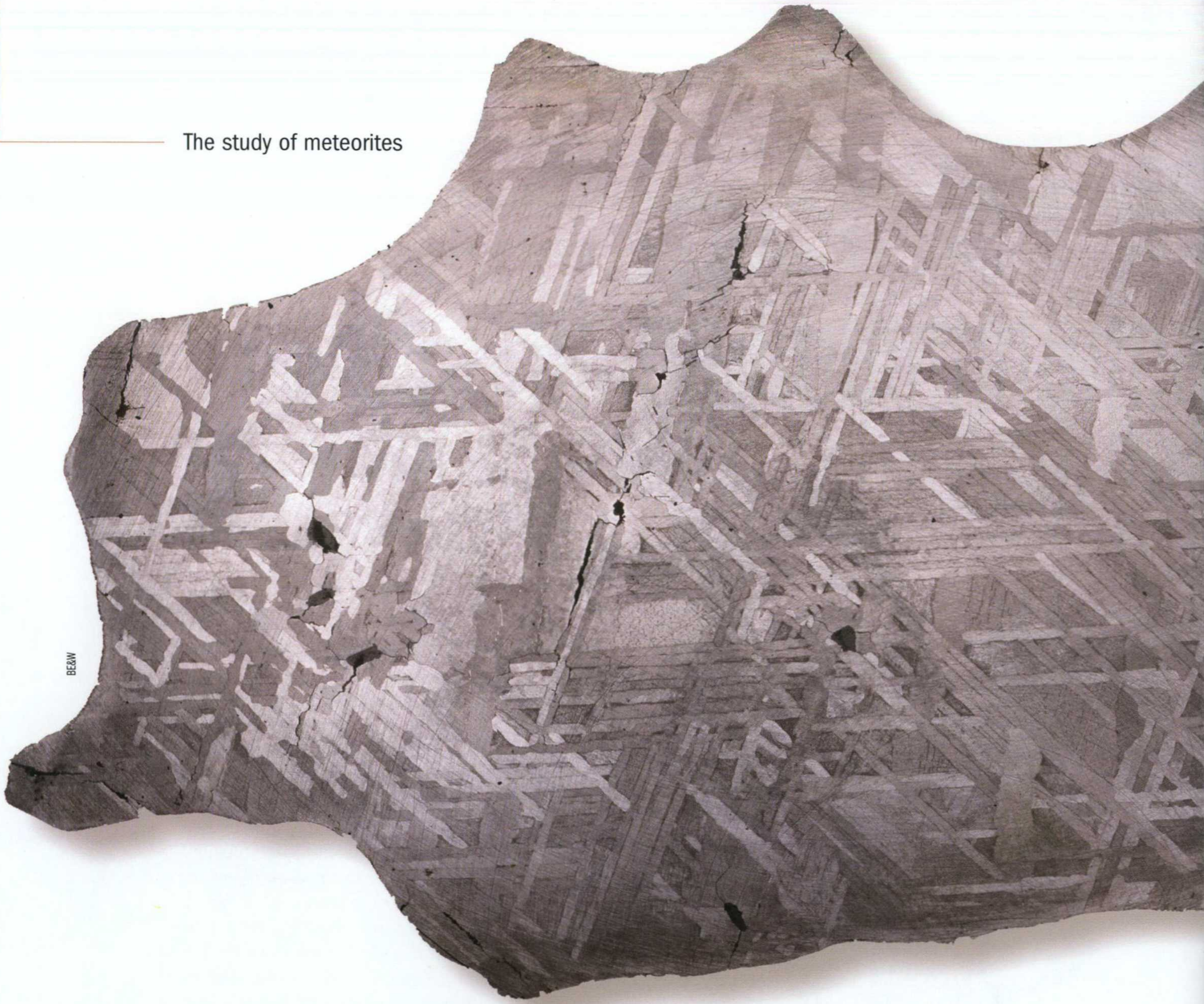
The study of meteorites



BE&W

Interplanetary Travelers

ELŻBIETA JACKOWICZ
Polish Geological Institute
- National Research Institute
elzbieta.jackowicz@pgi.gov.pl
Dr. Elżbieta Jackowicz is a petrographer interested in magmatic rocks and meteorites.

