Dusty disk winds as a variability source in structured protoplanetary disks

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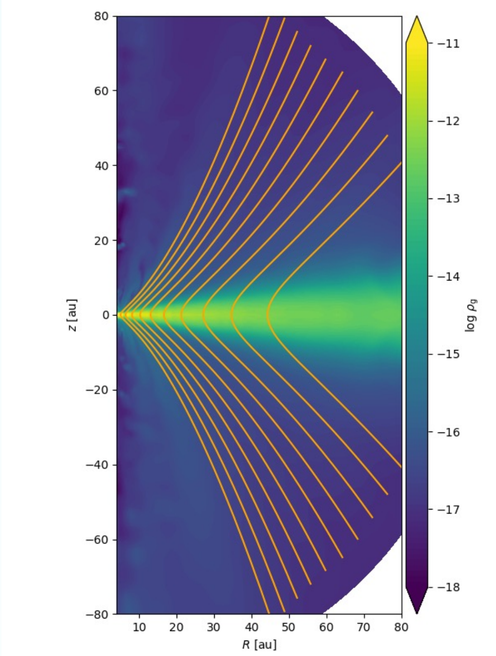
Abstract

The solid component of protoplanetary disks display varying types of radial and azimuthal substructure. In many cases, the same disks with substructures are also observed to launch wide-angle outflows or disk winds. In all protostellar systems, photometric and spectroscopic variability is an intrinsic property. We aim to describe the connection between these three phenomena—disk substructure, disk winds, and protostellar variability—by analyzing the results of 3D magnetohydrodynamic (MHD) simulations of circumstellar disks in which the processes of disk wind launching and substructure formation are inextricably linked. We first simulate the sizes of dust grains that can be entrained by a gaseous disk wind along magnetic field lines. Next, we use the resulting dust grain distributions as the input to radiative transfer simulations, from which we construct photometric light curves and near-infrared scattered light images. We find that grains with Stokes numbers less than or equal to unity in the wind region can have large enough densities in the wind to obscure the light of the central protostar over a range of wavelengths. The structured nature of the midplane dust density (seeded from the MHD simulations) results in variability due to the obscuration of the central protostar by varying amounts of dust in the high-altitude winds. For a fixed wind launching geometry, the obscuration depends on the inclination angle; a dusty disk wind observed at inclination angles between ~45 and 75 degrees could be responsible for some subset of variability in young stellar objects, e.g., dippers.

Introduction and Problem Setup

We find the vertical distributions of dust grains (sizes a = 0.1 - 100 μm) launched by MHD disk winds from protoplanetary disks with annular substructure, with the goal of describing the observational implications of a dusty disk wind.

The background dynamical gas quantities are interpolated from 3D MHD simulations (Suriano et al. 2019) onto a coordinate system along the initial magnetic lines (Zanni et al. 2007). The gas density and field line coordinates are shown in the figure to the right. A grid of 143 by 270 field lines are used with foot points in the r-ϕ plane. The innermost flux tube foot point radius is r = 5 au and the outermost is r = 50 au . The field line coordinates terminate at a maximum spherical radius of r = 90 au.

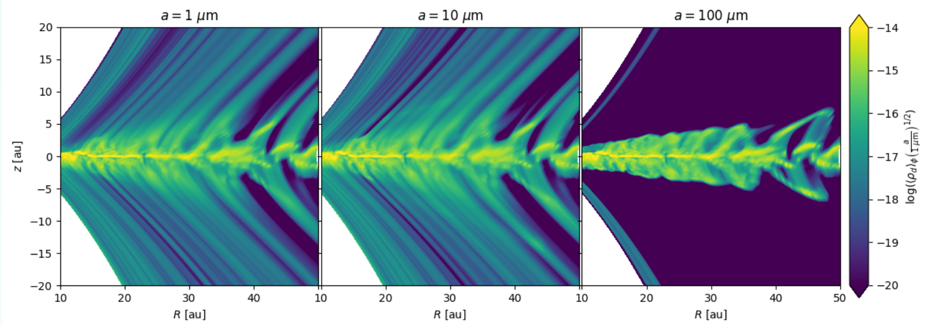


Dust Wind Results

We use the terminal velocity approach of Miyake et al. (2016) to simulate the transport of dust grains along the magnetic field line coordinates, s. The equation of motion for the dust grains is:

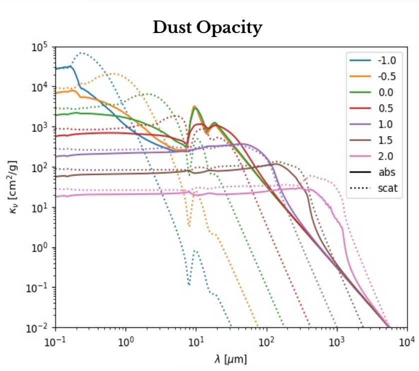
$$\frac{dv_{d,s}}{dt} = \underbrace{-\frac{\Delta v_s}{t_s}}_{\text{gas drag}} + \underbrace{\frac{J_s}{\rho_d t_s}}_{\text{turb. diffusion}} \underbrace{- \left(\frac{GM}{r^3}\right)(\vec{r}\cdot\hat{s})}_{\text{gravity}} + \underbrace{\Omega^2(\vec{R}\cdot\hat{s})}_{\text{centrifugal}}$$

