Transport of solids in protoplanetary disks: Comparing meteorites and astrophysical models

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Abstract

We review models of chondrite component transport in the gaseous protoplanetary disk. Refractory inclusions were likely transported by turbulent diffusion and possible early disk expansion, and required low turbulence for their subsequent preservation in the disk, possibly in a dead zone. Chondrules were produced locally but did not necessarily accrete shortly after formation. Water may have been enhanced in the inner disk because of inward drift of solids from further out, but likely not by more than a factor of a few. Incomplete condensation in chondrites may be due to slow reaction kinetics during temperature decrease. While carbonaceous chondrite compositions might be reproduced in a “two-component” picture (Anders 1964), such components would not correspond to simple petrographic constituents, although part of the refractory element fractionations in chondrites may be due to the inward drift of refractory inclusions. Overall, considerations of chondrite component transport alone favor an earlier formation for carbonaceous chondrites relative to their noncarbonaceous counterparts, but independent objections have yet to be resolved.

1. Introduction

With the accelerating pace of exoplanet detections, the protoplanetary disk phase of stellar evolution enjoys considerable interest. Thanks to increasing computational power, theorists can test mechanisms for disk transport (Turner et al. 2014) and planet formation (Youdin and Kenyon 2013). Observations of present-day protoplanetary disks (Williams and Cieza 2011) probe the disk mass, size, structure, chemical species and solids (Natta et al. 2007). However, even with the Atacama Large Millimeter/Submillimeter Array, it will remain challenging to resolve scales below a few AU and probe the optically thick midplane of the inner disks where planet formation should occur. To understand the evolution of solids in disks, we must turn our attention to constraints provided closer to us by our own solar system in the form of primitive meteorites, or chondrites. Indeed, chondrites date back to the protoplanetary disk phase of the solar system, 4.57 Ga ago, and with more than 40,000 specimens classified to date, not to mention samples returned from comet Wild 2 (e.g. Zolensky et al. 2008) or asteroid Itokawa (Nakamura et al. 2011), they offer a considerable wealth of petrographic, chemical, and isotopic data at all examination scales.

Yet chondrites arrive in our laboratories without geological context. While orbit determinations consistently assign their parent bodies to the asteroid main belt—with the exception of micrometeorites (e.g. Engrand and Maurette 1998) and perhaps some carbonaceous chondrites (Gounelle et al. 2008) possibly derived from further out—, exactly where and when they originally accreted is largely unknown. Still, chondrites exhibit considerable compositional variations, and space and time were obviously important dimensions behind them. In fact, each individual chondrite is a mixture of components (chondrules, refractory inclusions, etc.) formed in different locations, epochs and environments in the disk (Brearley and Jones 1998; Krot et al. 2009). This is evidence for considerable transport in the disk. In order to place the meteoritical record in context, the relevant transport processes have to be understood, and as such meteorites are sensors of the dynamics of protoplanetary disks.

Our purpose here is to review transport mechanisms of chondrite components before accretion. An earlier review on particle-gas dynamics was given by Cuzzi and Weidenschilling (2006) and Boss (2012) reviewed transport and mixing from the perspective of isotopic heterogeneity. The formation per se of chondrite components is essentially beyond our scope but the reader may be referred to recent reviews by Krot et al. (2009) and Alèon (2010). Wood (2005) and Chambers (2006) proposed syntheses on the origin of chondrite types from cosmochemical and astrophysical viewpoints, respectively. Here, the discussion will be organized around meteoritical constraints as follows: In section 2, we provide background on chondrites and the basic physics of the protoplanetary disk before embarking in section 3 on an examination of transport constraints from specific chondrite components. We then review the interpretation of fractionation trends exhibited by chondrites as wholes (section 4) in light of which we will discuss the chronological and/or spatial ordering of chondrite groups (section 5).

2. Background

2.1. Chondrites: a brief presentation

Chondrites are assemblages of various mm- and sub-mm-sized solids native to the protoplanetary disk. Oldest among them are the refractory inclusions (MacPherson 2005; Krot
et al. 2004), further divided in calcium-aluminum-rich inclusions (CAI) and (less refractory) amoeboid olivine aggregates (AOA), which presumably originated by high-temperature gas-solid condensation. 4568 Ma ago (Bouvier and Wadhwa 2010; Connelly et al. 2012; Kita et al. 2013), although many have since experienced melting. More abundant than those are chondrules, silicate spheroids 1-4 Ma younger than refractory inclusions (Kita and Ushikubo 2012; Connelly et al. 2012), likely formed by melting of isotopically and chemically diverse precursor material. The nature of the melting events remains however elusive, with “nebular” (e.g. shock waves) and “planetary” (e.g. collisions) environments still being considered (Boss 1996; Desch et al. 2012). Metal and sulfide grains also occur, either inside or outside chondrules (Campbell et al. 2005). All these components are set in a fine-grained matrix, a complex mixture of presolar grains, nebular condensates and/or smoke condensed during chondrule-forming events (Brearley 1996).

