

THE FORMATION, EVOLUTION, AND SURVIVABILITY OF DISCS AROUND YOUNG BINARY STARS

By

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Declaration

I hereby declare that the work in this thesis is that of the candidate alone, except where indicated below or in the text of the thesis. The work was undertaken between February 2015 and January 2019 at the Australian National University (ANU), Canberra. It has not been submitted in whole or in part for any other degree at this or any other university.

This thesis has been submitted as a Thesis by Compilation in accordance with the relevant ANU policies. Each of the three main chapters is therefore a completely self-contained article, which has been published in, or submitted to, a peer-reviewed journal. The thesis has been excellent preparation for post-doctoral research, as the candidate has experienced the full scientific process from planning and running simulations through to statistical analysis and producing peer-reviewed publications. The status of each article and extent of the contribution of the candidate to the research and authorship is indicated below:

- **Chapter 2: Kuruwita R. L.**, Federrath C. and Ireland M., *Binary star formation and the outflows from their discs*, 2017, MNRAS, 470, 1626-1641. RLK ran the simulations and analysed them with the guidance of CF and MI. RLK also wrote the paper with feedback from CF and MI.
- **Chapter 3: Kuruwita R. L.** and Federrath C., *Role of turbulence during the formation of circumbinary discs*, 2019, MNRAS, 486, 3647-3663. RLK ran the simulations and analysed them with the guidance of CF. RLK also wrote the paper with feedback from CF.
- **Chapter 4: Kuruwita R. L.**, Ireland M., Rizzuto A., Bento J. and Federrath C., *Multiplicity of disc-bearing stars in Upper Scorpius and Upper Centaurus-Lupus*, 2018, MNRAS, 480, 5099-5112. RLK carried out the majority of observations, with observations also taken by MI, AR, and JB. Targets were identified using the work of AR. All reduction and analysis of observations were done by RLK. All sections, bar Section 2.1, were written by RLK with feedback from co-authors. Section 2.1 was contributed by AR.

The candidate also made contributions to the following articles during the course of the candidature:

- **Kuruwita R. L.**, Staff J., De Marco, O., *Considerations on the role of fallback discs in the final stages of the common envelope binary interaction*, 2016, MNRAS, 461, 486-496.
- Green J. D., Kraus A. L., Rizzuto A. C., Ireland M. J., Dupuy T. J., Mann A. W., **Kuruwita R. L.**, *Testing the binary trigger hypothesis in FUors*, 2016, ApJ, 830, 29.
- Childress et al., *The ANU WiFeS SuperNova Programme (AWSNAP)*, 2016, PASA, 33, 29.
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Abstract

In the age of the *Kepler* space telescope and other exoplanet finding missions, a variety of exotic planets have been discovered. Some of these planets have been found to be in binary star systems — systems which have historically been overlooked in planet formation models. This is due to the single star scenario being simpler to model than binaries, as well our anthropocentric bias towards single stars like our Sun. However, planet formation around binary stars is an important topic because a large fraction ($\sim 50\%$) of stars form in binary systems.

In this thesis I investigated the physics that influences the creation, stability, and survivability of discs around binary stars with the broad understanding that the longer the lifetime of a disc (around a single or binary star) the higher the likelihood of producing planets.

The theoretical work of this thesis was conducted using the ideal magnetohydrodynamical numerical simulation program **FLASH**. I simulated the collapse of molecular cores until the formation of protostars and followed the early evolution of these systems. For the first theoretical project I investigated the influence that binarity had on the global evolution of a young stellar system. This included studying mechanisms such as accretion, jets and outflows, and dynamical interactions. I found that binary stars produce weaker outflows when considering the transport of mass, linear momentum, and angular momentum. For the second theoretical project I investigated the formation of discs in binary stars with the inclusion of turbulence in the initial conditions. I found that the turbulence helped to build large circumbinary discs which restructured the magnetic fields for efficient outflow launching, but too much turbulence may also disrupt this organisation of magnetic fields. Given the

environment where binary stars form (turbulent molecular cores), it appears that the formation of circumbinary discs should be common place, however circumstellar discs could also be destroyed quickly in these same environments.

My observational work aimed to determine the typical survivability of discs around binary star systems. This work was carried out by using the Wide Field Spectrograph (WiFeS) on the Australian National University 2.3m Telescope to search for radial velocity variation in disc-bearing members of the 11 Myr and 17 Myr old star-forming regions Upper Scorpius and Upper Centaurus-Lupus. I found that the binary fraction of disc-bearing stars in these regions do not differ significantly from the field star binary fraction. I hypothesised that this is due to two competing factors: *circumstellar* discs are disrupted by companions and are dispersed quickly, but *circumbinary* discs are more common than equivalently sized discs around single stars. These results suggest that the typical lifetimes of discs in single and binary stars are comparable.

Overall, I found that in some scenarios binary stars may produce hostile environments for planet formation via the destruction of *circumstellar* discs, but the formation of large *circumbinary* discs is likely to be a common occurrence. This suggests that planet formation is as likely around binary stars as single stars. Therefore, planet formation around binary stars needs to be considered to understand overall planet formation.

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1

Introduction

“For a moment it seemed that nothing was happening, then a brightness glowed at the edge of the huge screen. A red star the size of a small plate crept across it followed quickly by another one - a binary star system. Then a vast crescent sliced into the corner of the picture - a red glare shading away into deep black, the night side of the planet.

‘I’ve found it!’ cried Zaphod, thumping the console. ‘I’ve found it!’

Ford stared at it in astonishment.

‘What is it?’ he said.

‘That...’ said Zaphod, ‘is the most improbable planet that ever existed.’”

—Douglas Adams, *The Hitchhiker’s Guide to the Galaxy*

Science fiction has always been inspired by science, and continues to inspire scientific progress by imagining possibilities well before technology enables the gathering of evidence. Extrasolar planets (or exoplanets) had long been a thing of science fiction until the observations and discovery of planets around other stars in the 1990s. Some planets discovered had not been anticipated before by science fiction,

such as planets around pulsars (Wolszczan & Frail 1992), however others have since been confirmed such as the existence of circumbinary planets. Circumbinary planets are planets that orbit around two stars, imagined in pre-51 Peg b fiction, such as the famous Tatooine from Star Wars, or Gallifrey from Dr Who. The circumbinary planet Magrathea from Hitchhiker’s Guide to the Galaxy was described as “the most improbable planet that ever existed”, but was it really?

To date we know of ~ 24 circumbinary planets with ~ 16 of those being around main sequence binaries¹. Therefore, the evidence suggests that Magrathea is not “the most improbable planet that ever existed”, but the question remains open as to whether it is the unlikely or the common planet? What is the likelihood of planet formation around binary stars compared to single stars?

To answer these questions, I looked at the material that will eventually form these planets: the protoplanetary discs around binary star systems. My work was primarily concerned with understanding the creation, stability and lifetime of discs in binaries with the general understanding that the longer the lifetime of a protoplanetary disc, the higher the likelihood of forming planets. To understand the formation of planets around binary stars we must first understand star formation and disc evolution around single stars.

1.1 Star formation

In the following sections I will review the pre-main sequence evolutionary stages of a single star. After reviewing these stages, I will review what is known about the influence of multiplicity on these pre-main sequence classes. The evolutionary classes of protostellar evolution is described in terms of empirically defined classes numbered 0, I, II and III (Lada 1987; Andre et al. 1993).

Stars are formed in turbulent giant molecular clouds. The turbulence, coupled with gravity, causes the cloud to further fragment and the densest regions become the molecular cores where stars are born (McKee & Ostriker 2007). The cores that fragment from giant molecular clouds are pervaded by the magnetic field of the parent cloud (Han 2017). While the molecular core is rotating and collapsing, the magnetic field is pinched around the rotation axis of the core, creating an hourglass

¹Numbers taken from exoplanets.org.

shape. This structure of the magnetic field has been confirmed by the observations of magnetic field polarisation (Girart et al. 2006; Ching et al. 2016). Based on observations of Zeeman splitting, the magnetic field strength within molecular cores is too weak for magnetic pressure to prevent core collapse (Crutcher et al. 2009; Cortes et al. 2016). The mass-to-flux ratio, M/Φ , is often employed to describe the degree of magnetic support within a molecular core. The critical mass-to-flux ratio, $(M/\Phi)_{\text{crit}}$, which defines whether a molecular core will collapse, was calculated by Mouschovias & Spitzer (1976) to be $(M/\Phi)_{\text{crit}} = 0.53/(3\pi)(5/G)^{1/2} = 487 \text{ g cm}^{-2} \text{ G}^{-1}$. If the mass-to-flux ratio of a molecular core is greater than this value, the core is magnetically super-critical and gravity overcomes the force produced by the magnetic pressure gradient, such that the cloud collapses along the direction of the magnetic field vector.

1.1.1 Class 0

Initially, the collapse of a molecular core is isothermal because the gas is optically thin. While the core collapses, gravitational potential energy is converted to heat and is radiated away. When the collapse progresses until the cloud density is high enough that it is optically thick, the molecular core is called a Class 0 object in the protostar classification created by Lada (1987) and Andre et al. (1993). The spectral energy distribution (SED) of a Class 0 object is a blackbody spectrum of the core peaking in the infrared (IR), typically at temperatures of 6 – 12 K (Larson 2003). An example of the SED of a Class 0 object is shown in Figure 1.1. The temperatures of these cores are greater than the cosmic microwave background temperature (3 K) because they are located in molecular clouds that are in proximity to recent massive star formation. Most calculations of core collapse (including those in this thesis) assume an initial temperature within this 6 – 12 K range. The thermal pressure (P_{th}) of the gas, powered by the heating of the core due to gravitational contraction, can be described by a polytropic equation of state:

$$P_{\text{th}} \propto \rho^{\Gamma}, \quad (1.1)$$

where ρ is the gas density, and Γ is the polytropic index. In an isothermal regime $\Gamma = 1.0$.

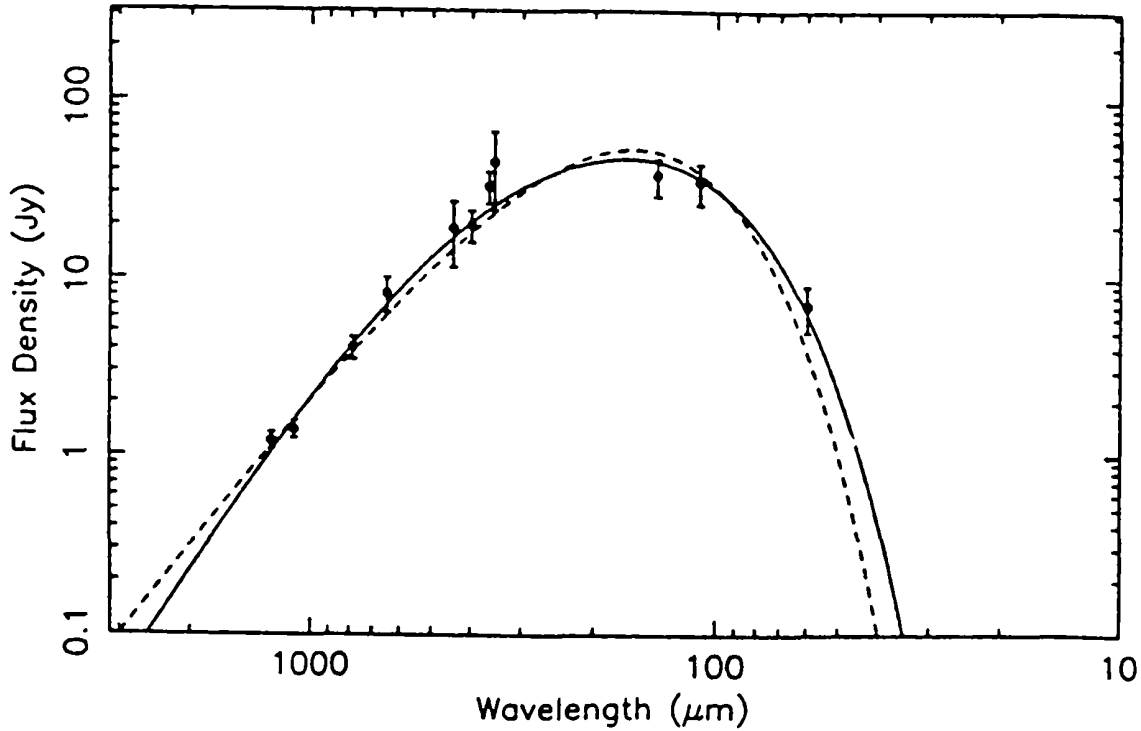


Figure 1.1: The spectral energy distribution (SED) of the Class 0 protostar B335. The dashed line is the observed SED, and the solid line is the best fit model assuming the gas is optically thick. Taken from Barsony (1994).

The density increases as the core collapses and the gas becomes optically thick to thermal radiation. When the optical depth (τ) is equal to one, the collapse transitions from being isothermal to fully adiabatic. The gas temperature begins to increase and radiative feedback becomes important. In the adiabatic regime, $\Gamma = 7/5 = 1.4$, however, Γ does not change directly from 1.0, in the isothermal collapse, to 1.4, during the adiabatic collapse. There is a transitional regime between when the gas temperature begins to increase, and the optical depth reaching unity. During this transitional period the core radiates away energy less efficiently than when the gas was optically thin. For a typical cloud mass of $1 M_{\odot}$ and opacity $\kappa = 0.1 \text{ cm}^2 \text{ g}^{-1}$ (taken from Semenov et al. (2003)), this transition from optically thin to optically thick occurs over the density range of $\sim 10^{-16} - 10^{-12} \text{ g cm}^{-3}$. Based on radiation-hydrodynamical simulations of molecular core collapse, Masunaga & Inutsuka (2000) found that $\Gamma = 1.1$ is appropriate to describe this less efficient radiative cooling during the transitional density range of $\sim 10^{-16} - 10^{-12} \text{ g cm}^{-3}$.

A polytropic index of $\Gamma = 1.1$ also applies beyond adiabatic collapse of the molecular core. During the adiabatic collapse the internal temperature of the core

continues to increase. When the density and temperature are $\rho \approx 10^{-7} \text{ g cm}^{-3}$ and $T \approx 2000 \text{ K}$, molecular H_2 begins to dissociate into atomic hydrogen. The breaking of the molecular bonds absorbs energy and the core is able to cool with $\Gamma \sim 1.1$ (Masunaga & Inutsuka 2000). The H_2 dissociation is complete at densities of $\rho \approx 10^{-2} \text{ g cm}^{-3}$. Beyond these densities, the core is primarily composed of atomic hydrogen and behaves like an ideal gas (i.e. $\Gamma = 5/3$).

During the collapse stages of the Class 0 phase, the molecular core is rotating (Bate 1998). Therefore, as the core is collapsing, a disc is formed around the central protostar due to conservation of angular momentum. This disc is formed within $\sim 10^4 \text{ yr}$ (Yorke et al. 1993; Hueso & Guillot 2005) and material is accreted through this disc onto the protostar. The Class 0 object transitions into a Class I object.

1.1.2 Class I-III

The Class 0 collapse and disc formation opens up cavities above and below the protostar and disc system, producing a Class I object. This opening up of a cavity is shown in simulations (Machida & Hosokawa 2013; Federrath et al. 2014; Offner & Arce 2014; Offner & Chaban 2017) and inferred from observations which find an excess in mid-IR emission compared to that of more spherically — and centrally — concentrated and obscured cores (Jorgensen et al. 2005). In this phase the SED is dominated by the core envelope, and thus has a large IR excess over the black body emission of the protostar, as shown in the top panel of Figure 1.2.

The envelope surrounding the Class I object is eventually completely depleted after $\sim 0.5 \text{ Myr}$, either via infall or being blown away by winds (Offner & Chaban 2017). When the protostar becomes optically visible it is classified as a Class II object. Spectral typing of the star can be carried out, even if the disc is edge-on, because there is often sufficient scattering of the stellar spectrum for characterisation (Appenzeller et al. 2005). The SED of this object, shown in the middle panel of Figure 1.2, is not dominated by the IR emission from the disc, however disc emission remains significant.

