Research statement

Min-Kai Lin
Steward Theory Fellow

Steward Observatory, University of Arizona

minkailin@email.arizona.edu

My primary research interest is theoretical astrophysical fluid dynamics with application to accretion disk and planet formation theory. I employ a combination of analytical methods and large-scale computer simulations to rigorously establish and understand new results. I summarize previous works in §1, and describe in more detail recent projects, including future directions in §2, and new research topics in §3.

1. Research areas

1.1. Structures in protoplanetary disks as signposts of planet formation

It is now possible to directly observe detailed sub-structures in protoplanetary disks (PPDs), such as gaps, rings, or spirals, which may be signposts of planets or the planet-formation process itself (Pohl et al. 2015; Dong et al. 2015a,b). Understanding physical mechanisms that lead to structured PPDs is essential to explaining observations and advancing planet formation theory.

Many PPDs show lopsided dust distributions (e.g., Casassus et al. 2015; Pinilla et al. 2015; van der Marel et al. 2015, and references therein). The leading explanation for such asymmetries is the presence of pressure bumps associated with large-scale vortices acting as dust-traps via frictional forces. Indeed, an analytic description of dust-trapping by disk vortices, developed by Lyra & Lin (2013), have been successfully applied to interpret such observations (Pérez et al. 2014; Marino et al. 2015). This idea also plays a prominent role in planetesimal formation (Barge & Sommeria 1995). Vortex dynamics is now an integral part of planet formation theory (Surville & Barge 2015).

Vortices in PPDs may also be evidence of already-formed, but unseen giant planets (van der Marel et al. 2013) because vortex-formation can be induced through disk-planet interaction. I developed a semi-analytic theory that explains, in detail, how a giant planet can open disk gaps that are in fact hydrodynamically unstable, and used numerical simulations to show the outcome of instability is vortex formation (Lin & Papaloizou 2010). These vortices subsequently collect dust (e.g. Fu et al. 2014; Zhu & Stone 2014).

I generalized the theory of planetary gap instabilities to self-gravitating disks (Lin & Papaloizou 2011a,b). I showed, through mathematical analysis and numerical simulations, that disk self-gravity has *profound* effects on gap stability. Vortex formation is discouraged in with increasing disk mass, and in very massive disks a new 'gravitational edge instability' develops instead, signified by large-scale spiral features associated with disk gaps.

I show in Fig. 1 disk-planet simulations that show gap instabilities as a function of disk mass (Lin 2012b). In this study, I extended the above thin-disk calculations to full 3D disk models by adapting the `Zeus-MP` code (Hayes et al. 2006) to compute disk self-gravity in spherical coordinates. More recently, I applied the `Pluto` code (Mignone et al. 2007) to show that vortex formation is sensitive to how the mass-accretion rate within the disk depends on the height from the disk midplane (Lin 2014b). Such variations are expected in realistic PPD models (e.g., Bai 2015; Simon et al. 2015; Gressel et al. 2015), so the existence of vortices in PPDs indirectly constrain the internal disk vertical structure.

These studies show that observable disk morphologies are intimately linked to the underlying disk/planet properties. For example, the observation of a single large-scale vortex implies the disk mass is low — a property that is difficult to directly infer, but crucial to planet formation. The importance of disk self-gravity when considering vortex formation is often overlooked because it is usually neglected in such studies. Thus the development of realistic models for explaining PPD sub-structures is necessary, in conjunction with observational data, to expose actual conditions for planet formation.

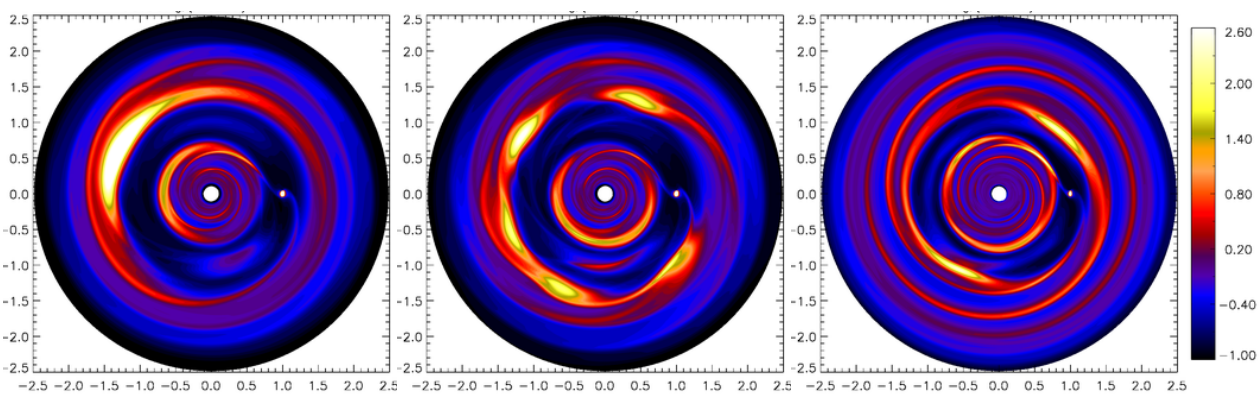

Fig. 1.— *Numerical simulations of 3D self-gravitating disk-planet interaction using the* `Zeus-MP` *code. Shown here are gap instabilities as a function of disk-to-star mass ratio* M_d/M_**. In low mass (left,* $M_d/M_* = 0.021$*) or moderately massive disks (middle,* $M_d/M_* = 0.056$*), gap edges undergo vortex formation, but the number of vortices increase with* M_d*. In very massive disks (right,* $M_d/M_* = 0.08$*), a spiral instability develops instead. The colorbar shows the relative density perturbation.*

1.2. Disk-planet interaction and orbital migration

The gravitational interaction between proto-planets and the gaseous PPD leads to orbital migration of the planet (Goldreich & Tremaine 1979; Lin & Papaloizou 1986). In standard, smooth disk models, orbital migrate is typically inwards to the central star. With the observational evidence of complex large-scale structures in PPDs, itself possibly caused by planets, it is now necessary to study orbital migration in non-smooth disks. However, theoretical models that attribute observed disk asymmetries to disk-planet interaction neglect migration (e.g. Ataiee et al. 2013; Pinilla et al. 2015).

