

ASTRONOMY

Timing of the formation and migration of giant planets as constrained by CB chondrites

Brandon C. Johnson,^{1*} Kevin J. Walsh,² David A. Minton,³ Alexander N. Krot,⁴ Harold F. Levison²

The presence, formation, and migration of giant planets fundamentally shape planetary systems. However, the timing of the formation and migration of giant planets in our solar system remains largely unconstrained. Simulating planetary accretion, we find that giant planet migration produces a relatively short-lived spike in impact velocities lasting ~0.5 My. These high-impact velocities are required to vaporize a significant fraction of Fe,Ni metal and silicates and produce the CB (Bencubbin-like) metal-rich carbonaceous chondrites, a unique class of meteorites that were created in an impact vapor-melt plume ~5 My after the first solar system solids. This indicates that the region where the CB chondrites formed was dynamically excited at this early time by the direct interference of the giant planets. Furthermore, this suggests that the formation of the giant planet cores was protracted and the solar nebula persisted until ~5 My.

INTRODUCTION

The CB metal-rich carbonaceous chondrites predominantly consist of submillimeter- to centimeter-sized Fe,Ni metal \pm sulfide nodules and nonporphyritic (cryptocrystalline and skeletal olivine) silicate chondrules, which crystallized from complete melts, and irregularly shaped chemically zoned Fe,Ni metal grains with compositions consistent with gas-solid condensation (1–3). CB chondrites are divided into two subgroups: coarser-grained CB_a and fine-grained CB_b. Zoned Fe,Ni metal grains and cryptocrystalline chondrules occur almost exclusively in the CB_b chondrites. CB chondrites are the youngest among known chondrite groups (1) and are thought to have formed in an impact-generated gas-melt plume $\sim 4.8 \pm 0.3$ My after the formation of Ca,Al-rich inclusions, the earliest solar system solids dated (4, 5). Detailed equilibrium condensation calculations (6) and bulk chemical and isotopic studies of CB chondrites (7, 8) suggest that at least one of the colliding bodies was differentiated (7), that is, had a Fe,Ni metal core and a silicate mantle, and that either collision occurred in the outer solar system (that is, beyond Jupiter) (8) or that one of the bodies was sourced from the outer solar system.

The vaporization of a Fe,Ni metal core and a silicate mantle from a differentiated body that was involved in the collision requires a high-velocity impact. During the impact, the passage of a shock wave compresses and heats the impactor and the target material. The amount of heating depends on the impact velocity and the materials that are involved. Laboratory experiments of the shock vaporization of iron coupled with detailed impact models indicate that the incipient vaporization of an impactor core material requires impact velocities exceeding 18 ± 5 km/s and that this threshold is relatively independent of preimpact temperature (9). The large uncertainty in this estimate includes normal experimental uncertainty and the effect of variations in impact angle.

Vaporization of a Fe,Ni metal core and a silicate mantle occurs if they are compressed and heated enough to form a supercritical fluid.

This supercritical fluid eventually decompresses, forming a liquid-vapor mixture (9, 10). As this mixture cools, the vapor will condense onto existing drops of molten metal and silicates. If the liquid drops decouple from the vapor or the liquid-vapor mixture is dominated by vapor, the vapor can produce metal and silicate condensates through the process of homogeneous nucleation (11). Either explanation for the observed chemical zoning in Fe,Ni metal grains in CB_b chondrites requires that a large fraction of material be in the vapor phase upon decomposition into a liquid-vapor mixture. Thus, chemical zoning in Fe,Ni metal grains in CB_b chondrites likely requires a significant fraction of metal to vaporize upon release, necessitating impact velocities well above 18 ± 5 km/s (9).

RESULTS AND DISCUSSION

Accretion and giant planet migration

To model planet formation and estimate the velocities of collisions occurring during planetary accretion, we use the recently developed Lagrangian Integrator for Planetary Accretion and Dynamics (LIPAD) (12). Our simulations model a typical minimum mass solar nebula (protoplanetary disk that contains the minimum amount of solids that are necessary to build the planets of the solar system, ~0.01 mass of the Sun) between 0.7 and 3.0 astronomical units (AU; 1 AU is the mean distance from the center of Earth to the center of the Sun) with a gas density that decays on a 2-My time scale (Supplementary Materials). In our models, Jupiter is initially 15 Earth masses and located at 3.5 AU. Gas-driven giant planet migration can fundamentally alter the structure and evolution of planetary systems (13, 14). To explore the effect of giant planet migration, we produced a series of three simulations in which Jupiter's mass was increased to its current mass (~318 Earth masses) instantaneously, at 2, 4, or 6 My, respectively, and subsequently forced to migrate, following the nominal model of the Grand Tack (15). Jupiter's 0.1-My inward migration stops when it reaches 1.5 AU, followed by an outward migration to 5.2 AU on a 0.5-My time scale. The inward-then-outward migration of Jupiter, or Grand Tack, can explain the relatively low mass of Mars and both the dynamical and compositional structures of the main asteroid belt (15–17).

