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Asteroids: Origin, Distribution and Relation to Meteorites

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Abstract: Asteroids are the remnants of the processes that occurred in the early solar system and of the bodies that were the building blocks of the terrestrial and gas giant planets. Many of the primitive asteroids contain materials that formed in the early solar system (organics, ices, minerals, refractory phases) and have later been partially to completely altered by different processes. Other asteroids contain materials that formed due to the partial or complete melting and differentiation of precursor materials. Knowledge about the composition and properties of asteroids comes from the study of meteorites, which are derived from different types of asteroids. Additionally, the ground- and space- based telescopes have also significantly enhanced our understanding of asteroids. We now know that the evolution and present distribution of asteroids were affected by complex dynamic processes such as impacts, gravitational forces, and migration of giant planets like Jupiter and Saturn. Using the study of meteorites and telescopic data, asteroids can be divided into different groups based on their mineralogy and spectral properties. All this information about asteroids has helped us in understanding the conditions and processes that occurred during the formation of the solar system, how the different planets formed and evolved, how water and volatiles came to Earth, which meteorites belong to which asteroid class, and solutions to many other questions. The past and present spacecraft missions to different asteroids have and will bring valuable samples for study using different state-of-the-art analytical instruments and will help in further enhancing our understanding of asteroids.
Keywords: Asteroids, asteroid-belt, meteorites, reflectance-spectroscopy.

Introduction

Asteroids are the surviving relics of the primary building blocks of the terrestrial planets (Mercury-Mars) and the solar system. They are also the parent bodies of most of the meteorites that fall on the surface of the Earth. During the formation of the solar system, dust and gas accreted and were heated to very high temperatures near the Sun (1-2 AU), but in the outer solar system (>3 AU), the temperature was still too cold for ice to be stable. Due to the high temperature, dust evaporated and different minerals recondensed with a decreasing temperature. The recondensed dust slowly started to accrete and form small bodies/planetesimals. The planetesimals grew into larger sizes, melted and differentiated, and formed the terrestrial planets, but >3-4 AU the giant planets Jupiter-Neptune formed by accreting ice, gas, organics, and minor silicate minerals. This is a very simplistic explanation of the early history of the solar system, but it suffices for explaining the formation and evolutionary history of asteroids. Asteroids are the relics of this early solar system process and sample materials both from the region where the terrestrial planets formed and also from the outer cold regions of the solar system. Based on their composition, asteroids can be broadly divided into three categories: silicate mineral-rich, metal-rich, and organic-rich.

During the initial phase of the formation of the solar system, some asteroids grew large enough to generate enough heat (heat due to radioactive decay and due to change of kinetic to potential energy during accretion of matter) to melt and differentiate like planets (e.g., iron-rich asteroids and some silicate asteroids), other asteroids were partially heated to cause low to high levels of partial melting (e.g., some silicate-rich asteroids), and some asteroids were never heated high enough to cause melting (e.g., some silicate-rich asteroids and organic-rich asteroids). Using short-lived radioactive isotopes (e.g., ^{26}Al (half-life: 0.71 million years (Ma)), ^{53}Mn (half-life: 3.7 Ma),^{182}Hf (half-life: 8.9 Ma)) it has been found that there were many differentiated planetesimals (with a core, mantle, and crust) 0.1-0.3 million years after the formation of the Ca-Al-rich inclusions (CAIs), which are the first solids to form in the solar system at ~4.567 billion years ago. Some of the remnants of these differentiated asteroids are present in our meteorite collection as iron meteorites and achondritic/igneous meteorites. It was previously believed that the silicate-rich asteroids formed closer to the sun and like the terrestrial planets, the organic-rich asteroids formed farther away from the sun. However, after detailed study of more asteroids, one does not clearly see such a stratification, and it seems that the giant planets (Jupiter, Saturn, Uranus, Neptune) have led to the mixing of asteroids that formed at different locations. It is also now clear that the early history of the solar system involved complex dynamic processes and radial mixing and migration of planets, asteroids, and materials.

The study of asteroids is the key to understanding the early evolution of the solar system, the environment where our solar system formed, how the different planets and materials in the solar system formed and accreted, and finally how the asteroids evolved with time. Here, I present a short review about the spatial distribution of asteroids, mineralogy and different known types of asteroids, the link between asteroids and meteorites, and the different spacecraft missions to asteroids. Due to the constraints of space, it is not possible to give a very detailed review of the geochemical and cosmochemical aspects of asteroid research. It is a very broad and interdisciplinary research field which is growing at a fast pace with new results from the new space-based telescopes and many spacecraft missions to different asteroids. For interested students, please look at the book by McSween and Huss (2010) for a broad overview about asteroids, and meteorite research.