I used numerical simulations to show that gap-edge vortices can in fact cause giant planets to undergo episodic orbital migration leaving sub-structures behind (Lin & Papaloizou 2010). In massive disks, I found that global spiral arms associated with unstable gaps (Fig. 1, right panel), can cause *outwards* orbital migration (Lin & Papaloizou 2012). This work was further expanded through the 2012 CITA Summer Student Program in which I supervised an undergraduate student to examine the role of planet mass (Cloutier & Lin 2013). We found that outwards orbital migration is generic for giant planets that open gaps in self-gravitating disks. This 'spiral-planet' interaction also explains outward migration in massive disks seen by other authors (Zhu et al. 2012; Stamatellos 2015).

1.3. Theory of astrophysical fluid instabilities

The 'vortex instability' described above is in fact applicable to any accretion disk that contain localized radial structure. Apart from disk gaps, the transition between actively accreting and 'dead' zones in PPDs are also possible sites for instability (Varnière & Tagger 2006; Lyra & Mac Low 2012). The original theory was developed for 2D (razor-thin) disks (Li et al. 2000), but real PPDs are three-dimensional.

I extended the theory of the vortex instability to 3D disks with varied thermodynamics (Lin 2012a, 2013b). A major effort in this work was the development of simple spectral and pseudo-spectral methods/algorithms to solve the associated partial differential equation eigenvalue problem (e.g. Lin 2013a). I found the 3D instability can have significant vertical structure with potentially observable consequences (e.g. lifting dust particles to the disk atmosphere). These calculations have been confirmed with direct hydrodynamic simulations performed by myself, and used by other researchers to benchmark their simulations (Meheut et al. 2012; Richard et al. 2013).

I have also begun to study magnetized self-gravitating disks with linear analyses of disks that permits both gravitational instability (GI) and magneto-rotational instability (MRI), including non-ideal effects (Lin 2014a). I showed that their interaction can be non-trivial, e.g., MRI can be stabilized or enhanced by disk self-gravity depending on the type of perturbation considered. Most importantly, this framework allows one to easily identify parameter regimes in which MRI-GI interaction is strongest. This will provide an important guide to non-linear simulations, which is my ultimate goal (§3.4).

2. Recent projects

2.1. Vertical shear instability in protoplanetary disks (Lin & Youdin 2015)

Astrophysical disks are generally *baroclinic* — surfaces of constant pressure and density do not coincide. Consequently, the disk's orbital frequency depends on the height from the disk midplane, $\partial_z \Omega \neq 0$. This free energy can be tapped through the *vertical shear instability* (VSI, Urpin & Brandenburg 1998; Urpin 2003). Because of this, the VSI has gained considerable interest as a route to purely hydrodynamic turbulence in PPDs (Nelson et al. 2013; Stoll & Kley 2014; McNally & Pessah 2015; Barker & Latter 2015; Mohandas & Pessah 2015), which is expected to play an important role in weakly ionized PPDs. While vertical shear is generic, VSI in realistic disks also require a short cooling timescale to overcome buoyancy forces. However, a quantitative criteria has not been determined until now.

I performed a detailed semi-global analysis of the VSI, focusing on its thermodynamic requirements and derived the remarkably simple result,

$$\beta \equiv t_{\mathrm{cool}}\Omega < \frac{h|q|}{\gamma - 1}, \tag{1}$$

for efficient VSI. Here, t_{cool} is the cooling timescale, h is the disk aspect-ratio, q is the local (logarithmic) radial temperature gradient and γ is the adiabatic index. Since $h \ll 1$ in PPDs, this requirement explains why $\beta \ll 1$ is needed to observe VSI in numerical simulations (Nelson et al. 2013). This criteria was also verified in our numerical stability calculations.

Eq. 1 allows one to immediately assess the importance of the VSI across a wide range of disk parameters, without resorting to costly computer simulations. By estimating cooling timescales based on dust opacity, we show that the VSI is indeed viable in realistic PPDs, with maximum activity between 5 and 50AU (Fig. 2), and smaller (larger) scale structures are expected in the inner (outer) disk.

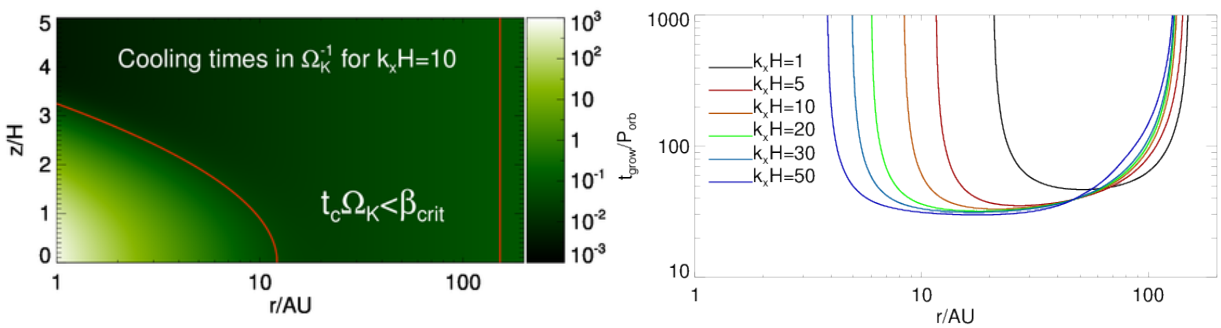

Fig. 2.— *Left: estimated cooling times in a standard PPD — the 'Minimum Mass Solar Nebula' (Chiang & Youdin 2010) — compared with the VSI requirement presented by Eq. 1 (red lines). Right: growth timescales (in local orbits) explicitly calculated from linear stability analysis, showing that VSI is most active at intermediate radii, consistent with Eq. 1 (i.e. left plot).*

This work presents a significant step in the theoretical understanding of the VSI. However, further development is still necessary to improve realism. I will extend this work to fully global, non-axisymmetric disk models with an improved treatment of heating and cooling processes (e.g. inclusion of viscous heating and radiative diffusion, as in Latter & Ogilvie 2006).

