A proposed origin for chondrule-forming shocks in the solar nebula

Andrew F. Nelson
Dept of Physics and Astronomy, 202 Nicholson Hall, Louisiana State University, Baton Rouge LA, 70803, USA

Maximilian Ruffert
School of Mathematics, University of Edinburgh, Edinburgh EH9 3JZ, UK

Abstract. We propose that the nebular shocks currently favored as a model to form chondrules and other annealed silicates in the solar nebula originate in the dynamical activity present in the envelope of forming Jovian planets. In contrast to the classic ‘core accretion model’, our 3D hydrodynamic simulations show that this envelope is not a 1D hydrostatic structure but is instead vigorously active and contains densities and temperatures that appear similar in magnitude and spatial extent to those thought to be responsible for the production of chondrules.

1. Introduction

According to the most likely theory for Jovian planet formation, Jupiter formed in a three stage process, lasting about 6 Myr. In the classic model (Wuchterl et al. 2000), a 5-15\( M_\oplus \) rock/ice core forms at a distance of \( \sim 5 \) AU from the central star (Boss 1995) over a period of about 1/2 million years. It then begins to grow a hydrostatic, gaseous envelope which slowly cools and contracts while continuing to accrete both gas and solids until the total core+envelope mass reach about 30 \( M_\oplus \), after another \( \sim 6 \) Myr have passed. In the final stage, the envelope begins to collapse and a period of relatively rapid gas accretion follows, ending with the planet in its final morphology. As stated, the timescale presents a considerable problem for the model because circumstellar disks are observed (Haisch et al. 2001) to survive for only \( \sim 4 \) Myr, though a large dispersion in age remains and a few survive until much later. More recent models (Inaba et al. 2003; Alibert et al. 2004; Hubickyj et al. 2004) cut the timescale to \( \sim 1 \) Myr by invoking additional physical processes such as migration or opacity modifications in the material in the forming envelope.

A critical assumption in all versions of the core accretion model is that the gaseous envelope is hydrostatic. We present a study designed to investigate whether this assumption is in fact valid, and to investigate the existence and character of the activity in the flow if it is not. Our motivation for this study is to begin an exploration of the possibility that the core accretion timescale may be further shortened by the dynamical activity without the costs associated with the other recent models. After finding that the flow is indeed quite active, we propose that one consequence of the shocks resulting from the activity is the production of chondrules and other annealed silicates in the solar nebula.
2. Initial Conditions and Physical Model

We simulate the evolution of the gas flow in a 3 dimensional (3D) Cartesian cutout region of a circumstellar disk in the neighborhood of an embedded Jovian planet core. We derive the initial conditions in a two stage process. First, we define a set of global conditions for the disk as a whole, then we extract a small volume for which we simulate the evolution.

The global conditions are similar to those described in Nelson & Benz (2003) and assume that the disk orbits a $1M_\odot$ star modeled as a point mass. The disk extends from 0.5 to 20 AU and is described by surface density and temperature power laws, each proportional to $r^{-1}$. We assume that at an orbital radius of $a_{pl} = 5.2$ AU the surface density and temperature are $\Sigma_{pl} = 500$ gm cm$^{-2}$ and $T_{pl} = 200$ K. We define the orbital velocities such that centrifugal accelerations are exactly balanced by the combined pressure and gravitational accelerations from the star and the disk. Radial and vertical velocities are set to zero. With these dimensions, the total implied disk mass of our underlying global model is $M_D \approx 0.035M_\odot$. At the core's orbit radius, the implied isothermal scale height is $H = c_s/\Omega \approx 0.40$ AU, where $c_s$ and $\Omega$ are the local sound speed and rotation frequency respectively. The disk is stable against the growth of gravitational instabilities as quantified by the well known Toomre $Q$ parameter, which takes a minimum value of $Q \approx 5$ near the outer edge of the disk. In the region near the core's orbit radius, its value is $Q > 15$.

To simplify the local initial condition, we neglect the $z$ component of stellar and global disk self gravity, but include the full contribution of the core's gravity and local disk self gravity, defined as the component of disk gravity originating from matter inside our computational volume. This simplification allows us to neglect the disk's vertical structure. Since we expect that the most interesting part of the flow will be confined to the volume in and near the core's Hill sphere, and both the grid dimensions and the disk scale height are significantly larger, neglecting the vertical stratification will have only limited impact on our results.

The origin of our coordinate grid is centered on a $10M_\oplus$ core, orbiting the star at $a_{pl} = 5.2$ AU. We use a modified 'shearing box' approximation to translate the cylindrical equations of motion into the rotating Cartesian frame. Our modification includes non-linear terms neglected in the standard form of Goldreich & Lynden-Bell (1965), allowing a closer correspondence between the global and local conditions. Our modification allows the shear in the $x$ direction, corresponding to the radial coordinate, first, to include a non-zero offset of the corotation radius from the core’s position and, second, does not need to vary linearly with $x$, as occurs when pressure contributes to the disk’s rotation curve.

