Evidence for a Vertical Dependence on the Pressure Structure in AS 209

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Abstract

We present an improved method to measure the rotation curves for disks with nonaxisymmetric brightness profiles initially published in Teague et al. Application of this method to the well studied AS 209 system shows substantial deviations from Keplerian rotation of up to ±5%. These deviations are most likely due to perturbations in the gas pressure profile, including a perturbation located at ≈250 au and spanning up to ≈50 au that is only detected kinematically. Modeling the required temperature and density profiles required to recover the observed rotation curve, we demonstrate that the rings observed in micrometer scattered light are coincident with the pressure maxima, and are radially offset from the rings observed in millimeter continuum emission. This suggests that if rings in the NIR are due to submicrometer grains trapped in pressure maxima, then there is a vertical dependence on the radius of the pressure minima.

Key words: circumstellar matter – ISM: kinematics and dynamics – planet–disk interactions – protoplanetary disks

1. Introduction

Long baseline observations with the Atacama Large (sub-)Millimetre Array (ALMA) have shown that substructures in the thermal continuum of protoplanetary disks are likely ubiquitous. These features are frequently interpreted in the context of gas pressure maxima into which grains are shepherded through complex gas–grain interactions (Birnstiel et al. 2012; Pinilla et al. 2012).

Identification of the main driver of these pressure maxima, such as an unseen planet or (magneto-)hydrodynamical instabilities, is hampered by the lack of a reliable tracer of the gas pressure profile. Although CO isotopologues are routinely found to exhibit structure in their emission profiles (Isella et al. 2016; Fedele et al. 2017), relating these to an accurate surface density profile requires several assumptions about the local physical and chemical conditions to be made.

Recently, Teague et al. (2018a) demonstrated a technique to measure highly precise rotation velocities in axisymmetric disks. For a geometrically thick disk with gradients in temperature and density, the rotation velocity is given by

\[
\frac{v_{rot}^2}{r} = \frac{GM_{r}r}{(r^2 + z^2)^{3/2}} + \frac{1}{\rho_{\text{gas}}} \frac{\partial P}{\partial r},
\]

where \(P = n_{\text{gas}}kT\) is the gas pressure and \(\rho_{\text{gas}}\) is the gas density. Thus, in combination with measurements of the emission surface (Pinte et al. 2018a), deviations from Keplerian rotation can be used to infer the pressure gradient. Teague et al. (2018a) used this to place tight constraints on the gas surface density profile of HD 163296 and to infer the presence of two Jupiter-mass planets.

Others have also advocated the use of kinematics to identify potential sources for changes in the pressure gradient. Pinte et al. (2018a) reported kinematic evidence of a wide separation \(\sim 2M_{\text{Jup}}\) planet at \(\approx 260\) au in HD 163296, extending far beyond the continuum edge. Similarly, Pérez et al. (2018) showed that planet–disk interactions will drive large non-Keplerian velocities, which can be used to locate potential perturbers.

In addition to searching for the signs of embedded protoplanets, constraints of the pressure gradient are invaluable for interpreting observations of the dust. The inward radial motion of particles due to the headwind from gas rotating at sub-Keplerian speeds, as the gas is supported by the radial pressure gradient, can very rapidly deplete the disk of dust. To slow this depletion, pressure bumps are frequently invoked, resulting in the trapping of particles and thus extending the lifetime of the dust disk (Pinilla et al. 2012). However, despite the necessity of such pressure traps, direct evidence of changes in gas pressure (rather than local enhancements of dust interpreted as a dust trap) are lacking.

In this paper, we present an improved method to measure the rotational velocity of a protoplanetary disk that relaxes assumptions of the azimuthal symmetry and intrinsic Gaussian line profiles, which is described in Section 2. In Section 3, we apply this method to archival ALMA data of AS 209 and present a discussion of the observed features. We summarize the findings and conclude in Section 5.

2. Measuring the Rotation Velocity

In Teague et al. (2018a), we presented a method to measure the rotation velocity of an axisymmetric disk. The method required the minimization of the width of the averaged line profile at a given radius after accounting for the projected rotation. While this method proved to be robust, it makes the assumption that the resulting averaged profile would be a single Gaussian component. We have improved upon this technique to relax this assumption by modeling the stacked spectrum as a Gaussian Process that allows a much more flexible model (Foreman-Mackey et al. 2017). In this section, we review the method and describe the updates.

We make use of the fact that protoplanetary disks are predominantly azimuthally symmetric. Line emission arising from the same radial location in the disk should therefore be tracing the same physical and chemical properties and thus possess the same profile. The only difference will be in the line center, which will be offset from the systemic velocity by \(v_{\text{rot}} \cdot \cos(\theta)\), where \(\theta\) is the polar angle measured from the
redshifted major axis. Note that this is not the polar angle measured in the sky plane but must be calculated taking into account the disk geometry (see the radial dotted lines in Figure 1).

