

## Hot Idea

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# The Composition of Asteroid 433 Eros



--- X-rays and reflected light suggest that asteroid 433 Eros is similar in composition to the most common type of meteorite--maybe.

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The Near-Earth Asteroid Rendezvous (NEAR) mission spent about a year orbiting the asteroid 433 Eros, a 33 x 13 x 13 km chunk of rock. The main goal of the mission was to determine the chemical and mineral make up of the asteroid and to try to settle an argument about the nature of S-asteroids. S-asteroids are a somewhat diverse group of little planets with similar characteristics in the spectra of light reflected from them. The consensus was that they are mixtures of iron-magnesium silicates with some metallic iron, but that is where the agreement ended. Some scientists argued that S-asteroids are like ordinary chondrite meteorites, which are unmelted rocks left over from when the solar system formed. Others argued just as vigorously that S-asteroids are differentiated objects, little worlds that were melted soon after they formed. Using measurements of x-rays emitted from the asteroid and light reflected off it, the consensus is that Eros is more like an ordinary chondrite than any other type, though a little bit of melting cannot be ruled out. This measurement of one S-asteroid, however, has not settled the argument. More asteroids need to be visited and samples returned from them.

### References:

Clark, Beth E. and 11 others (2001) Space weathering on Eros: Constraints from albedo and spectral measurements of Psyche crater. *Meteoritics and Planetary Science*, vol. 36, p. 1617-1637.

McCoy, Timothy J. and 16 others (2001) The composition of 433 Eros: A mineralogical-chemical synthesis. *Meteoritics and Planetary Science*, vol. 36, p. 1661-1672.

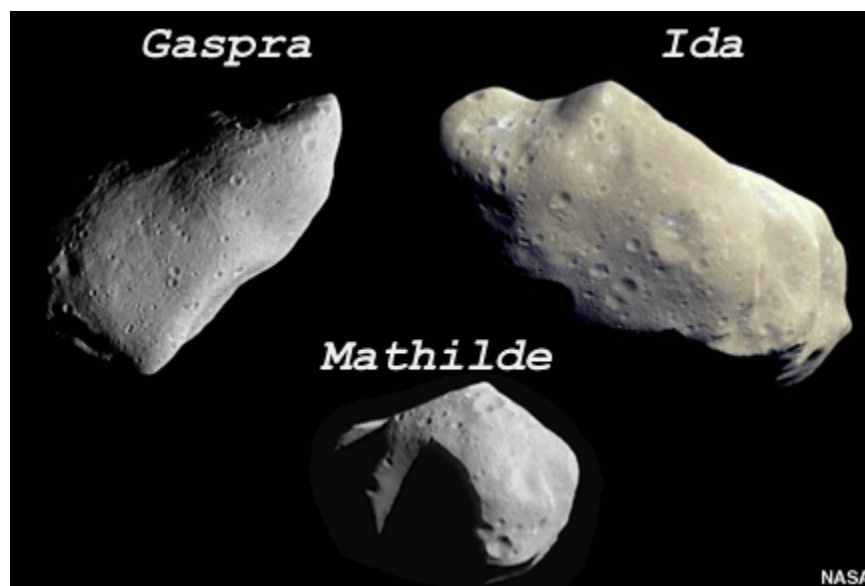
Nittler, Larry R. and 14 others (2001) X-ray fluorescence measurements of the surface elemental composition of asteroid 433 Eros. *Meteoritics and Planetary Science*, vol. 36, p. 1673-1695.

McFadden, Lucy A. and 7 others (2001) Mineralogical interpretation of reflectance spectra of Eros from NEAR near-infrared spectrometer low phase flyby. *Meteoritics and Planetary Science*, vol. 36, p. 1711-1726.

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## The importance of asteroids

Asteroids are planets whose growth was stunted when the solar system formed. This probably happened because of the rapid assembly of Jupiter, the largest planet. Jupiter's huge gravity field would have distorted the orbits of objects in the asteroid belt between Mars and Jupiter, preventing formation of a large planet. Instead, we ended up with a plethora of tiny planets. This turns out to be a lucky thing because asteroids preserve a record of the processes that operated as the solar system was forming from a cloud of gas and dust. They are also a natural laboratory for studying what happens when small bodies melted, sometimes forming cores and mantles like the Earth. Asteroids give us clues to the nature of the planetesimals that accumulated to form the planets. Besides providing this scientific treasure, asteroids might someday provide other kinds of treasure-- resources for space settlers throughout the solar system.



