Forging an Asteroid-Meteorite Link

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Hundreds of kilograms of material fall daily into the Earth's atmosphere from space and filter down to the surface as tiny grains and fine dust. Every few days a fragment larger than a few kilograms encounters the atmosphere at a relatively low velocity and partially survives to reach the Earth's surface. Most of these meteorites fall into the sea or in uninhabited regions and are never recovered. But the special nature of the meteorites that are recovered has been recognized since antiquity by many cultures. For scientists interested in the earliest history of the Earth and the solar system, such meteorites are Rosetta stones that include a wide variety of materials that have survived almost unaltered from the earliest period of solar system history. On page 186 of this issue, Binzel and Xu (*1*) present their decipherment of part of the story of meteorite origins: the connection between an important class of meteorites and a major asteroid.

A general model of the formation of the solar system has emerged on the basis of evidence gleaned from the meteorites and from telescopic investigations of asteroids in our solar system and of nearby star-forming regions in our galaxy (*2*). Although many uncertainties remain, current data and models indicate that about 4.5 billion years ago, a portion of an interstellar cloud attained a critical density and collapsed to form the solar nebula, a rotating flattened disk with a central bulge. Half or more of the mass of the solar nebula was concentrated into the central mass which subsequently evolved into the sun. In the extended disk outside the central condensation, a portion of the tiny fraction of the nebular mass that was in the form of solid grains settled out of the nebular gas to form a dust-rich layer in the central plane of the disk. In the warmer inner portions of the nebular disk, the dust consisted of grains of nickel-iron metal and silicate minerals. In the cooler outer portions of the nebular disk, abundant grains of water ice and organic compounds augmented this layer of solid matter.

Within this dusty layer, grains agglomerated to form clumps that continued to accrete until much of the solid matter was tied up in kilometer-sized planetesimals. Gravitational forces became important at this scale and larger bodies, hundreds of kilometers or more in diameter, formed by accumulation of these planetesimals. At some point in this process, a few of these bodies began to grow rapidly at the expense of their smaller neighbors and formed embryonic planets. In the cooler outer portions of the disk, nebular gas began to accrete onto these planetary cores and their masses swelled rapidly to form Jupiter and the other gas giant planets. In the inner portions of the disk, the nebular gas was either too hot to be held by the weak gravitational field of the growing terrestrial planets or had already been blown away by an early intense solar wind outflow from the evolving sun.

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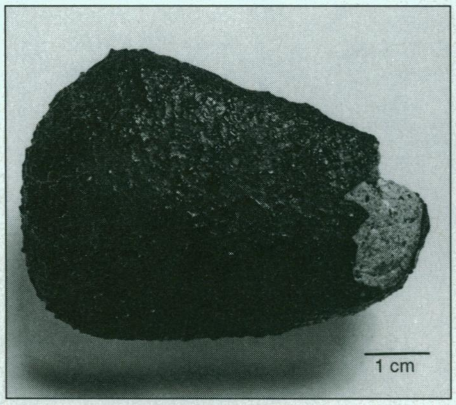
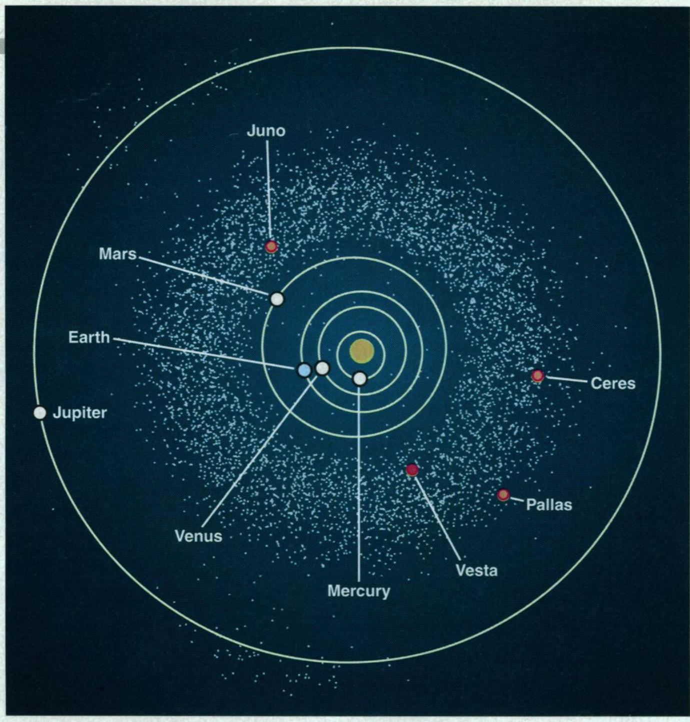