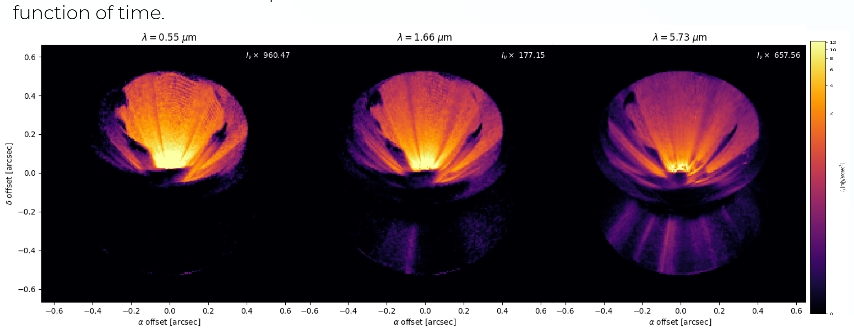
with velocity difference $\Delta v_s = v_d - v_g$, stopping time t_s , mass flux $J_s = -\rho_g \nu\, \partial_s(\rho_d/\rho_g)$, viscosity ν , and spherical and cylindrical radii r and R, respectively. The resulting ϕ-averaged dust densities are shown in the figure below for a = 1, 10, and 100 μm. Dust grains smaller than 100 μm are lifted into the MHD disk wind.

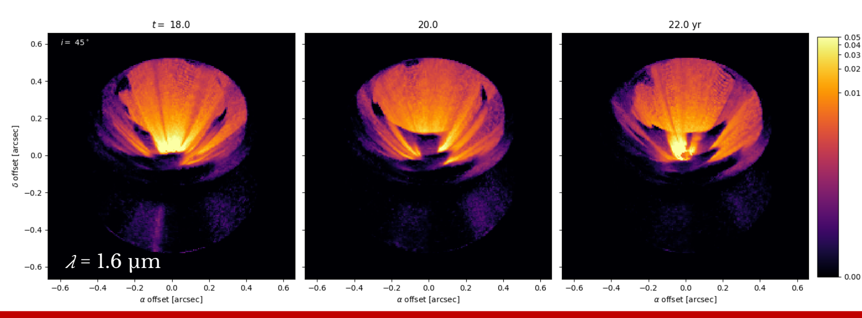


Radiative Transfer Results

We use the Monte-Carlo radiative transfer code RADMC-3D (Dullemond et al. 2012) to simulate the resulting synthetic images with a grain size distribution of $n(a) = Ca^{-3.5}$, total dust-to-gas mass ratio of 1 percent (for a total gas mass of 3 times the MMSN), and a central protostar of T_*= 4000 K. The figure on the right shows the absorption and scattering opacity for all grain sizes used in the simulations (legend is log(a)). The resulting images are shown in the figures below. The top row shows images across three wavelengths in the optical and IR, and the bottom row shows a time sequence of H-band images. All the disks are inclined at i = 45˚ . Denser regions of the dust wind (as a result of the midplane gas structure) are seen to obscure the central protostar as a function of time.



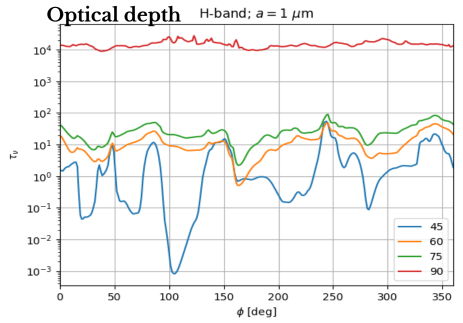




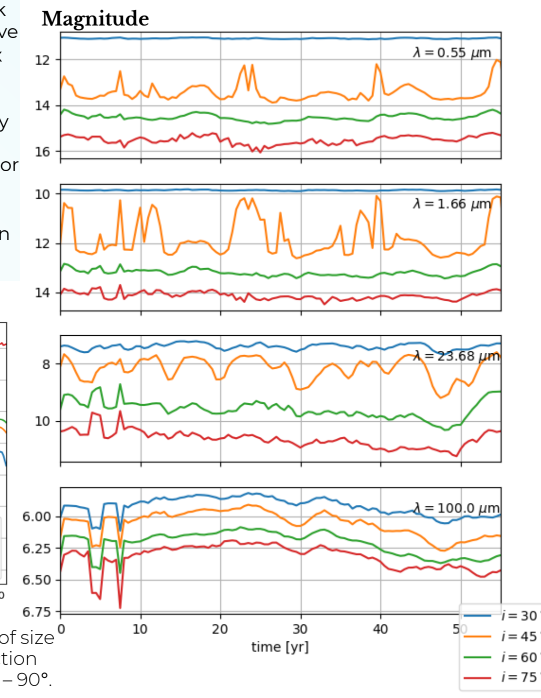
Conclusions

We simulate the dust grain transport in the MHD background wind and the RADMC-3D images over a time period of ~ 50 yr. The resulting light curves are shown in the figure on the right at four wavelengths (rows) and four inclination angles (line colors) from i = 30° to 70°. The obscuration of the central protostar is evident at intermediate inclination angles. Obscuring dust winds could be a viable candidate for photometric variability in protostellar systems.

In the H-band (second row), the dusty disk wind results in the most variable light curve when the disk is inclined 45°, with the flux varying by 2 magnitudes. Edge-on and close to face-on inclinations produce less variability, as expected. The obscuration by dusty wind depends on the wind opening angle and the viewing inclination angle. For observational wavelengths in the FIR (bottom row), variability across inclination angles is indistinguishable, as the emission is no longer from light scattered by dust grains at the wind surface.



The optical depth at λ = 1.6 μm due to grains of size a = 1 μm is show in the figure above as a function of position angle for inclination angles of 45° – 90°.



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