Coupling protoplanetary disk thermodynamics and geometry: toward a more self-consistent structure.

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The latest observations of the Taurus [1] and Ophiuchus [2, 3] young stars provided details about the large scale morphology of protoplanetary disks: surface mass densities, temperatures, heights, accretion rates. Among the recurring characteristics, surface mass density profiles are observed shallower than the usual Minimum Mass Solar Nebula standard model [4], while flaring angles of 0.03 to 0.23 constrain the photosphere height of the disks. The accretion rates are also recurrently found around 10^{-8} $M_\odot$ yr^{-1} providing constraints on the age of the disks.

In order to understand the large-scale evolution of protoplanetary disks, it is important to build an accurate model of the disk viscous evolution under both viscous and radiative heating. Indeed, the dynamical evolution is highly dependent on the viscosity which requires to know the temperature. While previous works often assume a simple fixed temperature profile or fixed photosphere geometry, we consider the coupling between these apects: the photosphere geometry controls the stellar irradiation, which influences the midplane temperature, modifying in turn the viscosity and therefore affecting both the viscous heating and spreading. We have implemented a self-consistent algorithm to determine simultaneously the geometry, temperature and viscosity all together assuming thermodynamical equilibrium, thus coupling the disk dynamical and thermodynamical evolutions. We report here the main characteristics and evolution of a standard disk corresponding to a solar type star surrounded by a Minimum Mass Solar Nebula as a fiducial test case. We show that most of the observed trends reported above are recovered provided that the disk geometry and thermodynamics are properly coupled to its dynamical evolution.

Model

We have designed a one dimension full model of viscous spreading of a protoplanetary disk following Lynden-Bell and Pringle's equation [5]:

$$\frac{\partial \Sigma}{\partial t} = \frac{3}{r}\frac{\partial}{\partial r}\left(\sqrt{r}\frac{\partial}{\partial r}\left(\nu\Sigma\sqrt{r}\right)\right) \qquad (1)$$

Our disk is heated both by turbulent viscosity and stellar irradiation, for which the geometry of the photosphere is critical since it controls the amount of energy the disk is receiving from the star. Starting from the Hueso and Guillot, 2005 [6] model of disk evolution using a fixed photosphere profile, we set this geometry free and determine it consistently with the temperature. Therefore, the temperature structure provides the viscosity that drives the dynamical evolution. The radiative transfer description is herited from Calvet et al., 1991 [7].

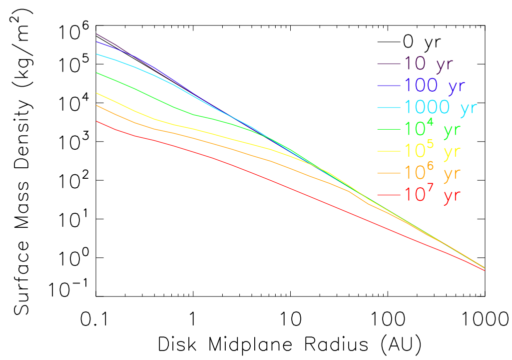

Figure 1: Evolution of the surface mass density profile over a protoplanetary disk lifetime.

Evolution of a standard disk: the Minimum Mass Solar Nebula

We first test our model in the case of an already formed Minimum Mass Solar Nebula (Weidenschilling, 1977 [4]): $\Sigma_0 \propto r^{-1.5}$. Figure 1 shows that the surface mass density profile follows a shallower profile with time: $\Sigma \propto r^{-1}$ after a few million years.

The accretion rates (Figure 2) show a rapidly evolving behavior: the disk starts spreading outward, then the inner edge begins to lose mass to the star. The frontier between inward and outward flows migrates outward until the disk is a full accretion disk after 4 Myr.

In the initial configuration, the inner part of the disk is not irradiated (viscous heating only). The entire disk becomes illuminated in less than 20,000 years. The outer regions, where the surface mass density is lower, are dominated by irradiation heating. The inner temperatures decrease strongly in the

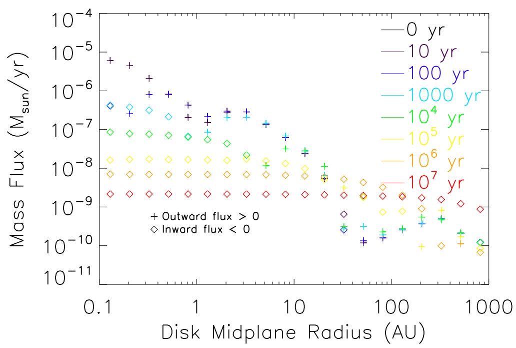

Figure 2: Evolution of the mass flux profile over 10 Million years.

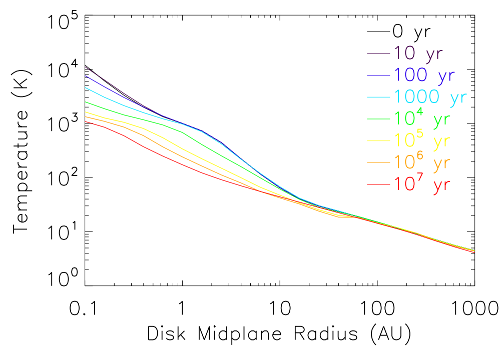

Figure 3: Evolution of the temperature profile in the midplane of protoplanetary disk.

first million years before stabilizing around 300 K at 1 AU. The sublimation zone ($T > 1500$K) is progressively restrained to the regions inside 0.1 AU while the snowline in the midplane settles around 1 AU.

Comparison with observations

We now apply our evolution code to actual observed stars in the Taurus-Auriga and Ophiuchus regions. The derived surface mass density profiles ($\Sigma \propto r^{-1}$ are consistent with the observations of Andrews et al., 2009 and 2010 [2, 3] and Isella et al., 2009 [1] who observed radial power-law index between -0.9 and -1.1: such disks could be the evolutions of MMSN-like disks. The slope of the photosphere height toward the outer edge of the disk ($H \propto r^{1.1}$) is quite close to the estimation provided by Chiang and Goldreich, 1997 [8] and the difference could be explained by the choice of non-free parameters such as the surface mass density or the temperature. The shadowing of the disk and the outward spreading are transient phenomena that quickly disappear once the temperature is stabilized. The vertical structures of the disk could be roughly estimated supposing hydrostatic equilibrium, revealing the presence of sublimation zones outside the disk midplane. We also derive mass accretion rates $\dot{M} \sim 10^{-8}$ $M_\odot$/yr, consistent with observed values.

Conclusions and Perspectives

The favorable conditions for the formation of CAIs can be met early in the stellar system history, in the inner part of the disk, when the temperature is high enough to sublimate the silicates and the mass flux still able to transport them outward. However, there appears to be a significant variation in timescales and accretion rates while the central body characteristics vary. Understanding how the disk scales with the protostar will certainly help targeting future JWST observations.

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