MODERN ASTRONOMY:
FROM THE EARLY UNIVERSE TO EXOPLANETS AND BLACK HOLES

Dynamics of dust grains and small bodies in accretion disks of young stars with fossil magnetic field

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Abstract. The paper discusses a numerical model that explores the dynamics of dust particles and small bodies within accretion disks that contain fossil magnetic fields. The model equations include gravitational force, centrifugal force, and drag force depending on particle size and speed. The disk structure is simulated using the magnetohydrodynamic model of Dudorov and Khaibrakhmanov, taking into account the effect of magnetic tensions on gas rotation speed. The dynamics of particles ranging in size from 10^{-4} cm to 10^{2} cm in an accretion disk of a typical T Tauri star are modeled. The simulations indicate that the dynamics of particles with a size of 1 m consists in fast sedimentation towards the midplane, followed by a slower radial drift. Sedimentation is accompanied by damped oscillations around the midplane. The slowdown of gas rotation due to magnetic tension leads to an increase in radial drift speed at the disk's periphery. Therefore, the depletion of solid particles in the outer regions of the disks and their accumulation in the "dead" zones with weak magnetic fields may occur more rapidly in disks with magnetic fields.

Keywords: ISM: magnetic fields, dust; accretion disks; magnetohydrodynamics (MHD); protoplanetary disks

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1 Introduction

The initial stages of star formation are associated with the formation of gas-dust accretion disks, which may develop into protoplanetary disks. The masses of accretion and protoplanetary disks around young stars are of 0.005–0.1 $M_\odot$, with radii varying from tens to hundreds of AU, and accretion rates between approximately $10^{-6}\,M_\odot$/yr and $10^{-8}\,M_\odot$/yr (Williams & Cieza 2011). Observations indicate that dust grains in the disks grow up to sizes of 1 mm and concentrate near the midplane of the disks.

Observational analysis suggests the existence of a large-scale magnetic field in the disks (Khaibrakhmanov 2024), which may have a notable impact on disk dynamics, particularly by decreasing the gas rotation speed in comparison to the Keplerian speed (Khaibrakhmanov & Dudorov 2022). This effect is expected to influence the radial drift speed of dust grains in disks. In the present work, we study the dynamics of solid particles in accretion disks with strong magnetic fields.

2 Model

Consider the motion of a spherical particle with velocity components $\mathbf{v} = (v_r, v_\varphi, v_z)$ and radius a_d in an accretion disk surrounding a young star with mass of $M = 1\,M_\odot$. The particle is influenced by stellar gravity, centrifugal force, and gas drag. It has the radius vector $\mathbf{r} = (r, \varphi, z)$ and angular momentum $j = rv_\varphi$. The disk is in hydrostatic equilibrium and described with velocity $\mathbf{u} = (u_r, u_\varphi, 0)$. The dynamics of the particle is described by the following systems of equations and initial conditions

$$\begin{cases} \dfrac{dr}{dt} = v_r, \\ \dfrac{dv_r}{dt} = \dfrac{j^2}{r^3} - \dfrac{1}{r^2} - \dfrac{v_r - u_r}{\tau_s}, \\ \dfrac{dj}{dt} = -\dfrac{r}{\tau_s}\left(\dfrac{j}{r} - u_\varphi\right), \\ \dfrac{dz}{dt} = v_z, \\ \dfrac{dv_z}{dt} = -\dfrac{z}{r^3} - \dfrac{v_z}{\tau_s}, \end{cases} \qquad \begin{cases} r(t=0) = r_{\text{init}}, \\ v_r(t=0) = 0, \\ j(t=0) = r_{\text{init}} v_K(r_{\text{init}}), \\ z(t=0) = z_{\text{init}}, \\ v_z(t=0) = 0, \end{cases} \tag{1}$$

where τ_s is the dimensionless stopping time, r_{init} and z_{init} are the initial radial and vertical coordinates respectively. Coordinates are expressed in units of $r_0 = 1$ AU, velocity components in units of the Keplerian velocity $v_0 = v_K(r_0) = 2.976 \times 10^6$ cm/s, time is measured in units of $t_0 = r_0/v_0$, and angular momentum is given in units of $j_0 = r_0 v_0$.

The system of eq. (1) is solved numerically using the `LSODA` method, as implemented in the SciPy library for the Python programming language.

