LATE FORMATION AND MIGRATION OF GIANT PLANETS AS CONSTRAINED BY FORMATION OF CB CHONDRITES. B. C. Johnson1, K. J. Walsh2, D. A. Minton3, 1Department of Earth, Environmental and Planetary Sciences, Brown University, 324 Brook Street, Providence, RI 02912, USA (Brandon_Johnson@Brown.edu), 2Department of Space Studies, Southwest Research Institute, 1050 Walnut Street, Suite 300. Boulder, Colorado 80302, USA, 3Department of Earth, Atmospheric, and Planetary Sciences, Purdue University, 550 Stadium Mall Drive, West Lafayette, IN 47907, USA.

Introduction: Although giant planets are generally thought to migrate inward in protoplanetary disks hydrodynamic simulations show that a system of multiple giant planets embedded in a gaseous nebular disks can also migrate outward [1]. An initial inward migration of Jupiter to 1.5 AU followed by a subsequent outward migration, or so called ‘Grand Tack’, can explain the relatively low mass of Mars and the general structure of the asteroid belt [2]. The timing of such a migration if it occurred remains largely unconstrained. Here we report that giant planet migrations can produce impact velocities exceeding those required to vaporize Fe and produce the zoned metal grains in CB chondrites [3,4,5]. We show that the Grand Tack creates a short lived spike in impact velocities. This implies that giant planet migration occurred at the time CB chondrites formed, ~4.8 Myr after the first solar system solids. Thus, the formation of the giant planets' cores was protracted and the solar nebula persisted until ~5 Myr.

In addition to chondrules, the sub-millimeter to centimeter sized previously molten spherules found in most meteorites, CB chondrites contain zoned metal grains [3]. The unique metal-rich CB chondrites, which formed later than other chondrites, are thought to be the product of a single large impact [3]. Moreover, the compositional zoning of Fe,Ni-metal grains in the CB chondrites indicates that these grains condensed from impact produced vapor-melt plume [3]. Recent detailed equilibrium chemistry calculations indicate that the metal that produced the zoned Fe,Ni-metal grains was sourced from the core of a differentiated CR chondrite body with a high water content [6]. This may imply that the impactor or target was originally from the outer solar system.

The vaporization of core material from the impactor or target requires a high velocity impact. Laboratory experiments of the shock vaporization of iron coupled with detailed impact models indicates that the incipient vaporization of impactor core material requires impact velocities exceeding 18±5 km/s [7]. The uncertainty in this estimate comes from variations in impact angle and experimental uncertainties in the entropy increase required to vaporize iron.

Methods: To model planet formation and estimate the velocities of impacts occurring during planetary accretion we use the recently developed Lagrangian Integrator for Planetary Accretion and Dynamics (LIPAD) [8]. Our simulations model a typical minimum mass solar nebula between 0.7-3.0 AU with a gas density that decays on a 2 Myr timescale. In our models, Jupiter is initially 15 Earth Masses and located at 3.5 AU. For a series of simulations Jupiter's mass was increased to its current mass instantaneously, at 2, 4, and 6 Myr, and was forced to migrate following the migration scheme in the Grand Tack [2]. Jupiter’s 100,000 year inward migration stops when it reaches 1.5 AU followed by an outward migration to 5.2 AU on a 500,000 year timescale.

Results: Gas in the solar nebula damps out eccentricities and inclinations keeping impact velocities relatively low. As bodies grow with time, impact velocities increase because of the higher mutual escape velocities as well as increasing eccentricities and inclinations from dynamical stirring and decreased damping effects from the dissipating gas-disk. Figure 1a shows that when no giant planet migration is included in our models, impacts are never energetic enough to vaporize iron. Models that include a Grand Tack, however, include a large spike in impact velocities around the time of Jupiter’s inward migration (Fig. 1b,c,d). The increase in maximum impact velocities that occur lasts for a few hundred thousand years. During this time, a few impacts occur at velocities that reach or exceed the threshold for vaporization of iron in each model. The model with a Grand Tack at 4 Myr has one impact that occurs at a velocity of ~40 km/s exceeding the impact velocity required for the vapor-phase to dominate the two fluid mixture of iron that ultimately forms potentially explaining the formation of zoned metal grains in CB chondrites even if the vapor and liquid do not spatially decouple.

Differences in maximum impact velocity between the different models that include the migration of Jupiter are most likely stochastic although the time dependent gas density may play some role as well as the increased chance of embryo-embryo collisions with time. We are working on including outer solar system material that ultimately gets implanted in the asteroid belt. However, we expect this material will experience high impact velocities similar to the impact velocities experienced by the inner solar system material modeled here.
Where canonical models with no migration fail (fig 1.a), models that included giant planet migration can produce the high impact velocities required to form the CB chondrites. Moreover, because the increased impact velocity only occurs for a short time 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.

Giant planets are thought to form through the process of core accretion, which requires the initial formation of a roughly 10 Earth mass planetary core followed by the accretion of gas. However, the time it takes to form a planetary core is not well constrained [eg. 9]. Once a planetary core is formed, it takes ~10^3-10^5 years for the growing gas giant to accrete a Jupiter mass, depending on the location at which the core forms and the density of the protoplanetary disk [1]. According to hydrodynamic simulations the inward and outward migration of Jupiter takes ~10^5-10^6 years and nominally stops once the solar nebula is depleted [1,2]. This means that after planetary cores are formed, the solar nebula will be depleted within a few hundred thousand years. Thus formation of the CB chondrites at 4.8±0.3 Myr after the first solar system solids [10], indicates that planetary cores took ~4.8 Myr to form. Moreover, it indicates the solar nebula lived at least until this time and likely dispersed shortly thereafter.

Astronomical surveys of young star clusters indicate that the typical lifetime of a protoplanetary disk is ~3-10 Myr and giant planet formation ceases around 5 Myr for solar mass stars [11]. The lifetime we estimate for the solar nebula is consistent with astronomical surveys of young star clusters but indicates that planetary core formation was comparatively slow in the solar system.


Figure 1: Impact velocities during planetary accretion. Fig 1a is from a run in which Jupiter does not change position. Fig 1b, c, and d are for models in which a Jupiter makes an initial migration to 1.5 AU at 2, 4, and 6 Myr, respectively, before migrating out to its current position. 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).