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# Investigating Effect of Planet Migration Speed on Gap Opening in Protoplanetary Disks

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# Abstract

A massive planet opens a gap in protoplanetary disks through disk-planet interactions. The criteria for gap opening is based on torque balance and depends on mass of the planet. In this project, we aim to understand how fast a Jupiter mass planet has to drift such that it does not open a gap. This shall allow us to develop a limit on the planet's migration speed to open a gap. This hydrodynamical problem is solved using a two-dimensional (2D) physical model and numerical approach. We use a *Python* package "Pyrodeo" which is an implementation of RODEO (ROe solver for Disk-Embedded Objects) and solve inviscid isothermal hydrodynamics. We simulate the system for different cases of migration speed and find that giant planets do not open gaps in disks in cases where they migrate at 30% of sound-speed or higher.

# Contents

# List of Figures

# 1 Introduction

Since ancient times, planets have always been central for civilisations. Various philosophers and ancient Greek astronomers have tried to understand the motion and origin of planets. The term *planet* itself originated from the Greek word *planetai* meaning wanderers. Over the last centuries astronomers including Tycho Brahe, Galileo Galilei, Nicolaus Copernicus and Johannes Kepler have developed theories or observed planets and their origin was debated. However, not much was known until the late $20^{th}$ century about how planets really evolved and how the Solar System came to be as seen in the present day.

The first planet outside the solar system was discovered in 1992 (Wolszczan and Frail (1992)) and since then there has been a growing number of discoveries of exoplanets. These discoveries have helped to test and modify theories of planet formation and evolution. Although progress has been made over the last three decades in this field, further work needs to be done to explain the vast diversity of planet population. Both ground based telescopes, like Atacama Large Millimeter/submillimeter Array (ALMA) and Very Large Telescope (VLT), as well as telescopes in space have aided in these discoveries. After the launch of the Kepler telescope in 2009, there has been an unprecedented growth in data, and the number of known exoplanets has increased to more than 3500 in just 10 years. After completing its primary and extended missions, Kepler telescope was retired last year and the work is being carried forward by Transiting Exoplanet Survey Satellite (TESS). Future telescope like James Webb Space Telescope (JWST) will help us to test our present understanding of planetary systems and refine planetary models.

Amongst other relevant findings, one of the most surprising observations in the field of planetary systems has been the discovery of objects called **Hot Jupiters**. These objects have similar mass to that of Jupiter but orbit around their host star in much shorter time period, usually in days. They orbit the star at close distances, usually 0.1 AU, hence the name hot Jupiters. Early discoveries of such exoplanets, like in Mayor and Queloz (1995), raised speculation if these hot Jupiters were indeed formed in-situ or if they migrated to their present locations. Over the last decade, a plethora of hot Jupiters has been discovered and it is widely believed to have been a result of planet migration. Thus, in order to completely explain the wide distribution of planets based on their orbital distance, inclination, and eccentricity it is extremely important to study the origin of planets and evolution of planetary systems.

This report shall begin by looking at the basics of star formation, which leads to the formation of a circumstellar disk. Such a disk is the cradle of planet formation. In the next chapter (2), structure of this disk shall be discussed. Chapter 3 deals with the underlying physics of how a planet embedded within a disk interacts with the disk and its effects. Chapter 4 delves further into the topic of planet-disk interactions and the question that this project attempts to answer is laid on the table along with a description of the physical model. It also discusses the numerical simulations that this project is based on, while chapter 5 puts forward the results and draws a conclusion of the project report.

## 1.1 An Overview of Star Formation

The solar system is believed to have been formed from the collapse of an original solar nebula which was less dense to begin with, and was perturbed by a shock front from a nearby exploding supernova (Carroll and Ostlie (2007)). This led to the formation of a proto-Sun surrounded by an accretion disk from which the planetesimals, meteorites, comets and planets must have been formed. Thus, formation of planets is directly linked to formation of protostars and accretion disks and this section shall explore the formation of protostars in brief.

A **protostar** is an extremely young star, which is in the early stages of evolution of a star. At this stage, the star has not yet started hydrogen fusion and has thereby not joined the main sequence in the Hertzsprung-Russell (H-R) diagram. Cores of interstellar molecular clouds are the nurseries of star formation. Fig. 1.1 shows a region in $\rho$ Ophiuchi dark cloud where young stars have been detected (Pillitteri et al. (2016)). If a certain mass criterion, known as *Jeans mass criterion*, is satisfied then dense molecular clouds can collapse rapidly under their own gravity and lead to the formation of protostars. This was first studied by Sir James Jeans in 1902 by considering *hydrostatic equilibrium* and *Virial theorem*.

Let us consider a spherical molecular cloud of mass $M$ and with uniform density $\rho$. The gravitational potential energy $U$ for a self-gravitating sphere can be calculated

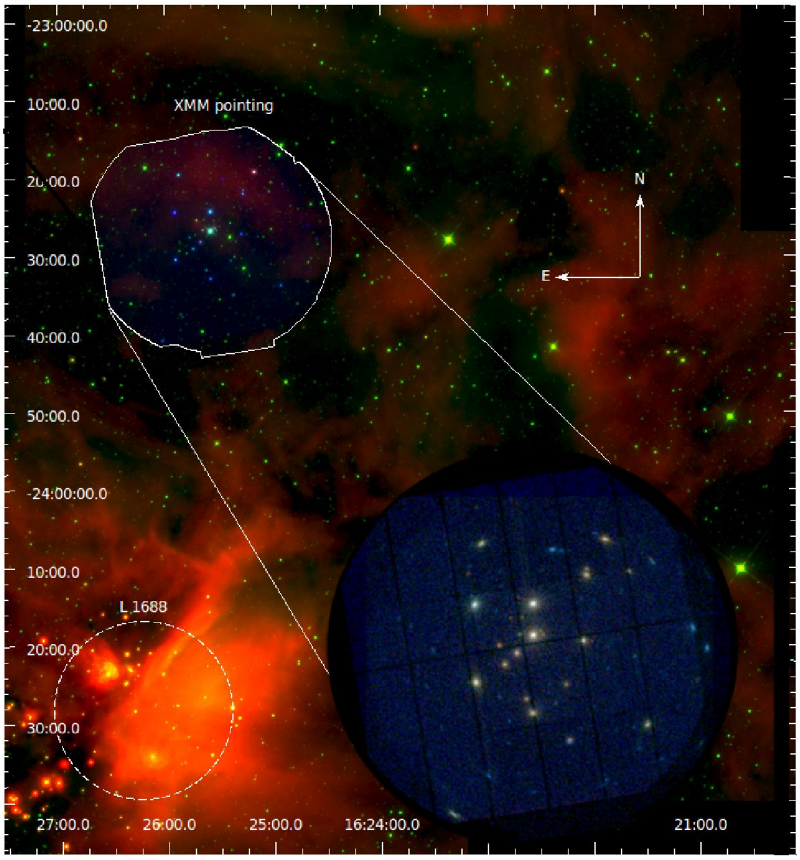


Figure 1.1: A composite RGB image from Wide-field Infrared Survey Explorer (WISE) images and XMM-Newton sources shows stars in $\rho$ Ophiuchi dark cloud. Adapted from: Pillitteri et al. (2016)

by integrating potential energy for the sphere of radius $R$, and is given by:

$$U = -\frac{3}{5}\frac{GM^2}{R} \tag{1.1}$$

For an isolated, gravitationally bound system the relationship between kinetic energy, $K$ and potential energy is described by the Virial Theorem:

$$2K + U = 0 \tag{1.2}$$

The molecular cloud is predominantly formed of hydrogen and can be assumed as a monoatomic gas. From thermodynamics, we know that kinetic energy for $N$ number of particles in an ideal, monoatomic gas is related to its average temperature $T$ by:

$$K = \frac{3}{2}Nk_BT \tag{1.3}$$

where $k_B$ is the Boltzmann constant. If $\mu$ is the mean molecular weight, mass of hydrogen is $m_H$, and mass of the entire gas cloud is $M$, then $N$ can be rewritten as:

$$N = \frac{M}{\mu m_H} \tag{1.4}$$

The gas collapse begins when the magnitude of gravitational potential energy is more than the internal kinetic energy, such that $\mid U \mid > 2K$. So this critical criterion can be written as:

$$\frac{3}{5}\frac{GM^2}{R} > \frac{3Mk_BT}{\mu m_H} \tag{1.5}$$

Also, density is related to mass as $M = \frac{4}{3}\pi R^3 \rho$. So Eq. 1.5 can be expressed as:

$$M = \left(\frac{5kT}{G\mu m_H}\right)^{\frac{3}{2}} \left(\frac{3}{4\pi\rho}\right)^{\frac{1}{2}} \tag{1.6}$$