While all chondrules roughly exhibit solar abundances for nonvolatile elements (Palme and Jones 2005), with CI chondrules providing the best match, they are petrographically, chemically and isotopically diverse, and 14 discrete chemical groups, each believed to represent a distinct parent body (or a family of similar ones), have hitherto been recognized. To first order, one may partition these groups in two super-clans (Kalleney et al. 1996; Warren 2011), namely the carbonaceous chondrites (with the CI, CM, CO, CV, CK, CR, CB, CH groups), and the non-carbonaceous chondrites, which comprise the enstatite (EH, EL), ordinary (H, L, LL) and Rumuruti (R) chondrites. Carbonaceous chondrites are more “primitive” in the sense that they have a higher abundance of refractory inclusions and matrix, a solar Mg/Si ratio, and an 16O-rich oxygen isotopic composition closer to that of the Sun (McKeegan et al. 2011). Non-carbonaceous chondrites, though poorer in refractory elements, are more depleted in volatile elements, have subsolar Mg/Si ratios and a more terrestrial isotopic composition for many elements (e.g. Trinquier et al. 2009). What these differences mean and how some may relate to the transport of chondrite components is one of the main focuses of this review.

2.2. Dynamics of the early solar system

The exact structure of our protoplanetary disk remains very conjectural. If we mentally add gas to a smoothed version of the sense that they have a higher abundance of refractory inclusions and matrix, a solar Mg/Si ratio, and an 16O-rich oxygen isotopic composition closer to that of the Sun (McKeegan et al. 2011). Non-carbonaceous chondrites, though poorer in refractory elements, are more depleted in volatile elements, have subsolar Mg/Si ratios and a more terrestrial isotopic composition for many elements (e.g. Trinquier et al. 2009). What these differences mean and how some may relate to the transport of chondrite components is one of the main focuses of this review.

2.2. Dynamics of the early solar system

The exact structure of our protoplanetary disk remains very conjectural. If we mentally add gas to a smoothed version of the current planetary system to restore solar abundances, we obtain a density profile known as the “Minimum Mass Solar Nebula” (MMSN; Hayashi (1981)) with an integrated mass \( \sim 0.01 \, M_\odot \) (1 M_\odot = 1 solar mass). While this agrees with disk masses estimated for most T Tauri stars (Williams and Cieza 2011), it may be one order of magnitude below the original disk mass expected at the cessation of infall from the parent molecular cloud (e.g. Yang and Ciesla 2012). The MMSN, though a useful reference, ignores the extensive redistribution and losses of gas and solids occurring in disks which funnel gas onto the central stars at observed rates of \( 10^{-8} \, M_\odot / a \) (Williams and Cieza 2011).

What drives the evolution of gas disks? Since the molecular viscosity is far too small to account for the \( \sim 1-10 \, \text{Ma} \) lifetime of protoplanetary disks (Williams and Cieza 2011), disk theoretical models generally rely on turbulence which, in a rough, large-scale sense, may mimic the effects of an enhanced viscosity

\[
\nu = \alpha \frac{c_s^2}{\Omega}
\]

with \( c_s \), the (isothermal) sound speed, \( \Omega \) the Keplerian angular velocity and \( \alpha \) the dimensionless “turbulence parameter” (see e.g. Balbus and Papaloizou (1999)), for which values around \( 10^{-2} \) are inferred from observations (Armitage 2011). The exact source of this turbulence is still contentious. As yet, the leading candidates are gravitational instabilities (Durisen et al. 2007) and the magneto-rotational instability (MRI; Balbus and Hawley (1998)). While the former would be important in the earliest epochs where the disk is massive enough, the latter essentially only requires the gas ionization fraction to be above a small threshold, and may operate at all times. However, this threshold may not be attained over a considerable range of heliocentric distances, yielding a dead zone of low turbulence, unless other instabilities are at work (see Turner et al. (2014)). Eventually, after the disk mass has significantly dropped, photodissociation due to the central star (and/or close neighbours) should completely clear the gas (Armitage 2011).