2.2. Eccentric modes in thermodynamically-forced accretion disks (Lin 2015)

The *locally isothermal disk*, in which the temperature is a prescribed function of position, is a widely used model for PPDs in studies such as disk-planet interaction. These models physically represent the situation where heating is dominated by an external source, e.g. the outer parts of PPDs (beyond few tens of AU) illuminated by stellar irradiation (Stamatellos & Whitworth 2008).

I showed that the propagation of waves in such a thermodynamically-forced disk (where the temperature is determined by external effects) is non-trivial: non-axisymmetric waves can undergo instability by extracting angular momentum from the background disk, a process mediated by the imposed temperature gradient. I described this new instability mechanism analytically, and used hydrodynamic simulations (with three independent codes: `Fargo`, `Zeus-MP` and `Pluto`) in both 2D and 3D to demonstrate how this mechanism can lead to the formation of one-armed or eccentric patterns (Fig. 3). This process may be relevant to PPDs at large radii, where large-scale spiral patterns are indeed observed (Rameau et al. 2012; Casassus et al. 2012; Muto et al. 2012; Grady et al. 2013; Benisty et al. 2015; Wagner et al. 2015). This work also made use of a newly developed Poisson solver for disk gravity for the `Pluto` code.

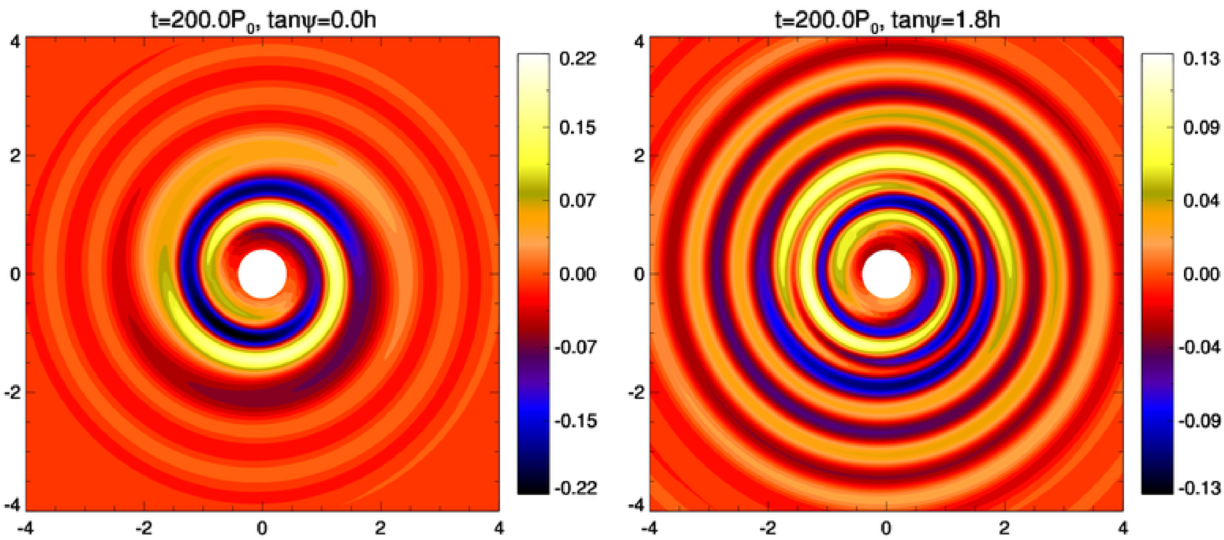

Fig. 3.— *Non-linear numerical simulation of a self-gravitating, locally isothermal 3D disk, using the* `Pluto` *hydrodynamics code. The component of the density field with azimuthal wavenumber $m = 1$ at the midplane (left) and approximately two scale-heights above the midplane (right) is shown.*

In the locally isothermal disk model, heating and cooling processes have associated timescales that are formally zero. It is therefore necessary to generalize this work to finite thermal timescales by including an appropriate energy equation. This will allow one to quantify the thermodynamic requirement for this new instability, and better constrain its application to PPDs. This will be done through both theoretical analysis as well as direct simulations (including extended calculations to explore its impact on the long term disk evolution).

2.3. Vortices in non-isothermal disk-planet simulations (Les & Lin 2015)

This project was undertaken by an undergraduate student as part of the 2014 CITA Summer Student Program, whom I directly supervised. We studied vortex formation through non-isothermal disk-planet interactions. This is an important generalization from previous studies which have employed locally isothermal disks. Through carefully-designed numerical experiments using the `Fargo` code (Masset 2000), we showed that slowly-cooled disks are more stable against vortex formation than rapidly-cooled disks. However, the overall lifetime of gap-edge vortices have a non-monotonic dependence on the cooling rate (Fig. 4): there is an optimal cooling rate that maximizes the lifetime, and hence observability, of such vortices. This result was later verified independently (Lobo Gomes et al. 2015). This means that observations of vortices can be used to constrain disk thermodynamics.

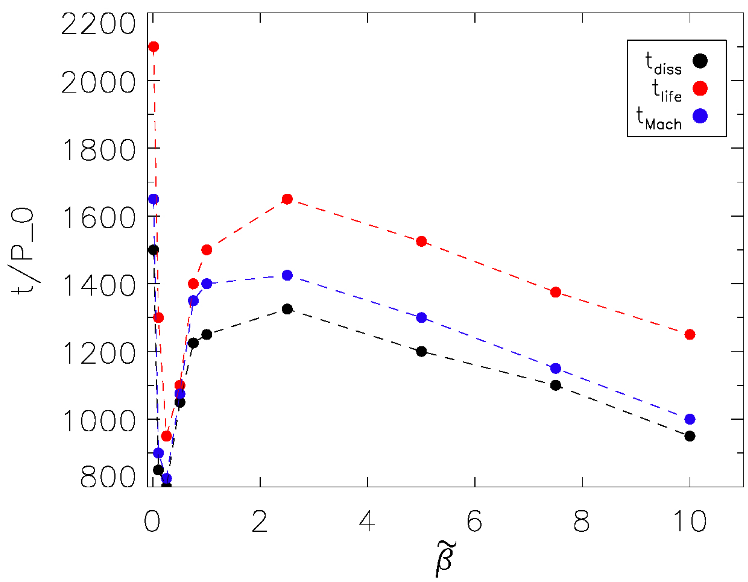

Fig. 4.— *Lifetimes of gap-edge vortices (in orbits) as a function of the dimensionless cooling time imposed in the disk. Colors indicate different metrics for the vortex lifetime, all of which display non-monotonic dependence on the cooling time.*

This project offers excellent research opportunities for students. I am interesting in working with undergraduate or graduate students to extend this work to include disk self-gravity, 3D (using the new `Fargo3D` code[1]) and/or orbital migration.