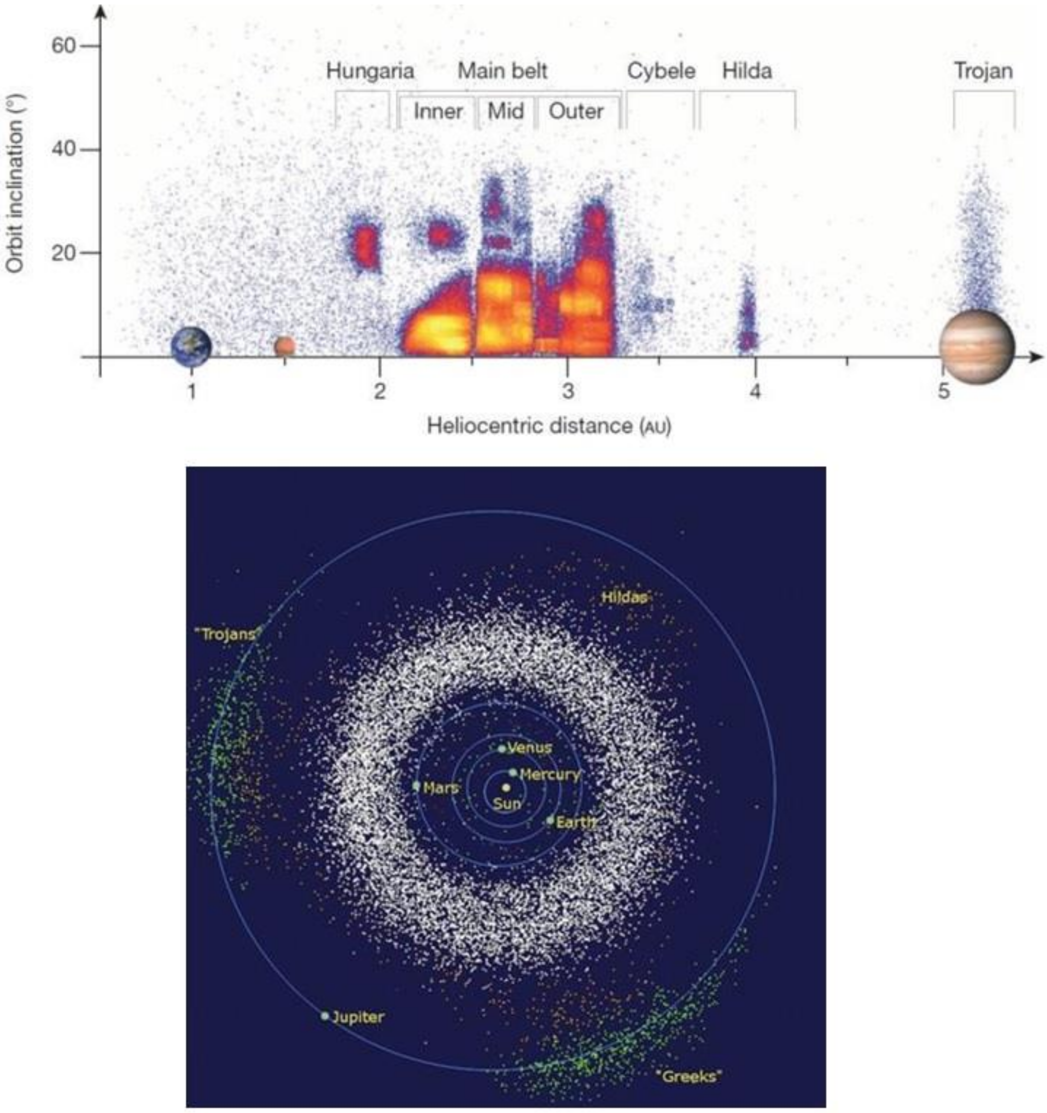

Fig. 1. Above: Distribution of asteroids at different heliocentric distances (distance from the sun) with respect to orbital inclination. The prominent Kirkwood gaps at 2.5 and 2.8 AU are clearly visible. The separation of the main asteroid belt into different regions and the distribution of Hungarian, Cybele, Hilda, and Jupiter Trojan asteroids are also shown (DeMeo and Carry, 2014). **Below:** The distribution of asteroids with respect to different planets, as seen normal to the orbital plane of planets.

Spatial distribution of asteroids

Asteroids revolve around the Sun in elliptical orbits, which are characterized by its semi-major axis (one-half of the longer dimension of the ellipse), eccentricity (degree of elongation of the ellipse) and inclination with respect to the ecliptic plane or the plane of Earth's orbit around the Sun. One approach to classifying asteroids is with respect to their distance from the Sun: (a) Near-Earth asteroids: They have an orbit that closely approaches the orbit of Earth; (b) Main belt asteroids: Asteroids whose orbits lie within Mars and Jupiter (semi-major axes between 2.1 and 3.3 AU); (c) Hilda: At a semi-major axis of 4 AU (d) Jupiter Trojan Asteroids: Semi-major axis of 5.2 AU (Fig. 1). Orbital resonance occurs when two bodies have orbital periods that are simple integer ratio of each other. Within the main asteroid belt, objects that have orbital periods in resonance with the orbital period of Jupiter are gradually ejected into different orbits. The best examples of orbital resonance within the main asteroid belt are 4:1 (2.06 AU), 3:1 (2.5 AU), 5:2 (2.82 AU), 7:3 (2.95 AU), and 2:1 (3.27 AU) resonance with Jupiter and are known as Kirkwood gaps. At this semi-major axes/regions, the gravitational effects of Jupiter have led to the removal of asteroids (see the gaps in Fig.1). For example, when materials are removed from asteroids due to impact and ejected into these gaps, they are scattered throughout the inner solar system. Some of these materials come to us as meteorites.

