Simulating asymmetric planet forming discs

James E. Owen, Imperial College London

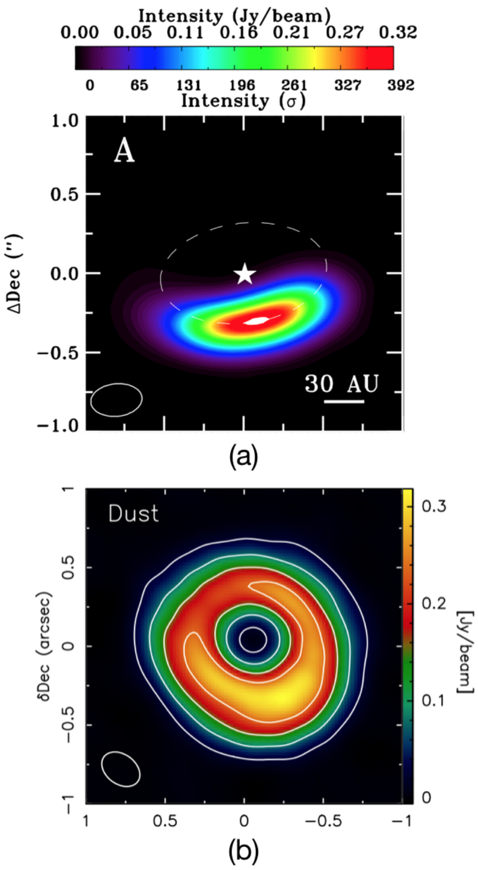

Figure 1: *ALMA sub-mm images of two lobsided protoplanetary discs: IRS 48 (a – taken from Van der Marel et al. 2013) and SAO 206462 (b – taken from Pérez et al. 2014)*

Understanding planet formation remains one of the great unsolved challenges in modern astronomy. Where, when and why planets form is still poorly understood, both in our solar system and around other stars. Until recently our knowledge of the environments in which planets form (so-called "protoplanetary discs") was limited and of little help constraining all but the most general ideas. The last five years have seen a rapid growth in high-resolution imaging of protoplanetary discs at mm and sub-mm wavelengths using the ALMA telescope and at NIR wavelengths using SPHERE and GPI. These new instruments have revealed a plethora of sub-structures including rings, spirals, holes and large scale asymmetries. Perhaps some of the most spectacular images of protoplanetary discs are ALMA images of large scale asymmetries, which present as lopsided or banana-shaped discs (see Figure 1).

These lopsided discs show small or undetectable asymmetries when they are imaged in molecular gas lines such as CO, but significant asymmetries with contrasts from factors of a few (e.g., SAO 206462 in Figure 1) to hundreds (e.g., IRS 48 in Figure 1) when imaged in the dust continuum. The standard interpretation of these images is they are large scale anti-cyclonic vortices (e.g., Lyra & Lin, 2013). Anti-cyclonic vortices are local pressure maxima and can therefore trap large quantities of dust particles with relatively small (factors of a few percent) increases in the gas density. One suggestion for how these vortices arise is through the Rossby wave instability (e.g., Lovelace et al. 1999, Lin 2012, Meheut et al. 2012), a hydrodynamical instability that can be triggered by the presence of a nearby giant planet. However, there are several problems with this idea. Firstly, there appears to be too small a giant planet fraction at large radius to be consistent with the fraction of discs that show such structures (Owen 2016). Secondly, vortices generated by the Rossby wave instability are prone to being disrupted and destroyed. For the scenario where the giant planet forms over the appropriate timescale (rather than the short simulated time adopted previously) the conditions for vortex formation are very difficult to achieve (Hammer et al. 2017). Understanding what mechanism generates the observed asymmetries and how they are related to planet formation is crucial as these lopsided discs will be some of the prime targets for observations for the next decade.

Project: accretion luminosity generated vortices

To overcome the short comings of the Rossby wave instability model for vortex formation, I recently proposed a new mechanism for large scale vortex generation in protoplanetary discs. In Owen & Kollmeier (2017), I demonstrated that thermal feedback from an accreting low-mass planet could locally heat a small patch of the disc making it baroclinic. Baroclinic regions are naturally unstable to vortex generation and can result in the production of a large scale vortex. Using gas only simulations, I showed that such a process could produce vortices of the required size to explain the observations (see Figure 2). I am requesting funding for one four-year Ph.D. student and the necessary computation equipment to explore the generation of large-scale vortices in protoplanetary discs from accreting low-mass planets. I have shown this mechanism is robust, yet many of the details have yet to be worked out, particularly any qualitative links to the observations, making it the perfect project for a Ph.D. student. The objectives of this project are as follows:

- Explicitly include the dust in the simulations of vortex formation and their feedback on the accretion luminosity.
- Follow the long-term evolution of the planet and vortex.
- Calculate synthetic observations from the simulations both in gas lines and in the continuum, making predictions for future observations.