3. Research proposal

3.1. Analytical fluid dynamics and applications

Modern astrophysical MHD make substantial use of direct numerical simulations to reveal new phenomena. However, physical understanding is often better clarified through analytical or semi-analytical methods. Such calculations are *essential* to verify and guide computer simulations, but are not always provided. This is particularly important when studying fluid dynamical instabilities, which are fundamental to many astrophysical processes. As numerical simulations become increasingly sophisticated, so too must analytical models.

[1] http://fargo.in2p3.fr/

For example, the importance of disk thermodynamics on gravitational instabilities in PPDs is evident from numerical simulations (e.g. Gammie 2001; Rice et al. 2005; Meru & Bate 2011; Paardekooper 2012). However, such studies still refer to the classic Toomre Q parameter that characterizes self-gravitating in highly idealized, 2D isothermal disks.

Recently, in collaboration with K. Kratter, we have begun to revisit the stability problem by expanding the analytical framework to match the more complex physical processes that modern simulations include. I show a preliminary result in Fig. 5 where growth rates of unstable modes in a self-gravitating disk are calculated with the inclusion of heating, cooling and turbulent processes (Lin & Kratter, in preparation). This framework will then be applied to actual PPDs, e.g. to determine regions of instability and characteristic lengthscales of the emerging structures. This approach enables large parameter surveys that are impractical by direct simulation.

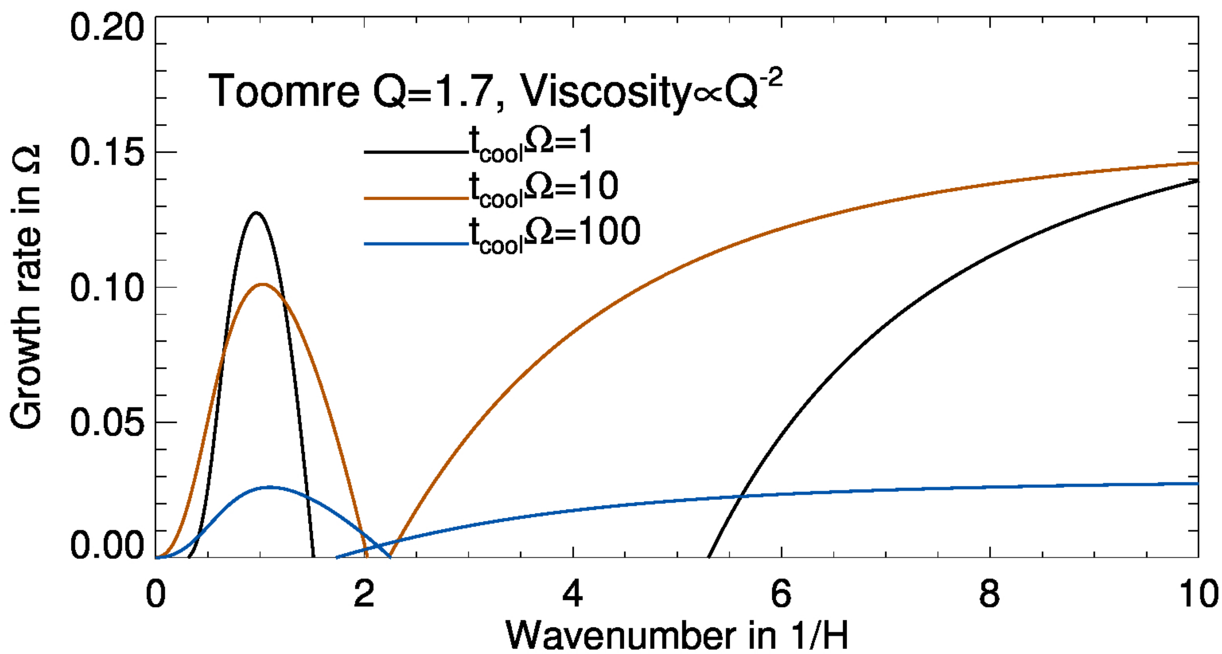

Fig. 5.— *Analytic growth rates of unstable modes in a self-gravitating, non-isothermal, turbulent accretion disk. The horizontal axis is the radial wavenumber of the perturbation under consideration. Colors indicate different imposed cooling timescales. Turbulence is modeled through an effective viscosity, here assumed to be of self-gravitational origin (Lin & Pringle 1987), so that viscosity increases with decreasing Toomre Q of the background disk.*

The goal of this line of work is to develop simplified PPD models based on rigorous analytical theory that provide in-depth understanding. A necessary effort is a realistic treatment of various fluid instabilities expected in PPDs (Turner et al. 2014) such as the vortex and vertical shear instabilities discussed above, among others (e.g. the recently discovered 'convective over-stability', Klahr & Hubbard 2014; Lyra 2014; Latter 2015). Additional physics to these stability problems include, but not limited to: self-gravity, non-ideal MHD, realistic thermodynamics, global and non-axisymmetric geometries.

