Chondrules and Nebular Shocks

E. I. Chiang

Center for Integrative Planetary Sciences
Astronomy Department
University of California at Berkeley
Berkeley, CA 94720, USA
echiang@astron.berkeley.edu

ABSTRACT

Beneath the fusion-encrusted surfaces of the most primitive stony meteorites lies not homogeneous rock, but a profusion of millimeter-sized igneous spheres. These chondrules, and their centimeter-sized counterparts, the calcium-aluminum-rich inclusions, comprise more than half of the volume fraction of chondritic meteorites. They are the oldest creations of the solar system. Their chemical composition matches that of the solar photosphere in all but the most volatile of elements, reflecting their condensation from the same pristine gas that formed the sun. In this invited editorial, we review the nebular shock wave model of Desch & Connolly (Meteoritics and Planetary Science 2002, 37, 183) that seeks to explain their origin. While the model succeeds in reproducing the unique petrological signatures of chondrules, the origin of the required shock waves in protoplanetary disks remain a mystery. Outstanding questions are summarized, with attention paid briefly to competing models.

Subject headings: meteors, meteoroids

Beneath the fusion-encrusted surfaces of the most primitive stony meteorites lies not homogeneous rock, but a profusion of millimeter-sized igneous spheres [see Hewins (1996) and other articles in the excellent compendium edited by Hewins, Jones, & Scott]. These chondrules, and their centimeter-sized counterparts, the CAIs (calcium-aluminum-rich inclusions), comprise more than half of the volume fraction of chondritic meteorites. They are the oldest creations of the solar system; the oft-quoted age of the solar system of 4.566 ± 0.002 billion years refers to the crystallization ages of CAIs as determined from radioactive isotope dating. Their chemical composition matches that of the solar photosphere in all but the most volatile of elements, reflecting their condensation from the same pristine gas that formed the sun. Their petrology is consistent with their being heated to super-liquidus temperatures for a period of a few minutes; their roundness suggests that the heating occurred while chondrule precursors were suspended in space, so that surface tension pulled their shapes into spheres. In the two hundred years since the discovery of chondrules, this heating event has shrouded itself in secrecy. Identifying the mechanism would be
prize enough in itself; but the stakes are potentially even greater for those who suspect that the primitive character of chondrules and their substantial volume-filling fraction implicate them in the equally mysterious process of planet formation; that micron-sized dust grains could agglomerate to kilometer-sized planetesimals only by first taking the form of millimeter-sized, molten marbles; that the chondrule heating mechanism and the means of planetesimal assembly are part and parcel of the same physical process.

