the orbital distribution of the initially quiescent Kuiper belt distribution. Early models attempted to excite the main belt's random orbital velocities this way and remove most of its objects (*32*), and other studies have tried to explain various aspects of the Kuiper belt in such a context (*33*, *34*). The rogue planet is usually eventually scattered out of the solar system, although there exists the possibility (*17*) that one or more could still survive and remain undetected in the distant portions of the scattered or extended scattered disks. A recent study (*28*) concluded that rogue planet scenarios produce an observational signature that is in conflict with the observational distribution of the extended scattered disk and that a stellar passage model is more likely. Other work shows that the secular interaction of the rogue planet with the scattered disk allows efficient perihelion raising (*35*). Both scenarios warrant further work.

The study of the minor planets in the Kuiper belt has yielded constant surprises both observationally and theoretically over the past 5 years. In few other fields in astronomy is there such a tight and rapid advance in both the developments coming from telescopic work (driven by improving detector technology) and computational dynamics (enabled by evolving computer hardware). Ten years from now, our perspective on the solar system's small-body disk will be considerably advanced by a more complete census of our outer solar system and the coming ability to directly probe the region of Kuiper belts around other stars promised by the next generation of telescopes.

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10.1126/science.1100553

VIEWPOINT

From Stars to Dust: Looking into a Circumstellar Disk Through Chondritic Meteorites

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One of the most fundamental questions in planetary science is, How did the solar system form? In this special issue, astronomical observations and theories constraining circumstellar disks, their lifetimes, and the formation of planetary to subplanetary objects are reviewed. At present, it is difficult to observe what is happening within disks and to determine if another disk environment is comparable to the early solar system disk environment (called the protoplanetary disk). Fortunately, we have chondritic meteorites, which provide a record of the processes that operated and materials present within the protoplanetary disk.

Chondrites are 4.5672 ± 0.6 billion-year-old (*1*) rocks derived from the aggregation of dust and other rocks within the protoplanetary disk (Fig. 1). Arguably the oldest components of chondrites are calcium- and aluminum-rich inclusions [CAIs (*2*)] that contain mineral phases predicted to be the first to condense from a gas of solar composition. These objects range in size from submillimeter to centimeter, the largest being igneous rocks (melted and crystallized). The dominant component of chondrites is chondrules—submillimeter- to millimeter-sized igneous rocks that are probably younger than CAIs. Chondrules have compositions less refractory than those of CAIs and are mostly composed of the Mg- and Fe-rich silicate minerals, olivine and pyroxene, with varying concentrations of glass (*3*, *4*).

From an astrophysical viewpoint, if the igneous components of chondrites did not exist, they would not be predicted to exist. They are argued to have formed as free-floating objects within the earliest stages of the protoplanetary disk before planet formation—melted and quenched by some unknown mechanism or mechanisms (*4*). It is important to understand how, when, and why they formed, because this will lead to an understanding of the early conditions in the protoplanetary disk and how planets grew and evolved from these chondritic building blocks.

The Chondrites and the Protoplanetary Disk workshop in Hawaii (*5*) brought together about 150 participants from meteoritics, cosmochemistry, planetary science, astronomy, and astrophysics to understand how chondrites formed and how their formation affected the evolution of the solar system. One key question addressed at this workshop was whether the Sun formed in an isolated environment or in a cluster, where contamination from other stellar systems would be possible. As Greaves discusses in her Review article (*6*), evidence for the existence of a radioactive isotope of aluminum, ^{26}Al, within the protoplanetary disk suggests that the Sun likely formed within a cluster of stars. The evidence of live ^{26}Al and other short-lived radionuclei such as ^{60}Fe (*7*) comes from

