Draft version July 10, 2018
Typeset using LaTeX **twocolumn** style in AASTeX62

Measuring Turbulence in Protoplanetary Disks through Dust Settling

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ABSTRACT

One of the key parameters in the planet formation process is turbulence, which governs dust settling as well as the growth of dust grains into planetesimals. Unfortunately, disk turbulence cannot be directly measured, and is difficult even to estimate. However, certain inclined disks offer a unique opportunity to constrain the dust settling and turbulence using a purely geometrical argument. Here, we estimate the settling of dust by comparing the gas and dust scale heights of several disks from the ALMA Large Program P484. [**Conclusions**]

Keywords: circumstellar matter — planetary systems: formation, protoplanetary disks — dust

1. INTRODUCTION

Background: Necessity of turbulence to understanding physical processes in disks. Laundry list of processes turbulence appears in. Discussion of difficulties involved in full forward modeling. Reference to other turbulence papers, primarily Richard Teague and Kevin Flaherty's recent work.

Introduction of new methodology: Here we aim to constrain the turbulence in the disk, not by full forward modeling, but instead by geometrical argument. A first estimate of turbulence can be obtained simply by examining rings in an inclined disk. For a settled disk, the dust will be mostly in the midplane, and so the rings will appear to be roughly the same width at all azimuth. This comes from a purely geometrical argument: if the dust is settled, most lines of sight passing through the ring will exit without touching the dust, for any angle. However, if the dust is puffed up through turbulence, lines of sight on along the minor axis will be more likely to intersect the dust than those along the major axis. Thus, by simply examining the morphology of the ring, a rough measure of the dust settling can be obtained.

With gas data, one can go a step further and offer a more quantitative measurement. Simple models for the distribution of gas and dust can be fitted, and used to constrain the scale height of the gas and dust. For highly turbulent disks, these scale heights should be the same, however, for more quiescent disks, the dust scale height should be much smaller than that of the gas. The scale height ratio can be used to estimate the turbulent α parameter via [**reference: Youdin & Lithwick, 2007**].

2. OBSERVATIONS

[**probably placeholder information on the observation, taken for now from Sean:**] The observations for this project were conducted from 2017 May to November as part of ALMA program 2016.1.00484.L. All measurements used the ALMA Band 6 receivers and correlated four spectral windows (SPWs) in dual polarization mode. Three SPWs were set in time-division mode (TDM), centered at 232.6, 245.0, and 246.9 GHz, with each sampling the continuum in 128 channels spanning 1.875 GHz (31.25 MHz per channel). The remaining SPW was set in frequency-division mode (FDM), centered at the ^{12}CO $J{=}2{-}1$ rest frequency (230.538 GHz), and covering a bandwidth of 937.5 MHz in 3840 channels (488.281 kHz channel resolution, corresponding to 0.635 km s^{-1}). The plan was to observe each target briefly in the C40-5 (hereafter "compact") configuration, and also for ∼1 h in the C40-8 or C40-9 configurations.

3. MODELING

To model the dust density structure of the disk, we begin with the similarity solution determined by [**is this from Lyndon-Bell & Pringle? Check**]. The surface mass density is given by:

$$\Sigma(r) = \Sigma_c \left(\frac{r}{r_c}\right)^{-\gamma} \cdot \exp\left[\left(\frac{-r}{r_c}\right)^{2-\gamma}\right] \tag{1}$$

Where r_c is the characteristic radius, and γ the power law index. Σ_c, the surface mass density normalization is determined from the disk mass via

$$\Sigma_c = \frac{M_d(2-\gamma)}{2\pi r_c^2} \tag{2}$$

The vertical density structure is taken to be a gaussian, so the density at a given point is given by:

$$\rho(r,z) = \frac{\Sigma(r)}{\sqrt{2\pi}h(r)} \exp\left(-\frac{z^2}{2h^2(r)}\right) \tag{3}$$

where $h(r)$ is the scale height:

$$h(r) = h_0 \left(\frac{r}{r_0} \right)^{\eta} \quad (4)$$

with characteristic radius r_0, normalization h_0, and power law index η.

To include gaps, we must modify equation **[ref]**. The gaps are taken to be gaussian, each with a representative position r^i_{gap}, width σ^i_{gap}, and depth Δ^i_{gap}, where the index i refers to the number of each gap. This gives a surface mass density of:

$$\Sigma^i_{gap} = \Sigma(r) \cdot \prod_i \left[1 - \Delta^i_{gap} \cdot \exp\left(\frac{-(r - r^i_{gap})^2}{2\sigma^i_{gap}} \right) \right] \quad (5)$$

The temperature profile is obtained by taking the density above and using the radiative transfer code RADMC 3D to perform Monte Carlo radiative transfer.

The opacity for the dust is taken from **[reference]**. This assumes a dust composition of silicates, water ice, and **[other components]**, and a power law grain size distribution. The grain size distribution is cut off at some maximum grain size, which is chosen so that the power-law index of the dust matches that determined by observation of each individual disk. **[references]**. Note that this assumes that the grain size distribution is constant across the disk, which has been observed not to be true. **[reference to Perez et al, others]**

With all disk parameters determined, ray tracing is performed using code described in **[reference to my other paper]**. After ray tracing, the output is Fourier transformed, so that fitting can be done to the observed visibilities.

4. FITTING

Fitting is done by calculating a best fit to the observed visibilities using a Markov Chain Monte Carlo code. Because the errors in the fourier plane are gaussian, the likelihood is simply determined via Chi squared. The full list of parameters to be fit is in table **[ref]**.

In order to keep the number of free parameters as small as possible, several disk parameters that have little bearing on the turbulence are held constant. These include the inclination and position angle of the disk, coordinates of the center of the disk, and the radius normalization for the scale height (r_0).

5. RESULTS

Table of parameters for each disk.

Determined alpha values for each disk

6. DISCUSSION

Table 1. Host Star and Accretion Properties

Symbol	Physical Meaning	Range	Notes
(1)	(2)	(3)	(4)
M	Disk Mass	$5 \times 10^{-3} M_{\odot} - 5 \times 10^{-2} M_{\odot}$	1
P	Surface Mass Density Index	$0 - 2$	1
r_c	Radius Normalization	$50 - 150$ au	1
h_0	Scale Height Normalization	$0.5 - 5$ au	1
S	Scale Height Index	$0 - 1.25$	1
r_{97}	Ring97 Position	97 ± 3 au	1
r_{125}	Ring125 Position	125 ± 5 au	1
Δ_{97}	Ring97 Depth	$0 - 1$	1
Δ_{125}	Ring125 Depth	$0 - 1$	1
σ_{97}	Ring97 Width	$0 - 10$ au	1
σ_{125}	Ring125 Width	$0 - 10$ au	1

NOTE—Caption goes here