METEORITE EVIDENCE FOR FORMATION OF JUPITER BY CORE ACCRETION.

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Introduction: The gas giants (Jupiter and Saturn) are thought to consist of ~5-25 Earth-mass ($M_\oplus$) rock-ice cores overlain by H and He-rich envelopes [1, 2]. There are two main formation models for gas giants. In the disk instability model, gravitational instabilities in the gaseous nebula generate spiral density anomalies that collapse to form giant planets [3]. In the core accretion model, first planetesimals accrete to form a ~10 $M_\oplus$ solid rock-ice core, then gas slowly accretes until reaching a mass of ~10-30 $M_\oplus$, and finally runaway gas accretion forms the final planet (~318 $M_\oplus$ for Jupiter) [4].

The timescale for giant planet formation by gravitational instabilities is very short (<1,000 y) [3], whereas the core accretion model likely requires $\geq$0.1-1 My to reach the threshold for runaway gas accretion [5, 6]. Furthermore, the combined duration of the first two stages of core accretion is thought to be at least an order of magnitude shorter than the $<\sim$0.1 My duration of runaway gas accretion stage (Fig. 1). As such, which (if either) of these two mechanisms actually formed Jupiter could be established with measurements of the tempo and duration of accretion. Here I show how magnetic and isotopic measurements of meteorites collectively constrain Jupiter's accretion rate as a function of time. The results support the core accretion model for Jupiter.

Meteorite data: This study considers two independent datasets that constrain the spatiotemporal evolution of the solar nebula: the paleointensity of the nebular field and the isotopic composition of nebular reservoirs.

Paleomagnetism. Theoretical studies predict that the solar nebula likely generated a large-scale magnetic field that played a central role in mass and momentum transfer in the disk [7]. Because the sustenance of magnetic fields requires a conducting medium, the dispersal time of the solar nebula can be timed by determining when nebular fields disappeared as inferred from the absence of paleomagnetism in meteorites younger than a certain age [8] (Fig. 2). Our recent paleomagnetic measurements of chondrules from the Semarkona meteorite [7] indicate the the existence of a solar nebula magnetic field of intensity 5-50 µT in the midplane at ~2-3 AU at ~1-3 My after the formation of calcium aluminum-rich inclusions (CAIs) (here taken to be 4567.30 ± 0.16 My ago [10], just after the collapse of the molecular cloud). These paleointensities are consistent with typically observed protostellar accretion rates of ~10^{-8} solar masses ($M_\odot$) year^{-1} [11]. Furthermore, our paleomagnetic studies of seven CM chondrites combined with I-Xe and Mn-Cr dating indicate they were magnetized by a field of >4 ± 3 µT sometime between 2.4-4 My after CAI formation, although it is unclear whether this field was nebular or generated by their parent body [12] (note these paleointensities are twice those reported by [12] to account for rotation of the CM body). Collectively, these data indicate a minimum duration of between ~2 ± 1 My after CAI formation for the nebular field.

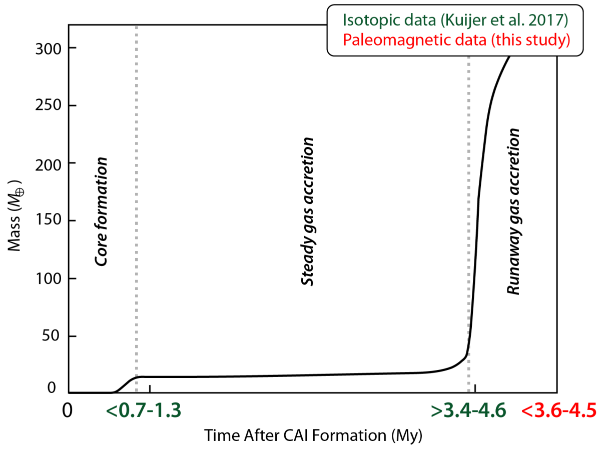

Fig. 1. Schematic of core accretion model for Jupiter compared to meteorite constraints on the timing of accretion. Although transition times between the three stage are not precisely predicted by core accretion models, runaway gas accretion is expected to be at least an order of magnitude shorter than the earlier two stages combined [4, 5]. Combining isotopic constraints on the times of formation and duration of isolated nebular reservoirs (green) with paleomagnetic constraints on the lifetime of the nebula (red) demonstrates that Jupiter grew from ~50 $M_\oplus$ at >3.4-4.6 My after CAI formation to 318 $M_\oplus$ over just ~0-1.1 My, indicating a growth rate ≥10× (and permissibly many orders of magnitude) higher than prior to 3.4-4.6 My. This transition from slow to rapid growth rate, combined with the protracted absolute growth timescale of 3.4 My, are both distinctive signatures of the core accretion model and inconsistent with typical gravitational instability models.