Except in late stages of the disk where photophoresis may become important (Wurm and Krauss 2006), the dynamics of small solids are primarily dictated by gas drag. The stopping time, for a spherical particle of radius \( a \) smaller than the molecular mean free path, is (Weidenschilling 1977):

\[
\tau = \frac{\pi \rho_s a}{8 \rho c_s}.
\]

with \( \rho_s \) and \( \rho \) the solid and gas densities, respectively. For instance, at 3 AU in a MMSN, 0.3 mm radius chondrule has \( \tau = 2 \, \text{h} \) at the midplane, much shorter than the orbital period. Hence, to zeroth order, chondrite components should follow the gas, but they cannot have exactly the same velocity because they do not “feel” the pressure gradient acceleration experienced by it. There is thus a systematic drift velocity of the solids relative to the gas in the direction of larger pressures, that is, toward both the midplane and the Sun. The radial drift is given by:

\[
v_{\text{drift}, R} \equiv \frac{\tau}{\rho} \frac{\partial P}{\partial R} = 0.004 \, \text{m/s} \frac{\partial \ln P}{\partial \ln R} \left( \frac{\rho_s a}{1 \, \text{kg/m}^2} \right) \left( \frac{10^{-6} \, \text{kg/m}^3}{\rho} \right) \left( \frac{1 \, \text{AU}}{R} \right) \left( \frac{T}{300 \, \text{K}} \right)^{1/2}
\]

with \( P \) and \( T \) the gas pressure and temperature and \( R \) the heliocentric distance. While this drift is generally smaller than the turbulent velocity fluctuations of the gas (\( \sim \sqrt{c_s} \)), it may become important in the long run as these average out. A measure of this importance is the “gas-grain decoupling parameter” (Cuzzi et al. 1996; Jacquet et al. 2012):

\[
S \equiv \frac{\Omega \tau}{\alpha}
\]

\[
= 0.1 \left( \frac{\rho_s a}{1 \, \text{kg/m}^2} \right) \left( \frac{10^{-8} \, M_\odot / a}{M} \right) \left( \frac{R}{1 \, \text{AU}} \right)^{3/2} \left( \frac{T}{300 \, \text{K}} \right)
\]

where the last equality is for a steady disk of mass accretion rate \( M \). For \( S \ll 1 \), the particles are tightly coupled to the gas, while
for $S \gtrsim 1$, they settle to the midplane (with a concentration factor $\sim \sqrt{S}$) and drift radially sunward faster than the gas.

Over time, grains collide and coagulate, as evidenced by detection, in protoplanetary disks, of mm-sized solids (Natta et al. 2007), much larger than typical interstellar grains ($\sim 0.1 \mu m$). Growth to meter size is frustrated by bouncing/fragmentation at high collision speeds and by increased radial drift which would remove them from the disk within centuries (Weidenschilling 1977; Brauer et al. 2007; Birnstiel et al. 2010). Settling to the midplane might help self-gravity of the solids to intervene but is limited by gas turbulence, so that other mechanisms such as turbulent concentration or streaming instabilities may have to bridge the gap (Cuzzi and Weidenschilling 2006; Youdin and Kenyon 2013). Here, we will mostly restrict attention to sub-mm/cm-sized bodies since chondrite composition was established at the agglomeration of such components.

3. Transport of chondrite components

With these fundamentals in mind, we now turn to constraints provided by specific chondrite components, and the astrophysical processes which may satisfy them.

3.1. Refractory inclusions

The oldest solids of the solar system, the refractory inclusions, are estimated to have formed at $\sim 1400-1800$ K (Grossman 2010). Such high temperatures, presumably due to small-scale dissipation of turbulence, did not obtain at heliocentric distances $> 1$ AU for more than a few $10^3$ years after disk formation (e.g. Yang and Ciesla 2012). This is consistent with the old age of CAIs and AOAs; yet to account for their presence in chondrites and even in comets (e.g. Simon et al. 2008), outward transport is in order. It would also account for the abundance of crystalline silicates in comets (e.g. Zolensky et al. 2008).

Shu et al. (1996) proposed that solids processed at $R < 0.1$ AU were entrained by stellar winds and fell back onto the disk further out (Hu 2010). Desch et al. (2010) however criticized the role of this “X-wind” in processing chondrite components e.g. regarding the very survival of solids (see also Cuzzi et al. (2005) on the formation timescales of Wark-Lovering rims) so that one may have to seek transport within the disk itself.

