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CHARACTERIZING SUBSTRUCTURES AND INTERACTIONS IN THE DISKS
AROUND MULTIPLE STELLAR SYSTEMS

TESIS PARA OPTAR AL GRADO DE
MAGÍSTER EN CIENCIAS, MENCIÓN ASTRONOMÍA

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To characterize the substructures induced in protoplanetary disks by the interaction between stars in multiple systems, we study the 1.25 mm continuum and the $^{12}\text{CO}(\text{J:2-1})$ spectral line emission of the triple systems HT Lup and AS 205, and the 0.87mm and $^{12}\text{CO}(\text{J:3-2})$ emission of the binary CS Cha. Our high angular resolution ALMA observations allow us to resolve spatial scales of about 5 to 8 au in dust, and 8 to 14 au in gas. In the AS 205 system, we find two symmetric spiral arms in the dust continuum emission of AS 205 N disk, extending from about 20 to 55 au in radius, distance at which the disk is no longer detected over the noise level. In the AS 205 S circumbinary disk, we detect a central cavity of ~ 2.8 au and a bright ring located at 34 au. The gas in the AS 205 system exhibits clear signatures of tidal interactions, with spiral arms, extended arc-like emission, high velocity gas and warped disk kinematics, possible evidence of a recent close encounter between the N and S disks, as these features are predicted by hydrodynamic simulations of flyby encounters. In the dust emission of the HT Lup system we are able to resolve a spiral arms of low pitch angle (4°) in the main disk HT Lup A, while HT Lup B and C are barely resolved, with deconvolved sizes of about 5 and 9 au. The gas kinematics of the HT Lup system indicates a different sense of rotation for the closest disks (A and B), which could be explained by either a counter rotation of the two disks in different, close to parallel, planes, or by a projection effect of these disks with a close to 90° misalignment. In CS Cha, we detect a central cavity in both dust continuum and ^{12}CO emission, expected for a circumbinary disk. A single circumbinary ring is the only substructure we resolve in this disk, which is not well modeled by a single gaussian ring profile. We do not detect dust or gas emission from the external companion CS Cha C, which was previously observed in optical and infrared wavelengths. Its non detection in our deep observations could be explained by a combination of low planet accretion, low planet temperature, and millimeter dust depletion, constraining the circumplanetary disk properties and formation mechanism. We find signs of tidal interactions in all of our multiple disks systems, as truncated radial extent compared to other single-star systems and spiral arms in the main disks. The outer radius truncation, central material depleted cavities, redistribution and exchange of material between disks could have an effect in the planet population of multiple stellar systems, although dedicated numerical modeling and further observations are needed to fully describe the nature of their orbital interactions and its impact on planetary formation. Nevertheless, these observations are the perfect natural laboratory to study disk-companion interactions.

CARACTERIZANDO SUB-ESTRUCTURAS E INTERACCIONES EN DISCOS ALREDEDOR DE SISTEMAS ESTELARES MÚLTIPLES.

Para caracterizar las subestructuras inducidas en discos protoplanetarios por la interacción entre estrellas en sistemas múltiples, estudiamos la emisión de continuo en 1.25 mm y la línea de emisión molecular $^{12}\text{CO}(\text{J:2-1})$ de los sistemas triples HT Lup y AS 205, y la emisión en 0.87 mm con la línea $^{12}\text{CO}(\text{J:3-2})$ de la binaria CS Cha. Nuestras observaciones a alta resolución con ALMA nos permiten resolver escalas espaciales entre 5 a 8 au en polvo, y 8 a 14 au en gas. En el sistema AS 205, encontramos dos brazos espirales simétricos en la emisión de continuo del polvo de AS 205 N, extendiéndose aproximadamente desde los 20 hasta los 55 au en distancia radial, desvaneciéndose cuando el disco deja de ser detectado sobre el nivel del ruido. En el disco circumbinario de AS 205 S detectamos una cavidad central de aproximadamente 2.8 au y un anillo brillante ubicado a 34 au. El gas en el sistema AS 205 muestra claros signos de interacciones de marea, con brazos espirales, emisión extendida en forma de arcos, gas a altas velocidades, y discos con cinemática perturbada, posible evidencia de un encuentro reciente entre los discos N y S, dado que estas características son predichas por simulaciones hidrodinámicas para encuentros cercanos. En la emisión de polvo del sistema HT Lup resolvemos brazos espirales con ángulo de apertura bajo (4°) en el disco principal HT Lup A, mientras que los discos de HT Lup B y C están apenas resueltos, con tamaños deconvolucionados de aproximadamente 5 y 9 au. La cinemática del gas en el sistema HT Lup indica que los discos más cercanos (A y B) están rotando en sentidos diferentes, lo que podría ser explicado ya sea por dos discos rotando en direcciones contrarias en planos casi paralelos, o por un efecto de proyección de estos discos con planos casi perpendiculares. En CS Cha, detectamos una cavidad central tanto en la emisión de continuo del polvo como en la emisión del ^{12}CO , tal como se esperaba para un disco circumbinario. Un anillo circumbinario es la única subestructura que podemos resolver en el disco, y no es bien descrita por un perfil de anillo gaussiano. No detectamos emisión de polvo o gas del compañero externo CS Cha C, que fue previamente observado en longitudes de onda de óptico e infrarrojo. Su no detección en nuestras observaciones profundas podría ser explicada por una combinación de baja acreción por parte del planeta, baja temperatura del planeta, y agotamiento de los granos de polvo milimétricos, acotando las propiedades de su disco circumplanetario y su mecanismo de formación. Encontramos señales de efectos de marea en todos nuestros sistemas con múltiples discos. La truncación del radio externo, las cavidades centrales sin material, la redistribución e intercambio de material entre discos podrían tener un efecto en la población planetaria en sistemas múltiples, sin embargo son necesarias simulaciones numéricas dedicadas y más observaciones para describir completamente la naturaleza de las interacciones y su impacto en la formación planetaria. Aun así, estas observaciones son el laboratorio natural perfecto para estudiar interacciones entre disco y compañeros.

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Chapter 1

Introduction

1.1 Objective

The main purpose of this M.Sc. thesis is to study the substructures in the solid and gaseous components of protoplanetary disks in multiple stars in young systems. To achieve this purpose, 3 different sources are studied: AS 205, HT Lup and CS Cha. All of them are multiple young stellar systems, with different configurations:

- AS 205 is composed of two disks, separated by > 168 au in projection. The main disk surrounds the main star system, while the secondary disk is located a spectroscopic binary.
- HT Lup is composed of three very compact disks, one around each star. The companions are located at > 25 au and > 434 au in projection to the main star.
- CS Cha has one circumbinary disk, with an external companion that has no observations published in radio wavelengths.

The dust emission of each protoplanetary disk will be characterized, describing every physical feature that can be observed such as radial average brightness, non symmetric structures, radial extent and disk mass. This characterization is complemented with data from molecular gas emission, through the study of the CO gas kinematics. Any deviation from pure Keplerian motion will provide information about the interaction of disks and companions, constraining orbital parameters for future dedicated simulations.

Necessary concepts and context of the planet formation field are presented in the subsequent sections of the current Chapter 1, as well as previous knowledge of the young systems studied in this thesis. In Chapter 2 we present our ALMA observations and describe their calibration and imaging procedures for both dust and gas emission. Chapters 3 and 4 present the results obtained for the AS 205 and HT Lup systems, which are published in Kurtovic et al. (2018), while Chapter 5 present our first results on the CS Cha system, and will be reported in a subsequent publication. A discussion of the substructures and kinematics in our observations is given in Chapter 6. Our conclusions are presented in Chapter 7.

1.2 Stellar and planet formation

Stars are born from the gravitational collapse of the dense cores in molecular clouds (Shu et al., 1987). Due to the extended size and mass of these cores, they are reservoirs of angular momentum, which has to be lost or redistributed before being completely accreted by the central forming object.

As the gravitational collapse decreases the size of the core, the conservation of angular momentum naturally increases the rotational velocity, thus forming a rotating disk structure around the young star. The dynamical scale of the disk rotation (at most in the order of 10^2 to 10^3 yr) is much smaller than the angular momentum redistribution, which disperses the disk in time-scales of 10^6 yr through interaction with magnetic fields, viscous accretion, stellar winds and photoevaporation (Armitage 2011), allowing internal disk processes to occur, such as grain growth and molecular chemistry (Booth et al. 2019). This process is diagrammed in Figure 1.1, starting from a pre-stellar core and finishing with a built planetary system.

Due to aerodynamic drag on the solid dust particles, they settle at the disk plane in short time scales (10^3 yr dust particles in a non-turbulent environment with grain growth, Armitage 2011). The gas, on the other hand, has pressure support in addition to gravitational forces, which vertically recirculates this component due to turbulence, allowing it to maintain a flared disk structure. Radially, the support induces the gas to rotate slightly sub-Keplerian. Gas mixing and recirculation opposes the dust settling due to drag, and the final distribution of solid particles depends on the equilibrium of these effects.

The higher density of dust particles at the midplane allows the small grains to stick to others, and through grain growth processes they can grow from micrometer to millimeter and centimeter sized particles. These bigger particles can keep growing to become planetesimals, the seed of planetary cores. The whole planetesimal building process and grain growth is continuously interacting with gas, since the gas affects the velocity of the particles (by turbulence and drag) and the dust likelihood to stick with others (e.g. by ice formation, see Hatzes et al., 1991; Güttler et al., 2010). In addition, the drag that particles feel due to the gas presence is dependent on the size of the grain. Smaller dust particles are more coupled to the gas, and tend to follow it towards the pressure maximum. On the other hand, as the particles grow to centimeter and larger sizes, they decouple from gas, and start moving around the star at Keplerian velocities, in opposition with the slightly sub-Keplerian velocity of the surrounding gas. Then, just as the drag is responsible for the vertically settling of dust at the midplane, it also decreases the angular momentum of the solids, inducing them towards smaller orbits, until they are accreted. This process is known as radial drift.

One of the key problems of radial drift resides in its timescale being smaller than the grain growth timescale (see Whipple, 1972; Weidenschilling, 1977; Andrews, 2015), therefore, the solids migrate faster than they form planetesimals. Latest exo-planetary searches show that most of the main sequence stars possess planetary systems (Borucki, 2016), meaning that as efficient as the radial drift process might be, the time-scale allows for planets to be formed. One of the solutions to overcome this radial drift problem is that pebbles do not necessarily migrate towards the central accreting object, instead, they migrate towards gas pressure maximum. These regions of high pressure can trap the dust particles (Whipple 1972)

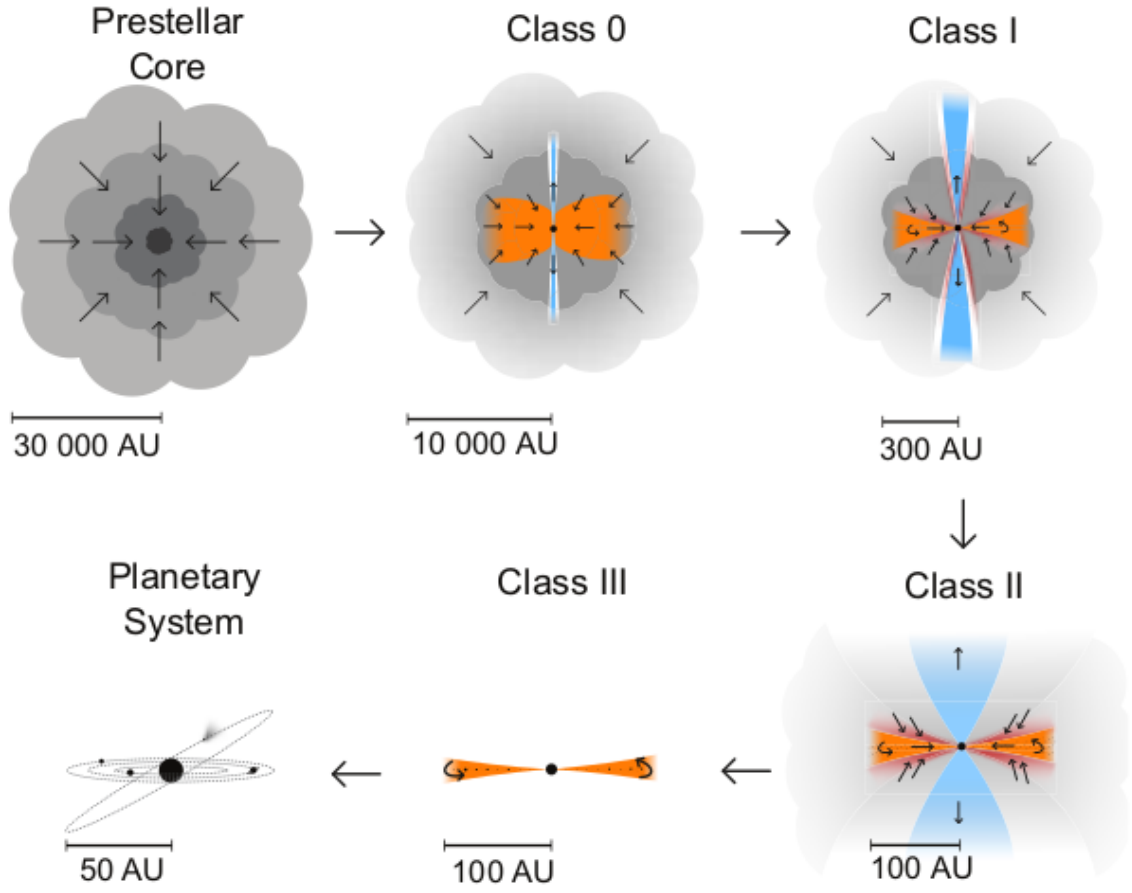


Figure 1.1: Evolutionary process of star and planet formation. The prestellar core collapses to a protostar. The envelope keeps falling in and a rotating disk forms around the star. The disk evolves from a massive gas-rich to a gas-poor debris disk, ending as a planetary system. Figure from van der Marel (2015) by Magnus Persson.

and reverse the drift direction.

Dust trapping regions will induce spatial differences of dust density, forming observable substructures on the disk. Their detection and characterization is key to understand planetary formation, since these trapping regions can concentrate large centimeter-sized dust particles and allow them to grow to planetesimal sizes. Since grain growth occurs at the locations of traps, the observation of substructures at continuum wavelengths, plus the differentiation of spectral index along the disk, may confirm the physical origin of substructures, and the processes occurring in it.

1.3 Observing disks around young stellar objects

Protoplanetary disks are mainly composed by gas and dust particles, the materials present on the interstellar medium. As the radial distance from the forming star increase, the density and

composition of the disk will change because of the decrease in gravity and stellar illumination, and an increase of cosmic ray ionization. Vertically, the material distribution will depend on the turbulence and mixing.

1.3.1 Observing dust particles

The temperature profile of the disk is mainly controlled by the passive stellar irradiation from the solid particles (Adams et al., 1987; Kenyon and Hartmann, 1987). The starlight heats the surface layers of the disk, which then radiates their energy to the outside and inside of the disk. Since the midplane gets the energy from the disk surface, it will always be comparatively at lower temperatures (Calvet et al., 1991; Chiang and Goldreich, 1997; D'Alessio et al., 1998). This effect has to be considered when choosing the best strategy to observe the midplane.

Even if the temperature of the disk is very low, the spatially extended emitting area of the disk can be over 10^9 bigger than the emitting surface of the star (for a sun-like star and disk of 100 au), allowing the observation of its solid components in dust continuum emission. There are mainly two continuum sources in a protoplanetary system: the thermal emission from the dust grains, and the scattered radiation from the star at the disk surface by the small grains.

The small micron sized particles will be well coupled to the gas, and the turbulence will move them towards the disk flared surface. Observations at near-infrared wavelengths can observe this effect by detecting the scattered light of the star on the disk (Grady et al., 1999; Muto et al., 2012; Benisty et al., 2018), but grain growth and planetary formation occurs at the disk midplane because most of the disk mass is there, so this observations can complement our studies, but do not trace where the particles are being trapped.

Thermal emission depends, on first order, on the temperature (by the Planck function $B_\nu(T)$) and the optical depth (τ_ν) at the observed wavelength. Because of the Wien law over B_ν , the shorter wavelengths will preferentially trace warmer material, which in protoplanetary disks is located closer to the forming star and to the surface of the disk. This is better seen in Figure 1.2, where the characteristic emitting regions for infrared and radio are shown. The near-infrared and mid-infrared emission are mainly contributed by the star and its closest surroundings. These wavelengths are optically thick due to the high density and opacity of the inner regions, thus they trace the upper layers of the disk. The far infrared emission comes from larger spatial scales on the disk and it can partially become optically thin, but does not trace the midplane particle distribution, where the environment is propitious for planetesimal formation. Finally, given the lower optical depths of radio wavelengths, the millimeter emission can penetrate along the vertical structure of the disk, and trace the emission from the cold dust at the midplane, even if it extends through several tens or hundreds of au in radius.

When observing sources in radio wavelengths, we need to consider that the opacity of dust will be dependent on the size of the solid particles. If a is the length of the cross section of a given particle, the opacity for wavelengths $\lambda \ll a$ is almost constant, while the opacity will

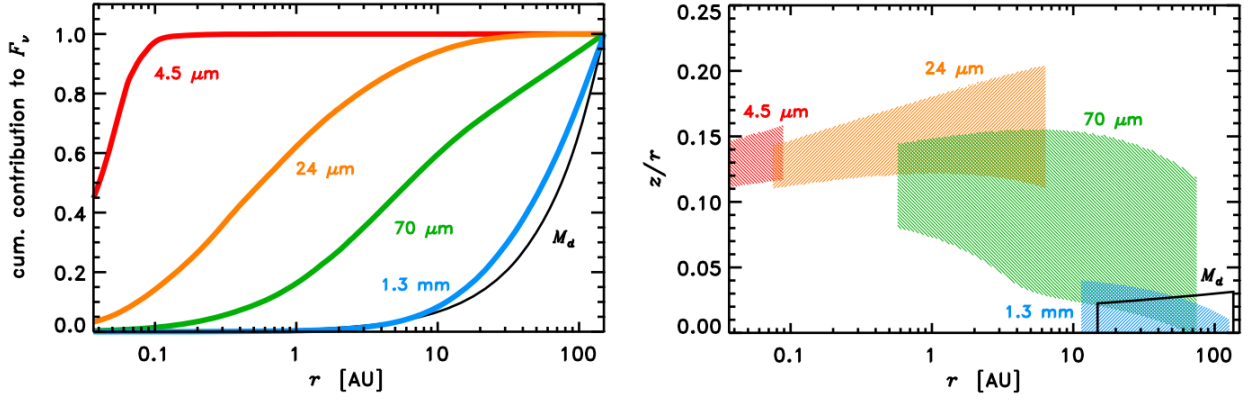


Figure 1.2: Top: Cumulative contributions to F_ν at four representative wavelengths as a function of r for the SED of GO Tau (Furlan et al. 2009, Andrews et al. 2013). The cumulative distribution of the disk mass M_d is shown in black color. The non zero values at $r = 0$ of 2.5 and 24 μm is due the contribution of stellar radiation. Bottom: Two-dimensional map of the regions that emit 80% of the flux (or enclose $0.8 M_d$). Figure from Andrews (2015).

be $\propto \lambda^{-2}$ for $a \gg \lambda$. At $a \sim \lambda$, opacity is increased by resonant interactions, thus, observing at a certain wavelength will trace more efficiently particles of that size.

