Predicting the Kinematic Evidence of Gravitational Instability

C. Hall1,2,3, R. Dong4, R. Teague5, J. Terry2, C. Pinte6,7, T. Paneque-Carreño8, B. Veronesi9, R. D. Alexander1, and G. Lodato9

1 School of Physics & Astronomy, University of Leicester, University Road, Leicester, LE1 7RH, UK; cassandra.hall@uga.edu
2 Department of Physics and Astronomy, The University of Georgia, Athens, GA 30602, USA
3 Center for Simulational Physics, The University of Georgia, Athens, GA 30602, USA
4 Department of Physics & Astronomy, University of Victoria, Victoria BC V8P 1A1, Canada
5 Center for Astrophysics, Harvard & Smithsonian, 60 Garden Street, Cambridge, MA 02138, USA
6 School of Physics and Astronomy, Monash University, Clayton Vic 3800, Australia
7 Univ. Grenoble Alpes, CNRS, IPAG, F-38000 Grenoble, France
8 Departamento de Astronomia, Universidad de Chile, Camino El Observatorio 1515, Las Condes, Santiago, Chile
9 Dipartimento di Fisica, Universita degli Studi di Milano, Via Celoria, 16, Milano, I-20133, Italy

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Abstract

Observations with the Atacama Large Millimeter/Submillimeter Array (ALMA) have dramatically improved our understanding of the site of exoplanet formation: protoplanetary disks. However, many basic properties of these disks are not well understood. The most fundamental of these is the total disk mass, which sets the mass budget for planet formation. Disks with sufficiently high masses can excite gravitational instability and drive spiral arms that are detectable with ALMA. Although spirals have been detected in ALMA observations of the dust, their association with gravitational instability, and high disk masses, is far from clear. Here we report a prediction for kinematic evidence of gravitational instability. Using hydrodynamics simulations coupled with radiative transfer calculations, we show that a disk undergoing such instability has clear kinematic signatures in molecular line observations across the entire disk azimuth and radius, which are independent of viewing angle. If these signatures are detected, it will provide the clearest evidence for the occurrence of gravitational instability in planet-forming disks, and provide a crucial way to measure disk masses.

Unified Astronomy Thesaurus concepts: Protoplanetary disks (1300)

1. Introduction

It has become clear that most, if not all, protoplanetary disks contain some degree of substructure. Specifically, spirals have been readily observed in disks in scattered light at micron wavelengths (Benisty et al. 2015; Stolker et al. 2016) and in dust emission at millimeter wavelengths (Pérez et al. 2016; Dong et al. 2018a; Huang et al. 2018). Unlike other structures, such as rings, which are readily explained by planets (Dipierro et al. 2015, 2018b) thanks to kinematic detections (Pinte et al. 2018, 2019, 2020; Teague et al. 2018, 2019a), thermal detections (Keppler et al. 2018), and accretion confirmation (Haffert et al. 2019), the origin of spiral morphology remains ambiguous.

Density waves excited by ≥ Jupiter mass planets can quantitatively match the observed spirals in scattered light in both contrast and morphology (Dong et al. 2015b; Fung & Dong 2015; Dong & Fung 2017). Some spirals may be due to binary companions, either internal to the disk (Price et al. 2018a) or external to it (Forgan et al. 2018b). While possible, it is unlikely that most spirals are caused by stellar flybys since close encounters between stars are statistically much rarer in the majority of star formation regions compared with the observed occurrence rate of spirals (Winter et al. 2018).

Meanwhile, gravitational instability (GI) can also produce spirals. As a rule of thumb, a disk-to-star mass ratio ≥ 10% is needed to trigger GI and produce detectable spirals (Dong et al. 2015a; Hall et al. 2016, 2019).