Eq. 1.6 is known as the Jeans mass criterion and if the mass of the molecular cloud is bigger than Jeans mass, the gas would collapse under self-gravity. In an uniform gas cloud all parts of the cloud would collapse at the same time under free-fall once the Jeans mass criterion has been satisfied. The free-fall timescale is given by Eq. 1.7, and a detailed derivation may be found in Carroll and Ostlie (2007):

$$t_{ff} = \left(\frac{3\pi}{32}\frac{1}{G\rho}\right)^{\frac{1}{2}} \tag{1.7}$$

It is evident from the above equation that the free-fall timescale is inversely proportional to the density of the cloud. Thus, as the collapse begins, the gas would be compressed and density would increase leading to shorter timescales. The collapse timescale is, in fact, quite short and is in the order of $10^5$ years. In addition to this, the initial molecular cloud may have inhomogeneities in density which may lead to fragmentation of the cloud and cause formation of a system of stars or cluster, rather than a massive star.

In the above discussion, several factors such as external pressure on the cloud, rotation, and magnetic fields were ignored although they may have an effect on the process of protostar formation. In particular, the effect of rotation is important in order to understand circumstellar disks. A spherically symmetric cloud may have an initial angular momentum due to rotation of the gas cloud. As the collapse begins, the radius of the cloud would decrease and due to conservation of angular momentum, the angular velocity of the cloud would increase. This would lead to a flattened disk-like structure surrounding the protostar, popularly called as **protoplanetary**

**disk**.

## 1.2 Planet Formation

Understanding planet formation is essential in order to understand the distribution of ranges of eccentricity, inclination and orbital periods of exoplanets. A look at these parameters for our solar system imply one fact immediately: the planets in our solar system must have a common origin and probably followed a similar path in their evolution because mostly their orbits lie on a plane with very little inclination. Also, most meteorites are older than 4.5 billion years which originate from the asteroid belt and they are almost as old as the solar system (Pfalzner et al. (2015)). In fact, the theory that planets form from a protoplanetary disk is supported by observations (Sec. 2.2), which makes its case stronger. From observation of masses in a planetary system, a minimum mass solar nebula can be derived which is the minimum amount of original gas that must have been present to create the planetary system.

The story of planet formation begins with a protoplanetary disk around its host star. These disks are made of dense gas and dust. Dust particles of a few microns collide and stay together due to interatomic forces. With time they "settle" and coagulate while growing in size. Growth in dust disks is still in debate but it is believed that as particles grow in size, gravitational forces take over intermolecular forces. This leads to the formation of metre sized "rocky" objects. These objects continue to grow further through collisions and form kilometre sized "planetesimals". After this stage, collisions continue and runaway growth leads to formation of larger but less numerous masses. The orbits of these young Earth-mass planets are refined by resonances and crossing orbits which lead to more collisions. This is how most terrestrial planets form (Armitage (2007)).

There are two dominant theories of formation of gas giants like Jupiter. The first model is called "core accretion model" (Mizuno (1980)), in which a rocky core initially forms, as discussed above. In the presence of a gas disk, the core is able to accrete gas from the disk. The core of a few Earth-masses is able to retain an envelop through hydrostatic equilibrium. The core can continue to accrete mass until the nebula has dissipated away or the planet has opened a gap in the disk. The planet may also migrate due to planet-disk interactions and this is explored further in chapter 3. Gap opening by Jupiter mass planets is an active area of research and is one of the main interests of this project.

According to another model, known as the “gravitational instability model” (Cameron (1978)), planets can form when parts of the gas disk become unstable and fragment and collapse under self-gravity. This model cannot explain the existence of dense cores in giant planets and how smaller objects like meteorites formed. Also, numerical simulations show that the timescale of formation would not be rapid enough to allow planets to reach Jupiter-masses before the gas dispersed.

# 2 Protoplanetary Disks

Protoplanetary disk is the result of star formation and is the birthplace for planet formation. In this chapter, the disk structure and physical parameters that govern it shall be discussed and some observational evidence of these disks shall be presented. Protoplanetary disks are quite difficult to study given their short lifespans of less than 10 Myr (Haisch et al. (2001)) and various physical factors that define their structure.

When a dense molecular cloud collapses to form a protostar, conservation of angular momentum causes the spherical cloud to speed up due to rotation as the disk radius shrinks. This rotation causes the disk to flatten out and the thickness to radius ratio of the disk is much smaller than unity. The timescale for this collapse to happen is in the order of $10^5$ years, after which the protostar may continue to accrete material from the disk and can be accompanied by jets. Such disks (ALMA Partnership et al. (2015)) are sometimes observed around T Tauri stars, which are a class of young variable stars in the pre-main sequence stage. The mass of the disk is much less than that of the stellar object and is made up of dust and gas. These disks can get heated up due to radiation and become visible in IR and near-IR bands of the electromagnetic spectrum. Spectroscopic studies of dust-disks (Pott et al. (2010)) inform us about their composition and properties.

## 2.1 Structure of Disk

The structure of the protoplanetary disk can be studied by simplifying the physics involved in the disk. For the purpose of this project, let us begin with a simple model in which the vertical component of stellar gravity is supported by gas pressure in the disk. The interest here is to develop a relation of disk density $\rho(r, z)$ in terms of vertical height $z$. The disk model is assumed to have negligible self-gravity in comparison to the stellar gravity and is isothermal. In this case, the pressure $P$ is related to density $\rho$ by $P = {c_s}^2 \rho$ (Armitage (2015)). Here, $c_s$ is the speed of sound

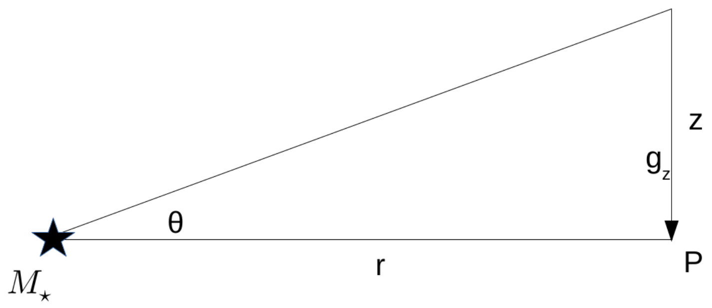


Figure 2.1: Vertical component of stellar gravity ($g_z$) in a protoplanetary disk at a distance $r$ from the star.

in the medium of the disk, and is related to temperature by,

$$c_s^2 = \frac{k_B T}{\mu m_H} \tag{2.1}$$

where symbols have their usual meaning as defined in section 1.1. Using cylindrical coordinates, with a star of mass $M_\star$ at origin and applying hydrostatic equilibrium equation at mid-plane ($z = 0$) at point P, which is at a radial distance $r$ from the star (Figure 2.1):

$$\frac{dP}{dz} = -\rho g_z = -\frac{GM_\star}{r^2 + z^2} \sin\theta \, \rho \tag{2.2}$$

where $g_z = \frac{GM_\star}{r^2+z^2} \sin\theta$ is the vertical component of the stellar gravity.
Also, $\sin\theta = z/(\sqrt{r^2 + z^2})$, so Eq. 2.2 can be expressed as:

$$\frac{dP}{dz} = -\frac{GM_\star}{r^2 + z^2} \frac{z}{\sqrt{r^2 + z^2}} \rho \tag{2.3}$$

Since such disks are thin compared to their radial extent, it can be assumed that $r \gg z$, such that Eq. 2.3 becomes:

$$\frac{dP}{dz} = -\frac{GM_\star}{r^3} z \, \rho \tag{2.4}$$

Let us now define $\Omega_K = \sqrt{GM_\star/r^3}$ as the Keplerian angular velocity. Using the isothermal equation of state, Eq. 2.4 takes the form:

$$c_s^2 \frac{d\rho}{dz} = -\Omega_K^2 \, z \, \rho \tag{2.5}$$

$$\implies c_s^2 \frac{d\rho}{\rho} = -\Omega_K^2 \, z \, dz \tag{2.6}$$

Integration of both sides from limits $z = 0$ to $z$ and $\rho(z = 0) = \rho_o$ gives us:

$$\rho(z) = \rho_o \exp\left(-\frac{z^2}{2H^2}\right) \tag{2.7}$$

where $H = c_s/\Omega_K$ is the **vertical scale height**. Eq. 2.7 describes the vertical profile of density of the disk and form of the equation shows us that it has a Gaussian shape. The vertical scale height is the height above the disk mid-plane ($z = 0$) at which the mid-plane density $\rho_o$ drops by a factor of $e$. At large radial distances, the scale height would drop quickly and the disk can be effectively treated as a two-dimensional structure. $H/r \approx 0.05$ for typical cases, which essentially means that the disk thickness can be ignored for practical purposes. Other factors such as adiabatic thermal profile or magnetic pressure may be present. However, these regimes shall not be discussed in this report.