Gas in the solar nebula damps eccentricities and inclinations, which keeps impact velocities relatively low. As bodies grow with time, impact velocities increase because of the higher mutual escape velocities, increasing eccentricities and inclinations from dynamical stirring and decreasing damping effects from the dissipating gas disk. Figure 1 shows

¹Department of Earth, Environmental and Planetary Sciences, Brown University, 324 Brook Street, Providence, RI 02912, USA. ²Department of Space Studies, Southwest Research Institute, 1050 Walnut Street, Suite 300, Boulder, CO 80302, USA. ³Department of Earth, Atmospheric, and Planetary Sciences, Purdue University, 550 Stadium Mall Drive, West Lafayette, IN 47907, USA. ⁴Hawai'i Institute of Geophysics and Planetology, School of Ocean and Earth Science and Technology, University of Hawai'i at Mānoa, 1680 East-West Road, Honolulu, HI 96822, USA.

*Corresponding author. Email: brandon_johnson@brown.edu

how impact velocities on growing planetary embryos in the inner solar system change with time. Even when tracking collisions by all impacting bodies larger than 10 km in diameter (that is, not only onto planetary embryos), the maximum impact velocity occurring in the canonical accretion model is 12.2 km/s around the time that CB chondrites formed (Supplementary Materials). Thus, the CB chondrites are unlikely to form as a consequence of normal planetary accretion. However, models that include a Grand Tack exhibit a large spike in impact velocities around the time of Jupiter's inward migration lasting a few hundred thousand years (Fig. 1, B to D). If the CB chondrites do contain outer solar system material, then a more suitable environment would be a dynamically mixed main asteroid belt that includes the taxonomic diversity that is currently observed.

Evolution of the excited main asteroid belt

Gas-driven giant planet migration can scatter inner and outer solar system material into the main asteroid belt (15), consistent with the suggestion that CB chondrites contain material from the outer solar system (8). However, LIPAD models that include both the inner and outer solar system are prohibitively expensive. Moreover, a multitude of giant planet migration pathways could produce a main asteroid belt that is excited to high inclination and eccentricity (18). Thus, we consider a more universal scenario and model the evolution of a population of bodies within the main asteroid belt region (1.8 to 3.6 AU), which have been excited to high inclination and eccentricity by giant planet migration (Supplementary Materials). Although these models nominally simulate the aftermath of a Grand Tack–like migration, any migration pathway, or any strong excitation mechanism (19), that yields a main asteroid belt of similar mass and dynamical excitement would produce comparable results (Supplementary Materials).

Several collisions capable of partially vaporizing metallic core material occur during the first 0.5 My of the evolution of this excited main asteroid belt (Fig. 2). The most extreme impact in this simulation, a 90-km-diameter body striking a 300-km-diameter body at 33 km/s, is capable of 30 to 60% vaporization of core material (9). This impact could easily produce the zoned Fe,Ni metal grains of CB_b chondrites. The relatively small number of impacts capable of vaporizing a significant fraction of core material may explain why there is no clear evidence yet of other CB-like events in the meteorite record. However, we note that two recently described metal-rich noncarbonaceous chondrites, NWA (Northwest Africa) 5492 and GRO (Grosvenor Mountains) 95551 (20), show some petrographic and mineralogical similarities to CB_a chondrites, including a high abundance of Fe,Ni metal and magnesian nonporphyritic chondrules, and may have originated in a CB-like impact plume. Unfortunately, the ages of chondrules in these meteorites are not yet known. In addition, the ureilites (carbon-bearing ultramafic achondrites) could be related to the heightened impact velocities associated with giant planet migration. Before it reaccreted, the ureilite parent body was disrupted by an energetic impact around the same time the CB chondrites formed (21, 22). Nominally, for a similar size distribution and dynamical excitement, the number of similar collisions would scale linearly with the total mass of the belt, such that a population twice as massive or half as massive may produce too many or too few high-velocity collisions, respectively.