We extract the local initial condition from the global condition by mapping the radial and azimuth coordinates of the two dimensional global initial condition directly onto the $x$ and $y$ coordinates of the local Cartesian grid, centered on the core, using the mapping: $x = r - a_{pl}$ and $y = r\phi$. Quantities in the $z$ direction are obtained by duplicating the midplane quantities at each altitude. The $x$ and $z$ velocities are defined to be zero. We obtain the $y$ velocity by subtracting off the orbital motion of the core from the azimuth velocity at each radius and mapping the remainder into our Cartesian grid at the appropriate $x$ position.

Although we avoid complications associated with modeling the disk's vertical structure because we neglect the $z$ component of stellar and disk gravity,
we still require a correspondence between the globally defined disk surface density and the locally defined volume density used in the actual calculations. To make the connection, we use the conversion \( \rho = \Sigma / H \), where \( \rho \) and \( \Sigma \) refer to the volume and surface densities respectively, and the isothermal scale height \( H = c_s / \Omega \). This conversion introduces a small physical inconsistency, since of course our physical model omits the physics responsible for producing vertical structure in the first place. The inconsistency means that the volume density will contain a small systematic error in its value, however since the exact value of the volume density in the Jovian planet environment is not well known, we believe this inconsistency will not be important for the results of our simulations.

We use an ideal gas equation of state with \( \gamma = 1.42 \) and include heating due to compression and shocks, but no radiative heating or cooling. This value of \( \gamma \) is chosen to be representative of values found in the background, solar composition circumstellar disk, for which temperatures imply that the rotational modes of hydrogen will be active. We expect the gas to be optically thick in the region of interest, so that thermal energy will remain with the fluid rather than being radiated away. The core is modeled as a point mass, onto which no gas may accrete. The conditions at the boundaries are fixed to the values of the global initial condition, resulting in a steady flow into and out of the grid that mimics the near-Keplerian flow of the underlying circumstellar disk.

On a global scale, the disk will respond only weakly to the influence of a 10\( M_\oplus \) core and will never form a deep gap (D’Angelo et al. 2002; Nelson & Benz 2003), so a time varying boundary condition is not required. A more serious concern is whether the flow within the simulation volume becomes sufficiently perturbed away from that inside the boundaries, to cause an unphysical back reaction to develop. We have monitored the flow for signs of such effects and have found that for the simulation presented here, perturbations have become well enough mixed with the background flow so that quantities near the boundaries are not altered substantially from their initial values. We believe effects from numerical perturbations of this sort will have minimal impact on the results. We caution that we have not found the same statement to be true throughout our parameter space, e.g., at very low background temperatures.

We use a hydrodynamic code (Ruffert 1992) based on the PPM algorithm (Colella & Woodward 1984), which has been adapted to use a set of nested grids to evolve the flow at very high spatial resolution. Both smooth and shocked flows are modeled with high accuracy because PPM solves a Riemann problem at each zone interface to produce the fluxes at each timestep. Shocks and shock heating are therefore included as an integral part of the method. No additional artificial viscous heating is required or included. Each successive grid is overlaid on top of the central portion of its parent grid, but with one half of its linear dimensions. Each grid in the nest contains an identical number of zones, so that the effective linear spatial resolution is doubled in the overlay region. In the model presented here, we use a nest of six grids. The simulation volume extends 4 Hill radii \( (R_H = a_{pl}(M_{pl}/3M_\oplus)^{1/3} \), corresponding to about 1.1\( H \)\) in each direction, defining a volume of \( (0.897 \text{ AU})^3 \). Regions both above and below the disk midplane are included in the simulation volume. The finest grid covers \( \pm 1/8R_H \) in each direction with a spacing of \( \sim 6.5 \times 10^9 \) cm per zone, corresponding to about 1.3 times the diameter of Neptune.
3. Results of our simulations

We have performed a large set of simulations covering a range of both initial conditions and physical models and a paper describing each of these studies is in preparation. For our purposes, it is sufficient to summarize the results by examining one model in detail, whose initial conditions were described in the last section, and which was run for a total of 100 yr of simulation time. We consider it to be the most realistic model of those we studied in the sense that it includes the most complete inventory of physical processes.

In Figures 1 and 2, we show 2D slices of the gas density and temperature, taken through the disk midplane at a time 74 yr after the beginning of the simulation. In both Figures, the structures are highly inhomogeneous and become progressively more so closer to the core. Densities both above and below that of the background flow develop due to shocks that produce hot ‘bubbles’, which then expand into the background flow. One such bubble is particularly visible in the plots of the temperature distribution, emerging to the lower right. Such structures are common over the entire the duration of the simulation and emerge in all directions, depending on details of the flow at each time. Activity persists for the entire simulation, and for as long as we have simulated the evolution without significant decay or growth. Lower resolution models that were run for much longer (~1600 yr) also display continuing activity. However, since we neglect cooling, we cannot expect the flow to become much less active over time.

