CONSTRAINTS ON JUPITER'S AGE AND FORMATION MECHANISM AND THE NEBULA LIFETIME FROM CHONDRITES AND ASTEROIDS. Edward R. D. Scott, Hawai'i Institute of Geophysics and Planetology, University of Hawai'i at Manoa, Honolulu, Hawai'i 96822, USA (escott@hawaii.edu).

Introduction: Since the major chondritic components—chondrules, Ca-Al–rich inclusions (CAIs), and amoeboid-olivine inclusions—formed in the nebula, their ages provide a limit for the lifetime of the solar nebula. If chondritic components accreted into asteroids before Jupiter formed, then these ages also provide constraints on the time of Jupiter's formation. Such constraints might identify whether Jupiter formed rapidly in 10^{3-4} yr by gravitational instabilities in the nebula [1], or more slowly by core accretion in a few Myr [2]. Comparison of the lifetimes of the solar nebula and protostellar disks and constraints on the formation ages of extrasolar planets may then offer some insights into the origins of extrasolar planets and differences between the orbits of solar and extrasolar planets.

Here we focus on constraints on the formation of Jupiter that can be derived from chondrites and asteroids and models for their accretion and the evolution of the asteroid belt. Three questions are addressed: When did the chondritic components form in the solar nebula? What role if any did Jupiter play in the formation of chondritic components? Did Jupiter form before the asteroids accreted?

When did chondritic components form in the nebula? Al-Mg data for CAIs show that they probably formed in $<10^5$ yr [3] at 4567.2±0.7 Ma according to Pb-Pb ages of CV CAIs [4], when the protosun was rapidly accreting as a class 0 or I protostar. Chondrules in CV and CR chondrites formed at 4566.7±1.0 and 4564.7±0.7 Ma [3], consistent with Al-Mg isotopic data that suggest that chondrule formation started 0-2 Myr after CAI formation and lasted for 2.5±1 Myr [4]. This period might be 2 Myr longer if CAIs formed at 4569.5±0.2 Ma as Baker et al. [6] infer by combining Pb-Pb and Al-Mg isotopic data for angrites with Al-Mg data for CAIs.

The youngest chondrules are those in CB chondrites that formed at 4562.8±0.9 Ma [7], 4.5 Myr after CAIs. However these chondrules have very unusual properties and clearly formed in very unusual circumstances.

Was Jupiter involved in chondrule formation? Three possible roles for Jupiter in forming chondrules have been proposed via either nebula shocks or colliding planetesimals. 1) Jupiter could have increased the eccentricities of 1000 km asteroids causing them to generate nebular bow shocks: chondritic material accreted onto the surfaces of early formed planetesimals or into new bodies amidst the excited asteroids [8]. 2) Jupiter itself may have driven strong shocks in the inner nebula for as long as gas remained [9]. 3) Alternatively, Jupiter may have caused planetary embryos to collide in the asteroid belt at high speeds generating melts and vapor that formed chondrules in CB chondrites [7]. The first mechanism requires that most asteroids accreted in the belt without any chondrules. However, with the possible exception of rare CI chondrites, there is no evidence that chondrule-free material accreted in the asteroid belt.

Before addressing the merits of these mechanisms we need to know if asteroids could have accreted after Jupiter formed, as these mechanisms infer.

Did Jupiter form before the asteroids accreted? Kortenkamp et al. [10] found that several Ceres-sized objects could form in 3 Myr at 2.3 AU after Jupiter and Saturn formed. However, three factors suggest that asteroids did not readily accrete after Jupiter reached its current mass and position. First, Kortenkamp et al. found that accretion beyond 2.3 AU was severely limited by resonances with the giant planets. Second, in their simulations they fixed the locations of Jupiter and Saturn at 1 AU outside their present positions (i.e., Jupiter at 6.2 AU and Saturn at 10.5 AU), arguing that this would allow for later migration caused by planetesimal scattering. However, numerical simulations of giant planet migration suggest that Jupiter would have migrated by less than 0.5 AU due to planetesimal scattering. Scattering of icy bodies into the Kuiper belt by Jupiter caused it to migrate inwards by less than 0.3 AU [11,12], while scattering of bodies in the asteroid belt caused a smaller shift [13]. The properties of the Hilda asteroids suggest that the total inward migration of Jupiter was ~0.45 AU [14].

The third reason for questioning whether chondritic asteroids could have accreted after Jupiter is that Jupiter may have been migrating inwards due to angular momentum exchange with the nebula. In this case, accretion in the asteroid belt would have been even more constrained as Jupiter's internal mean-motion resonances would have swept across the belt as it migrated. In their simulations, Kortenkamp et al. [15] found that the growth of large asteroids in the main belt was not possible if Jupiter migrated significantly (by 1-3 AU) while the planetesimals were accreting. In theory, asteroids might accrete in the main belt after Jupiter if Jupiter migrates from outside 7 AU after they form. But such a model appears implausible, as migration rates should decrease as the nebula gas accreted into the protosun.

Role of Jupiter in the early evolution of the asteroid belt. The preferred mechanisms for explaining the missing mass in the asteroid belt, the mixing of asteroids types, the excitation of asteroid orbits, and the existing size and family distribution all indicate that Jupiter form after the asteroids accreted.

The mass loss from the asteroid belt and the dynamical excitation of asteroid orbits are generally attributed to the formation of lunar-sized embryos in the asteroid belt. These bodies excited the asteroids via close encounters, ending accretion and starting fragmentation [16, 17]. The loss of 99% or more of the total mass including all of the embryos results from the appearance of Jupiter and the loss of material through secular and mean-motion resonances of the giant planets. However, some mass was also lost via sweeping resonances during Jupiter migration in the nebula, nebula removal [17], and scattering of planetesimals in the outer solar system by the giant planets [11].

Further constraints on the time of Jupiter's formation come from Bottke et al. [18,19] who investigated the early history of the asteroid belt by developing models that would generate the current size-frequency distribution of asteroids, and the numbers and ages of asteroid families. Bottke et al. infer from the current size distribution of asteroids that the main belt was once more massive that it is today. They require that asteroids <1000 km in diameter were ~150× more abundant in the belt for a period of 3.3±2.6 Myr. This intense period of collisional comminution ended when Jupiter reached its current mass and approximate position and ejected material through resonances.

Summary and conclusions:

1. Models for asteroid accretion and evolution that provide plausible explanations for the growth, depletion, mixing, and excitation of asteroids require that Jupiter reached its current size and approximate position (~0.3 AU beyond its current location) after the asteroids accreted and were subsequently orbitally excited and collisionally evolved.

2. Radiometric ages of chondritic components and achondrites and thermal models for ^{26}Al heating provide a fairly compelling case that chondrites accreted 1.5-4.5 Myr after CAI formation, following accretion of the differentiated asteroids [20, 21].

3. Asteroids probably accreted until at least 2 Myr after CAIs formed. Collisional evolution of a massive belt probably took another few Myr before Jupiter approached its current size and location [19].

4. If CB chondrules formed by impacts involving embryos [6], it is unclear how such chondrules could have accreted in the asteroid belt, except possibly into a short-lived satellite of an embryo. CAI accretion into CB chondrites 4.5 Myr after CAI formation requires a comparable lifetime for the solar nebula.

5. Jupiter probably formed by core accretion in 3-5 Myr. The solar nebula was unusually long-lived. Extrasolar planets at >0.1 AU have very eccentric orbits and probably formed much more rapidly when protostars were still interacting gravitationally [22].

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