Three dimensional (3D) hydrodynamical models of the evolution of marginally gravitationally unstable protoplanetary disks have shown that such disks are likely to form self-gravitating clumps that could become gas giant protoplanets, even when detailed thermodynamics is included [1]. Vertical convective motions appear to be crucial for providing a means of cooling the disk midplane sufficiently for clump formation [2]. Clump survival to form gas giant planets seems possible, provided that the clumps are sufficiently well-resolved [3]. However, calculations where artificial viscosity is employed generally have not found robust clump formation in either fully 3D [4] or thin disk models [5]. The lack of clump formation in the latter models [5] may be due to the prohibition against vertical convection in thin disk models. Here we show that when artificial viscosity is included in 3D disk models with radiative and convective cooling, the tendency to form clumps is reduced somewhat, but not eliminated, unless the artificial viscosity is increased by a factor of ten. This result suggests that disk instability remains as a possible means for forming the giant planets of our Solar System [7].

Artificial viscosity can be used to help stabilize numerical schemes and to provide microphysical heating within shocks. We use a tensor artificial viscosity [8], which enters into the giant planets of our Solar System [7].

\[
\varepsilon_r^\phi = \frac{\partial v_r}{\partial r} + \frac{v_r}{r} + \frac{v_\phi}{\partial \phi} = \frac{1}{r \sin \theta} \frac{\partial v_\phi}{\partial \phi} + \frac{1}{r} \frac{\partial v_\phi}{\partial r} + \frac{v_\phi \cot \theta}{r}.
\]

The models presented here have the standard resolution [1,2] of 100 radial grid points distributed uniformly between 4 AU and 20 AU, 256 azimuthal grid points, 22 theta grid points in a hemisphere (effectively over a million grid points), and include terms up to l, m = 32 in the spherical harmonic solution for the gravitational potential. The models begin after 322 years of inviscid evolution of a disk with an initial mass of 0.091 \(M_\odot\) [1,2], an outer disk temperature of 40 K, and a minimum Toomre Q = 1.3.

The four figures show the results for four 3D models which are identical except for their treatment of artificial viscosity. It can be seen that in the models with the standard artificial viscosity (Fig. 2: \(C_{\Delta r} = 1\), \(C_{\phi} = 0\), \(C_r = 10^{-7}\); Fig. 3: same as Fig. 2 but \(C_{\phi} = 1\)), clump formation occurs in a similar manner as in the model without artificial viscosity (Fig. 1, as in [1,2]). However, when the artificial viscosity is increased by a factor of 10 (Fig. 4), clump formation is significantly inhibited because of the heating associated with the assumed dissipation. These models support the suggestion that microphysical shock heating can be important for clump formation [4], though with the standard amount of artificial viscosity, the effects are relatively minor in these models.

Fig. 1. Equatorial density contours after 366 yrs for the standard model with no artificial viscosity. Hatched regions denote densities above $10^{-10}$ g cm$^{-3}$. Contours denote changes by factors of 2. Disk radius is 20 AU.

Fig. 2. Equatorial density contours after 364 yrs for model identical to Fig. 1 but with the standard amount of artificial viscosity in $r$, $\theta$, and $\phi$. Clumps still form.

Fig. 3. Equatorial density contours after 362 yrs for model identical to Fig. 1 but with the standard amount of artificial viscosity in $r$, $\theta$, and $\phi$. Clumps still form.

Fig. 4. Equatorial density contours after 366 yrs for model identical to Fig. 1 but with 10 times the standard artificial viscosity in $r$ and $\theta$ only. Clump formation is noticeably suppressed.