In conflict with the expectation from orbital mechanics that the flow of material approaching the Hill volume will turn around on a ‘horseshoe’ orbit, matter approaching the outer portion of the Hill volume is relatively unaffected, often passing completely through its outer extent with only a small deflection. In contrast with this quiet flow further away, material is very strongly perturbed on the scale of the accretion radius, where large amplitude space and time varying activity develops. This too conflicts with the orbital mechanics picture, in which matter inside the Hill volume simply orbits the core. Material can enter the Hill volume from the background flow and shocked, high entropy material can escape and rejoin the background flow. Changes in the flow pattern occur on timescales ranging from hours to years, with a typical encounter time inside the accretion radius of less than a month.

4. The new scenario for chondrule formation

As readers of this proceedings volume will be aware, the theory of chondrule formation suffers from no lack of data, but rather from insufficient understanding of what physical processes are present in the solar nebula, where they are present and whether they produce conditions appropriate for chondrule formation. Briefly summarized from Jones et al. (2000), we note for our purposes that chondrules underwent both a very rapid heating event to ∼2000 K, followed quickly by a rapid cooling event of magnitude 50-1000 K/hr. Among a veritable zoo of models purporting to produce such conditions, passage of solid material through nebular shocks is currently favored as among the most likely (see e.g., Desch et al., in these proceedings). Among its drawbacks are, first, that shocks that have the right density, temperature and velocity characteristics are hard to form and, second, that it is difficult to arrange for these shocks to
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Figure 1. The volume density in a 2D slice taken through the disk mid-plane for the full simulation volume (top), and a blowup of the region within ±1/2\(R_H\) of the core (bottom). Velocity vectors are shown projected onto the plane on the coarsest grid in the top panel, and on the fourth nested grid in the bottom panel. The white circles define the radius of the accretion sphere \(R_A = GM_{pl}/c_s^2\) (small circle) and the Hill radius (large circle). The grey scale is logarithmic and extends from \(~10^{-10}\) to \(~10^{-8}\) gm cm\(^{-3}\).
Figure 2. As in Figure 1, but showing temperature. The color scales are logarithmic and extend from 180 to 6500 K. Temperatures as high as 3-5000 K are common very close to the core, with temperatures decreasing rapidly to the background \( \sim 200 \) K value at increasing distance.
exist for a long enough time to produce enough bodies to match the current observations.

The parameter space for which chondrule production may occur in shocks (Desch & Connolly 2002, Table 5) is bounded by preshock densities within a factor of a few of $10^{-9}$ gm cm$^{-3}$, temperatures near 300 K and shock speeds near 6–7 km s$^{-1}$, and that enhancements in the particle density were important for formation models. Concurrent work of Ciesla & Hood (2002); Iida et al. (2001) come to similar conclusions. Figures 1 and 2 show that appropriate background conditions exist in our simulations, and we propose that dynamical activity in the Jovian envelope could provide a source for both shocks and reversible compressive heating that remedy the shortcomings noted above.

Although the basic temperature and density conditions can be seen in the Figures, ascertaining whether short duration heating and cooling events are also present requires additional analysis. We considered and discarded the option of including test particles that could be passively advected with the local flow, because of the significant added computational and storage cost they would require. Instead, we rely on the similar but not identical solution of ‘advecting’ test particles through a snapshot of the conditions at a specific time.

To that end, we have performed a streamline analysis of the trajectories of an ensemble of test particles injected into the simulation restart dump for the same time as that shown for Figures 1 and 2. Particles are placed at a set of locations at the edge of the grid and allowed to advect through the simulation volume using the local fluid velocity, linearly interpolated between the grid zones adjacent to the particle at each time. It is given a timestep based on that used to advance the gas at that location, so that it advances forwards through a fictitious time coordinate, passing through the volume at the rate of matter in the local flow. Similar linear interpolations of density and internal energy are used to derive the temperature from the equation of state.

In Figure 3, we show temperatures and densities for three test particles for which a passage through the environment of the core has occurred. The particles shown were chosen to illustrate the range of peak temperatures and densities that may be encountered by slightly different trajectories through the envelope. Each encountered a short duration heating and cooling event as they passed through the dynamically active region close to the core, but the magnitudes and duration varied in each case. In the top example (test particle 1), the peak temperature rose to well over 3000 K and the density to nearly $10^{-8}$ gm cm$^{-3}$ as the particle’s trajectory passed through the innermost regions of the envelope. The conditions encountered by the particle 2 were much more moderate, with peak temperature and density values of $\sim$ 1800 K and $4 \times 10^{-9}$ gm cm$^{-3}$ respectively. Particle 3’s trajectory took it only through the outer portion of the envelope, so that it encountered only much lower temperatures and densities, although in this case for a much longer period of time than either of the other two cases shown. All three particles encountered several days of cooler processing near 500-800 K, and a visual scan of many other similar events shows that such additional annealing is not uncommon.