During the Class II phase, the protoplanetary disc is unlikely to grow larger, and will begin to disperse via accretion onto the star, disc winds, and photoevaporation from the star (or nearby stars). The remaining mass in the disc of the Class II objects

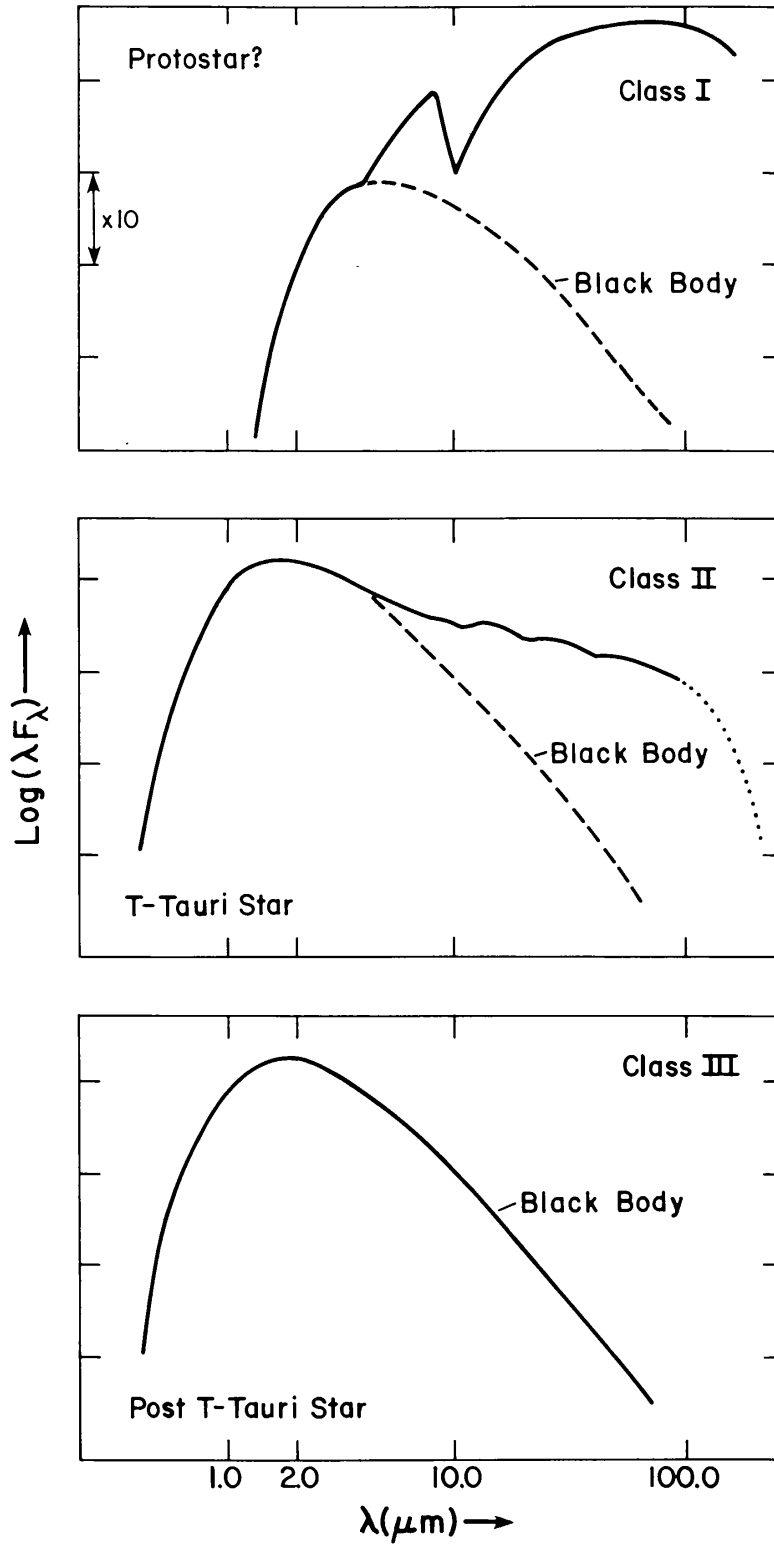


Figure 1.2: The spectral energy distributions of Class I (Top), Class II (Middle) and Class III (Bottom) protostars. The black body spectrum is the emission from the protostar. Any deviations from the black body spectrum can be due to emission from the envelope (as seen in the Class I phase) or a disc (as seen in Class II). We see that the contribution of disc emission on the SED decreases with protostellar class. Note that the wavelength on the x-axis is reversed to that plotted in Figure 1.1. Taken from Lada (1987).

is believed to be near the minimum mass solar nebula (MMSN) from which planets will form. The MMSN is the lowest necessary mass needed in a protoplanetary disc to form a solar system. It is derived from the chemical composition of the planets and host star, and is scaled to cosmic abundances by adding the necessary hydrogen and helium mass (Kusaka et al. 1970). For our solar system, Weidenschilling (1977) estimated a MMSN of $0.01 - 0.07 M_{\odot}$, but other solar systems, such as those with massive hot Jupiters, would require a larger MMSN.

A Class III object is formed when the gas disc has been dispersed and the SED emission is primarily the blackbody emission from the protostar (see bottom panel of Figure 1.2). At this stage there may be some minor IR excess caused by a debris disc.

Protostar evolution happens concurrently with circumstellar disc evolution, which funnels material onto the protostar as it ages. This process is discussed in the following sections.

1.1.3 Observed properties of circumstellar discs around young stars

In the following sections I will summarise observed properties of circumstellar discs around young stars, including their mass, radii, and disc structure.

Disc masses

The discs surrounding Class I protostars have masses ranging from $\sim 0.02 - 0.1 M_{\odot}$ with a median near $0.04 M_{\odot}$ (Jorgensen et al. 2009). These masses may be underestimated because they were derived from sub-millimetre fluxes. This underestimation may occur because grains that have grown to millimetre or larger sizes emit weak sub-millimetre flux per unit mass, with a negligible effect on the total sub-millimetre flux (Hartmann et al. 2006; Natta et al. 2007). Estimations also typically assume a cosmic dust-to-gas ratio of 1:100, despite this ratio evolving as the protostellar disc evolves. The gas fraction will change as gas is photoevaporated away and the dust fraction will change as planets are formed. Therefore, an assumed dust-to-gas ratio of 1:100 is problematic when determining gas masses of protostellar discs.

The disc mass range between Class 0 and I protostars is very similar, however the envelope mass varies significantly between the two protostellar stages. Class

0 protostars having an envelope mass of $\sim 1 M_{\odot}$ compared to an envelope mass of $\lesssim 0.1 M_{\odot}$ for Class I protostars (Jorgensen et al. 2009). This indicates that the mass from the envelope must be quickly transported through the disc onto the protostar to prevent the disc from growing faster than the star (Vorobyov & Basu 2010). Additionally, it is found that envelope infall rates are an order of magnitude higher than disc accretion rates in Class I protostars (Eisner et al. 2005), implying that mass builds up in the disc until a large amount of material is accreted quickly, producing a burst event. A survey of five nearby molecular clouds (Cha II, Lupus, Perseus, Serpens and Ophiuchus, Evans II et al. 2009) concluded that stars gain half of their final mass in $\sim 3.5 \times 10^4$ yr, implying very quick accretion of mass onto the protostar. Bursts of accretion are used to explain 'the luminosity problem' which occurs because Class I protostars are an order of magnitude less luminous than expected if the potential energy from the infalling material was radiated away steadily (Kenyon et al. 1990). This is because accretion events can periodically increase the luminosity while maintaining a low quiescent luminosity between accretion events.

The mass of discs around Class II objects are also measured using sub-millimetre observations as mentioned previously. From a survey of the star-forming regions Taurus-Auriga (Beckwith et al. 1990; Andrews & Williams 2007) and Ophiuchus (Andre & Montmerle 1994; Andrews & Williams 2005, 2007) using millimetre and sub-millimetre wavelengths, it was found that Class II objects have a median disc mass of $5 M_{\text{Jup}}$ with the star containing 99.1% of the total mass of the system. The uncertainty due to grain sizes mentioned previously also applies here. The assumption of a cosmic dust-to-gas ratio introduces uncertainties because the ratio has been altered by as a large amount of gas being removed from the system.

Disc sizes

The discs surrounding Class I protostars have very large radii, up to 1000 AU, with a mean radius of 200 – 300 AU (Jorgensen et al. 2005; Andrews & Williams 2007). Direct measurement of the radius of protoplanetary discs by looking at silhouettes of Orion proplyds (large protoplanetary discs) by Vicente & Alves (2005) found radii ranging from 50 – 200 AU, with a couple of outliers with radii 338 AU and 621 AU. Vicente & Alves (2005) note that their sample only accounts for half the stars in Orion that are known to have IR excesses, thus the other sources could have much

smaller discs. Ansdell et al. (2018) observed 22 protoplanetary discs in Lupus using ALMA and found that the radius of gas discs was about twice that measured for millimetre dust discs. They measured the radii of dust and gas discs to range from $\sim 40\text{--}330$ AU and $\sim 70\text{--}460$ AU respectively. Cieza et al. (2019) found that the radii of dust discs around 147 Ophiuchus Molecular Cloud objects were heavily weighted towards compact discs. 85% of the discs detected have radii < 15 AU. Barenfeld et al. (2017) also found discs around 57 Upper Scorpius objects to be compact with the median dust disc radii being 21 AU.

By fitting IR emission to millimetre SEDs and resolved millimetre maps, Andrews et al. (2009, 2010) found gas disc radii ranging from $14\text{--}198$ AU, and no dependence on the properties of the host star. Schaefer et al. (2009) observed Taurus-Auriga stars and also found no dependence on the disc sizes with the central star. However, measurements of the disc mass of Class II objects confirmed that lower mass discs are found around lower mass stars with a typical disc-to-star mass ratio of $M_d/M_* \sim 0.01$, but this relationship breaks down for high mass O stars (Williams & Cieza 2011).

Using SED fitting on a sample of stars in Taurus-Auriga, Isella et al. (2009) found radii ranging from $30\text{--}230$ AU and showed that older discs tend to be larger. The larger radii for older discs may be caused by viscous spreading of the material as angular momentum is being transported away from the disc, increasing the disc radius between the Class I and Class II stages (Lynden-Bell & Pringle 1974; Najita & Bergin 2018).

Disc structure

The distribution of mass, or surface density, of discs is described by a power law, $\Sigma \propto R^{-p}$, where Σ is the surface mass density, R is the radius in the disc, and p is an exponent typically in the range of $0\text{--}1.5$ (Mundy et al. 1996; Lay et al. 1997; Wilner et al. 2000; Kitamura et al. 2002; Andrews & Williams 2007; Williams & Cieza 2011).

The stability of a differentially rotating disc is given by the Toomre Q parameter (Toomre 1964). This parameter is derived from the interplay of gravitational collapse, angular momentum and thermal pressures keeping a disc from collapsing. The parameter is given by:

$$Q = \frac{c_s \Omega}{\pi G \Sigma} \quad (1.2)$$

where c_s is the sound speed, Ω is the angular frequency and Σ is the surface mass density. If this parameter is greater than one, the disc is considered to be stable, and if it is less than one, then it is considered to be unstable. Such unstable discs are susceptible to the growth of density perturbations which can lead to local collapse. This parameter is generally much greater than 1 for Class II objects suggesting their discs are gravitationally stable at all radii (Isella et al. 2009; Andrews et al. 2010). However, determining surface densities near the star (< 10 AU) has been difficult because observations are limited to resolutions down to 20 AU. It is crucial to understand the environment in this inner region because this is where planets will form. The densities in the disc mid-plane can be so high that ionisation due to radiation and cosmic rays may not be possible, and the region is shielded from magnetorotational instability (Bai & Stone 2013). However, there are other sources of ionisation within this layer which could also affect how the disc evolves, such as radioactive decay (Cleeves et al. 2013).

It is important to understand the thermal, chemical, and ionisation structure in protoplanetary discs in order to understand how various accretion mechanisms and photoevaporation may work within the disc. Protoplanetary discs are understood to have a flared geometry, based on observations giving larger IR excesses than could be accounted for if the discs had a flat geometry (Kenyon & Hartmann 1987). The interplay of thermal pressure of the disc against the stellar gravity determines the scale height of the disc. The thermal pressure of the disc is dependent on the radiation the disc receives, either from the host star or nearby stars. The scale height, like the surface density, also follows a power law as a function of radius (Chiang & Goldreich 1997): $H \propto R^h$ where H is the scale height, and h is from $\approx 1.3 - 1.5$ (Chiang & Goldreich 1997; D'Alessio et al. 1998; Dullemond et al. 2002). However, observations of mid-IR emission, which traces the dust in discs, is less than expected from the flaring described by the scale height power law. This can be attributed to the settling of dust towards the mid-plane, resulting in less reflected stellar emission than if the dust was uniformly distributed throughout the disc (D'Alessio et al. 1999; Chiang et al. 2001).

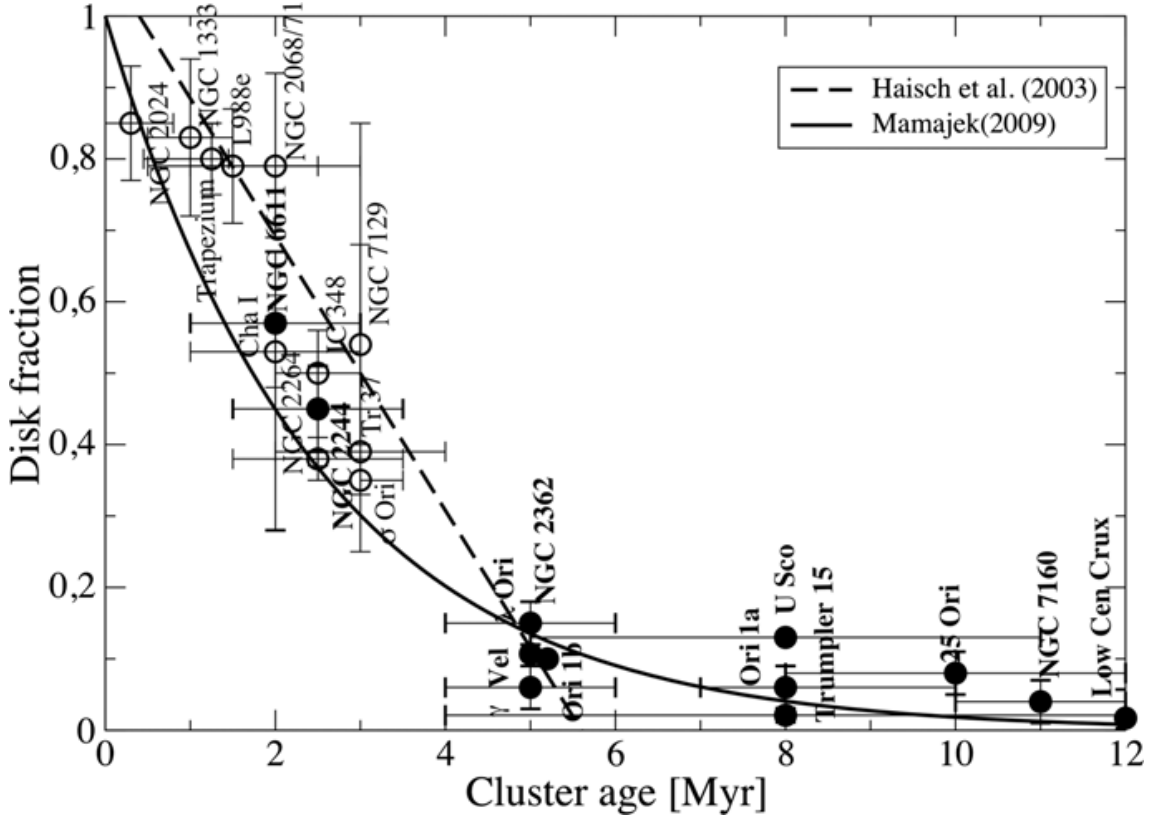


Figure 1.3: Shows the observed disk fractions of various star forming regions from the work of Haisch et al. (2001) and Mamajek (2009). The disk fraction falls to half after approximately 2 – 3 Myr. This age range is accepted as the typical protoplanetary disc lifetime. Taken from Pfalzner et al. (2014).

Observations of young Class I objects indicate that early discs follow a Keplerian profile down to the optically thick layers (Brinch et al. 2007; Lommen et al. 2008; Jorgensen et al. 2009). During the early stages of disc evolution, the gas disc is sub-Keplerian in the mid-plane because the gas pressure contributes to supporting the disc (Weidenschilling 1977). By the Class II phase, the velocity profiles of protoplanetary discs are expected to be Keplerian because the mass of the disc is very small compared to the mass contained within the star. The velocity profiles of these discs are difficult to determine because they are relatively small and faint, however, profiles of discs that have been measured are shown to be Keplerian (Dutrey et al. 1994; Mannings et al. 1997; Duvert et al. 1998; Guilloteau & Dutrey 1998).

