FORMATION OF CHONDRULES BY SHOCK WAVES. M. A. Morris[1,2] and A. C. Boley[3], [1]SUNY Cortland, P.O. Box 2000, Cortland, NY 13045-0900, melissa.morris@cortland.edu, [2]School of Earth and Space Exploration, Arizona State University, P.O. Box 871404, Tempe, AZ 85287-1404, melissa.a.morris@asu.edu, [3]University of British Columbia, 6224 Agricultural Road, Vancouver, BC V6T 1Z1, acboley@phas.ubc.ca.

Introduction: Understanding the "chondrule-formation mechanism" has been an elusive task for over a century [1]. Proposed formation mechanisms include lightning, interactions with the young sun, planetesimal impacts, and nebular shocks [2-5]. Among these, the heating of chondrule precursors in nebular shocks is one of the most fully developed and rigorous models for chondrule formation and is the most consistent with the meteoritic record [6], although some questions certainly remain.

Shock mechanisms: There are several possible mechanisms for driving shocks in the solar nebula, including gravitational disk instabilities, X-ray flares or accretion shocks, and bow shocks around planetesimals or protoplanets on eccentric orbits [7-10]. X-ray flares and accretion shocks have largely been eliminated as a possibile driver for chondrule-forming shocks, because these would take place at the surface of the disk, whereas chondrule precursors are expected to have settled to the midplane.

Gravitational Instabilities (GIs). Spiral asymmetries arising from disk instabilities can spontaneously form in massive protoplanetary disks when the magnitude of the disk's self-gravity is comparable to or greater than the vertical gravity (measured at the disk scale height) due to the central star [11]. These types of instabilities almost certainly occurred in the early solar nebula [12], driving strong shocks where high-density gas in the asymmetries collided with lower density gas. Such structure has recently been observed by ALMA in the disk around the young star Elias 2-27 [13].

Bow Shocks. Planetesimals/protoplanets on eccentric orbits while gas is present in the disk will induce bow shocks. At 2.5 AU, within the presumed chondrule-forming region, gas orbits the Sun at the Keplerian velocity of $v_K \sim 20$ km/s. A planetary body with eccentricity e will have phases of speeds relative to the gas of $\sim e\, v_K$. Planetesimals in resonance with a proto-Jupiter will have had eccentricities as high as $e \sim 0.3$-0.5 [9], driving strong bow shocks (~ 8 km/s).

Both GI-driven shocks and bow shocks have been shown to be consistent with the inferred range of thermal histories of porphyritic chondrules, with cooling rates at the low and high end respectively [5-6, 14].

Meteoritic Constraints: We discuss the wealth of meteoritic observations that constrain chondrule formation in general, and compare these to the results found through modeling of chondrule formation in nebular shocks. We discuss in particular the inferred thermal histories of chondrules [15] and their retention of volatiles [16], including recent studies that question the long-accepted thermal histories [17-18].

Discussion: We assess current shock models for chondrule formation and discuss what further work is needed. Models of large scale shocks, such as those driven by GIs, are most consistent with the cooling rates of chondrules, but have yet to be modeled with the high densities of solids thought to be necessary for volatile retention, and have not accounted for vertical energy losses. Bow shocks occur in an environment conducive to volatile retention, but cooling rates are at the very upper end of (or above) the range of the inferred thermal histories of chondrules. Finally, as both GI-driven shocks and bow shocks could have occurred in the solar nebula, we discuss predictions made by shock models and challenge the meteoritical community to examine available samples to test these predictions.

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