Ingredients of the planet-formation puzzle: Gas substructures and kinematics in transition discs

Wölfer, L.B.

The true sign of intelligence is
not knowledge but imagination.

Albert Einstein

English summary

Since the earliest history of mankind, people have gazed at the night sky studded with stars and wondered how they came to be. The question of the origin of the earth and its place in the universe has accompanied humans throughout all centuries and eventually triggered the development of telescopes reaching far beyond the human eye. These instruments are steadily improved, enabling scientists to study all corners of the cosmos in greater and greater detail, and bring us closer to answering the same questions raised long before.

One particularly interesting question is that of the origin of life. To date, we know only one place in the universe where life is possible: The Earth. About 30 years ago however, the discovery of the first planet orbiting another star than our Sun, an exoplanet, opened the door to a new era in Astronomy, making the possibility of life on other worlds a reality. Nowadays, more than 5000 exoplanets have been confirmed, a number that is growing each day and statistically speaking each star is on average orbited by one planet. While planets may be common inhabitants of the cosmos, they do exhibit a great deal of variety: planetary systems show a large scatter in terms of stellar and planetary mass and size as well as in system architectures such as the number, species, or distribution of planets.

In order to explain such diversity and ultimately to address the question of whether life is possible on other planets, we must first understand how planets are formed both from a physical and chemical point of view. To do so, we need to look at their birthplaces. These reside in the dusty and gaseous material surrounding a newborn star and are also called protoplanetary or planet-forming discs. They evolve and ultimately disperse over time, with the evolutionary processes shaping both the disc's appearance and the planet-formation mechanisms. At the same time, forming planets interact with their environment, while they grow from tiny grains to pebbles, planetesimals, and finally rocky planets and cores of gas giants, and they alter the structure of their host disc and influence its evolutionary path.

This dissertation focuses on the interpretation of disc substructures in terms of disc winds and planet–disc interactions. Modelling the dynamical processes in discs and characterizing the observed substructures represent key pieces in assembling the planet-formation puzzle and this thesis contributes to the understanding of how common substructures are and if they follow certain patterns.

Figure 1: Image of the pillars of creation, a star-forming region in the Eagle Nebula, taken with the James Webb Space Telescope. Credits: NASA, ESA, CSA, and STScI.

Young stellar systems

Stars are formed in slowly rotating giant molecular clouds, massive accumulations of interstellar material, predominantly containing molecular gas and some tiny dust particles. An example of such a star-forming region is shown in Fig. 1. Under certain conditions, the densest and coldest regions (cloud cores) can collapse under their own gravity and as density and temperature rise, young (proto-) stars are formed in the centre. At the same time, angular momentum needs to be conserved and the highest angular momentum material (which would break up the newly formed star) distributes into a circumstellar accretion disc from which the star is feeding during the first few million years of its lifetime.

The evolution of young stellar objects is illustrated in Fig. 2. After the collapse of a molecular cloud core and the formation of a prestellar core, the latter further collapses into a protostar surrounded by an infalling envelope. Already at this point, a disc is formed around the protostar, but remains deeply embedded (Stage 0 and I). Throughout these stages, accretion and outflows result in the envelope dissipating within 100 000 to a million years and left is a star surrounded by a gas-rich protoplanetary disc, which can directly be observed (Stage II). During another million to ten million years, disc material is either dispersed or assembled into planets and smaller bodies and the star is left with a gas-poor debris disc (Stage III). Eventually, the disc fully vanishes and a new planetary system such as our Solar System is born. The focus of this thesis are Stage II systems and their gas substructures, which can be observed directly with the Atacama Large Millimeter/submillimeter Array (ALMA).

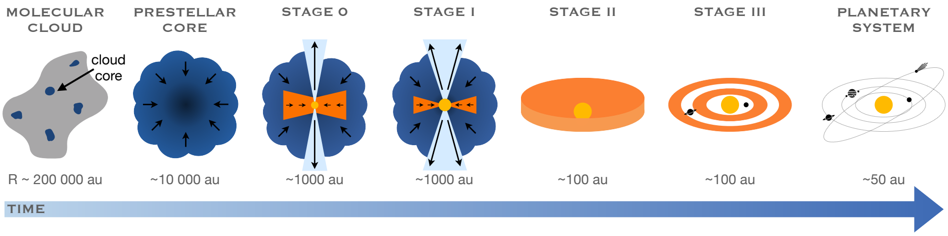

Figure 2: Schematic overview of the different stages of star formation. The focus of this thesis are Stage II objects, also known as protoplanetary discs. One astronomical unit, written here as au, represents the average distance between the Earth and the Sun.

