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Chemical evolution of planetary materials in a dynamic solar nebula

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Abstract. As observational facilities improve, providing new insights into the chemistry occurring in protoplanetary disks, it is important to develop more complete pictures of the processes that shapes the chemical evolution of materials during this stage of planet formation. Here we describe how primitive meteorites in our own Solar System can provide insights into the processes that shaped planetary materials early in their evolution around the Sun. In particular, we show how this leads us to expect protoplanetary disks to be very dynamic objects and what modeling and laboratory studies are needed to provide a more complete picture for the early chemical evolution that occurs for planetary systems.

Keywords. planetary systems: formation, planetary systems: protoplanetary disks, planets and satellites: formation, solar system: formation, comets: general

1. Introduction

Protoplanetary disks are chemical factories, inheriting materials from the Interstellar Medium and transforming them into the building blocks of the planets. Our understanding of these transformations have grown exponentially in recent years as the Atacama Large Millimeter Array (ALMA) has allowed us to begin probing these disks at spectral and spatial resolutions that were never before possible. Laboratory studies have been fundamental in helping us to interpret these observations. Experimental studies have focused on quantifying the rates of chemical reactions, the yields of photon-driven processes like photodesorption or dissociation, and the response to dust particles to the collisions or radiation fluences that they would see within these disks. In total, these individual measurements or results are brought together to build models and frameworks from which we begin to decipher the various stages of evolution and processes that operate to shape planetary materials in their very earliest stages of evolution.

Despite these recent advances and the imminent access to facilities such as the James Webb Space Telescope and extremely large telescopes on the ground, our ability to construct a complete picture of planet formation in this manner remains limited. Even with the large baselines that ALMA provides, spatial resolution is still limited to a few to many AU in all but the most nearby disks. Thus resolving what is happening on the scale of a region comparable to where all of the terrestrial planets in our Solar System lies is not possible. Further, due to optical depth effects, JWST, ALMA, and other observatories detect molecular emission arising from surface layers, while planets are assembled deep inside the disks around the midplane. Thus the relevance of these observations to the properties of the planets that form remains uncertain.

An important opportunity arises, however, as we can look to our own Solar System for clues about what conditions were present and what processes operated within the solar nebula, the protoplanetary disk that circled the Sun. Such clues come from all over the Solar System, as the compositions and the properties of the bodies in orbit around the Sun are the products of the same evolutionary stages that operate around other stars. While the planets have been subjected to significant geophysical processes that have largely erased signatures of nebular evolution, the asteroids and comets have largely escaped such processing due to their smaller sizes. These objects are leftover planetesimals that formed within the solar nebula, and thus serve as time capsules from that stage of planet formation.

Here we review some of the insights that meteorite and cometary analyses provide into the earliest stages of planet formation and how the stories that emerge from these insights compare to those developed from observations of protoplanetary disks. We end with a discussion of what additional laboratory measurements and developments are needed to further our understanding and would allow us to build a more comprehensive picture for planet formation.

2. Meteorites as insights into protoplanetary disk properties

Protoplanetary disks are dynamic objects, with mass pushed inward to feed the central star and angular momentum transported outward to compensate. While the driving forces and effects for this evolution remain uncertain (e.g. Hartmann & Bae (2018)), signatures of mass accretion from the disk onto the star are seen for millions of years (Hartmann *et al.* (2016)). Indeed, this is significant, as the lifetimes of protoplanetary disks are typically 3-5 Myr, though there is quite a large dispersion, with protoplanetary disks observed around disks up to ∼10 Myr (Lada & Lada (2003)). Such information is important as it provides a global view of the setting in which the early stages of planet formation is taking place.

This general picture and timeline is supported by analyses of extraterrestrial samples. Chondritic meteorites, are particularly useful in this regard, as they represent samples of asteroids that avoided large-scale heating that would have led to differentiation of their parent bodies. As such, these objects represent collections of the dust grains and aggregates which were floating around the solar nebula and were directly incorporated into planetesimals. Analyses of these samples show that they contain a wide array of materials, broken up into three major categories:

- *Calcium, Aluminum-rich Inclusions* (CAIs) are objects largely composed of calcium and aluminium oxides. The minerals that they contain are thermodynamically stable in a gas of solar composition only at temperatures in excess of ∼1300–1500 K (Grossman (1972); Ebel (2006)), pointing to a high-temperature origin for these grains. In addition, these objects contain oxygen isotope ratios that are enriched in ^{16}O compared to most planetary materials, having values closer to that of the Sun (Clayton *et al.* (1973); Clayton (1993); McKeegan (2011)). These objects consistently yield the oldest ages for objects that are dated using radiometric techniques, suggesting that they are the first objects to have formed within our solar nebula (Connelly *et al.* (2012)).
- *Chondrules* are roughly millimeter-sized iron-magnesium spherules that dominate the texture of many chondritic meteorites. Their rounded shapes and igneous textures indicate that they formed from a melt, meaning these objects saw temperatures of 1700–2100 K and then cooled at rates of 10-1000 K/hr (Connolly & Jones (2016)). While recording high temperature environments just like CAIs, chondrules are enriched in heavy isotopes of oxygen while also having ages that span to millions of years younger than CAIs (Connelly *et al.* (2012)).
- *Matrix* is the collection of fine dust that is interstitial to the other components of the meteorite. It is a collection of crystalline and amorphous silicates, organic molecules, and pre-solar grains. Importantly, this includes relatively fragile materials that would not survive the temperatures that are recorded by chondrules and CAIs.