Mineralogy and types of asteroids

The mineralogy of asteroids is obtained using telescopes on Earth through reflectance spectroscopy in the UV, visible, and near infrared (UV-VNIR) region and thermal emission spectroscopy. Light falling on the surface of asteroids interacts with the minerals, and some photons are reflected from grain surfaces, some pass through the grain, and some are absorbed. Photons or light is absorbed in minerals though different processes. For example, the absorption due to Fe^{2+} charge transfer in Fe- bearing minerals (olivine, pyroxene) leads to absorption bands in the 1µm and 2µm regions (Fig. 2).

The absorption bands due to the electronic transition in crystal structures (e.g., crystal field absorption due to Fe) can be found in any basic chemistry book. Solar energy is also absorbed by the minerals on the asteroid's surface and emitted in the thermal infrared wavelength (3.5 - 20µm). Different minerals have characteristic absorption bands in this region as well. One can also get reflectance VNIR spectra from different meteorites, and the spectroscopic match is used to link some meteorites with the asteroids (Fig. 2). Additionally, different spacecrafts have visited various asteroids: (a) Galileo spacecraft to 951 Gaspra and 243 Ida; (b) NEAR Shoemaker mission to 253 Mathilde and 433 Eros; (c) Mariner 9 spacecraft to Phobos and Deimos (the satellites of Mars); (d) Hayabusa I spacecraft to 25143 Itokawa; (e) Rosetta fly by mission to Steins and Lutetia; (f) Dawn orbiter to Ceres and Vesta; (g) Hayabusa 2 sample return mission to Ryugu (1999 JU3); (h) OSIRIS-Rex sample return mission to Bennu (Fig. 3). These spacecrafts used their onboard VNIR and thermal infrared spectrometers to determine the composition of the surface.

Based on these spectral datasets, asteroids are divided into different classes, and there are four different taxonomic systems. We will use the Tholen (1984) and Gaffey (1993) taxonomic system. Based on the recent classification scheme, there are three large classes of asteroids: S-complex, C-complex, and X-complex. These classes have many sub-classes of asteroids (a total of 26 sub-classes). By comparing the UV-IR spectral properties (i.e., reflectance spectra) of meteorites with the spectra of different classes of asteroids, it is possible to identify the parent asteroids from which a specific group of meteorites could have been extracted/ejected during an impact. Table 1 lists some of the asteroid classes and the different meteorites that have similar spectra. The S-complex asteroids are rich in silicate minerals and have characteristic bands at 1µm and 2µm due to the presence of abundant olivine and pyroxene. One subclass of the S-complex asteroids is the S(IV) and it is now known that the S(IV)asteroids are the parent bodies of the ordinary chondrite meteorites (Fig. 2, 5). Ordinary chondrites are rich in chondrules (which are molten droplets of silicate melts), and the dominant phases within the ordinary chondrite are olivine, pyroxene, Fe, Ni-metal, and troilite. Recently, samples returned from an S(IV) asteroid Itokawa showed that it is similar to a LL5-6 ordinary chondrite (Fig. 4). Similarly, the V-type asteroids and the asteroid Vesta are assumed to be the parent bodies of the HED (Howardite-Eucrite-Diogenite) class of meteorites (Figs. 2 and 5). Since Vesta is a differentiated body, the HED meteorites, derived from the surface of Vesta, are igneous rocks. Eucrites occurs both as basalt and as cumulate rocks. The basaltic eucrites are rich in pigeonite and plagioclase, and the cumulate eucrites have similar mineralogy but are coarse grained (Fig. 6). Diogenites are rich in orthopyroxene and have minor olivine and chromite. Howardites are breccias and are mixtures of both eucrites and diogenites (Fig. 5). The C-complex asteroids are rich in organics, carbon, and phyllosilicates (e.g. smectite, serpentine) and are very dark. The CI and CM carbonaceous chondrites are similar to these dark asteroids (Fig. 6), and have a similar mineralogy: rich in organic and phyllosilicate minerals (e.g. serpentine, talc, smectite), olivine, and pyroxene. These asteroids are assumed to have formed far from the Sun and accreted ice, organics, and silicate minerals. Phyllosilicates are the results of the aqueous alteration of the silicate phases with time. Other classes of asteroids have spectral properties that resemble different types of meteorites, and the most prominent among them are the E and M-types. The E-type asteroids have similar mineralogy to enstatite chondrites, which are rich in almost Fe-free enstatite, whereas the M-type asteroids are similar to iron meteorites (consisting of dominantly Fe, Ni-metal).