CONCLUSIONS

Where canonical accretion models with no migration fail (Fig. 1A), models of a main asteroid belt excited by giant planet migration can

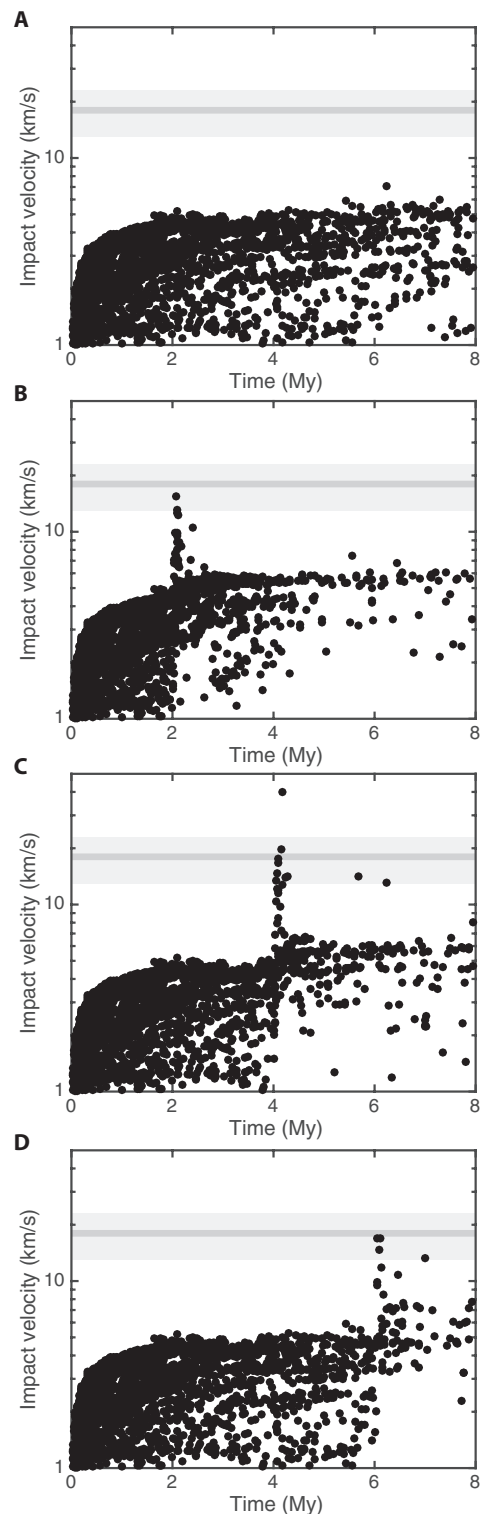


Fig. 1. Impact velocities on growing planetary embryos in the inner solar system.

(A) Impact velocity from a canonical accretion simulation. (B to D) Impact velocities for models in which Jupiter begins a 100,000-year inward migration to 1.5 AU at 2, 4, and 6 My, respectively, before migrating out to its current position on a time scale of 500,000 years. The gray line marks an impact velocity of 18 km/s with the box encompassing the full range of the uncertainty for incipient vaporization of iron in planetesimal cores, including the effect of impact angle (18 ± 5 km/s). All impacts onto bodies larger than 1400 km in diameter are plotted.

