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Headline Article

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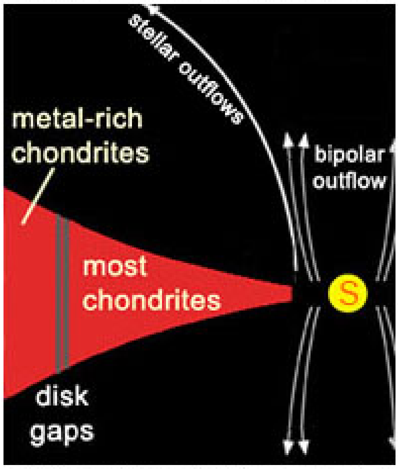
Primordial Molecular Cloud Material in Metal-Rich Carbonaceous Chondrites

--- Dust from the molecular cloud that gave birth to the Sun may be preserved in objects formed in the outer reaches of the Solar System.

***Written by* G. Jeffrey Taylor**
Hawai'i Institute of Geophysics and Planetology

Solar Protoplanetary Disk



PSRD graphic based on Van Kooten *et al*, 2016, *PNAS*, doi:10.1073/pnas.1518183113.

The menagerie of objects that make up our Solar System reflects the composition of the huge molecular cloud in which the Sun formed, a late addition of short-lived isotopes from an exploding supernova or stellar winds from a neighboring massive star, heating and/or alteration by water in growing planetesimals that modified and segregated the primordial components, and mixing throughout the Solar System. Outer Solar System objects, such as comets, have always been cold, hence minimizing the changes experienced by more processed objects. They are thought to preserve information about the molecular cloud. Elishevah Van Kooten (Natural History Museum of Denmark and the University of Copenhagen) and co-authors in Denmark and at the University of Hawai‘i, measured the isotopic compositions of magnesium and chromium in metal-rich carbonaceous chondrites. They found that the meteorites preserve an isotopic signature of primordial molecular cloud materials, providing a potentially detailed record of the molecular cloud's composition and of materials that formed in the outer Solar System.

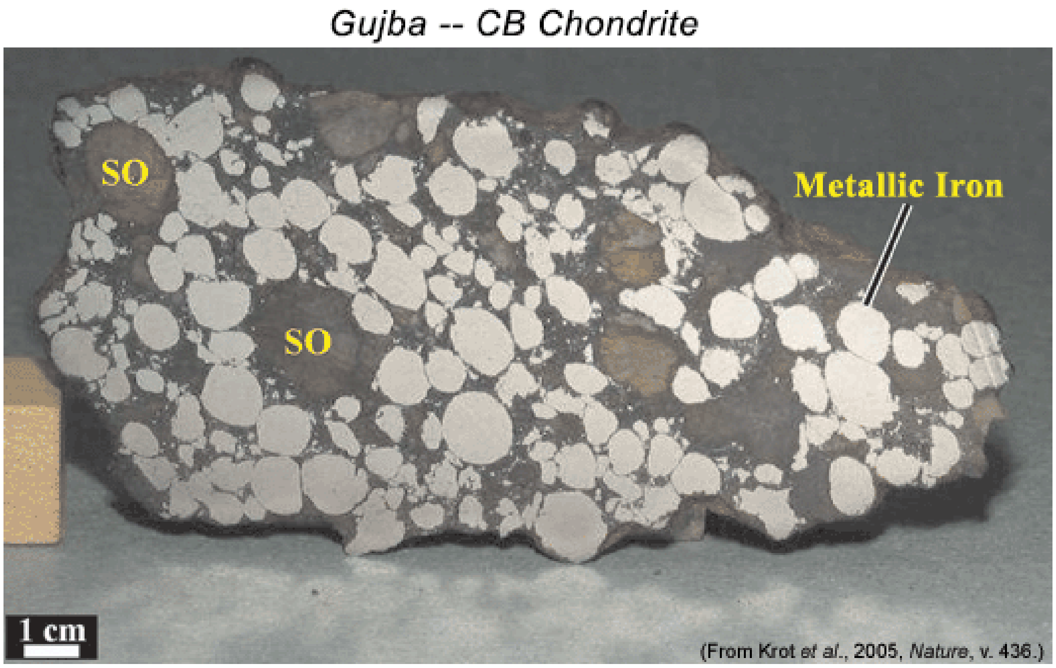
Reference:

- Van Kooten, E. M. M. E., Wielandt, D., Schiller, M., Nagashima, K., Thomen, A., Larsen, K. K., Olsen, M. B., Nordlund, Å., Krot, A. N., and Bizzarro, M. (2016) Isotopic Evidence for Primordial Molecular Cloud Material in Metal-rich Carbonaceous Chondrites, *Proceedings of the National Academy of Sciences,* v. doi:10.1073/pnas.1518183113. [**abstract**]
- **PSRDpresents:** Primordial Molecular Cloud Material in Metal-Rich Carbonaceous Chondrites --**Short Slide Summary** (with accompanying notes).

Comets, Chondrites, and the Outer Solar System

Besides offering impressive celestial displays, **comets** have long been valued by scientists because they were thought to have formed in the outer reaches of the Solar System where temperatures are so cold that not much chemistry would have gone on inside them. These frigid dust and ice objects would likely have preserved a record of the dust from which the Solar System formed. Measurements of particles collected from comet Wild 2 by the Stardust mission (see **PSRD** CosmoSparks report: **Meteoritics & Planetary Science—More Cosmochemical Results from the Stardust Mission to Comet Wild 2**) indicate that comets did preserve the dust in them, though it also revealed that the non-icy components originated throughout the Solar System.

Eli Van Kooten and colleagues studied samples from metal-rich **carbonaceous chondrites**. These rocks get their name from the high abundance of metallic iron in them combined with silicate **chondrules** that crystallized rapidly (see image below). Metal-rich carbonaceous chondrites come in three flavors that are abbreviated CH (high metal, even higher than in the other two groups), CB (those grouped with a chondrite named Bencubbin [**Data Link** from the Meteoritical Bulletin Database]), and CR (a group with similar properties to the Renazzo chondrite [**Data Link** from the Meteoritical Bulletin Database]). All metal-rich carbonaceous chondrites have the important attribute of having experienced essentially no heating after they were assembled. A bit of heating occurred —to cause primitive ice to melt and water-bearing minerals to form— but the temperature was never high enough to cause silicates and oxides to be altered. Metal-rich carbonaceous chondrites are good bets to preserve the chemical characteristics of their non-icy components. Of course, they do contain chondrules that are the products of heating in the proto-solar disk, but the metal-rich carbonaceous chondrites themselves were not heated significantly.



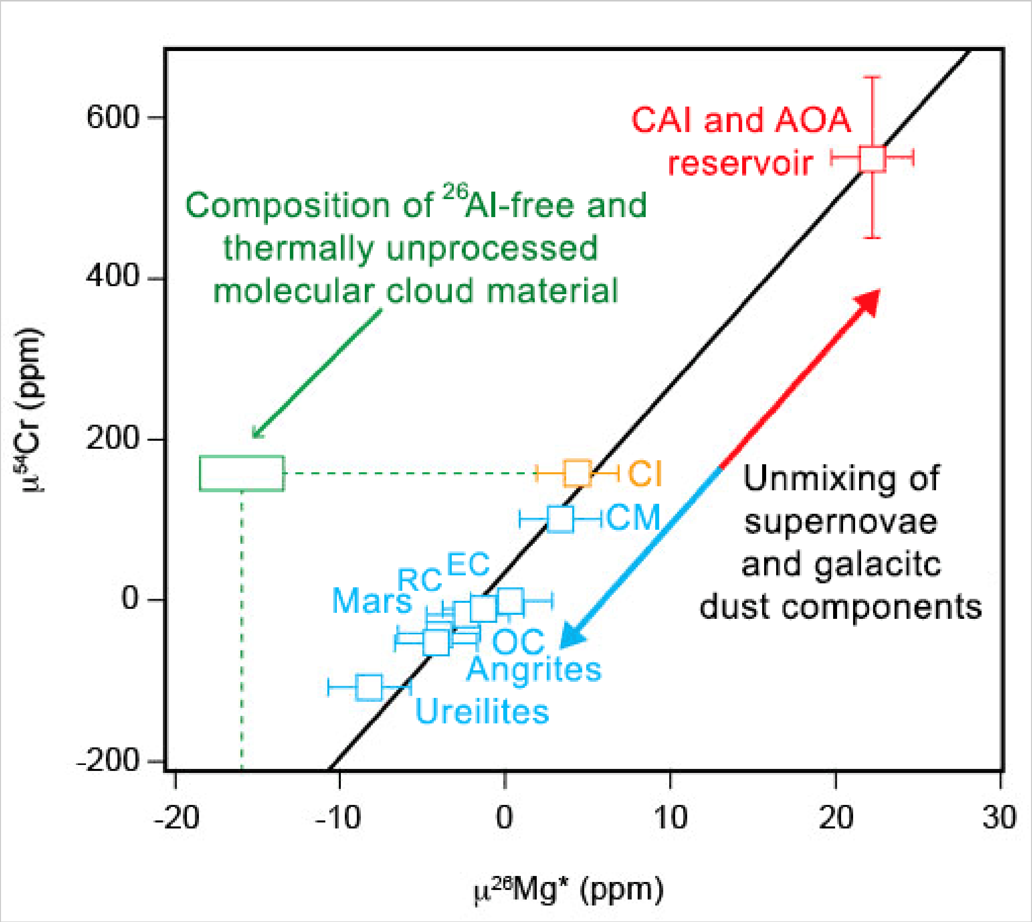
(From Krot *et al.*, 2005, *Nature*, v. 436.)

