where are the remnant building blocks of the terrestrial planets currently located?
- How do asteroids from the main belt evolve to Earth-crossing orbits and how similar or different are main belt and near-Earth asteroids?
It is likely that our knowledge of asteroid compositions will improve incrementally.

Continuing observations of asteroids using multiple techniques will gradually improve our view of the origin, structure, and composition of these important building blocks of our solar system.

Significant advances can be made by targeting sample return missions to representatives of key asteroid taxonomic classes, such the C-group, for which our understanding of composition is tenuous.
Selected references


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