However, directly measuring disk mass is almost impossible. The main constituent, molecular hydrogen (H2), lacks a dipole moment, and at the low temperatures found in the bulk of protoplanetary disks emits only through faint quadrupole transitions. Disk masses can, however, be estimated by converting continuum flux density at millimeter/submillimeter wavelengths to a total dust mass, then scaling by a constant ratio to obtain a total gas mass (Beckwith et al. 1990). This method is plagued by uncertainties in basic quantities such as the dust opacity and the dust-to-gas mass ratio (Andrews 2020). A method thought to be more accurate is measurement of line emission from other molecules thought to trace H2, including HD (Bergin et al. 2013; McClure et al. 2016), CO, and its less abundant isotopologues (Williams & Best 2014), and converted to H2 mass through assumed abundance ratios. However, molecular abundances are believed to vary both spatially and temporally within a disk (Ilee et al. 2017; Quénard et al. 2018; Zhang et al. 2019), rendering the conversion from measured line flux density to a total gas mass highly model dependent (Trapman et al. 2017).

Differentiating between these hypotheses is of crucial importance in planet formation. If spirals are predominately produced by giant planets, then the detection rate of such spirals can directly inform us about the occurrence rate and properties of giant planets (Hall et al. 2017; Dong et al. 2018b; Forgan et al. 2018). If, on the other hand, most spirals are caused by GI, their existence and morphology can be used to infer fundamental disk properties, such as disk mass (Dong et al. 2015a; Cadman et al. 2020; Haworth et al. 2020), and therefore constrain planetary mass budgets and formation timescales (Nayakshin et al. 2020) on a comprehensive scale.

However, identifying the true origin of spirals in disks is difficult. The best way to confirm the planetary origin is to directly detect the putative spiral-causing planets. Except in rare cases (Wagner et al. 2019), planets associated with spiral structures have largely evaded detection in direct imaging.
searches to date, possibly because they are faint (Brittain et al. 2020; Humphries et al. 2020).

Simulations have shown that it is theoretically possible to differentiate between GI and planets by measurement of spiral pitch angles. GI creates logarithmic, symmetric spiral arms (Hall et al. 2016; Forgan et al. 2018b), with the number of spiral arms, m, determined by the disk-to-star mass ratio such that \( m \sim \frac{1}{q} \) (Dong et al. 2015a). Planets and external binary companions, instead induce spirals with variable pitch angles (Dong et al. 2015b; Forgan et al. 2018b). However, in practice, synthesized observations of spirals formed through these two mechanisms, at both millimeter and micron wavelengths, appear very similar with current instrumentation (Dong et al. 2015a, 2015b; Meru et al. 2017).

Our approach in this work is to present the dynamical effect of GI on the gas disk, traceable with molecular line emission, and introduce new diagnostic tools to identify GI unstable disks with gas observations. In the planet-in-disk case, the bulk kinematics are dominated by Keplerian rotation, modulated by a radial pressure gradient such that the gas orbits at slightly sub-Keplerian velocity. If a planet is present, then its wake will cause a deviation that is strongest closest to the planet, resulting in a localized kink near the planet when observed in molecular line emission (Perez et al. 2015; Perez et al. 2018; Pinte et al. 2018, 2019, 2020; Tegue et al. 2018, 2019a).

2. Methods

2.1. Hydrodynamical Model

We performed a three-dimensional, dusty, gaseous global hydrodynamical simulation using the Phantom Smoothed Particle Hydrodynamics code (Price et al. 2018b). Dust was modeled self-consistently with the gas using the one-fluid technique (Ballabio et al. 2018; Hutchison et al. 2018) in the strongly coupled regime. We used 1 million SPH particles, and followed the grain fraction of dust particles in sizes ranging from 1 \( \mu \)m to 4 mm in 5 size bins. We included dust since the temperature of dust sets the thermal structure for the surrounding gas, and we also include the force exerted on the gas by the dust, since this has a pronounced effect on the ultimate gaseous structure (Dipierro et al. 2018a). We assumed a central stellar mass of 0.6 \( M_\odot \), and a total disk mass of 0.3 \( M_\odot \). The central star was represented by a sink particle (Bate et al. 1995), with accretion radius set to 1 au.

