Introduction: Chondrites have been compared to terrestrial sandstones, formed by the physical accumulation of unrelated grains followed by a lithification process. Tectonics and the simple weight of overlying layers provide the conditions for lithification of sandstones on Earth. What plays this role on meteorite parent bodies?

Present day asteroids cannot compact meteorites by their own self-gravity; lithostatic pressures even in the center of Ceres are far too small. Furthermore, it is likely that most asteroids are loose rubble piles, shattered and re-accreted. A high degree of impacting is evident in the meteorites: most meteorites are breccias, and the most common shock state of meteorites is S3 [1].

What does this tell us about the possible physical histories of the asteroids? Our measurements of the porosities, and model porosities, of ordinary chondrites [2] can be combined with other physical studies of meteorites such as shock state to put numerical limits on possible models for the lithification of the meteorites and their parent bodies.

We propose here three suggestions concerning meteorite lithification. It is possible that all or none of the proposed processes may actually have occurred in the early solar system. But confirming or eliminating any of these models can put useful constraints on our ideas about the accretion of material in the early solar system.

Porosity and Shock: Our previous work examining over 300 ordinary chondrites has shown that most ordinary chondrites have primordial porosities ranging from 5% to 15%, with a few rare cases having porosities up to 30%. We find no correlation between the metamorphic state of meteorites and their porosities. Other workers using optical methods to estimate the shock state of meteorites [1] have noted a lack of correlation between shock state and metamorphic state; thus one might expect, logically, that there should be no correlation between shock state and porosity.

In fact, as seen in Figure 1, the average porosity does indeed stay constant at around 10% for all shock levels. But there is a distinct second order effect: as shock state increases, the spread of the observed porosities about this mean decreases. While meteorites of shock state S1 and S2 average at 10% porosity with a spread up to 30%, those at shock state S5 and S6 average 10% porosity with very little spread away from that average. Clearly something subtle is going on here.

Porosity and Pressures: The lack of correlation between metamorphic state and porosity is not surprising; no asteroid is large enough for burial depth to change porosity. Experiments [3] on sandstones with original porosities ranging from 15% to 30% show that confining pressures of 0.3 - 0.4 GPa are required to fill their pore spaces with comminuted rock. By comparison, the central pressure of asteroid 1 Ceres is about 0.2 GPa. Note also that such compressed sandstone is still filled with microcracks and pore space of up to 10% porosity.

Experimentally shocked mineral powders (initial porosity 30%-35%) [4] reduced their porosity to about 10% when shocked to 2.5 GPa. Increasing the shock pressure only slightly decreased porosity from this point. This is consistent with impact processes in the early solar system being a source of compaction for the ordinary chondrites. If so, however, the persistence of some high porosity meteorites would still demand explanation.

In both cases, the experimental evidence is interesting but not conclusive. The behavior of sandstones is not consistent from sample to sample, and notoriously difficult to model. And the results of the shock experiments may be influenced by the use of closed containers, which may have overamplified the effect of the shock.

Why are there meteorites? Numerous workers have now pointed out that asteroids are likely loose piles of rubble (see references in [2]), and a number of models have shown how repeated impacts can fragment asteroids without totally dispersing them [5]. But all these models assume that one starts with a solid rocky body, impacted by other solid rocky bodies. Where did these original un-rubblized asteroids come from?
Most theories of solar system accretion assume at some point that dust in a relatively quiescent solar nebula was able to settle to the midplane and coagulate. But it is difficult to see how this coagulation could lead directly to rocky material with porosities as low as that seen in ordinary chondrites. Even sandstones formed in Earth gravity normally have much higher porosities; in the quiescent stage of the solar nebula, one might intuitively expect the original coalescent bodies to be better pictured as fluffy accumulates (like lunar “fairy castle” structure) rather than as solid bodies. What lithified these objects into dense, low porosity rocky meteorites?

Three unsatisfying models: Why do we see meteorites as rocks rather than dust balls? One suggestion is that in fact most material in space really is uncompacted orites as rocks rather than dust balls? One suggestion is that our meteorite samples have been hopelessly biased because such loose material would never survive passage through the atmosphere.

This suggestion has several difficulties, however. It is clear from our collections that a significant number of meteorites (especially when one includes carbonaceous chondrites) with porosity much higher than 10% and strength much lower than the 30% porous ordinary chondrites in our collection nonetheless have survived passage through the atmosphere.

Furthermore, if our ordinary chondrite collection represented only the tail of a much larger meteorite population, then at least an order of magnitude more material must strike the top of the Earth’s atmosphere than actually reaches the ground. But satellite observations of meteorites in our collection nonetheless have survived passage through the atmosphere.

A second suggestion is that the asteroid belt seen today is but a tiny fragmented remnant of a population of much larger proto-asteroids. Asteroids of 1000 km radius would have sufficient gravity in more than 80% of their volume to compact and lithify ordinary chondrites to a 10% porosity level. After the break up of these and the undoubtedly more numerous smaller, uncompacted parent bodies, the uncompacted material from the smaller asteroids could have been preferentially swept away with the dissipating nebula.

This suggestion is consistent with the concept that the majority of material in the asteroid belt has been lost, and that iron meteorites originated as the cores of many (at least 50) now-dispersed asteroids. And it provides a way of setting a basic 10% porosity for most meteorites.

However, it has several serious problems. The idea of creating dozens of bodies larger than all but the largest moons of the solar system — and then destroying and dissipating all of them, without exception — is rather unlikely. Indeed, the collisional lifetime of an asteroid that large is on the order of the age of the solar system.

Furthermore, one is left with the embarrassment of explaining asteroid 4 Vesta. Where absolutely no 1000 km proto-asteroid survives, this 400 km asteroid has lasted 4.5 billion years. Where none of the meteorites from these purported larger asteroids ever became hot enough to melt (the ordinary chondrites are not igneous), Vesta was thoroughly melted. (And Vesta’s spectral variations and its relatively well constrained density indicate that it is not just a large piece of a differentiated crust.)

A third possibility suggests that the initial compaction of meteorites may have occurred due to collisions at relatively slow impact velocities. A meteoroid impacting at a relative speed of 0.5 km/s has a kinetic energy density equivalent to 0.4 GPa. One might envision a protoasteroid whose crust has been relatively well compacted by impacts, but whose interior was still much more porous, and thus vulnerable to breakup by larger impacts. Perhaps Jupiter’s accretion was slow enough to pump up relative asteroid velocities slowly, enough to have a period of low speed collisions. Once Jupiter was formed, its resonances (whose locations change as Jupiter accretes) would sweep through the belt accelerating impactors, resulting in higher velocity shocks; enough to rubblize the asteroid and eventually launch a meteoroid from its parent body to an Earth-intersecting orbit.

But note that many of the competing theories for chondrule origin call for the presence already of a proto-Jupiter (to incite shock waves in the nebula, or accelerate impactors fast enough to melt target rock). Having chondrules in our meteorites implies that this proto-Jupiter already existed before the ultimate parent bodies of these meteorites were compacted. Thus whatever impacts occurred to compress these asteroids must have been at relatively high energies.

And note that compaction cannot take place directly under a hypervelocity impact: by definition the material in the target cannot move fast enough to compact itself in response to the presence of the impactor. Only the shock wave a certain distance away from the impact will allow for the compression of the rock. Thus, hypervelocity impacts can only lithify asteroids already large enough to survive such impacts, and already compact enough to transmit the shock waves. Depending on the mechanical characteristics of the proto-fluffy asteroids, we may still have a chicken-and-egg problem.