Gaspra, irregular in shape, measures 19x12x11 kilometers and is littered with impact craters. It might be a piece of a larger asteroid that was blown apart by a giant impact. Ida is a big sister look-alike to Gaspra, measuring 55 kilometers long. Mathilde, 59x47 kilometers, is also decorated with countless craters, some of which are very large. Scientists suspect that its angular shape resulted from violent impacts.

We have a huge number of samples of asteroids in the form of meteorites. These fascinating stones that fall from space contain lots of great information about the formation of the solar system and how small bodies melted. The only problem is that we do not know which asteroid each type of meteorite comes from, with one exception. The exception is a group of meteorites called howardites, eucrites, and diogenites (nicknamed HED meteorites). The HED meteorites apparently come from asteroid 4 Vesta. All the other types of meteorites come from somewhere out there, but we do not know where. The [Dawn](#) mission will orbit Vesta for a year, gathering photogeological, mineralogical, and chemical data, then move on to the largest asteroid 1 Ceres.

Asteroid specialists have tried to establish a link between some types of meteorites and specific asteroids or group of asteroids. Asteroids can be classified astronomically by the nature of the light reflected from them. One group of asteroids, the S-asteroids, has been the subject of spirited debate during the past two decades. One school of thought identified them as related to ordinary chondrites, the most common type of meteorite observed to fall on Earth. Chondrites were not melted after their components accreted to form asteroids and, thus, contain a wealth of information about the gas cloud surrounding the primitive Sun. The spectra of light reflected from S-asteroids does not match the spectra of chondrites measured in the laboratory, but scientists who advocate that S-asteroids are chondrites appeal to space weathering. Cynics might say that there is nothing like a mysterious process to help save your idea from the harsh reality of data, but we know from studies of the Moon that the spectral properties of planetary materials are changed by exposure to solar wind and micrometeorite impacts. We do not know much about space weathering on asteroids. Understanding it better was a goal of the NEAR mission.

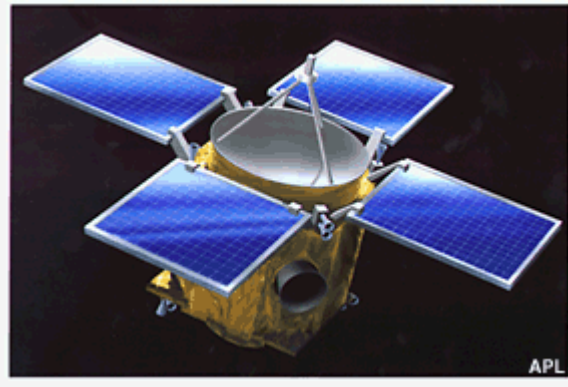
A second school of thought interprets S-asteroids as being small planets that were chemically processed to varying extents. Some might have melted so much that they formed cores and mantles. Others might have melted partially to form surfaces covered with lava flows. Others might have melted only a tiny amount, causing modest redistribution of rock and metallic iron and iron sulfide. Some S-asteroids have spectra similar to some partially melted meteorite groups, but not all do.

So, we have a dilemma: Two schools of thought arguing over ambiguous data. The spectra of reflected light cannot be interpreted in any straightforward way. (The record of the debate about S-asteroids and meteorites suggests, however, that the spectral observations can be over-interpreted in imaginative ways!) What we need is chemical compositions of the surface materials and new ways of determining the identities and abundances of the minerals present on the surface. NEAR gave us chemical information and improved spectral observations.

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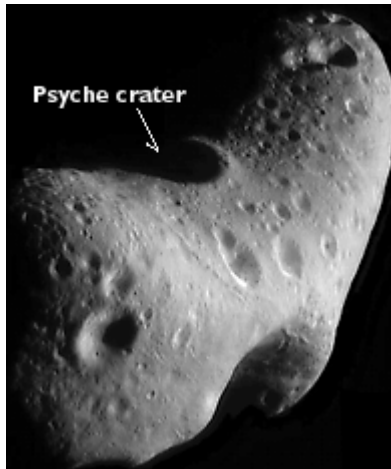
## The NEAR-Shoemaker Spacecraft

NEAR is one of the better acronyms in NASA's acronym-rich history. It stands for Near-Earth Asteroid Rendezvous. In March 2000 the spacecraft was named after Eugene Shoemaker, a brilliant, insightful planetary geologist and great man. Gene Shoemaker showed us that asteroid impact is an important process that shaped the planets. He also established the lunar geological time scale, which allowed us to date the relative ages of features on the Moon.