We set the initial inner and outer disk radii to 10 au and 300 au respectively. The surface density and sound speed profiles were set as \( \Sigma_g \propto R^{-1} \) and \( c_s \propto R^{-0.2} \) respectively. These properties are consistent with observed candidates for self-gravitating protoplanetary disks (Pérez et al. 2016; Andrews et al. 2018; Huang et al. 2018), and have been extensively used in previous modeling (Menu et al. 2017; Tomida et al. 2017; Hall et al. 2018, 2019). We assumed a polytropic equation of state, and heating in the simulation is provided by shocks and pressure–volume work. The disk was initially set as stable to self-gravitating spirals, such that the Toomre parameter (Toomre 1964), \( Q \) is

\[
Q = \frac{c_s \kappa}{\pi G \Sigma} \gtrsim 2
\]

everywhere in the disk, where \( \kappa \) is epicyclic frequency, which for a disk in Keplerian rotation is simply \( \Omega = \sqrt{\frac{GM}{R^3}} \), \( G \) is the gravitational constant and \( \Sigma \) is surface density. We implemented “\( \beta \)” cooling (Gammie 2001), a simple cooling prescription where the cooling timescale, \( t_c \), is a linear function of the dynamical timescale, such that \( t_c = \beta t^\text{dyn} \). The dynamical timescale is simply the rotation period, \( \frac{2\pi}{W} \), and we set \( \beta = 15 \). We evolved the disk for several outer orbital periods. The spatial distribution of a dust grain of size \( \alpha_i \) and density \( \rho_i \) is determined by its Stokes number (Birnstiel et al. 2010),

\[
St = \frac{\pi \alpha_i \rho_i}{2 \Sigma_g^2}
\]

The velocity of dust relative to the gas depends on \( St \). For \( St \ll 1 \), the dust is well-coupled and follows the gas drag. For \( St \gg 1 \), the dust is decoupled and does not respond to the gas. The maximum relative velocity occurs for \( St = 1 \), resulting in particle trapping in the disk as density gradients peak inside spiral arms (Rice et al. 2004). In our simulations, we see efficient trapping for particles \( \gtrsim \) mm. The model surface density is shown in Figure 1, along with two example grain sizes.

2.2. Thermal Disk Structure

We used the Monte Carlo radiative transfer MCFOST code (Pinte et al. 2006, 2009) to compute the disk thermal structure and synthetic \(^{13}\)CO \( J = 3 \rightarrow 2 \) line maps. We assumed \( T_{\text{gas}} = T_{\text{dust}} \) and used \( 10^8 \) photon packets to calculate \( T_{\text{dust}} \). We also assumed that the \(^{13}\)CO molecule is in local thermodynamic equilibrium.
Figure 2. Predicted emission for gravitational instability. Hydrodynamical model of a self-gravitating disk, post-processed with radiative transfer to produce emission maps of $^{13}$CO $J = 3 \rightarrow 2$ transition. Top row shows the unaltered, self-gravitating velocity structure, while the bottom row assumes a purely Keplerian velocity. The GI wiggle is circled in the top central channel, and is visible at all deviations from the systemic velocity. The bottom row shows this signature is not present if the velocities are not self-gravitating.

The velocity field of the simulation is shown in the leftmost panels of Figure 3. We determined the observed velocity field of this observation by calculating the intensity weighted average velocity of the emission line profile. This is also known as a moment-1 map, and is obtained through

$$\langle v \rangle = \frac{\int_{-\infty}^{\infty} vI(v)dv}{\int_{-\infty}^{\infty} I(v)dv},$$

(3)

where the denominator is simply the integrated line intensity. We then calculated Equation (3) for the case where velocities were set to exactly Keplerian, and subtracted this result from the original velocities. The resulting observed velocity is shown in the rightmost panel of Figure 3.