Numerous theories have been proposed for the formation of chondrules. Many are staged within the primordial solar nebula, the circumsolar disk of gas and dust from which the planets congealed. None of these proposals has gained general acceptance. The proposals (see the summary by Boss 1996) range from nebular lightning (but how can we hope to understand electrical discharges in the solar nebula when we fail to understand them on Earth?), to collisions between molten planetesimals, to irradiation by particle flares in the vicinity of a magnetically active early sun (Shu et al. 2000). Rarely are the predictions of any given theory so detailed as to warrant comparison with the wealth of experimental data available on chondrites. The article by Desch and Connolly constitutes one of these welcome exceptions. The potent combination of theoretical astrophysicist and experimental petrologist consider the hypothesis that chondrules were heated by shock waves propagating through the nebula. Without devoting much attention to the question of the origin of these shocks, they ask whether a nebular shock wave could \textit{in principle} generate thermal histories for chondrules that are consistent with the mineralogical and textural evidence (see also Hood & Horanyi 1993; Connolly & Love 1998). The answer is enthusiastically affirmative. Solving the equations of conservation of mass, momentum, and energy, they compute the detailed temperature and density profile of a one-dimensional, plane-parallel, steady shock. They conclude that shock waves propagating at velocities of $v_s \sim 7 \text{ km/s}$ through gas having initially undisturbed temperatures of $T_1 \approx 300 \text{ K}$, densities $\rho_1 \approx 10^{-9} \text{ g/cm}^3$, and chondrule concentrations of $10^{-8} - 10^{-6}$ precursor particles/cm$^3$ (where a chondrule precursor is a ferromagnesian sphere of radius 0.3 mm and density 3 g/cm$^3$) can reproduce empirically determined thermal histories for chondrules. These initial environmental parameters are chosen to resemble those of standard models of protoplanetary disks at a heliocentric distance of 2.5 AU [see, e.g., the minimum-mass solar nebula, obtained by augmenting the masses of the planets to solar composition and spreading that material in radius (Weidenschilling 1977).] On its approach to the shock front, the precursor is heated to temperatures of $\sim 1500 \text{ K}$ (just below the liquidus) for $\sim 1$ hour by absorbing radiation emitted by yet hotter chondrules and nebular dust that are further downstream past the front. Immediately after crossing the front, the precursor encounters a supersonic headwind of gas and is frictionally heated to temperatures of $\sim 1800 \text{ K}$ for a few minutes. Subsequent cooling is slowed by the fact that chondrules remain in thermal contact with hot shocked gas. The time to cool through solidus is given by the time the chondrule takes to travel several optical depths away from the intensely luminous shock front; this cooling timescale is several hours for the parameters above, in accord with experiment. Increasing the precursor concentration enhances the degree of pre-shock radiative heating and thereby increases the peak temperatures that chondrules attain. Since greater chondrule concentrations imply greater rates of collisions among them, and since higher peak temperatures give
rise to radial or barred textures as opposed to porphyritic textures in chondrules synthesized in the lab, the model predicts the incidence of compound chondrules (two or more chondrules bound together by a collision in which one or more of the bodies was still plastic) to be higher among radial/barred chondrules than among porphyritic ones. This correlation is, in fact, observed in nature.

Can shocks explain naturally the fact that chondrules have nearly uniform sizes of $\sim 1$ millimeter? Desch and Connolly defer this question to future work but we may guess that the answer is positive here as well. The maximum size of a chondrule would be set by the same physics that sets the size of a raindrop (P. Goldreich 1997). By balancing the cohesive force of surface tension against the destructive force of turbulent gas drag, we estimate a maximum chondrule radius of $\sim 4\gamma/\rho_2 v_s^2 \sim 4$ mm, where $\rho_2 \approx 10^{-8}$ g/cm$^3$ is the density just past the shock front and $\gamma \approx 500$ dyne/cm is the surface tension of molten rock. Molten droplets greater than this size would bifurcate as they plow supersonically through shocked gas. The minimum size would be set by evaporation in the post-shock flow; particles of radius $\lesssim 0.1$ mm sublimate away if kept at temperatures of $\sim 1700$ K for a few hours.

Nebular shocks may even provide a means of agglomerating chondrules after heating them. At post-shock distances greater than those considered by Desch and Connolly, we expect chondrules and gas to cool back down to their initial temperatures of $\sim 300$ K. The jump conditions for a one-dimensional, plane-parallel isothermal shock yield a final post-shock gas density $\rho_3$ that is greater than $\rho_1$ by a factor of order $mv_s^2/kT_1 \sim 10^2$, where $m$ is the mass of a hydrogen molecule and $k$ is Boltzmann’s constant. For standard parameters, $\rho_3 \sim 10^{-7}$ g/cm$^3$—great enough in the context of standard nebular models at heliocentric distances of 2.5 AU that matter may clump together under its own self-gravity.

