Meteoritics & Planetary Science 41, Nr 1, 3–6 (2006)
Abstract available online at http://meteoritics.org

Workshop on Chondrites and the Protoplanetary Disk Kaua'i, Hawai'i, 2004

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In November 2004, a diverse, multi-disciplinary group of scientists met to discuss the formation of the solar system. The main subject of their meeting was the formation of the foundation stones of the planets, samples of which fall upon the Earth in the form of meteorites.

Primitive meteorites, known as chondrites, probably formed around 4566 to 4564 million years ago (Amelin et al. 2002) when the solar system was a disk of gas and dust (the solar nebula) surrounding the early Sun. Such meteorites are mostly composed (60–80% by mass) of small ~0.1 mm, ferromagnesian silicate spherules called chondrules. They also contain other components, e.g., calcium-aluminum inclusions (CAIs) (0–10% by mass) and ameboid olivine aggregates (AOAs) (0–5% by mass), which are the earliest, or amongst the earliest, rocks that formed from the solar nebula (Kita et al. 2005).

Chondrules were first described over two hundred years ago (Howard 1802), and their formation mechanism has remained a mystery despite over twenty different theories being proposed to explain their origin (Grossman 1988; Boss 1996). Chondrite formation has not been important to most astronomers and astrophysicists, but the discoveries of planets around other stars have produced a surge of interest as researchers seek insight into the formation of these extrasolar planets by attempting to understand the formation of the solar system. As a result, the field of chondrite formation has grown, but understanding is hampered by the lack of data and the surfeit of theories.

Scientists representing many specialties (astrophysics, planetary science, meteoritics, thermochemistry) attended this once-in-a-decade meeting to discuss the formation of these foundation stones. The inaugural meeting in this series was held at the Houston-based Lunar and Planetary Institute in 1982 (King 1983), with a subsequent meeting at the University of New Mexico, Albuquerque, in 1994 (Hewins et al. 1996). The latest was held in Kaua'i, Hawai'i (8–11 November, 2004), with an attendance of around two hundred—two to three times that of the Albuquerque meeting.

The growth in chondrite research has produced unexpected and significant results in a number of different fields. One of the most important is the successful dating of chondrite components via U-Pb decay sequences (Amelin et al. 2002). Noriko Kita (Geological Survey of Japan) presented the latest results on formation times as obtained from short and long-lived radionuclides (Kita et al. 2005). Now, a good correlation exists between the absolute ages obtained from U-Pb dating and results from short-lived radionuclides, such as ^{26}Al. The preliminary results suggests that CAIs formed first at around 4567 million years ago, AOAs may have formed around half a million years later and most chondrules were then produced over a time of one to three million years after CAIs were formed. Thus the most refractory material, CAIs, was formed first with generally less refractory material formed later. This is qualitatively consistent with the accretion behavior of young stellar systems, whose mass accretion (and accretion energy) decreases over a time scale of around 3 million years (Calvet et al. 2004). It also suggests that many short-lived radionuclides were homogeneous within the solar nebula.

The origin of short-lived radionuclides in the solar nebula has been a subject of debate since 1960 when excess ^{129}Xe, produced from the β-decay of ^{129}I (half-life ~16 Myr), was discovered in a chondritic meteorite (Reynolds 1960). For many years, discussion has centered around two basic models: formation by irradiation from within the solar nebula and/or formation via nucleosynthetic sources such as asymptotic giant branch (AGB) stars and supernovae (Podosek and Swindle 1988). The latest versions of these ideas were presented at the meeting, where the recent discoveries of ^{10}Be in CAIs (McKeegan et al. 2000) indicate that some radionuclides were formed within the solar nebula, possibly by solar irradiation (Gounelle et al. 2001) or by cosmic rays in the nascent molecular cloud from which the solar nebula was formed (Desch et al. 2004), while the discovery of ^{60}Fe in chondrites adds to evidence that a supernova may have produced this and some other radionuclides (Zinner 2003). Multiple sources may have produced the short-lived radionuclides, however the amount produced from each source and the mode of transport to the chondritic meteorites is still a controversial subject (Goswami et al. 2005).

An unexpected result from long-lived radionuclides is the age of formation for CB chondrites, which appears to be around 5 million years after the CAIs (Kita et al. 2005). CB chondrites and chondrules have properties that are different from what is observed in other chondrites (Krot et al. 2002). This and their late age of formation has led to speculation that their formation mechanism may have been different from more typical chondrules, e.g., they may have been produced by the impact of two lunar-sized bodies (Krot et al. 2005).

The impact theory for chondrule formation was first suggested in 1953 (Urey and Craig 1953), but it fell out of favor at the first chondrules conference (Taylor et al. 1983), with only a trickle of development since that time. The reemergence of this theory has been driven by independent developments in the theory of crater formation and simulations of collisions between near planet-sized bodies. As detailed by Jay Melosh (University of Arizona), size really does matter. Small impactors produce only a small amount of melt and a larger amount of fragmented material. This situation reverses for larger impactors, where the interaction between escape velocities, melt surface tension, and explosive gas effusion can also produce an abundance of chondrule-like melt droplets.

The impact theory is an example of a "local" theory for chondrule formation. In general, local theories presume that the source of heating for chondrules, CAIs, etc., occurred at or around 3 AU from the Sun. The shock model is the most popular "local" theory. This theory assumes that sufficiently strong shock waves existed in the solar nebula and were able to produce temperatures of up to ~2000 K. The shock model has undergone consistent theoretical development since 1991 (Hood and Horányi 1991) and can now, in principle, provide conditions that are consistent with currently deduced conditions for chondrule formation (Desch and Connolly 2002). Shock waves are common in the interstellar medium and it is likely that they existed in the solar nebula. A number of possible shock wave mechanisms such as spiral density waves, X-ray flares, and planetesimal bow shocks were discussed at the meeting. Unfortunately, there is no consensus (Boss 2004) about what, if any, process was able to generate the appropriate shock waves over a time scale of at least three million years.