3.2. Elliptical vortices in 3D self-gravitating disks

As discussed above, vortex formation is an attractive explanation for observed sub-structures in PPDs, and they enhance planetesimal formation by acting as dust-traps. I will advance theoretical models of disk vortices to include more realistic physics, beginning with self-gravity. Several analytical and numerical studies show that self-gravity cannot be neglected for disk vortex dynamics *even when self-gravity is deemed unimportant* according to the classic Toomre Q criterion (Lin 2012b; Lovelace & Hohlfeld 2013). Furthermore, self-gravity plays a significant role in the early evolution of PPDs, during which vortex formation has been show to occur (Bae et al. 2015). These considerations motivate a proper study of the structure and evolution of vortices in 3D self-gravitating disks.

I show in Fig. 6 two preliminary simulations carried out with the `Athena` code (Stone et al. 2008). Here, a vortex is initialized in a local patch of an accretion disk and allowed to evolve. Both disks are gravitationally stable ($Q > 1$), but the vortex structure depends on the strength of self-gravity. This is expected to affect its long term evolution.

A key focus will be vortex stability. It is well-known that secondary, elliptic instabilities act to destroy non-self-gravitating vortices in 3D (Lesur & Papaloizou 2009; Railton & Papaloizou 2014). It is important to understand how this picture is modified in massive disks, and hence the expected vortex lifetimes in, for example, young PPDs. I will also explore the gravitational instability of vortices, possibly mediated by hydrodynamic turbulence due to the elliptic instability (Gammie 1996). I will begin with ideal, local disk models, which permits high numerical resolution, before moving onto global simulations where vortex migration can also be explored (Paardekooper et al. 2010).

I will also investigate dust-dynamics in self-gravitating 3D vortices. As seen in Fig. 6, the vortex attains vertical structure in massive disks, which may enhance vertical dust settling. Related to this problem is the gravitational stability of elliptical dust distributions in gaseous disks (Lyra & Lin 2013), which is essential to understanding planetesimal formation in disk vortices. I plan to pursue these issues analytically in conjunction with numerical simulations (using the `Athena` code).

3.3. Giant planet orbital migration and eccentric disks

A well-known obstacle in planet formation theory is that in typical disk models, proto-planets migrate inwards rapidly and are lost to the central star, thereby preventing the formation of gas giant planets. Recent theoretical efforts have thus been devoted to halting or reversing the inwards orbital migration of low-mass planets (see e.g., Baruteau et al. 2014, for a recent review).

The outwards migration of *giant* planets, however, have received much less attention. Only a limited number of studies have examined this possibility (Pepliński et al. 2008; Crida et al. 2009; D'Angelo & Marzari 2012). However, such mechanisms can potentially explain the (increasing) population of directly-imaged giant planets or companions on wide orbits (Marois et al. 2008; Lagrange et al. 2010; Rameau et al. 2013; Kuzuhara et al. 2013; Bailey et al. 2014; Galicher et al. 2014; Kraus et al. 2014; Mawet et al. 2015; Macintosh et al. 2015).

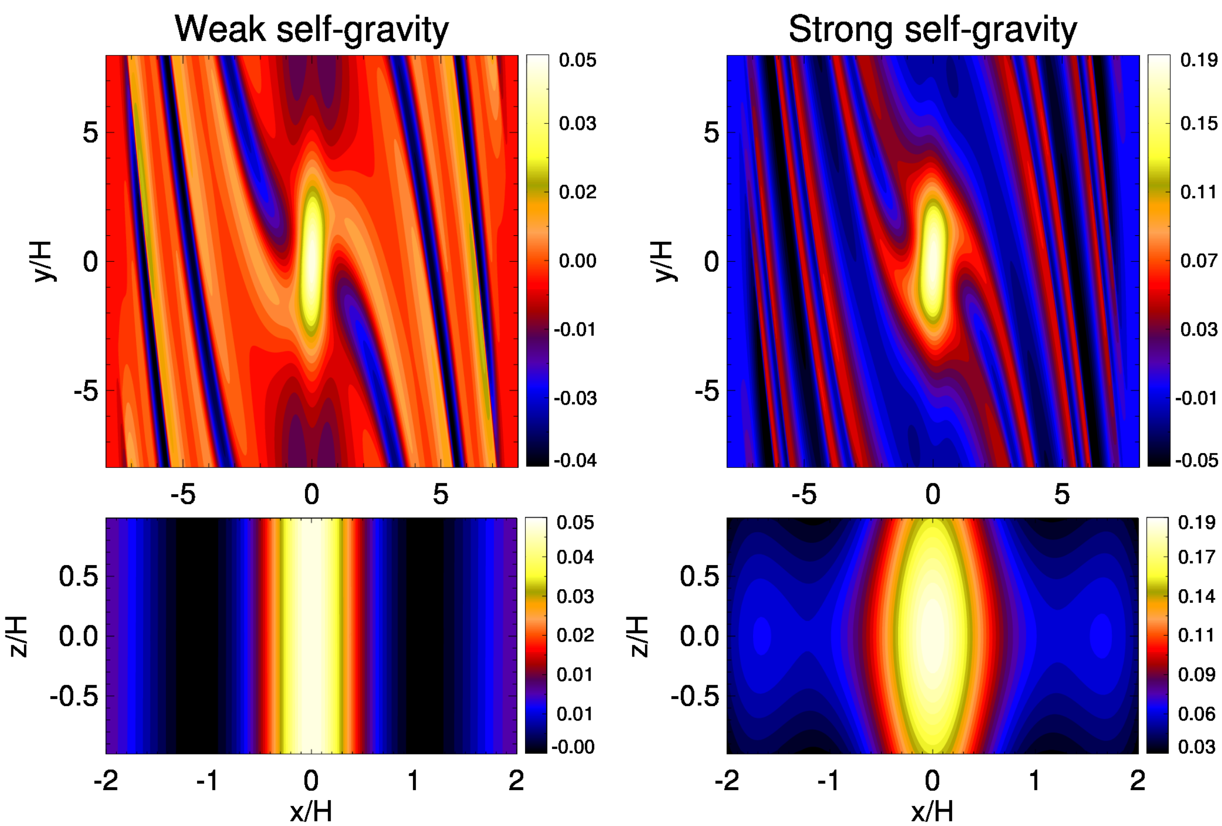

Fig. 6.— *Quasi-steady state vortex formed by initializing shearing-box simulations with a vortex perturbation for a weakly self-gravitating disk (left, with Toomre* $Q \simeq 160$*) and a strongly self-gravitating, but stable disk (right, with* $Q \simeq 1.6$*). Note that local gravitational instability in 3D requires* $Q \lesssim 0.8$ *(Mamatsashvili & Rice 2010). The colorbar shows the relative density perturbation at the midplane (top) and in the meridional plane (bottom).*

I will use 2D and 3D hydrodynamical simulations to study disk-planet interaction with focus on the outwards orbital migration of giant planets. I will go beyond previous efforts and consider self-gravitating disks, as appropriate for outer regions of PPDs, and improved thermodynamics. The key goals are to identify conditions (e.g. disk and planetary masses) under which outwards migration can occur, analyze its underlying mechanism, and determine how far can such mechanisms bring giant planets away from its host star.