In a turbulent disk, velocity fluctuations may send high-temperature material outward (e.g. Gail 2001; Bockelée-Morvan et al. 2002; Cuzzi et al. 2003; Boss 2004; Ciesla 2010; Hughes and Armitage 2010). The envisioned random-walk paths may explain complex thermal histories recorded by some refractory inclusions (Ciesla 2011; Boss et al. 2012). The efficiency of this turbulent diffusion against the mean inward flows depends sensitively on the Schmidt number $Sc_R \equiv v/D_R$, with $D_R$ the turbulent diffusivity, although many studies have simply equated it to 1. $Sc_R < 1$ seems required for efficient outward diffusion (Clarke and Pringle 1988; Pavlyuchenkov and Dullemond 2007; Hughes and Armitage 2010). While MRI-driven turbulence would likely not satisfy this requirement (Johansen et al. 2006), this is expected from hydrodynamical turbulence (Prinn 1999), but save for a few laboratory experiments, of uncertain relevance to protoplanetary disks (e.g. Lauder 1976; Lathrop et al. 1992), empirical evidence is largely wanting.

Turbulent diffusion may have been supplemented by outward advection flows early in the disk evolution. Indeed, the disk may have been initially compact ($\lesssim 10$ AU in radius), and its ensuing expansion would have begun in the condensation region of refractory inclusions (Jacquet et al. 2011; Yang and Ciesla 2012). Outward transport would then have been efficient for the earliest generation of CAIs, hence perhaps their narrow observed age range (Ciesla 2010; Yang and Ciesla 2012).

Outward flows have been proposed to persist around the disk midplane, even if the vertically integrated flow is inward, and ease the outward transport of inner disk material at later stages (Ciesla 2007; Hughes and Armitage 2010). This so-called meridional circulation arises when turbulence is modeled as a viscosity in a very literal sense (e.g. Takeuchi and Lin 2002). However, while the gross properties of turbulent disks may be obtained with this ansatz, there is no first principle reason that the resulting two-dimensional flow structure should also hold true, and in fact meridional circulation has not been observed in numerical simulations of MRI-driven turbulence by Fromang et al. (2011) or Flock et al. (2011). At any rate, Jacquet (2013) showed that even if meridional circulation existed, it would not, because of the inward flows in the upper layers, make a significant difference in terms of net radial transport compared to 1D models, given current uncertainties in turbulence parameters.

Not only were refractory inclusions transported in the disk, they were preserved there quite efficiently, for the CAI fraction in some carbonaceous chondrites is comparable to what in situ condensation out of a solar gas would have produced ($\sim 6\%$; Grossman 2010)). However, the inward gas flows and grain-gas radial drift have long been expected to remove them from the chondrite-forming regions within a few $10^3$ years— especially for the large type B CAIs in CV chondrites—, even though the drift slows down closer to the Sun (Laibe et al. 2012). Indeed turbulent diffusion calculations by Cuzzi et al. (2003) and Ciesla (2010) underpredicted CAI abundances by 1-
2 orders of magnitude—unless the “CAI factory” was enriched in condensable matter, which, if not very carbon-rich, would however yield too oxidizing conditions (Jacquet et al. 2011). In simulations starting with compact disks, however, Yang and Ciesla (2012) achieved retention of refractory inclusions for >2 Ma, presumably because many of them were sent far from the Sun (10-100 AU), their disk remained quite massive (≥0.1 M☉) even after a few Ma, and α was relatively low (10^{-3}; see also equation 8 of Jacquet et al. 2011). In fact, low turbulence levels α ≲ 10^{-4} could alone account for the preservation of refractory inclusions, assuming outward transport was accomplished somehow before, and low turbulence is exactly what is generically expected from the dead zone picture (Jacquet et al. 2011). Indeed, the dead zone, which would have emerged after an initially turbulent phase conducive to extensive transport, would slow down gas accretion toward the Sun, and by forcing gas to accumulate there, would also reduce the stopping time and thence the drift of refractory inclusions.

Importantly, efficient diffusion as expected in the early disk would rapidly homogenize any short-lived radionuclide like 26Al (e.g. Boss et al. 2012) and hence validate its use as a chronometer. Same would not hold, however, if such isotopes were injected into the disk after the formation of a dead zone.