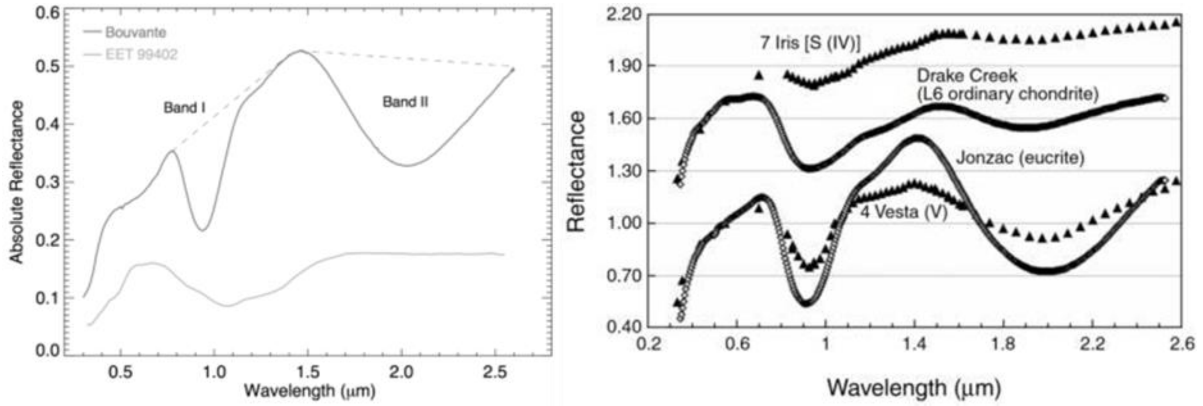

Fig. 2. **Left:** Reflectance UV-VNIR spectra taken from olivine (Fayalite35) from meteorite Bouvante and pyroxene ($Ferrosilite_{53}Wollastonite_{14}$) from meteorite EET 99402. The 1 µm and 2 µm bands in olivine and the 1 µm band in pyroxene due to the presence of Fe^{2+} are clearly visible (Reddy et al., 2015). **Right:** Reflectance UV-VNIR spectra of S(IV) asteroid 7 Iris and asteroid Vesta compared with the spectrum from ordinary chondrite and an eucrite meteorite. The similarity of the band positions is clear, although the depths of the bands are different. The difference in band depths is most likely related to the difference in abundance of the minerals and the viewing angle or grain size on the surface of the asteroid (Clark et al., 2002).

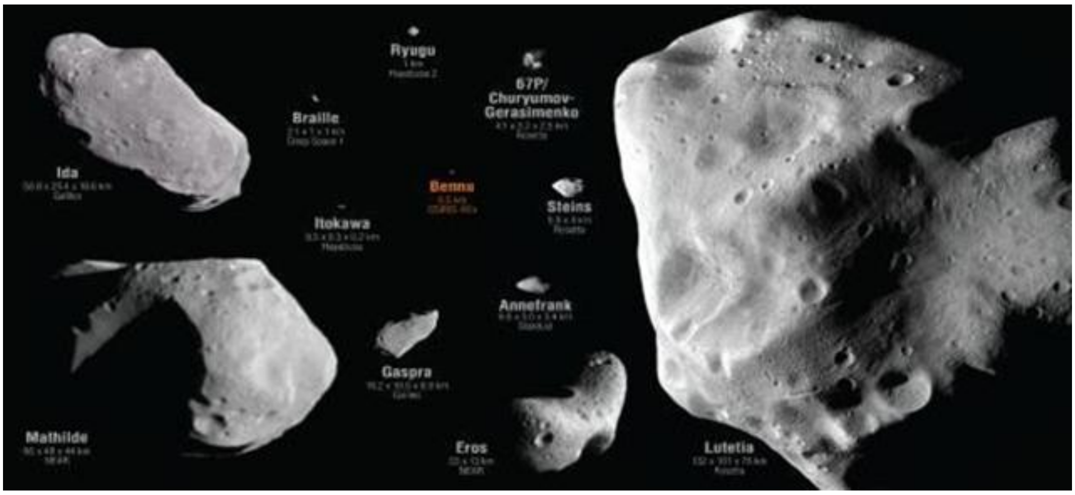

Fig. 3. The relative sizes of different asteroids that have been visited by different space crafts. The name of the spacecraft missions are given below the name of the asteroid (Source: Nasa.gov).

Table 1. A comparison of some asteroid classes and their possible meteorite analogous and the dominant phases present in them. Classes in brackets are from the Tholen nomenclature system.

Asteroid Class	Analog Meteorite	Phases
S-complex (SI-SVII)	Pallasite, Primitive achondrite meteorites,	Olivine, clinopyroxene, orthopyroxene, plagioclase, Fe,Ni-metal, troilite (FeS)
X-complex(M, E, P)	Iron meteorites, Enstatite chondrite, Carbonaceous chondrites	Enstatite, Fe,Ni-metal, Carbon and Organics
C-complex (B, C, F, G)	Carbonaceous chondrites	Phyllosilicates (Fe- or Mg-rich serpentine, chlorite, smectite, talc), organics, olivine, pyroxene
A and R	Pallasite	Olivine, Fe,Ni-metal
K	CV, CO carbonaceous chondrites	Olivine, pyroxene, organics
V	HED meteorites	Pyroxene, plagioclase

Spacecraft missions to asteroids

Near-Shoemaker mission to 433 Eros: 433 Eros is an S-class Near-Earth asteroid and was visited by the NEAR spacecraft on February 14, 2000. It has a potato-shaped body measuring 35 km long by 10 km across and has many impact craters (Fig. 7). The magnetometer onboard the NEAR spacecraft did not detect any magnetic field. Reflectance spectra showed the presence of 1 and 2 μm bands in the VNIR region, which are signatures for Fe-bearing olivine and pyroxene. From the mineralogy, it is probable that 433 Eros is similar to ordinary chondrite meteorites (Fig. 4). There were two other instruments onboard the NEAR spacecraft: an X-ray spectrometer (XRS) and a Gamma-ray spectrometer (GRS). The XRS detects fluorescent X-rays emitted from the surface of a body due to the interaction of X-rays produced by the sun with the atoms of different elements. Mg, Si, S, Ca, Cr, and Fe were detected on the surface of Eros using the XRS. GRS detects gamma-ray emissions from a surface due to the natural radioactive decay of ^{40}K or due to the interaction of some elements (e.g., O, Mg, Si, Fe) with galactic cosmic rays. Galactic cosmic rays are highly energetic particles consisting predominantly of H, travel almost at the speed of light, and are formed outside of the solar system due to events like supernova. The particles are ionized and are therefore deflected by the earth's magnetic field but, mostly in the equatorial region. The XRS and GRS data from the surface of Eros also show that the composition is similar to ordinary chondrite meteorites.