1.3.2 Observing gas

Most of the gas in protoplanetary disks is hydrogen and helium, but none of them can be observed at large distances from the central star, since they need to be ionized to emit. Instead, we can look at gas tracers in form of atoms, ions or molecules, which are stable at low temperatures and emit at well defined wavelengths through recapture of electrons, or changes in their vibrational or rotational states. Given that the energy of several transitions is well known from theory and laboratory measurements, we can use the redshifted and blueshifted emission to trace the kinematics of the disk, thus providing us an additional tool to understand the dynamics of the disk material.

The brightest molecular line available to observe at radio wavelengths are ^{12}CO ro-vibrational transitions, which trace the gas location and dynamics, but is susceptible to cloud contamination and extinction due to its high opacity. Although we are not able to observe the midplane with this bright line, the comparison between gas and dust substructures will give us additional information about the phenomena that is producing the dust trapping or material depletion. Additionally, gravitational interactions between disks and external companions are expected to produce perturbations to the pure Keplerian rotational pattern (Clarke and Pringle, 1993; Dai et al., 2015; Cuello et al., 2018), thus measuring the perturbations can constrain orbital parameters.

1.4 Binaries and multiple stellar systems

Most of the stars in the disk of the milky way were formed or live in a binary or multiple system (Duchêne and Kraus, 2013; Reipurth and Zinnecker, 1993), a trend that is also observed in young stellar associations (Leinert et al., 1993; Ghez et al., 1993; Reipurth et al., 2014), where multiplicity is ~ 0.7 in Class II/III stars, ~ 0.6 in Class 0 objects (Kraus et al., 2011; Tobin et al., 2016b, see Figure 1.1 for object reference). At these young stages, gravitational interactions by companions can exchange angular momentum of their disks, therefore, inducing changes in the material distribution and dynamics around each protostar (Bate, 2018). In single-star disks, numerical and theoretical estimates from bound orbits or fly-by interactions find that tidal forces may truncate the protoplanetary disks radial extension (Lin and Papaloizou, 1993; Manara et al., 2019), a phenomena that is stronger or weaker depending on the orbital parameters, as orbital separation a (or impact parameter b in fly-by), and inclination between orbit and disk planes. On circumbinary disks, this material truncation occurs in the inner regions, clearing the surroundings of the binaries until a distance of $r \lesssim 2 \sim 5 a$ (Lin and Papaloizou, 1993; Artymowicz and Lubow, 1994).

Since planets are born in protoplanetary disks, any perturbation to them will subsequently affect the future planet population. To date, planets have been detected in multiple systems (e.g. Eggenberger et al., 2007; Chauvin et al., 2011), and in circumbinary configurations (Doyle et al., 2011), even in systems with more than one planet (Kepler-47 Kostov et al., 2013). However, these planetary detections in multiples systems are not as frequent as in single stellar systems in adult stars, in concordance with Wang et al. (2014) findings that planets should be 4.5 ± 3.2 and 2.6 ± 1.0 times less frequent in a multiple systems (compared to single star systems), when a stellar companion is at a distance of 10 and 100 au, respectively (see also Kraus et al., 2016).

The differences between planets populations in single and multiple stellar systems must have a link to the perturbations induced on the protoplanetary disk by interactions with external components. Most observational studies at high angular resolution of millimeter dust in the midplane have so far focused on single stellar systems, and it is not clear how common the disk substructures are in multiple systems. Over the last two decades, a few multiple systems have been studied with sufficient angular resolution to resolve their components separately at radio wavelengths (Jensen et al., 1996; Jensen and Akeson, 2003; Harris et al., 2012), and thanks to ALMA capabilities these detections have become more frequent over the last few years (e.g., Akeson and Jensen, 2014; Jensen and Akeson, 2014; Brinch et al., 2016; Tobin et al., 2016a; Manara et al., 2019).

Misalignments between the disk rotation axis and the binaries orbit (Williams et al., 2014; Fernández-López et al., 2017), as well as tidal stripping and extended emission (Cabrit et al., 2006; Salyk et al., 2014; Rodriguez et al., 2018) have been detected in some of them. However, none of the previous observations reached the high spatial resolution required to study the substructure of disks in multiple systems. For example, spiral arms are expected to be triggered in the presence of one or multiple companions (Goldreich and Tremaine, 1979; Tanaka et al., 2002), and could potentially be detected in the dust continuum emission at millimeter wavelengths. But until today, most disks with known spiral-like structures in dust continuum emission (Pérez et al., 2016; Dong et al., 2018; Boehler et al., 2018; Huang et al.,

2018a) or gas emission (e.g., Tang et al., 2017) do not host any known stellar companion (an exception is HD 142527, Biller et al., 2012; Christiaens et al., 2014, 2018). This suggests that in these cases, the observed spirals might originate from other mechanisms, such as gravitational instabilities (Mayer et al., 2004; Lodato and Rice, 2004), shadowing in the disk (Montesinos et al., 2016), or alternatively, that the possible companion(s) have not yet been detected.

1.5 Disk Substructures at High Angular Resolution Project

Thanks to ALMA high sensitivity and extended baselines, the observatory has provided to the astronomical community a tool to detect and characterize at very high angular resolution the dust and gas structures in protoplanetary disks, helping us to understand the processes involved in the evolution of young stars and the formation of planetary systems. Millimeter images that trace dust emission have shown large azimuthal asymmetries (e.g., Casassus et al., 2013; van der Marel et al., 2013), spirals (e.g., Christiaens et al., 2014; Pérez et al., 2016; Dong et al., 2018), and bright/dark rings (e.g., ALMA Partnership et al., 2015; Andrews et al., 2016; Cieza et al., 2017; Dipierro et al., 2018; Long et al., 2018). The ubiquity of substructures in disks observed at high spatial resolution suggest they are common in protoplanetary environments, and therefore understanding their origin and role in planet formation is crucial to pave the link between theoretical works with the observation of young stellar objects and adult exoplanetary systems.

In this context, the Disk Substructures at High Angular Resolution Project (Andrews et al., 2018, DSHARP) is a survey designed to increase the sample of protoplanetary disks observed at high angular resolution, and move towards the study and characterization of substructures in them. The project was awarded with one of the first ALMA Large Programs, and its goal was to observe 20 protoplanetary systems at ~ 35 mas resolution using ALMA band 6 (~ 240 GHz), tracing the 1.3 mm sized dust at ~ 5 au spatial resolution for objects located at ~ 150 pc.

The selection criteria for the 20 systems was set to target disks transiting at high elevations during night in the period of 2017 June-July, and they had to be nearby enough to obtain ~ 5 au spatial resolution with 35 mas beam size. To avoid confusion with envelope emission, the targets were selected to be Class II, and a brightness cut was performed to ensure enough SNR to differentiate substructures from an otherwise smooth profile. The final sample is then biased towards brighter continuum sources, which are correlated with higher mass stars (Andrews et al., 2013).

Although 20 systems were observed, there are 23 detected disks in DSHARP sample, since the AS 205 system is composed by two independent disks, and the HT Lup system is composed by 3 (with 2 of them barely resolved). One of the key results of DSHARP is the finding of annular substructures in almost all of the well resolved disks (19 out of 21, see Huang et al. (2018a)), and 5 disks with spiral arms, of which 3 correspond to single disks systems (Huang et al., 2018b). The observational results (summarized in Figure 1.3) are presented in Andrews et al. (2018); Huang et al. (2018a,b); Isella et al. (2018); Guzmán et al.

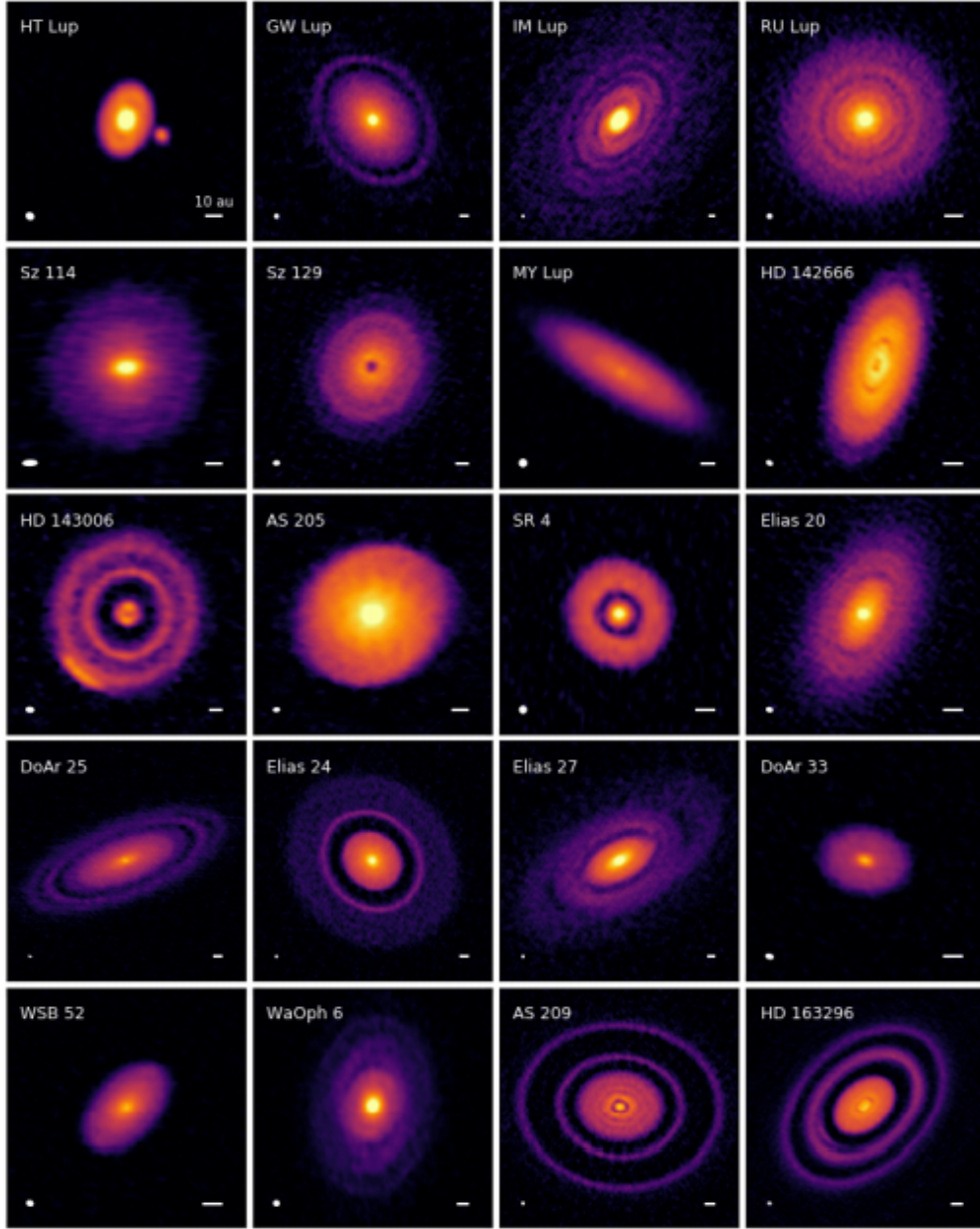


Figure 1.3: Millimeter continuum images of the DSHARP sample. The beam size is shown at the bottom left of each panel, and a 10 au scale bar is in the bottom right. All images are shown with an asinh stretch to reduce the dynamic range. Figure from Andrews et al. (2018).

(2018); Pérez et al. (2018) and Kurtovic et al. (2018), on which this thesis is based, while analysis and comparisons with theory and simulations are done in Birnstiel et al. (2018); Dullemond et al. (2018); Zhang et al. (2018).

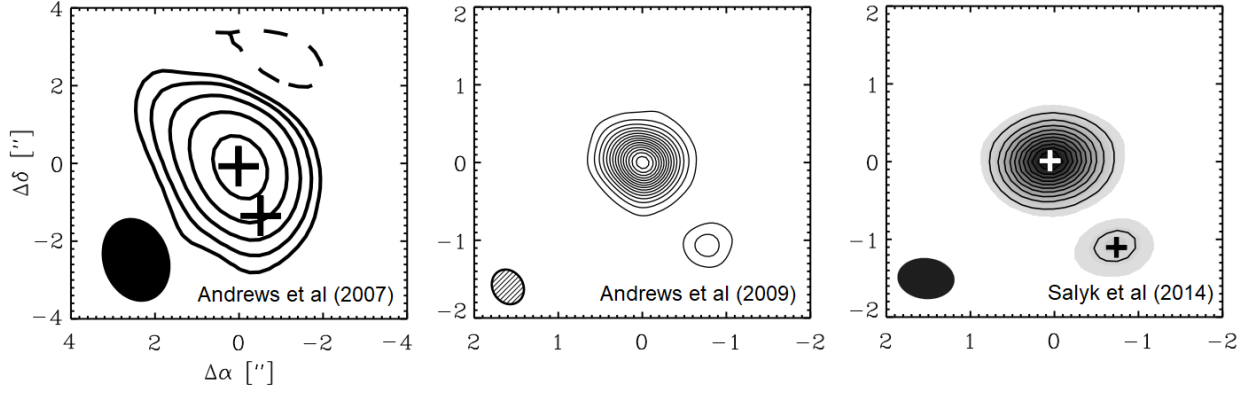


Figure 1.4: Millimeter continuum images of the AS 205 system. The beam size are $2.2 \times 1.7''$, $0.46 \times 0.37''$ and $0.76 \times 0.63''$ for Andrews and Williams (2007), Andrews et al. (2009) and Salyk et al. (2014) respectively, and are shown at the bottom left of each panel. Left and center panels were observed with SMA (Ho et al., 2004) at 1.3 mm and 0.87 mm respectively, while right panel is ALMA cycle 0 data at 1.3 mm. Positions of AS 205 N and S are marked with crosses. Contours begin at 3σ of each observations.

1.6 Our Multiple Systems

1.6.1 AS 205

AS 205 is a multiple stellar system located at a distance of 127 ± 2 pc (Gaia Collaboration et al., 2018) in the ρ -Ophiuchi star-forming region. The northern and southern components (from now on, AS 205 N and AS 205 S) have been detected at a projected separation of $1.3''$ with near infrared imaging (e.g., Ghez et al., 1993; Reipurth and Zinnecker, 1993; McCabe et al., 2006), and imaged in 1.3 mm continuum and different CO molecular lines observations (Andrews et al., 2009; Salyk et al., 2014), as shown in Figure 1.4 and 1.5. The brightest of these sources at millimeter wavelengths is AS 205 N, a K5 pre-main-sequence star of about 0.5 Myr of age, with a mass of $0.87^{+0.15}_{-0.1} M_{\odot}$ (Eisner et al., 2005; Andrews et al., 2018) and a mass accretion rate of $4 \cdot 10^{-8} M_{\odot} \text{ yr}^{-1}$ (Andrews et al., 2009; Eisner et al., 2015). It shows multiple molecular emission lines in radio and mid-infrared wavelengths (e.g., Öberg et al., 2011; Salyk et al., 2014), including water vapor lines (e.g., Salyk et al., 2008; Pontoppidan et al., 2010) and organics (Mandell et al., 2012). AS 205 S is itself a spectroscopic binary, with K7 and M0 spectral types and masses of 0.74 and $0.54 M_{\odot}$ (Eisner et al., 2005).

Strong deviations from Keplerian motion is detected in different molecular lines (Salyk et al., 2014) in this system and an extended emission is found around the disks (see Figure 1.5, for comparison, an example of Keplerian motion is shown in right panel of Figure 5.4), that is unlikely to arise from envelope emission, nor from a large reservoir of mass that is being accreted by these disks (Salyk et al., 2014). Instead, it might be due to a combination of disks winds and perturbations produced by the binary interaction. Given that in the previous observations by Salyk et al. (2014) the synthesized beam could barely separate the N and S components (beam size $\approx 0.6''$), only the large scale features of this system have been identified.

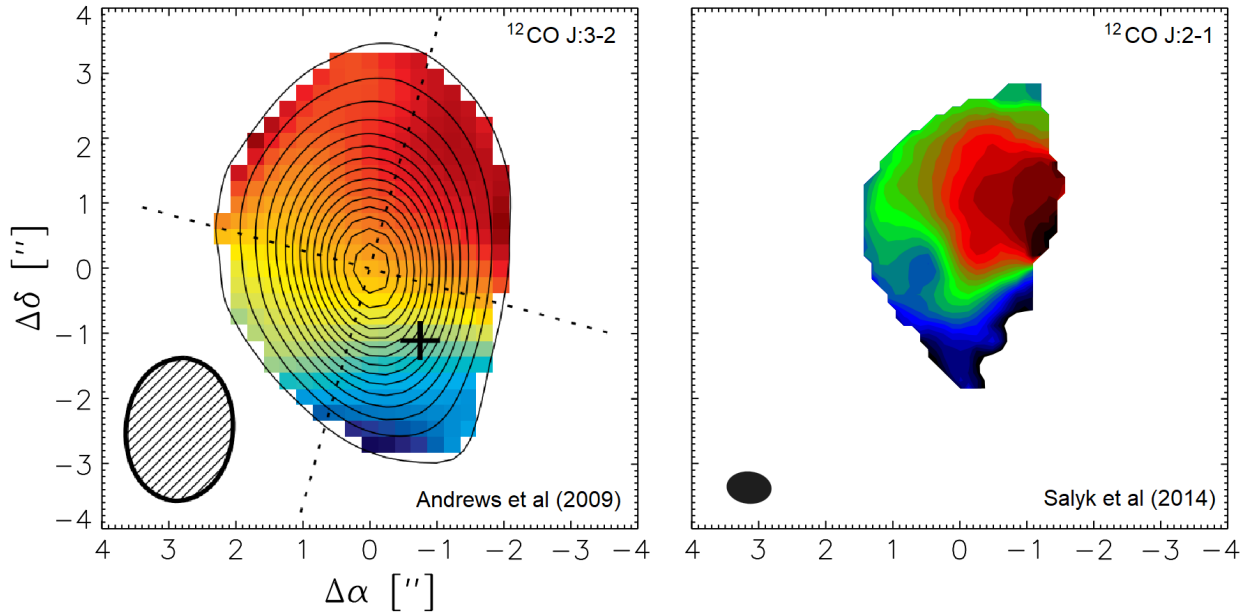


Figure 1.5: Moment 1 maps of the ^{12}CO in AS 205. Left panel: The transition J:3-2 observed by SMA (Andrews et al., 2009). The beam size is $2.19 \times 1.60''$ and contour levels represent the moment 0 intensity in 3σ intervals. The position of AS 205 S is marked with a cross, and the LSR velocities range between 3 to 5 km s^{-1} (blue to red respectively). Right panel: The transition J:2-1 observed by ALMA cycle 0 (Salyk et al., 2014). The beam size is $\sim 0.7 \times 0.5''$ and the LSR velocities range between 2.8 and 5.2 km s^{-1} (blue to red respectively). Both maps show only the 3σ detection.