Our recent studies of four other meteorite groups constrain the timing of the subsequent dispersal of the nebular field. First, the absence of stable high blocking temperature magnetization in the Kaba CV chondrite indicates that the field was less than ~0.3-3 µT at ~4-6 My after CAI formation as dated by I-Xe and Mn-Cr chronometry [13]. Second, volcanic angrites cooled in a null field environment (<0.6 µT) at ~3.8 ± 0.2 My after CAI formation as dated by Pb-Pb chronometry (adding the angrite and CAI ages uncertainties in quadrature) [8]. Thirdly, the absence of primary magnetization in the ungrouped achondrite NWA 7325 indicates that it also cooled in the absence of a field (<1.6 μT) at ~4.2 ± 0.3 My after CAI formation as indicated by Al-Mg chronometry [14]. Finally, ongoing analyses of CR chondrules [15] suggest that the local magnetic field was <15 μT by ~4.0 ± 0.6 My My after CAI formation (using the youngest Pb-Pb ages of CR chondrules [16, 17]).

The most precisely dated zero-field constraint (<0.6 μT inferred from angrites) suggests that accretion rates dropped to $<10^{-9}\ M_\odot\ \mathrm{year}^{-1}$ by 3.8 ± 0.2 My after CAI formation [8]. Astronomical observations and theory have found that such a decline in accretion rates is associated with near-total dissipation of the nebula in just 0.5 My [18]. Therefore, our near-zero paleointensities suggest that by ~3.6-4.5 My after CAI formation, the nebula itself had similarly dispersed. This sets a firm upper limit on the formation time of Jupiter (Fig. 1).

Isotopic measurements: It was recently found that two reservoirs with distinct Cr, Ti, Mo, and W isotopic compositions existed in the early solar system and which today are represented by "non-carbonaceous" and "carbonaceous" chondrites and achondrites (e.g., [19, 20]). Planetesimal thermal evolution models, combined with Hf-W model ages for core formation on carbonaceous iron meteorite parent bodies, indicate the bodies accreted at $0.9^{+0.4}_{-0.2}$ My after CAI formation, suggesting that the two reservoirs were already isolated by this time [20]. Assuming the two reservoirs were isolated by the opening of a gap in the disk by proto-Jupiter (see [21] for another viewpoint), this indicates that proto-Jupiter had reached ~20 $M_\oplus$ by this time (Fig. 1).

Furthermore, the two reservoirs apparently remained isolated until after the latest time of accretion of carbonaceous chondrites, dated by the youngest CR chondrule ages (i.e., ~4.0 ± 0.6 My My after CAI formation [16, 17]) [20]. Because it is expected that the two reservoirs would be dynamically mixed by gravitational scattering when proto-Jupiter reached ~50 $M_\oplus$, this sets an upper limit on the time when proto-Jupiter reached such a mass (Fig. 1) [20].

Synthesis: The minimum 1-3 My lifetime of the nebula inferred from meteorite paleomagnetism is compatible with both the core accretion and the gravitational instability models. However, isotopic measurements demonstrate that Jupiter grew to ~50 $M_\oplus$ at a mean accretion rate of less than 24 $M_\oplus\ \mathrm{My}^{-1}$ (using age extrema in Fig. 1). Note that this mass happens to be close to the minimum mass at which runaway accretion should initiate. Combining the isotopic and paleomagnetic measurements, we find that Jupiter grew to its final mass of ~318 $M_\oplus$ at more than 240 $M_\oplus\ \mathrm{My}^{-1}$ (and potentially orders of magnitude faster). The distinctive tempo of slow, protracted accretion followed by rapid end-stage growth is characteristic of core accretion models and inconsistent with typical gravitational instability models.

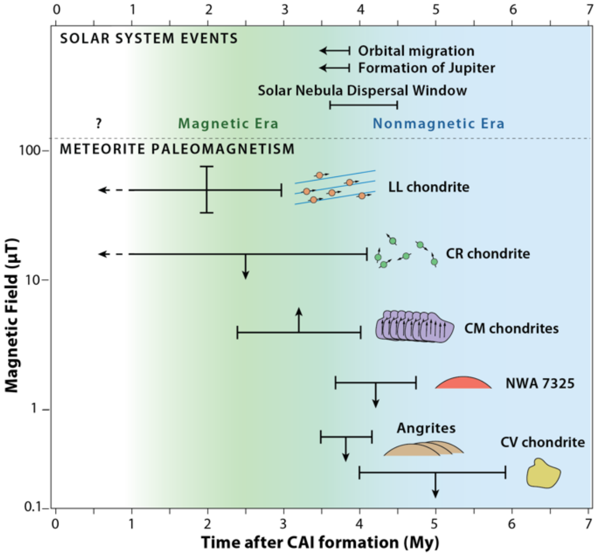

Fig. 2. Meteorite paleomagnetic constraints on the intensity and lifetime of the solar nebula field and inferred associated solar system events. Each point in the bottom panel represents the paleointensity of the ambient field from a given meteorite or meteorite group. Downward- (upward) pointing arrows indicate upper (lower) limits. See text for details and references.

Furthermore, the protracted (≥3.4 My) growth timescale is also inconsistent with typical gravitational models. We conclude that recent meteorite constraints on the evolution of the solar nebula composition and magnetism support formation of Jupiter by core accretion.

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