Most of us have had the opportunity to observe the sky and see the fleeting luminous streaks known as meteors. Such spectacles are caused by fragments of celestial bodies (meteoroids) entering the atmosphere at high speed. Some of them manage to reach the surface. How can these alien objects be told apart from Earth rocks and anthropogenic materials?

Meteoroids are fragments or lumps with varying composition, e.g. rock, metal, ice or solidified gases (e.g. methane, ammonia), and of varying origin. As they pass through the atmosphere, friction caused by air resistance heats their surface to the boiling point and the stripped material together with the ionized atmospheric gases leave a luminous trail across the sky.

Ice meteoroids originate from comets, which are small bodies from outside or on the periphery of the Solar System (the Oort cloud, the Kuiper belt). Cometary movement is susceptible to the gravitational influence of other bodies, especially the Sun and the gas giants. As they approach the Sun, comets not only lose mass as a result of melting and evaporation, they may also break up into tiny fragments rushing along in an orbit similar to the comet's orbit. If the Earth intersects the orbit of these cometary meteoroids, they fall into its atmosphere

Iron meteorite exhibiting Windmanstätten patterns

causing a meteor swarm. However, ice meteoroids do not reach the surface of the Earth - they completely vaporize in the atmosphere.

The meteoroids that do reach the Earth's surface, known as "meteorites," are made of rock and metal. It is estimated that several thousand meteorites weighing more than 1 kg fall on our planet every year (an area the size of Poland probably receives up to 175 meteorites weighing more than 100 g). Two-thirds fall into the oceans, and of the remaining an average of six meteorites a year are found and recovered.

Large meteoroids sometimes explode above the Earth and fall as a rain of meteorites. An example is the "Pultusk" meteorite, which fell in 1868 near the Polish town of Pułtusk, in the form of 70,000 fragments with a total weight of over 2 tons. After colliding with the Earth, the explosions of large lumps of rock will result in meteorite craters. Smaller meteorites of a few kilograms burrow into the ground, creating holes usually tens of centimeters deep.

Rock and metal meteorites usually come from the Solar System's main Asteroid Belt, which includes tens of thousands of objects moving between the orbits of Mars and Jupiter. Collisions have frequently occurred in this crowded space, and still do occur. Such collisions sometimes end up breaking asteroids apart, sending off fragments with altered trajectories.

A very few meteorites are fragments of rock originating from Mars or Earth's moon, ejected as a result of violent collisions with very large objects.

Getting to know our guests

Based on their mineral composition, meteorites are classified into several groups: stony meteorites, composed mainly of silicates, iron meteorites, formed predominantly with nickel-bearing iron, and stony-iron meteorites, which are midway between the other two types.

Stony meteorites represent about 86% of all meteorites that reach the Earth's surface and about 66% of all finds. They are composed mainly of silicates (olivine and pyroxene) and their density is usually approx. 3000-3700 kg/m^3. Stone meteorites come in two kinds: chondrites and achondrites.

Chondrites are by far the dominant type. Their name derives from the Greek "chondros," meaning seed. They contain chondrules, small silicate grains created from rapidly cooled melts in microgravity. Under such conditions, a liquid takes the form of spherical droplets. The material that chondrules formed out of came from mineral dust originating from the solar nebula, melted by thermal pulses in the protoplanetary disk. Accretion of chondrules with other material that condensed from the solar nebula drove the growth of the parent bodies of such meteorites. Chondrules are a typical form of the original matter in the Solar System, which now survives unchanged only in such small planetoids. Their isotopic age is within the range of 4.566-4.557 billion years, so they are older than the oldest rocks on Earth (3.8 billion years). They contain relatively small quantities of nickel-bearing iron.