The distances to each source in the AS 205 system used here were calculated from Gaia DR2 (Gaia Collaboration et al., 2018). However, we found a difference of almost 30 pc between AS 205 N and AS 205 S from their Gaia parallaxes (7.817 ± 0.098 and 6.376 ± 0.185 mas, respectively, at DR2). As it will be shown in Section 3, we are able to resolve the gas flow between the N and S components, previously detected in Salyk et al. (2014), and therefore conclude that the distance between disks must allow such an interaction. Since AS 205 S is an unresolved spectroscopic binary, Gaia DR2 did not account for the binary motion when calculating its parallax, which is calculated from the photocentre of each detected source (Lindgren et al., 2018). Because of this, in the following we consider the distance to AS 205 N (127 ± 3 pc) as being the same for both northern and southern sources.

1.6.2 HT Lup

HT Lup is a triple stellar system located at a distance of 154 ± 2 pc (Gaia Collaboration et al., 2018) in the Lupus star forming region, with an age of ≈ 0.8 Myr (Andrews et al., 2018). Its three components, hereafter referred to as HT Lup A, B, and C, have been identified through near infrared imaging (Ghez et al., 1997; Correia et al., 2006) and interferometry (Anthonioz et al., 2015), with separations of $\sim 0.1''$ between A and B, and $\sim 3''$ between AB and C, as shown in Figure 1.6. Both B and C companions have lower luminosities than the primary,

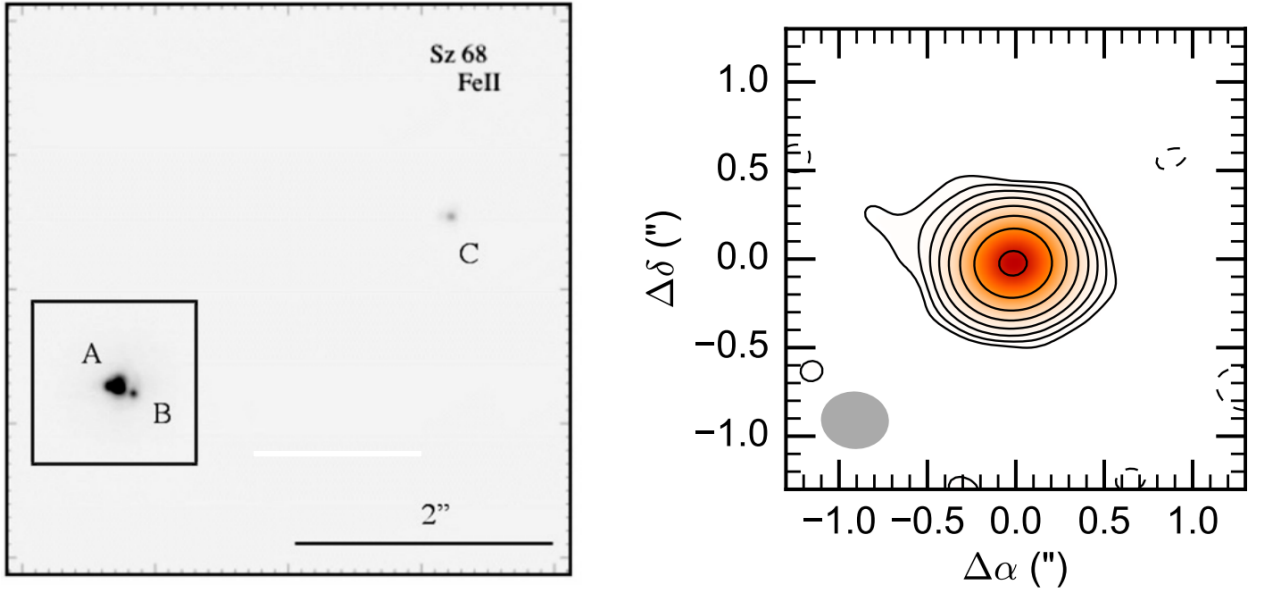


Figure 1.6: Left Panel: VLT/NACO image of HT Lup (Sz 68), in the FeII band ($1.644\,\mu\text{m}$, $0.023\,\mu\text{m}$ width), from Correia et al. (2006). The position of A, B and C stars are identified, and a $2''$ scale bar is shown at the bottom right. The square enclosing A-B represents the region imaged in the right panel. Right panel: ALMA 1.3mm continuum emission of HT Lup from Tazzari et al. (2017). The beam size is $\sim 0.34 \times 0.28''$ and contours start at 3σ level. The beam size is shown at the bottom left part of the image.

estimated to be 15% and 9.5% of that of HT Lup A (Anthonioz et al., 2015).

An extended nebulosity that resemble an arc-like structure is observed in the far infrared with Herschel photometry (Cieza et al., 2013; Bustamante et al., 2015), while cloud contamination is also found in optical spectra (Herczeg and Hillenbrand, 2014). At millimeter wavelengths, the HT Lup system has been observed by ALMA in continuum at $890\,\mu\text{m}$ and 1.3mm , and in CO molecular lines (Tazzari et al., 2017; Ansdell et al., 2018). All previous observations reach an angular resolution at best on the order of $0.1''$, unable to resolve the closest companion (see Figure 1.6), nor the individual disk structure and gas dynamics.

We estimate the distances for HT Lup A and C from Gaia DR2 (Gaia Collaboration et al., 2018), with the distance to C ($154 \pm 3\text{pc}$) being consistent with the A component at the 1σ level, showing that their proximity in the sky is not a projection effect.

1.6.3 CS Cha

CS Cha is a spectroscopical binary (Nguyen et al., 2012) located in the Chamaleon I region. The spectral type of the central object is K2 (Manara et al., 2014), with CS Cha B having a mass $\geq 0.1\,M_{\odot}$ and an orbital period $\geq 2482\text{d}$ (calculated by using a semi-major axis of $\sim 4\text{au}$ and a total system mass of $1\,M_{\odot}$, Guenther et al. (2007)). A large cavity was first identified by analyzing the spectral energy distribution of CS Cha, which shows an advanced stage of dust evolution (Espaillat et al., 2007) and a dip at $10\,\mu\text{m}$ (Gauvin and Strom, 1992;

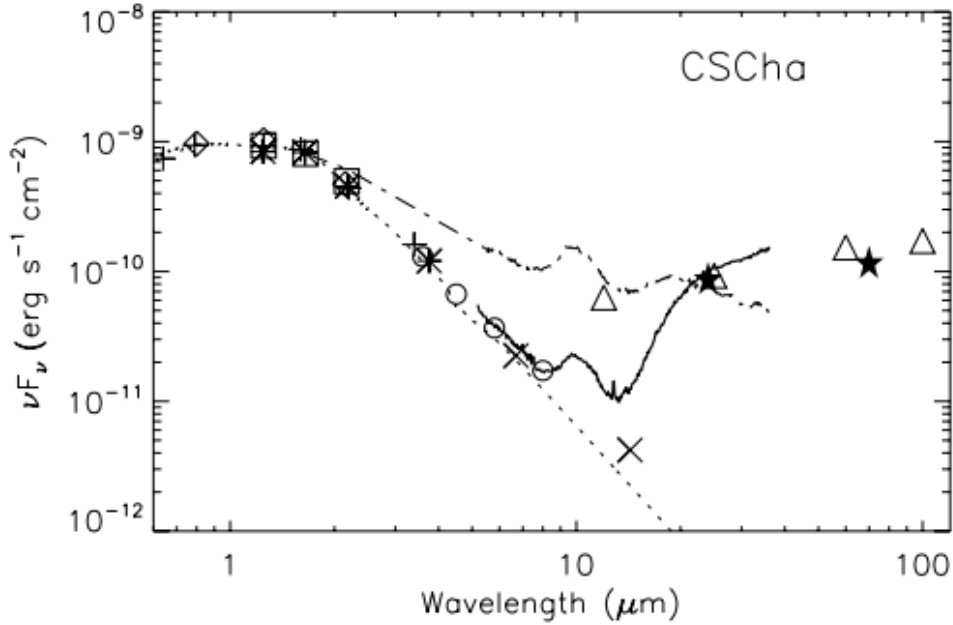


Figure 1.7: IRS spectrum (thick solid line, extinction corrected) of CS Cha. Other photometry correspond to: “+” - $R_c I_c JHKL$ from Gauvin and Strom (1992); “*” - JHKLM from Prusti et al. (1992); “o” from Luhman et al. (2008); “◊” from DENIS; “□” from 2MASS; “x” from ISO; “△” from IRAS; “★” from MIPS. The dotted line is the Kurucz photospheric model, and the median spectrum of Class II YSOs in Cha I is the dash-dotted line. Figure from Kim et al. (2009).

Kim et al., 2009; Espaillat et al., 2011; Nagel et al., 2012), as observed in Figure 1.7. The inner radius of this cavity was recently measured by Ribas et al. (2016) using data from the Herschel Space Observatory, finding that $R_{in} = 18^{+6}_{-5}$.

One interesting result from CS Cha is the detection of a polarized companion located at $1.3''$, or ~ 210 au in projected distance, by Ginski et al. (2018). This companion shows an high degree of polarization ($13.7 \pm 0.4\%$ in J band), which cannot be explained with a substellar companion (Stolker et al., 2017), meaning that this object must have a highly inclined disk or a disk with additional dust envelope. Although its measured J and H band brightness is compatible with a mass of a few M_{Jup} , its modeled SED does not fit with a non detection in the L-band (Ginski et al., 2018). Nonetheless, its detection was confirmed by different instruments along a time-span of ~ 20 yr, such as HST/WFPC2 (Trauger et al., 1994) from 1998, VLT/NACO (Lenzen et al., 2003; Rousset et al., 2003) data from 2006 and 2017, and SPHERE from 2017, as shown in Figure 1.8. The combination of archival data and dedicated observations allowed to constrain that this companion is co-moving with CS Cha, suggesting that it is gravitationally bounded to the main stars of the system (Ginski et al., 2018). From now on, we are referring to this companion as CS Cha C.

The CS Cha system has a parallax of 5.67 mas from GAIA DR2 (Gaia Collaboration et al., 2018), locating it at a distance of 176 ± 3 pc. Although the two closest companions are a spectroscopic binary, differently from AS 205, here the estimated angular distance between CS Cha A and CS Cha B (~ 4 au or 22.68 mas) is several times larger than the measured paral-

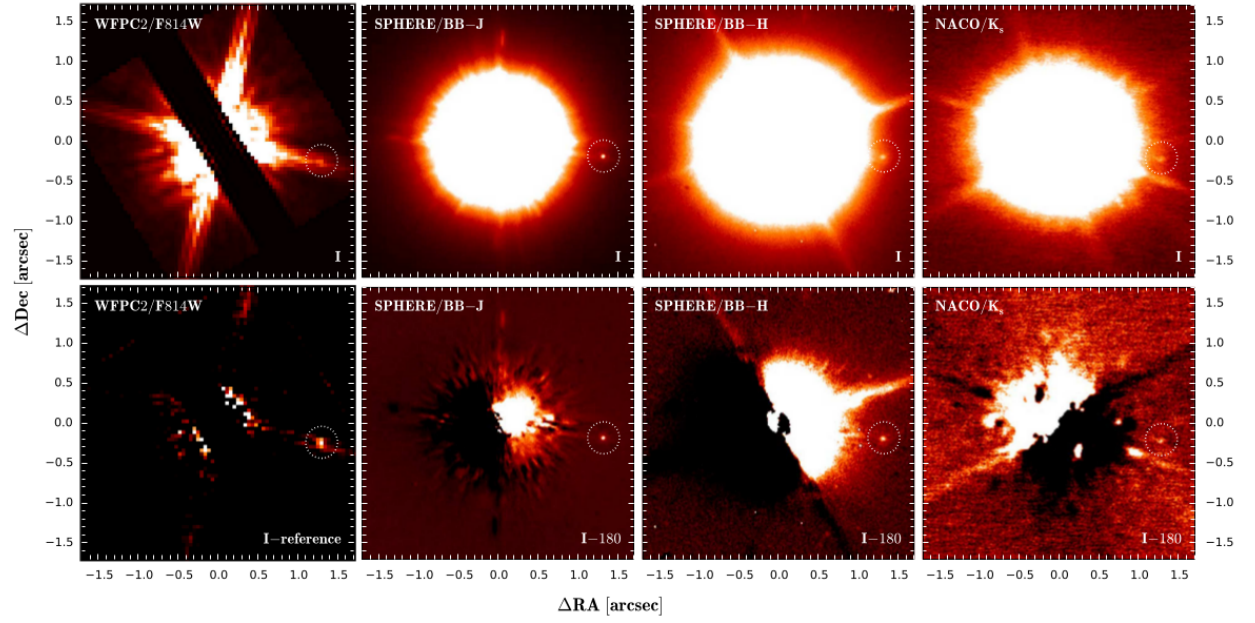


Figure 1.8: 1st row: From left to right, HST/WFPC2, SPHERE J and H-band intensity, and NACO K_s images of CS Cha. 2nd row: Same instruments as above, but with a subtracted 180° rotated version of themselves to remove the bright stellar halo. The position of CS Cha C is enclosed by a dotted circle in all images. Special considerations had to be taken to subtract the stellar emission from WFPC2, details and Figure from (Ginski et al., 2018).

lax, meaning that probably GAIA is only detecting the main component. This measurement is also in agreement with Voirin et al. (2018), where they estimate the distance to the Cha I cloud to be 179 pc.

Chapter 2

Observations

2.1 Datasets and calibration

This thesis makes use of data from the Atacama Large Millimeter/submillimeter Array (ALMA), located in the Chajnantor plateau in the north of Chile. The main ALMA antenna array is composed by 50 12m antennas that work as an interferometer, synthesizing the resolution of a single telescope with the size of the farthest located antennas. By changing the position configuration of the antennas in the plateau, different angular resolutions can be achieved along the year, a value that is also dependant on the wavelength that is being observed. Nowadays, ALMA can observe in 8 different frequency bands, ranging from 84 to 950 GHz, and inside each band the observer has to choose 4 independent spectral windows with the frequency range and resolution desired.

For comparison with our ALMA data, we will also use observations of the Spectro-Polarimetric High contrast imager for Exoplanets REsearch (SPHERE) (Beuzit et al., 2019), an extreme adaptive optics and coronagraphic instrument at the VLT. Two observing modes were used to obtain the images that are later shown in Chapter 5, the SPHERE Infra-Red Dual-beam Imaging and Spectroscopy (IRDIS, Dohlen et al., 2008), that can image in different bands between 1 and 2.3 μm , and SPHERE Zurich Imaging Polarimeter (ZIMPOL, Schmid et al., 2018), which works with smaller wavelengths than IRDIS, in the spectral range from 500 to 900 nm, thus achieving higher angular resolution.

The datasets presented in this thesis, listed in Table 2.1, are part of DSHARP (Andrews et al., 2018) for HT Lup and AS 205, with observations in ALMA band 6 at about 1.25 mm wavelength (Project number 2016.1.00484.L, PI: Andrews, Sean), and a DDT observation in band 7 for CS Cha, with wavelengths of about 0.87 mm (Project number 2017.1.00969.S, PI: Benisty, Myriam). For AS 205, we also include band 6 archival data from ALMA Cycle 0 (Project number 2011.0.00531.S, PI: Salyk, Colette), that were presented in Salyk et al. (2014), where the ^{12}CO J:2-1 line was also observed. A detailed description of the DSHARP data acquisition and sample selection can be found in Section 1.5 and in Andrews et al. (2018). Hereafter, we will use SB and LB as identifications for observations performed with “Short Baselines” and “Long Baselines” ALMA antenna configurations (as shown in Table 2.1), being

Table 2.1: Datasets used for each source. (a: This angular resolution is an estimation of the beam size using robust 0.5.)

Source Name	Obs. ID	Angular Resolution ^a (arcsec)	Integration (min)	Frequency range (GHz)	Executions	ALMA Cycle
AS 205	SB1	0.55	24.19	219.46 - 232.45	2	0
AS 205	SB2	0.26	17.14	230.07 - 247.90	3	4
AS 205	LB1	0.04	33.87	230.07 - 247.90	1	4
HT Lup	SB1	0.26	12.6	230.07 - 247.90	2	4
HT Lup	LB1	0.04	68.95	230.07 - 247.90	2	4
CS Cha	LB1	0.08	331.63	333.79 - 348.47	7	5

LB the observations where the angular resolution is $< 0.1''$.

All of our observations have 4 spectral windows per execution: 3 of them with dust continuum emission at low frequency resolution (128 channels of 31.248MHz for DSHARP, and 15.625MHz for CS Cha), and 1 with molecular line emission observed in a narrow frequency range, but higher frequency resolution (3840 channels of 488kHz for DSHARP, and 1920 of 122kHz for CS Cha). To extract only the dust continuum emission, we flagged all the channels within $\pm 25 \text{ km/s}^{-1}$ in the line spectral window (starting from the radial velocity of the source) to conservatively avoid any gas contribution, and the remaining channels were included in the dust continuum dataset.