Giant planets may also lead to globally distorted, eccentric disks (Papaloizou et al. 2001; Kley & Dirksen 2006; Dunhill et al. 2013; Duffell & Chiang 2015). In Fig. 7, I show preliminary simulations that improve upon previous studies by including disk self-gravity and/or non-adiabatic thermodynamics. I will characterize eccentric disk morphologies in relation to its self-gravity and thermodynamics. A related issue is that 3D eccentric disks are known to be hydrodynamically unstable (Papaloizou 2005b,a; Barker & Ogilvie 2014). I will study this instability in the context of planet-induced eccentric disks by performing global 3D numerical simulations (using the `Pluto` and the new `Fargo3D` codes), with the objective of quantifying the expected disk/planet eccentricities in realistic PPDs.

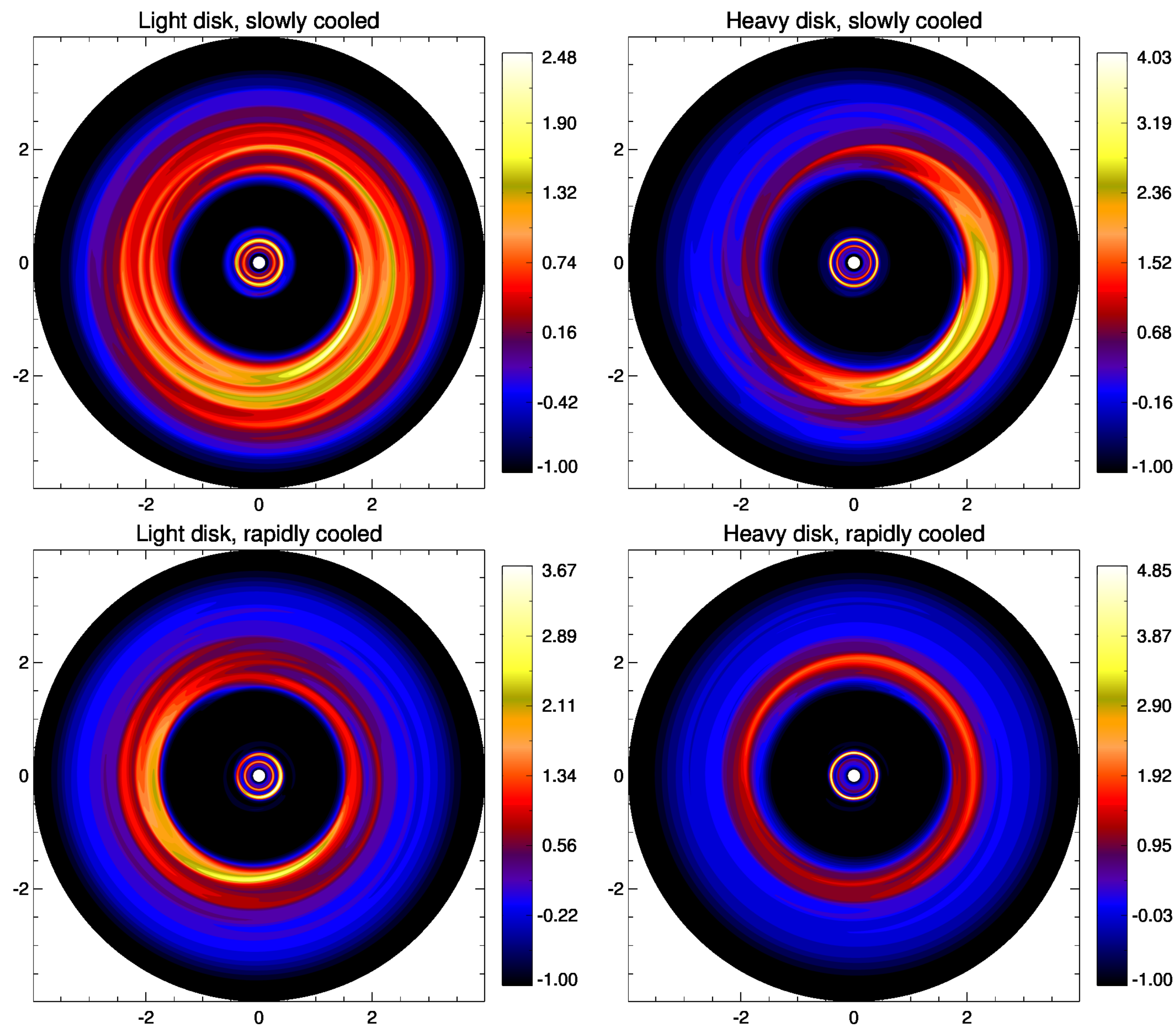

Fig. 7.— *Formation of eccentric gaps due to disk-planet interaction. Here, a 5-Jupiter mass planet is inserted into a self-gravitating, non-isothermal disk and held on a fixed, circular orbit. Top panels: slowly-cooled disks with* $t_{\rm cool} = 10\Omega^{-1}$*; bottom panels: rapidly cooled disks with* $t_{\rm cool} = 0.1\Omega^{-1}$*. (Here, 'cooling' refers to relaxation towards a prescribed temperature profile.) Left panels: light disks with* $M_d \simeq 0.0002M_*$*; right panels: heavy disks with* $M_d \simeq 0.05M_*$*. The colorbar shows the relative surface density perturbation.*

3.4. Magnetized self-gravitating disks

Magneto-hydrodynamic (MHD) turbulence and gravitational instability (GI) are the two mechanisms that robustly transport angular momentum and power accretion disks. These processes are typically studied in isolation (Turner et al. 2014). They may, however, simultaneously develop in the formation phase of PPDs (Inutsuka et al. 2010) and in layered-accretion models (Landry et al. 2013). Here, the PPD can be both self-gravitating and magnetized. Most models that account for both effects have done so implicitly through a viscosity prescription (Armitage et al. 2001; Zhu et al. 2010a,b; Martin et al. 2012; Rafikov 2015).