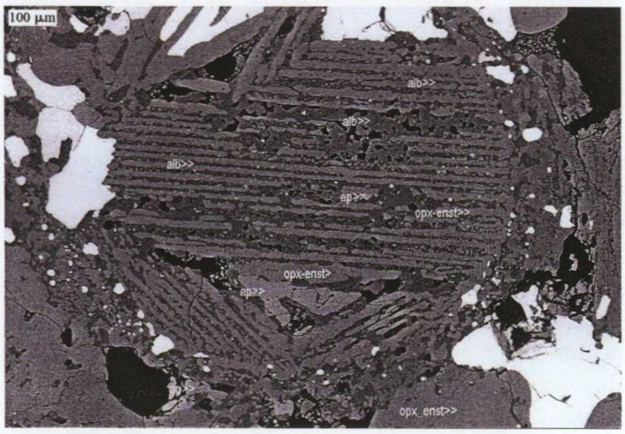
Ordinary chondrites are the most common, coming from planetoids formed relatively close to the Sun, but carbonaceous chondrites, which are fragments which formed far from the Sun, are more interesting. This is because their chemical composition is closest to that of the solar photosphere (apart from hydrogen and helium). They contain hydrated minerals, as well as organic compounds (accounting for up to about 6% of their content) of abiotic origin. These compounds may have played a significant role in the creation and development of life on Earth.

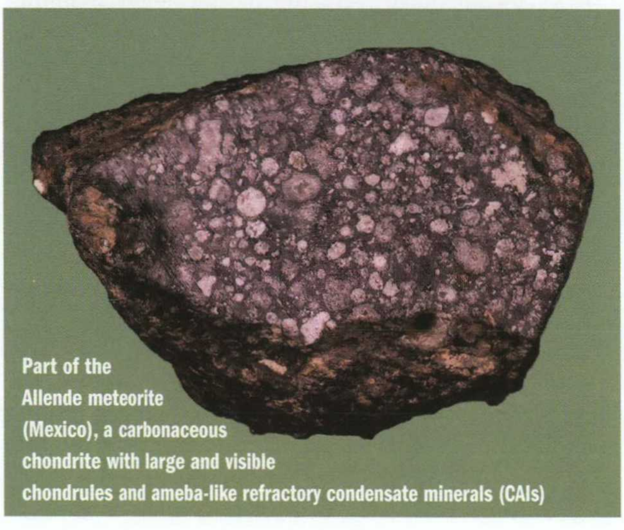
Carbonaceous chondrites also contain minerals (e.g. diamond, corundum, and silicon carbide) synthesized in the environment of pre-solar stars. At an early stage of development of the Solar System, grains of these minerals could only survive in the outer parts of the protoplanetary disk, as those closer to the center underwent melting and evaporation. The remaining material, enriched in refractory elements, formed the first, ameba-like mineral condensates, known by the abbreviation CAIs (Calcium-Aluminum Inclusions). They are approx. 4.567 billion years old.

Currently there are over 27,000 chondrites in collections around the world. The largest of them weighs 1170 kg and belongs to the group of meteorites from Jilin (China) from 1976.

Stony meteorites of the second kind, achondrites, represent approx. 14% of all meteorites found on the Earth's surface. They originate from the silicate crust of asteroids in which the primordial matter underwent melting and gravitational differentiation, giving rise to an iron core, a stony mantle (rich in olivine) and a basalt crust (making them structurally similar to Earth). The heat necessary to melt the matter came from the active young Sun and short-lived radioactive element decay (e.g. aluminum-26).