## 2.2 Observations: Stars with Protoplanetary Disks

With the advent of telescopes such as ALMA and VLA, high resolution images of protoplanetary disks have been obtained recently. Analysing and characterising these images are crucial because they help us constrain and test our models. Although direct imaging of protoplanets is rare, gaps in disks can be observed due to light scattered by the dust in disk or from thermal emission. As we shall see in Ch. 3, numerous simulations of gap opening in protoplanetary disks have been performed in past two decades. The gaps and spiral density wave patterns observed in such simulations closely match the data from direct imaging. For example, hydrodynamical simulations of the protoplanetary system AS 209 showed the presence of a giant planet which is responsible for opening a dust gap, and corresponds to ALMA 1.3 mm dust continuum observations of the system (Fedele et al. (2018)). These gaps, found in many protoplanetary disks, could possibly be regions of planet formation and may have been carved out by young and evolving planets. The wavelength of the light scattered depends on the size of dust in the disk. Gas and dust dynamics need to be decoupled before disk evolution process may be understood completely. There is an ever-growing list of protostars with disks and a few examples are presented here.

Fig. 2.2 shows ALMA 1.3 mm dust continuum image of protoplanetary system AS 209. A central bright object is observed along with dust rings and gaps. Numerical

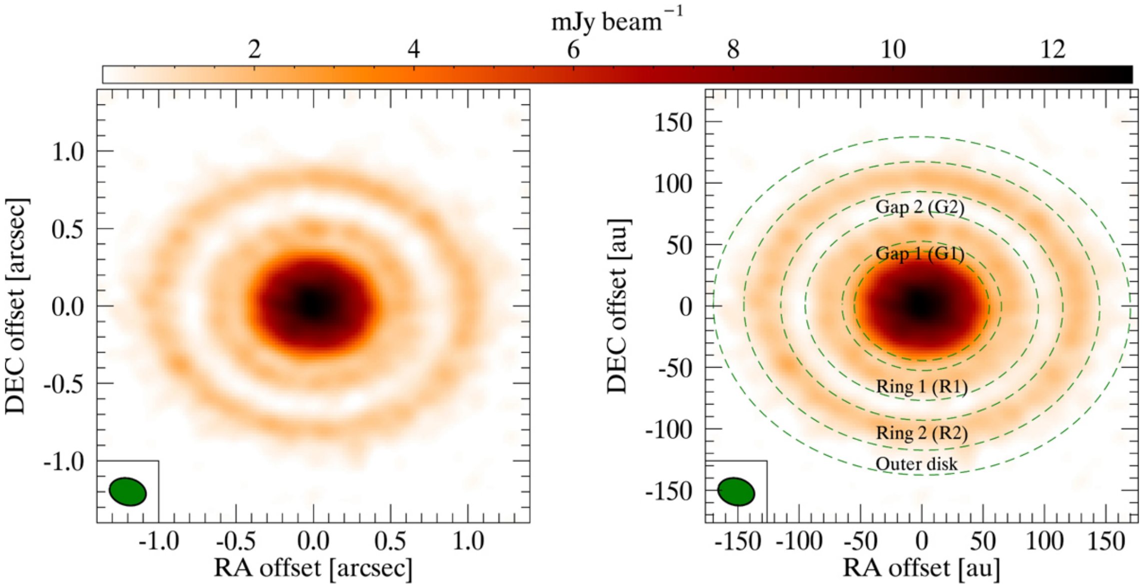


Figure 2.2: ALMA 1.3 mm dust continuum image of protoplanetary system AS 209. Some of the structures and gaps identified in the disk are shown on right side. Adapted from: Fedele et al. (2018)

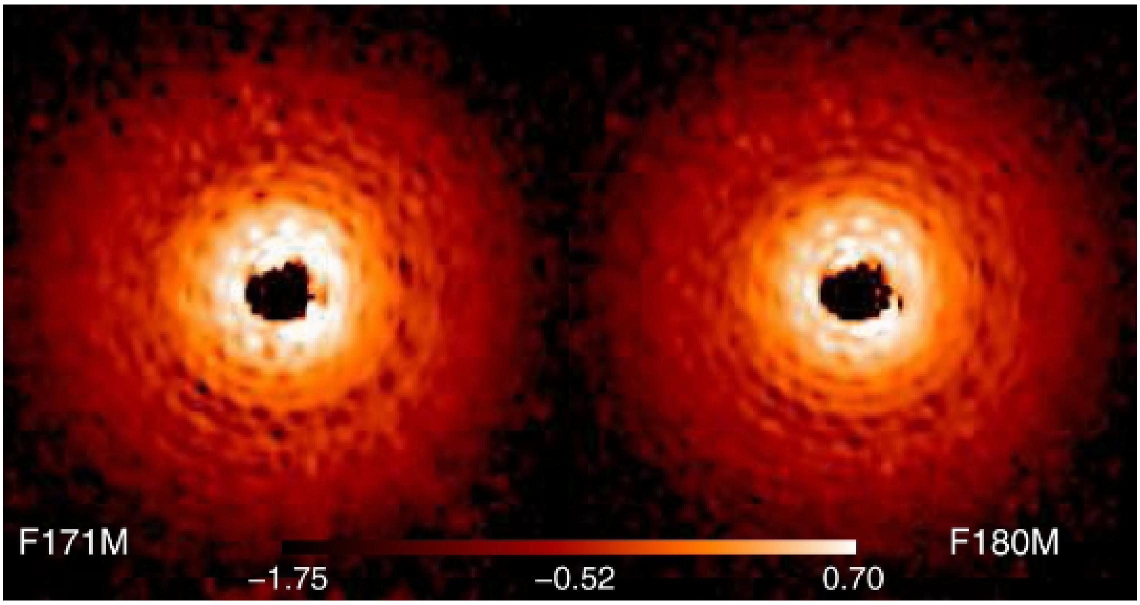


Figure 2.3: Scattered light spectrum of TW Hya in medium band filters. The central region with no data has been blacked out. A circumstellar disk around the central star is visible. Adapted from: Debes et al. (2013)