As with most theories, the shock wave model has its critics, e.g., Masayuki Uesugi (Kyushu University) detailed some possible difficulties with the shock model (Uesugi et al. 2005) where, say, a 9 kms^{-1} shock wave may preclude the formation of some observed compound chondrules (chondrules that have stuck together). Astronomical observational confirmation of shock formation in young stellar disks is still not available and may require micro-arcsecond resolution.

Xander Tielens (Kapteyn Astronomical Institute) discussed recent 20 milli-arcsecond observations from the Very Large Telescope (VLT), which provide an observational constraint on where thermal processing occurs in young stellar disks. These results (van Boekel et al. 2004) indicate that crystalline olivine and pyroxene dust is formed in the inner disk regions of the young stellar systems, within 1 or 2 AU from the star. Most interstellar dust is amorphous, but amorphous grains can be annealed into crystalline material via exposure to ~1000 K temperatures or crystalline dust can condense directly from the gas phase. Observations of Oort cloud comets indicate that around 70% of dust grains produced from such comets are crystalline (Wooden et al. 2004). Samples of cometary material also fall to the Earth's surface in the form of interplanetary dust particles (IDPs). A subset of IDPs contain crystalline silicates, such as olivine and pyroxene, which have been irradiated and also condensed from a hot nebular gas (Keller and Messenger 2005). Thus, there was probably a mechanism that transported crystalline dust from within 2 AU of the Sun to 5–40 AU, where the comets formed. This is consistent with "non-local" chondrite formation theories, which assume that the thermal processing of chondritic material occurred close to the Sun. The processed material was then transported from the inner to the outer disk regions via the agency of radial diffusion (Cuzzi et al. 2003) or bipolar jet flows (Skinner 1990; Liffman and Brown 1996; Shu et al. 1996), where the latter are observed, ~200 kms^{-1} flows that may be able to eject material from the inner to the outer regions of a disk. The observation that a major portion of outer nebula dust has undergone high-temperature processing was predicted by a jet flow model (Liffman and Brown 1996).

As discussed by Nuria Calvet (Harvard University), observations of young stellar disks shows that a "wall" of silicate dust exists at an inner radius of around 0.07 to 0.5 AU from the star (Muzerolle et al. 2003). This wall is produced by the sublimation of silicate dust at a temperature of ~1400 K due to irradiation from the star and accretion shocks (produced by disk material falling onto the star). This length scale is roughly greater than the co-rotation distance from the star, where the angular velocity of the stellar magnetic field equals the near-Keplerian angular velocity of the disk. High speed jet flow models that are used in chondrule/CAI formation theories are deduced to form at distances less than or at the co-rotation radius (Shu et al. 1996; Liffman 2005). Since the dust wall appears to be outside the co-rotation radius then it is possible that a solar bipolar jet had nothing to do with chondrule/CAI formation. Alternatively, the co-rotation radius and the wall radius may change with time. Initially, the co-rotation radius is inside the wall radius, but as the star spins down and its accretion luminosity decreases, the co-rotation radius moves outwards and the wall moves inwards. In this way, the jet flows may be able to eject less refractory materials as a function of time.

Many other aspects of star formation were discussed at the workshop, including how and when short-lived radionuclides entered the solar nebula (Connolly 2005). Jeff Hester (Arizona State University) outlined the case for the Sun forming in a cluster of stars, which contained one or more massive stars (Hester et al. 2004). Such stars could have altered the evolution of the solar nebula by bathing the nebula in extreme ultraviolet light and thereby truncating the infall of material onto the nebula and causing the nebula to photoevaporate. Such a massive star could also turn supernova and inject short-lived radionuclides into the nebula via dust grains that have condensed from the supernova remnant.

Another aspect of isotopic abundances was presented by Hisayoshi Yurimoto (Tokyo Institute of Technology), who attempted to explain the mass-independent ^{16}O enrichment observed in chondrites (Yurimoto and Kuramoto 2004; Clayton et al. 1973). Yurimoto and Kuramoto use the observed selective UV-dissociation of CO (also known as self-shielding of CO) in molecular clouds to derive a model where silicates, ices, and gases within the solar nebula gas had different levels of ^{16}O enrichment or depletion. It is suggested that the subsequent mixing and recombination of these components gave the ^{16}O enrichments or depletions that are now observed in chondrites. This is one of a number of CO self -shielding models that have arisen over the last few years. Two other models suggest that self-shielding might have occurred either in the inner solar nebula (Clayton 2002) or at the surface of the solar nebula (Lyons and Young 2005). There are still some difficulties with these models, in particular, the lack of experimental data for the dissociation of $C^{17}O$. So the $^{17}O/^{16}O$ fractionation relative to $^{18}O/^{16}O$ is still uncertain. Nonetheless, the self-shielding model found favor with many of the attendees.

The most poignant moment of the meeting was the retirement of John Wood, a celebrated founder of the modern field of meteoritics. Klaus Keil (University of Hawai'i) gave a well-received presentation in honor of John Wood, who was subsequently given a standing ovation (Keil 2005).

Although no consensus was reached on how chondritic components were formed, considerable progress has been made since the 1994 Albuquerque meeting. It is evident that amongst the major drivers for further progress will be the improved resolution and capabilities in the fields of young stellar astronomy and meteorite chronology.

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