

**LINKING CHONDRULES TO THE FORMATION OF JUPITER THROUGH NEBULAR SHOCKS.** A. C. Boley, R. H. Durisen, *Department of Astronomy, Indiana University, Bloomington, IN 47405-7105, USA, (acboley@astro.indiana.edu).*

**Introduction:** Chondrules and calcium-aluminum-rich inclusions (CAIs) are among the first thermally processed solids in the Solar System. Isotopic dating indicates that they formed between  $4567.2 \pm 0.6$  and  $4564.7 \pm 0.6$  Ma ago [1], with the earliest chondrules forming contemporaneously with CAIs [2]. Observed characteristics of these solids suggest that they have a nebular origin, and therefore chondrules and CAIs are encoded with the first three million years of the Solar Nebula's history,  $t = 0$  being the formation of the first CAIs. The principal pieces of evidence that suggest a disk origin include complementarity of chondrules and their matrix [3], the thickness of fine-grained rims on chondrules [4], collision histories inferred from compound and fractured chondrules [5], and oxygen fugacities [6].

The mechanism for thermally processing chondrules that best complements these findings is nebular shocks. In addition to demonstrating that shocks can create chondrule heating events, detailed 1D shock calculations with radiative physics are capable of reproducing the high cooling rates of chondrules in liquidus and the moderate cooling rates in solidus that are observed during laboratory experiments [5, 7, 8]. The best candidate for producing these shocks is spiral waves [9, 10, 11]. Here, like Boss & Durisen [11], we suggest that disk instability in the Solar Nebula led to clump formation and massive spiral arms that drove spiral shocks into the inner disk [see also, 12]. However, in Boss & Durisen, Jupiter and Saturn form quickly. This could be problematic because a Jupiter mass object should open a gap in the nebula [13]. The formation of a gap would suppress strong spiral shocks and halt chondrule formation. We, instead, conjecture that the duration of chondrule formation acts as a chronometer for the formation of Jupiter, i.e., Jupiter only became massive enough to open a gap in the Solar Nebula about 2-3 Ma after  $t = 0$ .

**Concept:** Disk instability can produce strong spiral shocks, possibly strong enough to process chondrule precursors; however, the inner nebula was probably too hot to be gravitationally unstable. Instead, we propose that a massive ring separating the inner and outer nebula underwent bursts of localized instability resulting in transient clumps or massive spiral arms. Massive clumps and arms can form spiral wakes that extend into the inner and outer nebula [10, 14], and result in strong shocks [12]. Since we presume they are transient, they dissipate before they open a gap. The spiral shocks will also generate disk turbulence and mix the nebula radially and vertically [12, 15]. After the massive clumps and arms are sheared away, the nebula returns to a state similar to the pre-burst phase, but now with processed silicates.

There are several possibilities for the formation of a ring; we emphasize two. First, the outer disk may be gravitationally unstable. Gravitational Instabilities (GIs) will drive inward mass transport to the edge of the gravitationally stable region and result in the formation of one or more rings [16]. Second, the magnetorotational instability [e.g., 17, 18, 19] could pos-

sibly create regions that have different accretion rates. If the accretion rate of the outer nebula is higher than the accretion rate of the inner nebula, perhaps due to changes in disk opacity or degree of ionization, then a ring may form.

Since chondrules have a very limited size range (0.1 to 1 mm), chondrules were probably aerodynamically size-sorted in disk turbulence [20]. Spiral shocks, due to their three-dimensional nature, generate large vortical flows in the disk [12], which could also generate disk turbulence and quickly size-sort and package the chondrules into their parent bodies after the chondrule precursors are thermally processed. Spiral waves will also mix the nebula vertically and radially [21].

Overall, we envision the first 2-3 million years of the Solar Nebula as a cycle of ring formation followed by a burst of GI activity in that ring. During a given burst, massive clumps and spiral arms are formed at the ring radius and drive spiral waves in the inner and outer nebula. These waves concentrate the solids [22], produce shocks for their annealing, and provide turbulence for aerodynamic size-sorting. The end of this cycle, and thus the chief chondrule formation period, would be due to the formation of a gap in the nebula, presumably due to a proto-Jupiter.

**Simulations:** To demonstrate the feasibility of this picture, we present two 3D hydrodynamics simulations of disks. A fluid element tracer is also used to follow the thermal histories of gas parcels and characterize the radial and vertical mixing that results from global spiral shocks in these disks. Our 3D hydrodynamics code [see, e.g., 23, 24] is second-order in space and time and solves the hydrodynamics equations of motion with self-gravity on a cylindrical Eulerian grid. The grid resolution is (256, 512, 64) cells above the midplane for ( $r$ ,  $\varphi$ ,  $z$ ) respectively. In these simulations, the disks are evolved using an energy equation, which relates the pressure  $p$  to the internal energy  $\epsilon$  by  $p = (\gamma - 1)\epsilon$ . Artificial viscosity is used to simulate heating by shocks.