The goal of this project is to develop models of self-gravitating PPDs including *explicit* MHD. Key questions include: to what extent does MHD and GI influence one another in terms of disk stability, how is angular momentum transport by GI affected by MHD and vice versa, and how does MHD turbulence influence the formation of giant planet via disk fragmentation?

There have been a limited number of attempts at this problem (Fromang et al. 2004a,b,c; Fromang 2005), but despite being over a decade old, these studies still represent the latest dedicated simulations. A major effort here will be to perform direct simulations of magnetized, self-gravitating disks that go beyond early numerical limitations with modern computational resources. This includes high numerical resolution and long-term simulations which are necessary to address the above questions.

I will begin with simulating local, 3D disk models with the `Athena` code, using Lin (2014a) to benchmark and guide the simulations. I will characterize turbulent activity as a function of self-gravity, magnetization, and non-ideal effects such as resistivity. I will also explore magnetized disk fragmentation including cooling (cf. Fromang 2005). I will then move onto global disk simulations (using the `Zeus-MP` and/or `Pluto` codes) to study realistic transport rates. Large-scale structure formation (e.g. vortices and spirals) will also be explored. These models will also serve as basis for studying disk-planet interaction in young PPDs which are massive and magnetized.

Analytical work will continue to play a pivotal role. I will further develop the models introduced in Lin (2014a), particularly to improve the treatment of disk thermodynamics (including heating and cooling processes) to properly study gravitational instabilities in magnetized disks.

REFERENCES

Armitage, P. J., Livio, M., & Pringle, J. E. 2001, MNRAS, 324, 705

Ataiee, S., Pinilla, P., Zsom, A., et al. 2013, A&A, 553, L3

Bae, J., Hartmann, L., & Zhu, Z. 2015, ApJ, 805, 15

Bai, X.-N. 2015, ApJ, 798, 84

Bailey, V., Meshkat, T., Reiter, M., et al. 2014, ApJ, 780, L4

Barge, P., & Sommeria, J. 1995, A&A, 295, L1

Barker, A. J., & Latter, H. N. 2015, MNRAS, 450, 21

Barker, A. J., & Ogilvie, G. I. 2014, MNRAS, 445, 2637

Baruteau, C., Crida, A., Paardekooper, S.-J., et al. 2014, Protostars and Planets VI, 667

Benisty, M., Juhasz, A., Boccaletti, A., et al. 2015, A&A, 578, L6

Casassus, S., Perez M., S., Jordán, A., et al. 2012, ApJ, 754, L31

Casassus, S., Wright, C. M., Marino, S., et al. 2015, ApJ, 812, 126

Chiang, E., & Youdin, A. N. 2010, Annual Review of Earth and Planetary Sciences, 38, 493

Cloutier, R., & Lin, M.-K. 2013, MNRAS, 434, 621

Crida, A., Masset, F., & Morbidelli, A. 2009, ApJ, 705, L148

D'Angelo, G., & Marzari, F. 2012, ApJ, 757, 50

Dong, R., Zhu, Z., & Whitney, B. 2015a, ApJ, 809, 93

Dong, R., Zhu, Z., Rafikov, R. R., & Stone, J. M. 2015b, ApJ, 809, L5

Duffell, P. C., & Chiang, E. 2015, ApJ, 812, 94

Dunhill, A. C., Alexander, R. D., & Armitage, P. J. 2013, MNRAS, 428, 3072

Fromang, S. 2005, A&A, 441, 1

Fromang, S., de Villiers, J. P., & Balbus, S. A. 2004a, Ap&SS, 292, 439

Fromang, S., Balbus, S. A., & De Villiers, J.-P. 2004b, ApJ, 616, 357

Fromang, S., Balbus, S. A., Terquem, C., & De Villiers, J.-P. 2004c, ApJ, 616, 364

Fu, W., Li, H., Lubow, S., Li, S., & Liang, E. 2014, ApJ, 795, L39

Galicher, R., Rameau, J., Bonnefoy, M., et al. 2014, A&A, 565, L4

Gammie, C. F. 1996, ApJ, 462, 725

—. 2001, ApJ, 553, 174

Goldreich, P., & Tremaine, S. 1979, ApJ, 233, 857

Grady, C. A., Muto, T., Hashimoto, J., et al. 2013, ApJ, 762, 48

Gressel, O., Turner, N. J., Nelson, R. P., & McNally, C. P. 2015, ApJ, 801, 84

Hayes, J. C., Norman, M. L., Fiedler, R. A., et al. 2006, ApJS, 165, 188

Inutsuka, S.-i., Machida, M. N., & Matsumoto, T. 2010, ApJ, 718, L58

Klahr, H., & Hubbard, A. 2014, ApJ, 788, 21

Kley, W., & Dirksen, G. 2006, A&A, 447, 369

Kraus, A. L., Ireland, M. J., Cieza, L. A., et al. 2014, ApJ, 781, 20

Kuzuhara, M., Tamura, M., Kudo, T., et al. 2013, ApJ, 774, 11

Lagrange, A.-M., Bonnefoy, M., Chauvin, G., et al. 2010, Science, 329, 57

Landry, R., Dodson-Robinson, S. E., Turner, N. J., & Abram, G. 2013, ApJ, 771, 80

