C. R. Geoscience 346 (2014) 3–12

Contents lists available at ScienceDirect

Comptes Rendus Geoscience

www.sciencedirect.com

Review article

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

Emmanuel Jacquet

Canadian Institute for Theoretical Astrophysics, University of Toronto, 60, St Georges Street, Toronto, ON M5S 3H8, Canada

ARTICLE INFO

Article history:
Received 22 January 2014
Accepted after revision 19 February 2014
Available online 17 April 2014

Keywords:
Chondrites
Protoplanetary disks
Turbulence
Chondrules
Refractory inclusions

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 non-carbonaceous 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 AUs 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 (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 (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

E-mail addresses: ejacquet@cita.utoronto.ca, ejacquet@phare.normalesup.org.

http://dx.doi.org/10.1016/j.crte.2014.02.004

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 Aléon (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* (Krot et al., 2004; MacPherson, 2005), 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 (Connelly et al., 2012; Kita and Ushikubo, 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 chondrites roughly exhibit solar abundances for nonvolatile elements (Palme and Jones, 2005), with CI chondrites 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* (Kallemeyn 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 ^{16}O-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 (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 ~ 0.01 $M_\odot$ (1 $M_\odot \equiv 1$ 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 at the cessation of infall from the parent molecular cloud (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 $10^{-8\pm1}$ $M_\odot$/a (Williams and Cieza, 2011).

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

$$\nu = \alpha \frac{c_s^2}{\Omega} \quad (1)$$

with c_s the (isothermal) sound speed, Ω the Keplerian angular velocity and α the dimensionless "turbulence parameter" (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