Pultusk meteorite chondrules; image (BEI) from an electron microscope. Symbols: opx-enst - orthopyroksene-enstatite; alb - albite; ap - apatite





Part of the Allende meteorite (Mexico), a carbonaceous chondrite with large and visible chondrules and ameba-like refractory condensate minerals (CAIs)

The composition of achondrites is close to that of basic and ultrabasic terrestrial rocks; they contain virtually no nickel-bearing iron. The isotopic age of some of these meteorites indicates that their magma crystallization ages range from about 4.558 to 4.399 billion years ago. The youngest achondrites are approx. 180 million years old and are basalts from Mars, indicating much more recent volcanic activity there than on other mother bodies of achondrites, whose ages fall in the range of 4.56-4.45 billion years.

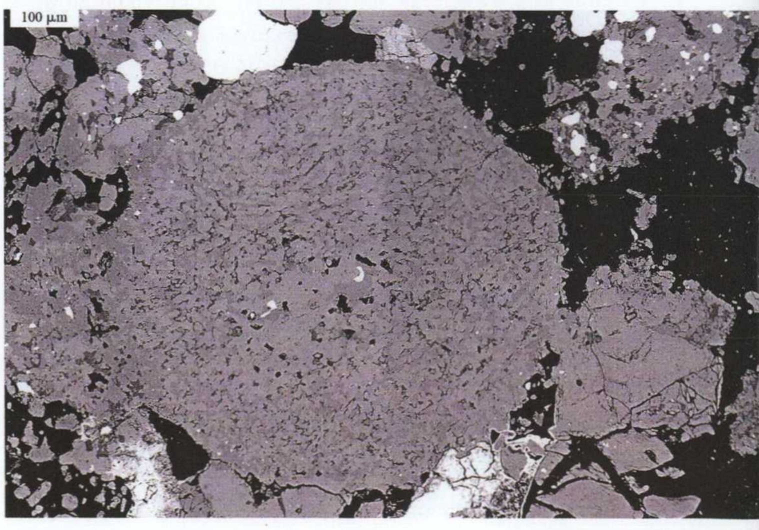
The next kind of meteorites, iron meteorites, account for approx. 5% of all meteorites falling to Earth and approx. 30% of all finds. They come from the core sections of the same type of asteroids that achondrites come from. They are composed mainly of minerals produced from an iron-nickel alloy, and their density is 7000-8000 kg/m^3. These minerals are strongly attracted by magnets. Because of their structural characteristics, iron meteorites are further divided into three groups.

Hexahedrites consist of kamacite, or mineral iron comprising up to 6% nickel. When polished surfaces of these meteorites are etched with a solution of nitric acid they reveal Neumann lines, a testament to the pressure surges caused by asteroid collisions.

Octahedrites are among the most common iron meteorites. They consist of kamacite and taenite - a mineral containing from 7 to 18% nickel in addition to iron. After being etched with nitric acid, structures called Windmanstätten patterns can be seen (a system of interleaved beams and plaques) on polished sections of these meteorites.

Ataxites, on the other hand, consist mainly of taenite and other minerals with still higher nickel content, with kamacite as a secondary component. After etching, polished sections of these meteorites show no structure.

Chondrules from the Baszkówka meteorite; image (BEI) from an electron microscope



The last major category of meteorites, iron-stone meteorites, represent approx. 9% of all those reaching the Earth's surface, but only approx. 4% of all finds. They come from the transition zone between the nucleus and the mantle of asteroids that underwent melting and gravitational stratification. They are among the most beautiful meteorites, featuring a distinctive aesthetic characterized by pallasites, composed of olivine crystals in a nickel-bearing iron matrix.

Recognizing the intruders

From this very general description of meteorites, it can be seen that most of them are different enough from the Earth's rocks and ores that their identification should be trivial. In practice, however, it turns out that in some cases even geologists cannot at first glance definitely assess whether a find is a meteorite, especially for specimens that have been subjected to many years of weathering on Earth. To recognize the vast majority of meteorites it is enough to identify the presence of nickel-bearing iron, chondrules, or both of these components (which do not occur in Earth's rocks and ores). Without laboratory tests this is sometimes impossible, however, because a reaction to a magnet is just a starting point and not proof of the presence of iron-nickel minerals, whereas chondrules may not be visible without a microscope. Without experience it can also be difficult to distinguish them from the spherical forms that occur in many terrestrial rocks. Trying to identify meteorite specimens based on their high density is likewise not foolproof, as less common terrestrial ores and rocks may also show similar density.