The lifetime of the inner disc may be estimated by studying the fraction of stars with IR-excesses at various stellar ages. Such studies have found that $\sim 70\%$ of stars younger than 1 Myr have IR excesses, while $< 10\%$ stars older than 10 Myr have excesses (Strom et al. 1989; Wyatt 2008). By observing the fraction of disc-bearing

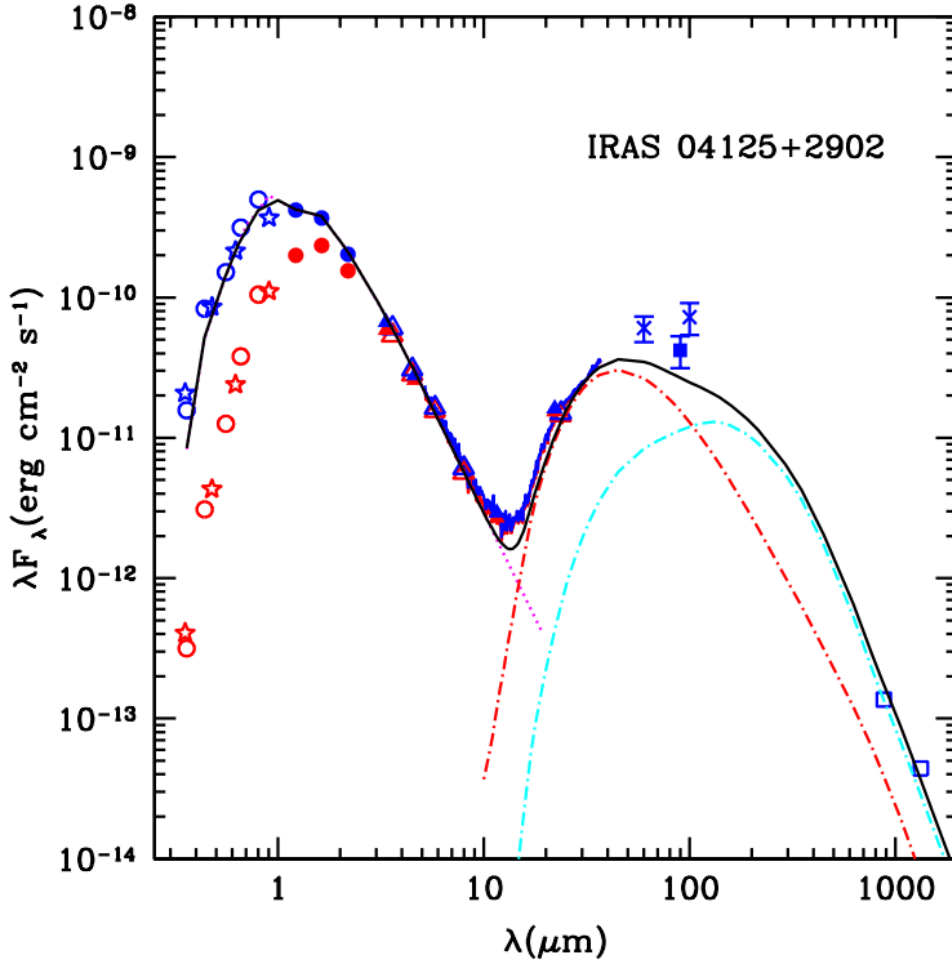


Figure 1.4: The spectral energy distribution of the transitional disc IRAS 04125+2902. Red data is the original measurements. Blue points are dereddened data. Black solid line is the disc model fit. The bluer wavelengths originate from the black body emission from the star, and the excess at redder wavelengths is the emission from the transitional disc. Taken from Espaillat et al. (2015).

stars in various star forming regions, Haisch et al. (2001) and Mamajek (2009) found the typical protoplanetary disc lifetime to be 2 – 3 Myr, with the majority of discs dissipating within 10 Myr. The results from these two works are shown in Figure 1.3. The disc disperses in an inside-out fashion based on the observations of discs that show a lack of near-IR ($\lambda \lesssim 2 \mu\text{m}$) emission, but show mid-IR ($\lambda \gtrsim 2 \mu\text{m}$) excess. These objects are called transitional discs. An example of an SED from an object known to be a transitional disc is shown in Figure 1.4. Due to the rarity of these transitional discs, it is implied that once the inner disc is no longer being accreted onto the star, the outer disc is rapidly lost (Andre & Montmerle 1994; Andrews & Williams 2005, 2007).

1.1.4 Disc evolution mechanisms

Various mechanisms play a role in the evolution and dispersal of circumstellar discs during star formation. These mechanisms include accretion of disc material onto the protostar, jets and outflows, and photoevaporation.

Accretion

Protostars grow as they evolve through the protostellar stages and gas from the molecular envelope moves quickly through the circumstellar disc onto the protostar (Vorobyov & Basu 2010). A number of mass transportation mechanisms have been proposed such as hydrodynamical, magnetic, and gravitational stresses (McKee & Ostriker 2007).

The angular momentum of the molecular cores that form protostars is significantly greater than the maximum angular momentum that can be contained by a single star. About 99% of the angular momentum of the molecular core must be transported out of the system to produce the angular momentum values observed for single stars. It is not understood how this high proportion of angular momentum can be removed and this is known as the ‘angular momentum problem’ (Mestel & Spitzer 1956; Spitzer 1968; Bodenheimer 1978, 1995; Frank et al. 2014). As a result, the investigation into accretion mechanisms typically consider angular momentum transport when determining the plausibility of the mechanism.

Accretion mechanisms have generally been investigated via numerical hydrodynamic simulations. Many of these simulations have implemented the α -disc model of angular momentum transport. In this regime, a shear stress tensor, $\mathbf{T}$, is defined which describes the viscous torque between rings in a differentially rotating disc (Shakura & Sunyaev 1973; Lynden-Bell & Pringle 1974; Pringle 1981). The shear torque between rings at radius R and $R + dR$ with orbital frequencies of Ω and $\Omega + d\Omega$ respectively is given by:

$$\mathbf{T} = \mu \frac{d\ln\Omega}{d\ln R} \quad (1.3)$$

where μ is the viscosity of the fluid. Shakura & Sunyaev (1973) note that the viscosity has the same units as pressure, so (as an ansatz) may be considered proportional

to the gas pressure, P . Thus μ can be expressed as $\mu = \alpha P$, where α is a dimensionless factor between 0 and 1. Since the torque describes angular momentum transport between shear layers, we can calculate the total change in angular momentum by integrating over the torques between all layers. With this α -disc prescription it is possible to follow angular momentum transport through a disc.

Determining realistic values of α is difficult. Hartmann et al. (1998) found $\alpha \sim 10^{-2}$ for discs on the scale of ~ 10 – 100 AU, which is incompatible with Rozyczka et al. (1994) who found values of $\alpha \sim 10^{-3}$ for radii larger than 0.5 AU.

When considering this α -disc prescription and planet formation, the MMSN (discussed in Section 1.1.2) is likely too small, and the protoplanetary disc that formed the solar system was much more massive and had a large radius to account for planetary migration (Crida 2009).

We now review various angular momentum transport mechanisms and the values of α found by these mechanisms:

Hydrodynamic mechanisms: Turbulence is created in circumstellar discs through heat, convection, and shearing of different moving layers; and even via infall of envelope material. Simulations of discs with convection such as those done by Ryu & Goodman (1992); Stone & Balbus (1996) and Johnson & Gammie (2006) all show that the angular momentum transport is inwards, i.e. angular momentum is being deposited into the inner disc, which can be problematic for accretion.

When considering instabilities caused by shearing in the Keplerian disc, large transient growths are found in simulations (Chagelishvili et al. 2003; Umurhan & Regev 2004; Johnson & Gammie 2005; Afshordi et al. 2005). If this turbulence caused by shearing could be maintained, angular momentum could be transported outwards (Lithwick 2007). But, these growths formed between shearing layers appear to dissipate quickly, and Ji et al. (2006) found that Keplerian-like rotation profiles are very inefficient in angular momentum transport, corresponding to $\alpha < 10^{-6}$.

Another consideration is that the discs are born with initial perturbations due to the infall of material from the envelope. 3D simulations show that these large perturbations can be destroyed quickly (Shen et al. 2006), although some off-mid-plane instabilities can live longer (Barranco & Marcus 2005). Generally these simulations show that initial instabilities are also not very efficient with angular momentum

transport, however further investigation is needed as continual mass injections could maintain the instabilities and produce $\alpha \sim 10^{-2}$ (Hartmann et al. 1998).

Magnetohydrodynamic mechanisms: Balbus & Hawley (1991) realised that weakly or moderately magnetised, differentially rotating discs are subjected to a powerful local shear instability, commonly referred to as magnetorotational instability (MRI). Numerical simulations in 3D show that MRI maintains turbulence in the disc and that angular momentum transport is outwards (Brandenburg et al. 1995; Hawley et al. 1995; Matsumoto & Tajima 1995; Gellert et al. 2012; Kunz & Lesur 2013). The efficiency of angular momentum transport via MRI is dependant on a number of factors, but in general angular momentum and mass transport primarily occurs at pericentre in eccentric discs (Chan et al. 2018), or in the inner regions in circular discs. It is also found that the value of α is dependent on the average vertical magnetic flux through the disc, which evolves over the lifetime of the disc (Stone & Balbus 1996; Sano et al. 2004; Pessah et al. 2007).

Though MRI likely plays an important role in accretion in young protoplanetary discs, the extent to which it is effective is dependent on the ionisation of regions throughout the disc. Portions of protoplanetary discs may have ionisation fractions that are too low for MRI to be effective, creating a ‘dead zone’ (Gammie 1996; Jin 1996; Glassgold et al. 1997; Igea & Glassgold 1999). However, Gole & Simon (2018) find that even in regions of low ionisation ambipolar diffusion dominant regions, MRI can persist as long as there is no ionized surface layer generating strong toroidal fields. Recent ALMA observations have shown that the magnetic field in the outer regions of discs have weak vertical components, and ionisation levels should be relatively low (Simon et al. 2018), therefore, MRI is not likely to be effective in the outer disc. Within a MRI dead zone, angular momentum transport would follow that described in the hydrodynamic regime (Hertfelder & Kley 2015).

MRI can operate effectively at radii $R \lesssim 0.1$ AU, where temperatures are ~ 2000 K and the gas is sufficiently ionised. However, further out, ionisation of the disc is more complex. If column densities in these regions are low enough, gas can be ionised by X-rays or cosmic rays, but the extent of the instability is sensitive to the size and distribution of dust grains. If dust grains are well mixed into the disc, MRI can be inhibited, however, if dust settles in the mid-plane, MRI can be amplified (Sano

et al. 2000; Fromang et al. 2002; Salmeron & Wardle 2005). If the surface of the disc is ionised sufficiently such that MRI is effective, but a dead zone is sandwiched between the two active surface layers, mass can build up in the dead zone until it becomes dynamically unstable (Landry et al. 2013). This dynamical instability may lead to gravitational stresses transporting angular momentum outwards, while the built up mass is accreted, leading to an outburst (Gammie 1996; Armitage et al. 2001). Episodic accretion onto a star can also occur in cases where the rotation rate of the magnetised star is greater than that of the inner disc, and material builds up in the inner disc until a massive accretion event occurs (Lii et al. 2014).

Gravitational mechanisms: Numerical simulations of discs with cooling functions where the disc radiates away energy due to mass accretion show that discs can reach a semi-steady state with Toomre parameter $Q \sim 1$. This is provided that $t_{\text{cool}}\Omega$, where t_{cool} is the cooling time for the disc, is not too small. If the disc cools rapidly it will fragment (Gammie 2001; Lodato & Rice 2004; Mejía et al. 2005; Rice et al. 2005).

For hotter discs, the sound speed is higher, thus increasing the Q parameter when compared to cooler discs. For hot discs, the effect of gravitational instability is dependent on the surface densities in the regions. In regions where $Q \gtrsim 1.4$, gravitational stresses are present but are not strong enough to cause fragmentation of the disc.

For discs with temperatures similar to those observed (50 – 150 K Boss 1998), more massive discs ($\gtrsim 0.1 M_{\odot}$) are likely to have significant mass transport due to gravitational stresses (Mayer et al. 2014). Due to the relatively high mass fraction between the disc and protostar, bursts of accretion due to gravitational stresses are likely to be present early in the protostellar evolution (Laughlin & Bodenheimer 1994; Vorobyov & Basu 2005, 2006; Zhu et al. 2009). Many protostars have already been observed to experience bursts of activity due to high accretion possibly caused by large gravitational instabilities. Such events include FU Orionis outbursts (named after the first identified case) and it is estimated that low-mass protostars experience about ten or so phases during their formation (Hartmann & Kenyon 1996; Dunham et al. 2010).

Jets and outflows

High velocity jets and lower velocity outflows are launched from a protostellar system as the disc material is accreted. The jets produced by young stellar objects are typically observed to be strongly collimated. The “aspect ratio” is used to quantify how collimated a jet is, and is defined as the ratio of the length of the jet to its width. Many jets are observed to have aspect ratios of at least 10, sometimes as high as 100, with some jets extending as far as a parsec from the source (Bally et al. 2007).

When the jets and outflows of a protostar are observed to produce shocks in the surrounding gas, the object is termed a Herbig-Haro object (Ambartsumian 1954; Hoyle 1956). An example of a Herbig-Haro object is shown in Figure 1.5. Herbig-Haro objects are characterised by bipolar jets of ionised gas travelling at $\gtrsim 100 \text{ km s}^{-1}$ and outflow of molecular gas at approximately $10 - 50 \text{ km s}^{-1}$. When probing near the sources of the jets, both the high velocity jet component and low velocity outflow component are observed (Hartigan et al. 1995; Hirth et al. 1997; Bacciotti et al. 2000; Pyo et al. 2005).

The range of velocities implies that the winds that produce Herbig-Haro objects are launched from different radii in the disc. The high velocities of the jets indicate that jets originate in the inner part of the disc. The low-velocity molecular outflows are likely material entrained by the disc winds. Jets from protostars tend to exhibit a series of knots that are consistent with shock heating. The shock velocities are a few tens of kilometres per second, associated with post-shock temperatures of 10^4 K (Hartigan et al. 1987, 1994). The series of bow shocks and knots in jets suggest that the protostar experiences a series of ejections (Lee et al. 2002), possibly caused by accretion events.

The currently accepted mechanism for the launching of jets is a result of magnetic stresses. The momentum of these outflows is too large for the jets to be driven by radiation pressure alone (Lada 1985). The disc wind model (Blandford & Payne 1982; Konigl & Pudritz 2000), the magnetic tower (Lynden-Bell 2003) and “X-wind” model (Shu et al. 1994) are the main models that have been proposed to explain the launching of these jets and outflows.

The *disc wind model* assumes that the protostar’s magnetic field lines thread



Figure 1.5: The highly collimated jets of the Herbig-Haro object HH24. These jets are launched from an observed protostar. We see knots and shock heating along the jets. Image Credit: NASA, ESA, Hubble Heritage (STScI/AURA)/Hubble-Europe Collaboration; Acknowledgement: D. Padgett (NASA's GSFC), T. Megeath (U. Toledo), B. Reipurth (U. Hawaii). Taken from Astronomy Picture of the Day, 2018 March 11 (<https://apod.nasa.gov/apod/ap180311.html>).

through much larger regions of the disc. The winds produced from this model are much slower, with velocities that reflect the rotation profile of the disc. Blandford & Payne (1982) calculated that centrifugally driven outflows can be launched from a disc if the poloidal component of the magnetic field makes an angle of less than 60° with the disc surface. The velocities produced by this mechanism are similar to those observed and thus, suggested to be the source of the disc winds in protostars (Pudritz & Norman 1983).

The *magnetic tower* describes the launching of jets via a magnetic pressure gradient. Lynden-Bell (2003) use highly coiled up magnetic structures and the pinching of magnetic fields to produce strong pressure gradients away from the disc, producing a force that significantly overcomes the gravitational force. Many ideal MHD simulations of molecular core collapse and protostar formation find that this mechanism is what drives the initial jet launching (Banerjee & Pudritz 2006; Machida & Matsumoto 2012).

The *X-wind model* mainly concerns regions in the inner disc where the magnetosphere of the star and the disc are corotating. Because protostars are fast rotators, the winds launched by the X-wind mechanism have velocities of a few 100 km s^{-1} , similar to velocities observed in protostellar jets. It was previously thought that it is a combination of the disc wind and X-wind model that work together to produce the outflow features observed in protostars, with the X-wind producing the highly collimated jet and the disc-wind producing the lower velocity outflow. However, Desch et al. (2010) find that the observed rotation of protostellar jets do not match that predicted by the X-wind model. Observations also find that particles within the launching radii for the X-wind model ($< 0.1 \text{ AU}$, Shu et al. 2001) cannot escape being accreted.

Photoevaporation and radiation feedback

The objects that are found with mid-IR excess and no near-IR excess are called transitional discs (Strom et al. 1989), and the mass of the disc at this stage is $\lesssim 1 - 2.5 M_{\text{Jup}}$ (Andrews & Williams 2005, 2007; Cieza et al. 2008, 2010). The SED of young stars at this phase of disc dispersal look like that in Figure 1.4, where we see two large black body components caused by the star and the outer disc. During the early protostellar stages, the inner disc is being accreted onto the star,

and mass flows inward in the disc to feed this accretion. When accretion stops, the outer disc photoevaporates rapidly due to UV and X-ray radiation that originates from the host star or nearby stars. The photoevaporation rate is greater for higher mass stars because the X-ray luminosity produced by accretion is higher (Preibisch & Feigelson 2005; Güdel et al. 2007; Kastner et al. 2016). As a result, the disc lifetime is likely to be shorter around higher mass stars. This effect is supported by observations that show a mass dependence on disc occurrence, with discs being less frequent around higher mass stars of the same age (Kennedy & Kenyon 2009).