Dawn mission to Vesta and Ceres: The Dawn spacecraft mission imaged and studied the 510 km diameter asteroid Vesta. The VNIR spectra from HED meteorites match that of the surface of Vesta, and it is assumed that Vesta is the parent asteroid from which HED meteorites originated (Figs. 2 and 5). Since HED meteorites are igneous rocks, Vesta should have seen extensive igneous activity and using the data from the Dawn mission, it was found that Vesta has a 220 km diameter metallic core. After completing all the studies on Vesta, the Dawn spacecraft went to the largest asteroid, Ceres.

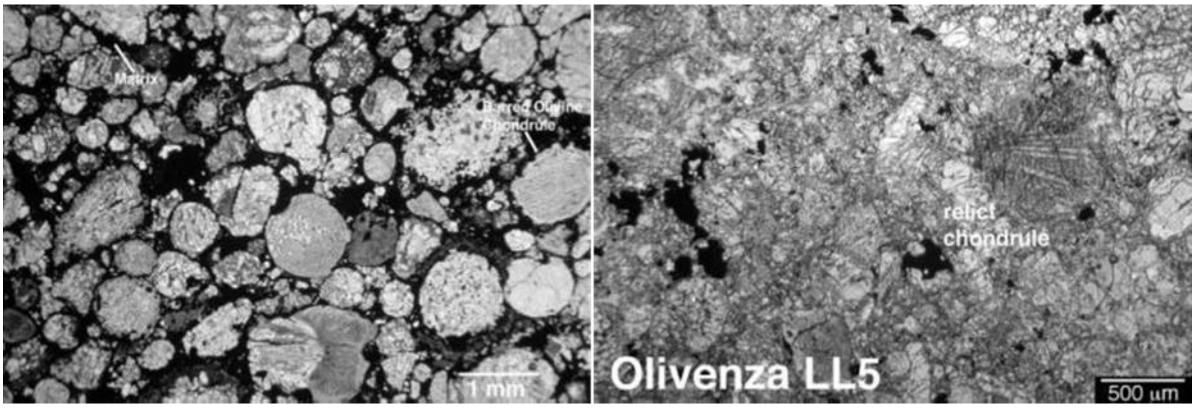

Fig. 4. Plane polarized light image of two ordinary chondrite meteorites. **Left:** Plane polarized light image of L3.0 ordinary chondrite Semarkona. The round objects are chondrules, which are surrounded by a dark matrix consisting of very fine-grained olivine, pyroxene, and carbon. **Right:** Plane polarized light image of an LL5 ordinary chondrite Olivenza that has been highly metamorphosed (thermal metamorphism). The thermal metamorphism led to the obliteration of the boundary between the chondrules and that recrystallization of the matrix (Weisberg et al., 2006).

Ceres, with a diameter of ~ 940 km is the largest object in the main asteroid belt. Although Vesta is a differentiated rocky asteroid, Ceres is completely different: a water-rich silicate body, volatile rich with an icy crust. The icy crust has a density of ~ 1.3 gcm^{-3} and there is a brine layer (salt-water mixture) above the mantle. Most likely, during the accretion of Ceres, both ice, organics, and silicate minerals were mixed together, and later melting of the ice led to aqueous alteration forming phyllosilicates. Dawn spacecraft detected Mg- and ammonium-bearing phyllosilicates and salt deposits ((Mg,Ca)-carbonates, Na_2CO_3). Salt deposits are formed due to active volcanism, but cold volcanism is called cryovolcanism. Cryovolcanism is an active process on the icy moons of Jupiter, Saturn, Uranus, and Neptune. During the cryovolcanism, brine erupts on the surface and the water evaporates, leaving behind salts (e.g., Na_2CO_3). The presence of cryovolcanism on Ceres shows that the body is still active, unlike Vesta and other large asteroids.