3.2. Chondrules

The low turbulence levels invoked above for the preservation of refractory inclusions would as well account for the few-Ma age range of chondrules measured in single meteorites (Kita and Ushikubo 2012; Connelly et al. 2012), for chondrules and refractory inclusions have comparable sizes. However, Alexander and Ebel (2012) argued that turbulent mixing would homogenize chondrule populations over chondrule-forming regions within a few 10^5 years, at variance with the distinctive chondrule populations of the different chemical groups (Jones 2012). They thus suggested that the Al-Mg ages—although broadly corroborated by Pb-Pb dating—were perturbed (but see Kita and Ushikubo (2012)) and that the data are consistent with chondrule formation immediately preceding chondrite accretion. From an astrophysical standpoint, this may be a premature conclusion, though. The diffusion length after a time t is

\[ \sqrt{2D_{\text{eff}}} = 1\text{AU} \left( \frac{t}{1 \text{Ma}} \right)^{1/2} \frac{\alpha}{R} \frac{300 \text{K}}{T} \left( \frac{R}{1 \text{AU}} \right)^{1/2} \]

So whether this exceeds the separation between different chondrule-forming regions depends, among other things, on the exact values of \( \alpha \) and on where the chondrule- and chondrite-forming regions actually were in the disk. These locales may have been quite distinct from the present-day position of chondrite parent bodies, in the asteroid main belt, especially if their orbits were significantly reshuffled e.g. during a “Grand Tack” (Walsh et al. 2011). Moreover, this calculation ignores the barrier that gas drag-induced drift may have posed to outward mixing (if \( S > 1 \)). In fact, if mixing had been as efficient as to homogenize the chondrule-forming region in ≤1 Ma timescales, bulk chemical fractionations observed across chondrite groups would be difficult to understand (see section 4).

Another constraint that chondrule transport must satisfy is chondrule-matrix complementarity (Huss et al. 2005). This is the observation, for carbonaceous chondrites, that while the bulk rocks have solar Mg/Si ratios (or other interelement ratios, see Hezel and Palme (2010)), this does not hold for chondrules or matrix taken individually. Complementarity, if confirmed (but see Zanda et al. (2012)), requires that chondrules and matrix be genetically related (unlike, e.g., a X-wind scenario), but also that chondrules and dust from a given chondrule-forming region did not drift apart until accretion. While a particular chondrule and a particular dust grain would quickly separate barring immediate accretion, this would not be true of the populations of chondrules and dust grains as wholes which would remain spatially indistinguishable for some time due to turbulence. In fact, in the regime \( S < 1 \) (for chondrules), Jacquet et al. (2012) showed that this overlap would continue over their whole drift timescale, so that accretion at any time would yield complementarity. Complementarity would not be compromised by mixing between products of several chondrule-forming events provided transport from each of these sources was likewise unbiased as to the chondrule/dust ratio (Cuzzi et al. 2005; Jacquet et al. 2012). Chondrule transport in the disk is thus still compatible with observations, although a link between chondrule and chondrite formation cannot be ruled out.

3.3. Metal and sulfide grains

Chondrites, and especially non-carbonaceous ones—plus the very metal-rich CHs and CBs, although their genesis likely was very anomalous (e.g. Krot et al. 2005)—, have undergone metal/silicate fractionation prior to accretion (Larimer and Wasson 1988b; Wood 2005). While early workers invoked some separation of metal grains directly condensed from the hot solar nebula, e.g. because of ferromagnetically enhanced coagulation (Harris and Tozer (1967); see also a review by Kerridge (1977)), there is little evidence of isolated pristine nebular metal condensates in meteorites, although such grains are found enclosed in refractory inclusions (Weisberg et al. 2004; Schwander et al. 2013). Actually, chondrite metal grains mostly seem to be byproducts of chondrule-forming events (Campbell et al. 2005). Metal/silicate fractionation may have arisen locally by aerodynamic sorting (e.g. Zanda et al. 2006), e.g. because of differential radial and/or vertical drift, or turbulent concentration. Indeed, in both ordinary (Kuebler et al. 1999; Nettles and McSween 2006) and enstatite (Schneider et al. 1998) chondrites, metal and sulfide grains have a somewhat lower ρ,α than chondrules on average, but are closest to aerodynamic equivalence with them for their most Fe-rich varieties (H and EH, respectively) which have the smaller chondrules. Therefore, metal/sulfide grains and small chondrules could have been segregated together. Alternatively, metal/silicate fractionation might reflect varying contributions of debris of differentiated planetesimals predating chondrule formation (e.g. Sanders and Scott (2012); but see Fischer-Gödde et al. (2010)).