An identification of the peak position in sources with multiple observations is needed to align the position of the emission center. For AS 205 we fit a 2D Gaussian to AS 205 N and matched the centers between SB2, SB3 and LB1, using LB1 as the true position given that its the higher angular resolution dataset (see Table 2.1 for datasets tags). The same approach cannot be applied to the HT Lup system, since HT Lup A and B components can only be resolved using the extended baselines configuration, therefore, the peak location of HT Lup A could not be identified in the shortest baselines datasets. Given that HT Lup C was $2.8''$ apart from the AB pair and isolated, we used its position as an alignment reference, before starting the self-calibration process. The phase center for imaging is respectively the center of HT Lup A and AS 205 N in the high angular resolution observations, while for CS Cha the center is the central cavity.

Due to time variability in the radio emission of the flux calibrators used in ALMA, we found discrepancies in the relative flux scales between different observations of the same source. In HT Lup, the difference between the executions of LB1 (see table 2.1) was 9%, and it was 13% when compared to SB1. To solve these discrepancies, we rescaled the discrepant datasets to match SB1, since its 2 executions were consistent and the calibrator was measured within 1 day of our observations. For AS 205, the maximum difference was 8%, which was corrected to match the first execution of SB2, which was the DSHARP observation of AS 205 with the lowest rms. For CS Cha all executions had consistent relative fluxes, and no scaling was applied.

Each individual baseline of the interferometer measures the phase and amplitude of the cross-correlated signal of that pair of antennas, and several effects can corrupt the true measurement of these visibilities, from pointing and electronic issues, to clouds moving above the antennas. These problems will remain even when the astrometric and relative flux discrepancies are solved, and to correct then we apply self-calibration.

Self-calibration consist in iteratively correct the visibilities by comparing the data with a model, which can be generated from the data itself. In each iteration, the time interval used to average the data and search for solutions is decreased, thus we can sequentially correct smaller time-scale perturbations to the visibilities. This process can only be used when the number of baselines is much grater than the number of antennas (N), since we need this redundancy to correct the antennas phases and amplitudes. We also need a high signal to noise observation, otherwise our model to correct the data would not be trustworthy, and Point Spread Function (PSF) artifacts or noise could be interpreted as signal from the source. Taking these considerations into account, we self-calibrated following two main steps:

1. Step 1: The bigger synthesized beam size in the shorter ALMA baselines configurations encloses more flux per beam, thus increases the peak emission in flux/beam units. We take advantage of this higher signal to noise (SNR) in short baselines observations, and self-calibrate them without combining data from different spectral windows.
2. Step 2: With the compact observations already self-calibrated, we combined them with the long baselines datasets, and self-calibrated again. To increase the SNR on the longer baselines we combined the spectral windows for each execution, thus avoiding excessive flagging due to low SNR in the extended baselines. The self-calibration solutions, in each step, were only applied to the non flagged data.

For the phase only calibrations, a minimum of 1.5 SNR was set for each solution to be applied. The solution intervals for phase calibration were integer multiples of 6s, the time-averaged scan interval. For amplitude calibration, the minimum SNR of a solution was increased to 3 SNR, and only 1 iteration in each step was applied, using as a solution interval the longer solution interval used in the phase only calibration.

The solution calibration tables obtained for the dust continuum were applied to the molecular line spectral window, which was also previously aligned by relative flux and centroiding. This can be done because the frequency range of the molecular line spw is very close to the dust continuum spws, and along our frequency coverage the emission from sources does not morphologically change.

2.2 Imaging dust continuum emission

We generated continuum images using the `tclean` task in CASA 5.1 for HT Lup and AS 205, and CASA 5.4 for CS Cha (McMullin et al., 2007). The image properties are shown in Table 2.2, while the phase centers for each source are listed in Table 2.3. When imaging, the weight we give to each baseline will determine the PSF structure, thus changing weights can allow us to also modify the angular resolution of the image. There are 3 basic weightings to image:

Table 2.2: Dust continuum images properties. (Column 1: Name of the system. Column 2: Robust parameter used to image. Column 3: uv-tapering applied. Column 4: Synthesized beam Full Width at Half Maximum (FWHM). Column 5: rms noise in the image. Column 6: Individual disk from the system. Column 7: Peak SNR based on the peak intensity and the rms. Column 8: integrated flux density of the disk).

Source	robust	uv-tapper (mas)	beam (mas)	rms (μ Jy/beam)	Disk	Peak SNR	F_ν (mJy)
AS 205	0.5	none	37×24	16.1	N	390	358.01
					S	105	38.13
AS 205	0.5	$40 \times 0, 90^\circ$	48×48	17.8	N	645	357.03
					S	189	37.73
AS 205	-0.5	none	29×16	26.4	N	136	356.11
					S	34	37.61
HT Lup	0.5	none	37×33	13.8	A	583	76.7
					B	116	3.48
					C	134	2.41
CS Cha	0.5	none	85×59	12.6	AB	496.4	182.12
					C	—	< 0.038

(a) Natural weighting, that gives weights based on the noise of the visibilities, and usually returns good SNR images but with poor angular resolution; (b) Uniform weighting, where all visibilities have the same weight, thus emphasizing the extended baselines and increasing the angular resolution, but with poor SNR images; (c) Briggs weighting, where a “robust” parameter can vary between -2 and 2 to give more uniform or natural weightings respectively. The later is the one we use for our imaging. Additionally, we can apply “uv-tapering” to multiply the weights of the visibilities by a Gaussian, giving us more control over the geometry of the PSF.

We generated 3 dust continuum images for AS 205. At first, balancing high angular resolution and SNR, we used a robust parameter of 0.5 to image the system. Then, we applied uv-tapering to circularize the beam, and this second image was used to analyze the substructures in AS 205 N. Finally, we increased the angular resolution by imaging with a robust -0.5, losing SNR to extended emission, but decreasing the smaller spatial scale being resolved in the brightest regions of AS 205.

To image HT Lup dust continuum we also chose a robust parameter of 0.5, allowing us to image at 5 au scales with high SNR. When increasing the angular resolution, the SNR decreased, and then the substructures in HT Lup A could not be well described. Because of this, we only used 1 continuum image to study the system.

The CS Cha source had a deep ALMA observation (5.5 hours on source), allowing a high SNR observation with the moderately extended baselines configuration. In this case, since no short baseline execution were performed, we skipped step 1 (compact baselines step) of self-calibration, and started immediately with step 2 procedure.

Table 2.3: Phase center for each source in J2000 coordinates.

Source	RA	Dec
AS 205	16h 11m 31.352s	−18d 38m 26.233s
HT Lup	15h 45m 12.847s	−34d 17m 31.01s
CS Cha	16h 11m 31.352s	−18d 38m 26.233s

2.3 Imaging molecular gas emission

Most of the ^{12}CO J:2-1 maps in other DSHARP sources are imaged with beams of ≈ 100 mas (see Andrews et al., 2018), however, for the disks around these multiple systems we synthesized beams with smaller size, in order to spatially distinguish structures inside the most compact sources.

Channel maps from ^{12}CO in AS 205 were generated using a robust parameter of 1. to obtain a beam of 90×67 mas (≈ 8.5 au at best), which led to a rms of 1.42 mJy/beam per velocity channel, and a peak SNR of 35.3. The AS 205 channel maps are presented in Figure 3.6.

For HT Lup, we found the ^{12}CO emission to be severely contaminated by the surrounding cloud, completely extinguishing the channels with velocity close to the one of the HT Lup A. In order to obtain the cleanest possible ^{12}CO map, we excluded baselines smaller than 150 m, thus, decreasing the sensitivity to scales larger than $2''$, emphasizing compact emission. The ^{12}CO images used a robust parameter of 1.5, and we additionally applied a uv-tapering of 20×5 mas with $PA = 150^\circ$, resulting in a beam of 53×50 mas (≈ 8 au). The rms of this spectral cube is 1.2 mJy/beam per velocity channel, with a peak SNR of 10.5. The HT Lup channel maps are presented in Figure 4.5.

For CS Cha we observed the ^{12}CO J:3-2 transition, and we imaged it with robust 0 and applied uv-tapering of 95×57 mas with $PA = 80.835^\circ$, resulting in a resolution of 98×92 mas (≈ 17 au). The rms of the spectral cube is 1.54 mJy/beam, with a peak SNR of 45.

Chapter 3

AS 205

3.1 Dust continuum emission in the AS 205 system

In the continuum emission, the AS 205 system resolves into two disks whose peaks are separated by about $1.31''$, or 168 au in projected separation (central panel, Figure 3.1), along a position angle of 217° (measured from north to east, with east towards the left). The AS 205 N disk is not azimuthally symmetric, instead, a spiral-like pattern with low contrast is observed (left panel, Figure 3.1). The AS 205 S disk is fainter and smaller in angular size than AS 205 N, and it exhibits a narrow ring around an inner disk (right panel, Figure 3.1), where a cavity of ~ 22 mas (~ 2.8 au) is observed when imaged at high angular resolution (see inset on the right panel, Figure 3.1).

In other DSHARP targets with spiral features (e.g. Elias 2-27 or IM Lup, Huang et al., 2018a) there are symmetric substructures (bright or dark rings) that can be used to constrain the geometry of the disk. However, the lack of symmetric features in AS 205 N implies that we have to use a different method to constrain the disk inclination (i) and position angle (PA). Given that the two sources are well separated in the sky, we fitted a 2D Gaussian model to each disk using the CASA task `imfit`. For AS 205 N, we used the continuum image generated while excluding the longest baseline dataset, with a beamsize of 270×227 mas, to avoid including any asymmetric feature. The best-fit values are given in Table 3. With the values of i and PA derived, we find that the angular momentum vectors of the disks are misaligned by either 46° or 94° (see equation in e.g., Jensen and Akeson, 2014), depending on whether the two disks share the same near side (the disk side closer to the observer).

3.1.1 Spirals in AS 205 North

We calculate the azimuthally averaged radial profile of the continuum emission, considering i and PA as constrained above, and using the peak of emission as center (which coincides with the peak of the 2D Gaussian fitted within 3 mas, about 1/10 of the beam size). After subtracting this radial profile from the continuum image, a clear spiral structure is revealed,

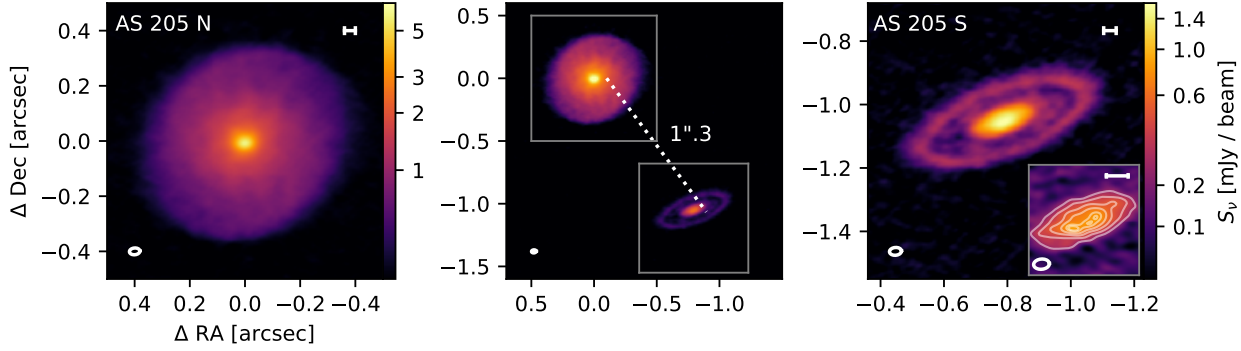


Figure 3.1: Continuum brightness distribution in AS 205 system. The central panel indicates the separation between the two disks on the sky, while the left/right panels show AS 205 N/AS 205 S, respectively. An inset on the lower-right corner of the AS 205 S panel presents a zoom to its inner disk, with observations imaged with different imaging parameters that provide higher spatial resolution (see section 2.1). The coordinates have their origin in the continuum peak of AS 205 N. The beam size is 37×24 mas (4.7×3.0 au), as shown in the lower left corner of each panel, except for the inset in the AS 205 S panel, with a beam size of 29×16 mas (3.7×2.0 au). In this inset, the contour levels correspond to 10, 15, 20, 25, 30 and 32σ , where σ is the image rms. A scale of 5 au is indicated by the horizontal bar in the upper right corner on the AS 205 N and S panels. An arcsinh stretch is used for the color scale.

as shown in Figure 3.2. These spiral features can be traced between ~ 20 to 55 au, beyond this radius the intensity of the continuum disk goes below the 3σ level. To trace the north-west (NW) and south-east (SE) spiral arms, we define a set of discrete points that correspond to the peak of emission along the radial direction, spaced by 10° in azimuth (which corresponds to one synthesized beam at ~ 30 au) and identified where the disk emission is above 3σ .

To characterize each spiral, we consider models of a Logarithmic and Archimedean spiral defined as:

$$r_{\log} = r_0 \cdot \exp(b\theta) \quad (3.1)$$

$$r_{\text{arch}} = r_0 + b\theta \quad (3.2)$$

where θ is the azimuthal angle, r_0 the radius when the angle is 0, and b relates to the pitch angle μ of the spiral. For the logarithmic spiral, the pitch angle is constant along all radii and it is calculated as $\mu = \arctan(1/b)$, while for the Archimedean model, the pitch angle depends on the radius as $\mu = b/r$.

The NW and SW spirals are assumed to share the same center (located at the peak of emission), while the spiral parameters r_0 and b are fitted separately for each arm to test if these are symmetric or not. We also include the observed inclination (i) and position angle (PA) as free parameters, assuming both spirals share the same geometry. Therefore, we have 6 free parameters ($r_{0,NW}$, $r_{0,SE}$, b_{NW} , b_{SE} , i , PA). To fit the spiral prescriptions above, we use an MCMC routine based on `emcee` (Foreman-Mackey et al., 2013). A flat prior probability was used for all parameters. For each fit, we use 250 walkers with two consecutive burning stages of 1000 and 500 steps, and then 1500 steps to sample the parameter space. The results

Table 3.1: Results of 2D Gaussian fit to AS 205 continuum disks. Values for major and minor axis correspond to the deconvolved size. For AS 205 N the fit was done on the short-baseline images only, to avoid including non azimuthally symmetric substructure.

Source	AS 205 N	AS 205 S
RA (J2000)	16:11:31.352	16:11:31.296
Dec (J2000)	-18:38:26.34	-18:38:27.29
major axis (mas)	414 ± 6	185 ± 6
minor axis (mas)	388 ± 6	77 ± 3
i	$20.1^\circ \pm 3.3^\circ$	$66.3^\circ \pm 1.7^\circ$
<i>PA</i>	$114.0^\circ \pm 11.8^\circ$	$109.6^\circ \pm 1.8^\circ$

Table 3.2: Best fit and 1σ uncertainties from the fit of the spiral shape in AS 205 N. The pitch angles μ are calculated from b . For the Archimedean model, μ is calculated at 35 au.

Parameter	Log.	Arch.
$r_{0,NW}$	$26.1^{+1.3}_{-1.1}$ au	$36.0^{+2.0}_{-1.8}$ au
$r_{0,SE}$	$11.9^{+0.7}_{-0.6}$ au	$7.2^{+2.1}_{-1.6}$ au
b_{NW}	$0.244^{+0.005}_{-0.006}$	$9.32^{+0.23}_{-0.15}$
b_{SE}	$0.246^{+0.005}_{-0.006}$	$9.10^{+0.16}_{-0.23}$
μ_{NW}	$13.9^{+0.3}_{-0.3}$	15.3° at 35 au
μ_{SE}	$13.7^{+0.3}_{-0.3}$	14.9° at 35 au
i	$15.1^{+1.9}_{-3.2}$	$14.3^{+1.3}_{-5.3}$
<i>PA</i>	$-9.1^{+10.7}_{-8.7}$	$59.6^{+13.0}_{-10.3}$

of the logarithmic and Archimedean spiral model fit are given in Table 3.1.1. We note that the reduced χ^2 in the Archimedean spiral model is factor of 1.5 better than in the logarithmic model. Figure 3.2 shows the best-fit Archimedean spiral and the location of emission maxima in the image (top panel) and in polar coordinates (bottom panel).

We also tested a model that allows for an offset of the spirals with respect to the center (two additional free parameters). The model finds an offset that is smaller than ≈ 3 au, with the NW and SE spirals pitch angle differing but consistent with each other within 1σ . Since the reduced χ^2 is comparable to the model with fixed center, we chose to use the latter for simplicity.

We calculate the contrast between the spiral and inter-spiral region, by comparing the intensity of each arm with the lower 5% intensity of a ring at the same radial distance. We found the arms to be of low contrast, with only a factor of 1.4 and 1.3 (median value) between the spiral and the inter-spiral region, for the NW and SE spirals, respectively. The contrast between the NW and SE spirals is small, ≈ 1.1 on average.