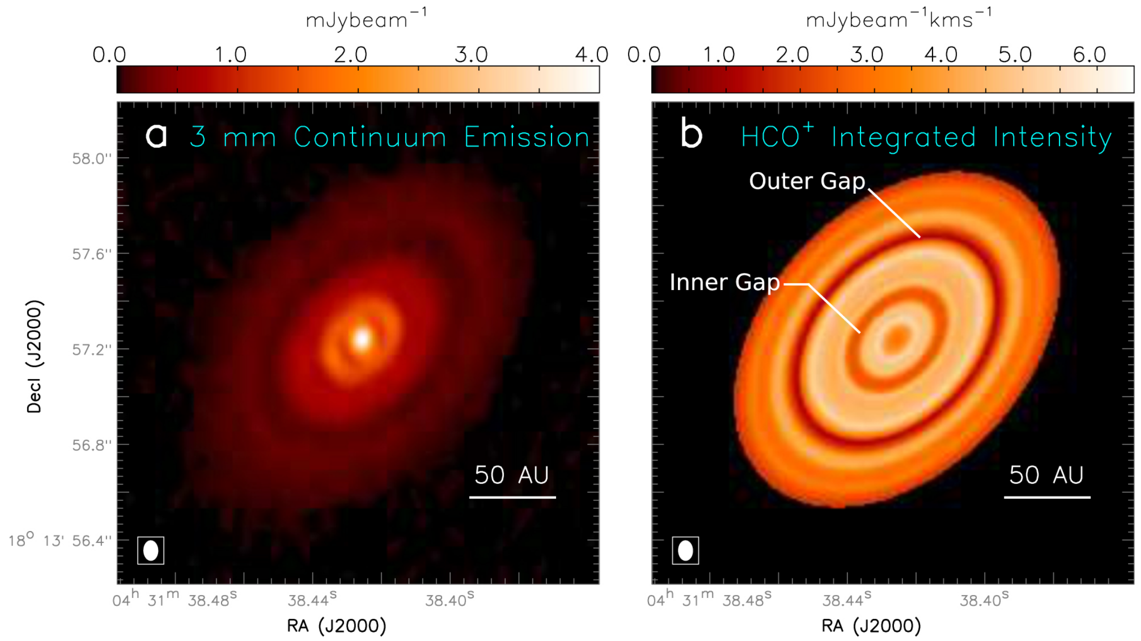


Figure 2.4: 3 mm continuum image of disk around HL Tau observed with ALMA shows ring-like gaps. On right, is the high resolution image of $HCO^+$ integrated intensity of the disk with distinct gaps. Adapted from: ALMA Partnership et al. (2015)

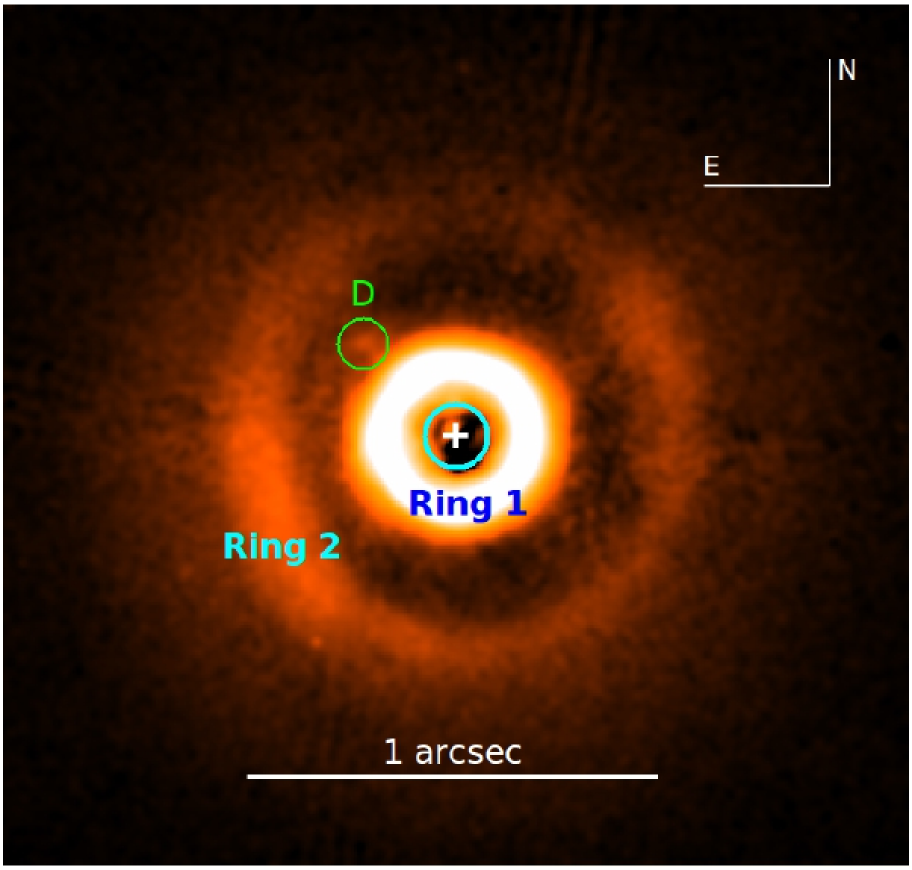


Figure 2.5: Polarimetric observation of the disk surrounding HD 169142 shows rings and faint structures. The central circle refers to the mask used in imaging while circle labelled "D" shows an interesting blob which may be linked to planet formation. Adapted from: Gratton et al. (2019)

simulations show that the gap has been carved out by a Saturn-like planet. Fig. 2.3 shows a circumstellar disk around TW Hya which is a T Tauri star. Independent studies and hydrodynamical simulations suggest the existence of a protoplanet embedded in the dust disk (Debes et al. (2013), Setiawan et al. (2008)). A 3 mm continuum image of disk around HL Tau, which is another young T Tauri star, is shown in Fig. 2.4. The spectacular image obtained using the ALMA long baseline campaign shows clear gaps at around 28 AU and 69 AU (ALMA Partnership et al. (2015)). Comparisons with analytical framework and numerical studies suggest that these gaps have been opened by Jupiter-mass or Saturn-mass planets. Fig. 2.5 shows a protoplanetary system around young star HD 169142, observed with VLT, with atleast three rings and spiral structures. Polarimetric observations shows blobs which may have originated due to the presence of a planet and might be responsible for the spiral structures (Gratton et al. (2019), Quanz et al. (2013)). Such observations help us put tight constraints on analytical and numerical models of planet formation, disk structure and gap opening. There is now a general consensus that planets form in protoplanetary disks around young stars and often migrate or clear ring-like gaps in the disk (Baruteau et al. (2014)).

# 3 Planet-Disk Interactions

In section 1.2, the basic theories of planet formation were discussed. Once a planet has been formed, or even during its formation, it can interact with the surrounding gas in the disk. In this chapter, the physics regarding these planet-disk interactions is described. These interactions are a continuous process during the evolution of a planetary system and are due to angular momentum exchanges between the planet and gas in the disk. Planet-disk interactions are believed to be a major ingredient in planetary system formation and can modify almost all the physical parameters of a planet such as eccentricity, inclination and semi-major axis (Baruteau et al. (2014)). It can also change the density distribution of the disk and the scale height $H$ as defined in section 2.1. Understanding the underlying physics of these interactions and developing numerical simulation techniques can help us understand the statistical distribution of properties of exoplanets.

Since the discovery of a hot Jupiter around star 51 Pegasi (Mayor and Queloz (1995)), many such giant exoplanets with orbital period less than 10 days have been discovered. The main school of thought is that these hot Jupiters did not form in-situ and must have migrated inward towards the star from their original location of formation. This is well supported by numerical simulations, for example Coleman and Nelson (2016), who showed agreement between inward migration of giant planets and the occurrence rate of hot Jupiters (Wang et al. (2015)). Dawson and Johnson (2018) suggest that about one in ten giant planet systems have a hot Jupiter. Although there are discrepancies in the occurrence rates of hot Jupiters, it is most likely that planet migration and planet-disk interactions are quite common in the evolution of planetary systems. Data from Kepler mission and the broad distribution of eccentricities and inclination of hot Jupiters have helped in putting constraints on planet-disk interaction models. Thus, these interactions play a prominent role in defining orbital period and semi-major axis of young planets.

## 3.1 Planet Migration

The theoretical foundation for excitation of density waves in a two-dimensional gas disk and rate of angular momentum transfer between disk and planet was studied in detail by Goldreich and Tremaine (1979) and Goldreich and Tremaine (1980), many years before the discovery of the first exoplanet. It is important to mention here that in planetary systems, resonances play an important role and may have physical implications. A **resonance** occurs when two frequencies have an "integer" relationship with each other. Many exoplanets discovered using the Kepler telescope are resonant systems, and in our solar system itself there are numerous examples of such orbital resonances.