Disc evolution

In order for a circumstellar disc to evolve, angular momentum needs to be either lost or redistributed. Otherwise, the disc material would continue to orbit the star at the same radius for all eternity. Two main mechanisms, which are not mutually exclusive, have been proposed to decrease angular momentum and govern disc evolution: disc winds and viscosity. In a viscously evolving disc, angular momentum is redistributed as a shear between gas particles causes one particle to move inwards by losing angular momentum to the other particle, which moves outwards. The exact source of viscosity remains a topic of active research, but turbulence is commonly invoked to account for viscous evolution. Disc winds on the other hand provide a way to remove angular momentum from the disc without the need for it to be turbulent. In the presence of a magnetic field, magnetically-driven winds can be launched from the disc surface, carrying away angular momentum. Consequently, the remaining material needs to lose angular momentum and moves towards the star where it is accreted.

In the simple picture of viscous evolution, the dispersal of a protoplanetary disc is predicted as a long-lasting process, where the disc is steadily and homogeneously fading. There is no evidence for such slowly draining discs and thus an alternative mechanism is required to rapidly disperse the disc at later stages. One mechanism which is proposed to play a significant role in that regard is photoevaporation. Photoevaporation describes the irradiation of disc material with highly energetic stellar photons, which heat up the upper disc layers to energies larger than the gravitational binding energy, launching a photoevaporative wind. For most of the disc's lifetime, the evolution is governed by viscosity and the mass loss due to photoevaporation is negligible. Over time, however, the accretion onto the star and the surface density of the disc decrease and the photons can penetrate into deeper disc layers. Once the accretion rates drop below the wind mass-loss rates, photoevaporation starts to dominate disc evolution. Inwards-flowing parcels are blown away with the wind rather than being accreted, and an annular gap which detaches the inner and outer disc regions from each other is formed. Without the resupply of matter from the outer disc, the inner disc rapidly drains on the star

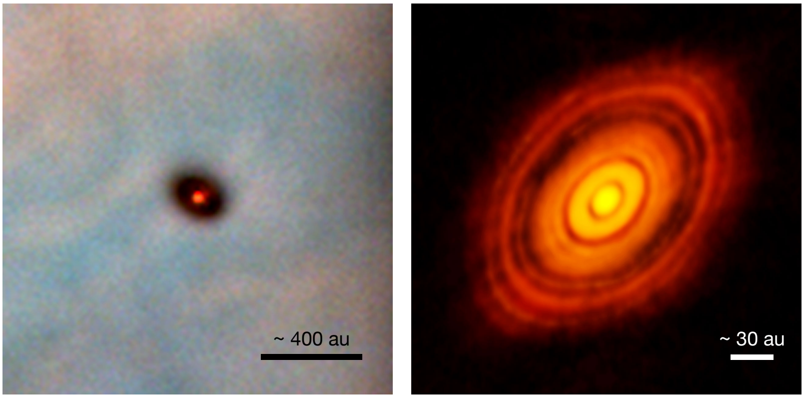

Figure 3: Left: Optical image of a protoplanetary disc in the Orion Nebula Cluster, taken with the Hubble Space Telescope. Credit: Mark McCaughrean (MPIA), C. Robert O'Dell (Rice University), and NASA/ESA. Right: ALMA image of the HL Tau disc at millimetre-wavelengths. Credit: ALMA (ESO/NAOJ/NRAO).

and the outer disc, now directly illuminated, experiences a fast inside-out clearing.

In the context of gaps and cavities in protoplanetary discs, the term 'transition disc' is to be noted. Transition discs are characterized by inner regions depleted in dust (and possibly gas) and were first identified observationally through a lack of infrared excess in the spectral energy distribution of young stellar objects. Being a natural outcome of photoevaporation, they were initially thought to be on the verge of dispersal, representing a transitioning phase between an optically thick and a debris disc. However, from an observational point of view, transition discs present to be a diverse group of objects and are marked by various substructures, which suggests different formation mechanisms. Especially those discs that exhibit large cavities and simultaneously vigorous accretion can hardly be explained by photoevaporation. Planet–disc interactions provide an alternative explanation and at least some of the observed cavities are expected to result from dynamical clearing rather than representing an evolutionary state. Transition discs provide us with great laboratories to study disc evolution and planet formation and may even enable us to catch planet formation in action. This dissertation, therefore, sets a special focus on this intriguing class of objects.