Figure 1 shows a toy model as an example. In panel (a), the projected line-of-sight velocity is shown by the filled contours. As the disk is flared, we see both the top side and far side of the disk, and this demonstrates the need to correctly account for the emission height of the disk. The dotted lines trace lines of constant $r$ and $\theta$. Spectra extracted at the black dots, as shown in the panels (b)–(d), will be the same shape, but offset on the velocity axis (shown in black). If $v_{\text{rot}}$ is known, these spectra can be shifted back to the systemic velocity, ready to be stacked, as shown by the gray lines. This technique has been used previously to significantly boost the S/N of spectra and increase sensitivity in the outer edge of the disk (Teague et al. 2016; Yen et al. 2016; Matrà et al. 2017) and a similar method used by Yen et al. (2018) to measure dynamic stellar masses.

Rather than assuming $v_{\text{rot}}$ a priori, we can use the deprojected spectra to infer what the correct value is. In Teague et al. (2018a), we used the line width of the stacked spectrum as a proxy. If the lines are deprojected using an incorrect value, the line centers will still have some offset leading to a broadening of the final line profile. Thus, the $v_{\text{rot}}$ value that minimizes the final line width is the correct value as this is when all the spectra are correctly aligned. However, this assumes that the final profile is Gaussian, which is often not the case. For example, optically thick lines, such as $^{12}$CO and potentially $^{13}$CO, will have line profiles that deviate significantly from a Gaussian due to the saturation of the line core.

Here we argue that a more flexible approach is to model the stacked spectrum as a Gaussian Process (essentially a probabilistic approach to modeling smooth, nonparametric functions) and find the value of $v_{\text{rot}}$, which minimizes the variance in the residuals. A similar approach has been used by Czekala et al. (2017) to model the spectra of binaries.

An example of this approach is shown in Figure 2 where the left column shows the situation where an incorrect $v_{\text{rot}}$ value has been assumed for the deprojection and thus there is significant scatter in the residual around the line wings, as shown in panel (b). Conversely, when the correct $v_{\text{rot}}$ has been used, as shown in the right column, the scatter in residuals is near constant across the profile. This allows for the case of highly non-Gaussian profiles or if there is significant differences in line brightness as a function of azimuth.

Figure 2 also demonstrates why a precision well below the velocity resolution can be achieved. As the line profile is sampled at different locations due to shifts from the rotation, the deprojected spectra result in a sampling of the intrinsic line profile at a factor of ~10 higher. The gray bars in the residual plots show the width of a single channel and demonstrate that the profile is sampled at a much higher frequency after the shift. Although some broadening may be present due to the Hanning smoothing applied in the correlator, the resulting $v_{\text{rot}}$ will be insensitive to this as the optimization does not care about the properties of the stacked line profile other than that it is smooth.

In practice, this is performed using the Python package celerite (Foreman-Mackey et al. 2017). This approach has the added advantage that a more robust uncertainty can be derived for $v_{\text{rot}}$. As celerite naturally considers correlations between pixels, any spatial correlations arising from the imaging (such as those described in Flaherty et al. 2018) will be accounted for in the uncertainty. Furthermore, this approach more readily allows for the inclusion of priors for $v_{\text{rot}}$ or a more specific model for the noise (for example, the correlated noise described in Teague et al. 2018b).

We have tested this method with various levels of noise, velocity resolutions, azimuthal asymmetries in both line width
and peak and non-Gaussian lines profile. A thorough
examination of the accuracy and precision achieved is
presented in the Appendix, including the impact of azimuthal
structure in the line profiles or when the near and far sides of
the disk are spatially resolved. In brief, however, the accuracy
achieved by this method when there is no strong azimuthal
structure can be estimated by

\[ 44.4 \pm 0.1 \text{ m s}^{-1} \times \left( \frac{2\pi r}{\theta_{\text{beam}}} \cdot \frac{S/N}{10} \right)^{-1.12 \pm 0.01}, \]  

where \( S/N \) is the signal-to-noise ratio achieved in a single pixel
at radius \( r \) and \( \theta_{\text{beam}} \) is the beam FWHM. Azimuthal deviations
in the line width and peak do not significantly hinder this
approach unless they are greater than \( \approx 50\% \) in magnitude.

Examples of the code used for this and Jupyter Notebooks
containing guides on how to use them can be found at https://
github.com/richtague/eddy. Version 1.0 of the code used for
this paper can be obtained from https://doi.org/10.5281/
zenodo.1440051.