3. Results

Our results show that GI, unlike an embedded protoplanet, causes deviations from Keplerian rotation throughout the disk, resulting in velocity kinks across the entire radial and azimuthal extent of the disk. This is shown in the channel maps in Figure 2. We call these kinks the GI wiggle.

We circle the GI wiggle at the systemic velocity; however, it is clearly seen at all velocities in the disk. Unlike a planet-induced perturbation, which results in a localized kink, there are multiple kinks in the Keplerian cone. In the bottom row of Figure 2, the velocity of the hydrodynamics simulation was set to equal exactly Keplerian, and synthetic line maps were generated in the exact same way as for the self-gravitating case. There is no observed substructure in this case, which demonstrates that it is velocity perturbation, rather than perturbation of density structure, which is the cause of this GI wiggle.

The velocity field of the self-gravitating disk is shown in Figure 3. The top left panel shows the radial velocity in the reference frame of the star, the top center panel shows the deviation from Keplerian rotation (where we define $v_{\text{ kep}} = (GM_*/r)^{1/2}$ in azimuthal velocity, and the top right shows the $z$-component of velocity (where positive $z$ is out of the page) all calculated directly from the hydrodynamics simulation. In Keplerian rotation, $v_r = 0$ and $v_\phi - v_{\text{ kep}} = 0$. Bottom panels show each contribution to the

2.3. $^{13}$CO Channel Map and Object Velocity Field

The system was synthetically observed at a distance of 140 pc and inclination of 30°. We assumed a turbulent velocity of 0.05 km s$^{-1}$. $^{13}$CO maps were generated at a Hanning-smoothed spectral resolution of 0.03 km s$^{-1}$, and then convolved with a beam of size 0′′11 × 0′′07, with a position angle of −38°, matching recent Atacama Large Millimeter/Submillimeter array (ALMA) observations that had the spectral and spatial resolution to kinematically detect a planet (Pinte et al. 2019). Since we do not aim to perform a detailed fitting to any particular observation, we show our synthetic maps with fully sampled $uv$-plane. It has already been determined that this process does not affect observational results compared to more sophisticated analysis, and does indeed provide a good approximation for comparing models to data (Pinte et al. 2019). The resulting channel map is shown in Figure 2.

(LTE). It is reasonable to assume LTE for low- $J$ lines since CO density is above the critical density for collisions to dominate over radiation. We set the $^{13}$CO abundance equal to $7 \times 10^{-7}$ relative to the local H$_2$. The parameters for the central star were set to match those of a typical self-gravitating protostellar disk candidate, the Elias 2–27 system (Andrews et al. 2009), with temperature $T = 3850$ K, $M = 0.6 M_\odot$, and $R_* = 2.3 R_\odot$.

The SPH density structure underwent Voronoi tessellation such that each SPH particle corresponds to an MCFOST cell. The dust composition was assumed to be a mixture of silicate and amorphous carbon (Draine & Lee 1984) and optical properties were calculated using the Mie theory. We used a grain population with 100 logarithmic bins ranging in size from 0.03 $\mu$m to 4 mm. At each position in the model, the dust density of a grain size $a_i$ was obtained by interpolating from the SPH dust sizes. We assumed that grain sizes smaller than half the smallest SPH grain size (so 0.5 $\mu$m) are perfectly coupled to the gas distribution. We assume there are no grains larger than those present in the SPH simulation. The dust size distribution was normalized by integrating over all grain sizes, where a power-law relation between grain size $a$ and number density of dust grains $n(a)$ was assumed such that $dn(a) \propto a^{-3.5} da$.

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observed velocity \( v_{\text{obs}} \) is given by

\[
v_{\text{obs}} = v_{\text{rot}} \sin(i) \cos(\phi) + v_{\text{rad}} \sin(i) \sin(\phi) + v_{\text{vert}} \cos(i) + v_{\text{sys}}.
\]  

The rightmost panel is the observed velocity field (moment-1), with observed Keplerian rotation subtracted. It clearly shows interlocking, finger-like structure between \([0^\circ, 0^\prime] \) and \([0^\prime, 1^\prime 5^\prime] \). This deviation essentially pushes extra emission into adjacent channels at a given velocity, causing the GI wiggle seen in Figure 2. We emphasize that perturbations do not create extra emission, but simply relocate emission in position–position–velocity space.