Artist's conception of the NEAR-Shoemaker spacecraft in space. The instrument payload is in the golden area beneath the blue solar cells. The high-gain antenna above the solar cells is 1.5 meters across and was used to send data back to NASA's deep space network on Earth. Courtesy Applied Physics Laboratory.

The spacecraft was sent to asteroid 433 Eros, which is one of numerous asteroids whose orbits approach that of Earth. These are relatively easy to get to, therefore requiring less fuel than do asteroids way out in the main belt between Mars and Jupiter.



Eros, 33 x 13 x 13 kilometers, looks like a giant peanut. Like other asteroids, Eros is pockmarked with craters, the largest of which is Psyche (5.3 km in diameter) indicated by the arrow.

NEAR-Shoemaker carried several instruments, but two are central to determining the mineralogical and chemical composition of the asteroid: the x-ray gamma-ray spectrometer (XGRS for short) and the NEAR infrared spectrometer (NIS). The XGRS is really two instruments, one that detects x-rays generated by high-energy x-rays from the Sun, and another that detects gamma rays generated in the asteroids by cosmic rays. Both give elemental abundances, but during the mission the gamma ray spectrometer had some difficulties and did not return useful data from orbit. The x-ray spectrometer returned the abundances of magnesium, aluminum, silicon, iron, calcium, and sulfur.

The NIS was a spectrograph that used a diffraction grating to disperse the infrared light reflected from the asteroid onto two electronic detector arrays. The instrument recorded the intensity of light reflected at 64 different wavelengths between 804 and 2732 nanometers. It was able to measure rectangular regions on the surface of about 650 x 1300 meters, or square regions 1300 x 1300 meters. Because different minerals have specific spectral characteristics, the NEAR team hoped that they could identify the types of minerals present on the surface.

NEAR-Shoemaker also carried a color camera called the multispectral imager (MSI). The MSI provides visible and near-infrared images of the asteroid surface, with a spatial resolution of 10x16 meters from 100 kilometers away. It has an eight-position filter wheel covering the spectral range from 450 to 1100 nm (visible to near infrared).

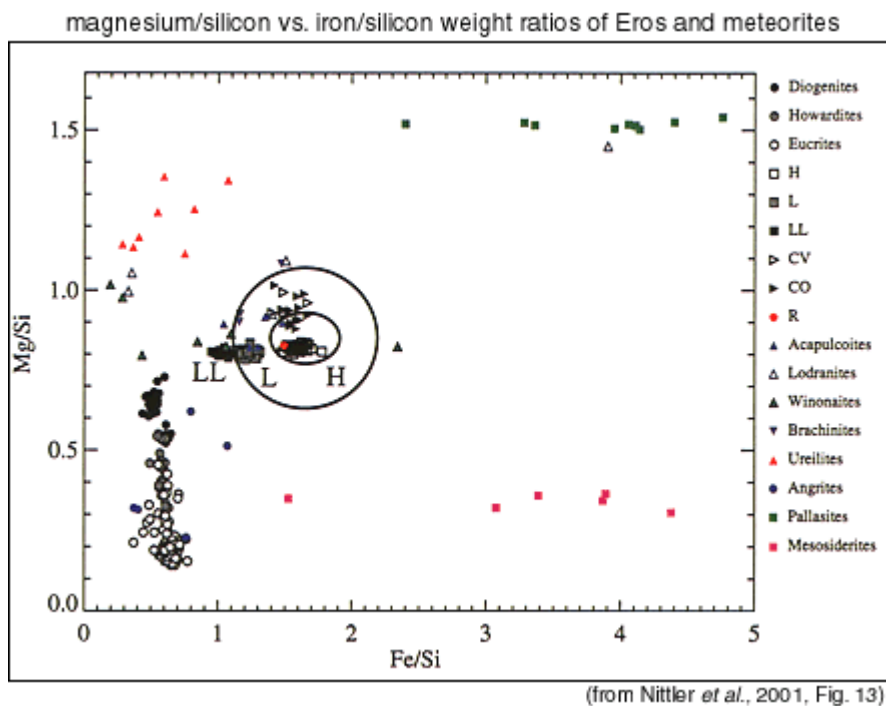
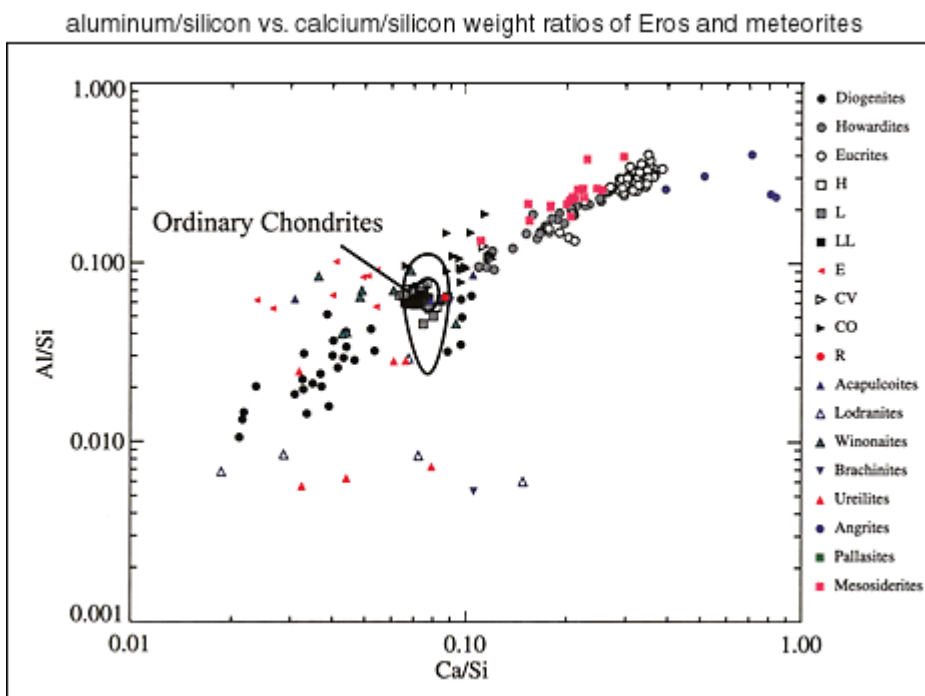
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## Chemical composition of Eros