Photograph of a polished slab of the CB chondrite Gujba [Data Link from the Meteoritical Bulletin Database.] The bright, round objects are composed of metallic iron. Darker objects (SO) are chondrules, in this case containing rapidly-crystallized, skeletal-olivine (SO) chondrules. (The term skeletal refers to boney, skinny structure of arms of olivine, which only forms during rapid cooling from thoroughly melted silicate droplets.)

Inner Solar System Isotope Correlations

Van Kooten and her colleagues analyzed chromium (Cr) and magnesium (Mg) **isotopic** compositions. Each element and its isotopes provide different information. The ratio of chromium-54 to chromium-52 (^{54}Cr/^{52}Cr) provides information about the contribution to the Solar System from variations in the amount of ^{54}Cr produced from **stellar winds** and **supernovae**; a greater contribution leads to higher ^{54}Cr/^{52}Cr. The magnesium-26 to magnesium-24 ratio (^{26}Mg/^{24}Mg) reflects stellar formation of ^{26}Al, which decays to ^{26}Mg. The decay happens rapidly as ^{26}Al has a half-life of only 700,000 years. The important point is that ^{54}Cr/^{52}Cr and ^{26}Mg/^{24}Mg contain a record of mixing of different components produced by stellar winds and supernova explosions of massive stars, versus the long history of the **molecular cloud** where the Sun and Solar System formed, which is also called the "galactic" component.

New and published data show a striking correlation between the isotopic compositions of chromium and magnesium, as shown in the diagram below, where the isotopes are plotted as deviations of ^{54}Cr/^{52}Cr and ^{26}Mg/^{24}Mg from a terrestrial standard in parts per million (the μ notation). ^{26}Mg* gets an asterisk to show that it derives from the decay of ^{26}Al. On the diagram, calcium-aluminum-rich inclusions (**CAIs**) and primitive amorphous olivine aggregates (AOAs) plot in the upper right, at the highest isotopic ratios. Chondrites, differentiated meteorites, and planets plot lower, spreading out along a line that crosses the CAI and AOA point. The correlation arises because the molecular cloud consists basically of two dust components: fragile supernova dust enriched in ^{54}Cr and ^{26}Al and more thermally-robust galactically inherited dust that is poor in ^{26}Al. When this initially homogenized dust (CI-like composition) is thermally processed, the more fragile dust will evaporate faster creating a gas reservoir enriched in ^{26}Al and ^{54}Cr, from which CAIs and AOAs form. The residue (chondrites, planets, etc.) will be depleted in ^{54}Cr and ^{26}Al. Thermal processing of dust is thought to happen in the warm inner Solar System (<5 astronomical units (**AU**) from the Sun), so Van Kooten and team speak of an inner Solar System correlation line. Thus, the CAI-AOA value represents the initial isotopic composition of the region of the solar nebula in which CAIs formed. The data also show that the initial amount of ^{26}Al must have varied in the Solar System, an important point demonstrated by Kirsten Larsen and colleagues in 2011.