Photoevaporation becomes significant in clearing the disc when the migration of mass inwards that feeds accretion is too slow and the gas in surface layers is heated such that its thermal velocity surpasses its escape velocity. The protoplanetary disc is eroded from the inside out creating the SED shown in Figure 1.4. The “UV switch” models (Alexander et al. 2006b,a) demonstrate this quick dispersal of the disc via photoevaporation, on a time scale much less than 1 Myr once accretion has stopped.

Giant planet formation best explains the low accretion and steep rise in the mid-IR excess observed in these objects. Formation of giant planets may reduce accretion, triggering the photoevaporation of the disc (Rosotti et al. 2013). When the gas disc has dispersed and all that remains is a debris disc, the system has reached the Class III phase, in which the SED only has a small IR excess (as seen in Figure 1.2).

1.1.5 Planet formation

Planets are formed within the protoplanetary discs around young stars. The first step of planet formation is the growth of dust grains. Within the protoplanetary disc, grains are initially swept along with the gas, but as they grow, they are subject to larger drag forces and settle into the mid-plane of the disc. This dust settling encourages further grain growth because the dust densities are greater. Observations show that small grains are persistently present throughout all the protostellar stages and therefore must be continually replenished. Dullemond & Dominik (2008) conclude the continuous production of dust comes as a balance of dust coagulation and fragmentation due to collisions. The growth of grains up to a metre in size can

be explained via coagulation, however explaining growth beyond this size remains a challenge. Metre-sized clumps suffer significantly from being destroyed in collisions and also rapidly fall inwards towards the star due to drag against gas in the disc (Weidenschilling 1977).

A possible solution to this ‘metre barrier problem’ is that rather than coagulation, planetesimals quickly grow via an instability. Planetesimals are objects that are approximately a kilometre in size, and their motion is predominantly influenced by gravity as opposed to dynamical drag. Goldreich & Ward (1973) proposed that with the settling of dust into the mid-plane of the disc, the concentration becomes large enough that the dust is unstable to its own gravity. This scenario was initially thought to require low turbulence which may be difficult to achieve, however high turbulence may aid the formation of planets by creating temporary overdensities (Johansen et al. 2006; Cuzzi et al. 2008). These overdensities could collapse to planetesimals with sizes already between 100 – 1000 km (Morbidelli et al. 2009).

The growth of planetesimals to protoplanets is typically believed to be via the accretion of smaller planetesimals onto larger planetesimals (Goldreich et al. 2004). The growth from protoplanets to giant planets is understood to follow one of two proposed theories. The first is the core-accretion model (Pollack et al. 1996), where once a protoplanet has grown to $\sim 10 M_{\oplus}$, it begins to rapidly accrete a gaseous envelope. The initial growth of the envelope increases the gravitational capture radius of the planet, allowing more planetesimals to be captured, thus increasing its core mass. The increasing core mass also enhances the capture radius allowing more gas to be accreted. This runaway growth continues until most of the nearby gas and debris is accreted onto the giant planet. The time scale necessary for the core accretion model of giant planet formation is often taken to be $\sim 1\text{--}10$ Myr (Pollack et al. 1996), however other models are able to simulate the growth of a Jupiter mass planet via core accretion in 1 Myr (Hubickyj et al. 2005). The other giant planet formation model is gravitational collapse (Boss 2001; Rafikov 2005), which suggests that gaseous planets form from an instability in the disc leading to a gravitationally bound clump which becomes a giant planet on a time scale of 10^4 yr. This mechanism requires a massive disc, and thus is believed to occur early in the protoplanetary disc evolution, or at large radii. This pathway of planet formation

is challenged by the lack of giant planets observed by direct imaging (Vigan et al. 2017).

Another giant planet formation model considers the formation of large giants at large radii (Bate et al. 2002). This model considers giant planets represent the lowest mass end of the brown dwarf populations and these types of giants are formed from molecular cloud fragmentation. The time scale for giant planet formation via this pathway is significantly shorter, being on the order of thousands of years (Boss 2002).

With the number of proposed giant planet formation mechanisms, it is clear that there are still many mysteries to solve on this front. This picture of star and planet formation is also very single star centric because the single star scenario is simple, and the vast majority of planets discovered to date orbit single stars. But a large portion of stars are in binary star systems, with more massive stars being more likely to host other stellar companions, as shown in Figure 1.6 (Moe & Di Stefano 2017). We have also discovered planets in binary star systems. The formation of these planets should also be studied and can help to determine likely planet formation pathways. To begin understanding planet formation around binaries, we should review what is known about binary star formation.

1.2 Binary star formation

The fraction of all stars that are members of binary systems depends on the mass of the system as shown in Figure 1.6. When studying multiple star formation the *multiplicity fraction* (MF) is often employed to quantify how many multiple star systems are within a population. The multiplicity fraction is defined as:

$$MF = \frac{B + T + Q + \dots}{S + B + T + Q + \dots} \quad (1.4)$$

where S, B, T, Q are the number of single, binary, triple, quadruple, etc. systems (Reipurth & Zinnecker 1993). For solar type stars with effective temperature between 4800 K and 6550 K, the multiplicity is approximately 50 – 60% (Duquennoy & Mayor 1991; Raghavan et al. 2010), while lower mass stars and dwarfs have a multiplicity of 30% down to 10% (Lada 2006; Basri & Reiners 2006; Ahmic et al. 2007). The prevalence of binary systems is important, and the consequence of multiplicity on protoplanetary disc evolution and planet formation should be understood.

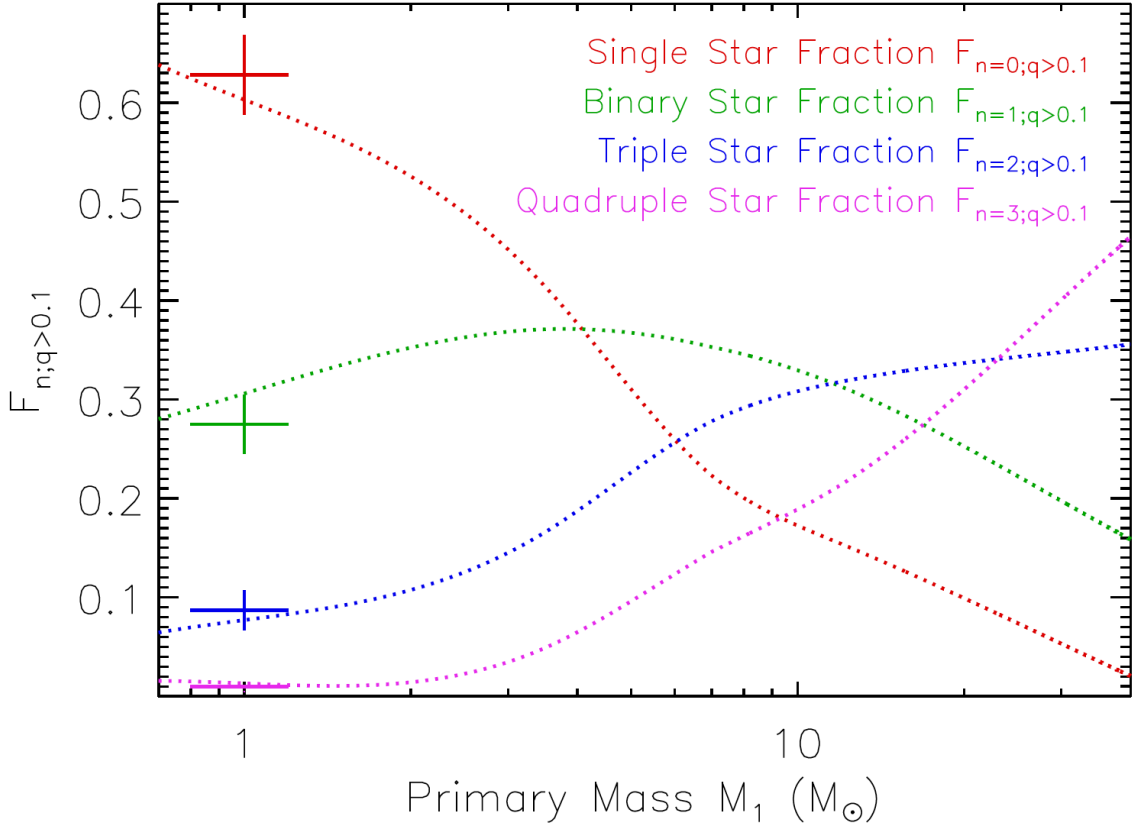


Figure 1.6: Multiplicity fraction as a function of primary star mass. The binary fraction increases to a primary star mass of $\sim 5 M_\odot$ before being overtaken by higher order triple and quadruple star fractions. Taken from Moe & Di Stefano (2017).

In the following sections we will review how multiple star formation may affect the protostellar stages discussed in Section 1.1.

1.2.1 Class 0 multiple star evolution

The formation of binary star systems is believed to be triggered by the fragmentation of protostellar cores as they collapse (Offner et al. 2010; Murillo et al. 2016). Chen et al. (2013) carried out a survey for 33 Class 0 objects and found a multiplicity of $MF = 0.64 \pm 0.08$ for separations ranging from 50 – 5000 AU. However, these results should be taken as a lower limit because they do not probe smaller separations. The work of Chen et al. (2013) and other surveys show that the multiplicity of young stars actually decreases with protostellar stage (Connelley et al. 2008). This is shown in Figure 1.7. This high multiplicity at early stages implies core fragmentation yields a high initial multiplicity rate (Duchêne et al. 2007) with each core producing approximately 2 – 3 stars (Goodwin & Kroupa 2005).

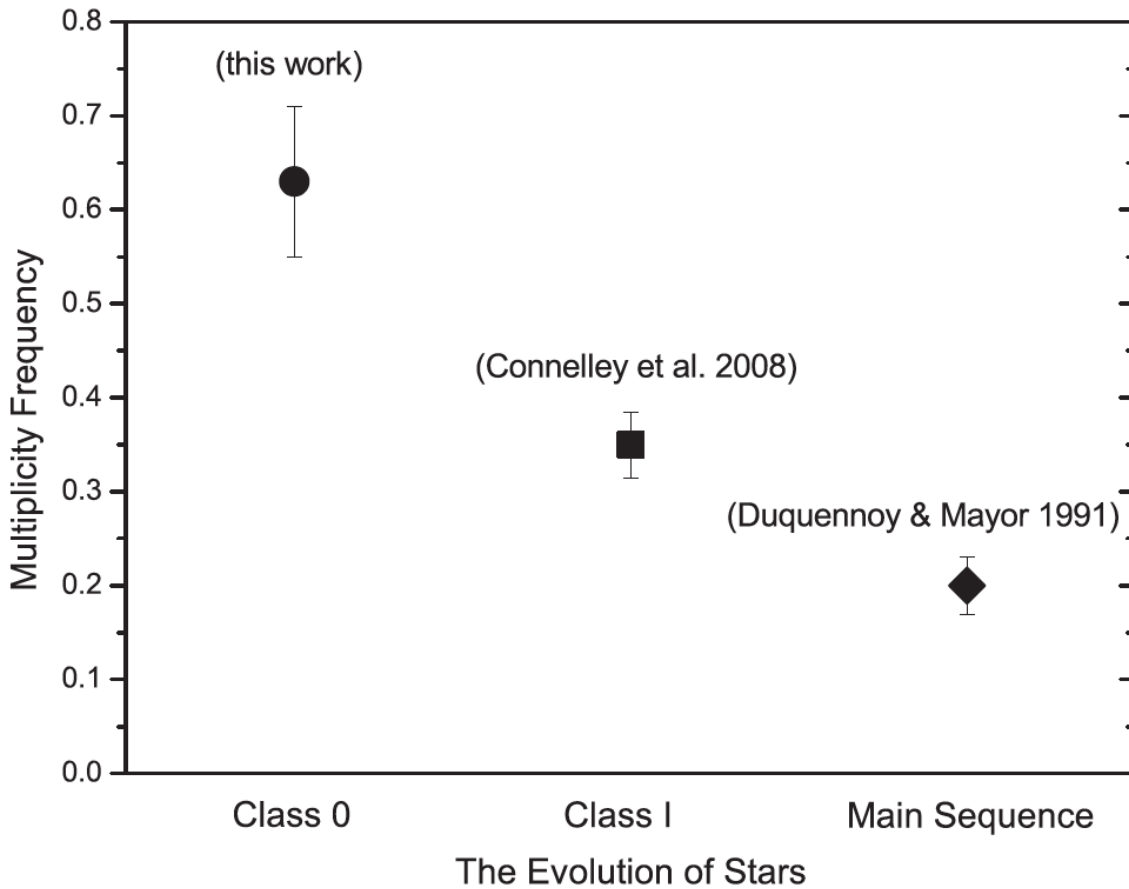


Figure 1.7: Shows the decreasing stellar multiplicity over protostellar class. This implies that most stars are born in multiple star systems that disintegrate over time. Taken from Chen et al. (2013).

The formation of binary systems requires the loss of 99 – 99.9% of the initial angular momentum contained within the molecular cores (Frank et al. 2014). Angular momentum can be carried out of the system via jets and outflows as mentioned previously, or via the ejection of a third companion (Armitage & Clarke 1997; Reipurth 2000; Reipurth et al. 2014). The formation of the binary star system is then thought to broadly follow the single star birth described in Section 1.1.

1.2.2 Class I-III multiple star evolution

Another proposed pathway of multiple star formation is the fragmentation of massive discs into stellar companions with separations < 100 AU. Initial hydrodynamical simulations found this pathway to be as plausible as core fragmentation, however when considering radiation feedback this pathway becomes less viable due to radiation increasing the fragmentation scale (Offner et al. 2010). Therefore, it is likely that most multiple star systems form via the fragmentation of the initial molecular core.

The well documented decreasing multiplicity fraction over protostellar class (see Figure 1.7) implies that powerful dynamical processes must occur to disperse these multiple star systems (Reipurth et al. 2014). In the following sections we will review the formation of binaries, what is known about discs and planets in binary systems.

Dynamical evolution of young multiple star systems

The ejection of a tertiary or multiple companions has often been cited as a pathway for forming close binaries with separations of $\sim 1\text{--}200$ AU (Armitage & Clarke 1997; Reipurth 2000). Many theoretical works show that during the dynamical evolution of a three-body system, the lightest companion is ejected, either into a wider orbit creating hierarchical configurations where the separation of the third body is greater than ~ 10 times the separation of the inner binary, or out of the system entirely (Anosova 1986; Sterzik & Durisen 1998; Umbreit et al. 2005). This hypothesis has also been investigated observationally by Connelley et al. (2009), who found that every young binary system that they observed with a close companion (< 200 AU) also had another protostar within 25,000 AU projected separation. These results are interpreted to be strong evidence that many close binaries form via ejections.

Ejection of tertiary companions is sufficient to help explain the formation of

binary systems with separations of a few tens of AU but struggles to solely explain the formation of spectroscopic binaries which often have a separation on the order of < 0.1 AU. The orbital separation of these spectroscopic binaries is much smaller than the initial hydrostatic core that collapses to form the protostar (~ 5 AU), thus binaries of separations < 10 AU cannot form in situ during collapse. These binaries with semi-major axis $a < 10$ AU likely form via the in-spiral of a wide binary possibly via viscous evolution through a disc (Gorti & Bhatt 1996; Stahler 2010; Kornreich et al. 2012) or the Kozai-Lidov mechanism (Kiseleva et al. 1998). The ejection of a companion may enhance or initiate these processes. During viscous evolution with surrounding circumstellar gas or discs, the angular momentum of the binary can be transferred to the gas, shrinking the orbit of the binary.

The Kozai-Lidov mechanism requires a three-body system to operate. This mechanism describes the exchange between orbital eccentricity and inclination for the inner binary and the outer third body. During the formation of close binaries, it is believed that the third body drives the inner binary to have higher eccentricity to the point at which tidal forces become significant at periastron. These tidal forces lead to the decay of the orbit to shorter periods (Moe & Kratter 2018). This formation pathway for close spectroscopic binaries is strongly supported by observational evidence finding $63 \pm 5\%$ of spectroscopic binaries being in higher order multiple star systems (Tokovinin et al. 2006). This fraction increases to 96% for periods less than 3 days (Tokovinin et al. 2006).

Discs in binary star systems

During the formation of binary stars, discs may form around individual components as “circumprimary” and “circumsecondary” discs, or around both stars as a “circumbinary” disc. As mentioned previously, it is believed that young binary stars would spiral inwards towards each other through viscous evolution. During this evolution the binary system may shrink to a separation at which material in *circumstellar* discs is redistributed to form one *circumbinary* disc (Reipurth & Aspin 2004).