One very good indicator for identifying meteorites is the presence of a "fusion crust" - a rough layer with a glossy or dull finish, made of residual molten matter that was not stripped off the surface of the meteoroid by the rush of air and resolidified. The thickness of this film, covered in places by rivulets and bumps, is no more than 1 mm and it is usually black in color, although under the influence of weathering it may over time change to rusty or brownish.

Another hallmark indicator of a meteorite is the presence of regmaglypts, which are sculpted indentations on the surface resembling fingerprints left in soft clay, caused by the penetrating activity of air vortices. However, regmaglypt forms, the fusion crust, and the streamlined shapes of meteorites caused by melting can all be disrupted by the breakup of a meteoroid close to the surface of the Earth or by its collision with the ground.

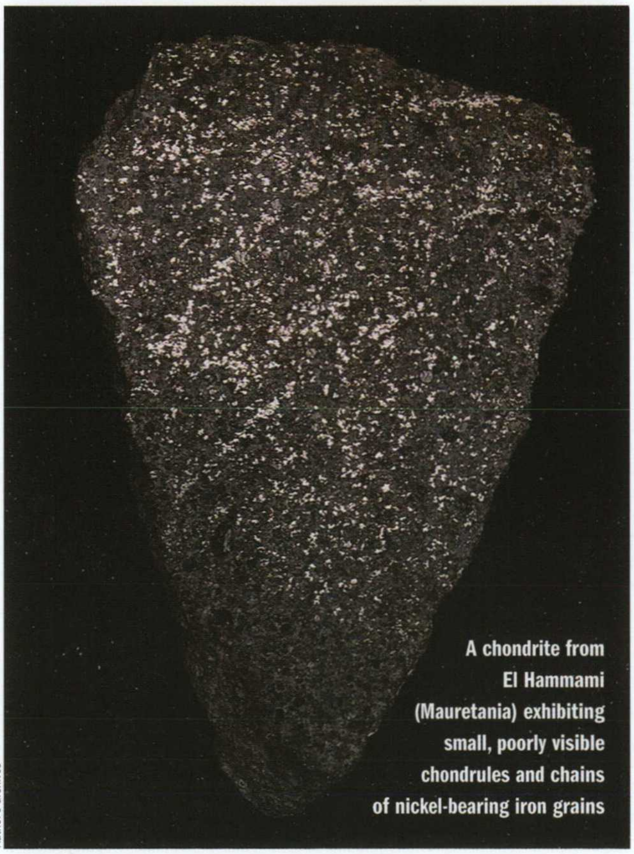
Meteorites are invaluable as a scientific research material, containing information about the history of the Solar System that is impossible to obtain in any other way. All the difficulties involved in actually distinguishing meteorites from terrestrial rocks and from the products of human activity (e.g. scrap metal, slag) should not be considered discouraging, but rather looked upon as a challenge, inspiring potential meteorite-hunters to learn more about these fascinating interplanetary travelers. ■

Further reading:

Robert F. (2001). Signed carbon. In: Zanda B., Rotaru M. (eds.) *Meteorites: Their impact on science and history.* Cambridge University Press, 86-93.

Manhes G. (2001). The age of the solar system. In: Zanda B., Rotaru M. (eds.) *Meteorites: Their impact on science and history.* Cambridge University Press: 102-111.

Regmaglypts and slightly oxidized fusion crust of the Sikhote-Alin meteorite (Russia)



A chondrite from El Hammami (Mauretania) exhibiting small, poorly visible chondrules and chains of nickel-bearing iron grains

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