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Protoplanetary migration in non-isothermal disks with turbulence driven by stochastic forcing

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Abstract

Low-mass objects embedded in isothermal protoplanetary disks are known to suffer rapid inward Type I migration. In non-isothermal disks, recent work has shown that a negative entropy gradient can lead to a strong positive corotation torque which can slow down or reverse Type I migration in laminar viscous disk models. We examine the impact of turbulence on the torque experienced by a protoplanet embedded in a non-isothermal protoplanetary disk. We performed 2D numerical simulations using a grid-based hydrodynamical code in which turbulence is modelled as stochastic forcing. We find that the running time-averaged torque experienced by a protoplanet embedded in a non-isothermal turbulent disk is in good agreement with laminar disk models with appropriate values for the thermal and viscous diffusion coefficients. In disks with turbulence driven by stochastic forcing, the corotation torque therefore behaves as in laminar viscous disks and can be responsible for significantly slowing down or reversing Type I migration.

1. Introduction

Tidal interaction of a protoplanet with the disk in which it formed is known to cause a significant change of the planet semi-major axis under the process of Type I migration. The gravitational torque exerted by the disk on the planet and causing Type I migration consists of two components: the differential Lindblad torque and the corotation torque which is due to the torque exerted by the material located in the coorbital region of the planet. The corotation torque consists of a barotropic part which scales with the vortensity (i.e. the ratio between the vertical component of the vorticity and the disk surface density) gradient plus an entropy-related part which scales with the entropy gradient. A negative vortensity (resp. entropy) gradient gives rise to a positive vortensity (resp. entropy) related corotation torque. To date, it is not clear how disk turbulence probably due to the magneto-rotational instability really impacts the corotation torque. Using 2D hydrodynamical simulations in which disk turbulence is modelled through stochastic forcing, Baruteau & Lin [1] showed that in isothermal disks, the running-time averaged torque experienced by a protoplanet is in good agreement with that obtained from a laminar disk model with a similar vortensity diffusion coefficient. Here, we adopt a similar strategy but focus on non-isothermal disks in which the corotation torque has an additional contribution due to the presence of an entropy gradient across the horseshoe region.

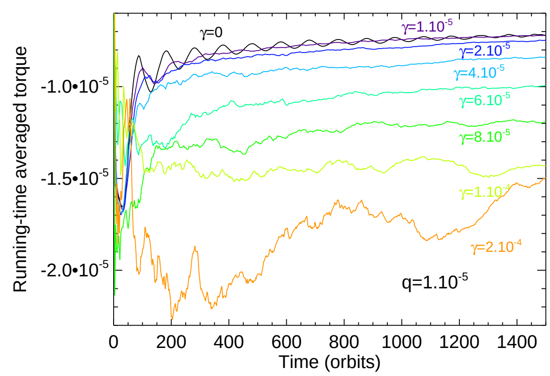

Figure 1: Time evolution of the running time-averaged torque for different values of the amplitude of turbulence γ and for $q = 10^{-5}$.

2. Numerical model and turbulence properties

We performed 2D numerical simulations using a grid-based hydrodynamical code. The disk model is such that the initial surface density, temperature and entropy

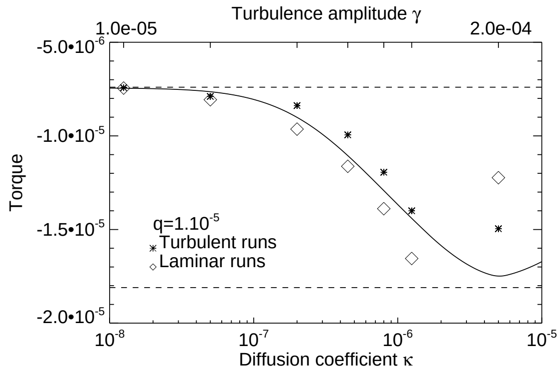

Figure 2: Running time-averaged torque (stars) in turbulent runs as a function of the turbulence amplitude γ (top axis) and as a function of the entropy diffusion coefficient κ (bottom axis). Diamonds correspond to the results of laminar runs and the solid line depicts the formulae of Paardekooper et al. [3].

profiles are $\Sigma \propto R^{-3/2}$, $T \propto R^{-0.4}$ and $S \propto R^{3/5}$. respectively. The aspect ratio at the planet position of $h_p = 0.03$. We considered planets with mass ratio $q = 5 \times 10^{-6}$ and $q = 10^{-5}$ which corresponds to planets with masses of $1.6\ M_{\oplus}$ and $3.2\ M_{\oplus}$ if the central star has a solar mass. Turbulence is modelled by applying at each time-step a turbulent potential to the disk ([1], [2]) and corresponding to the superposition of 50 wave-like modes. This turbulent potential should reproduce the main statistical properties of MHD turbulence. Turbulent density and entropy fluctuations generate transport of heat and momentum inside the disk and it appears that both the associated viscous diffusion coefficient ν and the thermal diffusion coefficient κ scale as γ^2, where γ refers to the amplitude of the turbulent forcing. This results in a turbulent Prandtl number $Pr = \nu/\kappa$ which is almost constant with γ and with a value $Pr \sim 1.2$.

3. Results

For $q = 10^{-5}$, Fig. 1 shows the time evolution of the running time-averaged torque for turbulent runs with γ in the range $10^{-5} - 2 \times 10^{-4}$. These values correspond to values for the α viscous stress parameter ranging from 3×10^{-6} to 10^{-3}. We see that the stationary value for the running time-averaged torque becomes more and more negative as γ increases. Since the barotropic part of the corotation torque cancels for our disk model, this suggests that turbulence does unsaturate the entropy-related corotation torque which is here negative due to the entropy gradient being positive. In Fig. 2 are plotted the running-time averaged torques as a function of the estimated entropy turbulent diffusion coefficient κ (bottom axis) and as a function of the γ parameter (top axis). The solid line in Fig. 2 depicts the torque formulae of Paardekooper et al. [3]. We also plot the results of laminar runs in which the values for the viscous and thermal diffusion coefficients correspond to the effective diffusion coefficients in turbulent runs. One can see that good agreement is obtained between the laminar and turbulent runs for moderate values of γ, which confirms that the entropy-related horseshoe drag takes similar values in turbulent and laminar disk models.

4. Summary and Conclusions

We have presented the results of 2D hydrodynamical simulations which study the interaction of an embedded protoplanet with a non-isothermal disk in which turbulence is driven by stochastic forcing. We showed that desaturation of the entropy-related corotation torque occurs in turbulent disks and proceeds similarly to that in laminar disk models. In the context of planetary synthesis models, this suggests that taking into account the entropy-related corotation torque may help to reduce discrepancies between these models and observational data without artificially lowering Type I migration rates. Our results however await confirmation from MHD non-isothermal turbulent simulations.

References

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