The initial disk is taken to be an isentropic ideal gas with a ratio of specific heats  $\gamma = 5/3$ . The disk surrounds a  $1 M_{\odot}$  star and contains  $0.035 M_{\odot}$  within 6 AU. The first simulation forces a spiral wake in the disk by placing a  $10 M_J$  point mass on a fixed, circular orbit at 5.2 AU, similar to a simulation presented in [12] but at higher resolution. We stress that, although treated numerically as a point mass, one should interpret this as a massive, but transient, clump that is suddenly formed by gravitational instabilities in a ring. The simulation is meant to demonstrate shock parameters in disks when a very massive perturbation occurs.

The second simulation adds a ring of material, into the same disk described above, centered on 5.2 AU, totaling about  $0.014 M_{\odot}$  in mass, with a FWHM of about 0.9 AU. The ring is in equilibrium, but the enhancement to the surface density brings the  $Q$  value within the ring from 2 to about 1. A salt-and-pepper density perturbation is used at the beginning of the simulation to generate background noise, and a slow cooling

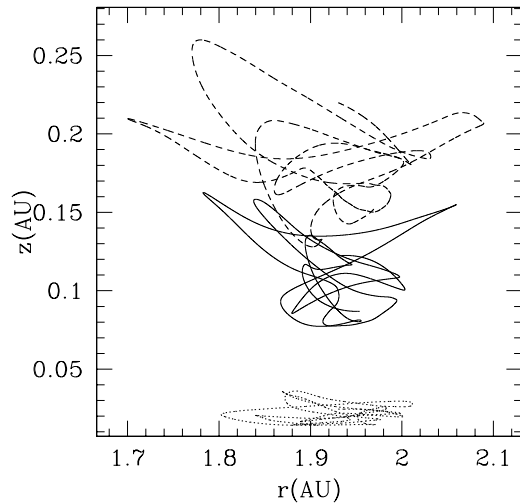


Figure 1: The projections of three fluid elements, all starting at 1.9 AU, onto the  $r$ - $z$  plane. Each fluid element experiences large radial and vertical excursions, the excursions increasing with altitude as expected in hs-jump theory [21].

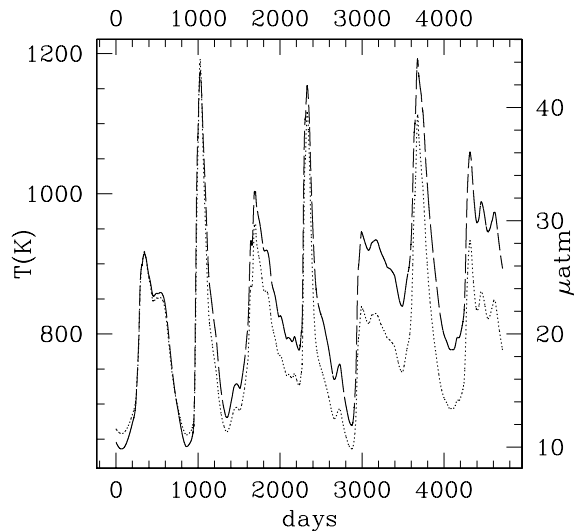


Figure 2: Temperature (solid) and pressure (dotted) for the middle-altitude fluid element in Figure 1 (solid line). The fluid element experiences a variety of shock conditions and strengths, as indicated by the peaks with short rise times. The density corresponding to the pre-shock values is on order of  $10^{-9}$  g/cc and the pre-shock velocity, in the frame of the spiral pattern, is about 5.5 km/s. The shock that occurs near 1000 days may have chondrule-producing properties, according to [8].

time of four orbit periods at 5.2 AU is applied to the ring region. The point of this simulation is to model shocks that are produced when spiral arms form from an unstable ring.

**Discussion:** Details of these simulations will be presented during the meeting, and we expect results similar to the  $10 M_J$  calculation presented in [12]. Figures 1 and 2 are created from the same data used by Boley et al. and are for fluid elements passing through spiral shocks caused by a  $10 M_J$  clump at 5 AU. Figure 1 demonstrates that waves and hydraulic-shock jumps (hs-jumps) [21] place fluid elements on large radial and vertical excursions, which can result in mixing. Figure 2 demonstrates the wide variety of shocks that the middle-altitude fluid element from Figure 1 (solid line) encounters. We should stress that, due to the artificial viscosity algorithm in our code, shocks are smeared out over several cells, so the peak temperatures of shocks are diminished. To evaluate whether these shocks could produce chondrules, we look at the pre-shock conditions, which our code can accurately determine, and compare them to results of 1D shock simulations [e.g., 8].

**Summary:** We conjecture that chondrules were made in spiral shocks that were driven by disk instabilities in massive rings. These shocks produced size-sorting turbulence and mixed the Solar Nebula. The chondrule formation period ended when a permanent proto-Jupiter became large enough to open a gap.

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