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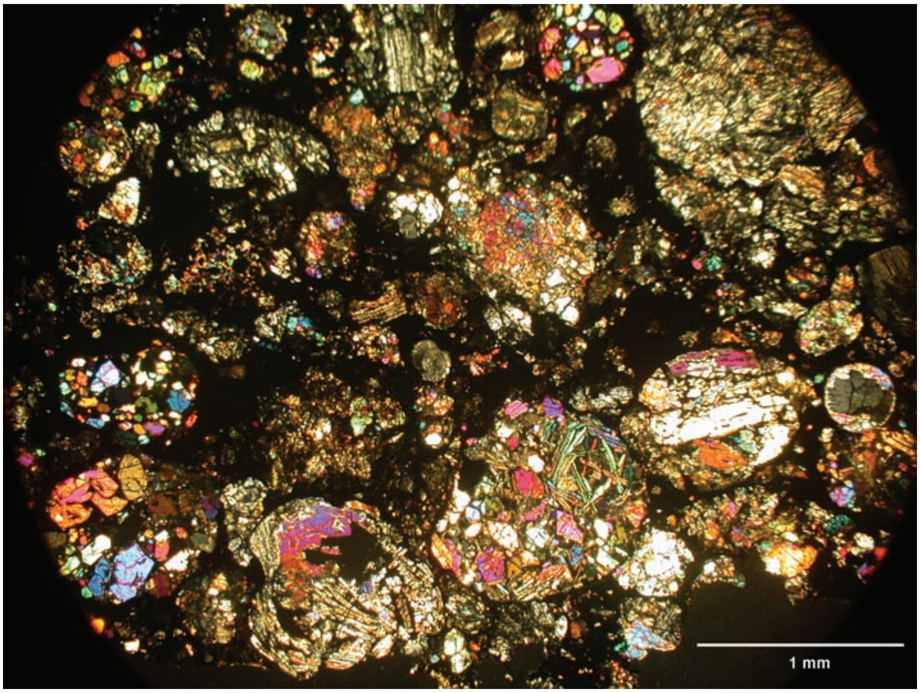

Fig. 1. Crossed polarized light image of a thin section of the ordinary chondrite Chainpur. The round objects are the chondrules, filled with angular minerals (olivine and pyroxene) and glass, whereas the finer-grained and darker materials are the matrix. CAIs are generally found within the matrix but are very rare in ordinary chondrites and too small to be seen in this image.

chondrites. The observed abundance of ^{60}Fe and its inferred initial abundance require a supernova source in the vicinity of the Sun at or slightly after the contraction phase of the solar molecular cloud (solar nebula). Some short-lived radionuclei, such as ^{10}Be, may have been produced through spallation reactions in the solar system (*8*), although these radionuclei may also be explained as cosmic rays trapped within the solar nebula (*9*). Models (*8*) have been proposed to extend the production of most short-lived isotopes through irradiation from energetic solar particles within the solar system, but such results are not widely favored by meteoriticists. Thus, some radioactive nuclei, particularly ^{26}Al and ^{60}Fe, require a nearby supernova explosion to contaminate the solar nebula, whereas other nuclei may be produced within the evolving solar system.

Formation of the solar system within a star cluster may have affected the disk's evolution in other ways. It has been suggested (*10*) that close encounters with a rogue star during the earliest stages of formation may have truncated the disk outside of Neptune's orbit. Gladman in his Review article (*11*) suggests that such a process may have had an impact on the formation of Kuiper Belt objects. There is little evidence from chondrites to address this idea. One exception may be CAIs known as FUN inclusions, which contain fractionated unidentified nuclear isotopic anomalies (*2*). Although speculation, they or their precursors might have been injected into the disk during a close pass with a rogue star, and thus FUN inclusions could predate other CAIs.

Non–mass-dependent variations in the stable isotopes of oxygen (^{16}O, ^{17}O, and ^{18}O) are observed within CAIs and chondrules. CAIs are generally enriched in ^{16}O compared with chondrules (*12*). Until recently, the major cause of this difference was thought to be a gas-solid exchange process in the solar nebula. In this model, light oxygen was inherited within solids from a stellar source—injected into the solar nebula or young disk—and during high-temperature processing of solids, the oxygen isotopes were exchanged between the gas and the modified solids. However, the hypothesis now in favor attributes the oxygen isotopic variations to effects of photodissociation and photo-evaporation (*12*). The source of the evaporation could have been the young Sun or another stellar source close to the solar nebula and/or young disk (*12*, *13*).

CAIs and chondrules provide two other important clues to the protoplanetary disk. First, the environment in which CAIs formed was different from that of chondrules. CAIs have different oxygen and magnesium isotopic compositions (the latter suggesting mass-dependent fractionation due to evaporation), and petrographic and chronologic data indicate that they melted at different times (*7*, *14*). CAIs likely formed within a single environment poor in dust with few proto-CAIs that were later scattered within the disk, whereas chondrules likely formed in areas rich in dust and proto-chondrules. This conclusion does not, however, require different melting mechanisms for the objects. It does mean that the dust that eventually formed the building blocks of planets varied within the disk. Second, chondrule formation lasted for 2 to 5 million years (*7*, *14*). The protoplanetary disk must have lasted at least this long. Here the rock record of processes within a disk agrees with observations of the lifetimes of protoplanetary disks (*15*). Thus, the meteorite record and observations of the cosmos are converging on the lifetime of disks and suggest solar system formation within a stellar cluster.

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