Figure 3 shows that GI spirals have strong velocity perturbations across their azimuthal extent. This is why the GI wiggle is seen in multiple channels, as shown in Figure 2. Planetary companions, on the other hand, create velocity deviations that are only strong enough to be detected in line emission close to the planet. Figure 3 also shows that GI
spirals have multiple perturbations across the radial extent of the disk, which is why the GI wiggle has multiple inflection points.

It is difficult to directly relate the velocity structure in the left and center panels of Figure 3 to the observed velocity, since the observed velocity, \( v_{\text{obs}} \), is the superposition of the projection of rotational, radial, and vertical components, as demonstrated in Equation (4).

Under the assumption of an azimuthally symmetric velocity distribution, these three velocity components are readily disentangled (Teague et al. 2019b), since they each have differing dependence on azimuthal angle \( \phi \). However, as demonstrated by Figure 3, the velocity distribution in a self-gravitating disk deviates strongly from azimuthal symmetry.

We attribute these features to the underlying disk structure in Figure 4. Left panel shows \( v_{\text{obs}} - v_{\text{obs}}^{\text{kep}} \) in the moment-1 map, where we have traced the line of \( v_{\text{obs}} - v_{\text{obs}}^{\text{kep}} = 0 \) in the interlocking fingers. Center panel shows the projected surface density of the disk calculated at the observed inclination angle (30°), integrated along this line of sight. The location of \( v_{\text{obs}} - v_{\text{obs}}^{\text{kep}} = 0 \) is plotted in black. The strong perturbations in radial velocity, shown in Figure 3, cause a radius of faster rotating material to have a higher velocity in the redshifted side of the disk, but a lower velocity in the blueshifted side.

The right panel of Figure 4 is a zoomed in version of the velocity centroid (\( \Delta v = 0.0 \, \text{km s}^{-1} \)) in Figure 2. Overplotted in white is the line \( v_{\text{obs}} - v_{\text{obs}}^{\text{kep}} = 0 \). At the base of each finger there is missing emission, which has been stolen by the adjacent velocity channel. For the \( v_{\text{obs}} < v_{\text{obs}}^{\text{kep}} \) fingers, it has been stolen by the slower velocity channel adjacent to the centroid. For the \( v_{\text{obs}} > v_{\text{obs}}^{\text{kep}} \) fingers, it has been stolen by the faster velocity channel adjacent to the centroid. At the tip of each finger, extra emission is present by the same mechanism.

### 3.1. Contribution of Velocity Components

The six leftmost panels in Figure 3 show that GI disks differ significantly from Keplerian rotation in \( v_r \), \( v_z \), and \( v_{\phi} \). To determine which velocity component deviations contribute most strongly to the GI wiggle, we repeat the procedure outlined above for three additional cases:

![Figure 5. Emission for GI and Keplerian velocity components. Top two rows show predicted emission for GI and for exactly Keplerian rotation. Center row shows GI z-velocity component, with \( v_r \) and \( v_{\phi} \) set to Keplerian, and bottom two rows show \( v_r \) and \( v_{\phi} \) GI velocity with all other velocity components set to Keplerian. Perturbations in \( v_r \) are strongest and are seen throughout disk azimuth and radius. Perturbations in \( v_{\phi} \) are weaker but visible throughout azimuth and radius. Perturbations in \( v_z \) only seen at specific azimuths.](image-url)
1. \( v_z \) as the perturbed GI velocity, \( v_r = 0 \) and \( v_f = v_{\text{Keplerian}} \).
2. \( v_r \) as the perturbed GI velocity, \( v_f = v_{\text{Keplerian}} \) and \( v_z = 0 \).
3. \( v_{\phi f} \) as the perturbed GI velocity, \( v_r = 0 \) and \( v_z = 0 \) set to Keplerian rotation,

where \( v_r = v_z = 0 \) in Keplerian rotation. This is shown in Figure 5. We determine that the perturbations in \( v_r \) are the strongest contributors to the GI wiggle, and are visible throughout azimuthal and radial disk extent. The \( v_z \) perturbations are also

