CHONDRULE FORMATION BY CLUMPY ACCRETION ONTO THE SOLAR NEBULA. A. P. Boss & J. A. Graham, DTM, Carnegie Institution of Washington, 5241 Broad Branch Road N.W., Washington DC 20015.

Chondrule textures and compositions appear to require rapid heating of precursor grain aggregates to temperatures in the range 1500 K to 2100 K, cooling times on the order of hours, and episodic and variable intensity events in order to produce chondrule rims and chemically distinct groups. Nebula shock waves have been proposed by Hood and Horanyi as a physical mechanism that may be capable of meeting the meteoritical constraints. Motivated by astronomical observations of the close environments of young stars, we suggest that the source of the nebula shock waves may be clumpy accretion onto the solar nebula – that is, episodic impacts onto the nebula by discrete cloud clumps with masses of at least 10^{22} g. If the cloud clumps are massive enough ($\sim 10^{26}$ g), the resulting shock wave may be able to propagate to the midplane and process precursor aggregates residing in a dust sub-disk.

INTRODUCTION. Laboratory analyses of meteoritical chondrules provide constraints on physical conditions in the solar nebula at the time of their formation. The spheroidal shape of most chondrules implies a molten phase [1], while their granular and porphyritic textures require cooling rates of $\sim$ 1000 K per hour [2]. Maximum temperatures were probably in the range 1500 K to 2100 K, depending on whether or not unmelted dust grains impacted the molten grains [3] and on the initial heating rate [4]. The initial heating must have taken place in less than an hour because chondrule compositions are not in equilibrium with nebular gas at these temperatures [1]. These physical conditions seem to require a localized heating event, and given the widespread occurrence of chondrules in primitive meteorites [5], and high temperature rims on many chondrules [6], chondrule formation must have been episodic. Compositional differences [7] imply that the formation mechanism was able to produce a range of end-products, perhaps indicative of variable intensity processing. A number of imaginative ideas have been advanced for chondrule formation [1,5,8]. Shock waves within the nebula [9] appear to be capable in principle of matching these constraints, provided an episodic source of shock waves is identified. Here we point out that astronomical observations of young stars suggest that clumps of gas and dust may impact the nebula at high enough velocities to cause shock wave processing in at least the outer layers of the solar nebula [10].

OBSERVATIONS OF YOUNG STARS. Three types of observations suggest the presence of clumps of optically thick matter in the close environments of young stars. (A) Irregular variations occur in the brightness of young stars over short (days) time periods [11] without accompanying spectral changes [12,13]. (B) Changes in the illumination of extended reflection nebulae are apparently caused by shadowing of the central star [14,15]. (C) Night-to-night changes in spectral features are attributed to accretion of low density circumstellar matter [16]. All of these observations are consistent with the presence of opaque clouds of gas and dust with speeds up to 250 km/sec. Estimates of the masses of the obscuring clouds are $> 10^{22}$ g [15,17]. While the origin of such clumps is unclear and their lifetimes are likely to be short (years), they may result from the interaction of outflowing stellar winds with infalling or disk gas.

CLUMP-NEBULA IMPACTS. If clumps of gas and dust are moving at high velocity and high inclinations in the vicinity of young stars, they will eventually impact the disk, leading to localized heating and possibly driving shock waves into the nebula (Figure 1). Using conservation of the vertical component of the momentum and assuming that the shock front propagates like a cylindrical snowplow through the underlying nebula, the surface density of processed disk matter σ_d is related to the clump surface density σ_c by $\sigma_d = \sigma_c(v_c/v_z - 1)$, where v_z is the vertical shock velocity and $v_c \sim 50$ km/sec is the clump impact velocity. Detailed calculations of dust grain shock heating [9] show that shock speeds of at least $v_z \sim 5$ km/sec are required to thermally process chondrule precursor aggregates.

Assuming that clump-disk impacts occur repetitively and that each impact processes a fresh batch of aggregates, the total fraction of the nebula dust aggregates which can be thermally processed F_p is

$$F_p \approx 0.8\left[\frac{t_i}{10^6 yr}\right]\left[\frac{f_i}{52 yr^{-1}}\right]\left[\frac{M_c}{10^{22} g}\right]\left[\frac{10^3 gcm^{-2}}{\sigma_n}\right],$$

where t_i is the duration of the impact phase, f_i is the impact frequency, M_c is the clump mass, and σ_n is the nebula surface density. Clump masses of order 10^{26} g may be necessary however in order for the shock waves to propagate all the way to the midplane of a minimum mass nebula.

CONCLUSIONS. Given the existence of clumpy disk accretion, the resulting nebular shock waves appear to be capable of thermally processing a significant fraction of nebula dust aggregates. However, processing will only occur close to the nebula surface unless the impacting clumps are considerably more massive ($\sim 10^{26}$ g) than the present observational lower bound of ($\sim 10^{22}$ g). Further observational evidence for clumpy disk accretion is necessary to learn if this scenario is reasonable.

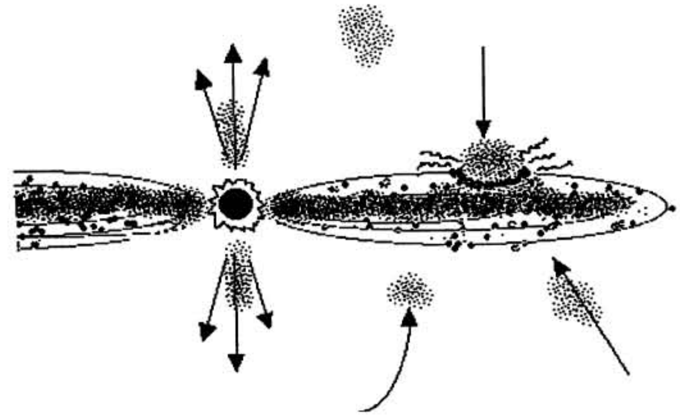

Figure 1. Schematic diagram (not to scale) of the clumpy disk accretion scenario for chondrule formation. Opaque clumps of gas and dust moving at high velocity close to young stars (possibly with bipolar outflows) may strike the disk, dissipating kinetic energy and driving shock waves which thermally process precursor dust aggregates in the disk.

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