**D**ata from the x-ray spectrometer consists of counts of x-rays with different energies. It takes a heroic effort to convert these to percentages of elements (see article by Nittler and others). In fact, it is almost impossible to obtain reliable estimates of elemental abundances. Instead, the NEAR team used ratios of elements. These work just as well for most purposes.

The diagrams below show the some of the NEAR data (aluminum/silicon vs. calcium/silicon, and magnesium/silicon vs. iron/silicon) as circles with symbols for numerous types of meteorites. The circles represent variations in the measurements of different regions on Eros (large circles) or the uncertainty in the mean of the data (small circles). Meteorites that formed by melting on their parent asteroids do not match the composition determined for Eros. The HED meteorites (howardites, eucrites, and diogenites) are basalt lava flows (eucrites), coarse-grained

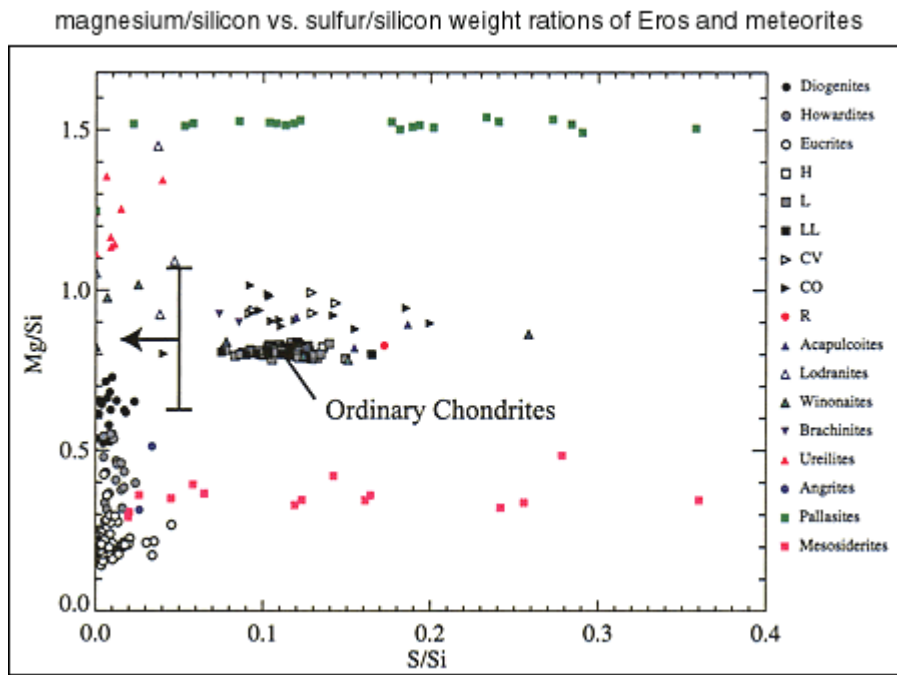
igneous rocks (diogenites), or mixtures of the two (howardites). They are very different in composition from Eros. Angrites are basaltic meteorites with substantial amounts of calcium, making them clearly different from Eros. Pallasites and mesosiderites are mixtures of rock and metallic iron, and their compositions plot far from the Eros analyses. Ureilites are complicated carbon-bearing rocks that appear to be the residues from partial melting of an asteroid. Their compositions, especially their high Mg/Si, rule them out as candidates for Eros. So, all those meteorites can be ruled out on compositional grounds. This means that Eros did not undergo a global melting event.