(From Van Kooten *et al.*, 2016, *PNAS*, doi: 10.1073/pnas.1518183113.)

Plot of ^{54}Cr/^{52}Cr vs ^{26}Mg/^{24}Mg in μ notation (deviation of the ratio from a terrestrial standard in parts per million) for assorted Solar System materials. Calcium-aluminum-rich inclusions (CAIs) and primitive amorphous olivine aggregates (AOAs) represent a component with the highest proportion of materials from supernova/stellar winds. Other materials have less of this component and have been thermally processed, except for CI and most CM chondrites. The green box is the inferred composition of the molecular cloud material. Its μ^{54}Cr is assumed to be the same as CI carbonaceous chondrites and its μ^{26}Mg* is derived from the systematics of Mg and Al isotopic compositions in a range of components in chondrites. The size of the rectangle indicates uncertainties in the estimate of the compositions of the ^{26}Al-free material.

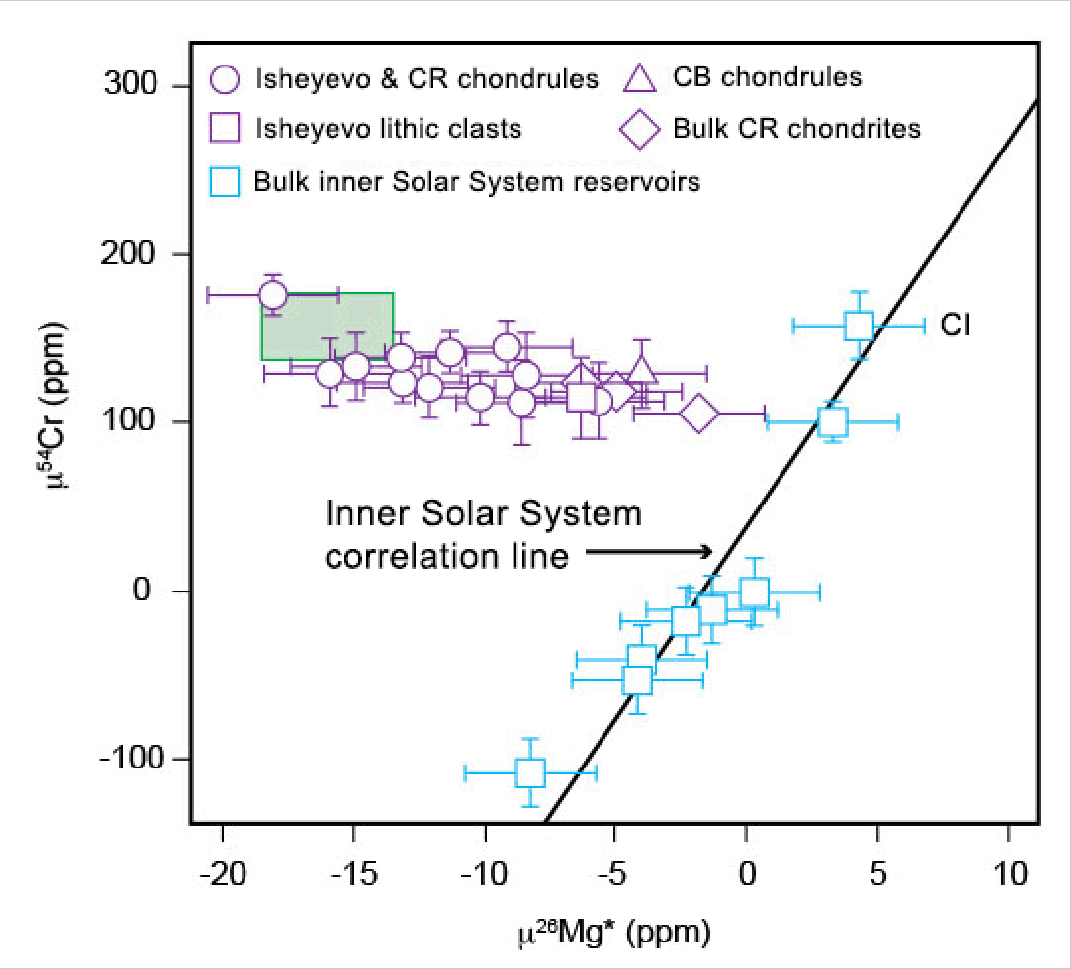
Metal-Rich Carbonaceous Chondrites Contain Molecular Cloud Material