3.1.2 A ring in AS 205 South

The disk around AS 205 S is also well resolved in the continuum. The peak of emission for this component is 2.4 mJy/beam (185σ), which is only 29% of the AS 205 N peak, the mean

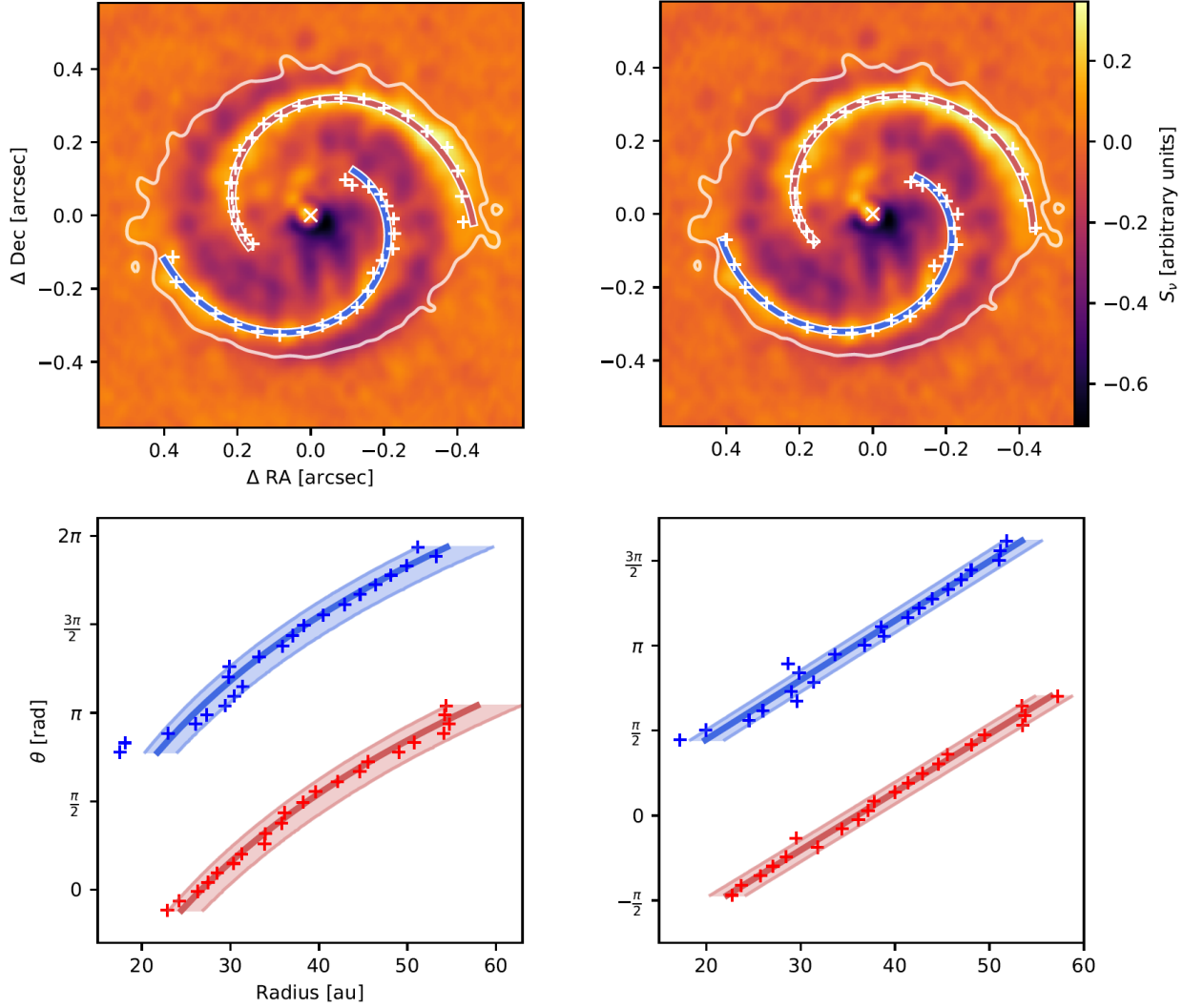


Figure 3.2: Top panels: Continuum emission of AS 205 N after subtraction of its azimuthally averaged radial profile. The plus symbols mark the location of the maximum of emission along the spiral arms. The best-fit of logarithmic and archimedean model are shown at left and right respectively. In red is shown the NW spiral, and in blue the SE. The contour level surrounding the disk marks the 5σ level of the original image (before subtraction of the radial profile). The center of the spirals was fixed, and its position is marked with a white cross. Bottom panel: Deprojected spirals, with colors as in the top panel. The best fit model is shown with a solid line, and the shaded region represents the 1σ uncertainties of our best-fit.

surface brightness of the ring is around $57.6 \mu\text{Jy}/\text{beam}$ (32σ).

At equally spaced intervals of 18° , i.e. points are roughly spaced by one synthesized beam, we search for the position of the maximum emission along the ring. The points were then fitted with an ellipse using a MCMC routine based on `emcee` (Foreman-Mackey et al., 2013), letting the center, major axis, minor axis, and position angle free to vary. The walkers and steps used are similar to the spiral fit. The points selected along the ring and the best-fit model are shown in Figure 3.3, while the best-fit parameters are given in Table 3.1.2.

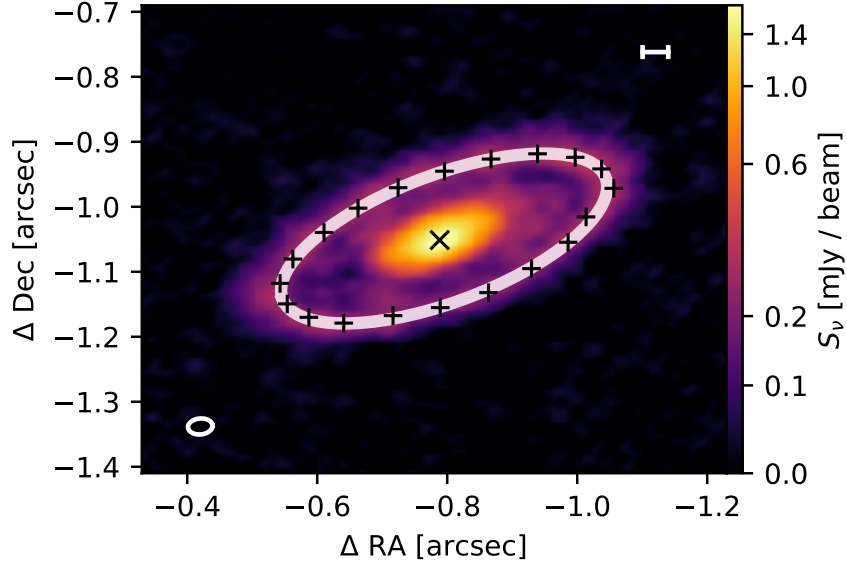


Figure 3.3: Fit of an ellipse to the AS 205 S ring in the outer disk. The plus symbols mark the maximum emission along the ring, while the white line shows the best fit. At the center, the black cross marks the best-fit center of the ellipse. The beam is given in the bottom left corner, and a 5 au scale bar is in the upper right corner for comparison.

Table 3.3: Results from the MCMC search for best-fit parameters of a ring in AS 205 S. Errors correspond to 1σ . Note that the major axis corresponds to the radius of the ring.

Parameter	Value.
Δx	$-0.42^{+0.22}_{-0.3}$ au
Δy	$0.23^{+0.17}_{-0.18}$ au
major axis	$33.8^{+0.3}_{-0.4}$
minor axis	12.4 ± 0.2 au
i	$68.4^{+0.5}_{-0.7}$
PA	$110.6^{+0.5}_{-0.4}$

From the fit, we find that the ring center matches the peak flux within 3 mas ($\sim 1/10$ of the beam size), and that the ring inclination and position angle are also in good agreement with the values obtained with the 2D Gaussian fit to the image.

3.2 Gas emission in the AS 205 system

We detect CO emission from this system from $v = -7.6$ km/s to $+12.0$ km/s, with little cloud contamination over this velocity range. Figure 3.4 shows the integrated intensity (moment 0) while Figure 3.5 also presents the intensity-weighted velocity field (moment 1) computed from the CO datacube, clipping at 3σ and including only channels with detected emission (see Figure 3.6 for channels of interest). Evidence of tidal interaction is clearly seen in the

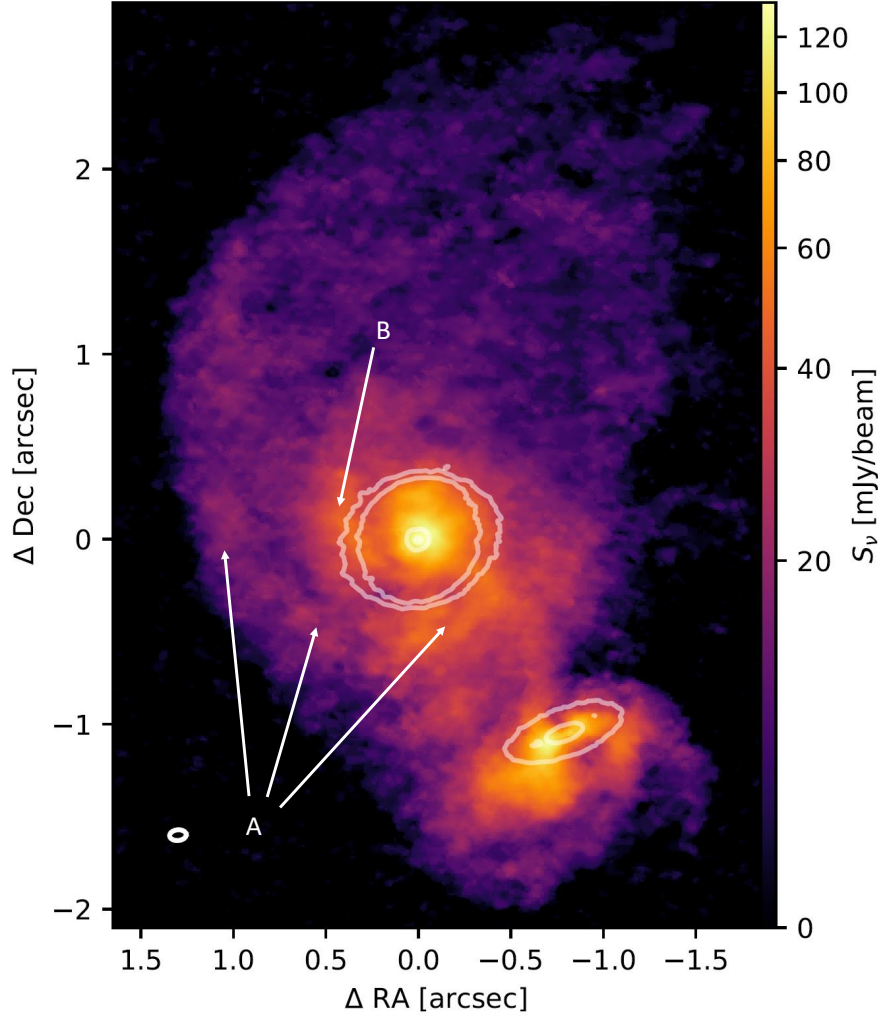


Figure 3.4: Integrated emission map (moment zero) of the CO spectral cube in the AS 205 system. The two main arcs of emission in AS 205 N are labeled A and B (See Figure 3.6). The contour levels represent 5, 25 and 300σ of the continuum emission, for comparison. Only emission over 3σ in the channel maps from Figure 3.6 was considered to build this image.

gas tracer, with CO emission between the two continuum sources on channels between $v = 3.25$ km/s and 5.35 km/s. The AS 205 N velocity maps shows a butterfly pattern characteristic of Keplerian motion around the central star, which allow us to estimate its systemic velocity to be ≈ 4.5 km/s (emission above 3σ is observed from $v = -0.1$ km/s to $+8.5$ km/s). However, this Keplerian pattern only holds inside the region where the continuum emission is above 3σ , at approximately 60 au from disk center. Outside this region, we observe extended emission and several arc-like structures that extend to the outskirts of the disk (at most at 410 au, $\approx 3.2''$).

In the north and south sides of the continuum disk, there are arc-like structures in CO that resemble spiral arms. The most prominent arc (that starts in the west and turns clock-wise to the south and then east, labeled A in Figure 3.4), roughly coincides with the NW continuum spiral, as is shown with the best-fit model for this spiral in dotted lines in Figure 3.5 (left panels). However, further out than ~ 80 au ($\sim 0.5''$) the arc does not have the

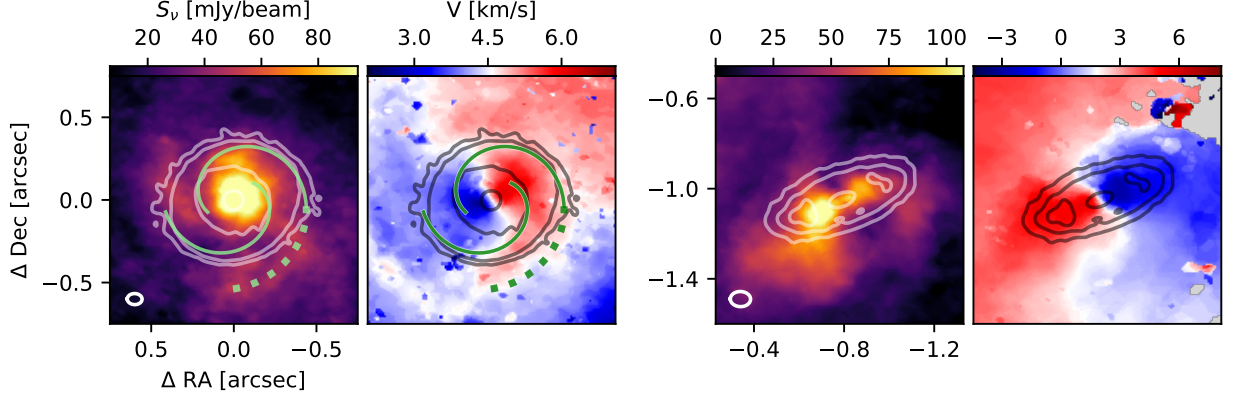


Figure 3.5: Moment 0 and moment 1 images of the CO emission in AS 205 N (left panels) and AS 205 S (right panels). The beam size (57×54 mas) is shown at the bottom-left corner of each moment 0 image. For AS 205 N, we draw in green the best archimedean fit to continuum spirals, and the NW spiral is extended as a dashed line for comparison. The contour lines mark the 5σ , 25σ , 120σ and 300σ level in the continuum image. Only emission over 3σ in the channel maps from Figure 3.6 was considered to build this image.

same opening angle as the NW continuum spiral. In the moment 1 map from Figure 3.5, the trace of arc A appears to have constant velocity (~ 4.5 km/s) over its extension outside of the continuum disk. In the moment 0 map, another spiral-like structure can be distinguished towards the east (labeled B in Figure 3.4), but this feature is not co-located with the best-fit SE continuum spiral. Furthermore, arc B is not clearly observed across channels maps, and no velocity structure that corresponds to this arc can be distinguished in the moment 1 map either.

As can be seen in the moment 1 map of the CO in AS 205 S (Figure 3.5, rightmost panel), the southern component shows disk rotation, but quite perturbed. First, due to its high inclination ($\sin i \approx 0.9$) the inner disk emission can be seen at high velocities from $v = -7.6$ km/s to $+12.0$ km/s, which is about a factor of two wider velocity range than for AS 205 N. Non-Keplerian motion is seen in the south-east of AS 205 S over all channels. At velocity channels near 4.3 km/s, the gas emission appears as a broad arc towards the south, better appreciated as the bright emission in the south of the AS 205 S moment 0 map.

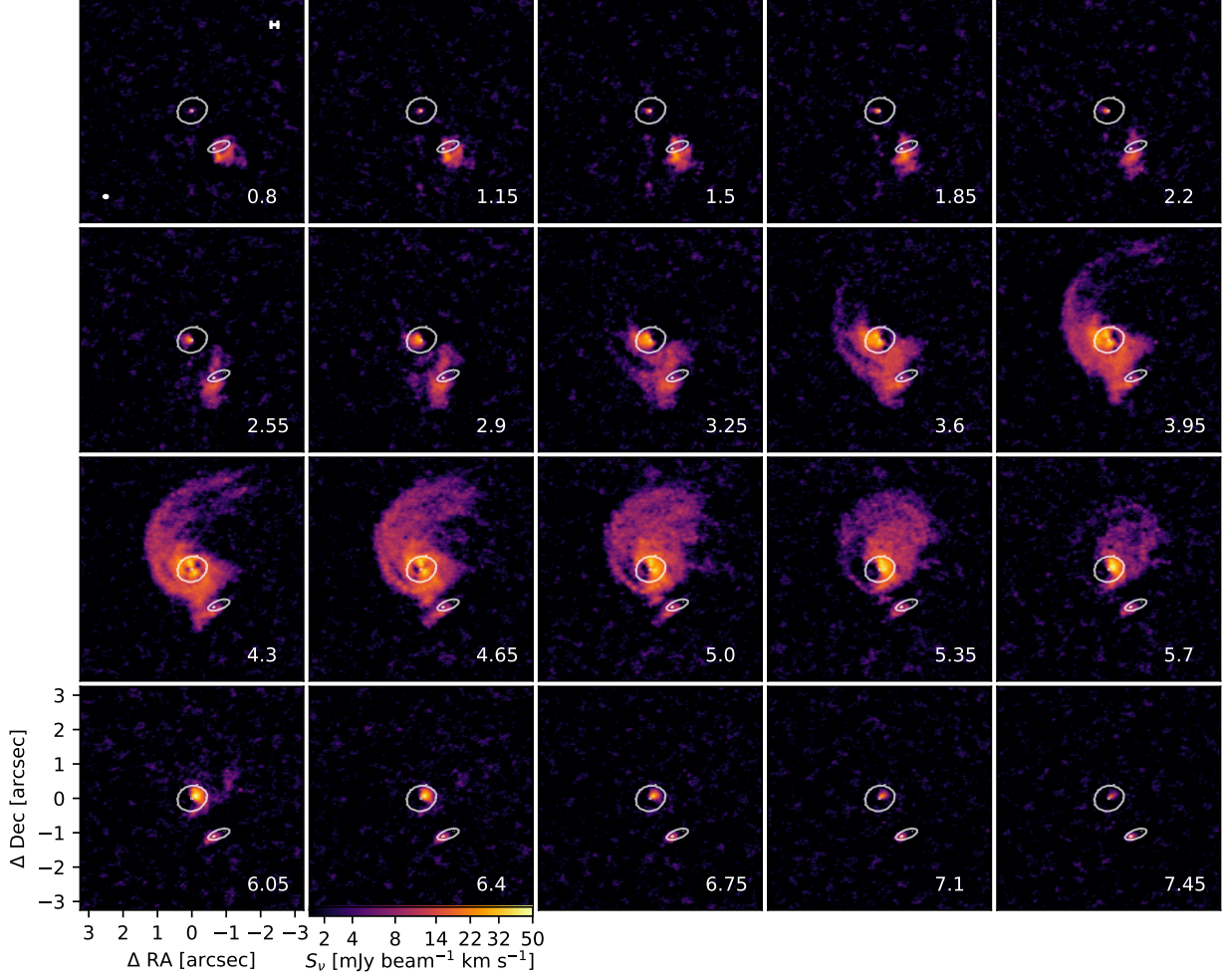


Figure 3.6: CO emission of AS 205. Each box is $7.5''$ wide and centered at the continuum brightness peak of AS 205. The LSRK velocity is printed in the lower right corner of each frame, while the beam size and a 25 au scale bar are printed in the first image at the upperleft frame. The contour levels correspond to 5σ and 300σ in continuum, for comparison.

Chapter 4

HT Lup

4.1 Dust continuum emission in the HT Lup system

Three components are detected in this system, Figure 4.1 shows the 1.3 mm continuum map where we are able to spatially resolve the dust continuum emission around the closest pair: HT Lup A and B. The angular separations between HT Lup A and B, and HT Lup A and C are $0.161''$ and $2.82''$, respectively, which corresponds to a projected separations of 25 and 434 au. We fitted a 2D Gaussian using `imfit` in CASA to derive inclinations and position angles for all disks, listed in Table 3. From these values, and following the same procedure used in AS 205, we estimate the misalignment between the angular momentum of the disks to be either 91° or 164° for HT Lup A and B, and 76° or 108° for A and C.