The data imply that Eros is somewhat primitive in composition. Chondritic meteorites are good candidates, and the ordinary chondrites (H, L, and LL types) consistently fall inside the Eros bull's eye on the diagrams. The compositions of enstatite (E) chondrites and two types of carbonaceous chondrites (CV and CO) are not as consistent and can probably be ruled out. R chondrites (another type of carbonaceous chondrite) fall within or close to the Eros ranges and remain viable candidates. There are other types of fairly primitive meteorites and their compositions are generally consistent with that of Eros. These include acapulcoites and lodranites, which come from the same asteroid, winonaites, and brachinites. All have been melted to varying amounts, but not so much that their compositions are drastically altered from that of chondrites.

One measurement surprised the NEAR team. The sulfur/silicon ratio is far below that of ordinary chondrites (see diagram below). Does this rule out ordinary chondrites? Certainly not--we can always appeal to space weathering. The surface of airless bodies like asteroids, the Moon, and Mercury are bombarded with solar wind ions and micrometeorites. Nittler (Carnegie Institution of Washington) and others calculate that the

upper 5 cm of Eros could have lost all its sulfur in 10 million years. Since the x-rays used for chemical analysis come from the upper 100 micrometers, we would expect a low sulfur/silicon ratio.



Although most chemical parameters provide good fits between ordinary chondrites and Eros, the x-ray spectrometer measurements indicate that sulfur is much lower than in ordinary chondrites. This might be due to space weathering effects involving the volatilization of sulfur, or partial melting that removed sulfur-rich melts from the body.

There are other explanations for the low sulfur on Eros, and Nittler and colleagues review them. If it is not just a surface effect, and the entire body is depleted in sulfur, perhaps it simply formed that way. However, we have no primitive extraterrestrial material that contains so little sulfur. This explanation is unlikely. Alternatively, the sulfur might have been lost through partial melting. As mixtures of iron, nickel, and sulfur are heated, the first melt to form is very rich in sulfur, containing about 30 wt%. Lodranites, which are the residues of partial melting, have very low sulfur/silicon ratios. They lost their sulfur by migration of the first, sulfur-rich liquid to form. Nittler argues that it might not be easy to lose the sulfur-rich melt without melting the silicate, too. However, calculations by my colleagues Lionel Wilson and Klaus Keil show that sulfur-rich melts might be driven to the surface so fast that they would escape an asteroid. For now, the NEAR team favors the space weathering explanation.

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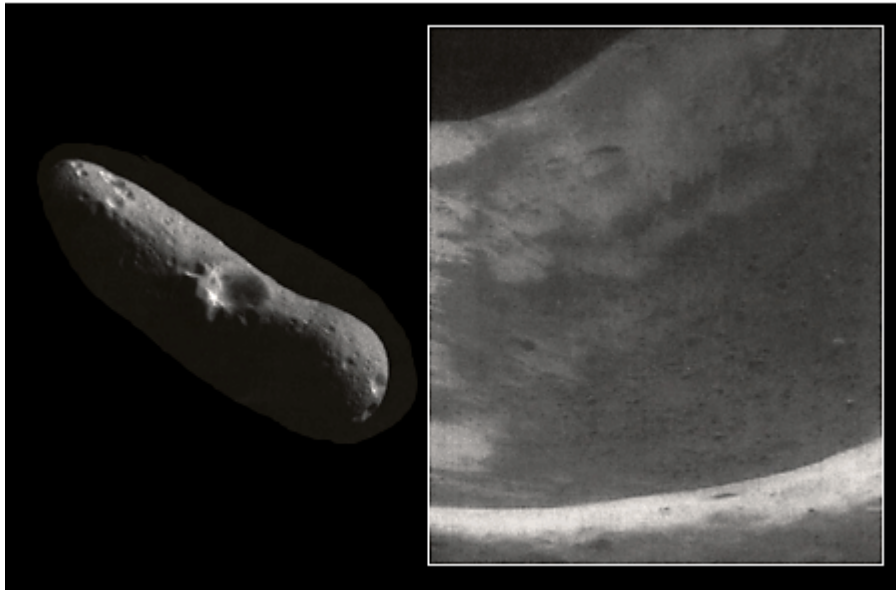
## Mineralogical composition of Eros