The fact that such different materials which are clearly sampling a wide range of solar nebular environments are intimately mixed on the scale of centimeters within chondritic meteorites points to a dynamic solar nebula, one where materials are carried from an array of environments and packed together into common meteorite parent bodies.

Dynamical evolution within the nebula is further supported by the presence of high-temperature materials in comets, including crystalline grains (Bockelée-Morvan *et al.* (2002)) as well as CAI and chondrule-like materials that appear istopically coeval with their chondritic counterparts (Brownlee *et al.* (2006); McKeegan *et al.* (2006)). Such transport and mixing is consistent with global models of protoplanetary disks which undergo mass and angular momentum transport as part of their viscous evolution (Cuzzi *et al.* (2003); Ciesla (2007, 2010); Jacquet *et al.* (2011)) or being marginally gravitationally unstable (Boss (2008)). Such models result in mass accretion rates similar to those observed in protoplanetary disks, opening the door to the possibility that the mixing we see in meteorites and comets is a natural consequence of the dynamical evolution of protoplanetary disks.

The range of ages of the components found in chondritic meteorites also support the astronomical estimates for protoplanetary disk lifetimes. CAIs represent the oldest objects that have been dated, with chondrules found that measure as much as 3 Myr younger. CB chondrites, which are metal-rich chondrites, have ages that extend to ∼5 Myr after the formation of CAIs (Krot *et al.* (2005)). Given that these materials formed independently of one another and then were incorporated into planetesimals suggests that the nebular gas was present for this period of time (3–5 Myr). If the gas had dissipated in less time, the solids would not have accumulated into planetesimals; rather than being concentrated into larger objects, they would have been dispersed by radiation pressure and other effects. While we cannot rule out a longer lifetime of the protoplanetary disk, the absence of bodies with significantly younger ages suggests that much of the solid mass of the solar nebula was incorporated into planetesimal-sized objects by this time. Thus, again, meteoritic samples suggest that the lifetime of the solar nebula was comparable to the ages of protoplanetary disks estimated from astronomical observations.

3. Dynamic solar nebula

While the exact driving force for protoplanetary disk evolution remains the focus of ongoing work, it is thought that some level of turbulence is present, leading to diffusive redistribution of materials within the disk (Hartmann & Bae (2018)). The magnitude diffusivity that arises from this process is often parameterized by the α parameter within disks, giving an effective diffusivity of gas and fine-grained materials of $D_g = \alpha c_s^2/\Omega$, where c_s is the local speed of sound in the disk and Ω is the local Keplerian frequency. The value of α depends on the source of the turbulence within the disk, but current astronomical observations suggest the value is greater than 10^{-4} (Dullemond *et al.* (2018)) but less than $\sim 3\times10^{-3}$ (Flaherty *et al.* (2018)). The effect of this turbulent diffusion is that disk materials are constantly jostled and stirred throughout this epoch of planet formation. This leads to the gas and dust undergoing random walks through the disk, which, combined with the structure of the disk, exposes them to an array of environments (pressures, temperatures, radiation fluxes).

This exposure to different environments will be have an important effect on the overall chemical evolution of disk materials. Protoplanetary disks are generally broken up into three chemical processing regions: the cold, dark midplane where gas-solid interactions dominate; the warm, molecular layer where temperatures are sufficient to permit reactions among various species within the gas; and the photon-dominated layer where UV photons and X-rays penetrate, leading to much higher temperatures and driving disequilibrium reactions (Henning & Semenov (2013)). Thus dust grains and gas

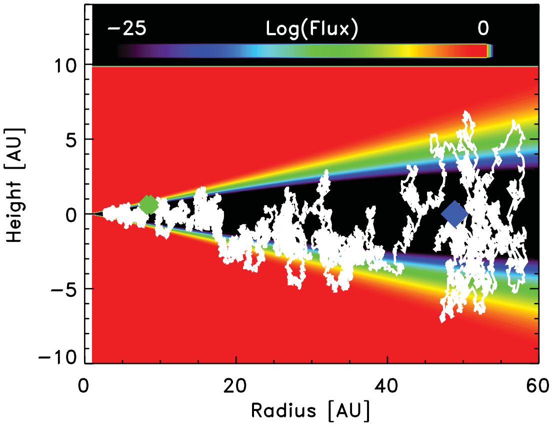

Figure 1. Path of 1 μm grain within a diffusive solar nebula superimposed on top of the UV radiation flux within the disk. The grain begins at the midplane of the disk 30 AU from the Sun, and over 1 Myr is subjected to turbulent diffusion which carries through an array of environments which will then determine the chemical evolution that occurs. Figure from Ciesla & Sandford (2012).

will move in and out of these different processing zones, and we must be able to track this movement if we want to understand how materials are processed within disks.