Cosmochemists, always on the lookout for unaltered **pre-solar** materials, have good reasons for thinking that metal-rich carbonaceous chondrites contain primitive Solar System dust. One reason is that the CAIs occupying space between roundish blobs of metallic iron contained only tiny amounts of ^{26}Al when they formed. They are inferred to be the earliest-formed CAIs. These **refractory inclusions** would have been melted before ^{26}Al was injected into the collapsing molecular cloud. They are primitive, implying that other materials in metal-rich carbonaceous chondrites are also primitive.

In addition, one group of metal-rich carbonaceous chondrites, the CR chondrites, contain the highest abundance of pre-solar grains among the carbonaceous chondrites. Cosmochemists identify pre-solar grains by their unusual (compared to most Solar System materials) isotopic compositions of elements such as carbon, silicon, and titanium. The tiny grains, including microscopic diamonds and metal oxides, are survivors of the processes involved in Solar System formation, representing tiny pieces of the molecular cloud. They formed in stars that no long exist. (For more information, see **PSRD** articles: **Stardust—Snapshots of Stars**, **Festival on the Formation of the First Solids in the Solar System**, and **Moving Stars and Shifing Sands of Presolar History**.)

If a meteorite was heated too much in its asteroidal parent body, these tiny pieces of stardust disappear, merging with other grains, their former existence as interstellar dust erased. By implication, the relatively high abundance of pre-solar grains in CR chondrites implies little heating, hence preservation of the materials in them. In addition, other features, such as nitrogen isotopic composition and the relatively young ages of chondrules in metal-rich carbonaceous chondrites—5 million years after CAIs formed compared to about 3 million years for chondrules in other chondrite types—also point to their primitive, low-temperature origins (discussed further below).

The startling observation made by Eli Van Kooten and co-workers is that the Cr and Mg isotopic compositions of metal-rich carbonaceous chondrites and the components in them (chondrules, pieces of primitive rock) lie along a line from the CI chondrite point on the inner Solar System line (shown above) to the predicted isotopic composition of materials that were not processed in the solar nebula and were free of ^{26}Al when they formed (see diagram below). The team argues that this trend implies that metal-rich carbonaceous chondrites contain materials that derived from the molecular cloud in which the Sun formed, before it was mixed with supernova/stellar wind material containing freshly synthesized ^{26}Al. These special chondrites formed from materials distinct from most of the ingredients in other chondrite types and the planets.



(From Van Kooten *et al.*, 2016, *PNAS*, doi: 10.1073/pnas.1518183113.)

Isotopic data from samples of metal-rich carbonaceous chondrites form an array that drifts almost horizontally from CI chondrites on the line defined by thermally-processed Solar System materials to the composition predicted to exist in the molecular cloud that was parental to the Solar System. The data suggest that the metal-rich carbonaceous chondrites contain dust that originated in the vast cloud of gas and dust in which the Sun formed.