Meteorite origins. Although asteroids range up to nearly 1000 km in diameter, from Earth they appear to be unresolved points that move across a background of stars, as in this image of 2100 Ra-Shalom (**above right**). [Courtesy: E. F. Helin, California Institute of Technology] The Pasamonte eucrite (**above**), which fell in New Mexico in 1933, is one of a class of basaltic meteorites that Binzel and Xu have linked to the main-belt asteroid 4 Vesta. [Courtesy: U.S. National Museum of Natural History] Close-up of the Millibillillie eucrite showing the outer fusion crust (**below right**). [D. W. Dietz/Visuals Unlimited]

The main-belt asteroids, located between Mars and Jupiter, represent the surviving inner solar system remnants of this early planetesimal and planetary embryo population. Meteorites are small naturally delivered fragments of some portion of the asteroid population. Laboratory studies of the meteorites have provided detailed insights into the conditions and time scales of events during the formation of the inner solar system (*3*). Telescopic studies of asteroids have also provided important constraints on the origin and early evolution of the solar system (*4*). No other sources of data are available that provide direct insight into this period of early inner solar system history. The similar evidence once present on the Earth and other major terrestrial planets has been erased by erosion, metamorphism, melting, and other geologic processes. The telescopic observations of star-forming events currently occurring in nearby nebulae have a spatial resolution comparable to our entire planetary system and hence cannot be used to investigate small-scale processes such as planetesimal and planet formation. Moreover, these activities are hidden within dense dust clouds until quite late in the evolutionary sequence.

Meteorite evidence therefore plays a very major role in our models for solar system formation. However, the specific source bodies of particular meteorites are not known. Meteorite investigations thus provide a very good clock of events and conditions during the formation epoch, but the actual locations of those events and conditions within the early solar system remain uncertain. In contrast, most of the main-belt asteroids apparently remain near their original formation locations (*5*). The asteroids can thus provide the spatial context for the detailed meteorite data if links can be established to specific asteroids. The work of Binzel and Xu (*1*) provides the first convincing evidence of a direct link between an important meteorite type (the basaltic achondrites) and a main-belt source body (4 Vesta).

The bulk non-ice solid material of the solar nebula accreted to form the chondrite meteorites. The achondrites ("not-chondrites") were produced from chondritic parent materials by igneous melting and phase segregation within strongly heated parent bodies. The basaltic achondrites include three types of meteorites (eucrites, howardites, and diogenites) all of which were produced by melting or partial melting of chondritic parent material. The basaltic achondrites are the second most abundant general meteorite class and make up about 6% of the meteorite falls. Melts of basaltic composition are less dense than their solid parent materials and tend to rise in planetary bodies. Thus, basalts are very common rocks on the surfaces of the Earth, moon, and the other terrestrial planets. The parent body of the basaltic achondrites is (or was) also surfaced with basalts. Earth-based spectral observations in the late 1960s showed the presence of a basaltic surface on the main-belt asteroid 4 Vesta. Subsequent observational investigations strengthened that conclusion and further showed that Vesta was unique in this respect among the large main-belt asteroids. Thus Vesta has been long identified as a potential parent body of the basaltic achondrites.