There is, however, an entire other dimension to the experimental data that the mechanism of nebular shocks does not address: the presence of once-active, short-lived radionuclides such as $^{26}$Al in CAIs (Lee et al. 1976). The long-standing hypothesis that these radionuclides were produced in supernovae that externally seeded the solar nebula has been called into question by the discovery of $^{10}$Be in CAIs (McKeegan et al. 2000), since $^{10}$Be is not a stellar nucleosynthetic product. The recent competing theory of Shu et al. (2000) and Gounelle et al. (2001) that chondrules were irradiated by particle flares in the vicinity of an active early Sun offers a framework for understanding the origin of radioactive nuclides in CAIs, including $^{10}$Be. It is not clear, however, that the latter theory can account for the extensive petrographic data on which Desch and Connolly focus.

Finally, what is the origin of nebular shocks? Desch and Connolly espouse self-gravitating clumps of matter (the potential building blocks of proto-Jupiter) that orbit at $\sim 5$ AU and that gravitationally drive density structures within the chondrule forming region at $\sim 2.5$ AU. This and other proposals are not sufficiently developed to predict the number of times a given chondrule passes through shock fronts. Empirically, the number of times a chondrule is heated must be between 1 and $\sim 3$, based on observations of chondrule rims (Rubin & Krot 1996; Hewins 1996).
The proposal for the origin of shock waves by Desch and Connolly may run aground on this point—if the massive bodies at \( \sim 5 \) AU are present for the lifetime of the nebula, \( T \sim 10^6 \) yr, then shock fronts will have processed material along the entire circumference of the asteroid belt \( T/T_{con} \sim 3 \times 10^4 \) times, where \( T_{con} \sim 30 \) yr is the time between conjunctions of a body at 5 AU and a body at 2.5 AU. While Desch and Connolly provide useful, state-of-the-art computations of the thermal histories of particles traversing shock fronts, until a convincing source of shock waves is identified, the problem of chondrule formation will remain unsolved at the zeroth order level.

REFERENCES

Boss, A.P. (1996) A concise guide to chondrule formation models. In *Chondrules and the Protoplanetary Disk* (eds. R.H. Hewins, R.H. Jones, & E.R.D. Scott), pp. 257–263. Cambridge Univ. Press, Cambridge.

Connolly, H.C., Jr., & Love, S.G. (1998) The formation of chondrules: Petrologic tests of the shock wave model. *Science* **280**, 62–67.

Goldreich, P. (1997) personal communication.

Gounelle, M., et al. (2001) Extinct radioactivities and protosolar cosmic rays: self-shielding and light elements. *Astrophys. J.* **548**, 1051–1070.

Hewins, R.H. (1996) Chondrules and the protoplanetary disk: An overview. In *Chondrules and the Protoplanetary Disk* (eds. R.H. Hewins, R.H. Jones, & E.R.D. Scott), pp. 3–9. Cambridge Univ. Press, Cambridge.

Hood, L.L., & Horanyi, M. (1993) The nebula shock wave model for chondrule formation—onedimensional calculations. *Icarus* **106**, 179–189.

Lee, T., Papanastassiou, D.A., & Wasserburg, G.J. (1976) Demonstration of Mg-26 excess in Allende and evidence for Al-26. *Geophys. Res. Lett.* **3**, 41–44.

McKeegan, K.D., Chaussidon, M., & Robert, F. (2000) Evidence for the in situ decay of 10Be in an Allende CAI and implications for short-lived radioactivity in the early solar system. *31st Annual Lunar and Planetary Science Conference* **31**, abstract no. 1999.

Rubin, A.E., & Krot, A.N. (1996) Multiple heating of chondrules. In *Chondrules and the Protoplanetary Disk* (eds. R.H. Hewins, R.H. Jones, & E.R.D. Scott), pp. 173–180. Cambridge Univ. Press, Cambridge.

Shu, F.H., et al. (2000) The origin of chondrules and refractory inclusions in chondritic meteorites. *Astrophys. J.* **548**, 1029–1050.

Weidenschilling, S.J. (1977) The distribution of mass in the planetary system and solar nebula. *Astrophysics and Space Science* **51**, 153–158.

This preprint was prepared with the AAS \LaTeX{} macros v5.0.