Latter, H. 2015, ArXiv e-prints, arXiv:1510.06247

Latter, H. N., & Ogilvie, G. I. 2006, MNRAS, 372, 1829

Les, R., & Lin, M.-K. 2015, MNRAS, 450, 1503

Lesur, G., & Papaloizou, J. C. B. 2009, A&A, 498, 1

Li, H., Finn, J. M., Lovelace, R. V. E., & Colgate, S. A. 2000, ApJ, 533, 1023

Lin, D. N. C., & Papaloizou, J. 1986, ApJ, 309, 846

Lin, D. N. C., & Pringle, J. E. 1987, MNRAS, 225, 607

Lin, M.-K. 2012a, ApJ, 754, 21

—. 2012b, MNRAS, 426, 3211

—. 2013a, MNRAS, 428, 190

—. 2013b, ApJ, 765, 84

—. 2014a, ApJ, 790, 13

—. 2014b, MNRAS, 437, 575

—. 2015, MNRAS, 448, 3806

Lin, M.-K., & Papaloizou, J. C. B. 2010, MNRAS, 405, 1473

—. 2011a, MNRAS, 415, 1426

—. 2011b, MNRAS, 415, 1445

—. 2012, MNRAS, 421, 780

Lin, M.-K., & Youdin, A. N. 2015, ApJ, 811, 17

Lobo Gomes, A., Klahr, H., Uribe, A. L., Pinilla, P., & Surville, C. 2015, ApJ, 810, 94

Lovelace, R. V. E., & Hohlfeld, R. G. 2013, MNRAS, 429, 529

Lyra, W. 2014, ApJ, 789, 77

Lyra, W., & Lin, M.-K. 2013, ApJ, 775, 17

Lyra, W., & Mac Low, M.-M. 2012, ApJ, 756, 62

Macintosh, B., Graham, J. R., Barman, T., et al. 2015, Science, 350, 64

Mamatsashvili, G. R., & Rice, W. K. M. 2010, MNRAS, 406, 2050

Marino, S., Casassus, S., Perez, S., et al. 2015, ApJ, 813, 76

Marois, C., Macintosh, B., Barman, T., et al. 2008, Science, 322, 1348

Martin, R. G., Lubow, S. H., Livio, M., & Pringle, J. E. 2012, MNRAS, 423, 2718

Masset, F. 2000, A&AS, 141, 165

Mawet, D., David, T., Bottom, M., et al. 2015, ApJ, 811, 103

McNally, C. P., & Pessah, M. E. 2015, ApJ, 811, 121

Meheut, H., Keppens, R., Casse, F., & Benz, W. 2012, A&A, 542, A9

Meru, F., & Bate, M. R. 2011, MNRAS, 411, L1

Mignone, A., Bodo, G., Massaglia, S., et al. 2007, ApJS, 170, 228

Mohandas, G., & Pessah, M. E. 2015, ArXiv e-prints, arXiv:1510.02729

Muto, T., Grady, C. A., Hashimoto, J., et al. 2012, ApJ, 748, L22

Nelson, R. P., Gressel, O., & Umurhan, O. M. 2013, MNRAS, 435, 2610

Paardekooper, S.-J. 2012, MNRAS, 421, 3286

Paardekooper, S.-J., Lesur, G., & Papaloizou, J. C. B. 2010, ApJ, 725, 146

Papaloizou, J. C. B. 2005a, A&A, 432, 757

—. 2005b, A&A, 432, 743

Papaloizou, J. C. B., Nelson, R. P., & Masset, F. 2001, A&A, 366, 263

Pepliński, A., Artymowicz, P., & Mellema, G. 2008, MNRAS, 387, 1063

Pérez, L. M., Isella, A., Carpenter, J. M., & Chandler, C. J. 2014, ApJ, 783, L13

Pinilla, P., van der Marel, N., Pérez, L. M., et al. 2015, ArXiv e-prints, arXiv:1509.03040

Pohl, A., Pinilla, P., Benisty, M., et al. 2015, MNRAS, 453, 1768

Rafikov, R. R. 2015, ApJ, 804, 62

Railton, A. D., & Papaloizou, J. C. B. 2014, MNRAS, 445, 4409

Rameau, J., Chauvin, G., Lagrange, A.-M., et al. 2012, A&A, 546, A24

—. 2013, ApJ, 772, L15

Rice, W. K. M., Lodato, G., & Armitage, P. J. 2005, MNRAS, 364, L56

Richard, S., Barge, P., & Le Dizès, S. 2013, A&A, 559, A30

Simon, J. B., Lesur, G., Kunz, M. W., & Armitage, P. J. 2015, MNRAS, 454, 1117

Stamatellos, D. 2015, ApJ, 810, L11

Stamatellos, D., & Whitworth, A. P. 2008, A&A, 480, 879

Stoll, M. H. R., & Kley, W. 2014, A&A, 572, A77

Stone, J. M., Gardiner, T. A., Teuben, P., Hawley, J. F., & Simon, J. B. 2008, ApJS, 178, 137

Surville, C., & Barge, P. 2015, A&A, 579, A100

Turner, N. J., Fromang, S., Gammie, C., et al. 2014, Protostars and Planets VI, 411

Urpin, V. 2003, A&A, 404, 397

Urpin, V., & Brandenburg, A. 1998, MNRAS, 294, 399

van der Marel, N., Pinilla, P., Tobin, J., et al. 2015, ApJ, 810, L7

van der Marel, N., van Dishoeck, E. F., Bruderer, S., et al. 2013, Science, 340, 1199

Varnière, P., & Tagger, M. 2006, A&A, 446, L13

Wagner, K., Apai, D., Kasper, M., & Robberto, M. 2015, ApJ, 813, L2

Zhu, Z., Hartmann, L., Gammie, C. F., et al. 2010a, ApJ, 713, 1134

Zhu, Z., Hartmann, L., & Gammie, C. 2010b, ApJ, 713, 1143

Zhu, Z., Hartmann, L., Nelson, R. P., & Gammie, C. F. 2012, ApJ, 746, 110

Zhu, Z., & Stone, J. M. 2014, ApJ, 795, 53