Disc observations

Until a decade ago, the circumstellar material could not be resolved in detail due to a lack of resolution of the former-generation telescopes. Observations showed flat and smooth structures which appeared to be symmetric around the central star, and it was not until the advancement of ALMA or the Spectro-Polarimetric High-contrast Exoplanet REsearch (SPHERE) on ESO's Very Large Telescope(VLT) that astonishing substructures were captured (see Fig. 3).

To study protoplanetary discs, the millimetre regime is particularly well suited, as the cold molecular gas emits predominantly at these wavelengths and the dust distribution is dominated by millimetre-sized grains. The best facility to observe millimetre emission is ALMA because it provides the sensitivity, spectral resolution, and spatial resolution needed to map out individual discs in detail. At the same time, it has also allowed for large population studies. Altogether these observations have revealed that protoplanetary discs are marked by a large variety of substructures, including gaps or cavities, rings, spiral arms, and azimuthal asymmetries. This dissertation focuses on the gas content of discs, which yields the advantage of having information on the disc dynamics or kinematics: molecular line emission of rotating gas is red- and blueshifted, depending on whether the gas moves away from or towards us.

Disc kinematics

While the ultimate goal is to directly image embedded planets and thus confirm their link with the observed substructures, the dense and opaque environment surrounding young planets makes such a task very challenging. It is not surprising that to date, the only robust detections of embedded planets are those of the PDS 70 system. Therefore, more indirect detection techniques have been developed and a particularly promising one is to study the velocity field of the rotating gas, accessible with molecular line observations. Searching for deviations from Keplerian rotation can be used to understand which processes, all leaving their individual fingerprints in the kinematics, are shaping the disc. The kinematical features induced by planet–disc interactions are particularly exciting, with the amplitude and morphology of these perturbations depending on the location and mass of the planet, but also the disc structure. While several observations of kinematical deviations such as non-Keplerian spirals, meridional flows, or kink features have been linked to the presence of planets, it remains difficult to distinguish them from other underlying mechanisms. To better understand the individual contributions, dedicated modelling efforts are needed in combination with exceptionally sensitive observations at high spectral and spatial resolution. Such observations come at high observational costs and there are limited sources for which the kinematics have been thoroughly analysed. The field of kinematics is thus still in its infancy but brings the opportunity to find young, still forming planets, which escape the classical detection techniques. The properties of these planets yield important implications for planet-formation and -migration models and the timescales of these processes. Linking these properties to those of the mature exoplanet populations is crucial to solve the planet-formation puzzle.

This thesis

In this dissertation, the gas content of protoplanetary discs and their substructures are studied in the context of disc winds as well as planet–disc interactions. The variety of observed substructures, coupled with the lack of directly observed planets in discs, has triggered the following main questions which are tackled in this thesis:

1. Are the diverse substructures observed in discs the result of planet–disc interactions or other mechanisms?

2. If planets are the cause, what can we learn about these planets, for example in terms of location or mass, and if not planet-driven, what can we learn about the disc?

3. What modulates angular momentum transport in the disc as well as disc dispersal, influencing its lifetime and thus the time available to build planets?

The following paragraphs provide a brief summary of the individual chapters and their main results.

Chapter 2 investigates the effects of X-ray photoevaporation, acting in protoplanetary discs in which, as commonly observed, volatile carbon is depleted. Being one of the main contributors to the X-ray opacity, a gas-phase depletion of carbon is expected to enable larger X-ray penetration depths and here it is explored how this influences the strength of the photoevaporative mass loss and the formation of cavities. For this purpose, radiative transfer calculations and hydrodynamical models are combined, modelling discs irradiated by internal X-ray+EUV radiation and with different degrees of carbon depletion. The results show that photoevaporative winds are - with respect to solar metallicity discs - stronger in such carbon-depleted discs, resulting in enhanced mass-loss rates and mass-loss profiles that extend to larger radii. These results may explain a larger number of the observed transition discs. Additionally, very high carbon depletion may represent a mechanism of very fast disc dispersal towards the end of the lifetime of a disc.

