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Chondrites as samples of differentiated planetesimals

Linda T. Elkins-Tanton *, Benjamin P. Weiss, Maria T. Zuber

Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA, USA

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ABSTRACT

Chondritic meteorites are unmelted and variably metamorphosed aggregates of the earliest solids of the solar system. The variety of metamorphic textures in chondrites motivated the “onion shell” model in which chondrites originated at varying depths within a parent body heated primarily by the short-lived radioisotope ^{26}Al, with the highest metamorphic grade originating nearest the center. Allende and a few other chondrites possess a unidirectional magnetization that can be best explained by a core dynamo on their parent body, indicating internal melting and differentiation. Here we show that a parent body that accreted to >~200 km in radius by ~1.5 Ma after the formation of calcium–aluminum-rich inclusions (CAIs) would have a differentiated interior, and ongoing accretion would add a solid undifferentiated crust overlying a differentiated interior, consistent with formational and evolutionary constraints inferred for the CV parent body. This body could have produced a magnetic field lasting more than 10 Ma. This hypothesis represents a new model for the origin of some chondrites, presenting them as the unprocessed crusts of internally differentiated early planetesimals. Such bodies may exist in the asteroid belt today; the shapes and masses of the two largest asteroids, 1 Ceres and 2 Pallas, can be consistent with differentiated interiors, conceivably with small iron cores with hydrated silicate or ice–silicate mantles, covered with undifferentiated crusts.

1. Introduction

The antiquity and abundance of CAIs in CV chondrites have long suggested an early parent body accretion age. New Pb–Pb and Al–Mg ages of chondrules in CVs indicate that they may be among the oldest known in any chondrite class, with ages ranging from ~0 to ~3 Ma after CAIs (Amelin and Krot, 2007; Connelly et al., 2008; Hutcheon et al., 2009) (Fig. 1). The time of accretion of a body controls the amount of initial ^{26}Al, which was likely uniformly distributed in the inner protoplanetary disk (Jacobsen et al., 2008). Bodies that accreted to more than ~20 km radius before ~1.5 Ma after the formation of CAIs likely contained sufficient ^{26}Al to melt internally from radiogenic heating (Hevey and Sanders, 2006; Merk et al., 2002; Sahijpal et al., 2007; Urey, 1955). These early-accreting bodies would have melted from the interior outward, resulting in an interior magma ocean under a solid, conductive, undifferentiated shell (Ghosh and McSween Jr., 1998; Hevey and Sanders, 2006; McCoy et al., 2006; Merk et al., 2002; Sahijpal et al., 2007; Schölling and Breuer, 2009). This shell would consist of the same chondritic material that made up the bulk accreting body before melting began; further, and critically, ongoing accretion would add undifferentiated material to the crust, and this material may even have bulk compositions distinct from the differentiated interior.

Allende and a few other chondrites possess a unidirectional magnetization (Butler et al., 1972; Nagata and Funaki 1983; Carporzen et al., 2010; Weiss et al., 2010). Funaki and Wasilewski (1999) suggested a liquid metallic core dynamo origin for magnetism on the CV parent body. Carporzen et al. (2010) described how unidirectional magnetization in Allende is consistent with a field lasting >10 Ma. The variety of metamorphic textures in chondrites originally motivated the “onion shell” model in which chondrites originated at varying depths within a parent body heated primarily by the short-lived radioisotope ^{26}Al, with the highest metamorphic grade originating nearest the center (Miyamoto et al., 1981; Taylor et al., 1987). Now, the metamorphic, magnetic, and exposure age data collectively indicate a new model for the CV chondrite parent body in which interior melting is incomplete and a magma ocean remains capped by an undifferentiated chondritic shell. This conductive lid insulates the internal magma ocean, slowing its cooling and solidification by orders of magnitude while still allowing sufficient heat flux out of the core to produce a dynamo with intensities consistent with magnetization in Allende [see analysis in Weiss et al. (2008, 2010)]. Materials in the undifferentiated lid experienced varying metamorphic conditions.

Chondritic meteorite samples, including Allende, provide motivation for this study. We seek to define the accretion age and size that would allow internal differentiation of a body consistent with Allende originating in the unmelted crust. A chondritic surface, a silicate or

* Corresponding author at: Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA 02139, USA. Tel.: +1 617 253 1902.
E-mail addresses: ltelkins@mit.edu (L.T. Elkins-Tanton), bpweiss@mit.edu (B.P. Weiss), zuber@mit.edu (M.T. Zuber).