In planet-disk interactions, resonances are important because angular momentum exchanges occur at these locations. Presented here, is a review of this background theory, adopted from Armitage (2007) and Baruteau et al. (2014). Let us assume a planet of mass $M_p$ is orbiting a star with angular frequency $\Omega_p$. There are two types of resonances, namely *corotation* and *Lindblad*, which are the locations where density waves can originate. If orbital frequency $\Omega$ equals $\Omega_p$, it results in corotation resonance. In contrast, Lindblad resonance originates when the condition,

$$m(\Omega - \Omega_p) = \pm\kappa_o \tag{3.1}$$

is satisfied, where $m$ is an integer number and $\kappa_o$ is *epicyclic frequency* of the disk. In Eq. 3.1, the $+$ sign corresponds to the inner part of a Lindblad resonance, whereas $-$ sign refers to the outer part of the orbit of the planet. So, for every value of m, there are two Lindblad resonances. At resonant locations, as a result of conservation of angular momentum, the planet interacting with disk on the inner part gains angular momentum, while the gas loses it. This leads to the planet being driven outward. By converse argument, a planet-disk interaction in the outer region makes the planet lose angular momentum and migrate inwards towards the star. At locations of these resonances, spiral density waves are excited that take energy and momentum away from the planet, resulting in a torque on the planet. The sign and magnitude of the torque determines the direction and speed of migration of a planet. A negative torque drives the planet inward, which is usually the case (Lubow and Ida (2010), Kley and Nelson (2012)). The effects of pressure, temperature and self-gravity have not been taken into account here.

The second type of torque, *corotation torque*, arises at locations where angular frequency at that point is same as the planet's angular frequency. The corotation torque has a complicated dependence on surface density, disk's viscosity and temperature and is still an area of active research. The density waves launched due to corotation torque do not propagate away and remain localised in the region, called *horseshoe region*, around resonance. This type of torque may have a positive value. However, a three-dimensional study of planet-disk interactions in an isothermal profile was done by Tanaka et al. (2002), and it was found that Lindblad torque almost always dominates over corotation torque. These interactions and torques govern planet migration and there are three types of migration: namely Type I, Type II and Type III. These regimes, of which we shall discuss Type I and Type II, are dependent on planet mass, viscosity of disk and they determine the rate of migration and structure of the disk.

## 3.2 Type I Migration

Planets of few Earth-masses, i.e. so-called *low-mass* planets, do not perturb the density of the disk significantly and planet-disk interactions can be treated as a linear theory. In this case, the total torque on the planet is a sum of all the torques at each value of integer $m$. As a result of the net torque on the planet, the semi-major axis of the planet undergoes changes and this is termed as **Type I migration**. The total torque is directly proportional to $M_p^2$, while the migration time-scale varies as inverse of $M_p$. This means that planets with heavier masses will migrate faster. In fact, it is found that Type I migration timescales are extremely short when compared to disk lifetimes (Armitage (2007)). If these simplified disk structures are assumed correct, a planet would fall into the star as it migrates inward fast. This poses as a serious challenge to planet formation theory and is one of the open questions. The fact that problems exist with this model shows that, in real, more complicated disk structures exist and Type I migration needs to be made less efficient. Type I migration can be slowed down or stopped by improving the model to include stronger corotation torques, sharp density gradients in the disk and studying the effect of magnetic fields. Evaluating the torque on the planet is not simple. The corotation torque which contributes to the net torque gets saturated, unlike the Lindblad torque. This is due to the absence of angular momentum exchange in the horseshoe region. Over the last decade or so, numerical simulations have helped to improve the torque formula. Paardekooper and Mellema (2006b) showed that Type I migration rate is also affected by the temperature profile of the disk. Paardekooper and Papaloizou (2009) studied corotation torques on low-mass planets embedded in isothermal disks using two-dimensional calculations and a good agreement between linear and non-linear approaches was found. Three-dimensional numerical simulation of disk-planet torques in a locally isothermal disk was done by D'Angelo and Lubow (2010), the results of which are in good agreement with the analytical calculations.

## 3.3 Type II Migration

In the case where planet mass is larger and is of the order of Jupiter-masses, the planet-disk interactions become non-linear and this can change the density distribution in the disk. Torque exchanges between the planet and disk can push the gas in the disk away from the planet, such that the surface density of the disk around $r = r_p$ drops causing a gap. This is called *gap opening* by a planet, and it is a ring-shaped region along the planet's orbit where density is lesser than the average surface density. Due to damping of angular momentum by viscosity, the disk on the inner part of the orbit loses angular momentum, and moves further inwards away from the planet. Similarly, the gas disk outside the planet's coorbital region gains angular momentum and moves away from the planet's orbit. This process leads to the formation of a deep gap (Lin and Papaloizou (1986)). In addition to the viscous damping criteria, the Roche radius of a planet must be of the same order as the disk thickness $H$ in order to open a gap. Roche radius is given by,

$$r_{Roche} = \left(\frac{M_p}{3M_\star}\right)^{\frac{1}{3}} \tag{3.2}$$

In general, planets of the order of Saturn-masses or more can open a gap. The planet is *tidally locked* in the gap and gets pushed towards the centre of the gap. This planet migrates inwards and the timescale is given by viscous evolution (Ward (1997)) and is known as **Type II migration**. In the annular gap region, the corotation torque is negligible and this results in slower migration rate. Effectively, the migration speed of Type II is lesser than Type I. There have been many numerical simulations that explore this type of migration and the disk properties that affect its migration speed, for example Robert et al. (2018). Also recent observations, as mentioned in section 2.2, brings home the idea that gaps observed in disks are most likely carved by planets and these interactions are central to the physics of planet formation and disk structure evolution.

# 4 Physical Model

Over the past decade, an area of active research has focused on understanding the regimes of Type I and and Type II migration, and the conditions under which planets open a gap in a disk. Although progress has been made regarding the torque criterion for gap opening (Crida et al. (2006)), a consensus has not yet been reached. It has been stated in Crida and Bitsch (2017) that migrating giant planets always open a gap once the mass condition has been satisfied. The question, that this project aims to answer, is whether this is true for all giant planets irrespective of their migration speed. Such challenging questions are best tackled by using numerical methods and since early 2000s hydrodynamical simulations have taken the spotlight in this field. Numerical simulations allow researchers to study specific questions by simplifying the problem and analyse the dynamics of angular momentum exchange and study the density structure of disk as a function of time.

In this project two-dimensional (2D) hydrodynamical simulation is used to study the effect of migration in a protoplanetary disk. Three-dimensional (3D) modelling is computationally expensive and 2D modelling is usually the preferred choice so that detailed numerical analysis can be done. 2D treatment of protoplanetary disks is a good trade-off between realistic modelling and computational complexity, because such disks are thin (see section 2.1) and may be effectively treated in a 2D setup. The 2D approach uses a vertical averaging technique where state variables are integrated in the vertical ($z$) direction. This means that $z$ vanishes from the equations and equations need to be solved only in two dimensions. The equations involved in the model are discussed in the following section.

## 4.1 Basic Equations

We use cylindrical coordinates $(r, \phi, z)$ to model a disk in 2D, such that the disk lies in the $z = 0$ plane. The disk is centred on the star at $r = 0$. Here, $r$ is the radial coordinate while $\phi$ is the azimuthal coordinate. The basic governing equations are obtained from conservation of mass and momentum. In the 2D setup, the continuity equation (Kley et al. (2012)) is given by:

$$\frac{\partial \Sigma}{\partial t} + \nabla \cdot (\Sigma \boldsymbol{v}) = 0 \tag{4.1}$$

where $\Sigma = \int_{-\infty}^{+\infty} \rho dz$ is the vertically averaged surface density and $\boldsymbol{v} \equiv (v_r, v_\phi)$ is the velocity vector in the plane of the disk. On considering the vertically integrated pressure $P$, gravitational and inertial forces, we get the momentum equation:

$$\frac{\partial \Sigma \boldsymbol{v}}{\partial t} + \nabla \cdot (\Sigma \boldsymbol{v}\boldsymbol{v}) = -\nabla P - \Sigma F_{total} \tag{4.2}$$

where $F_{total} = F_{gravity} + F_{inertial}$ is the external force, which is the sum of gravitational forces and Coriolis term arising from the rotating coordinate system. The self-gravity of the disk is not taken into account here.