3. The Rotation Curve of AS 209

To demonstrate this method, we use archival data of AS 209
(2015.1.00486.S, PI Fedele, D.). Continuum observations from
this project have been previously presented in Fedele et al.
(2018), which have suggested that multiple gaps in the
continuum can be driven by a single planet. Here we focus
only on \(^{12}\text{CO} \) emission, leaving a thorough analysis of the three
CO isotopologues and DCO\(^+\) to be presented in a future work
(T. Favre et al. 2018, in preparation).

3.1. Observations

Data reduction followed the same process as that outlined in
Fedele et al. (2018). The data were calibrated using the
provided scripts in casa v4.4 before moving to casa v5.2
for the imaging and self-calibration. Phase gain tables were
calculated on the continuum window, then applied to the three
spectral line windows containing \(^{12}\text{CO} \) emission.

We consider two cases, both with and without the continuum
subtracted from the line data. The continuum is removed using
the task \texttt{uvcontsub}, which linearly interpolates the the
continuum from line-free channels in the \( uv \)-plane. As
discussed in Boehler et al. (2017), this can lead to an
underestimation of the true total intensity of the line as the
molecular gas will absorb some of the continuum. While this
will affect the inferred temperature or column density, which
require absolute flux measures, our method is insensitive to
such effects. As the effect is essentially independent of
frequency, at least across the line profile, see for example
Figure 8 in Boehler et al. (2017), then the change in the line
profile will be symmetric about the line center and thus not
change our derivation of velocity.

Imaging the continuum emission, we used uniform weight-
ing resulting in a beam size of \( 0''15 \times 0''13 \) at a position angle
of \( 2^\circ.6 \). An rms noise of \( \sigma = 65 \mu\text{Jy beam}^{-1} \) was measured
in continuum free regions of the continuum map and an integrated
intensity of 251 mJy was measured, consistent with previous
observations (Öberg et al. 2011; Huang et al. 2016).

We perform a different approach for the \(^{12}\text{CO} \) emission.
Using the \texttt{tclean} task, we first image the emission with
natural weighting, to maximize sensitivity, and with a square
\( 3'' \times 3'' \) box as the mask. From this image, we generate a first
moment map clipping values below \( 2\sigma \), where \( \sigma \) was measured
in a line-free channel. To this first moment map, we fit a
Keplerian profile to derive a position angle, \( v_{\text{LSR}} \), and \( M_{\text{star}} \),
holding the inclination constant at \( i = 35^\circ.3 \) (Fedele et al. 2018)
in order to break the \( M \cdot \sin i \) degeneracy. These values were
then used to generate a Keplerian mask (masking out regions
where, given the derived rotation pattern, we would not expect
emission to arise) for the data that was convolved with the
beam and checked to encompass the whole emission. The data

Figure 2. Demonstration of the quality of fit method used. Each point represented a channel in a spectrum given some velocity shift. The blue lines are the Gaussian Process (GP) model of these data and the gray solid line shows the true intrinsic line profile. The bottom row shows the residual between the individual points and the GP model. If an incorrect \( v_{rot} \) is used to deproject the data (left column) significant variance is seen in the residuals. Conversely, when the correct \( v_{rot} \) is used (right column), the variances in the residuals is minimized. The shading in the residual plots shows the channel width, demonstrating that after the deprojection of all the spectra, we sample the intrinsic line profile at a much higher rate than the observations, allowing us to achieve a much higher precision on \( v_{rot} \) than the native channel width.
were then imaged and CLEANed again using this Keplerian mask.

For precise measurements of \( \nu_{\text{sys}} \), sensitivity is more important than spatial resolution. Therefore, we use natural weighting for the imaging yielding beam sizes of \( 0''23 \times 0''19 \) at a position angle of \(-79.3^\circ\). The data were imaged at a velocity resolution of \( \approx 160 \text{ m s}^{-1} \) (\( \approx 244 \text{ kHz} \)). The rms noise in a line-free channel was 3.3 mJy beam\(^{-1}\) and we measure an integrated flux of 7.99 Jy km s\(^{-1}\), consistent with previous measurements (Huang et al. 2016).

Figure 3 summarizes the observations, showing the velocity integrated fluxes (using a 2\( \sigma \) clip and the CLEAN mask), and their radial profiles. Significant absorption is seen in the west half of the \(^{12}\)CO emission, likely due to cloud contamination at \( v_{\text{LSR}} \lesssim 5 \text{ km s}^{-1} \) (Oberg et al. 2011; Huang et al. 2016). Assuming that for \( v_{\text{LSR}} \gtrsim 5 \text{ km s}^{-1} \) the emission is free from absorption, ratios of the intensity profiles suggest that the cloud absorbs \( \approx 30\% \) of the \(^{12}\)CO emission on the western side of the disk.

There are no clear deviations from a Keplerian pattern observed in the channel maps indicative of large-scale kinematic features (Perez et al. 2015; Pinte et al. 2018b); however, the cloud contamination and limited sensitivity may limit the visibility of such features.