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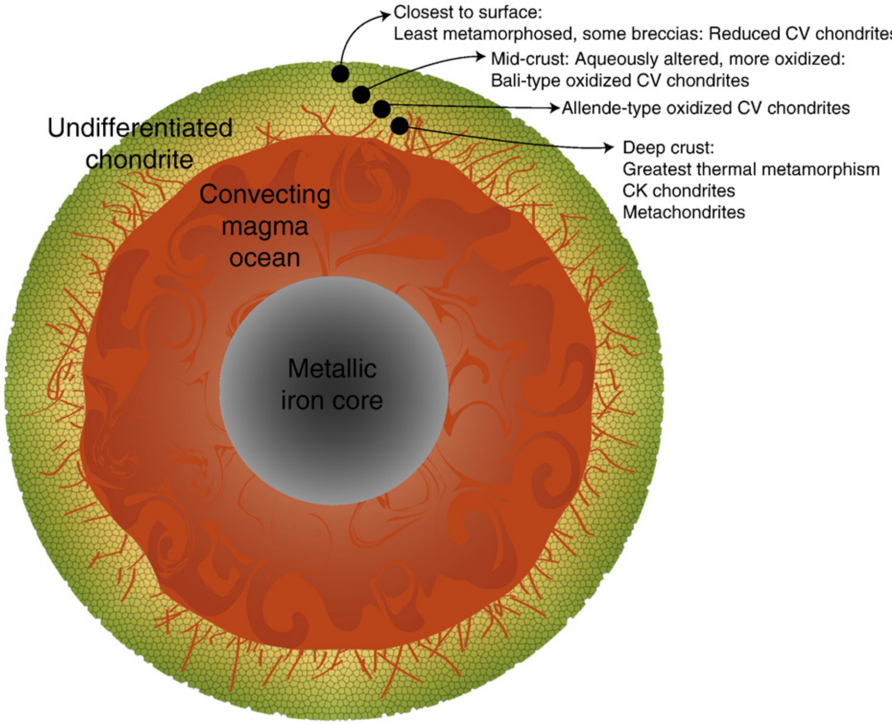

Fig. 1. Schematic diagram of proposed structure for the CV parent body, including an iron core, internal magma ocean, and undifferentiated chondritic crust with varying levels of metamorphism and metasomatism.

ice–silicate mantle and crust, and an iron core should characterize such a body. Further, we will investigate the implications of internally differentiated bodies, including their possible existence in the asteroid belt today. This study is designed to test the feasibility of internal differentiation with a retained primitive crust, and the feasibility of generating a long-lived magnetic core dynamo on such a body.

2. Models and methods

To calculate heat fluxes, the possibility of a core dynamo, and temperature gradients in the unmelted crust, we assume instantaneous accretion and solve the heat conduction in a sphere with initial ^{26}Al evenly distributed (Hevey and Sanders, 2006). The body is heated homogeneously but radiates energy into space, producing a hot interior and chilled crust. If the interior exceeds its solidus temperature sufficiently, the resulting interior magma ocean would advect heat to the base of the crust, where heat transfer continues through the far slower process of conduction.

Although new models and observations indicate rapid accretion (Johansen et al., 2007), the accretion of planetesimals early in solar system history was certainly not instantaneous, as discussed in Ghosh et al. (2003), Merk et al. (2002), and Sahijpal et al. (2007). The heat of accretion during incremental accretion may be neglected here; it does not significantly change the thermal results of these models. A hypothetical parent body with 300-km radius receives ~10^{25}J in kinetic energy during incremental accretion, sufficient to heat the body homogeneously by only 10 to 20 °C (see SD). Thus the first-order temperature driver prior to 2 Ma after CAIs was ^{26}Al heating. The complexity and stochastic nature of boundary conditions, sizes and rates of impactors, and energy partitioning during incremental accretion also mean that incremental model results are necessarily non-unique. Incremental accretion models are likely therefore to require a Monte Carlo approach. Because our intention is to demonstrate the feasibility of partial differentiation rather to model it explicitly, we conclude that instantaneous accretion is a reasonable simplification for calculating core heat flux.

Incremental accretion, though it may not influence the heating of the body, does strongly influence cooling. A thickening conductive undifferentiated lid added to an initially partially melted planetesimal will slow its heat flux into space and therefore lessen the driving mechanism for a magnetic core dynamo, while lengthening its duration. A simple model of incremental accretion is considered in comparison to the instantaneous models; this model is described below.

2.1. Heating and heat transfer

The initial ^{26}Al content of CV chondrites is a controlling parameter in these calculations. Kunihiro et al. (2004) find that there is insufficient radiogenic aluminum in CO chondrites to cause more than minimal melting even with the help of radiogenic ^{60}Fe, and also argue that the CV parent body was unlikely to have melted. However, their conclusion for CV chondrites is based on an initial ^{26}Al content identical to that of CO chondrites and instantaneous accretion. Here we find that the potentially older age of CV chondrules (the youngest being up to 1 Ma older than those in CO chondrites) combined with non-instantaneous accretion mean the CV body could have melted. See Table 1 for model parameters including bulk aluminum content.

Following Hevey and Sanders (2006) we begin by assuming instantaneous accretion and solve the heat conduction in a sphere with initial ^{26}Al evenly distributed:

$$\rho C_P \frac{\partial T}{\partial t} = \frac{1}{r^2}\frac{\partial}{\partial r}\left(kr^2\frac{\partial T}{\partial r}\right) + A_0(r,t), \quad (1)$$

where ρ is density, C_P is the heat capacity of the chondrite, T is temperature, t is time, r is radius, k is thermal conductivity, and A_0 is the radiogenic heat source per volume per time. The temperature