Part I: dust feedback – *Year 0 → Year 1.5*

The source of the solid material that accretes onto the forming planet are dust particles in the form of "pebbles" (mm to cm sized dust particles), through a process known as pebble accretion (e.g., Lambrechts & Johansen 2012). Dust particles and pebbles experience drag forces from the gas disc which cause them to drift towards regions of high pressure. Therefore, dust particles and pebbles will drift towards and become trapped in an anticyclonic vortex. Furthermore, when these pebbles become trapped in the vortex, they will no-longer be available to accrete onto the forming planet. Once the accretion rate onto the planet drops, so will its accretion luminosity. If the luminosity becomes too small, the disc will no-longer be baroclinic and unstable to vortex formation. This will lead to a duty-cycle, where accretion onto the planet forms a vortex, the vortex then traps the pebbles, which shuts off accretion onto the planet. The vortex will then dissipate after some time releasing the dust particles and pebbles which are then free to accrete onto the planet, starting the process over again. Simulating this cycle has not been done before and requires the dust particles and pebbles to be explicitly included in the simulations. To complete this goal, the student will build a model for the luminosity output of an accreting planet as a function of accretion rate and time, both analytically and numerically. This model can then be used to calculate the disc temperature around the forming planet.

The student will then use the FARGO hydrodynamics code (specifically designed for protoplanetary discs) to follow the evolution of the gas, dust and the accreting planet. Since FARGO is optimized to use GPU architectures, I have specifically requested funds to purchase this specialised computer equipment. Dust particles have recently been included in FARGO by collaborators of mine, who have made the modifications freely available for this project. The student will then calculate the evolutionary cycle, making predictions of the fraction of time the disc should present with a vortex or not. These simulations will consist of a significant number of 2D runs (R, ϕ) and several 3D runs. The student will also include self-gravity of the gas disc itself as this has been shown to affect the evolution of vortices in discs (Lin & Papaloizou 2011; Zhu & Baruteau 2017).

Part II: long-term evolution – *Year 1.5 → Year 2.75*

In part I the student will have studied the cycle between planet accretion and vortex generation. However, these simulations will still only last a fraction of the total disc's lifetime. On these longer timescales, the planet can gravitationally interact with the gas disc and migrate, changing its orbital location. In part II, the student will identify observationally relevant setups from the simulations in part I by comparison to the data. The student will then follow these simulations for longer times, similar to the million year lifetime of protoplanetary discs; to do this the student will parametrise the details of the dust-feedback on the vortex formation. These simulations will be carried out in 2D only for feasibility, and in some cases will be gas only. Calculating the long term evolution will then allow the student to make predictions as to the final properties of the formed planets (masses, orbital separation, etc.), as well as the orbital distances at which vortices should and should not be seen.

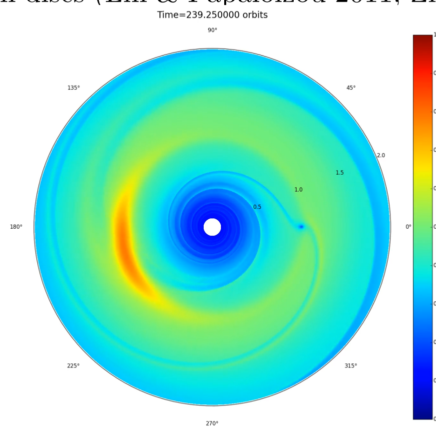

Figure 2: *The output of a gas only simulation of vortex generation by an accreting low-mass planet. The colour map shows the gas surface density, where a large scale vortex is present on the left-hand side of the disc (Owen & Kollmeier 2017).*

Part III: calculation of synthetic observations – *Year 2.75 → Year 3.5*

Simulations performed in this project will be accurate enough to be directly compared to the observations since they will include the dust particles. The student will then post-process their simulations using the publicly available RADMC code to make synthetic observations. In the continuum, this will include simulated images as a function of wavelength and time. The student will specifically look at how the continuum contrast in the vortex evolves as a function of time, allowing them to use the current observations to make inferences about ongoing planet formation in the observed systems. The student will also collaborate with colleagues at Imperial to follow the chemical evolution of gas-phase species to predict the molecular gas species that will be present with and without the forming planet to make unique predictions about what the accretion luminosity generated vortices should look like in molecular lines accessible with ALMA.

If time allows the student will then collaborate with observational astronomers to propose for observations to test the model they have developed. Many of the continuum images will be obtained independently within the time frame of the Ph.D. project; however, specific gas phase molecular ALMA observations are likely to need a specific proposal. These gas-phase predictions will allow the student to collaborate with astrochemists and observers, people they may not ordinarily interact with during their Ph.D. program. The final six months of the project is allotted to the student's thesis preparations and any overrun if necessary.

Summary

In this project, a Ph.D. student, under my primary supervision will study the interaction between a forming low-mass planet and its parent protoplanetary discs. They will examine how this process can lead to vortex formation and its relevance to current state-of-the-art observations, using numerical models and simulations. They will gain skills in radiative transfer, numerical hydrodynamics, and high-performance computing.

References: Hammer et al., 2017, MNRAS 466 3533 ■ Lambrechts & Johansen, 2012, A&A 544 32 ■ Lin & Papaloizou, 2011, MNRAS 415 1426 ■ Lin, 2012, ApJ 754 21 ■ Lyra & Lin, 2013, ApJ 775 17 ■ Lovelace et al., 1999, ApJ 513 805 ■ Meheut et al., 2012, MNRAS 422 2399 ■ Owen, 2016, PASA 33 e005 ■ Owen & Kollmeier, 2017, MNRAS 467 3379 ■ Pérez et al., 2014, ApJ 783 L13 ■ van der Marel et al., 2013, Science 340 1199 ■ Zhu & Baruteau, 2017, MNRAS 458 3918