The truncation of discs in binary systems has been observed extensively (Harris et al. 2012; Cox et al. 2017), with the data showing that the presence of a stellar

companion can influence the evolution of protostellar discs. Figure 1.8 shows measured millimetre fluxes for a large number of protostellar discs. Millimetre flux is used as a proxy for disc mass, with larger discs producing greater flux. This proxy is under the assumption that the disc is completely optically thin which is not true in reality, but it still provides a good comparison between different binary configurations. The distribution of disc sizes around single stars is shown as the black points to the right of the figure. For binary systems of projected separations greater than 300 AU, the distribution of disc sizes follows that of the single stars. However, for binaries with projected separations less than 300 AU, disc sizes are smaller, with smaller separations producing less flux. This effect is attributed to the truncation of the *circumstellar* discs by the binary companion (Artymowicz & Lubow 1994). The trend of smaller discs for smaller separation binaries does not appear to apply to *circumbinary* discs. In Figure 1.8, the circumbinary discs (the purple points) are very large and comparable to the largest discs around single stars.

The data raises questions: are circumbinary discs generally very large compared to most circumstellar discs (around both single and binary stars)? What are the implications of massive discs for planet formation? Would more massive discs provide more material to build planets? Massive discs are necessary for fragmentation via gravitational instability to be possible, as a result, could giant planets or stellar companions form via gravitational instabilities in these discs?

Another peculiar characteristic of some circumbinary discs is the observed ages. There are a number of known circumbinary discs that have very old ages (> 10 Myr); for example HD 98800 B (10 ± 5 Myr, Furlan et al. 2007), AK Sco (18 ± 1 Myr, Czekala et al. 2015), V4046 Sgr ($12 - 23$ Myr, Rapson et al. 2015) and St 34 (also known as HBC 425, ~ 25 Myr, Hartmann et al. 2005). As discussed in Section 1.1.2, the typical lifetime of a protoplanetary disc is $2 - 3$ Myr, and most discs are expected to dissipate within 10 Myr. The ages of these circumbinary discs are significantly older than the typical lifetime of a protoplanetary disc. From these known objects it is difficult to determine whether circumbinary discs are longer lived compared to circumstellar discs, or whether these objects are statistical outliers.

If circumbinary discs generally have longer lifetimes with respect to circumstellar discs, there may be interesting implications for the likelihood of planet formation. In

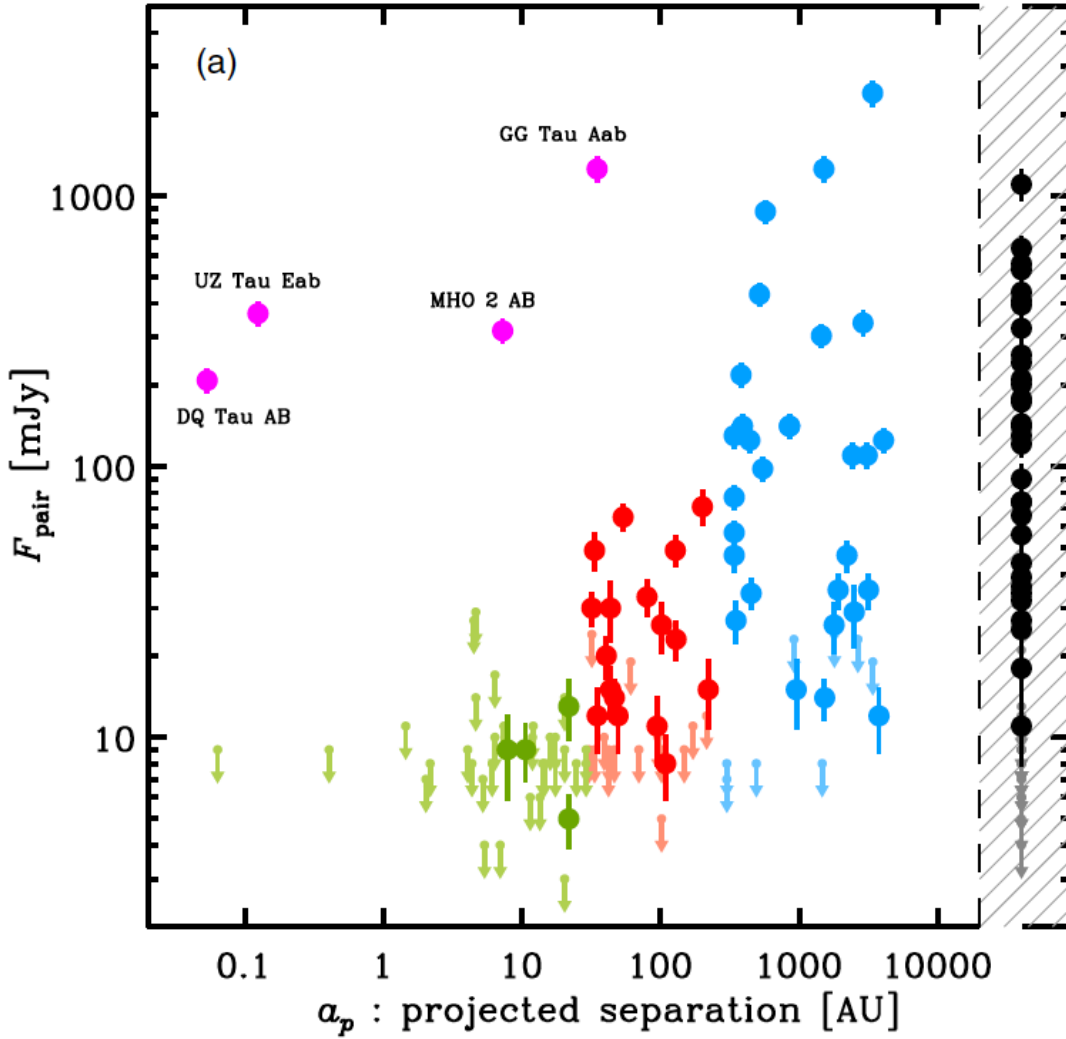


Figure 1.8: Shows a comparison of millimetre flux densities (as a proxy for disc mass) from potentially interacting pairs as a function of the projected pair separation. Single stars are shown to the right of the plot as black points for reference. The pair population can be distinguished into four clear sub-categories: wide ($a_p > 300$ AU), medium ($a_p = 30 - 300$ AU), and small ($a_p < 30$ AU) pairs, and circumbinary discs (purple). Taken from Harris et al. (2012).

Section 1.1.5 two theories of giant planet formation were discussed: the core accretion mechanism and gravitational instability. The consensus is that the formation of close (within a few tens of AU separation) giant planets is likely via the core accretion mechanism, despite the time scale for this mechanism (on the order of millions of years (Pollack et al. 1996; Hubickyj et al. 2005)) being barely compatible with the typical protoplanetary disc lifetime. If circumbinary discs are longer lived, would this provide the opportunity for larger giant planets to form since the gas disc survives longer allowing the accretion of a larger planetary atmosphere? Or would the longer lifetime simply make planet formation easier due to a larger window of

opportunity for planetesimal formation and accretion?

In order to understand how binarity can affect disc lifetimes, we need to investigate how binarity affects the various disc evolution mechanisms described in Section 1.1.2 (i.e. accretion, jets and outflows, and photoevaporation). A review of the effect of binarity on these mechanisms is presented below.

Accretion of discs in binaries

Many circumbinary disc hosting systems are shown to still be accreting. Most of these show accretion events that are correlated with the periastron of the binary (for example, DQ Tau (Mathieu et al. 1997; Tofflemire et al. 2017), AK Sco (Gómez de Castro et al. 2013) and TWA 3A (Tofflemire et al. 2017)). An example of these periodic accretion events is shown in Figure 1.9. In the top panel we see the measured accretion rate for the binary system TWA 3A phase-folded around its orbital period. At periastron (i.e. orbital phase of 0.0 and 1.0), the accretion rate increases to up to ~ 5 times the quiescent accretion rate. This suggests that the accretion of the disc is triggered by the binary companion (Green et al. 2016).

Some of the earliest work on circumbinary disc evolution was carried out by Artymowicz & Lubow (1994), who simulated the evolution of a smooth thin disc, supported by gas pressure, aligned with the orbital plane of a binary star. They showed from simulations that the disc around each stellar component is truncated at the outer edge, whereas circumbinary discs are truncated along the inner edge. For circular orbits, the circumstellar disc is truncated at $\sim a/2$, and the circumbinary disc is truncated at $\sim 2a$. Higher eccentricities will lead to greater dynamical erosion of the discs, thereby varying the sizes of circumstellar and circumbinary discs. In general, it was found that for smaller separations, the circumstellar discs are smaller, which is consistent with observations (Cieza et al. 2009; Duchêne 2010; Harris et al. 2012; Cox et al. 2017). Circumstellar discs can also be absent in binaries with very small separation as suggested by close binaries having relatively little sub-millimetre and millimetre flux (Jensen et al. 1994, 1996; Andrews & Williams 2005).

Circumbinary discs can produce SEDs which are similar to those of transitional discs because of millimetre flux absence. For example, CoKu Tau 4 was classified as a transitional disc, but was found to be a circumbinary disc surrounding a binary with separation ~ 8 AU (Ireland & Kraus 2008). Ruíz-Rodríguez et al. (2016) estimated

that the fraction of objects that are classified as transitional discs but are actually circumbinary discs is 0.38 ± 0.09 .

Lindblad resonances are caused by the differential angular velocity between the binary system and the inner disc (Muñoz et al. 2019). Within circumbinary discs, Lindblad resonances can cause material in the disc to prefer certain orbital periods that are multiples of the binary orbit’s epicyclic frequency (the rate at which periastron precession occurs). Lindblad resonances are caused by gravitational torques between the binary star system and the disc. Much like the Kozai-Lidov mechanism, the Lindblad resonances describe how eccentricity and inclination are exchanged between the components. If the angular velocity of a circular binary star orbit is

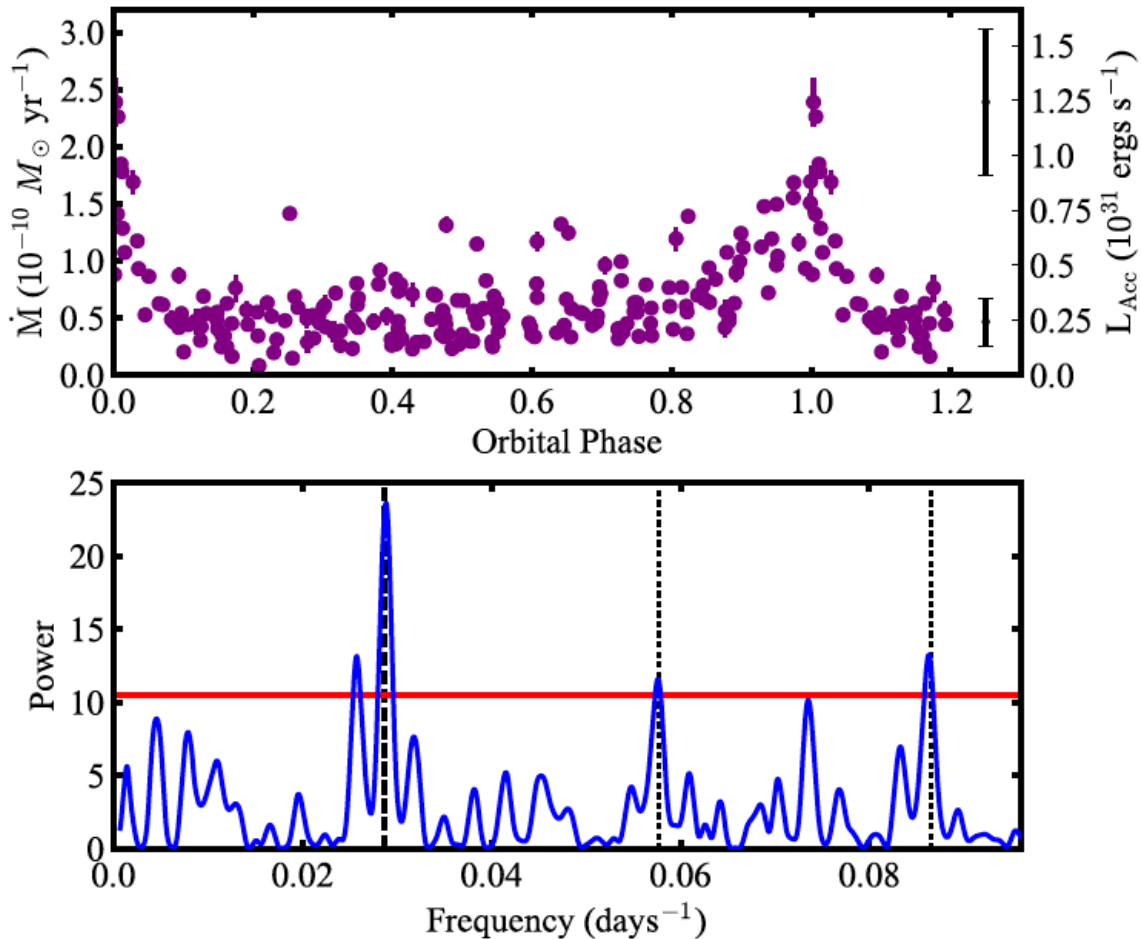


Figure 1.9: Top: shows the mass accretion rate and accretion luminosity (phase-folded about the orbital period) for the 5–10 Myr binary TWA 3A, which is accreting from a circumbinary disc. Black error bars on the right correspond to the propagation of the systematic error of their photometric calibration. Bottom: periodogram of the mass accretion rate measurements. Episodic accretion occurs at periastron (orbital phase = 0.0 = 1.0). Taken from Tofflemire et al. (2017).

greater than that of the inner disc, the gravitational torques from the disc will decrease the speed of the binary stars. Reducing the binary star speed at apastron, when the stars are closest to the inner edge of the disc, leads to an increase in the binary star eccentricity. The exchange of momentum from the binary star orbit to the disc increases the angular velocity of the inner disc. Angular momentum can be transported from the binary system to the disc via this interaction. These resonances may also encourage planet formation, by forcing gas and dust to fall into particular orbits creating overdensities (Bromley & Kenyon 2015). Simulations of circumbinary discs also find that circular binaries host eccentric discs and vice versa (Thun et al. 2017).

Multiplicity can affect the disc lifetime, because the truncation of circumstellar discs by the companion may result in entire discs being accreted faster, in ~ 0.3 Myr (Williams & Cieza 2011). However, the truncation of the inner radius of a circumbinary disc has not been shown to shorten the lifetime of the disc.

Outflows from young binary systems

Accretion events triggered by the presence of a companion have often been employed to explain periodic outbursts such as the short period EXor type outburst (on the order of months to years, Herbig 2007), and the longer period FUor type outburst (10,000 yr, Herbig 1977). Thermal instabilities in the circumstellar disc have also been proposed as a trigger for these outbursts (Bell & Lin 1994).

The binary trigger hypothesis has been proposed to explain the outbursts of FU Orionis (Bonnell & Bastien 1992; Clarke & Syer 1996), however, FU Orionis itself is yet to be identified as a binary star system. Malbet et al. (1998) obtained interferometric data with resolution down to 2 AU of the IR emission around FU Orionis. The authors found that the IR emission was equally likely to be caused by a close companion (< 1 AU), or an accretion disc. Wang et al. (2004) discovered a companion with close projected separation which Reipurth & Aspin (2004) hypothesise may be the outlying member of a triple star system. Reipurth & Aspin (2004) also suggest that FU Orionis may have undergone a recent interaction in which this third body was being ejected and FU Orionis is a < 10 AU binary. They claim that if FUor outbursts occur preferentially in close binaries that have undergone an ejection, and this type of outburst should be observed in $\sim 20\%$ of young star

systems.

Green et al. (2016) used interferometry to observe three known FUor objects to find companions on the scale of the protoplanetary discs that feed the stars. The authors only resolved one companion (around V1057 Cyg) of the three objects observed, but also state that they could only detect companions with luminosities near or greater than the pre-outburst luminosity of the FUor object. Therefore, it remains plausible that FUor outbursts could be tied to the presence of a close binary companion.

Observational studies into the triggers of EXor outbursts are very limited compared to FUor outbursts because it is still a young area of research. However, observations have determined that EX Lupi (the first observed EXor object) is not a binary (Herbig 2007). Cieza et al. (2018) measured the masses of discs around FUor and EXor objects and find that discs are more massive around FUors ($\sim 80\text{--}600\text{ M}_{\text{Jup}}$) than EXors ($\sim 0.5\text{--}40\text{ M}_{\text{Jup}}$). From this result Cieza et al. (2018) suggest that the large differences in disc masses and outflow activity are a consequence of the two types of objects representing different evolutionary stages.

Various outflow morphologies have been observed around proto-binary systems in addition to outbursts observed from FUors and EXors. Observational studies of young binary and multiple star systems have often found the outflow orientation to be misaligned from the angular momentum vector of the system (Lee et al. 2016; Offner et al. 2016). Multiplicity may produce misaligned outflows, however misaligned outflows can also be produced in turbulent environments (Fielding et al. 2015). Young multiple star systems can also produce individual jets from each stellar component. Examples include L1551 IRS5 shown in Figure 1.10, as well as L1551 NE, UY Aurigae, BHR 71 and L723.