3.4. Matrix grains

The grains of chondritic matrices are typically sub-μm-sized (Pontoppidan and Brearley 2010), likely too small to show
any decoupling relative to the nebular gas prior to agglomera-
tion as fluffy aggregates or fine-grained rims around chondrules
(e.g. Metzler and Bischoff 1996). For $\alpha = 10^{-3}$, surface den-
sities below 1 kg/m$^2$ (2 orders of magnitude lower than the
MMSN at 30 AU) would be required to see any effect on ra-
dial drift (i.e. $S \gtrsim 1$). It is then surprising that silicate and
sulfide grains in chondritic porous interplanetary dust particles
are aerodynamically equivalent (Wozniakiewicz et al. 2012); if
non-coincidental, it could indicate very low densities in the
outer disk when these (likely comet-derived) objects formed.

While no differential drift of dust grains is expected anyway
in the inner disk, presolar grains show some variations across
chondrite groups, e.g. the proportions of type X SiC grains
(Zinner 2003) or the carriers of $^{54}$Cr anomalies (e.g. Trinquier
et al. 2009). These may be due to non uniform injection or
thermal processing of these grains (Trinquier et al. 2009) and
their persistence (at a few tenths of the anomalies of refrac-
tory inclusions) suggest limited turbulence levels, as similarly
inferred above for refractory inclusions and chondrules. As
the high-temperature events which produced the latter would
have destroyed presolar grains, their very survival indicates that
these events were localized, allowing subsequent mixing be-
tween processed and unprocessed matter.

3.5. Water

Water makes up about half of condensable matter in a so-
lar mix (Lodders 2003). While chondrites that survive atmos-
pheric entry are mostly dry, hydrated silicates, mostly found in
carbonaceous chondrites, testify to aqueous alteration on their
parent body (Brearley 2003). Also, water may have been partly
responsible for the high oxygen fugacities recorded by many
chondrules (e.g. Schrader et al. 2013), which require 10-1000-
fold enhancements over solar abundances. Water was likely
$^{16}$O-poor (Sakamoto et al. 2007), and possibly responsible for
the variations of the oxygen isotopic composition of the inner
solar system, from $^{16}$O-rich signatures of CAIs to $^{16}$O-poor,
"planetary" ones (but see Krot et al. (2010); see also Yurimoto
et al. (2008) for an overview of oxygen isotopic data).

In protoplanetary disks, water condenses as ice beyond the
"snow line" (~170 K). Ice and intermingled silicates would drift
inward and enrich the inner disk inside the snow line (Stepinski
and Valageas 1997; Cuzzi and Zahnle 2004). In the popular CO
self-shielding scenario, whether in the parent molecular cloud
(Yurimoto and Kuramoto 2004) or in the disk (Lyons et al.
2009), as $^{16}$O-poor water may be most efficiently produced
and/or preserved at large heliocentric distances, this would ac-
count for its addition to inner solar system material, although
detailed calculations of O isotopic evolution in disks have yet
to be published (it remains in particular to be seen whether the
existence of both $^{16}$O-rich and -poor reservoirs already during
CAI formation as recorded by some reversely zoned melilite
grains (Park et al. 2012) can be reproduced). Because of the fi-
nite supply of water in the outer disk (and/or the "bouncing bar-
rier" to grain growth which would limit drift), the enrichment
would be limited to a factor of a few (Ciesla and Cuzzi 2006;
Hughes and Armitage 2012), insufficient to account for FeO
contents in chondrules. Settling to the midplane might further
enhance the (dust ± ice)/gas ratio to the desired levels, depend-
ing on the enhancement due to radial drift, but would require
very low turbulence (Cuzzi and Weidenschilling 2006). Turbu-
 lent concentration is yet another possibility (Cuzzi et al. 2001).

For efficient ice accretion beyond the snow line (e.g. Steven-
sen and Lunine 1988), diffusion may later deplete the inner disk
in water, perhaps accounting for the (reduced) enstatite chon-
drites (Pasek et al. 2005), although replenishment from further
out would limit this to a factor of a few (Ciesla and Cuzzi 2006).
Another important constraint on water is the D/H ratio which,
for carbonaceous chondrites appears systematically lower than
most comets (Alexander et al. 2012). This may require ef-
cient outward diffusion (i.e. low Schmidt number) of D-
poor water from the warm inner disk (Jacquet and Robert
(2013); see also Yang et al. (2013)), consistent with the require-
ment of efficient outward transport of high-temperature miner-
als (Bockelée-Morvan et al. 2002); see section 3.1).