Chapter 3 presents high-resolution Band 6 ALMA observations of the circumstellar disc around CQ Tau. Three CO isotopologues ^{12}CO, ^{13}CO, and $C^{18}O$ are analysed both in terms of their kinematics and brightness temperatures. A Keplerian disc model is fitted to the velocity field to search for deviations from Keplerian rotation and variations in the temperature structure. The analysis yields significant spiral features in the residuals of both the velocity and gas brightness temperature after the model is subtracted from the data. The velocity and temperature spirals are partly aligned, suggesting a common origin. Their morphology, number, and pitch angles support a dynamical formation scenario. Together with (co-locating) spirals observed in the near-infrared and an observed deep gas and dust cavity, the spirals point towards a massive body such as a planet or binary companion located inside of about 25 au.

In chapter 4, the analysis of the gas kinematics and brightness temperatures conducted in the previous chapter is expanded to a sample of 36 large cavity transition discs, pushing the available ALMA observations to their limits. For the analysis, archival CO data taken in different cycles in Band 6 and Band 7 are used. For the first time, the substructures found in the kinematics and brightness temperature residuals are compared with other indicators for the presence of planets for a large sample of sources. The results yield strong features such as arcs or spirals, possibly associated with the presence of planets or companions, in about

20 % of discs, while the majority of the sources do not present as clear signatures. Almost all discs that exhibit spirals in near-infrared scattered light show at least tentative features in the CO data.

Chapter 5 presents a multi-line study of the disc surrounding the Herbig star HD 100546, which represents a particularly interesting target in terms of planet–disc interactions. For the analysis, several CO lines observed at high spectral and spatial resolution with ALMA in Band 6, 7, and 10 are used. To model the line emission for each intensity cube, a channel-map fitting package is used. The analysis reveals extended spiral structures in the kinematical residuals of all lines and their overall morphology is well reproduced by linear and logarithmic functions. They are consistent with spirals driven by an embedded planet or stellar companion inside of 50 au. Indications of a second companion, located further out at around 90-150 au are seen in the form of meridional flows towards the midplane and pressure minima, as well as a tentative gap in the more optically thin tracers. An asymmetry in the emission heights of the blue- and redshifted sides may indicate infalling material on the redshifted side of the disc or an inner warped disc, casting a shadow over the outer disc.

Future outlook

ALMA has transformed our view of planet-forming discs, revealing a wealth of substructures. However, we have only just started to really disentangle the different mechanisms being at play and the origin of the substructures remains a burning open question. At the same time, we have now reached a stage where new and exciting opportunities are opening up both with ALMA and JWST, providing a sensitivity and resolution exceeding all previous observations.

ALMA observations of molecular gas emission bring the advantage of allowing one to map the gas flow throughout the disc, and with sufficient sensitivity and resolution, this opens up a unique new window to detect embedded planets and probe physical processes in the disc. The field of disc kinematics has just started to emerge, and very deep line observations will allow us to also detect smaller mass planets at shorter periods.

One ultimate goal is to link the properties of discs and their young planets to the mature and very diverse exoplanet populations. Therefore, systematic and comprehensive surveys of a large number of discs are needed, including also the smaller ones, generally thought to be less structured, in addition to the massive and bright discs that are typically studied in detail. This is an essential step to understand if there are systematic differences between these groups and if in particular Herbig Ae/Be or T Tauri discs follow different patterns. So far, kinematic studies have mostly focused on the brighter CO lines but to really disentangle the mechanisms behind the observed substructures, it is crucial to trace them throughout the full radial and vertical extent of the disc. This requires observations of a range of molecular tracers, which also brings the opportunity to understand the chemical signatures of planets.

To interpret the observations, fundamental work is also required on the theoretical side. Dedicated modelling efforts are needed to understand which imprints planet–disc interactions or other disc-shaping mechanisms, such as disc winds or gravitational instabilities, leave in the kinematics or temperature structure. This is crucial to understand which role the individual processes play in the planet-formation puzzle and will help us to assess which targets are best suited for direct imaging programs with JWST and the future Extremely Large Telescope (ELT). Together with ALMA, these ground-breaking facilities will enable us to access the connection of inner and outer disc structures, which is so far not fully understood. They will pave the way for a comprehensive characterization of the youngest exoplanets.