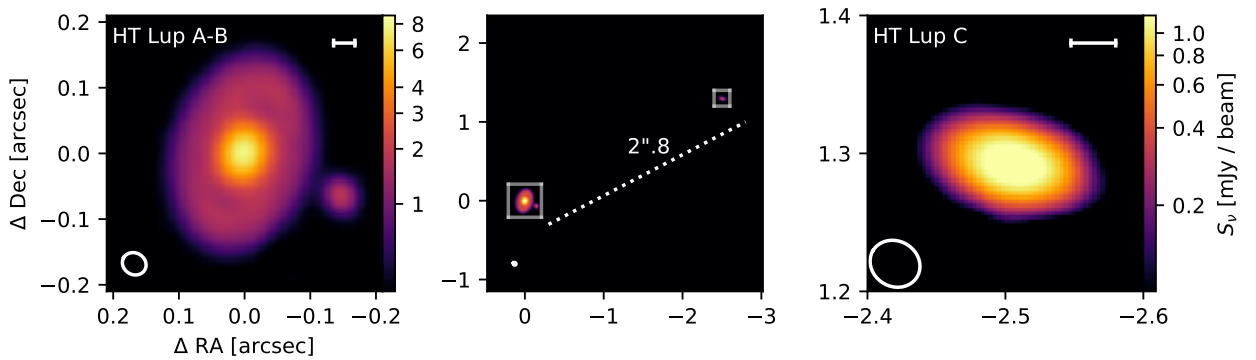


Figure 4.1: Continuum brightness distribution in the HT Lup system. The central panel shows the separation between the three disks on the sky, while the left/right panels show HT Lup A-B/HT Lup C, respectively. The coordinates have their origin in the continuum peak flux of HT Lup A. The beam size is 32×37 mas, as shown in the lower left of each panel, and a scale of 5 au is indicated by the horizontal bar in the upper right corner. An arcsinh stretch is used for the color scale.

4.1.1 Spirals in HT Lup A

HTLup A is the brightest and more extended disk in the system, with emission above 3σ detected up to 33 au (≈ 0.21) from the center. Computing an average radial profile of emission on this disk is difficult due to the presence of the companion at close distance (HTLup B). Thus, to subtract the overall disk emission and enhance the non axisymmetric features in the disk, we use an unsharped masking technique. We first convolve the image with a Gaussian of 66 mas FWHM and then subtract it from the original continuum image, multiplying by a weighting factor of 0.95. We chose these unsharp masking parameters as they better enhanced the low-contrast spiral features (convolution with larger Gaussians smooths out the disk emission excessively, smaller Gaussians do not smooth out the non-symmetric features and these end up being subtracted instead of enhanced). The resulting image, shown in Figure 4.2, reveals an underlying spiral structure. We trace the arms as in AS 205 N, finding the maxima along radial directions separated by 8° . The spirals extend from ≈ 16.5 to ≈ 19 au in radius, and each arm covers an azimuthal extent of $\approx 100^\circ$.

Following the procedure in Section 3.1.1, we fit a logarithmic and Archimedean spiral model, with the best-fit parameters presented in Table 4.1.1. The results show spirals with low pitch angles and quite symmetric, however, they are so compact that possible asymmetries might remain unresolved by our observations. The inclination and position angle are in agreement with the values obtained from Gaussian fitting.

Table 4.1: Best fit and 1σ uncertainties from the fit of the spiral shape in HTLup A. The pitch angles μ are calculated from b . For the Archimedean model, μ is calculated at 18 au.

Parameter	Log.	Arch.
$r_{0,N}$	$15.4^{+1.9}_{-1.8}$ au	15.3 ± 0.8 au
$r_{0,S}$	$19.7^{+0.8}_{-0.7}$ au	$19.7^{+0.7}_{-0.8}$ au
b_N	$0.073^{+0.025}_{-0.03}$	$1.28^{+0.5}_{-0.51}$
b_S	$0.064^{+0.025}_{-0.03}$	$1.17^{+0.5}_{-0.51}$
μ_N	$4.15^\circ^{+1.4}_{-1.7}$	4.1° at 18 au
μ_S	$3.69^\circ^{+1.4}_{-1.7}$	3.7° at 18 au
i	$52.2^\circ^{+0.6}_{-0.9}$	$53.0^\circ^{+0.6}_{-0.7}$
PA	$14.3^\circ^{+2.3}_{-1.8}$	$14.2^\circ^{+2.2}_{-2.1}$

4.1.2 Companions: HT Lup B and HT Lup C

HTLup B appears barely spatially resolved, its peak intensity (1.85 mJy/beam, 131σ) is 23% of the HTLup A peak intensity. From the 2D Gaussian fitting we obtain a deconvolved FWHM size of 31 ± 2 mas, corresponding to a disk size of ~ 5 au.

The farthest companion, HTLup C, is the faintest source in the system, with a peak intensity of 1.6 mJy/beam (20% of the peak of HTLup A) and a total integrated flux of 3.48 mJy. From the 2D Gaussian fit, we measure a deconvolved size of 59 ± 1 mas, which corresponds to a disk size of ~ 9 au.

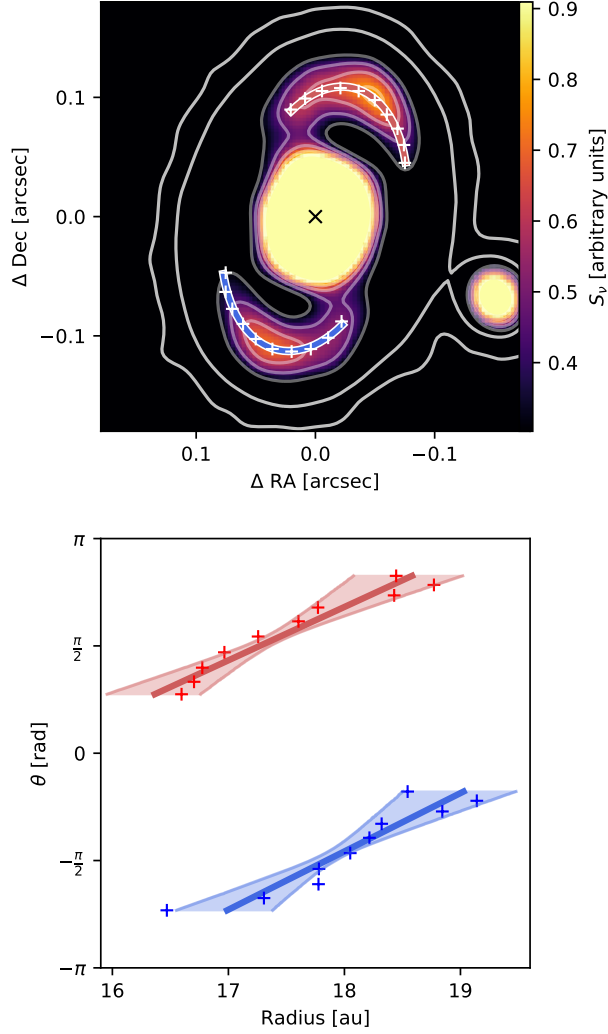


Figure 4.2: Top panel: The HT Lup A/HT Lup B unsharp-masked continuum image. The plus symbols mark the maximum emission along the spirals. In colored solid line the best Archimedean spiral models. Solid outer lines show contour levels at 5σ and 28σ of the original continuum image. The color scale was chosen to emphasize spiral arms. Bottom panel: Deprojected spiral wake, with colors as in the top panel. The best fit model is shown as a solid line, and the shaded region represents the 1σ uncertainties of our best-fit.

4.2 Gas emission in the HT Lup system

A map of the CO emission was obtained following the DSHARP procedure (Andrews et al., 2018). However, the CO was found to be highly contaminated by extended cloud emission and foreground absorption near the systemic velocity ($v_{sys} \approx 5.5$ km/s), at the level of completely erasing the signal from the disks between 3.75 and 4.8 km/s. For HT Lup A, blueshifted emission is seen in the north, while redshifted emission appears in the south. The opposite is observed for HT Lup B (see Figure 4.5). This is better seen in the first moment map of CO emission, presented in Figure 4.3, in which the disks appear to be counter-rotating. HT Lup C is also observed in the CO, with emission detected from $v = 2.7$ to 9.7 km/s, extending $\sim 0.2''$

along its major axis, which lies horizontally as expected from its continuum shape.

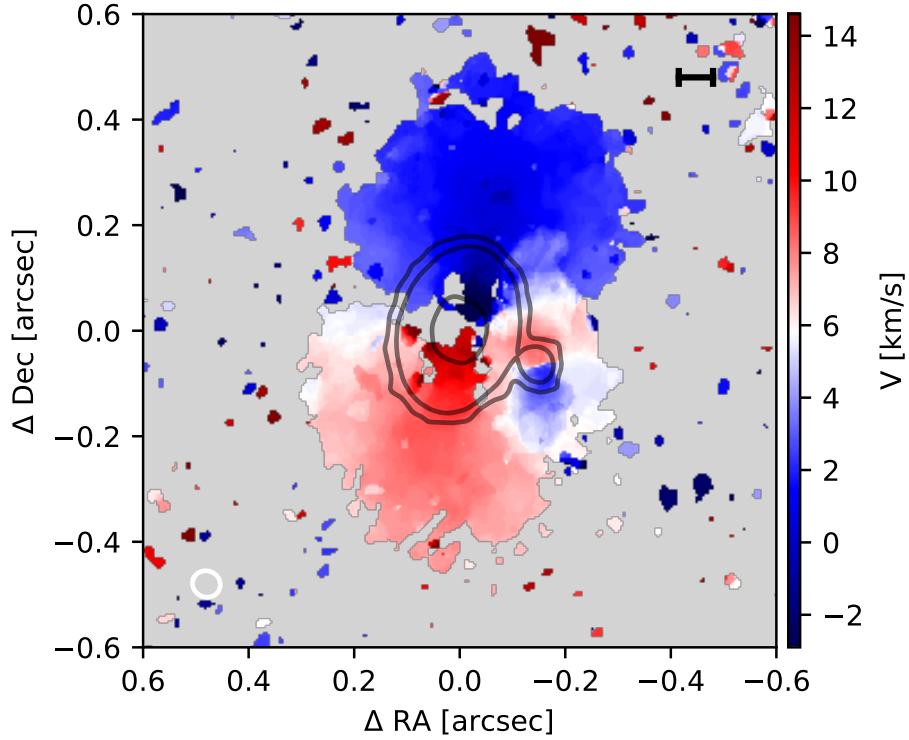


Figure 4.3: Moment 1 of the CO emission in the region of HT Lup A and HT Lup B. The beam size is 53×49 mas, presented in the bottom left corner of the image, as well as a 10 au scale bar at the upper right corner. The contour lines mark the 5σ , 28σ and 150σ level of the continuum image, for comparison. Only emission over 3σ in the channel maps from Figure 4.5 was considered to build this image.

For HT Lup B and C, we computed the position-velocity diagrams, to compare the gas rotation with a Keplerian profile, as shown in figure 4.4. The extra emission in HT Lup B PV belongs to HT Lup A, as they share spatial location of CO emission (see Figure 4.3), while the lack of emission in HT Lup C is due to the cloud extinction. Given the intense extinction and cloud contamination of CO, it is not possible to confidently recover the mass of HT Lup B and C by adjusting a Keplerian rotation pattern, although we find good match with 0.09 and $0.1 M_{\odot}$ respectively.

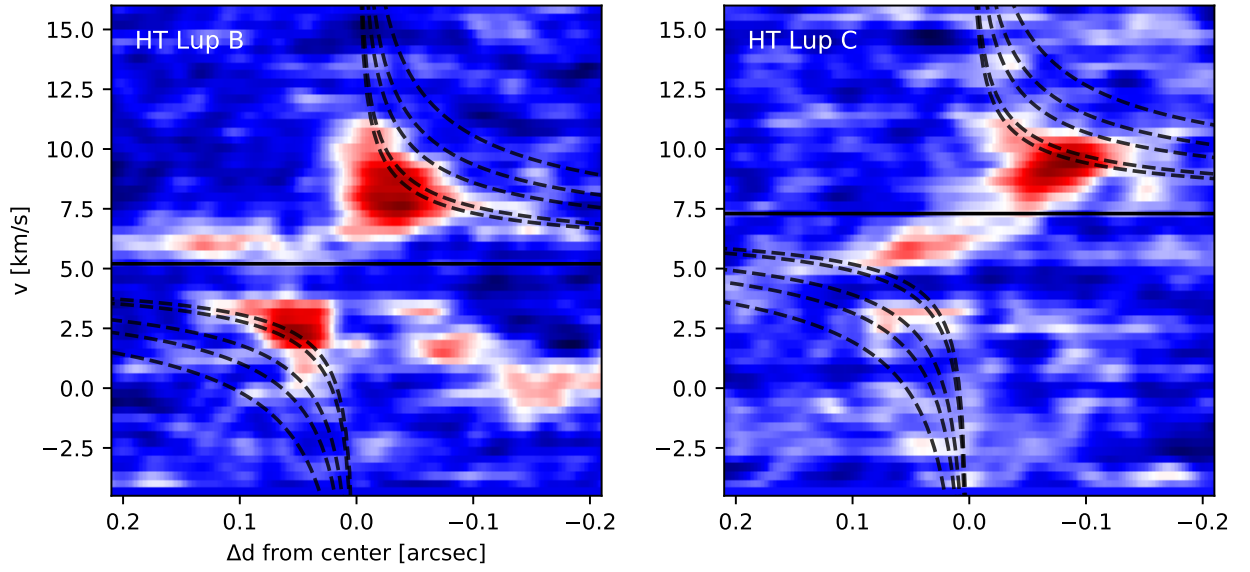


Figure 4.4: Position-Velocity Diagram of HT Lup B and C, in left and right panel respectively. The black dashed curves represent Keplerian rotation for central bodies of 0.078, 0.1, 0.2, 0.3, and $0.5 M_{\odot}$, with the higher mass being the outermost ones. The horizontal lines are 5.2 and 7.3 km/s, the central velocity of B and C respectively. Both PV diagrams are measured along the major axis of the sources.

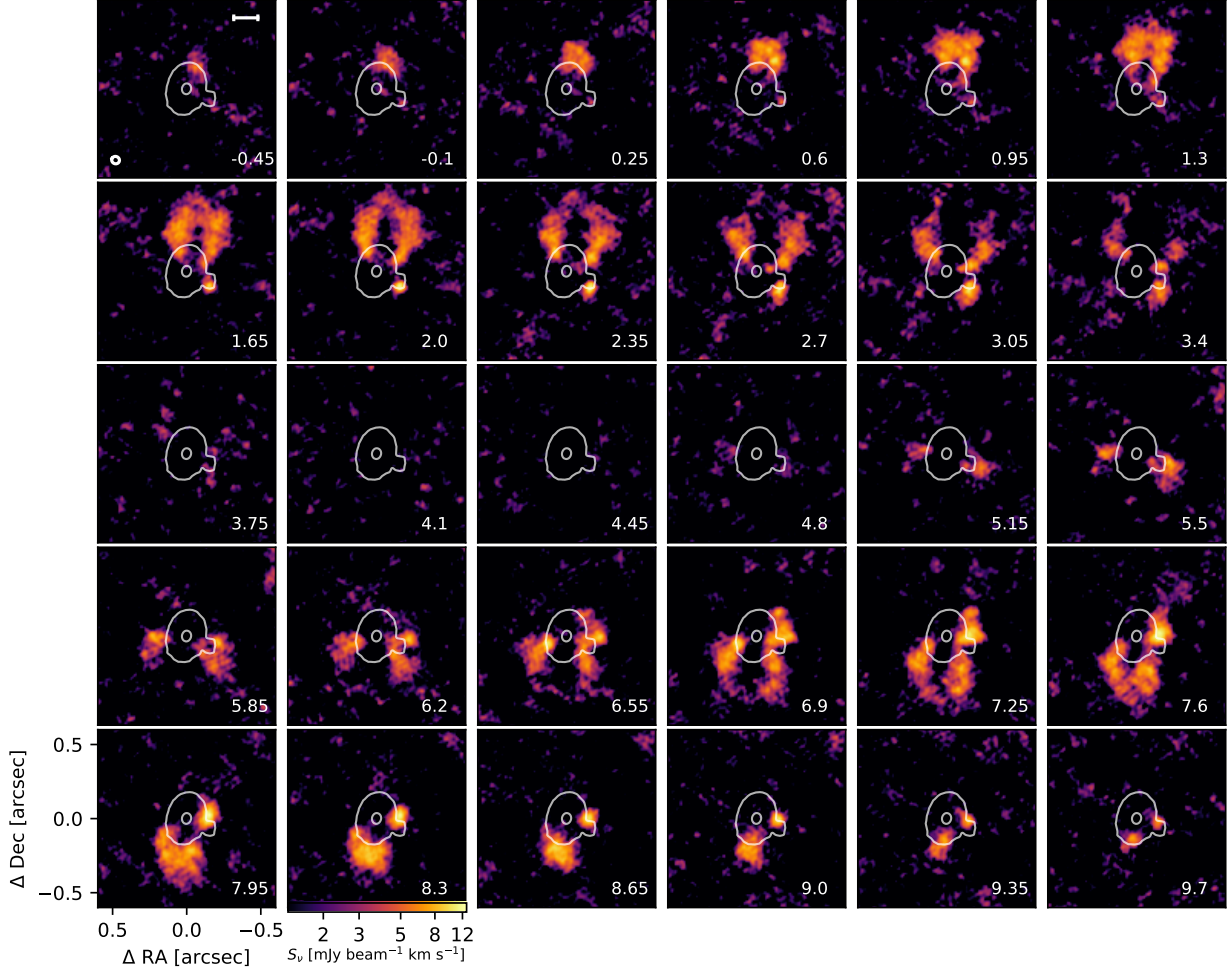


Figure 4.5: CO emission of HT Lup A and B. Each box is $1.2''$ wide and centered at the continuum brightness peak of AS 205. The LSRK velocity is printed in the lower right corner of each frame, while the beam size and a 25 au scale bar are printed in the upper left frame. The contour levels correspond to 5σ and 300σ in continuum, for comparison.

Chapter 5

CS Cha

5.1 Dust continuum emission in the CS Cha system

In CS Cha we resolve at 0.87 mm wavelength the circumbinary ring around the binaries CS Cha A-B, as it is shown in Figure 5.1, where the band 7 observations are compared with SPHERE data. We detect a central cavity where millimeter grains are almost depleted, with a radius of ~ 18 au. The geometry of the disk coincides with the one observed in scattered light, of a close to face-on configuration.