This need motivated the development of *particle tracking techniques*, which are methods that allow us to calculate the movements of individual grains or parcels of material throughout the time that they reside within a protoplanetary disk (Ciesla (2010, 2011)). An example of such movement is shown in 1, from Ciesla & Sandford (2012). In this case the grain begins in the cold, dark (UV shielded) disk midplane in the outer disk. Over time, the grain migrates around the disk, spending much of its time deep inside the disk and exposed to similar conditions that were found at its initial location. However, the grain experiences short, periodic excursions to high altitudes in the disk. These excursions are important, as they carry the grain into regions of higher temperatures, lower density, and with high exposures to radiation, which can lead to significant chemical processing that would not otherwise occur further within the disk. Likewise, materials that would otherwise be destroyed in the active chemical zones in the upper layers of a disk may be preserved if they migrate down to the disk midplane before he reactions take place.

The movement of materials in and out of different chemical zones as described above is critical for us to consider as it is expected to be a natural consequence of protoplanetary disk evolution, and as such, a process to which all planetary materials are subjected. This runs counter to most astrochemical models for protoplanetary disk studies which tend to assume solids and gas remain situated at a given location (and thus exposed to fixed conditions) for timescales of millions of years. Instead, all planetary materials will be subjected to a range of physical environments which will lead to constantly changing chemistry until they are locked up into planetesimals.

4. Need for laboratory studies

A major finding from the calculations described above is that each solid grain in a protoplanetary disk follows its own, unique path through the array of environments which are present. And these grains do not simply reflect the properties of just one of disk location, but rather, the *time-integrated effects of each environment to which they were exposed.*

A critical challenge in the coming years will be to understand the chemical evolution that results from the migration of materials through the disk and how they respond to the different conditions that they see. Such work has been the focus of previous studies, with experiments being developed to determine how grains or molecules are processed as they are exposed to a range of different physical environments. Further work along these lines are necessary, as it is critical to understand the kinetics of various reactions, or the particular yields that can occur from a variety of reactions.

However, it is also clear that detailed experiments are needed to fully appreciate the complex array of outcomes that can develop from this processing. For example, as reviewed in Ciesla & Sandford (2012), icy grains that are carried into photon-rich layers of the disk would see many of the simple molecules they contain broken apart by the energetic radiation, resulting in the production of a number of ions and radicals within the icy mantle. Upon warming, these species could react with one another to form more complex species than were present before, including organic molecules. The precise outcome is stochastic as it depends on the compositions of the ices and the ability of ions and radicals to find one another, and thus predictive models of what will be produced in disk surfaces.

Further, as shown in Fig. 1, even after grains move out of the photon-dominated layer, they might return. Thus it would not simply be the original, simple molecules that are subjected to the photolysis expected in those regions, but also the products of those reactions. The residues, would thus further be subjected to radiation which may further drive chemical reactions or alter the structures of those species that remain. Experiments that mimic the cycling of materials in and out of different environments akin to those expected in a disk and tracks not only what is created, but also how they are modified will be important in deciphering the various clues we have regarding this stage of planet formation.

5. Summary

While astronomical observations are providing new insights into the properties and processes operating within protoplanetary disks, there are limits to what these observations can reveal about the process of planet formation. Spatial resolution will always be a challenge, limiting our ability to see processes occurring on sub-AU scales. Further, we are largely limited to seeing the surface layers of the disks, not their optically thick interiors where planets are actually assembled. However, within our Solar System, we have records of this evolution in the form of meteorites and cometary samples that can be combined with astronomical observations to build a more complete picture of planet formation.

A fundamentally important outcome that is reached from both astronomical and meteoritic studies is that protoplanetary disks, like our solar nebula, are dynamic processes, through which materials are in constant motion. This leads to planetary materials being exposed to a large array of environments throughout this epoch of planet formation, which will ultimately determine the level of chemical processing that occurs. The effects of these motions on the chemistry that occurs within disk gas and solid grains must be understood and should be the focus of future experimental studies.

It is also critical to recognize the information that can be provided by laboratory analyses of extraterrestrial samples. These objects represent direct analogs of the solids that are observed around other protoplanetary disks; their chemical and isotopic compositions tell us information about the reactions that occurred within the disk, the timing during which they were processed, and the extent to which materials were redistributed after they formed. Developing laboratory techniques that are better able to characterize these samples and link them to the materials seen in other protoplanetary disks will not only improve our understanding of planet formation, but also allow us to draw comparisons about how our Solar System compares to others throughout the galaxy.

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