Let a planet of mass $M_p$ orbiting a central star of mass $M_\star$, be located at $r = r_p$ and $\phi = \phi_p$. The net gravitational potential includes the stellar gravity as well as direct and indirect terms of the planet's potential and is given as :

$$\Psi(r, \phi) = -\frac{GM_\star}{r} + \frac{GM_p}{r_p^2} r\cos(\phi - \phi_p) - \frac{GM_p}{\sqrt{r^2 + r_p^2 - 2rr_p\cos(\phi - \phi_p) + \epsilon^2}} \tag{4.3}$$

To account for the 3D structure of the disk, the gravitational potential of the planet is treated as a softened point mass (Paardekooper et al. (2010)), and $\epsilon$ is the softening parameter. We define here the aspect ratio, $h = H/r_p$ where H is the local scale height. $\epsilon$ varies as $h$ and typical range of $\epsilon$ is from $0.4h$ to $0.6h$. To complete the set of equations, an equation of state is required. We limit the discussion to the isothermal temperature profile, such that the thermal structure of the disk is constant. In this case, the energy equation is not relevant and pressure P is related to surface density by $P = \Sigma c_s$ where $c_s$ is the isothermal sound speed in the disk and is given by (Paardekooper and Mellema (2006a)):

$$c_s = h\sqrt{\frac{GM_\star}{r}} \tag{4.4}$$

The isothermal case is valid if the disk radiates energy and cools efficiently.

In this project, we wish to study the effects of planet migration on the structure of the disk. To this end, we allow the disk to flow in the radial direction with a drift velocity $v_r = v_d$, while the planet is held fixed at $r = r_p$. The angular momentum transport equation is:

$$\frac{\partial}{\partial t}(r\Sigma L) + \frac{\partial}{\partial r}(r\Sigma L v_r) = \Gamma = \frac{1}{2}r^2\Omega_K\Sigma v_d \tag{4.5}$$

where angular momentum $L \equiv L(r) = rv_\phi$, $\Gamma$ is the torque and $\Omega_K = \sqrt{GM_\star/r^3}$ is the Keplerian angular velocity as defined in section 2.1. Eq. 4.5, which originates from the Euler equations, is of the form:

$$\frac{\partial \boldsymbol{W}}{\partial t} + \frac{\partial \boldsymbol{F}}{\partial r} = \boldsymbol{S} \tag{4.6}$$

Here, $\boldsymbol{W}$ is the state, $\boldsymbol{F}$ is the radial flux and $\boldsymbol{S}$ is the source term.

This project heavily relies on *Pyrodeo*, which is a *Python* implementation of RODEO (ROe solver for Disc-Embedded Objects). RODEO (Paardekooper and Mellema (2006a)) is a Roe solver aimed to model disk-planet interactions in protoplanetary disks. *Pyrodeo* uses the dimensional splitting technique to solve differential equations. In order to deal with source term, Eq. 4.6 is split into two ordinary differential equations which can be solved by standard integration techniques. The new equations are:

$$\frac{\partial \boldsymbol{W}}{\partial t} = \boldsymbol{S},\ \frac{\partial \boldsymbol{F}}{\partial r} = 0 \tag{4.7}$$

Then Eq. 4.5 reduces to:

$$\begin{aligned}
\frac{\partial}{\partial t}(r\Sigma L) &= \frac{1}{2}r^2\,\Sigma\,v_d\,\Omega_K \\
\implies r^2\,\Sigma\,\frac{\partial v_\phi}{\partial t} &= \frac{1}{2}\,r^2\,\Sigma\,v_d\,\Omega_K \\
\implies \frac{\partial v_\phi}{\partial t} &= \frac{1}{2}\,v_d\,\Omega_K
\end{aligned} \tag{4.8}$$

Also, from equation of continuity we have,

$$\frac{\partial}{\partial t}(r\Sigma) + \frac{\partial}{\partial r}(r\Sigma v_d) = 0 \tag{4.9}$$

Assuming steady state, the time derivative vanishes. This give us

$$r\,\Sigma\,v_d = constant \tag{4.10}$$

Choosing $v_d$ as a constant, gives us the surface density profile

$$\Sigma \propto \frac{1}{r} \tag{4.11}$$

## 4.2 Simulation Setup

In this project *Pyrodeo v0.0.9* has been used for simulating inviscid isothermal hydrodynamic equations in cylindrical coordinates. An overview of the algorithm may be found in Paardekooper (2018). We adopt dimensionless units for radial distance and a planet at $(r, \phi) \equiv (1, 0)$ is embedded in an unperturbed disk. The mass of the planet is given in terms of a dimensionless number $q = M_p/M_\star$. For a Jupiter-mass planet q = 0.001. The density profile is given by Eq. 4.11 and the source term integration follows from Eq. 4.8. The disk is allowed to flow radially with velocity $v_d$, which is set to be a constant. Softening parameter $\epsilon$ is taken as $0.6h$, where $h = 0.05$ as usual. The unit of time is the inverse of angular velocity and gravitational constant $G$ is set to unity. So, in these units $GM_\star = 1$ and one orbital period is $2\pi$ time units. The 2D grid dimensions are set to ensure that the planet is safely located away from the edges of the simulation box and the boundaries of the box are set as non-reflecting.

# 5 Results

It is fundamental to study gap-opening in protoplanetary disks in order to understand early evolution of planetary systems. We focus our attention to the question: How fast should a Jupiter-mass planet migrate such that a gap is not opened? The numerical setup is performed as discussed in Ch. 4. The unperturbed density profile is initially tested and the disk is allowed to flow in the radial direction at a constant rate. Fig. 5.1 shows that the unperturbed density profile behaves as expected and is governed by Eq. 4.11. A Jupiter-mass planet with $q = 0.001$ then introduced at $r = r_p = 1$ and the system is allowed to evolve for 100 orbits. The drift velocity is slowly increased from 0% to 50% of sound-speed in steps. In the following section, we present some of the intriguing results obtained from the 2D hydrodynamical simulation.

## 5.1 Simulation Plots

The simulation result for a non-migrating Jupiter-mass planet at $r_p = 1$ after 100 orbits is shown in Fig. 5.1. The unperturbed surface density profile is shown for reference. We here define a **gap** as an annular region in the surface density where its value drops to less than 10% of the value of unperturbed density at that location. We note that this is similar to the gap definition used by Crida et al. (2006). A deep gap is visible around $r = 1$ which has been carved out by the planet. In the next case, as shown in Fig. 5.2, the migration speed is increased to 30% of sound-speed and the Jupiter-mass planet is at $r = 1$. We observe changes in the profile and the planet does not seem to have carved a clear gap in this case. Fig. 5.3 shows the same scenario with migration speed set to 50% of sound-speed in the material, and surface density of the disk definitely shows no gap around the location of the planet at $r = 1$. This is an interesting and unexpected result. Crida et al. (2006) described a *torque balance criterion*, which is a general criterion for gap opening in disks. According to the criterion, planets that satisfy the condition should open gaps and migrate in Type-II regime. We find that, even though Jupiter-mass planets

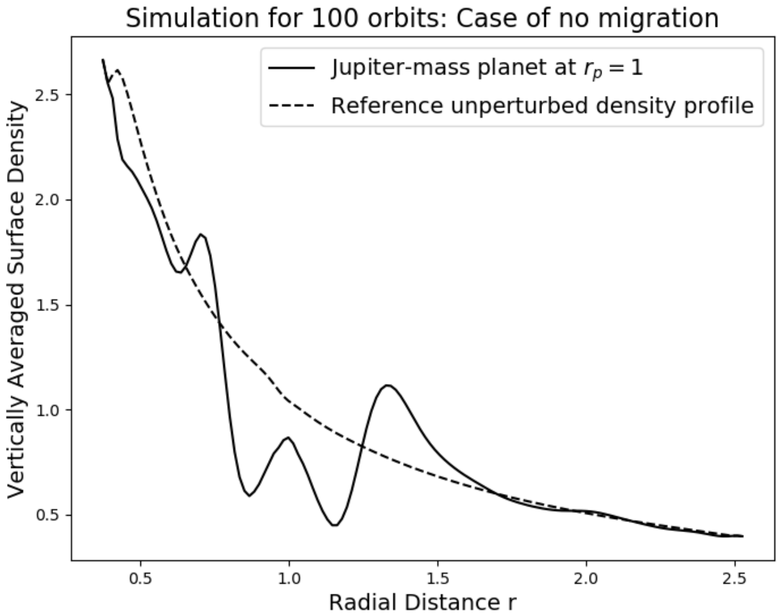


Figure 5.1: A Jupiter mass planet is introduced to an unperturbed disk and is held at $r = 1$. No migration is allowed in this case. Solid line refers to the surface density of the disk with no planet migration while dashed line shows initial unperturbed density profile. The figure shows vertically averaged surface density plotted against radial distance after 100 orbits of simulation. A clear gap is carved out by the planet around $r = 1$.