4. Fractionation trends in chondrites

We have investigated above the constraints given by individ-
ual petrographic components of chondrites on their transport in
the protoplanetary disk. On a more integrated perspective, such
redistribution of material may have caused the compositional
variations exhibited by the different chemical groups of chon-
drites. We have already mentioned metal/silicate fractiona-
tion (section 3.3); here, we focus on lithophile element fractiona-
tions and their possible dynamical interpretations.

With respect to solar abundances, the most striking pattern
exhibited by bulk chondrite chemistry (except CIIs) is the de-
pletion in volatile elements, increasing with decreasing nomi-
 nal condensation temperature (Palme et al. 1988). How did this
incomplete condensation come about? Yin (2005) suggested
that it was inherited from the interstellar medium, but isotope
systems involving elements of different volatilities (e.g. Rb-
Sr) yield whole-rock isochrons consistent with the age of the
solar system (Palme and Jones 2005), indicating, along with
the very existence of undepleted CI chondrites native to the so-
lar system, that the depletion arose in the disk itself. Cassen
(1996) reproduced some of the elemental trends by assuming
that the chondrite parent bodies started to form while the disk
was hot and massive, but this is inconsistent with more recent
evidence that chondrites accreted after a few Ma (Ciesla 2008).
Timescale considerations also exclude the suggestions by Was-
son and Chou (1974) of gas-solid separation by settling, radial
drift (both of which require $S > 1$ which would obtain late in
the disk history (Jacquet et al. 2012)), or gas photoevaporation.
The last plausible alternative may then be a slowing of reac-
tion kinetics upon decrease of temperature—which are anyway
required to explain the preservation of CAIs in the first place
(Ciesla 2008). Whether the temperature changes witnessed by
individual condensates (over 10-1000 years in simulations by
Boss et al. (2012) and Taillillet et al. (2013)) would be suffi-
ciently rapid to incur such an effect has yet to be investigated.
Whatever process caused incomplete condensation, it did
not operate to the same degree in all regions and epochs of
the disk, and undoubtedly, there has been mixing by diffusion
and differential drift between these different reservoirs. For example, CM chondrites are enriched in refractory lithophile elements but moderately volatile elements exhibit a plateau at about half the CI chondritic value, suggesting a 50% admixture of CI-like material to an otherwise smoothly volatile-depleted material (Cassen 1996). Anders (1964) proposed that the composition of chondrites resulted from varying proportions of an unfractionated CI chondritic and a high-temperature component. Zanda et al. (2006) recently developed this "two-component model" by identifying these components with petrographic constituents such as CAIs, chondrules and matrix, whose proportions would have varied independently across the different chondrite groups (this may be called the "strong" two-component model). It is however questionable whether these petrographic components were dynamically independent from each other, in particular for carbonaceous chondrites. In the regime $S < 1$, which would hold for the first few Ma, there would be indeed little decoupling between these. Observational evidence for coherence between chondrite components is provided by (i) matrix-chondrule complementarity (see section 3.2) and (ii) the subsolar Al/Si ratios of CAI-subtracted carbonaceous chondrites (Hezel et al. 2008), contrary to a simple picture of CAI addition to a CI chondritic material, suggesting a genetic link between at least some of the CAIs and their host chondrite (Jacquet et al. 2012). Also, the distinctiveness of chondrules in different chondrite groups (Jones 2012) excludes that a single chondrule population was distributed throughout the disk. Thus, while carbonaceous chondrite bulk compositions might conceivably be modeled in a simple two-component picture (Zanda et al. 2012), with higher high-temperature fractions presumably representing earlier times and/or shorter heliocentric distances, such chemical components would likely have no straightforward petrographic manifestation.

Non-carbonaceous chondrites, to which we now turn attention, are depleted in refractory lithophile elements relative to CI, but this trend does not actually simply complement the enrichment exhibited by carbonaceous chondrites, as it is accompanied by a decrease in the Mg/Si ratios (roughly uniformly solar for carbonaceous chondrites; Larimer and Wasson 1988a). Another process must be at play. Larimer and Wasson (1988a) proposed a loss of a refractory olivine-rich material, possibly AOAs (see also Ruzicka et al. 2012). This could be accomplished by inward drift to the Sun (in the regime $S > 1$) provided that this component was present in grains systematically coarser than the other (Jacquet et al. 2012)—at least before chondrule formation. Hutchison (2002) proposed instead the addition of low Mg/Si material to CI composition to account for non-carbonaceous chondrite composition, which may be implemented in a X-wind model but would be subject to the drawbacks of such scenarios (Desch et al. 2010). In the case of enstatite chondrites, which have the lowest Mg/Si ratios of chondrite groups, Lehner et al. (2013) proposed that sulfidation of silicates may have led to evaporative loss of Mg. The concentration of chondrules, e.g. due to preferential settling (Jacquet et al. 2012) or turbulent concentration (Cuzzi et al. 2001), might explain the volatile-depleted composition of non-carbonaceous chondrites relative to their carbonaceous counterparts.