### 3.2. Measuring Rotation Curves

In order to use the method presented in Section 2, an initial estimate of the rotation profile and the emission height, in order to properly deproject the data into annuli of constant radii are required.

For an initial estimate of the expected rotation profile, we fit a Keplerian pattern, including a conical emission surface (Rosenfeld et al. 2013) using the MCMC ensemble sampler emcee (Foreman-Mackey et al. 2013). We calculate a map of the line-of-sight velocities using the method presented in Teague & Foreman-Mackey (2018), which fits a parabola to the pixel of peak intensity and its two neighboring pixels. This method allows us to discriminate between emission arising from the near side of the disk and the far side, while achieving a subchannel precision measurement of the line centroid. In addition, the cloud absorption will less strongly bias the measurement of the maximum coordinate. The emission surface is calculated as \( z = r \cdot \tan \psi \), where \( \psi \) is the angle between the disk midplane and the emission surface.\(^4\) In addition, with each call of the likelihood function the rotation pattern was convolved with a 2D Gaussian, matching the synthesized beam for each observation to account for convolution effects in the inner regions of the disk (Walsh et al. 2017).

The best-fit rotation pattern, assuming a fixed inclination \( i = 35.3^\circ \), was described with \( M_\star = 1.16 \pm 0.01 M_{\odot} \), \( PA = 86.7^\circ \pm 0.1^\circ \), \( v_{\text{LSR}} = 4670 \pm 5 \text{ m s}^{-1} \), and \( \psi = 13.1^\circ \pm 0.3^\circ \). The uncertainties are the standard deviation of the posterior distribution. The inferred stellar mass is slightly larger than the previously found \( M_{\star} = 0.9 M_{\odot} \) (Andrews et al. 2009), likely due to better resolution of the emission in high velocity channels that contain the most information to distinguish between stellar masses. The position angle and systemic velocity are consistent with previous determinations (Andrews et al. 2009; Huang et al. 2016).

Using the method presented in Pinte et al. (2018a) to measure the emission height, we find good agreement with a conical model with \( \psi \approx 13^\circ \), consistent with the determination from the ninth moment map fitting. As the emission surface determination relies on the asymmetry across the major axis of the disk, cloud absorption will not impact this result as this only results in an asymmetry across the minor side of the disk. Offsets in the ellipse centers were found in the northern direction, meaning that the southern side of the disk is more consistent with the preferred orientation proposed by Avenhaus et al. (2018) who showed that features in the near-infrared (NIR) scattered light better align with continuum features when the southern side, rather than the northern side, is closer. This orientation is also consistent with that found from the fitting of the ninth moment map.

Following the method in Teague et al. (2018a) and with the modification described in Section 2, we measure an azimuthally

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\(^4\) We have also tried a more complex surface of \( z = z_0 \times r^{\psi} \); however, the spatial resolution of the data meant that the fits were unable to converge.
averaged rotation profile. We consider three cases: first, we deproject the sky-plane coordinates into disk coordinates to correctly account for the flaring; second, we consider a geometrically thin disk; and, finally, we consider the flared disk with no continuum subtraction. For each case, we then bin the data into annuli with a width of a quarter of the beam ($\approx 0.05$ as) and derive a $v_{\text{rot}}$ value. We further model the radial profile as a Gaussian Process, requiring the profile to be smoothly varying and to account for the correlations due to the sub-beam size sampling.

These rotation profiles are shown in Figure 4(a), with $1\sigma$ uncertainties. The dotted line is a fit of a geometrically thin Keplerian rotation profile assuming $i = 35.7$ and resulting in $M_{\text{star}} = 1.25 M_{\odot}$. This profile is used as the reference profile for the derived values; however, we stress that this should not be taken as the true stellar mass because we are unable to disentangle large-scale effects of the pressure gradient from the stellar mass. The middle and bottom panels show the residual in m s$^{-1}$ and as a percentage, respectively. Gray and black lines show the locations of rings observed in the millimeter continuum and NIR scattered light, respectively.

All three scenarios yield comparable radial $v_{\text{rot}}$ profiles that are consistent within $3\sigma$ of one another. This suggests that continuum subtraction does not significantly affect the derived rotation profile.

When plotting residuals from a Keplerian profile, as in panels (b) and (c), large negative gradients are indicative of a pressure maximum, while large positive gradients are indicative of pressure minima (for example, see Figure 1 of Teague et al. 2018a). We see that the two inner rings for both millimeter and NIR emission are centered on pressure maxima, as predicted from grain evolution models (Birnstiel et al. 2012; Pinilla et al. 2012). The outer ring in scattered light, however, appears at the outer edge of a large pressure minimum centered at $\approx 250$ au. This will be discussed in the following section.