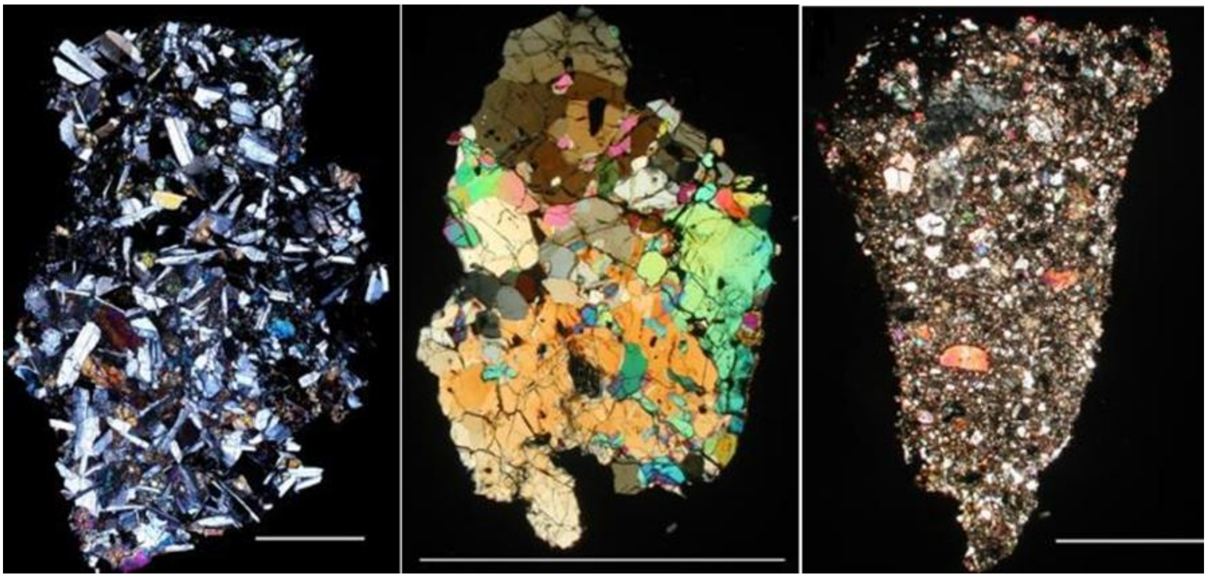

Fig. 5. Photomicrographs taken with crossed nicols. **Left:** Basaltic eucrite QUE 97053. Subophitic plagioclase is enclosed by pyroxene. **Middle:** Olivine-rich diogenite GRA 98108. **Right:** Howardite PCA 02019 is composed of eucrite and diogenite clasts. Scale bar: 2.5 mm (McSween et al., 2011).

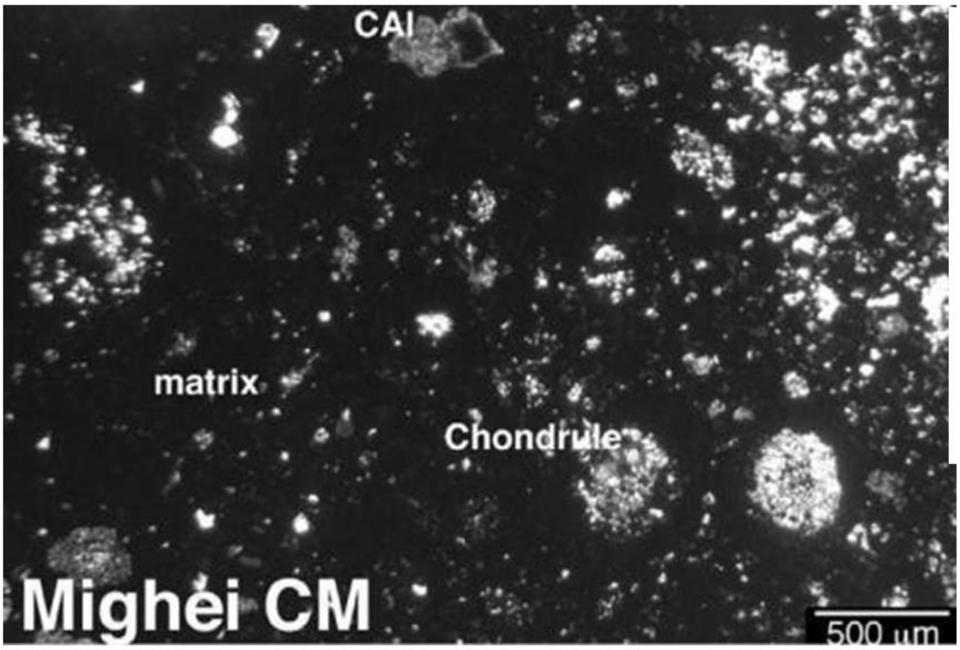

Fig. 6. Plane polarized light image of the CM carbonaceous chondrite Mighei. Note the high abundance of matrix (about 70%) and very small chondrules in comparison to the ordinary chondrites. The matrix is rich in organics, phyllosilicates, and carbon. Weisberg et al. (2006).

Hayabusa mission to 25143 Itokawa: The Hayabusa mission successfully brought back samples (dust particles) from the surface of the S-type asteroid Itokawa (535 x 294 x 209 m), thereby becoming the first asteroid from which a sample has been recovered. The surface is covered with many boulders and regolith, and due to the high porosity of Itokawa it is considered to be a rubble-pile asteroid (formed by agglomeration of some fragments produced by the break-up of the original asteroid) (Fig. 8). Ordinary chondrites contribute to 85% of the observed meteorite falls, so there should be many ordinary chondrite-like asteroids. Reflectance spectra show that Itokawa is similar to ordinary chondrite (LL5-6 chondrite). Minerals present within the collected sample are: olivine, low-Ca pyroxene, high-Ca pyroxene, plagioclase, troilite, kamacite (α-Fe,Ni-metal), taenite (γ-Fe,Ni-metal), chromite, apatite, and merrillite (Figs. 9 and 10). All these minerals are also seen within LL5-6 ordinary chondrites (Fig. 4).