Accretion of Metal-Rich Carbonaceous Chondrites in the Cold Outer Solar System

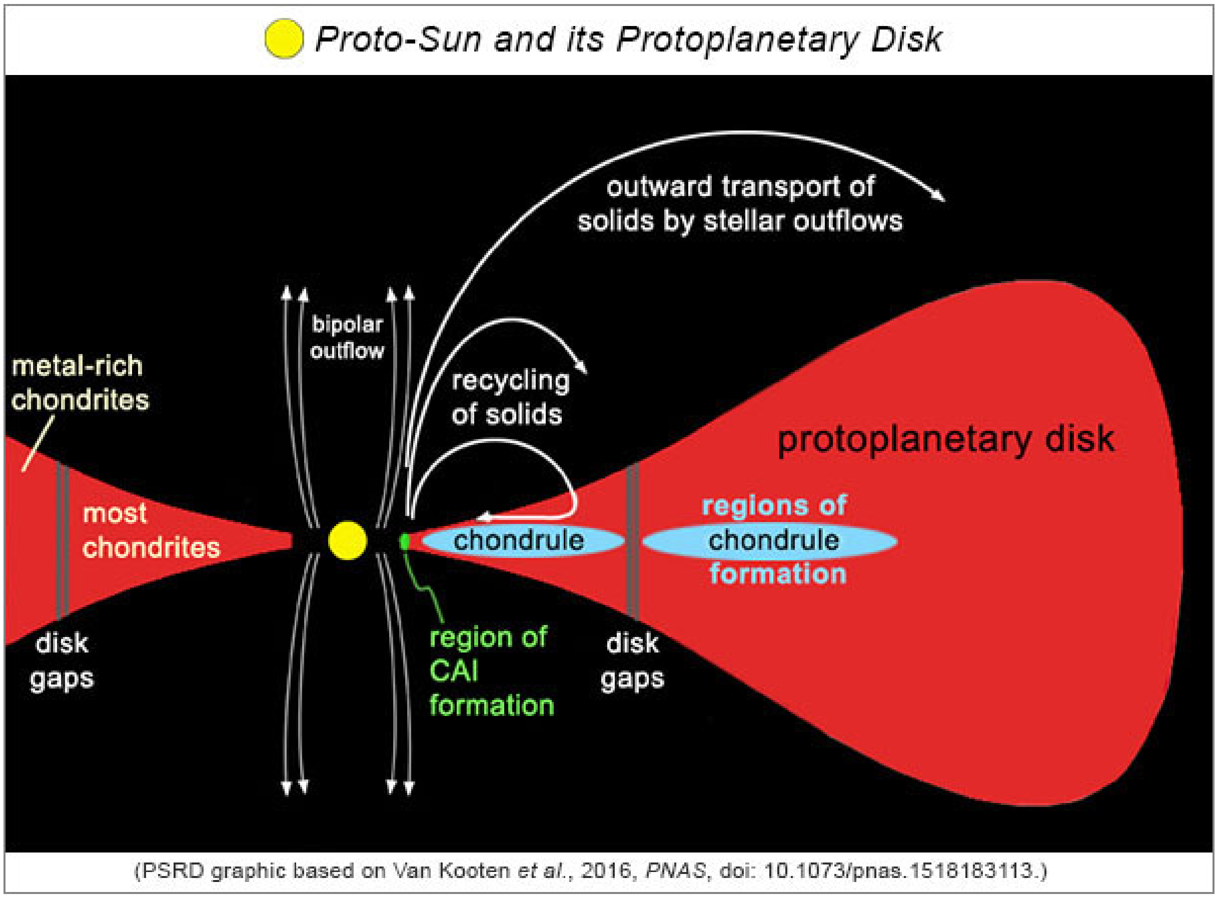
Metal-rich carbonaceous chondrites are clearly distinct from other chondrite types, differentiated meteorites, and the inner planets. There are hints that the differences correlate with where they formed: metal-rich carbonaceous chondrites (and comets) formed in the other Solar System, while other chondrites, melted asteroids, and planets formed in the inner Solar System. The primitive nature of metal-rich carbonaceous chondrites described above point to low temperatures, a characteristic of places distant from the Sun. Survival of pre-solar grains and other features of these special chondrites point to a cold, thermally unaltered origin. The strong evidence for the presence of ^{26}Al-free molecular cloud material reinforces the interpretation that the metal-rich carbonaceous chondrites formed in the outer Solar System where cosmochemists and astronomers think comets also formed. In contrast, most other chondrites formed in the inner Solar System, sunward of where Jupiter is today. Conveniently, asteroids composed of metal-rich carbonaceous chondrites drifted into the inner Solar System because of migrations of Jupiter and other gas giants early in the history of the Solar System, allowing impacts to chip off pieces that made their way to us as meteorites.