4. A Perturbed Physical Structure

As the deviations from a smooth rotation curve can be driven by changes in local temperature, density, and the height of the emission, it is hard to isolate the main driver. In this section, we use a toy model that we perturb in order to reproduce the observed deviations in rotation velocities and to infer the underlying pressure profile.

4.1. The Toy Model

The model is based on the commonly used prescription using a simple physical structure (Rosenfeld et al. 2013; Williams & Best 2014), with specific values taken from Huang et al. (2016). The
total gas surface density is given by Lynden-Bell & Pringle (1974),
\[ \Sigma_{\text{gas}}(r) = \Sigma_0 \left( \frac{r}{r_0} \right)^\gamma \exp \left( - \left[ \frac{r}{r_0} \right]^{2-\gamma} \right), \]
(3)
where \( r_0 = 100 \text{ au} \), \( \gamma = 1 \), and \( \Sigma_0 = 4.95 \text{ g cm}^{-2} \) such that the total disk mass is \( 0.035 M_{\text{Sun}} \), a factor of 100 times larger than the dust mass used in Fedele et al. (2018). This is inflated to a volume density assuming a Gaussian density profile
\[ \rho_{\text{gas}}(r, z) = \frac{\Sigma_{\text{gas}}(r)}{\sqrt{2\pi} H_p(r)} \exp \left( - \frac{z^2}{2H_p(r)^2} \right) \]
(4)
with the scale height parameterized as \( H_p = 10 \times (r/r_0)^{1.26} \text{ au} \).

The thermal structure follows the prescription in Dartois et al. (2003), which smoothly connects two boundary layers, the midplane and the atmosphere, through a trigonometric function,
\[ T = \begin{cases} T_{\text{atm}} & z \geq z_q \\ T_{\text{atm}} + (T_{\text{mid}} - T_{\text{atm}}) \cos^2 \left( \frac{z}{2z_q} \right) & z < z_q \\ \end{cases}, \]
(5)
where \( \delta = 2 \) and \( z_q = 4H_p \). The midplane and atmospheric temperatures are also described by radial power laws, \( T_{\text{mid}}(r) = 15.7 \times (r/r_0)^{-0.48} \text{ K} \), and \( T_{\text{atm}}(r) = 47.4 \times (r/r_0)^{-0.50} \text{ K} \), respectively.

Following Huang et al. (2016), we consider a homogeneous distribution of CO throughout the disk without taking into account the freeze-out or photodissociation. As the model in Huang et al. (2016) only considers CO rather than HD, we chose a relative abundance of \( x(\text{CO}) = 1.7 \times 10^{-6} \) in order to recover their prescribed column density profiles.

4.2. Perturbations

We only consider the emission region of the \( \text{^{12}CO} \), which should be narrow in the vertical direction due to the high optical depth of the line. From the model, we find that the \( \text{^{12}CO} \) contribution function weighted height, temperature, and gas density are well described by power laws over the region of interest, \( 30 \text{ au} \leq r \leq 320 \text{ au} \):
\[ T_{\text{^{12}CO}}(r) = 41 \text{ K} \times \left( \frac{r}{100 \text{ au}} \right)^{-0.57}, \]
(6)
\[ n_{\text{^{12}CO}}(r) = 9.6 \times 10^6 \text{ cm}^{-3} \times \left( \frac{r}{100 \text{ au}} \right)^{-2.29}, \]
(7)
\[ z_{\text{^{12}CO}}(r) = 23 \text{ au} \times \left( \frac{r}{100 \text{ au}} \right)^{1.04}. \]
(8)

The subscript \( \text{^{12}CO} \) is to show that these profiles trace the \( \text{^{12}CO} \) emission region and do not necessarily trace a fixed height in the disk.

Taking each of these quantities in turn, we model a perturbation vector as a sum of six Gaussian curves and multiply the power law describing that property by this to create a perturbed profile (similar to the perturbations used to model the continuum intensity profile Fedele et al. 2018). Using this perturbed profile and fixing the other two properties, \( v_{\text{rot}} \) is calculated using Equation (1) and compared to the observed \( v_{\text{rot}} \) profile. Although in reality these three properties are highly coupled, this approach allows us to quantify the extreme cases, which are consistent with the data.

The resulting best-fit perturbed profiles are shown in Figure 5. For comparison, the brightness temperature, a proxy of the local temperature for optically thick lines, of the \( \text{^{12}CO} \) emission from the cloud-free region is shown in panel (b) and the derived \( \text{^{12}CO} \) emission surface is shown in panel (c), both with blue error bars. The error bars on the perturbed model represents the scatter of 200 draws from the MCMC fitting.

Decreases in the density are found coincident with the gaps observed in the millimeter continuum centered at 62 and 103 au (Fedele et al. 2018). Additionally, a peak is observed at \( \approx 150 \text{ au} \), consistent with the required excess used to explain the ringed CO isotopologue emission (Huang et al. 2016).