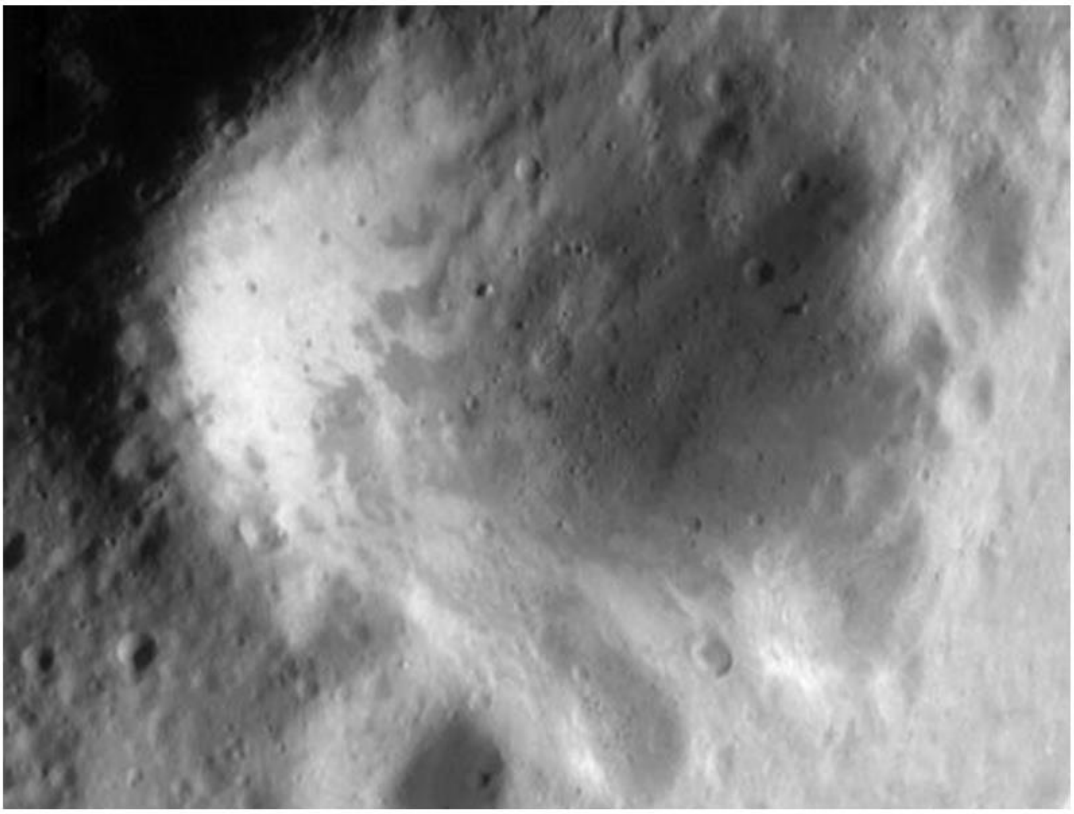

Fig. 7. An impact crater imaged on 433 Eros by the NEAR spacecraft. The surface ice was covered with a fine- grained regolith due to the pulverization and melting of rick due to the impacts of meteorites and micrometeorites (micron sized dust particles). See the difference in color or albedo between different regions of the crater. The darkening of the surface occurs with time due to a process called space weathering. The impact of micrometeorites and energetic ions (H^+, He^+) from the sun causes this darkening over time.

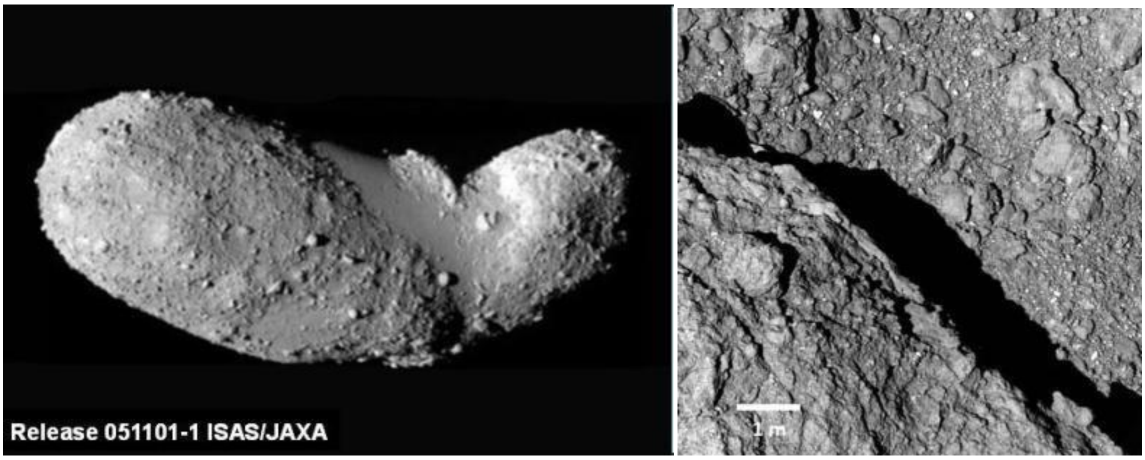

Fig. 8. Image of Itokawa captured by the camera onboard the Hayabusa I mission. **Left:** The shape of the asteroid shows that it is most likely an agglomeration of fragmented bodies. A region of fine regolith is present in the middle of the asteroid. **Right:** High resolution image of the surface shows the presence of many boulders whose surfaces have darkened with time due to space weathering. Note the absence of fine regolith in this region.

Ongoing spacecraft missions to asteroids and future directions
The Hayabusa-2 and OSIRIS-Rex missions are studying the near-Earth asteroids Ryugu (C-type) and Bennu (B-type) respectively. Both the asteroids are carbon- and organic-rich and similar to the carbonaceous chondrite meteorites (Fig. 6). The Hayabusa 2 should return the samples by the end of 2020, and OSIRIS-Rex should bring the sample by end of 2023.