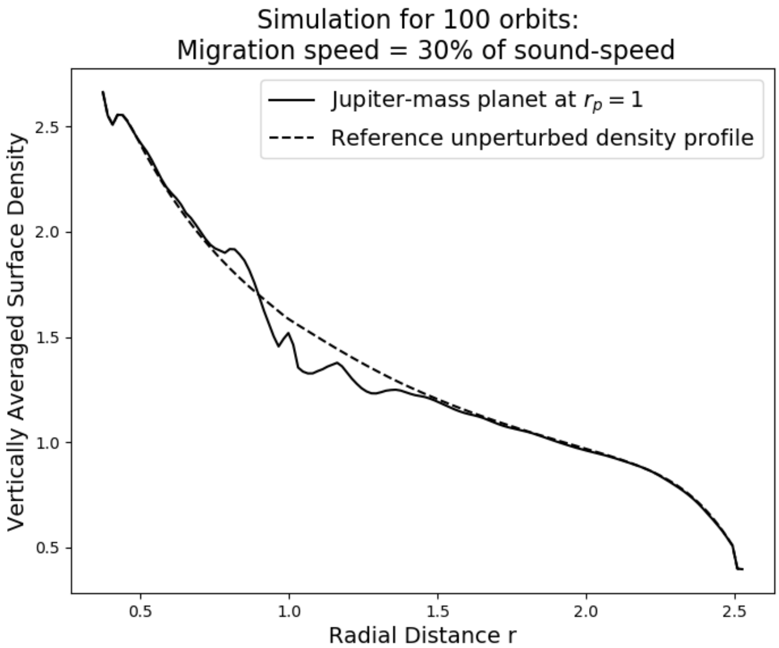


Figure 5.2: A Jupiter-mass planet is at $r = 1$ while the disk material flows radially at 30% of sound-speed in the medium. The solid line shows the surface density of the disk and the dashed line represents unperturbed surface density for reference. No clear gap is visible around the location of the planet.

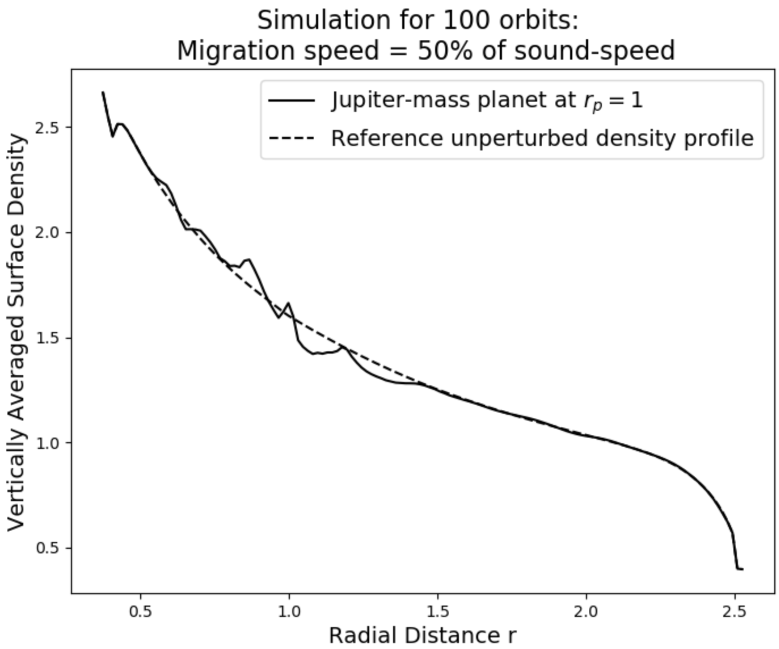


Figure 5.3: Disk material is allowed to drift at 50% of sound-speed while a Jupiter-mass planet is at $r = 1$. The gap has completely disappeared in this case. The solid line shows vertically averaged surface density of the disk with planet after 100 orbits and the dashed like represents the initial unperturbed surface density before introducing the planet.

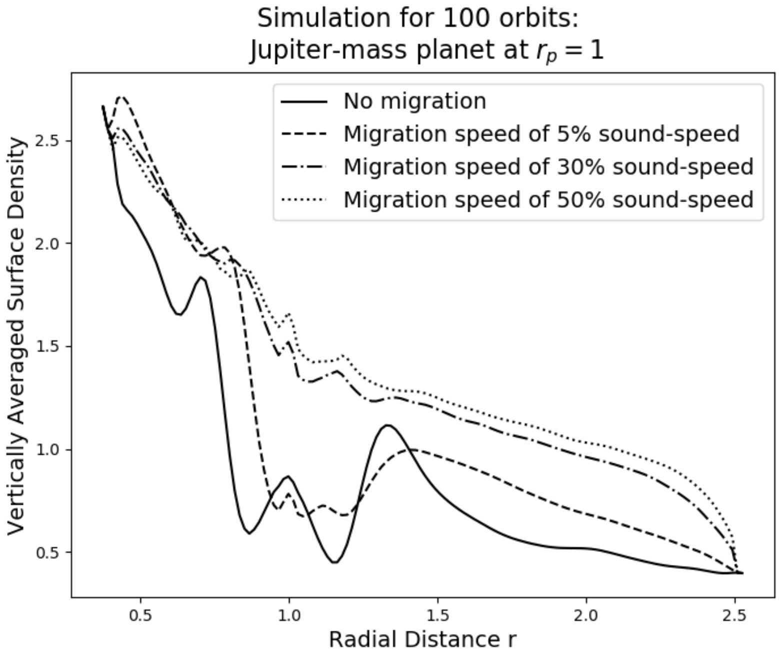


Figure 5.4: A comparison of all Jupiter-mass planet migration cases ($r_p = 1$) after 100 orbits. For the case of no planet migration and that of migration at 5% of sound-speed, a gap is carved out by the planet around it's location. At migration with 30% of sound-speed, the gap depth drastically reduces and eventually disappears when migration speed reaches 50% of sound-speed.

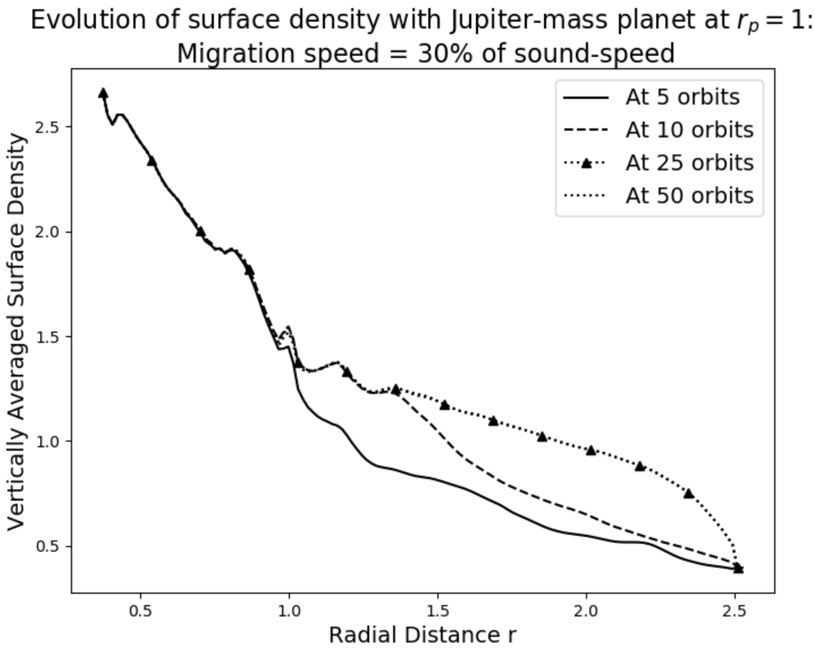


Figure 5.5: Change in surface density after simulating for different number of orbits for a Jupiter-mass planet ($r_p = 1$) migrating at 30% of sound-speed is shown. Profile after 25 and 50 orbits are unchanged showing that the system approaches steady state near 25 orbits.