Large changes in temperature as shown in panel (b) can be ruled out by the line emission as \( T_B \ll T_{\text{gas}} \) (note, however, that these temperatures may be underestimated, particularly over the dust rings, due to over subtraction of the dust continuum). Analysis of alternative transitions of \( \text{^{12}CO} \) will help constrain the temperature structure within the inner disk and provide limits for possible changes in temperature, while higher angular resolution will allow for small, local changes to be resolved.

Changes in the emission height, shown in panel (c), require larger deviations, particularly between 150 and 250 au, than are allowed from observations. In addition, these perturbations would place the continuum rings centered at local minima in Figure 5. Perturbed physical profiles resulting in the observed \( v_{\text{rot}} \). The red dotted lines show the fiducial models while the red error bars show the 16th–84th percentile range from 200 draws from the posterior distributions. The blue error bars show the observations; \( \text{^{12}CO} \) peak brightness temperature for the temperature and the inferred emission surface. Note that there are no observable constraints on density. Gray and black vertical lines show the location of the rings in millimeter continuum and NIR scattered light, respectively. In panel (c), the shaded region shows the shadowed region for the perturbed model showing that many of the NIR scattered rings would be located in shadow.
match to the pressure maxima with the micrometer sized particles.

The absolute scaling of this pressure profile is dependent on the density assumed for the disk model (Equation (7)). Changes in the density structure will result in different amplitude perturbations. Despite this degeneracy, the location of the perturbations will remain constant.

Due to the limited resolution of these observations ($\approx 29$ au for the line emission) the velocity features are not resolved and so will underestimate the true depth. Future, higher resolution observations of the line emission will better constrain the depth of these pressure perturbations and thus their gradient. Such observations will be essential in constraining the level of particle trapping in such pressure maxima.

Only the outer most ring at $\approx 250$ au does not coincide with a pressure maxima, rather with a pressure minima. One possible interpretation of this is that such a drop in pressure will result in a decrease of the disk scale height. If this is only a shallow perturbation, such that the far side is not shadowed, then the outer wall of this dip will have a larger angle of incidence for stellar light and thus scatter more effectively from the submicrometer grains, resulting in a ring despite the lack of a pressure maxima.

5. Discussion

We have demonstrated that we are able to use gas kinematics to infer the presence of perturbations in the physical structure of AS 209 and to infer the radial pressure profile. As these constraints are free of assumptions about the line excitation, they are hugely complimentary to traditional methods aiming to recover emission morphology.

5.1. Vertical Dependence of Pressure Traps

Better correlation is found between the pressure maxima and the rings observed in NIR scattered light than the the millimeter continuum. This suggests that if the rings are due to pressure confinement of the submicrometer sized grains in the disk atmosphere, there is a vertical dependence on the location of this maxima. This is consistent with the radial offsets found in the location of pressure minima traced at different heights in HD 163296 (Teague et al. 2018a) and with similar features seen in three-dimensional simulations (see, for example, Figure 4 of Fung & Chiang 2016).

However, it is unclear whether small particles can be trapped as efficiently at higher altitudes as larger, millimeter-sized particles in the midplane. As the particles become trapped, the rate of collision increases and grain growth is hastened. Larger grains will rapidly settle toward the midplane and drift radially inward (Dullemond & Dominik 2004). Two-dimensional simulations combined with accurate vertical profiles for the pressure gradient will be required to properly test this claim.

5.2. Sources of Perturbations

To account for the observed deviations in velocity, we require at least three significant perturbations to the physical structure of the disk at approximately 50, 100, and 250 au. The most attractive scenario for the source of these perturbations is the presence of planets. Fedele et al. (2018) demonstrated that the continuum emission profile can be explained either by a Saturn mass planet at 95 au and potentially a second planet less than 0.1 $M_{\text{Jup}}$ at 57 au. The density contrast required to recover
the rotation velocities are broadly consistent with those used to model the continuum emission profile.

The pressure minima at ~250 au is less likely to be opened by a planet. Dynamical timescales at these radii are prohibitive for core formation and the formation of planets, although planet formation via gravitational instability is a possibility (Boss 1997). Recently, Pinte et al. (2018b) found similar kinematic signatures for a ~2 $M_\text{Jup}$ planet at 260 au in the disk around HD 163296. This suggests that there may be a population of massive, wide separation planets that continuum observations are not sensitive to.

Aside from a planetary origin, other hydrodynamic instabilities have been shown to result in similar perturbations to the disk physical structure. The magnetorotational instability has been shown to drive large gaps in the gas surface density at the outer edge of the dead zone (Flock et al. 2015). However, estimates of the dead-zone extent only reach out to ~60 au (Cleeves et al. 2015), far further in than the observed deviation. Higher resolution observations of molecular line emission will help constrain the local physical properties where perturbations are observed and help distinguish between possible sources.