5. Chondrites in space and time

In this final section, we would like to return to our original question—how the different chondrite groups may be ordered in space and time in the early protoplanetary disk.

It is widely assumed that chondrite groups represent different heliocentric distances of formation, with enstatite chondrites closest to the Sun, followed by ordinary, Rumuruti and carbonaceous chondrites (e.g. Rubin and Wasson 1995; Wood 2005; Warren 2011). Certainly, spectroscopic observations—and the sample return mission to S(IV) asteroid Itokawa (Nakamura et al. 2011)—suggest that enstatite, ordinary and carbonaceous chondrites are associated with E, S, and C-type asteroids, respectively, and these do exhibit this radial sequence (Burbine et al. 2008), although with wide overlap (e.g. Usui et al. 2013) find that most of the large E-type asteroids actually lie in the middle of the asteroid belt).

*Ab initio* rationalization of this trend as a purely spatial effect is however problematic. It is e.g. no longer possible to ascribe the implied increase in oxidation state with heliocentric distance to a temperature decrease as in the classic "hot solar nebula" picture, not only because high temperatures would not have prevailed long, but also because ferroan olivine in chondrites is difficult to ascribe to nebular condensation (Grossman et al. 2012); and in fact, chondrules in carbonaceous chondrites are more reduced than their ordinary chondrite counterparts. The nonmonotonic trend in isotopic ratios of oxygen or other elements (Warren 2011) is also difficult to ascribe to episodic infall (Rubin and Wasson 1995) as infall would long have ceased.

Could time of formation have then played a role? We have seen in the previous section that carbonaceous chondrites were enriched in refractory elements (in particular in CAIs) compared to non-carbonaceous chondrites. Regardless of the details of the fractionation mechanisms, if, from the above, they did not form closer to the Sun, it seems unavoidable that they formed earlier, as proposed by Cuzzi et al. (2003) (specifically for CV chondrites with their large type B CAIs, similar to Wood (2005)) and Chambers (2006). Jacquet et al. (2012) showed that the retention of CAIs required, along with other properties, that $S < 1$ for carbonaceous chondrites, and which would also plead in favor of an earlier epoch, as $S$ tends to increase with time and heliocentric distance (see equation (4)). The fact that noncarbonaceous chondrite parent bodies seem on average closer to the Sun may be due to inward drift which tended to increasingly concentrate solids in the inner regions. Then, the $^{16}$O-poorer composition of non-carbonaceous chondrites may be ascribed to a later, more advanced stage of influx of $^{16}$O-poor water from the outer disk if the self-shielding picture holds.

While modelling of chondrite component transport thus suggests that carbonaceous chondrites accreted earlier than non-carbonaceous chondrites, other points of view are allowed by other lines of evidence. One is that chondrules in CO and LL chondrites exhibit a similar range of Al-Mg ages ($\sim 1 - 3$ Ma after CAIs, with younger ages in CRs and EHs (Kita and Ushikubo 2012; Guan et al. 2006)). While not strictly contradicting a difference in chondrite accretion time, this could indeed suggest that time was not an important factor. Also, non-
carbonaceous chondrites have generally been more thermally metamorphosed on their parent body than carbonaceous chondrites (Huss et al. 2006). If the heating is ascribed to $^{26}$Al decay, which should decrease over time, this would on the contrary suggest that carbonaceous chondrites accreted later than non-carbonaceous chondrites (see Grimm and McSween (1993)), unless the higher water content of the former or some difference in the structure or size of the parent bodies was responsible (Chambers (2006); see also Elkins-Tanton et al. (2011)).

It thus appears that there are cogent arguments for the three possible chronological orderings of carbonaceous and non-carbonaceous chondrites (with the former either older, younger or contemporaneous with the latter). Obviously, however, two of these reasons have to give, but it may still be dicey to decide which with any authority. Resolution of this critical issue in the interpretation of the meteoritical record will await further advances on the transport of chondrite components, as reviewed here, but also on their formation models as well as the thermal and collisional evolution of the chondrite parent bodies.

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