Most minerals reflect visible and infrared light in unique ways. In principle, this allows us to identify which minerals are present, a key aid to rock identification. Too bad it is not easy to do. The way light reflects depends on the grain sizes of the minerals, the temperature, the sun angle, and the extent of space weathering, besides what minerals are present. Spectroscopists must also calibrate the camera system. It is all quite tricky (and explains why I work with other types of data).

An important and striking characteristic of the spectra of light reflected from Eros is that it is virtually the same everywhere, except for some areas being brighter than others are. Compositional variations are no more than a few percent. This is what one would expect from an unmelted asteroid or from one melted only very slightly. Lucy McFadden (University of Maryland) and co-authors made a detailed study of the spectra taken of Eros and conclude that the spectral properties are consistent with that of an ordinary chondrite.

Beth Clark (Ithaca College) and her colleagues studied spectra of Psyche crater to try to understand the process of space weathering. Even in the low gravity of a small asteroid, rock and dirt can slide downhill, leaving behind patches of fresher, lighter materials. The lighter materials may have experienced less space weathering, so by comparing light and dark areas it may be possible to understand the process.

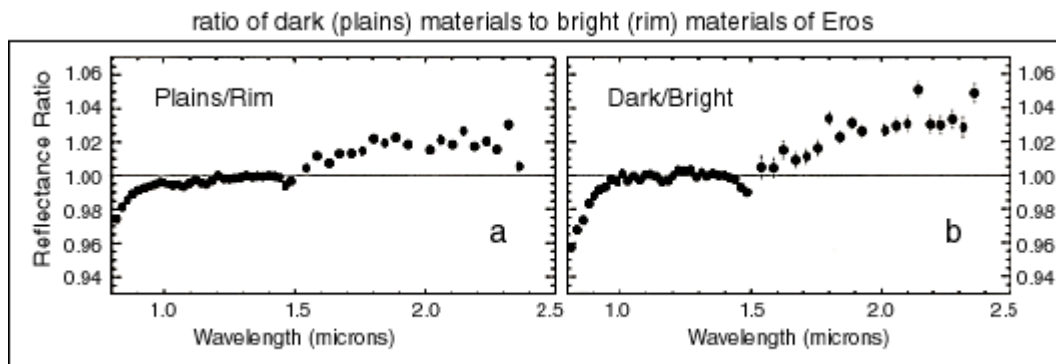
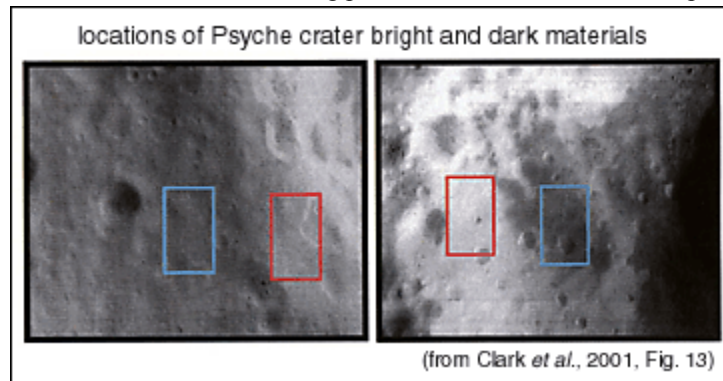
## Psyche crater on asteroid 433 Eros



(from Clark *et al.*, 2001, Figs. 1 and 2)