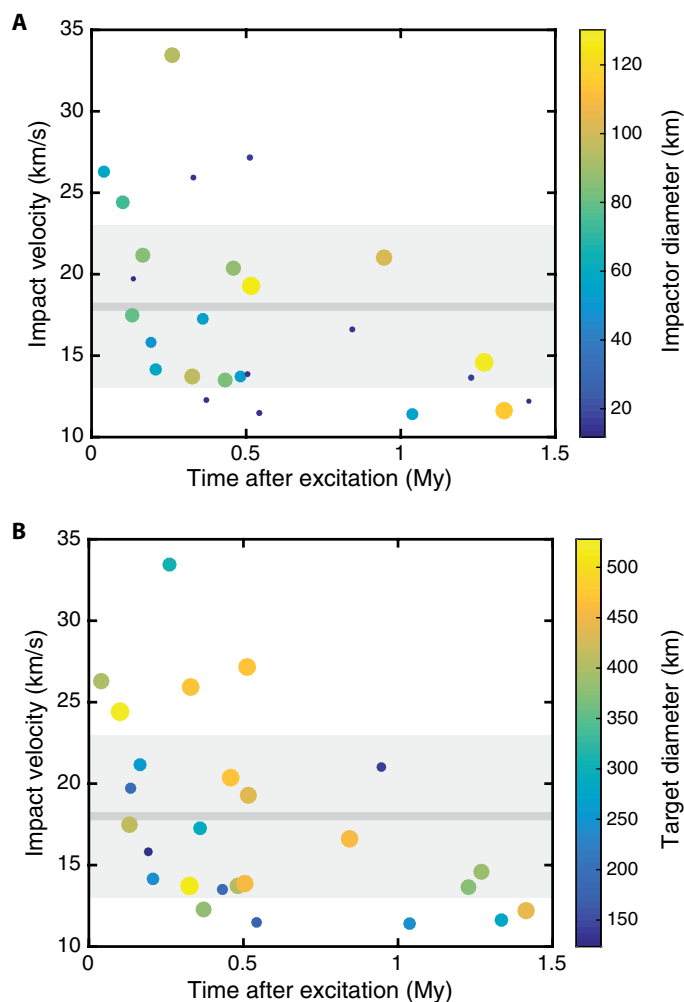


Fig. 2. Impact velocities in a dynamically excited main asteroid belt disk. Impactor (A) and target (B) diameters are indicated by the color bar and marker size. The gray line marks an impact velocity of 18 km/s with the box encompassing the full range of the uncertainty for incipient vaporization of iron in planetesimal cores, including the effect of impact angle (18 ± 5 km/s). All impacts by bodies larger than 10 km in diameter are plotted.

generate the high-impact velocities required to produce the CB chondrites (Fig. 2). Because the increased impact velocities only persist for ~ 0.5 My following the onset of migration, the age of the CB chondrites effectively constrains the timing of giant planet migration. This finding has important implications for the timing of giant planet formation and the lifetime of the solar nebula.

The giant planets of our solar system are thought to form through the process of core accretion, which requires the initial development of a roughly 10–Earth mass planetary core, followed by the runaway accretion of gas (23, 24). The time that it takes to produce a planetary core is weakly constrained and model-dependent (24, 25). Once a planetary core forms, it takes $\sim 10^3$ to 10^5 years for the growing gas giant to accrete a Jupiter mass of gas, depending on the location where the core forms and the density of the protoplanetary disk (26–28). According to hydrodynamic simulations of our solar system, the migration of the giant planets takes $\sim 10^5$ to 10^6 years and nominally stops once the solar nebula is depleted (28, 29). This means that after planetary cores are formed, the solar nebula will be depleted

within 10^5 to 10^6 years. Thus, the formation of the CB chondrites at 4.8 ± 0.3 My after the first solar system solids (5) indicates that planetary cores took ~ 4.5 to 5 My to form and that the gaseous solar nebula existed at least until this time and dispersed shortly thereafter.

Astronomical surveys of young star clusters indicate that the typical lifetime of a protoplanetary disk is ~ 3 to 10 My (30) and that giant planet formation ceases around 5 My for solar mass stars (31). The lifetime that we estimate for the solar nebula is consistent with astronomical surveys of young star clusters. However, our estimate for the time scale of planetary core formation suggests that the process was comparatively slow in the solar system but seems to be in good agreement with pebble accretion models (25). This time scale is also consistent with models that show that giant planet migration occurred after the relatively quick accretion of Mars (32, 33). Accretion of ejecta from the CB forming impact requires that sufficient gas was present in the solar nebula (Supplementary Materials). Thus, the region where the CB chondrites formed was dynamically excited during the epoch of the gaseous solar nebula. This extreme dynamical excitation is not an expected result of the classical accretion of bodies and demands the interference of the giant planets.

MATERIALS AND METHODS

In most previous simulations, collisions between interacting bodies resulted in simple growth by the merging of bodies, such that one could model planets growing from a sea of smaller planetesimals and planetary embryos. Here, with LIPAD, we used “tracer” particles that each contained a significant total mass for gravitational calculations but represented a swarm of particles of a smaller radius, s . For small sizes, the tracers represented a huge number of small bodies and required collisional probabilities to be calculated for each tracer as a function of the size s that it represented and the same for its neighbors—all while continuing gravity calculations.

When collisions occur, LIPAD relies on a fragmentation law based on the works by Benz and Asphaug (34) and Durda *et al.* (35) to determine the outcome of collisions between particles. Thus, the total system’s size distribution is built from the total number of particles with different sizes s . Meanwhile, the population of tracers can affect the local dynamics through dynamical friction and viscous stirring effects while also experiencing the local gas effects from the solar nebula. Fundamentally, the Lagrangian nature of the code allows for the dynamics to be preserved, whereas the collisional effects can model growth from dust all the way to planets. LIPAD can track the collisions that happen in our modeled disk, either by the individual embryos or the statistical tracking of tracer particles. Although computationally expensive, LIPAD can effectively track every collision occurring in the simulation down to arbitrarily low impact velocities and small impactor sizes. We refer the reader to the work by Levison *et al.* (12) for consideration of a suite of tests to demonstrate LIPAD’s capabilities in matching an array of previous works.

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at <http://advances.sciencemag.org/cgi/content/full/2/12/e1601658/DC1>

Supplementary Materials and Methods

fig. S1. Model setup for an excited post-migration main belt.

fig. S2. Impact velocities in an excited post-migration main belt disk with no gas present.

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