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**Figure 6.** Emission for different viewing angles. All disks are observed at an inclination of 30°, with azimuthal viewing angle varying as \( \theta = 90^\circ, 180^\circ, \) and \( 270^\circ \). The GI wiggle is visible at all viewing angles, but does vary in number of observed inflection points and amplitude of wiggle.

**Figure 7.** Column density and velocity field for different viewing angles. Top panel shows integrated column density in units of \( \log_{10} \text{g cm}^{-2} \), at an inclination of 30° and varying viewing angle. Bottom panels show the observed velocity field with Keplerian rotation profile subtracted. Strong interlocking fingers are only seen in \( \theta = 90^\circ \), but non-axisymmetry is present at all viewing angles.
visible throughout azimuthal extent, but are of smaller observed amplitude. The perturbations in $v_\phi$ are not seen throughout azimuthal extent.

3.2. Robustness to Viewing Angle

We ensure that the detection of the GI wiggle is robust to the geometry of the observation by generating synthetic observations at azimuthal viewing angles $\theta = 90^\circ$, $180^\circ$, and $270^\circ$. We show the resulting channel maps in Figure 6. The GI wiggle is observed at all radii and azimuths in the disk for all viewing positions in the channel maps. It does, however, have some variation both in amplitude and number of inflection points.

Self-gravitating disks, by nature, are not axisymmetric. Therefore, some variation with viewing angle is expected. We plot integrated column density at an inclination of 30° in the top panels of Figure 7, for the viewing angles $\theta = 90^\circ$, $180^\circ$, and $270^\circ$. The corresponding moment-1 maps, with Keplerian background subtracted, are shown below. For $\theta = 90^\circ$, an interlocking finger-like structure is observed, while this is not present for $\theta = 180^\circ, 270^\circ$. However, in all cases, the velocity field shows clear deviation from axisymmetry and from Keplerianity. We conclude that the GI wiggle in the channel maps is the strongest kinematic signature for GI, and most likely to be detected, and interlocking structure in the moment-1 deviation from Keplerian is a strong secondary signal that may depend on viewing angle.

4. Conclusion

We have demonstrated that velocity perturbations due to gravitational instability, in a disk imaged at 140 pc, have a clear kinematic signature that is detectable with current ALMA capabilities: a spatial resolution of $\sim 0.01$ pc and a spectral resolution of 0.03 km s$^{-1}$. Although planetary in origin, analysis of archival ALMA data by Pinte et al. (2018) recovered velocity perturbations of similar amplitudes in the protoplanetary disk HD 163296, with a total observing time of 4.7 hr, and 2.5 hr on the science target (Isella et al. 2016).

Unlike spirals caused by embedded planets, GI spirals do not cause a localized velocity deviation. They perturb the velocity throughout the disk, resulting in sustained GI wiggles that are visible at all disk radii and all azimuthal angles. Furthermore, they may leave clear, finger-like signatures in the observed velocity field of the system, particularly pronounced when a Keplerian rotation profile is subtracted. The detection of the GI wiggle would provide strong evidence for the existence of gravitational instability in protoplanetary disks.

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ORCID iDs

C. Hall https://orcid.org/0000-0002-8138-0425
R. Dong https://orcid.org/0000-0001-9290-7846
R. Teague https://orcid.org/0000-0003-1534-5186
J. Terry https://orcid.org/0000-0002-8590-7271
C. Pinte https://orcid.org/0000-0001-5907-5179
R. D. Alexander https://orcid.org/0000-0001-6410-2899
G. Lodato https://orcid.org/0000-0002-2357-7692

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