Outward mixing of hot grains. Dependance of crystallinity compositions on disk parameters

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Here we present a follow-up to our study of the outward mixing of hot grains in evolving protoplanetary disks presented in Hughes & Armitage [1]. For both studies, we have simulated the radial transport of an ensemble of particles in a 1D evolving protoplanetary-disk model under the influences of gas drag and turbulent diffusion at the disk midplane.

In [1] we found that the degree of outward mixing was strongly dependent on both the initial compactness of the disk, and the (presently unknown) scaling between the disk viscosity and diffusivity. The most transport of inner disk grains to the outer disk is seen for the initially most compact disks and the most diffusive simulations. We found a cutoff grain size for outward mixing, with grains larger than a few millimeters unable to reach Kuiper-belt distances where Jupiter-family comets like 81P/Wild 2 (found by the *Stardust* mission to have large fractions of crystalline silicate material [2]) are thought to have formed. The vertical structure of radial gas flows in protoplanetary disks is not well constrained, and we presented upper-limits to the outward transport of grains using the case of outward-flowing gas at the disk midplane [3]. This case produces orders of magnitude more outward mixing than the results using the 1D accretion-flow fo the disk gas for the radial component of the gas drag. However, the trends with the other parameters agree between both cases.

Here we present further results for the dependence of the outward mixing of inner-disk grains on model-disk parameters. As shown in Figure 1, we confirm the results of [4] that the greatest outward mixing occurs for particles formed near the beginning of the disk lifetime.

Among other parameters, we investigate the mixing dependence on the scaling of α for the model disk viscosity, and on the initial mass of the model disk, M_{D0}. As shown in Figures 2 & 3, we find little dependence on the outward mixing of grains on these parameters. This is somewhat surprising in the case of the α parameter, which is directly proportional to the disk viscosity and therefore the diffusivity of the particle ensemble. It demonstrates the importance of considering disk evolution simultaneously with particle transport in studies of evolving disk composition. In the case of the initial-disk-mass parameter, that the outward mixing shows little dependence on M_{D0} is in good agreement with surveys of disks around other stars that find no dependence of the disk crystallinity on the masses of the disks observed [5].

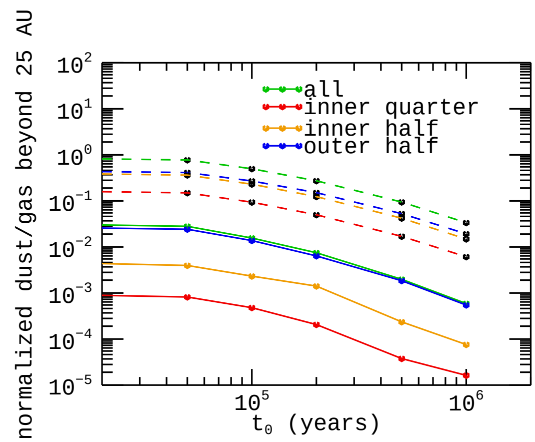

Figure 1: Plot of the maximum contamination concentration in the outer disk (beyond 25 AU) as a function of initiation time, t_0, for 20μm grains from 4 source regions: the inner-quarter region (0.5–2.5 AU), inner-half region (0.5–5 AU), outer-half region (5–10 AU), and all (0.5–10 AU). Dashed lines with black markers plot the extreme upper-limits achieved using the case of outward-flowing gas at the disk midplane, while solid curves plot the results using the 1D accretion-flow of the gas. $M_{D0} = 0.03M_\odot$, $R_d = 20$AU, $\alpha = 10^{-2}$.

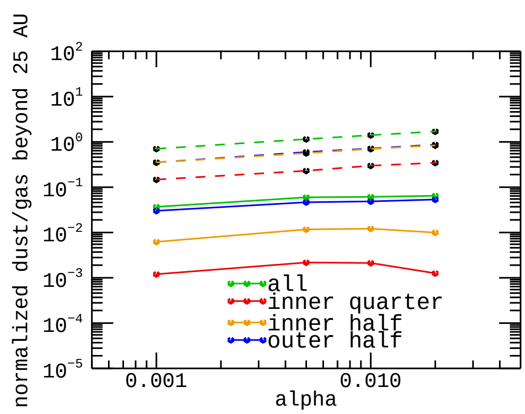

Figure 2: Plot of maximum outer-disk contamination varying the α parameter of the disk viscosity. Disks have an initial mass of 0.03 $M_\odot$ and an initial-compactness parameter of 20 AU. Plot for 20μm grains.

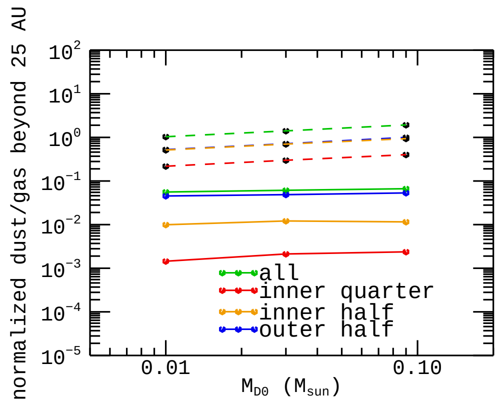

Figure 3: Plot of maximum outer-disk contamination varying the initial mass of the model disk. Disks have an initial-compactness parameter of 20 AU and evolve following an alpha viscosity with $\alpha = 10^{-2}$. Plot for 20μm grains.

References: [1] Hughes, A.L.H., & Armitage, P.J., ApJ 719, 1633-1653 (2010); [2] Brownlee D. et al., Science 314, 1711-1716 (2006); [3] Takeuchi T., Lin D.N.C., ApJ. 581, 1344-1355 (2002); [4] Ciesla, F.J., & Yang, L., 41^{st} LPSC, abstract no. 1081; [5] Watson, D.M. et al., ApJS 180, 84-101