The circumbinary ring peaks at ~ 38 au and appears smooth, with no obvious substructure such as multiple rings or spirals at the spatial resolution of our observations (~ 12 au). Two asymmetries are observed in the millimeter image, as shown with level curves in the right most panel of Figure 5.1. These structures does not correlate with the position of the binaries inside the cavity as observed by SPHERE ZIMPOL (as shown in right panel of Figure 5.1), instead, their positions and orientation are similar to the major axis of the synthesized beam, and are most likely a result of deconvolution.

To recover the disk geometry parameters, we fitted a Gaussian ring to the visibilities using *galario* (Tazzari et al., 2018), with the profile defined as:

$$G(r) = A \cdot \exp\left(\frac{-(r - R)^2}{2\sigma^2}\right), \quad (5.1)$$

where r is distance from the center, A is amplitude, R is the radius at which the Gaussian is centered, and σ relates to the Gaussian width. This Gaussian ring was inclined and rotated by i and PA , to match the geometry of CS Cha. The best fit parameters with 1σ errors are presented in Table 5.1. Although the disk inclination and position angle are consistent with the measurements from scattered light those in Ginski et al. (2018), and also to our gas observations (as shown in 5.3), the dust emission from the disk is not fully described by a single Gaussian ring. Figure 5.2 shows the best Gaussian ring fit and residuals, where emission is still detected at the 60σ level (12% of the peak SNR in the original image).

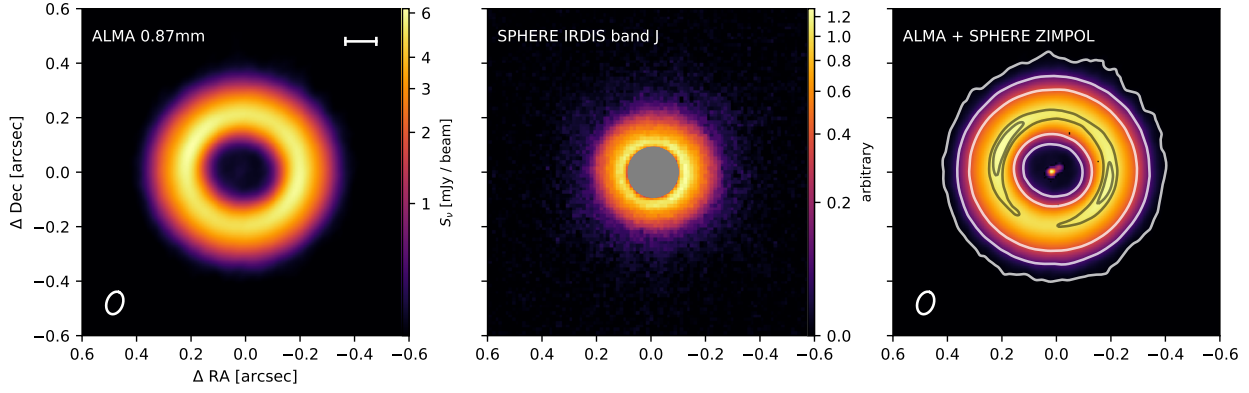


Figure 5.1: The left panel shows the continuum brightness of the circumbinary ring around CSCha A-B. The beam size of 59×85 mas is shown at the bottom left, while a scale bar of 20 au is shown at the upper right side. The central panel shows the SPHERE band J scattered light image. The right panel shows the ALMA image, as in left panel, but with contours to emphasize the apparent substructure. A SPHERE ZIMPOL image is plotted over the ALMA image, where the binaries are resolved, showing its orientation. The sigma levels are 5, 30, 100, 280, and 320σ . All images are at the same spatial scale.

Table 5.1: Best fit parameters of the Gaussian ring to the visibilities of CS Cha circumbinary disk.

Parameter	Best fit
i	$17.76 \pm 0.03^\circ$
PA	$95.53 \pm 0.1^\circ$
A	$6.1 \pm 3.9 \cdot 10^{-6}$
R	39.48 ± 0.01 au
σ	8.79 ± 0.01 au

Another interesting feature from the CS Cha millimeter dust continuum emission is the apparent non-completely dust depleted central cavity, better observed as emission from the central region in the residuals from Figure 5.2, with a peak SNR of 12σ .

5.2 Non detection of the external companion

CSChaC is an external companion detected in optical and infrared wavelengths by Ginski et al. (2018), as shown in Figure 1.8. No circumplanetary disk (CPD) around CS ChaC is detected in our 0.87 mm and 12 au spatial resolution observations of CS Cha, as shown in Figure 5.3, where the location of the companion is enclosed by a box, and compared to the detection in scattered light by SPHERE (Ginski et al., 2018, Kurtovic et al. in prep.).

In Ginski et al. (2018) the radial extent of the CPD is constrained to be ~ 2 au, since its emission was not resolved by their observations. Given our synthesized beam size of about 12 au, our observations would not have resolved it either. From our rms of $12.6 \mu\text{Jy}/\text{beam}$ in

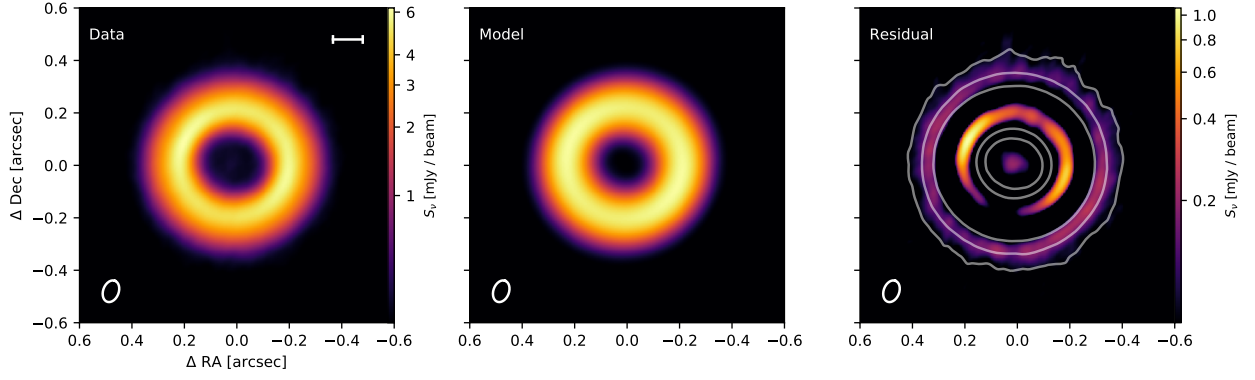


Figure 5.2: The left panel shows the continuum brightness of the circumbinary ring around CSCha A-B, as in Figure 5.1. The central panel shows the best Gaussian ring fit to the visibilities, and the model residuals are shown in the right most panel. The sigma levels are 5, 30 and 100 σ of the original continuum image. All images are at the same spatial scale and resolution.

continuum, we can constrain the CPD flux at 0.87 mm wavelength to be $< 37.8 \mu\text{Jy}$, which is our 3σ level. We are also unable to detect the ^{12}CO J:3-2 emission from the CPD, where our rms is 1.18 mJy/beam, and a beam size of 114×82 mas, meaning the ^{12}CO emission from CSCha C is below 3.54 mJy.

5.3 Gas emission in the CS Cha system

We resolve the ^{12}CO J:3-2 emission from the CSCha A-B disk. When imaged with robust 0.5, the synthesized beam is 114×82 mas ($\sim 20 \times 16$ au), with a peak SNR of 61σ in the channel maps of 0.35 km s^{-1} , and a rms of 1.18 mJy/beam. The gas emission also shows a cavity in the inner regions, however, the lower resolution of the gas observations compared to dust continuum (81×114 mas, or $14 \sim 20$ au) hinder the direct measurement of the inner cavity radius. The peak brightness of the CO emission is at ~ 21 au, and does not coincide with the radial location of the dust continuum peak. No obvious Keplerian deviations are detected.

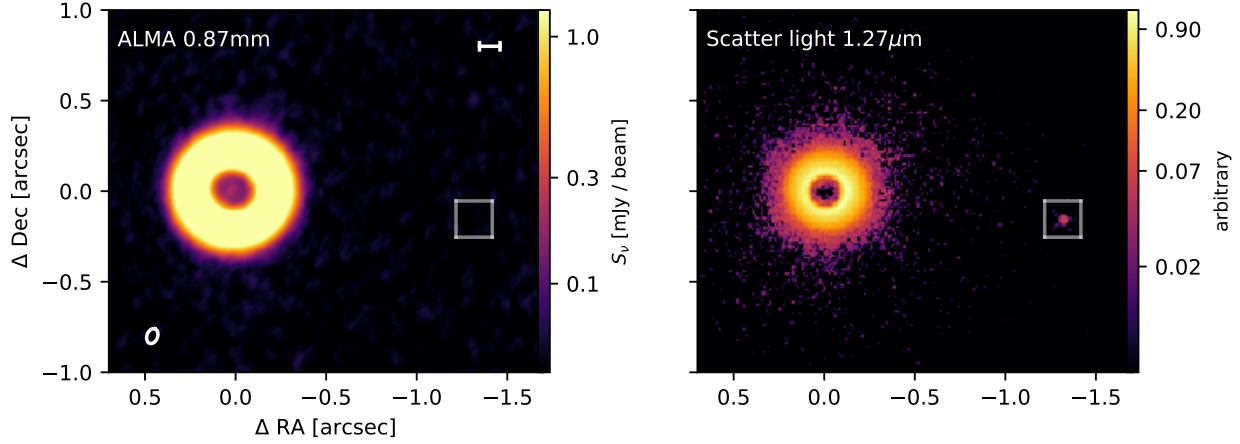


Figure 5.3: External companion observations. Left panel: ALMA dust continuum emission from Figure 5.1, with the same scale bar and beam size, but saturated at 20% of the peak flux to emphasize weak emission. Right panel: Scatter light image from SPHERE band J, with the detected companion, as published in Ginski et al. (2018). The white square represents the same location in both images, which are at the same spatial scale.

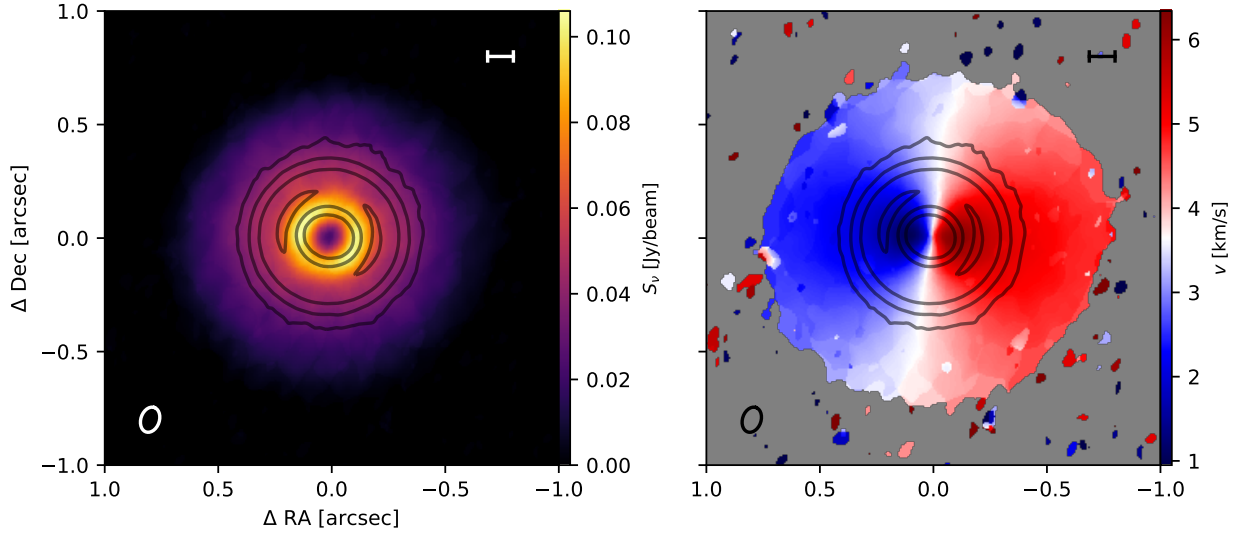


Figure 5.4: The left panel shows the integrated emission from ^{12}CO J:3-2 in the CS Cha system. The beam size of $81 \times 114 \text{ mas}$ is shown at the bottom left, while a scale bar of 20 au is shown at the upper right side. The right panel shows the moment 1 from ^{12}CO J:3-2, with a central velocity of 3.65 km s^{-1} , represented in white. The black contours levels are from the continuum image, at 5, 30, 100, 280, and 320 σ . Both maps only consider the CO emission over 3σ in the channel maps.

Chapter 6

Discussion

6.1 Ruling out chance alignment in binary disks

Given that the AS 205 components have different parallaxes as measured by Gaia DR2 (resulting in a difference of almost 30 pc in distance, see Section 1.6.1), and that for the HT Lup system there are no constraints on the distance to source B (while the A and C components have consistent Gaia parallaxes), one could argue that the observed vicinity of these pairs is due to chance alignment. In the case of AS 205, we rule out the coincidental alignment possibility based on the interaction between AS 205 N and S observed in ^{12}CO emission, as well as in earlier works (Salyk et al., 2014).

In the case of HT Lup, with speckle imaging, Ghez et al. (1997) find that the angular separation between HT Lup A and B is 107 ± 7 mas in 1997, while Correia et al. (2006) measure a separation of 126 ± 1 mas with data from 2004, using VLT observations. In this work, we constrain a separation of 161 ± 3 mas with data from 2017. Thus, in the span of ~ 20 years, HT Lup A and B have changed their separation by ~ 50 mas. Given the proper motion of HT Lup A ($\mu_{R.A.} = -13.63 \pm 0.13$ mas/yr, $\mu_{Dec} = -21.61 \pm 0.08$ mas/yr, Gaia Collaboration et al. (2018)), if the pair was aligned by chance, then their separation should have changed by ~ 500 mas over this time-span, an order of magnitude larger than measured. We therefore conclude that most likely, the HT Lup A and B stars as well as the AS 205 N and S components are not aligned by chance.

6.2 Substructures in the dust continuum emission of AS 205 and HT Lup

The high resolution observations of the multiple systems HT Lup and AS 205 have allowed us, for the first time, to directly constrain the type of substructures present in protoplanetary disks that have an ongoing interaction. In the following, we discuss the different substructures found in gas and dust tracers, and compare with other systems or numerical simulations.

6.2.1 Spiral arms

The spiral arms observed in the primary components of these systems are quite different from each other, and only AS 205 N looks similar to the spirals observed in single systems from the DSHARP sample (e.g. WaOph 6 and IM Lup, Huang et al., 2018a).

The HT Lup A disk is quite compact (32 au radius) and the radial extent of the spirals is only ~ 4 au (about 10% of the disk size). However, to describe the maxima of emission in the unsharped masking image, our modeling prefers a spiral over a ring for these substructures in HT Lup A: solutions with 0° pitch angle (i.e. a ring) are excluded at the 2.5σ level. But even at this high angular resolution it is difficult to resolve the substructure in HT Lup A. A bar-like emission is observed connecting the two spiral arms with the inner disk, something that is not described by our models (Figure 4.2).

On the other hand, the AS 205 N disk has spiral features that are well resolved by our observations. These spirals appear to be better described by an Archimedean model than a logarithmic one, in terms of the reduced χ^2 of each model, and since the former model better captures the spiral shape at both spiral ends. Thus, a variable pitch angle is preferred over a constant pitch angle to describe the AS 205 N spirals.

Interestingly, HT Lup A and AS 205 N show spiral features in the dust over a smaller range of radii and azimuthal angles than the other DSHARP spiral detections in Huang et al. (2018a). In fact, the radial extent of the spirals (≈ 36 au for AS 205 N and ≈ 4 au for HT Lup A) are smaller than the spirals observed in Elias 27, IM Lup, and WaOph 6, which range in radial extent from ≈ 50 au to ≈ 200 au (see Figure 6.1). This difference in size could be explained by the truncation of the outer disk predicted in binary disks simulations or simulations of disks that have been involved in fly-by encounters (Clarke and Pringle, 1993; Breslau et al., 2014; Winter et al., 2018), and is also found in recent unbiased binaries surveys (Manara et al., 2019). This will be further discussed in Section 6.3.

6.2.2 Axisymmetric substructures

The bright rings and dark annulus observed in the single disks systems with spirals from DSHARP (Huang et al., 2018a) are not observed in the disks of the multiples systems presented here. The lack of additional substructures may be explained by the small disk sizes: in the single systems with spiral arms, the gaps/rings usually show up at radial distances $\gtrsim 75$ au, while our largest disk (AS 205 N) appears truncated at $\lesssim 60$ au. If ring-like substructures are formed from pressure traps induced by planets, the lack of this substructures in HT Lup A and AS 205 N disks might suggest that stellar encounters and close binary companions inhibit planet formation, through disk truncation and material stripping, in agreement with the lower frequency of planet detections around binaries compared to single star systems (Wang et al., 2014).

Only AS 205 S displays a prominent outer ring at 34 au, with a bright inner disk out to ~ 20 au, with both substructures separated by a gap. The unperturbed nature of this dust ring is puzzling. Assuming the spectroscopic binary has a total mass of $1.3 M_\odot$ (Eisner et al.,

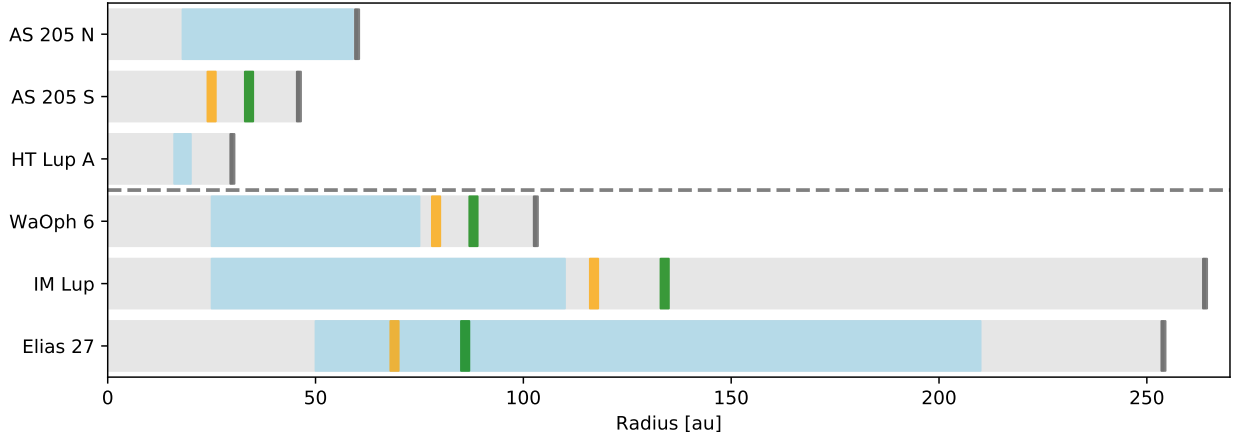


Figure 6.1: Radial location of substructures in DSHARP sources with spirals or multiple disk systems. Below the dotted line are the disks studied by Huang et al. (2018b), while over the dotted line are the disks of this work. The light blue range represent the radial extension of the spirals, the yellow and green lines mark the location of gaps and bright rings respectively, and the black line denotes the 3σ extension of the disk. HT Lup B and C were not included, since we cannot resolve substructure in their interior.

