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Meteoritic and planetary data constrain models of disk evolution, support magnetorotational instability models with non-uniform alpha

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The magnetorotational instability (MRI) is predicted to occur in the more ionizaed regions of protoplanetary disks (PPDs), but it is recognized that the MRI cannot act in magnetically "dead", less ionized zones (Jin et al. 1996; Gammie 1996; Sano et al. 2002, etc.). As the actions of Ohmic dissipation, ambipolar diffusion and Hall effects have become better understood, doubts have been raised about the ability of the MRI to drive angular momentum transport in PPDs. Attention is turning to disk winds and non-turbulent mechanisms. In this abstract I argue that models of disk transport must consider two pieces of information from meteoritics and planetary science: the efficient outward transport of refractory materials from the inner solar system, confirmed by the Stardust mission; and the structure of the Minimum Mass Solar Nebula as revised by Desch (2007). These constraints support models of a PPD in which the MRI is active in its outer regions but must be frustrated by a large dead zone in the inner regions.

Models of PPD evolution are always better constrained by data from meteoritics and planetary science than by astronomical observations. After decades of ambiguous modeling efforts, the discovery of refractory inclusions like Inti in the Stardust sample at once confirmed that materials were efficiently transported from a few AU to the comet-forming region. The masses and location of the planets is still our best guide to the structure of the protoplanetary disk. Using the new starting positions of the planets from the Nice model (Gomes et al. 2005), Desch (2007) showed that the outer solar system (5-30 AU) surface density had to vary as r-2.2. A disk with such a steep surface density profile must be marked by net outward transport. But models of disks with uniform "alpha"viscosity (Shakura & Sunyaev 1973) typically predict disks with shallower profiles like r-1 (Hartmann et al. 1998). What is the cause of this steep profile? Desch (2007) invoked external photoevaporation of the disk, but Mitchell & Stewart (2010) showed that while this effect steepens the profile to r-1.85, it alone is not the cause of an r-2.2 profile.

We have constructed disk evolution models including external photoevaporation by nearby massive stars, but also including non-uniform alpha. For the external photoevaporation we follow Adams et al. (2004) and assume G0=300, an ultraviolet flux like those seen by disks forming in massive clusters. We compute the ionization chemistry due to X-ray ionization from the central star (with Lxr=10^30 erg/s), simple grains-free chemistry, and then use the computed ion fraction to calculate a viscosity using the formulation of Bai & Stone (2011, 2013), assuming saturation of the magnetohydrodynamic turbulence so that $\alpha = 1/2\beta$. The disk surface density is evolved using the standard formulas of Lynden-Bell & Pringle (1974). We find that throughout most of the evolution a dead zone exists inside a few AU, but the average alpha is still somewhat high, α ~ 10-3. In the active layers > a few AU, α ~ 10-2 or more. Because alpha is high in the outer layers, they evolve rapidly, transporting mass from the region < a few AU to the outer photoevaporated disk edge at ~ 50 AU. Consistent with this outward transport, the surface density profile $\Sigma(r)$ in the relevant 5-30 AU region is steep, with slope between r-2 and r-3 throughout the evolution. Without non-uniform alpha we would have reproduced the slope of Mitchell & Stewart (2010), r-1.85. We conclude that non-uniform alpha is required to reproduce the structure of our disk inferred by Desch (2007), and to explain the efficient outward transport of inner solar system materials.

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