The object L1551 IRS5 is one of the most studied proto-binaries. In the top left corner of Figure 1.10 it is possible to make out two individual jets launched from each component of this system (Pyo et al. 2005; Wu et al. 2009). The separation of the system is estimated to be $40\text{--}50\text{ AU}$ (Bieging & Cohen 1985; Lim & Takakuwa 2006). Villa et al. (2017) used millimetre observations to determine the mass and orbital period of the system to be $1.7\text{ M}_{\odot}$ and 246 yr , respectively. This binary is likely to have a low eccentricity ($e < 0.3$), and the stars host circumstellar discs of



Figure 1.10: The individual outflows from each component of the protobinary L1551 IRS5 (upper left in pale orange) that have burst through the cloud surface. The outflows produce an intricate shock structure as Herbig-Haro objects. Deep H α and [SII] images were obtained by Reipurth & Bally (2001) at the 8 m Subaru telescope; colour composite by Robert Gendler. Taken from Fridlund (2016).

radii ~ 17 AU (Lim & Takakuwa 2006). The truncation radius of these circumstellar discs is smaller than that predicted by Artymowicz & Lubow (1994) for circular orbits, which Lim & Takakuwa (2006) explain by invoking a mild eccentricity in the binary orbit. As the jets from this system travelled out to the surrounding medium, shocks were produced, shown by the H α emission (pink in Figure 1.10). Due to the observed alignment of the jet axis and the rotation of the surrounding envelope, Lim & Takakuwa (2006) and Lim et al. (2016) argue that the fragmentation of the molecular core that produced this binary is rotationally driven rather than turbulence driven. Simulations also find that faster rotating molecular cores can fragment into more protostars than slower rotating cores (Machida et al. 2005).

Near L1551 IRS5 is the binary system L1551 NE that also produces strongly collimated jets (Hayashi & Pyo 2009), and that hosts a ~ 300 AU rotationally-supported

circumbinary disc (Takakuwa et al. 2014, 2015). The object UY Aurigae is another circumbinary disc-hosting system for which individual jets from both components have been observed (Pyo et al. 2014).

The binary systems described above show aligned protostellar jets, however, young binaries with misaligned outflows have also been observed. The binary system BHR 71 has been shown to have misaligned and colliding outflows (Zapata et al. 2018). The system NGC 1333-IRAS4A also has two misaligned jets from each component. The primary star produces a high-velocity, collimated outflow, while the secondary companion produces a low velocity outflow that precesses (Santangelo et al. 2015).

A single bipolar outflow has also been observed from young binary systems, either launched from a circumstellar disc around one of the components of the binary (e.g. SMM1-b (Hull et al. 2017) and CO Ori (Davies et al. 2018)), or from the circumbinary disc around both components (e.g. HH30 (Louvet et al. 2018) and IRAS 18144-1723 (Varricatt et al. 2018)). Features in outflows, such as precession and knots, seen in objects with a single bipolar outflow have often been explained by the presence of a companion (e.g. IRAS 16253-2429 (Hsieh et al. 2016), G35.20-0.74N (Beltrán et al. 2016) and V380 Ori NE (Choi et al. 2017)).

By looking at the direction of outflowing material and circum-multiple dust in the Perseus star forming region, Tobin et al. (2018) derived conclusions on the fragmentation pathway that created these systems. They concluded that systems with outflows perpendicular to the bulk circum-multiple material were likely to have formed via disc-fragmentation, and systems with misaligned outflows may have formed from cloud fragmentation.

Photoevaporation and radiation feedback in binary stars

The lifetime of a disc is ultimately determined by when the photoevaporation rate overtakes the accretion rate, and then how long it takes for photoevaporation to disperse the disc material. Alexander (2012) uses observed circumbinary disc masses and ages to derive an upper limit to the photoevaporation rate of $< 10^{-9} \text{ M}_{\odot} \text{ yr}^{-1}$. This rate is at least an order of magnitude lower than what models produce for discs around single stars, and as a result Alexander (2012) conclude that circumbinary discs around close binaries ($a \lesssim 1 \text{ AU}$) are longer-lived than otherwise identical

discs around single stars. Alexander (2012) also conclude that circumbinary disc lifetime would decline with increasing binary separation, leading to relatively short lifetimes for binaries with separation $\gtrsim 10$ AU. Shadmehri et al. (2018) derive similar conclusions suggesting that the dispersal of circumbinary discs occurs over a longer time because the radial temperature gradient is steeper compared to circumstellar discs.

Observations of circumbinary discs may also suggest they are longer lived than their single star counterparts. As mentioned previously, circumbinary discs have been observed that have ages significantly greater than the typical disc lifetime around single star i.e. $2 - 3$ Myr (c.f. Section 1.1.2). Observations of circumbinary material suggest that photoevaporation rates are weaker around binaries, prolonging disc lifetime. Ribas et al. (2018) measured the circumbinary ring about HD98800 B to be ~ 2 AU thick and contain a significant mass of gas. A ring this thick would have a very limited lifetime around a single star, therefore Ribas et al. (2018) conclude that photoevaporative winds are weaker in circumbinary discs.

Rosotti & Clarke (2018) examined the clearing of circumstellar discs around the primary and secondary components via simulations, and concluded that the separation of the binary dictates whether the disc-clearing mechanism is dominated by dynamical evolution or photoevaporation. For systems with a separation in the range $20 - 30$ AU, tidal torques hasten the dispersal and circumstellar discs are cleared in an outside-in fashion. In this scenario the circumstellar disc around the secondary component is cleared faster because it is smaller and has a shorter viscous time-scale. For wider binaries the circumstellar disc lifetime depends on the photoevaporation from only the host star. In this scenario the circumstellar disc around the primary is expected to be cleared faster due to the higher x-ray luminosity. However, this is contradictory to observations of circumstellar disc frequencies for wide binaries (projected separations of $280 - 450$ AU). Itoh et al. (2015) found in systems that only had one disc, it was the primary component that hosted it. Itoh et al. (2015) also conclude that due to the high frequency of discs with radii $30 - 100$ AU in wide binaries compared to single stars, the lifetime of circumstellar discs may also be greater.

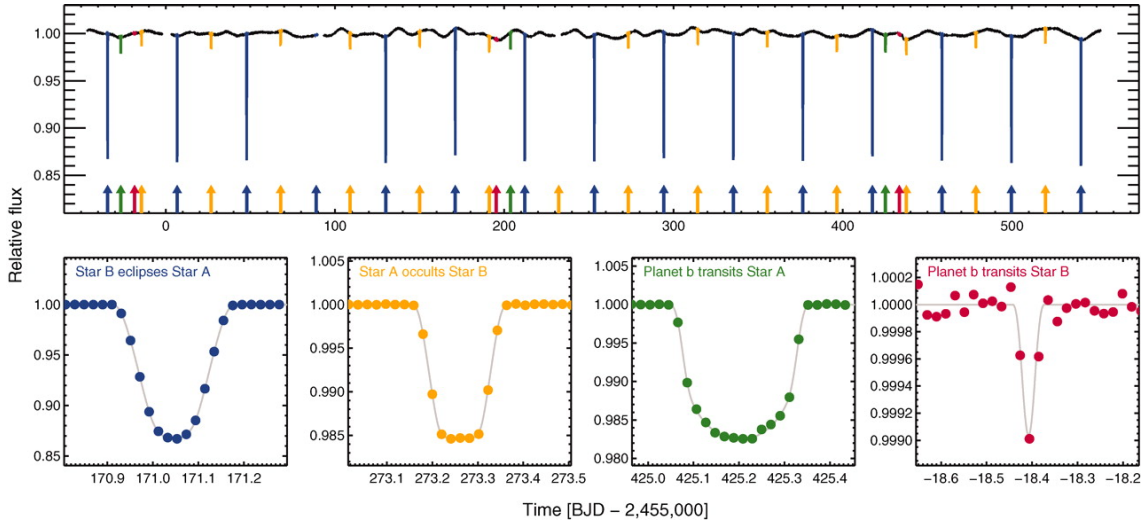


Figure 1.11: The transit light curve of the Kepler-16 system, the first circumbinary planet discovered by the *Kepler* space telescope. The blue and yellow data show the eclipses of the primary and secondary stars. The green and red data show the transit of the planet (Kepler-16b) across the primary and secondary component. Taken from Doyle et al. (2011).

In order to model photoevaporation and radiative feedback in binary-disc systems it is important to consider the periodic accretion (as in Figure 1.9). This periodic accretion will cause periodic variation in the photoevaporation rate and the temperature structure.

1.2.3 Planets in binary star systems

Many planets have been discovered around binary stars. Some of these planets are in circumstellar, or S-Type, orbits where the planet orbits one star in the binary system (e.g. γ Cephei Ab (Neuhäuser et al. 2007) and HD 196885 Ab (Chauvin et al. 2007)) and others are in circumbinary, or P-Type, orbits where the planet orbits both stars (e.g. Kepler-16b (Doyle et al. 2011), Kepler-47b and c (Orosz et al. 2012), PH-1 (Schwamb et al. 2013), ROXs 42Bb (Kraus et al. 2014) and OGLE-2007-BLG-349L(AB)c (Bennett et al. 2016)). As of January 2019, ~ 700 exoplanets are known to be in binary or multiple star systems and ~ 20 of these planets are in circumbinary orbits². Various methods such as transits, binary eclipse timing variation, and microlensing have been used to detect these planets. The detection of planets in S-Type orbits is similar to detecting planets around single stars. However, detecting circumbinary planets can be more complex.

²Numbers taken from exoplanets.org.

Most circumbinary planets have been detected via the transit method. The light curve of Kepler-16b, the first circumbinary planet discovered by the *Kepler* space telescope, is shown in Figure 1.11. In this system, the binary star and the planet are aligned, which is why we are able to see the primary and secondary eclipse of the stars (the blue and yellow data), as well as the transit of the planet across the stars (the green and red data). This method requires the inclination of the respective orbital planes of the binary star and planet to be aligned, which may not be the most common configuration of circumbinary planets. Circumbinary discs with very high inclination to the binary orbit have been observed, such as IRS 43 (Brinch et al. 2016) and HD 98800 (Kennedy et al. 2019), implying that circumbinary planets could form in highly inclined orbits. By studying *Kepler* planet occurrence rates, Armstrong et al. (2014) calculated the occurrence rate for circumbinary planets of $R_p > R_\oplus$ and periods < 300 day to be $\sim 10\%$ for coplanar orbits to $> 47\%$ for an isotropic distribution of inclinations. To characterise the distribution of inclinations that circumbinary planets can exist, we need to observe more misaligned circumbinary planets.

Direct imaging and microlensing are other techniques that are less dependent, than the transit method, on the orbital alignment of the system. A coronagraph was used to directly image the circumbinary planets ROXs 42b and FW Tau b (Kraus et al. 2014). Direct imaging is possible with these planets because they are very massive and have large separations from the host binary star. The microlensing technique has discovered the lowest mass circumbinary planet to date, OGLE-2007-BLG-349L(AB)c, which has a mass of $80 \pm 13 M_\oplus$ (Bennett et al. 2016). Most known circumbinary planets have masses less than $1 M_{\text{Jup}}$ which is peculiar given that more massive planets would be easier to detect. However, massive planets are also less common and it is not clear whether the observed lack of known giant circumbinary planets is significant.

Mentioned previously, Artymowicz & Lubow (1994) described a region of instability around binary stars that truncates the inner circumbinary disc radius at $\sim 2a$. This same instability can be hostile to the survival of circumbinary planets. Many of the known circumbinary planets (particularly the *Kepler* planets) reside near this region of instability, and this is illustrated in Figure 1.12. It is not clear whether

the proximity of circumbinary planets to this instability region is an observational bias, or due to migration. Do most circumbinary planets migrate to the edge of the instability region? Or do many migrate *into* the instability region to be destroyed or ejected?

Circumbinary planets have not been discovered around very close ($P < 7$ day) binaries, despite planet detection being easier around these types of systems. Martin et al. (2015) suggested that the lack of circumbinary planets in close binaries may be due to the presence of a third body which shrunk the inner binary orbit by the process of Kozai-Lidov cycles and tidal friction, hindering the formation or stability of circumbinary planets. Muñoz & Lai (2015) explored the tightening of binaries via the Kozai-Lidov mechanism with a tertiary companion and the inner binary hosting a circumbinary planet. They found that for initial tertiary inclinations of $\lesssim 75^\circ$ it was possible for a circumbinary planet to survive this evolution, and the planet would migrate to a higher inclination. For initial tertiary inclinations of $\gtrsim 80^\circ$ the circumbinary planet developed erratically evolving eccentricity and inclination, and was often ejected or collided with a star. Muñoz & Lai (2015) conclude that circumbinary planets may exist around very close binaries, but are on inclined orbits making their detection difficult. However, Fleming et al. (2018) argue that the circularisation via tidal evolution of close binaries can expand the region of instability to the region where planets might reside. During this circularisation, circumbinary planets could be destabilised and destroyed leading to a lack of circumbinary planets observed around very close binary stars.

While it appears the formation of circumbinary planets is very sensitive to the environment and evolution of the binary, it also appears that binaries can hinder the formation or survival of planets in circumstellar orbits. Kraus et al. (2012) compiled a census of discs around binaries in the Taurus-Auriga region and found that the disc fraction (circumstellar and circumbinary) of binaries with separations $\lesssim 40$ AU was a third of the disc fraction for wider binaries or single stars. This implied that disc dispersal may be very rapid around binaries with these separations, hindering planet formation. The results of Kraus et al. (2012) is reflected by the results of Kraus et al. (2016) who find the planet occurrence rate in binaries with a separation less than 50 AU is approximately one third that of wider binaries or single stars. Despite

Observed circumbinary planets (orbits normalized to the instability region)

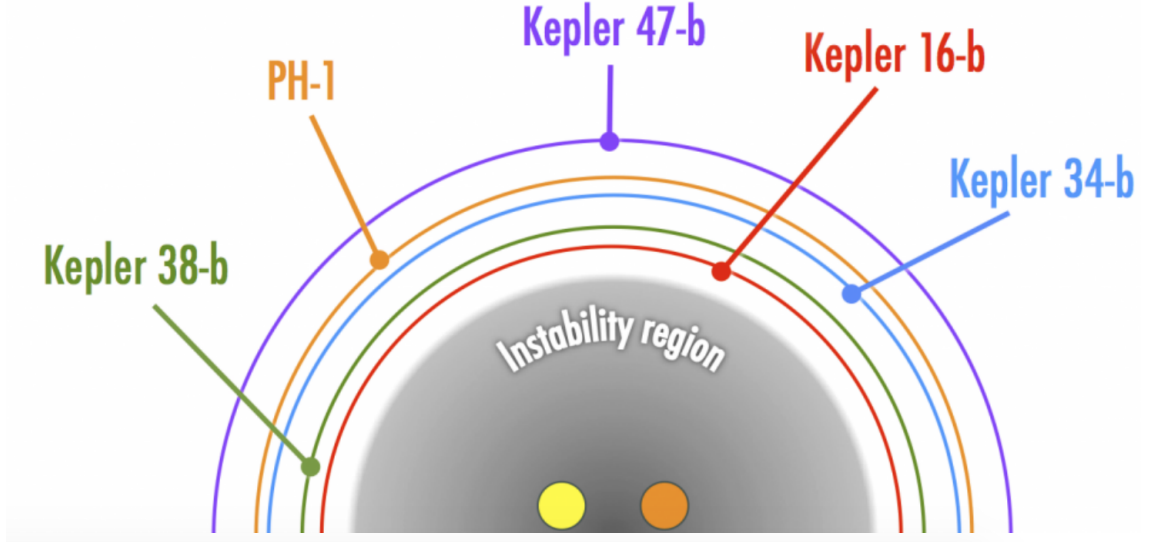


Figure 1.12: A schematic showing the proximity of known circumbinary planets to the region of instability caused by the host binary star described by Artymowicz & Lubow (1994). Taken from planethunters.org.

binaries of separation $\lesssim 50$ AU appearing to be hostile to planet formation, Rafikov & Silsbee (2015) suggest that planet formation in binaries down to separations of ~ 20 AU is possible if the circumstellar disc is sufficiently massive ($\gtrsim 0.01 M_{\odot}$) and the binary has low eccentricity. Fragione (2019) find that the survivability of planets in S-Type orbits for binary separations less than 50 AU is dependent on the mass ratio of the binary. The results of Sutherland & Fabrycky (2016) imply that planets in S-Type orbits likely formed in situ and did not fall into those orbits via some dynamical interaction. They carried out N-body simulations of a Jupiter mass planet in the instability region around 1 AU binary stars of varying mass ratios to determine the likelihood of falling into an S-Type orbit or ejection. They find that $\sim 80\%$ of the simulations lead to the ejection of the planet, $\sim 20\%$ lead to the planet striking one of the stars and less than $\sim 1\%$ lead to the capture of the planet around one of the stars.