This leads to a picture of the Solar System in which components derived from exploding supernova or stellar winds from a massive star are distributed heterogeneously, partly because pre-supernova (poor in

^{26}Al) materials end up being incorporated into the outer Solar System. Eli Van Kooten and colleagues also point out that the supernova/stellar wind debris may be more easily affected by heating, leading to Cr and Mg being incorporated into the gas in the solar nebula. This leads to the positive correlation between Cr and Mg isotopes in inner Solar System materials.

The Windy Solar Nebula

Van Kooten and her team put these results into the larger context of transport in the solar nebula. It makes for a complicated yet coherent, and certainly interesting, picture. Besides emphasizing that supernova-poor materials flowed into the evolving Solar System from the interstellar molecular cloud, they also point out that the presence of high-temperature, processed components, such as CAIs, in comets shows that inner Solar System materials must have been transported to the outer Solar System. Mechanisms proposed previously on the basis of astronomical observations and theory for this transportation system include protostellar outflows (jets emanating from the proto-Sun) and disk winds, which are associated with jets. For discussions of transport in the solar nebula, see, for example, **PSRD** articles: **Chronicle of a Chondrule's Travles** and **A Traveling CAI**. The short answer is that meteorite components such as CAIs form at high temperature in the inner Solar System and are blown out to the outer reaches of the Solar System to be incorporated into objects that, ironically, have always been cold.


Proto-Sun and its Protoplanetary Disk

(PSRD graphic based on Van Kooten *et al.*, 2016, *PNAS*, doi: 10.1073/pnas.1518183113.)

Van Kooten and colleagues suggest that outward transport may be most efficient early in Solar System history, implying that metal-rich carbonaceous chondrites would have accreted then. Later (meaning after a few million years), transport is confined to the inner Solar System. This is due to formation of gaps in the proto-solar disk due to the formation of the gas giants.

One of the enduring debates in cosmochemistry is how chondrules formed. See, for example, **PSRD** articles: **Dating Transient Heating Events in the Solar Protoplanetary Disk** and **Ancient Jets of**

Fiery Rain. Part of the solution to this age-old debate is knowing where chondrules formed. We know ***when*** chondrules formed, which was a bit after CAIs to 4 million years after CAIs, but we do not know ***where*** they formed. Combining models for the formation of the outer planets with ages of chondrules, Van Kooten and co-workers suggest that chondrule formation occurred in both the inner and outer Solar System.

The story told by Eli Van Kooten and coworkers may not be completely correct in detail, but their data and interpretations depict a grand picture of the origin of the Solar System from a molecular cloud, collapse of that cloud, patchy addition of ^{26}Al formed in stellar winds and supernovae of massive stars, and formation of the Solar System by a complicated set of processes that included transport of inner Solar-System materials outwards. Perhaps most intriguing, the data on metal-rich carbonaceous chondrites show that unprocessed molecular cloud material is accessible in the inner Solar System and could be retrieved easier than if it resides only in the outer Solar System.

Additional Resources

Links open in a new window.

- Larsen, K. K., Trinquier, A., Paton, C., Schiller, M., Wielandt, D., Ivanova, M. A., Connelly, J. N., Nordlund, Å., Krot, A. N., and Bizzarro, M. (2011) Evidence for Magnesium Isotope Heterogeneity in the Solar Protoplanetary Disk, *Astrophysical Journal Letters,* v. 735(2):L37, doi: 10.1088/2041-8205/735/2/L37. [**abstract**]
- Van Kooten, E. M. M. E., Wielandt, D., Schiller, M., Nagashima, K., Thomen, A., Larsen, K. K., Olsen, M. B., Nordlund, Å., Krot, A. N., and Bizzarro, M. (2016) Isotopic Evidence for Primordial Molecular Cloud Material in Metal-rich Carbonaceous Chondrites, *Proceedings of the National Academy of Sciences,* v. doi:10.1073/pnas.1518183113. [**abstract**]