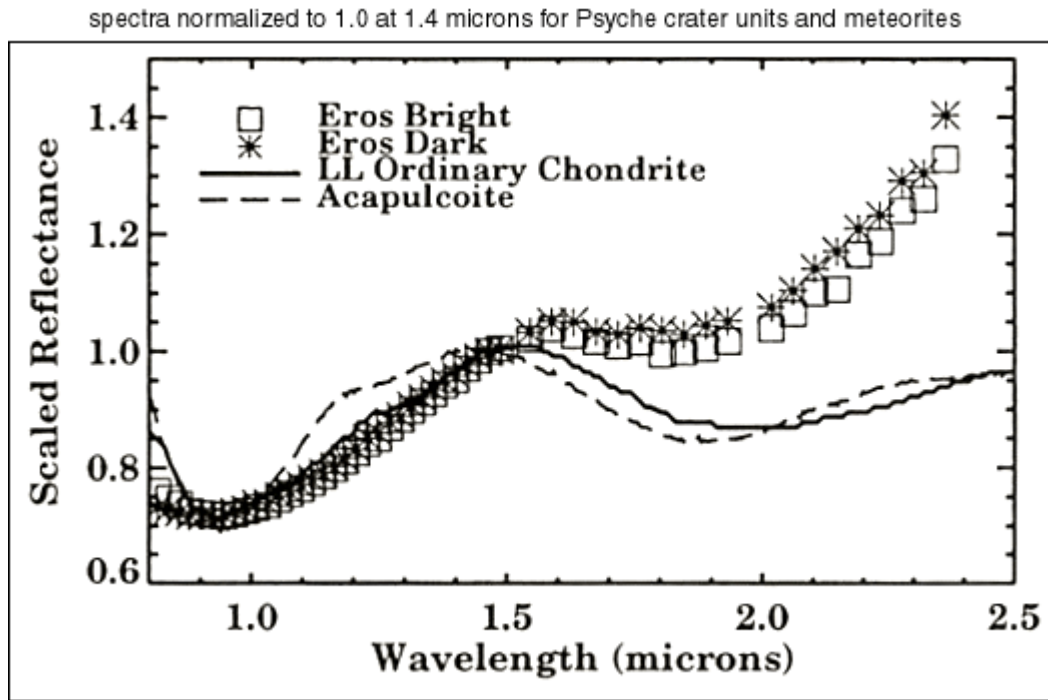
Psyche crater (5.3 kilometers in diameter) dominates one hemisphere of Eros (left). Peeking inside the crater (right) we see lighter and darker regions formed when materials moved down the steep slopes. Note the boulders (several meters across) collected in the bottom of the crater.

The spectra taken of lighter and darker areas in Psyche differ by several percent. Several factors affect the spectra of reflected light: the sizes of the grains making up the surface, the amounts of olivine and pyroxene (iron-magnesium silicates), and the effects of space weathering. These effects can be modeled mathematically. Clark's modeling calculations indicate that the spectral variations in Psyche cannot be caused solely by variations in grain size, olivine, pyroxene, or a moon-like weathering process. Other factors must be operating.



Beth Clark concludes that the spectral variations might be caused by an enhanced concentration of iron sulfide (the mineral troilite), which darkens the material, combined with lunar-like space weathering. This would seem to be contradictory to the XGRS data, which indicate that sulfur is depleted on the surface of Eros. However, it takes only a few percent of a dark mineral to affect the brightness of a surface deposit. Overall, the spectral properties of even the freshest surfaces do not make perfect matches for ordinary chondrites or primitive achondrites, the best candidates for matching the composition of Eros. Chondrites are a good match at wavelengths up to 1.5 microns, but depart significantly at longer wavelengths. Primitive achondrites such as acapulcoites do not fit as well even at wavelengths shorter than 1.5 microns. The best bet is

that space weathering has affected the surface materials and altered the spectral properties.