The diversity of planets in binaries is only beginning to be comprehended. To understand the formation of these diverse planets we must consider the environments

in which they form. This problem is the topic of this thesis.

1.3 Previous simulations of binary star formation

Simulations of binary and multiple star formation have been explored through various avenues, including cluster simulations (Bate 2012; Dorval et al. 2017; Belloni et al. 2017; Jones & Bate 2018) and formation from fragmenting molecular cores (Goodwin et al. 2004; Tomisaka et al. 2004; Price & Bate 2007; Machida et al. 2009; Seifried et al. 2013; Offner et al. 2016; Lewis & Bate 2017; Matsumoto et al. 2017).

The two main pathways for binary star formation are determined to be either via the fragmentation of the parent molecular core, or the fragmentation of massive protostellar discs. Simulations with varying levels of input physics argue which formation pathway is mostly likely for different types of binary systems. The simplest models investigated the collapse of rotating molecular cores. Because these molecular cores inherit angular momentum from their parent clouds, the cores are also rotating. These simple simulations find that clouds with angular frequencies (Ω) greater than 20% of the cloud free-fall time (t_{ff}) fragment easily into multiple protostars (Bodenheimer 1978; Boss & Bodenheimer 1979; Banerjee et al. 2004). Banerjee et al. (2004) find in these simulations that disc fragmentation occurs frequently, as well as cloud fragmentation. However, this frequency of fragmentation changes when further physics is introduced.

The introduction of ideal MHD provides magnetic pressure support that can reduce the collapse rate. Magnetic fields are integral for launching protostellar outflows and must be considered when studying star formation. The mass-to-flux ratio is discussed previously in Section 1.1. Hennebelle & Teyssier (2008) find magnetic pressure can also prevent cloud fragmentation and rotation alone cannot lead to efficient fragmentation, unless the rotation rates are significantly high (Banerjee & Pudritz 2006). They also suggest that strong density perturbations are necessary in the initial cloud core to overcome the magnetic pressure, or other mechanisms such as ambipolar diffusion to reduce the magnetic field strength, for cloud fragmentation to occur (Hennebelle & Teyssier 2008). B urzle et al. (2011) also find that strong magnetic fields suppress fragmentation within a core, but found that the magnetic

‘cushion’ created in circumstellar discs surrounding individual components in a binary aided binary fragmentation. Price & Bate (2007) find that the orientation of the magnetic field to the rotation axis can either hinder (when they are parallel) or aid (perpendicular) fragmentation. However, based on simulations of molecular core collapse Tomisaka et al. (2004) find that even if the initial magnetic field and angular momentum vector are misaligned, the resulting disc is perpendicular to the magnetic field, but the inner disc remains aligned perpendicular to the rotation axis (Lewis & Bate 2017). Tomisaka et al. (2004) Also find that despite magnetic pressure suppressing core fragmentation, the discs formed were able to fragment into binary star systems (Machida et al. 2004). All of these studies find that cores with sufficient density perturbations will fragment in the presence of even strong magnetic fields.

Despite ideal MHD showing magnetic fields can hinder fragmentation, non-ideal MHD effects have been employed to help overcome the magnetic pressure preventing fragmentation. While ambipolar diffusion can help a sub-critical molecular core become supercritical, the magnetic pressure can continue to suppress fragmentation (Hosking & Whitworth 2004). Machida et al. (2008) and Machida et al. (2009) also find that fragmentation of molecular cores is only possible after the magnetic field strength is reduced via Ohmic dissipation. Wurster et al. (2017) carried out a comprehensive study of the effect of Ohmic dissipation, the Hall effect and ambipolar diffusion on binary star formation in perturbed molecular cores with varying initial orientation of the magnetic field to the rotation axis. Overall they find that the non-ideal effects have only a small impact on binary formation and early evolution, with the initial conditions playing the dominant role.

Radiation feedback should also be considered when modelling binary star formation, because young stars are very luminous objects. Previous simulations of star formation with radiation feedback find that fragmentation in molecular cores and massive discs is suppressed due to the increased temperature leading to larger Jeans lengths within the gas (Krumholz et al. 2007; Offner et al. 2009; Bate 2012; Federrath et al. 2017). Federrath et al. (2017) and Cunningham et al. (2018) find that radiation feedback plays the dominant role of fragmentation suppression in molecular cores. Despite radiation feedback helping to suppress fragmentation, Bate (2012)

find that gravity and gas dynamics have a greater influence in determining the properties of the formed multiple star systems. Radiation feedback in discs is found to be strong than feedback during the initial molecular cloud collapse, leading to the conclusion that binaries form predominantly via core fragmentation rather than disc instabilities (Offner et al. 2010).

While magnetic fields and radiation may suppress fragmentation, the predominant mechanism leading to the formation of binary and multiple star systems is turbulence creating overdensities. Simulations of molecular cloud fragmentation with varying levels of turbulence generally find that stronger turbulence leads to stronger fragmentation (Goodwin et al. 2004). Turbulent simulations produce Keplerian discs which planets can form in (Seifried et al. 2013).

Numerical simulations are a good tool for exploring how various physics influences binary star formation, however, they are not useful without being compared with observation. Synthetic observations can be produced from these simulations using radiative transfer codes such as **RADMC3D** (Dullemond et al. 2012), **Polaris** (Reissl et al. 2016) or **PyRaTe** (Tritsis et al. 2018). These techniques can produce images from a 3D structures and convolve them with a point spread function simulating observational data. The main difficulty in comparing simulations to observations is due to projection effects and varying opacities (Haworth et al. 2018). Bertram et al. (2014) compared synthetic ^{12}CO and ^{13}CO maps produced by **RADMC3D** with their physical 3D positions of H_2 and CO in turbulent simulations. They find that the synthetic observations are able to trace dense environments well where the hydrogen is mostly molecular, but fails for low density environments. Bertram et al. (2015) find that the CO gradients produced by synthetic observations are shallower than that produced by the 3D simulation. Similarly, based on comparisons to synthetic observations and 3D simulations, Offner & Arce (2014) find that ^{12}CO would be ideal to trace protostellar outflows.

1.4 Aim of this thesis

In this thesis I studied how binary star formation affects the creation, stability and lifetime of discs. I carry out both theoretical investigations with the ideal-magnetohydrodynamic adaptive mesh refinement code **FLASH**, and observations using the Wide Field Spectrograph (WiFeS, Dopita et al. 2007) on the Australian National University 2.3 m Telescope.

1.4.1 Overview of chapters

Chapter 2: Effect of binarity on the global evolution of molecular core collapse

I simulated the collapse of molecular clouds to form binary star systems, as well as a single star as a control. The initial conditions for these simulations are idealised but nevertheless the results provide insights into how binarity affects outflow morphology and efficiency during the early stages of molecular core collapse and protostar accretion. Because the focus of this chapter is on the outflow morphology, I also investigated the magnetic field structure in these systems to understand the launching mechanisms. This work was published in Kuruwita et al. (2017).

Chapter 3: Turbulence and disc formation in binary star systems

I continued the work of Chapter 2 and ran the simulations of Chapter 2 longer, and also performed other simulations that introduce turbulence typical of molecular cores. In this chapter, I investigated the disruption of circumstellar discs and the formation of circumbinary discs. I also studied the role of turbulence in building discs and its influence on outflows. I quantified the disc radii and masses, and drew conclusions regarding the assembly of large, massive circumbinary discs. This work was published in Kuruwita & Federrath (2019).

Chapter 4: Survivability of discs in binary star systems

While the work of my numerical simulations can provide insight into the formation and evolution of discs in binaries, high computational demands prevent insights into the longevity of these discs. In this chapter, I describe my observational study to determine the multiplicity of disc-bearing objects in the 11 Myr old (Pecaut et al. 2012) Upper Scorpius and 17 Myr old (Mamajek et al. 2002) Upper Centaurus-Lupus

star forming regions. The aim was to determine if the presence of a companion affects the survivability of discs at these ages. This work was published in Kuruwita et al. (2018).

Chapter 5: Conclusions and future work

I summarise the results of the previous chapters and draw broad conclusions regarding how the thesis contributes to understanding the formation, evolution and lifetime of discs in binaries. I list some outstanding questions and describe future research projects. Future projects include investigating the episodic accretion seen in the simulations of Chapter 3, and studying disc evolution during three-body interactions.

Chapter 6: Appendix

The appendix presents supplementary material from the published papers. This material includes convergence tests of simulations for the numerical work, and tables of observed targets, as well as data from each epoch of observation.

2

Effect of binarity on the global evolution of molecular core collapse

This chapter is published in Monthly Notices of the Royal Astronomical Society as Kuruwita R. L., Federrath C. and Ireland M., Binary star formation and the outflows from their discs, 2017, MNRAS, 470, 1626-1641.

2.1 Abstract

We carry out magnetohydrodynamical simulations with **FLASH** of the formation of a single, a tight binary ($a \sim 2.5$ AU) and a wide binary star ($a \sim 45$ AU). We study the outflows and jets from these systems to understand the contributions the circumstellar and circumbinary discs have on the efficiency and morphology of the outflow. In the single star and tight binary case we obtain a single pair of jets launched from the system, while in the wide binary case, two pairs of jets are observed. This implies that in the tight binary case the contribution of the circumbinary disc on the outflow is greater than that in the wide binary case. We also find that the single star case is the most efficient at transporting mass, linear momentum, and angular momentum from the system, while the wide binary case is the least efficient ($\sim 50\%$, $\sim 33\%$, $\sim 42\%$, of the respective quantities in the single star case). The tight binary's efficiency falls between the other two cases ($\sim 71\%$, $\sim 66\%$, $\sim 87\%$, of the respective quantities in the single star case). By studying the magnetic field

structure we deduce that the outflows in the single star and tight binary star case are magnetocentrifugally driven, whereas in the wide binary star case the outflows are driven by a magnetic pressure gradient.

2.2 Introduction

Stellar multiplicity is a critical output of star formation, with most solar mass or higher mass stars forming in multiple systems (Raghavan et al. 2010). The fraction of all stars that are members of binary systems (multiplicity) depends on the mass of the system. For solar-type stars with effective temperature between 4800 K and 6550 K, the multiplicity of field stars is approximately 50–60% (Duquennoy & Mayor 1991; Kraus et al. 2011), while lower mass stars and dwarfs have a multiplicity of 30% down to 10% (Lada 2006; Basri & Reiners 2006; Ahmic et al. 2007). The prevalence of binary systems thus shows that a complete understanding of star and planet formation requires an understanding of binary formation.

The current picture of star formation is that stars form preferentially in multiple star systems. The formation of binary star systems is believed to be triggered by the fragmentation of protostellar cores as they collapse. Each core produces around on average 2–3 stars due to fragmentation (Goodwin & Kroupa 2005). Models suggests fragmentation would occur via turbulent fragmentation (Klessen et al. 1998; Offner et al. 2010, 2014) or via gravitational instability in the protostellar disc (Takahashi et al. 2016; Kratter et al. 2010). Individual star formation requires the loss of 99 – 99.9% of the initial angular momentum carried by the molecular cores (Frank et al. 2014), and a significant fraction of this angular momentum can be stored in a multiple star system rather than lost. Angular momentum can be carried out of the system via jets, outflows (there is no strict definition of the difference between a jet and outflow, but a jet is generally considered to be a high velocity and strongly collimated outflow) or the ejection of a third companion. The formation of the binary star is then thought to broadly follow the single star birth.

During the formation of the binary, discs may form around individual components as circumprimary and circumsecondary discs, or around both stars as a circumbinary disc. The resonances produced by the binary system can greatly influence the evolution of the protoplanetary disc. Artymowicz & Lubow (1994) showed in

smoothed particle hydrodynamics (SPH) simulations that discs around each stellar component are truncated at the outer edge, and circumbinary discs are truncated along the inner edge. For a circular orbit, the circumstellar disc is truncated at $\sim a/2$, and the circumbinary disc is truncated at $\sim 2a$ where a is the semi-major axis of the binary system. Greater eccentricities will lead to greater erosion of the discs, varying these values. The host binary may also affect the disc by exciting resonances that can encourage planet formation, by forcing gas and dust to fall into particular orbits (Bromley & Kenyon 2015). Binaries with $a < 40$ AU are half as likely to harbour circumprimary/circumsecondary discs than binaries with separations 40 – 400 AU (Cieza et al. 2009; Duchêne 2010; Kraus et al. 2012). This is also suggested by close binaries having less sub/millimetre flux due to absence of an inner disc (Jensen et al. 1994, 1996; Andrews & Williams 2005).

Multiplicity may affect the disc lifetime, as the truncation of circumstellar discs by the companion may mean that disc material is accreted faster, on the order of ~ 0.3 Myr (Williams & Cieza 2011). Despite the assumption that circumbinary discs may have a shorter lifetime due to multiplicity, it has not been shown that circumbinary discs are short-lived compared to discs around single stars. There is also evidence for very long-lived circumbinary discs such as AK Sco (18 ± 1 Myr, Czekala et al. 2015), HD 98800 B (10 ± 5 Myr, Furlan et al. 2007), V4046 Sgr ($12 - 23$ Myr, Rapson et al. 2015) and St 34 (also known as HBC 425, ~ 25 Myr, Hartmann et al. 2005).

The primary mechanisms for disc dispersal are: 1. accretion of material onto the stars, 2. photoevaporation of the disc, 3. jets and outflows, which carry mass and momentum away from the system (Tomisaka 2000, 2002) and are tied to the accretion history. Here we focus on how binarity affects the outflows and jets from young forming binary systems. The study of jet/outflows has so far focussed mostly on single stars. As most systems form binaries, it is important to quantify and understand the outflow properties and launching mechanisms in binary star systems.

To understand the outflows and evolution of binary stars we simulate the formation of a tight binary (< 10 AU) and a wide binary (> 10 AU), as well as a single star for reference. The set-up and numerical methods of the simulations are described in Section 2.3. In Section 2.4 and 2.5 we present the results from our simulations

and discuss the impact binarity has on the outflows from the young systems. In Section 2.6 we summarise our results and present our conclusions.

2.3 Method

2.3.1 FLASH

The simulations are carried out with the magnetohydrodynamic (MHD) adaptive mesh refinement (AMR) code **FLASH** (Fryxell et al. 2000; Dubey et al. 2008). The standard set of ideal MHD equations are:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0, \quad (2.1)$$

$$\rho \left(\frac{\partial}{\partial t} + \mathbf{v} \cdot \nabla \right) \mathbf{v} = \frac{(\mathbf{B} \cdot \nabla) \mathbf{B}}{4\pi} - \nabla P_{\text{tot}} + \rho \mathbf{g}, \quad (2.2)$$

$$\frac{\partial E}{\partial t} + \nabla \cdot \left((E + P_{\text{tot}}) \mathbf{v} - \frac{(\mathbf{B} \cdot \mathbf{v}) \mathbf{B}}{4\pi} \right) = \rho \mathbf{v} \cdot \mathbf{g}, \quad (2.3)$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}), \quad (2.4)$$

$$\nabla \cdot \mathbf{B} = 0. \quad (2.5)$$

Here ρ , $\mathbf{v}$, $\mathbf{B}$, P_{tot} , $\mathbf{g}$, E denote the gas density, velocity, magnetic field strength, total pressure (thermal plus magnetic), gravitational acceleration of the gas, and total energy density, respectively. Equations 2.1, 2.2 and 2.3 describe the conservation of mass, momentum and energy, respectively, including the effects of magnetic fields and gravitational acceleration. The total pressure used is the sum of the magnetic pressure and the thermal pressure, where the magnetic pressure is given by:

$$P_{\mathbf{B}} = \frac{|\mathbf{B}|^2}{8\pi}, \quad (2.6)$$

and the thermal pressure is defined by a piecewise polytropic equation of state (EOS),

$$P_{\text{th}} = K \rho^\Gamma. \quad (2.7)$$

FLASH calculates the thermal pressure from this polytropic equation of state. Because of this, we technically do not use the internal energy from Equation 2.3.

The Γ used in our simulations is derived from Masunaga & Inutsuka (2000):

$$\Gamma = \begin{cases} 1.0 & \text{for } \rho \leq \rho_1 \equiv 2.50 \times 10^{-16} \text{ g cm}^{-3}, \\ 1.1 & \text{for } \rho_1 < \rho \leq \rho_2 \equiv 3.84 \times 10^{-13} \text{ g cm}^{-3}, \\ 1.4 & \text{for } \rho_2 < \rho \leq \rho_3 \equiv 3.84 \times 10^{-8} \text{ g cm}^{-3}, \\ 1.1 & \text{for } \rho_3 < \rho \leq \rho_4 \equiv 3.84 \times 10^{-3} \text{ g cm}^{-3}, \\ 5/3 & \text{for } \rho > \rho_4. \end{cases} \quad (2.8)$$

These values approximate radiative transfer effects on the local cell scale in the gas including the initial isothermal contraction, adiabatic heating of the first core, the H_2 dissociation during the second collapse into the second core and the return to adiabatic heating. The polytropic constant used is $K = 4.0 \times 10^8 \text{ cm}^2 \text{ s}^{-2}$. The value for the polytropic constant is derived from setting $K = c_s^2$, where c_s is the sound speed. In the isothermal regime ($\Gamma = 1$) of our piecewise EOS, the sound speed is $c_s = 2 \times 10^4 \text{ cm s}^{-1}$ for a temperature of 11 K for gas with mean molecular weight of $2.3 m_{\text{H}}$ (where m_{H} is the mass of a hydrogen atom).