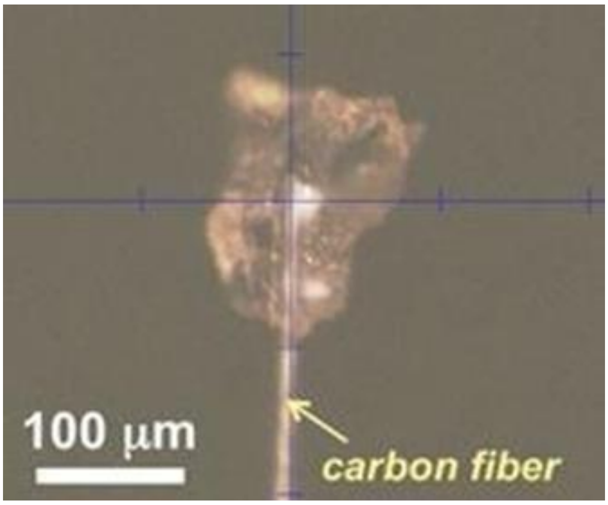

Fig. 9. An optical microscope image of a grain from the surface of Itokawa. The grain is mounted on a carbon fibre for X-ray tomography studies.

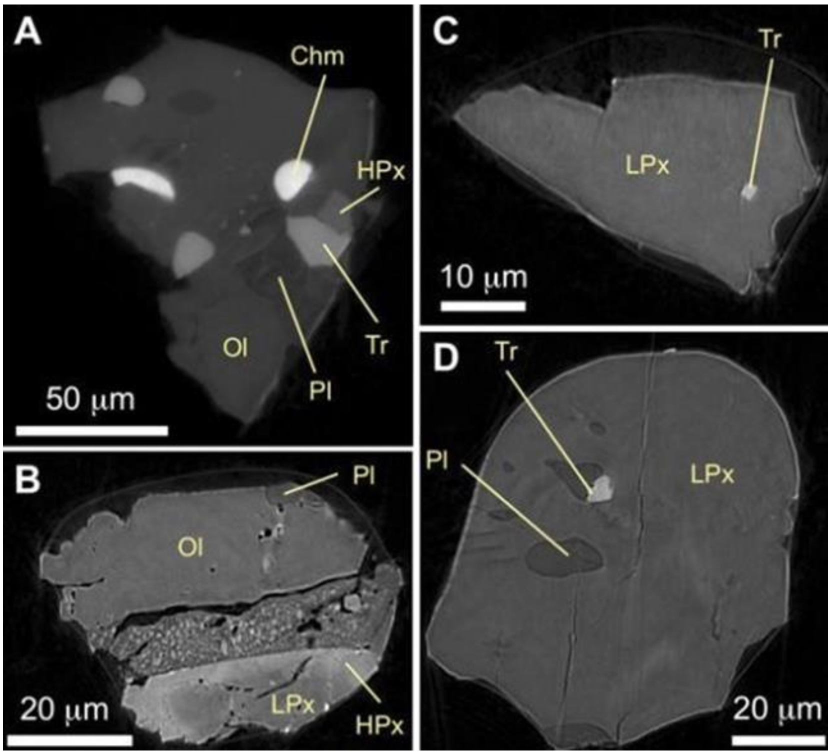

Fig. 10. Electron microscope images of different grains from Itokawa (Tsuchiyama, 2014). Ol = olivine, LPx = low-Ca pyroxene, HPx = High-Ca pyroxene, Pl = plagioclase, Tr = Troilite, Chm = chromite.

The surfaces of both Ryugu and Bennu have materials that formed in the early stages of the evolution of the solar system, and the aim of studying the samples is to understand the evolution of our solar system. The material within these two asteroids formed far away from the Sun and was not highly processed during the initial stage of the formation of the solar system. The cold outer regions of the solar system escaped significant changes, and Ryugu and Bennu most likely contain these old and pristine materials. Since ice was present when Ryugu and Bennu accreted, the minerals have suffered significant alteration with time, but the bulk isotopic composition of the material has not changed. So an isotopic and mineralogical study of these samples can give us a complete picture of the pre- and post-alteration environments of the solar system and the asteroids. Organics present within these two asteroids hold clues to the evolution and processing of organics in the solar system and will help in answering how water was delivered to the Earth. There are still many mysteries and unanswered questions related to the formation and evolution of asteroids. A few of the important questions are: (a) are there remnant Asteroids, which are the building blocks of the Earth and brought water to it? (b) What is the source of the gradient in composition within the asteroid belt? (c) What is the composition of different asteroids with respect to their size: composition of a <1 km sized asteroid vs. 1-20 km size asteroid (d) Although there are lots of iron meteorites and iron-rich asteroids, there are very few olivine-rich asteroids. Iron-rich asteroids should be the remnant of the cores of previous planets, and olivine-rich asteroids should be the remnant of the mantle. So, it is intriguing that there are so few olivine-rich asteroids (e) How representative is our meteorite collection with respect to the different types of asteroids (f) How did asteroids dynamically evolve with time, and how many parent bodies of different meteorites are actually present in the asteroid belt. With the new spacecraft missions bringing back samples from different asteroids, the new generations of space-based telescopes, the study of more asteroids by ground-based telescopes, and the comparison of the spectra of asteroids with different types of meteorites, the future of asteroid research is going to be very exciting.

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