The disk structure is calculated using the magnetohydrodynamic model (see Khaibrakhmanov & Dudorov 2022). Three runs for modelling disk structure are considered:

1) an analytical solution of the model equations (Dudorov & Khaibrakhmanov 2014), where the radial profiles of the disk properties are described as power-law functions of r, with a fixed gas velocity deviation from Keplerian $u_\varphi/v_K = 0.9987$;
2) a numerical solution of the model equations that calculates the gas rotation speed considering the contribution of the gas pressure gradient;
3) a numerical solution of the model equations that further incorporates the influence of magnetic tensions on the gas rotation velocity.

In run 2, the value of u_φ/v_K ranges from 0.9960–0.9899 depending on r, while it ranges from 0.9950–0.9798 in run 3. In the simulations of the particle dynamics, the following parameters were used: $a_d = 1\ \mu\text{m}-1$ m, $r_{\text{init}} = 1$, 10, 50, 100 AU, and $z_{\text{init}} = 3H$, where H is a local scale-height.

3 Results

The simulations indicate that the dynamics of the particle with $a_d = 1$ m involve two stages: a rapid sedimentation towards the equatorial plane, followed by damped oscillations around $z = 0$, and a subsequent slower radial drift towards the star. The sedimentation times are 2.7, 8.1, 89.5, 252 yrs for $r_{\text{init}} = 1$, 10, 50, 100 AU respectively, while the drift times are 0.097, 4.459, 84.54, 306 kyr.

In Fig. 1, we plot the radial profiles of the radial drift speed for the particle with $a_d = 1$ m and $r_{\text{init}} = 100$ AU. In run 1, the v_r increases as the particle moves from r_{init} towards the star, reaching a maximum value of $2.150 \times 10^{-3} v_0 = 6.397 \times 10^3$ cm/s at $r \approx 0.36$ AU. After that, the speed decreases down to approximately 30 m/s near the inner edge of the disk at $r \approx 0.05$ AU. A small jump in the $v_r(r)$ profile near the maximum corresponds to the transition from the Epstein drag law in the outer disk to the Stokes law in the inner disk. The radial drift time is approximately 85 kyr.

In runs 2 and 3, the drift speed also increases initially and then decreases. However, the drift occurs at a higher speed. In run 2, the velocity is greater by $6.4 \times 10^{-5} v_0 \approx 190$ cm/s in the region from r_{init} to $r \approx 0.3$ AU. In run 3, the drift speed is greater by $2.8 \times 10^{-4} v_0 \approx 833$ cm/s. The higher drift velocities observed in runs 2 and 3 can be attributed to the greater deviations of the gas speed from the Keplerian one.

4 Summary

The simulations show that the dynamics of dust grains and small bodies involve of two stages: sedimentation toward the equatorial plane followed by radial drift

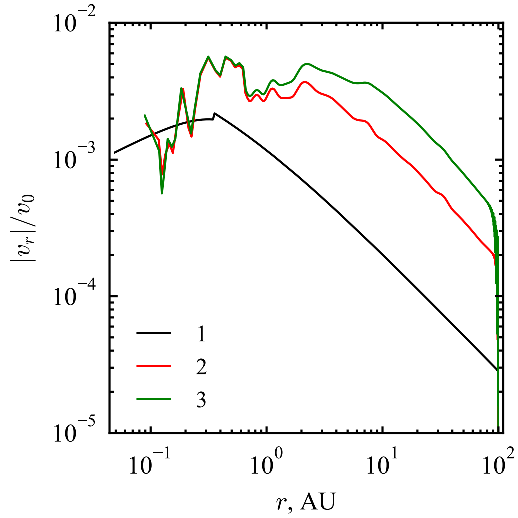

Fig. 1. Radial profiles of the radial drift velocities of particles with a radius $a_d = 1$ m in runs 1–3.

toward the star. Small particles, $a_d \lesssim 1$ cm, move steadily towards the star, while larger bodies accelerate at the disk's periphery and slow down as they near the star. The sedimentation timescales are 1–3 orders of magnitude shorter than the radial drift timescales. After sedimentation, bodies measuring 1 m or more may undergo damped oscillations around the equatorial plane, potentially leading to variations in their size distribution.

The reduction in gas rotation speed relative to the Keplerian one, attributed to magnetic tensions, leads to an increase in radial drift speed at the disk's periphery. This suggests that the depletion of solid particles in the outer regions of the disks and their accumulation in the "dead" zones with weak magnetic fields may occur more quickly in disks with a magnetic field.

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