Title: Motions of protoplanets in an evolving gaseous disk

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Abstract:

Planets form from protoplanets orbiting young stars, when gaseous disk still exists. This gas gravitationally interacts with protoplanets, alongside mutual perturbations between protoplanets. This phenomenon is known as planetary migration. Our aim is to investigate the role of planetary migration, specifically, in the context of the terrestrial planets (Mercury, Venus, Earth, Mars). This has been studied previously with a stationary prescription for migration and without simulating the evolution of the disk (Brož et al. 2021). Instead, in this work we use formulae for migration torque based on actual profiles of the evolving disk. We used an N-body symplectic integrator to describe motions of protoplanets (Duncan et al. 1998). Evolution of the gas disk was modeled by 1-D hydrodynamics, considering turbulent viscosity and magnetically-driven disk wind (Suzuki et al. 2016). Migration torques were computed according to Paardekooper et al. (2011), from actual profiles of the disk. Moreover, our model included close encounters, collisions of protoplanets (merging), mutual resonances, eccentricity and inclination damping. In some simulations, we also considered the hot-trail effect (Chrenko et al. 2017), acting as eccentricity or inclination 'pumping'. Initially, we assumed a system of 28 protoplanets, with the masses in the range 0.05 to 0.1 Earth mass (i.e., a total 2 Earth masses). Simulations of a viscous disk with wind-driven mass loss were performed. For a high value of viscosity ($\alpha = 8 \cdot 10^{-5}$) and a moderate wind ($C_{\mathrm{W}} = 1 \cdot 10^{-5}$), dispersal of the disk is too rapid and migration has little influence on protoplanets. The collisional rate is also too low. For a low value of viscosity ($\alpha = 8 \cdot 10^{-6}$) and a weak wind ($C_{\mathrm{W}} = 1 \cdot 10^{-6}$), a rapid migration of protoplanets occurs, but the convergence zone is too small and high-mass planets end up close to the Sun. Eventually, an intermediate-viscosity model with strong wind shows some features of the terrestrial zone, like low-mass planets (Mercury, Mars) at the boundaries, and more massive planets (Venus, Earth) close to the centre. For this model, we computed a statistics of 25 simulations. There are two types of evolution: without late instabilities that leads to a larger number of low-mass planets, and with late instabilities, which occur after gas dispersal, leading to 4-6 planets. According to our best simulations, the hot-trail effect should excite the eccentricities of planets up to 0.07.

Keywords: protoplanetary disk, planets, migration, hydrodynamics, viscosity, disk wind