2005), the orbital period at the ring location would be 173 yr. Close encounter simulations of star-disk interactions show that tidal stripping and arc-like features can be induced in timescales from hundred to few thousand years (e.g. RW Aurigae, Dai et al., 2015). Thus, if the AS 205 system had a fly-by interaction (see Section 6.3) the ring at 34 au in AS 205 S has only had $\lesssim 10$ orbits to recover its structure after the interaction. Most likely, the dynamical interaction could not have originated from a very close encounter, which would have disrupted or severely affected this ring.

6.3 A fly-by in AS 205 system?

By analyzing the gas kinematics, disk rotation is identified in the N and S components of AS 205. However, we also observe non-Keplerian features such as the flow or bridge of material between the disks, an extended arc-like emission (arc A in Figure 3.4) towards the north in AS 205 N, an asymmetric emission towards the South-East in AS 205 S, and a tilt/twist of the projected axis of rotation in AS 205 N and S (see moment 1 map of these object in Figure 3.5).

These features are quite similar to the ones observed in fly-by interactions in parabolic-like orbits. For example, the 3D hydrodynamic fly-by simulations from Dai et al. (2015) and Cuello et al. (2018) exhibit several of the non-Keplerian features present in the AS 205 system, such as the gas bridge between the disks and the arc-like structure extending from the main component. Since for prograde encounters (i.e. when the interaction occurs in the same direction as the disk rotation) the material stripped and/or transferred from one disk to the other is more pronounced, rather than for retrograde encounters (Clarke and Pringle, 1993; Dai et al., 2015; Cuello et al., 2018), it seems that the prograde case is a closer match to

our observations. In addition, an orthogonal or prograde non-coplanar encounter is expected to produce a warp in the disk (Clarke and Pringle, 1993; Cuello et al., 2018), tilting and then twisting it, modifying the line of nodes, as observed in the velocity field of AS 205 N and S (moment 1 maps, Figure 3.5).

The truncated spatial extent of AS 205 N in the dust can also be explained by a prograde fly-by interaction, which would strip off material from the main disk resulting in a outer disk radius that depends on the companion mass, the angle of interaction between disk plane and companion orbit, and the distance at periastron (Clarke and Pringle, 1993; Cuello et al., 2018). Further simulations and observations will help to better constrain this parameters.

6.4 Disk misalignment in the HT Lup A-B binary

In the close binary HT Lup A-B, we observe an apparent counter-rotation of their disks in Figure 4.3. Given the degeneracy in the estimate of the misalignment between the disks, two different cases can explain the observations, as shown in Figure 6.2:

1. The angular momentum vectors are misaligned by 91° , leaving the disks almost perpendicular to each other. If we assume that the spiral arms in HT Lup A are trailing (i.e. the disk rotation is counter-clockwise) then the nearest side of the disk is in the East. For such a misalignment, assuming counter-clockwise rotation, the nearest side in HT Lup B would then be in the West, and the observed counter-rotation of the two disks would merely be a projection effect. Since we do not observe features in the CO channel maps that indicate transfer of material, an obvious perturbation in the butterfly pattern, or disk truncation in gas, this configuration is only possible if their physical separation is large enough in our line of sight.
2. The angular momentum vectors are misaligned by 164° , with the disks close to parallel and counter rotating. As the trailing spirals assumption implies that HT Lup A rotates counter-clockwise, HT Lup B would in this case rotate clockwise, and its nearest side towards us would be its East side. As in the previous case, this would only be possible if the two disks are not in the same plane but instead, physically distant along our line of sight.

Misalignments have been previously identified in other multiple systems (Jensen and Akeson, 2014; Williams et al., 2014; Brinch et al., 2016), but the separations of these systems are much larger (hundreds of au) than in HT Lup A-B. Bate (2018) present hydrodynamical simulations that indicate that misaligned disks in binaries are possible, mainly due to fragmentation in turbulent environments and stellar capture. In addition, a complete flip of the disk orientation can occur due to gas accretion from the cloud with different angular momentum. These results show that in principle misalignments can arise in any direction depending on the cloud surroundings and environment where the disks are formed. A possible scenario for the formation of the HT Lup A-B system is an independent fragmentation of the binary components from the cloud, followed by a capture and subsequent orbital decay, leaving them close together and misaligned.

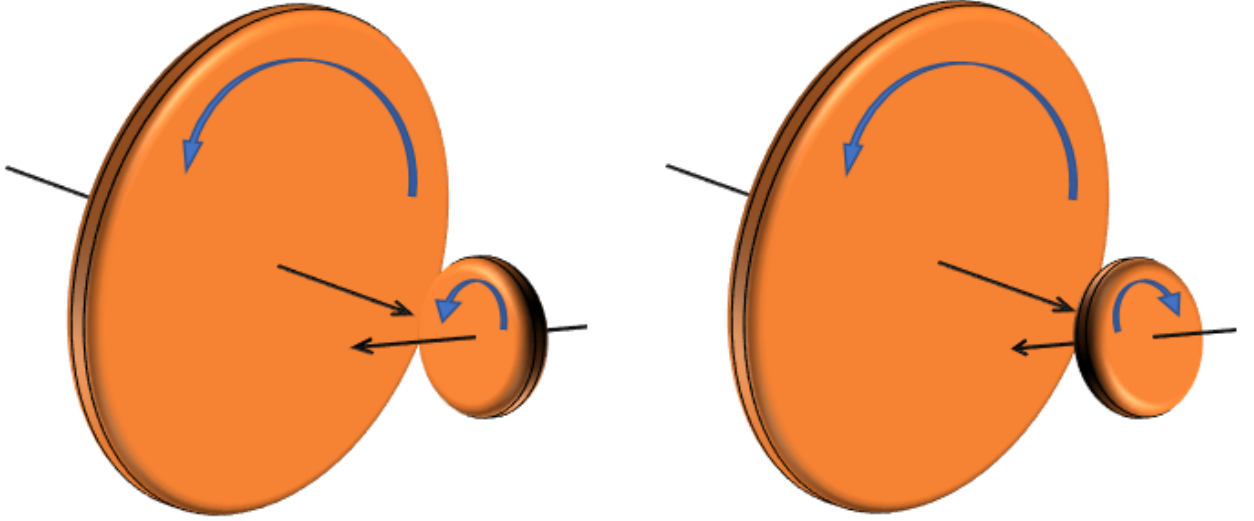


Figure 6.2: The two possible geometry configurations to explain the CO kinematics, assuming that the east-side of HT Lup A is the one closer towards us. In the left, the angular momentum vector are almost perpendicular, with a 91° misalignment. In the right, the disks are counter-rotating with disks close to parallel. Same reasoning can be done by assuming the west side of HT Lup A is closer towards us.

Future observations with high SNR in molecular lines, less contaminated from the cloud, and at similar or higher angular resolution, should be able to discern between the two scenarios, solving the degeneracy of disk orientation. A follow up of the HT Lup B and HT Lup C orbital positions will be also needed to get a complete description of the heavy truncation, misalignments, and dynamics in the HT Lup system.

6.5 Circumbinary disks: AS 205 S and CS Cha

Two of the disks of our sample, AS 205 S and CS Cha, are hosts to spectroscopical binaries (Eisner et al., 2005; Nguyen et al., 2012), and both of them have detected inner cavities in our millimeter data. From Lin and Papaloizou (1993) and Artymowicz and Lubow (1994) we expect the cavities inner edges to be located at $r_{\text{inn}} = 2a \sim 5a$, with a the orbital separation between the binaries (e.g., Lin and Papaloizou, 1993; Artymowicz and Lubow, 1994). This is, indeed, satisfied by our measurements of CS Cha disk, where the cavity inner edge is at $\sim 18 \text{ au}$, $\times 3$ the orbital separation of $a = 5 \sim 6 \text{ au}$ as observed with SPHERE/ZIMPOL data.

In AS 205 S, however, we do not have previous constrains on their separation. When imaged with a robust value of -0.5 we obtain an image of the disk with a smaller synthesized beam ($\sim 16 \text{ mas}$, 2 au resolution at best), in which the inner disk is no longer centrally peaked, and a cavity starts to be resolved (see Figure 3.1). Along its major axis, the size of the cavity is about $\sim 22 \text{ mas}$ or $\sim 2.8 \text{ au}$, constraining the spectroscopic binary separation to be smaller than $\sim 1.5 \text{ au}$.

A simple Gaussian ring does not describe the emission profile of CS Cha circumbinary ring, but it does recover the inclination and position angle. The CS Cha asymmetries located on the peak brightness radius are not geometrically positioned with the binaries, instead, they orient along the major axis of the synthesized beam, meaning that they might come from the elongated beam. Any possible non-axisymmetric substructures are likely of low contrast, and uv-modeling will be needed to describe them properly.

6.6 Non-detection of circumplanetary disk in CS Cha C

Previous modeling used to predict the observability of CS Cha C is based on the circumplanetary disk model of Isella et al. (2014), where the disk emission at a given wavelength is given by:

$$F_{0.87\text{mm}} = 2\pi \cos(i) \int_{r_{\text{in}}}^{r_{\text{d}}} \left\{ 1 - \exp \left[\frac{-\sigma_{\text{d}}(r) \kappa_{0.87\text{mm}}}{\cos(i)} \right] \right\} \cdot B_{\nu}[T_{\text{d}}(r)] \frac{r}{d^2} dr, \quad (6.1)$$

where the flux $F_{0.87\text{mm}}$ is estimated by knowing the inclination of the disk i , the opacity $\kappa_{0.87\text{mm}}$, its surface density $\sigma_{\text{d}}(r)$ and temperature profile $T_{\text{d}}(r)$. If we suppose an optically thin disk, a planetary mass of $M_p = 15M_{\text{Jup}}$, a planet temperature of $T_p = 2300\text{ K}$, a dust opacity of $7.5\text{ cm}^2\text{g}^{-1}$, a surface density as power law $\propto \sigma(r)$ and a gas-dust ratio of 100, the model calculates that a disk mass of $\sim 0.05 M_{\oplus}$ should have a flux in 0.87 mm wavelength of $\sim 90\text{ }\mu\text{Jy}$, which is 7σ in our observations.

Two possibilities arise from the non-detection of the CPD around CS Cha C: either the disk mass is lower than expected, or one(some,most) of the parameters assumed is incorrect. On the disk mass, the $\sim 0.05 M_{\oplus}$ limit is about 4 times the Earth Moon mass, and its in the order of Jupiter Galilean moons total mass ($\sim 0.066 M_{\oplus}$). Given the expected mass of CS Cha C (between 4 and $20 M_{\text{Jup}}$), it seems unlikely that its CPD has fewer mass than Jupiter’s CPD, therefore, if the disk mass estimated from the 0.87 mm continuum is $< 0.05 M_{\oplus}$, its possible that most of the mass is not in millimeter grains.

On the other hand, from equation (6.1) we see that surface density $\sigma_{\text{d}}(r)$ and $T_{\text{d}}(r)$ are the variables on which $F_{0.87\text{mm}}$ mostly depends. The lack of 0.87 mm could have been produced by a depletion of millimeter grains by radial drift, leaving only the micrometer sized dust (which is well coupled to the gas) on the disk, thus reducing the surface density.

In Isella et al. (2014) the disk temperature is modeled as:

$$T_{\text{d}}^4 = T_{\text{irr},\star}^4(R) + T_{\text{irr},p}^4(r) + T_{\text{acc}}^4(r) \quad (6.2)$$

where $T_{\text{irr},\star}$ is the temperature contribution from the host star (in our case the CS Cha A-B binary), $T_{\text{irr},p}$ is the contribution from the planet, and T_{acc} is the contribution from viscous dissipation within the circumplanetary disk. For simplicity, let us consider the star contribution to the disk temperature to be non-dominant when compared to planet or accretion. From the planetary models of Spiegel and Burrows (2012), Isella et al. (2014) study the temperature of Lk Ca 15 b planet by assuming two possible scenarios, depending on its formation process. A planet formed by gravitational instabilities (“Hot start”) is expected to

be at higher temperature than one formed through core accretion (“Cold start”), with temperatures of $T_p \sim 2500$ K and 700 K respectively, assuming 2 Myr old and $10 M_{\text{Jup}}$. Our initial assumption of $T_p = 2300$ K could be overestimating the planet temperature based on an incorrect origin, and because of Raileigh-Jeans law, a temperature of $T_p = 1000$ K would already reduce the planet contribution to the temperature to less than a half of the modeled.

For Lk Ca 15, Isella et al. (2014) finds that for a $10 M_{\text{Jup}}$ the disk temperature is dominated by the accretion contribution when $M_{\text{acc}} > 10^{-6} M_{\text{Jup}} \text{ yr}^{-1}$, which yields temperatures over 1500 K in the CPD inner regions. Although this accretion rate would build a $10 M_{\text{Jup}}$ in a timescale of 10 Myr (too long for the M_p estimated for CS Cha C), different accretion phases might induce periods of intense accretion and emission, and others with lower activity.

Even in the pessimistic case of a planetary mass $M_p = 4M_{\text{Jup}}$, a disk mass of $M_d \sim 0.09 M_{\oplus}$ would still be 7σ in our observations. The non-detection of CS Cha C circumplanetary disk is most likely a combination of all the previous named factors, and it will be further analyzed by modeling the emission and comparing between datasets.

6.7 Future work

Our first look with high angular resolution imaging in millimeter radio wavelengths of these multiple systems is just the beginning of a deeper understand on how planet formation is affected by external companions. The improvement of angular resolution in surveys of multiple stellar systems (e.g. Akeson and Jensen, 2014; Manara et al., 2019) will allow for the comparison of different substructures between the systems, and statistically characterise the role of parameters such as masses, orbit and disk orientation, minimum distance of interaction, and disk ages.

For AS 205, the kinematics and substructures of its ^{12}CO emission is being compared with dedicated simulations, thus constraining the interaction of both disks, and also their dust radial distribution previous to the close encounter. This work will be published in Cuello et al. (in prep).

In HT Lup, higher resolution observations of dust continuum are needed to better characterise the spiral substructures. Also, the severe cloud contribution and extinction does not allow precise measurements of Keplerian deviations due to the interaction. To study the gas kinematics in a less contaminated molecular line, an ALMA proposal was submitted to cycle 7 under the project 2019.1.01167.S (PI: N.T. Kurtovic), requesting 4.3hrs in the C43-9 configuration (20 mas angular resolution) and 2.2hrs in the C43-6 configuration to recover the extended emission, for a total of 12.7hrs when adding calibration. This proposal was ranked B and its awaiting to be observed in 2020 southern hemisphere winter.

The CS Cha system has to be further analyzed by modeling the disk emission in our deep 0.87 mm observations, both using uv-modeling and radiative transfer. The characterisation of the 0.87 mm emission, the ^{12}CO J:3-2 emission and kinematics, and the scattered light images from SPHERE, will allow us to describe the structure of the disk and how the central

binaries have affected the dust distribution. Dedicated modeling will also give us precise constraints on CS Cha C properties.

Chapter 7

Conclusion

We present very high resolution (~ 5 au scales) ALMA observations of the multiple stellar systems AS 205 and HT Lup, and moderate angular resolution (~ 12 au scales) observations of the circumbinary disk CS Cha.

In the dust continuum emission, the AS 205 system resolves into two separate disks located at 168 au projected separation. The disk around AS 205 N shows two spiral arms extending from about 20 to 55 au in radius and over 180° in azimuthal angle. By fitting them with an Archimedean and logarithmic spiral models, we find these arms to have similar pitch angles, close to 14° , although these are better described by the Archimedean model with a radially varying pitch angle. The southern component, AS 205 S, displays an inner disk and a bright ring at 34 au, with a gap between the inner disk and outer ring that is not devoid of continuum emission. The CO observations of AS 205 show extended emission in the form of arc-like structures, with non-Keplerian motions observed around both disks. We found evidence to support that these features were triggered by the binary interaction via a close encounter or fly-by, which was also suggested by Salyk et al. (2014). In this scenario, the AS 205 system would have either a highly eccentric orbit between its components, or had a recent unbound interaction. Nevertheless, the regularity of the AS 205 S dust ring puts constraints over the proximity and timescale of this interaction, since the dust ring does not appear as perturbed as the gas.

For the first time at millimeter wavelengths, we resolve the two companions (B and C) in the HT Lup system, the closest one with a projected separation of 25 au from HT Lup A. HT Lup C is located at more than 400 au from HT Lup A-B. The disks around HT Lup B and C are the smallest objects in the DSHARP sample, with deconvolved sizes of ≈ 5 and ≈ 9 au, respectively. The HT Lup A disk is resolved and spiral structure is observed, which we constraint to be symmetric with a pitch angle close to 4° . However, the spirals are quite compact and appear to connect with the inner disk through a bar-like structure. Higher angular resolution might be needed in future observations to completely characterize this additional substructure. The kinematics of the CO emission in the closest binary, HT Lup A-B, shows an apparent counter-rotation of their disks. Given the degeneracy in disk orientation, we find two possible explanations depending on the angle between their angular momentum vectors, which could either be a near to perpendicular relative orientation of their disks, in

which case the counter-rotation would only be a projection effect, or alternatively, a close to parallel orientation of the disks with a physical counter-rotation that requires the disks to not be on the same plane.

We do not detect the millimeter emission from the circumplanetary disk in CS Cha C. Further modeling has to be performed on this source to precisely constrain its upper limits, however, its possible that the non-detection is due to a combination of low accretion, low planet temperature, and millimeter dust depletion. The circumbinary disk around the CS Cha binaries is well resolved, and we are able to confirm the existence of a cavity in our dust and gas observations, which is not well described by a simple Gaussian ring.

The observations of multiple young stellar systems presented here, as well as future ALMA observations of gas and dust tracers at high angular resolution, are excellent laboratories to study dynamical interactions in multiple systems and to understand how this may affect the process of star and planet formation. This work is the first step towards a better understanding of how binary interactions and fly-bys affect disks structures, its evolution, and its later impact on the exoplanet population.

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