5.3. CO Desorption Front

Huang et al. (2016) interpreted the ringed structure observed in C$^{18}$O emission (and tentatively in $^{13}$CO) at 150 au as an enhancement in the local abundance of CO due to a desorption front. The authors argued that the lower opacity of the disk in regions beyond the millimeter continuum edge would allow for more efficient nonthermal desorption processes to occur resulting in a local enhancement in CO abundance as hypothesized by Cleeves (2016).

As shown in Section 4, we require enhancements in the H$_2$ gas pressure at 150 au in order to explain the velocity structure, either through an increase in density or temperature. Such changes can also explain the increase in the optically thin line emission without the need for an enhancement in the local CO abundance. However, such changes in the physical structure are likely to also affect the chemistry with an increase in temperature leading to more thermal desorption and higher CO column densities.

6. Conclusions

We have extended the method presented in Teague et al. (2018a) for measuring rotational velocities to allow for non-Gaussian line profiles and for objects with significant azimuthal structure. Application of this method to archival data of AS 209 revealed persistent deviations from a smooth Keplerian profile.

Using a toy model of AS 209, we are able to quantify the deviations required in the temperature, density, and height of the emission to match the observed perturbations resulting in deviations of up to 80%. Future work using models with self-consistent physical structures will be able to disentangle the relative contributions from the density and temperature terms. Comparison of the resulting pressure profiles provides evidence for the pressure trapping of submicrometer particles in the disk atmosphere, while a radial offset in the ring locations for the millimeter continuum and the scattered NIR light suggest that the location of the pressure minimum moves radially outward at higher altitudes in the disk.

A perturbation in the disk structure is inferred at ~250 au, far beyond the edge of the millimeter continuum, resulting in deviations of up to 5% from Keplerian rotation. A planetary origin for this object is unlikely as the dynamical timescales at such large radii make the initial stages of core accretion inefficient.

This work demonstrates the utility of studies of the gas kinematics and the ability to provide unique constraints for the interpretation of high angular resolution continuum observations.

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Appendix

Recovering the Rotation Velocity

In this appendix, we demonstrate the robustness of the derived $v_\text{rot}$ and quantify the precision that can be achieved with this method. The code used to calculated $v_\text{rot}$ and the model spectra can be found at https://github.com/richteague/eddy. Version 1.0 of the code used for this paper can be obtained from https://doi.org/10.5281/zenodo.1440051.

A.1. General Properties

We first consider the case of well behaved data: intrinsic Gaussian profiles with Gaussian noise. To model the $^{12}$CO emission, we generated 20,000 sets of model data. Each sample contained a random number of spectra, $N \in [6, 60]$, linearly spaced across the $2\pi$ azimuth. This range encompasses the expected number of independent beams for disks observed with ALMA at ~0.01 resolution: $N \approx 2\pi r/\theta_\text{beam}$.

The underlying profile was assumed to be Gaussian described by $T_B \in [5, 40] K$, $\Delta V \in [100, 400]$ m s$^{-1}$ and $v_{\text{los}} \in [0.5, 3.5]$ km s$^{-1}$. Each was then corrupted by Gaussian noise to achieve a S/N $\in [2, 20]$. These values were chosen to
represent typical line properties observed in protoplanetary disks. They were calculated on a velocity axis with a resolution of 160 m s$^{-1}$, meaning that the FWHM of the line was sampled between roughly one and four times.

For each sample of lines, we inferred $v_{\text{rot}}$ following the method described in Section 2. The differences from the true value are shown in Figure 7. As expected, the accuracy achieved increases with the S/N of the data and the number of lines used as both of these increase the S/N of the stacked spectra. Marginalizing over all intrinsic line properties, we can model the accuracy of this method via the power law to the 16th and 84th percentile range of residuals (shown by the dotted lines in Figure 7) as

$$\text{Accuracy} = 44.4 \pm 0.1 \text{ m s}^{-1} \times \left( \frac{2\pi r}{\theta_{\text{beam}}} \cdot \frac{S/N}{10} \right)^{-1.12 \pm 0.01},$$

showing that with S/Ns readily achievable by ALMA (due to both the overall sensitivity and the small beam sizes achieved in order to better sample the annulus), accuracies of a few meters per second are possible. A measure of the precision of the results can be estimated by the width of the posterior distribution for $v_{\text{rot}}$ for each case. This is well fit with the profile,

$$\text{Precision} = 23.9 \pm 0.6 \text{ m s}^{-1} \times \left( \frac{2\pi r}{\theta_{\text{beam}}} \cdot \frac{S/N}{10} \right)^{-1.39 \pm 0.04},$$

which is roughly a factor of two larger than the accuracy. Thus the assumed 3$\sigma$ uncertainties quoted in this work (and Teague et al. 2018a) are consistent with the true $v_{\text{rot}}$ value.