Asteroid orbits. Solar system map showing postions of major main-belt bodies, including 4 Vesta. [Courtesy: R. P. Binzel, Massachusetts Institute of Technology]

However, there is strong dynamical evidence that Vesta itself could not be a major contributor to the meteorite flux reaching the Earth (*6*). The main-belt asteroids have survived for 4.5 billion years because they are not subject to strong gravitational perturbations by Jupiter or the other planets. The early solar system was once full of such asteroidal bodies, but those subject to such perturbations had their orbits changed until they either impacted one of the major planets or were expelled from the solar system by a planetary close encounter. Most of the material that escapes from the present asteroid belt is lost through several chaotic zones located at particular orbital positions. Unfortunately for its proposed role as the basaltic achondrite parent body, Vesta is located far from these "escape hatches" and therefore should only rarely contribute to the meteorite flux reaching Earth.

An apparent paradox existed. The telescopic observers maintained, quite correctly, that Vesta was unique among large main-belt asteroids and therefore almost certainly must be the source of the basaltic achondrite meteorites. With equal vigor, the dynamical investigators maintained, equally correctly, that Vesta could not contribute significantly to the meteorite flux. The detection of three small Earth-approaching basaltic achondrite asteroids provided immediate near-Earth source bodies for the basaltic achondrite meteorites (*7*). However, such Earth-approaching asteroids are very short-lived compared to the age of the solar system and must be regularly replenished from some long-lived reservoir such as the main belt. The presence of three such objects in near-Earth space suggested a strong source, a condition which Vesta itself could not satisfy.

The spectral observations of Binzel and Xu have cut this particular Gordian knot (*1*). During an investigation of small main-belt asteroids, they observed the members of a cluster of small bodies which orbit the sun along paths very similar to the orbit of Vesta. This Vesta family had been identified previously on the basis of the similarity of orbits. Binzel and Xu showed that the small members of the Vesta family were spectrally identical to Vesta (asteroid taxonomic type V). The small Vesta family members are therefore pieces of the basaltic crust of Vesta ejected from the surface during the formation of a large impact crater. The size of these family objects are substantially larger than previously believed to be commonly ejected during such impacts.

But the Vesta family still lies far from the "escape hatches" and does not resolve the apparent paradox. However, while investigating small asteroids in the general region of Vesta, Binzel and Xu discovered a continuous bridge of V-type objects extending from Vesta up to the edge of the 3:1 Kirkwood Gap (the heliocentric distance where an object orbits the sun three times for every one orbit of Jupiter around the sun) at 2.5 astronomical units (AU) (1 AU = Earth-sun distance or 149.6 million kilometers). Large fragments ejected from Vesta thus extend far beyond the previously defined Vesta family and include objects at the edge of the chaotic zone associated with the 3:1 resonance.

Fragments knocked off these V-type objects by small impacts can be readily injected into the chaotic zone and be rapidly transferred into Earth-crossing orbits. Thus both the basaltic achondrite meteorites and the small near-Earth basaltic asteroids represent material excavated from Vesta by a large impact which was transferred directly into the 3:1 chaotic zone or which derive from large fragments of Vesta ejected to locations adjacent to this zone.

Although many details remain to be resolved, it is now clear that the basaltic achondrite meteorites in our museum collections are natural samples of the main-belt asteroid 4 Vesta. We now know, with some degree of certainty, where the conditions, processes, and sequence of events recorded in these meteorites actually occurred in the early solar system. This provides strong constraints on temperature and pressure models of the solar nebula. It also strengthens our constraints on the nature of the early exotic heating events that melted the parent bodies of the achondritic meteorites and which also presumably heated the planetesimals that subsequently accreted to form the Earth and other terrestrial planets. The presence of comparably large fragments (up to 10 kilometers) among the objects ejected from Vesta at moderately high velocities also requires that we reevaluate our previous conceptions of the size and speed limits on fragments ejected during large impact events. An improved understanding of collisional ejection processes will have implications for the lunar and Martian ejecta (the lunar and SNC meteorites) reaching Earth. The results of Binzel and Xu clearly demonstrate the rewards which await investigators of the small main-belt objects and of the asteroid families.

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