The temperature peaks for test particles 1 and 2 offer widths of $\leq 1$ day, with both a very rapid rise and fall. Close examination of their trajectories reveal that the widths reflect essentially the crossing time for a single grid zone.
Figure 3. The temperature (left panels) and density (right panels) encountered by three test particles as they are advected through a snapshot of the simulation volume, each as functions of a fictitious time coordinate. The zero point for time has been arbitrarily shifted in each case so that the peak temperature occurs at $\sim 10$ days.
in the simulation. Therefore, although already quite narrow, we believe that they are actually overestimates of the true widths that would be obtained from the models as realized at still higher resolution. The dynamical activity in the envelope, coupled with the temporally very narrow temperature/density peaks, especially in cases similar to that of particle 2, offer evidence that chondrule production could occur in the environment of Jovian planet formation.

5. Concluding comments, questions and skeptical remarks

The scenario we present offers a number of attractive advantages over other models for shock formation in the solar nebula. First, it naturally provides a mechanism for producing very short duration heating and cooling events with thermodynamic characteristics similar to those expected to produce chondrules. Unlike models using global gravitational instabilities in the circumstellar disk, it does not require a massive disk for the activity to exist, and in particular, for a massive disk to continue to exist for the long period of time required to produce chondrules in large quantities. Production in this scenario will endure for a significant fraction of the formation timescale for Jovian planets (itself a significant fraction of the disk lifetime), resulting both in a large yield of objects and allowing both processing and reprocessing events to occur. Also, because there were a number of similar proto-Jovian objects in the solar system, processing will occur in many locations. If correct, our results mean that the standard core accretion model for Jovian planet formation will require significant revision, and will imply both link between the timescales for chondrule formation and planet formation, and that chondrules represent a physically examinable link to the processes present during the formation of Jovian planets.

There are still many unanswered questions contained in this scenario, however. Before any detailed analysis of the conditions will be of real use for either the theory of chondrule formation or planet formation, we must perform simulations that include both radiative transport and a non-ideal equation of state for the gas. Without them, the densities and temperatures obtained in our simulations will contain significant deviations compared to the real systems they are intended to model. Moreover, including them means the dynamical properties of the system will change, perhaps eliminating the shocks altogether. Preliminary indications with locally isothermal and locally isentropic equations of state suggest that at least some activity will remain, so we remain hopeful.

We have simulated only a 100 yr segment of the Jovian planet formation history, during a time when the envelope did not contain much mass. We cannot be certain that the activity will remain when the envelope becomes more massive.

If we find that shocks are produced in more physically inclusive models, it will be interesting to perform a significantly more detailed analysis of the conditions in those shocks, including their velocities relative to the fluid flow. Will such analysis show that the shocks fit into the required density/temperature/velocity parameter space? One concern already apparent is that the flow velocities of material flowing through the shocks (1-2 km s$^{-1}$, as estimated from the directly available fluid flow velocities themselves) are uncomfortably low compared to those quoted by Desch & Connolly (2002) and Iida et al. (2001). It seems unlikely that the velocities will be increased as dramatically as that by any of the improvements to the models we might make.
Although the results from our streamline analysis are promising, they are no substitute for an investigation of the trajectories of specific packets of material through system. A detailed study of this issue will be important on several levels. First, it is not clear that a particle’s thermodynamic trajectory will be the same when it is advected through an actual time dependent flow, as opposed to the fictitious advection through a fixed flow that we have performed. It will also be important to understand what fraction of material that approaches the core actually encounters conditions appropriate for chondrule formation during its passage, in comparison to material that instead encounters regions that are inappropriate. From a slightly broader perspective, the same question becomes what fraction of the total budget of solid material in the solar nebula undergoes such processing? Secondly, after ejection from the envelope, it will be important to understand how the processed materials get from where they form (near 5 AU) to their final locations, in meteorites throughout the inner solar system.

Finally, in our discussion we have focused solely on the conditions required for the production of chondrules. On the other hand, they are not the only meteoritic material that has undergone heating and cooling events. Harker & Desch (2002) discuss one such class of material, composed of annealed silicates found in comets, for which the required temperatures and densities are much lower. Will our scenario be able to produce material of this sort as well?

In future work, we plan to implement successively more advanced models to simulate the Jovian planet formation process. One important aspect of this project will be to address questions important for the formation of chondrules and other annealed silicates in much more detail than our current models allow.

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