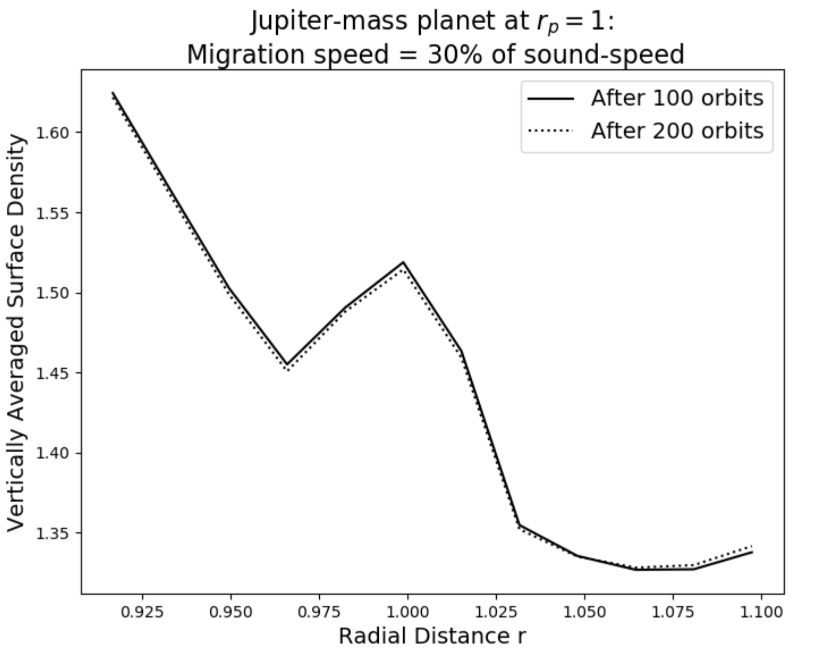


Figure 5.6: Comparison of surface density after 100 and 200 orbits for Jupiter-mass planet ($r_p = 1$) migrating at 30% of sound-speed is presented. Only a small radial range around $r = 1$ has been plotted to show the marginal change in surface density.

satisfy this criterion, they fail to open gaps when migration speed is 30% of speed of sound or higher. Fig. 5.4 shows the comparison of cases of migration with various speeds. It is evident that a gap is cleared out by the planet when the drift velocity is 5% of sound-speed or lesser. At migration of 30% of sound-speed the gap starts to vanish and no gap is seen at all when migration speed is 50% of sound-speed. Fig. 5.5 shows a plot of surface density at different simulation epochs for a case of migration with 30% of sound-speed. We observe that there is gradual change in surface density initially, until the simulation reaches 25 orbits. The surface density after 50 orbits has the same profile as that after 25 orbits showing that there is not much variation in the system after around 25 orbits. This fact is reiterated in Fig. 5.6, which shows the same system after 100 and 200 orbits. Miniscule difference in surface density distribution brings home the message that the system has indeed reached a steady-state.

## 5.2 Discussion and Conclusion

The gap-opening criterion is an open question and is indispensable to understand disk-planet interactions. A frequently used general criterion for gap-opening is described by Crida et al. (2006) and the criterion is satisfied by planets which have more mass than Saturn and Jupiter. Recent studies on migrating giant planets in 2D locally isothermal disks by Crida and Bitsch (2017) stress that Jupiter-mass planets open a gap in around 100 orbits. They simulated a Jupiter-mass planet in an unperturbed disk which was forced to migrate at a constant rate, and demonstrated that gap-opening is not affected by planet migration and that all migrating giant planets open a gap. Further, gap opening by accreting giant plants was also studied which shall not be discussed here as it is not the purpose of this project.

In this project, we studied the effect of a migrating Jupiter-mass planet in 2D isothermal disk. The disk material was forced to drift at constant velocity in the radial direction to simulate the case of a migrating planet embedded in a disk, and various migration speeds were analysed. The results infer that, even though these planets satisfy the gap-opening criterion, they fail to open gaps if migration speed is 30% of sound-speed or higher. Sound-speed ($c_s$) is given by Eq. 4.4 and using $GM_\star = 1$ units and setting $h = 0.05$, at $r = r_p = 1$ we get :

$$\text{30\% of sound-speed} = 0.3 \times c_s = 15 \times 10^{-3} \text{ units} \tag{5.1}$$

A giant planet migrating at this speed would not transition into Type-II migration and would continue to migrate inwards in Type-I migration.

In the simulations done by Crida and Bitsch (2017), migration rate is defined as $\tau_m = -a/\dot{a}$, where $a$ is semi-major axis of the planet, such that it reaches $a_{final} = 0.25$ in 100 orbits. Setting $a_{initial} = 1$ and orbital period is $2\pi$ in $GM_\star = 1$ units, we find migration speed $\approx 1.2 \times 10^{-3}$ units. This is around 12 times lesser than the migration speed criteria calculated in Eq. 5.1, and is effectively lesser than 5% of sound-speed. This comparison agrees well with our argument that gap-opening in disks is hindered only when migration speed is $0.3\,c_s$ or more and as shown in Fig. 5.4, a clear gap is visible at migration speed of 5% of $c_s$ or lesser. The discussion by Crida and Bitsch (2017) for the case of "*Fixed mass with forced migration*" has been limited to a fixed migration speed and scenarios with higher migration speeds have not been probed. We deduce from our results that gap-opening would be expected at the migration rate set by Crida and Bitsch (2017), but gap-depth would be drastically suppressed at a higher migration speed of $0.3\,c_s$. We used $\Sigma(r) = \Sigma_0 \times (1/r)$ for the surface density profile and $\Sigma_0 = 1$ has been assumed for the simulations. In the model used by Crida and Bitsch (2017), the initial surface density of the gas disk is of the form $\Sigma(r) = \Sigma_0 \times (L/r)$, where $\Sigma_0(r) = 10^{-4}(L/r)\,M_\star/L^2$ and $L$ is an arbitrary length unit set to 1. At $r = 1$ and setting $M_\star = 1$, we get $\Sigma_0 = 10^{-4}$ units. This is 4 orders of magnitude lesser than the value used in our simulations, and a much more massive disk would be needed in the model used by Crida and Bitsch (2017) to prevent gap opening.

A test of the gap-opening criterion by Malik et al. (2015) showed that the criterion itself is not sufficient for opening a gap. It was pointed out that in addition to the gap-opening timescale, $t_{gap}$, it is crucial to take into account how quickly a migrating planet can cross the width of the gap and this timescale is given by crossing time, $t_{cross}$. Malik et al. (2015) used the Minimum Mass Solar Nebula (MMSN, Hayashi (1981)) model for surface density, and gap-opening criterion for a variety of disk masses was tested. They concluded that gap-opening is significantly sensitive to disk mass and higher disk masses inhibit gap opening. Our results are consistent with this trend and Fig. 5.4 seems to suggest that at higher cases of migration speeds, the surface density increases. This shows that there is an increased mass in the disk and gap-opening is possibly hindered in disks with high mass. That being said, it should be noted that the surface density profile used by Malik et al. (2015) is different from our model. Also, effect of mass accretion by planets, self-gravity and viscosity have not been studied.

In this report, we started with an overview of star and planet formation which allowed us to lay the foundation for concepts related to protoplanetary disks. The idea of planet migration and gap-opening was discussed. The question we asked ourselves was how does planet migration affect gap-opening in disks and results from hydrodynamic simulations based on a physical model were presented. Despite the limitations, this project has demonstrated that, gap-opening depends on migration speed. In particular, we emphasise on the fact that satisfying the gap-opening criterion is a necessary but not a sufficient condition for gap-opening. In addition to the mass of the planet, attention needs to be paid to the disk mass and migration speed. High migration speeds and heavy disks inhibit gap formation. We conclude that even when the torque balance criterion is satisfied, a Jupiter-mass planet does not open a gap if the migration speed is 30% of sound-speed or higher.

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