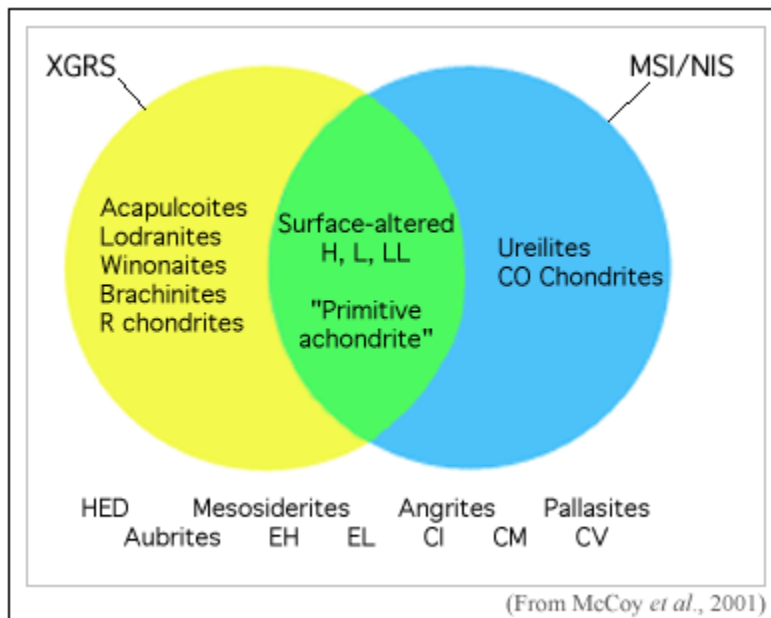


(from Clark *et al.*, 2001, Fig. 25)

This is a plot of the relative amount of light reflected in wavelengths from 0.8 to 2.5 microns on Eros. The Eros data are compared to LL ordinary chondrites and a primitive type of achondrite called acapulcoites. Clark and co-workers scaled the reflectance to be exactly 1 at 1.4 microns so the shapes of the spectra could be compared easily. Chondrites are similar at wavelengths less than 1.5 microns, but differ at longer wavelengths.

### Putting it all together

Tim McCoy (Smithsonian Institution) and others synthesized all the observations to derive the best guess as to what type of meteorite is most similar to Eros. They examined the data in detail and tried to devise a unique solution. Unfortunately, they conclude that a unique solution is not possible. Nevertheless, they do show that the possibilities are reasonably narrow. Using a Venn diagram, they infer that only ordinary chondrites (if space weathered) and primitive achondrites match both the XGRS chemical data and the MSI, NIS mineralogical data. Venn diagrams are used in mathematics to show the relationships between sets, but they have many other uses as well.



(From McCoy *et al.*, 2001)

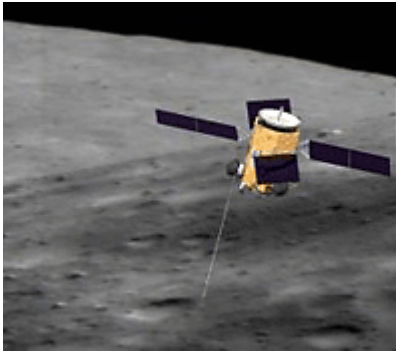
In this diagram, only those types of meteorites that satisfy both chemical and spectral data are likely candidates for Eros.

In the Venn diagram, the types of meteorites outside any circle do not have chemical or spectral properties like those of Eros. Some meteorite groups (acapulcoites, lodranites, winonaites, brachinites, and R chondrites) have chemical compositions consistent with that of Eros, but do not match in spectral properties. Conversely, ureilites and CO chondrites are similar to Eros spectrally, but do not match in chemical composition. Only surface-altered chondrites and a type of as-yet-undiscovered primitive achondrite are likely candidates.

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## What next?

The NEAR science team did excellent, creative work in trying to determine which, if any, type of meteorite matches the properties of Eros. No type fits exactly, though some candidates are clearly better than others. We need more precise mineralogical and chemical data of both surface materials and bedrock. As McCoy and his colleagues note, the way to get the highest fidelity information is to return samples from asteroids to Earth for intense study in laboratories. Scientists studying the materials would be able to see what space weathering processes operate on asteroids, the relation of bedrock to altered materials, and the detailed nature of the rock making up each asteroid from which we grab samples. Such a mission would also carry remote sensing instruments to help select sampling sites.



Derek Sears (University of Arkansas) and a group of colleagues are developing a concept for an asteroid sample-return mission. The spacecraft would obtain samples from several places on three different asteroids and return them to Earth. This artist's rendition of the Hera concept is courtesy of The Arkansas-Oklahoma Center for Space and Planetary Science.

## Additional Resources

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Clark, Beth E. and 11 others (2001) Space weathering on Eros: Constraints from albedo and spectral measurements of Psyche crater. *Meteoritics and Planetary Science*, vol. 36, p. 1617-1637.

### [Dawn mission](#)

McCoy, Timothy J. and 16 others (2001) The composition of 433 Eros: A mineralogical-chemical synthesis. *Meteoritics and Planetary Science*, vol. 36, p. 1661-1672.

Nittler, Larry R. and 14 others (2001) X-ray fluorescence measurements of the surface elemental composition of asteroid 433 Eros. *Meteoritics and Planetary Science*, vol. 36, p. 1673-1695.

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