FORMATION OF NEBULAR SHOCK WAVES AND RESULTING THERMAL HISTORIES OF CHONDRULE PRECURSOR GRAINS;

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Previous work has indicated that gas dynamic shock waves occurring within the protoplanetary nebula could represent a plausible source of transient heating events needed to explain the existence of meteoritic chondrules (1,2). Quantitative tests of this proposed mechanism are possible for specific shock wave generation models. In this paper, we explore the consequences of shock wave generation in the nebula due to inhomogeneous disk accretion from the surrounding molecular cloud core. In particular, astrophysical evidence suggests that multiple infalling molecular cloud core clumps may have produced shocks that could have thermally processed a large fraction of dust grains in the nebula (3). Alternatively, larger-scale inhomogeneities could have produced time-dependent and axially asymmetric structures in the evolving disk as suggested by the FU Orionis phenomenon (4). Here, numerical calculations of a representative shock wave in the nebula are combined with calculations of the thermal histories of precursor dust grains exposed to such a shock wave. Results allow direct comparisons with meteoritic evidence relating to the heating and cooling rates of chondrules.

A basic state nebula is adopted with midplane number density $n(r,0) = 5 \times 10^{13}$ (1 a.u./r)^2 cm^{-3} and z-independent temperature distribution $T(r,z) = 400(1\text{a.u.}/r)^{\frac{1}{2}}$ K. The nebula is in hydrostatic equilibrium in the z direction and, for simplicity, rotates at the Keplerian speed. For a disk radius of 100 a.u., the disk mass is 0.054 M_{sun}. The midplane mass density at 2.5 a.u. is 3.2×10^{-11} gm cm^{-3} and the column mass density at this radial distance is $\sim$ 150 gm cm^{-2}. In order to generate a representative shock wave in the basic state nebula, we consider the impact onto the nebula of a "standard" molecular cloud clump as defined in ref. 3. The clump has a mass density of $\sim 3 \times 10^{-15}$ gm cm^{-3}, a radius of $\sim$ 0.06 a.u., and impacts vertically onto the disk at r = 2.5 a.u. with a speed of 50 km s^{-1}. The resulting hydrodynamic disturbance is calculated using a two-dimensional piecewise parabolic method that is especially accurate for shocks (5). Beginning the calculation when the clump is at a distance of 0.7 a.u. above the midplane, the resulting shock 30 days later is shown in the figure. The average shock velocity is 8-10 km s^{-1} (Mach $\sim$8). Further integration shows that the shock slows and penetrates no closer than $\sim$0.3 a.u. from the midplane. More massive clumps ($\sim 10^{24}$ gm) result in shocks that penetrate almost to the midplane.

We investigate gas-grain energy transfer due to passage of the representative shock shown in the figure. Post-shock radiative cooling of the shocked nebular gas (6) is included in the calculations. Cases considered include (a) a single isolated mm-sized spherical grain; (b) a cloud of mm-sized grains sufficiently dense to minimize radiative energy losses while not so dense as to damp out the shock; and (c) a bimodal size distribution consisting of both mm-sized and micron-sized grains. Results show that heating of grains is most efficient at intermediate heights above the midplane where the shock is still relatively strong but the gas density is also large enough to produce significant viscous (drag) heating of grains.

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