### A.2. Azimuthal Asymmetry

For the case of AS 209, there is strong azimuthal asymmetry due to the cloud absorption. In this section, we demonstrate how such azimuthal structure in either $T_B$ or $\Delta V$ affects the inferred $v_{\text{rot}}$. Similar to the previous examples, we generate model spectra; however, we reduce the parameter space by considering only $\Delta V = 300$ m s$^{-1}$, $N = 20$, and S/N = {5, 10, 15}. We then include a periodic perturbation in $\Delta V$, $T_B$ or both parameters, parameterized as

$$\delta = 1 + \delta_0 \cdot \sin \left( \frac{\theta + \chi}{f} \right),$$

where $\delta_0$ controls the strength of the deviation, $\chi \in [-\pi, \pi)$ is a random number to offset the deviation, and $f$ is an integer frequency. For this appendix, we only consider $f = \{1, 2\}$ and $\delta_0 \in [0, 0.5]$. For the case of AS 209, the cloud contamination leads to a $\delta_0 \approx 0.3$.

The results are shown in Figure 8, where each panel shows 1, 100 samples. The dotted lines show the 16th and 84th percentiles of the distribution and the solid line shows the median. These show that accuracy is not strongly affected by the inclusion of azimuthal structure. This suggests that the method is able to robustly recover an accurate measure of the line to an accuracy of $\leq 20$ m s$^{-1}$ even when both $\Delta V$ and $T_B$ have perturbations of up to 30%.

### A.3. Spatially Resolved 3D Structure

With ALMA now able to routinely spatially resolve the near and far sides of the disk for molecules with high emission surfaces (de Gregorio-Monsalvo et al. 2013; Rosenfeld et al. 2013), emission from both the top and bottom sides of the disk will be visible along a line of sight. This results in two components rather than a single component that could potentially cause problems, as demonstrated in Figure 9.
To demonstrate the robustness of this technique against such contamination, we consider a simple model setup. Each line of sight will be the combination of a main Gaussian component from the near side of the disk and a slightly offset secondary peak from the rear side of the disk. The secondary peak will have a smaller amplitude as this will be tracing the snow surface of the far side of the disk \citep{Pinte2018b}, thus

\[ T_{\text{B}}. \]

To calculate the offset of the secondary peak, we consider a disk with a given stellar mass, \( M_\ast \), inclination, \( i \), and emission surface described by \( z = z_0 \times \sin(\theta) \cdot \cos(\phi) \), where \( z_0 = 0.3 \) and \( \phi = 1.25 \). For a given radius, we first calculate the mapping of disk coordinates to sky coordinates via \citep[see also][]{Rosenfeld2013}:

\[
\begin{pmatrix}
    x_{\text{sky}} \\
    y_{\text{sky}}
\end{pmatrix} = \begin{pmatrix}
    x_{\text{disk}} \\
    y_{\text{disk}} - z_{\text{disk}} \sin(\theta) \cdot \cos(\phi)
\end{pmatrix}.
\]

We then calculate where these sky coordinates intercept the far side of the disk. For the emission surface of the far side of the disk, we consider a smaller aspect ratio of \( z/r = 0.1 \) as this emission will arise from the snow surface, as discussed previously, and thus be tracing a deeper (closer to the midplane) region. This results in two sets of coordinates: \((x_{\text{disk}}, y_{\text{disk}}, z_{\text{disk}})\) for the front side of the disk and the same for the far side of the disk. The front side coordinates will describe a ring of radius \( r_{\text{disk}} \) with height \( z_{\text{disk}} \), while the rear side will sample a range of \( r_{\text{disk}} \) values and thus different \( z_{\text{disk}} \) and \( v_{\text{rot}} \) values.

Figure 10(a) shows example spectra for disk matching the parameters of AS 209. The contamination from the rear side of the disk is seen as small components offset from the main line center with the largest deviations in the regions between the major (\( \theta = 0 \)) and minor (\( \theta = \pm \pi \)) axes.

In Figure 10(b), we show an annulus of spectra including the appropriate noise (\( \sigma_{\text{rms}} \approx 2 \) K) and channel width (\( \Delta V_{\text{chan}} = 160 \) m s\(^{-1}\)). The red lines show the line centers before deprojection. Figure 10(b) shows the deprojected spectra (in gray dots) and the stacked profile as a solid line. As the rear side components are varying in their offset for each line, they do not stack coherently and are thus lost in the noise, allowing for a good fit of \( v_{\text{rot}} \) to be found even in this scenario, achieving an accuracy of \(<0.4\%\).

In the case of very high signal-to-noise data with very small beam sizes, the far side components will become more apparent. This can be circumvented using the initial method of minimizing the width of a Gaussian line profile as this prior will be less sensitive to the contamination.
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