The gravitational acceleration contains both the contribution from the gas and the sink particles, calculated using:

$$\mathbf{g} = -\nabla\Phi_{\text{gas}} + \mathbf{g}_{\text{sinks}}, \quad (2.9)$$

where Φ_{gas} is the gravitational potential of the gas and $\mathbf{g}_{\text{sinks}}$ is the gravitational acceleration from the sink particles (described in Section 2.3.2). FLASH integrates the ideal MHD equations such that the contribution from the gas and implemented sink particles is taken into account.

We use the HLL3R Riemann solver for ideal MHD (Waagan et al. 2011). The gravitational interactions of the gas are calculated using a Poisson solver (Ricker 2008). The interactions between sink particles and the gas are computed using N -body integration.

2.3.2 Sink particles

In our simulations the formation of a protostar is signalled by the formation of a sink particle (Federrath et al. 2010, 2011, 2014). If a cell exceeds the density threshold, derived from the Jeans length, given by:

$$\rho_{\text{sink}} = \frac{\pi c_s^2}{4Gr_{\text{sink}}^2}, \quad (2.10)$$

it may collapse (subject to additional checks; see below). The Jeans length must be resolved with at least four grid cells such that fragmentation is not artificial (Truelove et al. 1997). To prevent artificial fragmentation of a volume with radius $r_{\text{sink}} = 2.5\Delta x$, where Δx is the cell length on the highest AMR level, centred on the cell exceeding ρ_{sink} the volume must also meet the following criteria described by Federrath et al. (2010). In order for a volume to create a sink particle the gas in the volume needs to:

1. be on the highest level of grid refinement,
2. not be within r_{sink} of an existing sink particle,
3. be converging from all directions ($v_r < 0$),
4. have a central gravitational potential minimum,
5. be bound ($|E_{\text{grav}}| > E_{\text{th}} + E_{\text{kin}} + E_{\text{mag}}$), and
6. be Jeans-unstable.

If a cell exceeds the density threshold while within r_{sink} of another sink particle, and bound and collapsing towards the sink, it will be accreted onto the sink particle. The accretion is carried out such that mass, momentum and angular momentum are conserved (Federrath et al. 2014).¹

A second-order leapfrog integrator is used to update the particle positions using a velocity and acceleration based time step. A sub-cycling method is implemented to prevent artificial precession of the sink particles (Federrath et al. 2010).

¹Refer to figure 1 of Federrath et al. (2010) for implementation of gravitational softening and sub-cycling to prevent artificial precession.

2.3.3 Simulation set-up

Using FLASH and the sink particle implementation described above, we simulate the formation of binary star systems and a single star for comparison of outflow quantities and structure of gas around the protostars. Because FLASH uses AMR to achieve higher resolution in regions with higher density, the effective number of cells (resolution) in each spatial dimension is defined as 2^L where L is the level of refinement.

The size of the computational domain is 1.2×10^{17} cm (~ 8000 AU) along each side of the 3D computational domain. The minimum effective resolution in the simulation is 2^6 , thus one side has a minimum of 64 cells, with the cells being ~ 125 AU across. The highest level of refinement in these simulations is $L = 12$, making the highest resolution cells ~ 1.95 AU across. At this resolution the accretion radius of sink particles is $r_{\text{sink}} \sim 4.8$ AU. A convergence test has been carried out and the results are presented in Appendix A.

Our simulations begin with a large spherical cloud of mass $1 M_{\odot}$, and radius ~ 3300 AU. The cloud is given solid body rotation with angular momentum of 1.85×10^{51} g cm² s⁻¹. With this angular momentum, the product of the angular frequency and the freefall time of the cloud is $\Omega \times t_{\text{ff}} = 0.2$ (see Banerjee & Pudritz (2006) and Machida et al. (2008)). A magnetic field of $100 \mu\text{G}$ is also threaded through the cloud in the z -direction. This gives a mass-to-flux ratio of $(M/\Phi)/(M/\Phi)_{\text{crit}} = 5.2$ where the critical mass-to-flux ratio is $487 \text{ g cm}^{-2} \text{ G}^{-1}$ as defined in Mouschovias & Spitzer (1976).

In the single star case (hereafter known as *Single Star*) the cloud is given a uniform density of $\rho_0 = 3.82 \times 10^{-18} \text{ g cm}^{-3}$. In the binary star cases a density perturbation is imposed on the cloud. This is to seed the formation of a binary star system. The density in this case is determined by:

$$\rho = \rho_0[1 + \alpha_p \cos(2\phi)], \quad (2.11)$$

where ϕ is the azimuthal angle around the z -axis and α_p is the amplitude of the perturbation. For *Single Star*, α_p is simply 0. For the tight binary simulation (hereafter known as *Tight Binary*), $\alpha_p = 0.25$ and for the wide binary simulations (hereafter known as *Wide Binary*), $\alpha_p = 0.50$. The cloud core rotates around the

Simulation name	α_p	a (AU)
<i>Single Star</i>	0.0	-
<i>Tight Binary</i>	0.25	~ 2.5
<i>Wide Binary</i>	0.50	~ 45

Table 2.1: The middle column gives the density perturbation amplitude (α_p) as described by Eq. 2.11. The right column gives the semi-major axis (a) of the resulting binary system formed in astronomical units. The semi-major axis is calculated from the last periastron and apastron passed shown in Figure 2.1

z -axis.

In the region outside the spherical cloud, there is gas density $\rho_0/100$ with a given internal energy such that the cloud and surrounding material is in pressure equilibrium. At the boundaries of our computational domain we use inflow/outflow boundary conditions.

We evolve three simulation set-ups described in Table 2.1. The results of these three cases are presented in Section 2.4.

2.4 Results

First, the morphology of the jets and outflows for each scenario (*Single Star*, *Tight Binary*, *Wide Binary*) is discussed. Second, the quantitative analysis of the outflows is described and discussed. Lastly the identification of discs and jet launching are explored.

2.4.1 Time evolution of the systems

As the simulations progress, the spherical cloud collapses and sink particles are created in collapsing regions (c.f. Section 2.3.2). In *Single Star* a single sink particle forms at the centre of the computational domain. With the binary cases two sink particles form, which fall towards the centre of the computational domain. The initial separation that the sink particles have is dependent upon the strength of the density perturbation, with stronger perturbations creating wider initial separations. This is because sink particles form earlier and at wider separations.

The evolution of the sink particle separation in the *Tight Binary* and *Wide Binary* are presented in Figure 2.1. In *Tight Binary* we see the particles form with

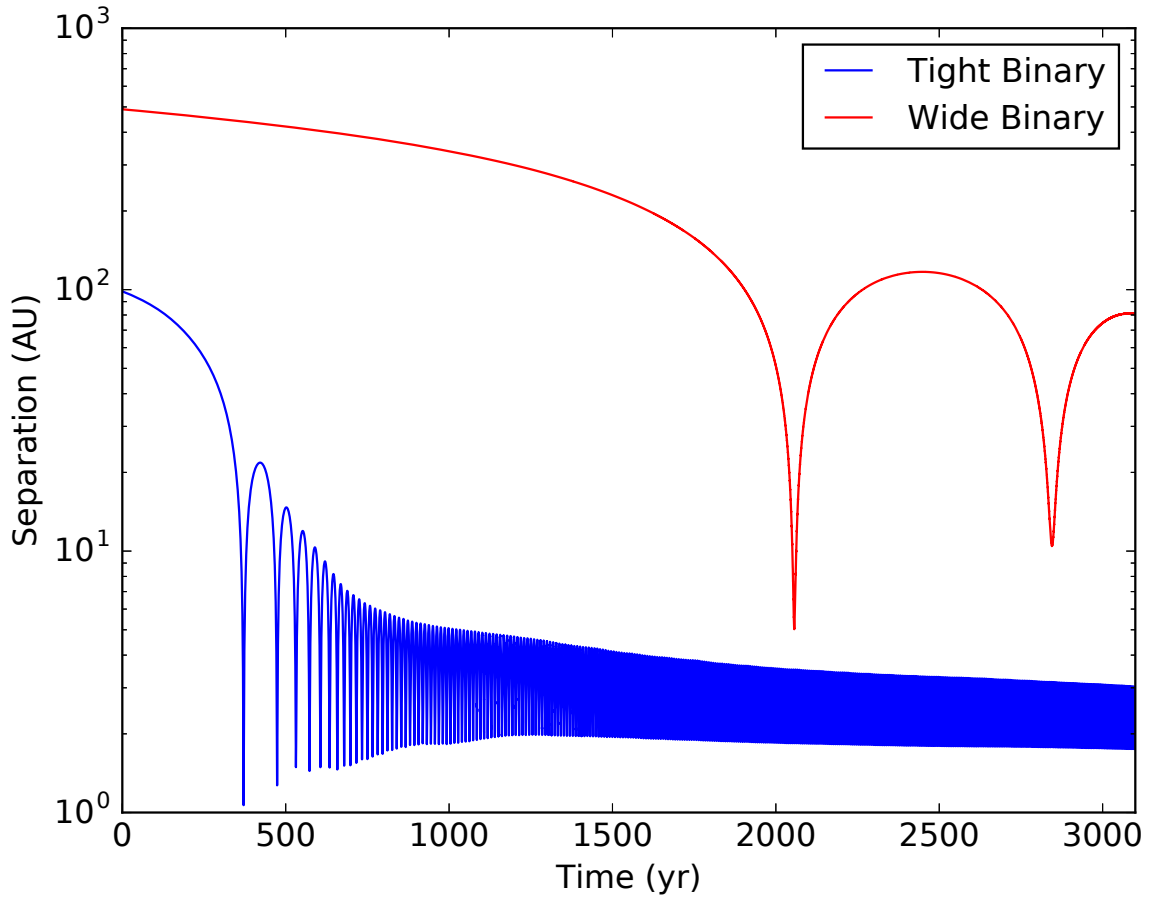


Figure 2.1: Time evolution (since protostar formation) of the separation of the binaries, for the *Tight Binary* (blue) and *Wide Binary* (red) simulations.

a separation of 100 AU and fall into a steady orbit after a few dozen orbits with semi-major axis ~ 2.5 AU. *Wide Binary* forms particles with initial separation of 500 AU. This system does not fall into a steady orbit in the duration of our simulations.

2.4.2 Morphology of the outflows

Gas density slices through the xz -plane for *Single Star* and along the separation axis for the binary star cases are shown in Figure 2.2 at 500 yr intervals since the formation of sink particles. The left, middle and right column show slices for the *Single Star*, *Tight Binary* and *Wide Binary* simulations, respectively. Figure 2.2 qualitatively shows the outflow morphology in the three cases. *Single Star* shows a strong jet breaking out of the disc, like in the simulations of Federrath et al. (2014). *Tight Binary* also produces a single jet which breaks out of the outflowing gas, but the launching time is delayed compared to that of *Single Star*. The velocity of the *Tight Binary* jet is also slower than that of *Single Star*. *Wide Binary* produces two

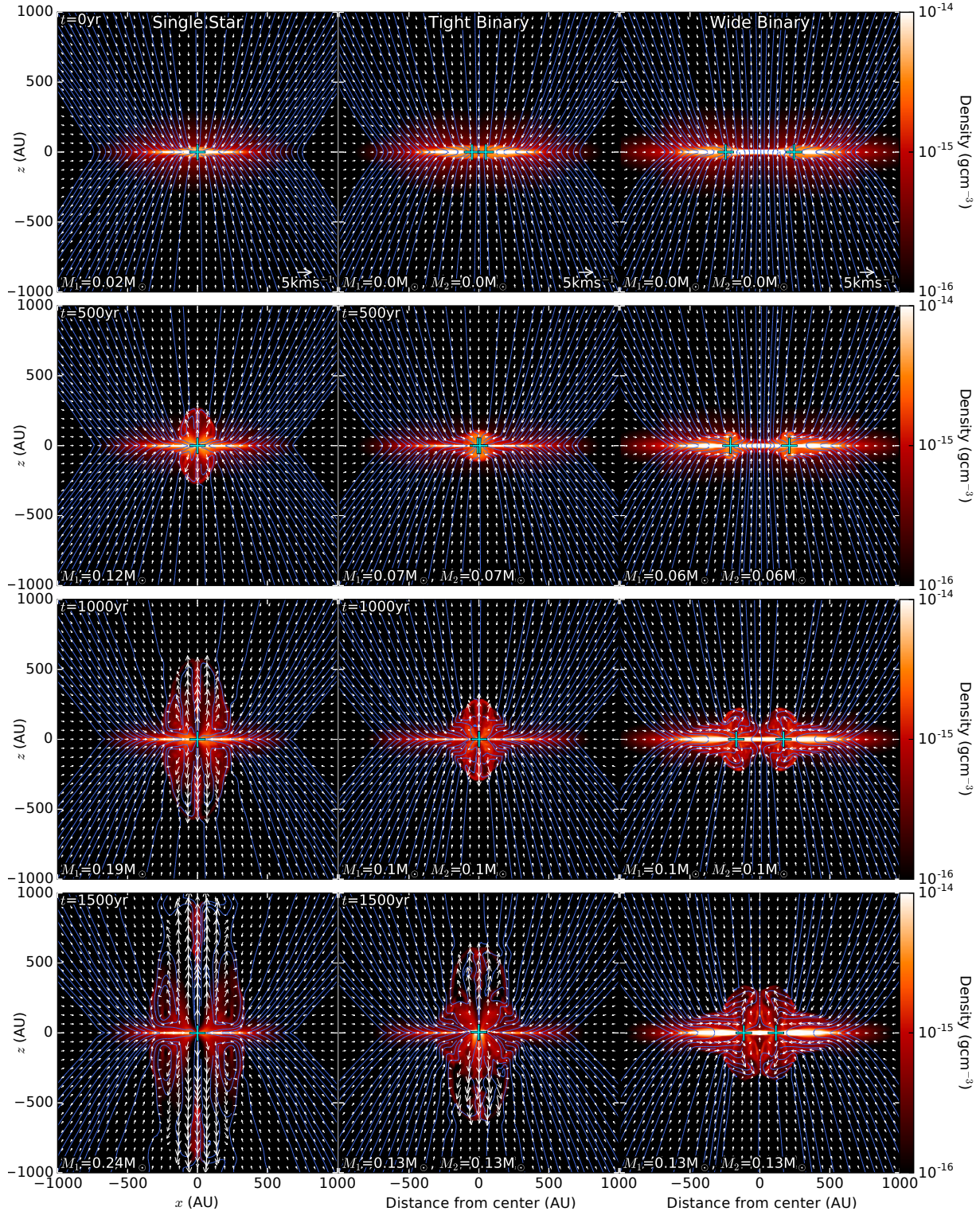


Figure 2.2: Slices along the xz -plane for *Single Star* (left column) and along the separation axis such that the slice captures the two sink particles for *Tight Binary* (middle column) and *Wide Binary* (right column). Each row progresses at 500 yr intervals since protostar formation. The thin lines show the magnetic field, and the arrows indicate the velocity field. Crosses show the position of the sink particles. The mass accreted by the sink particles in the simulations is indicated on the bottom left of each panel.

individual jets, with launching time scales similar to *Tight Binary*. These jets have even lower outflow velocities with respect to *Single Star* and *Tight Binary*. The outflow velocities for *Single Star* and *Tight Binary* are primarily perpendicular to the disc, whereas the outflow velocities of *Wide Binary* bend towards the central axis of rotation of the binary system.

The jets in *Tight Binary* are weaker relative to *Single Star* likely because the inner edge of the circumbinary disc is truncated. The fastest components of outflows from centrifugally driven winds is launched from the innermost radii and the launching velocity of the outflows reduces with increasing radius (Blandford & Payne 1982). However, in circumbinary discs, this inner edge is truncated (Artymowicz & Lubow 1994), reducing the velocity of outflows. *Wide Binary* has the lowest outflow velocities from the two jets. This may be due to a different launching mechanism, which is discussed in Section 2.5.1.

The outflow velocity of the jets in *Wide Binary* may be skewed due to infalling material imparting momentum on the outflows pushing them inwards. We will also see in Section 2.5.1 that the magnetic field structure is strongly asymmetric, which may contribute to outflow velocities that are not perpendicular to the disc.

2.4.3 Time evolution of outflow quantities

The outflows from a protostellar system are one of the mechanisms that carry away mass and momentum from the disc. Here we measure these outflows quantities in our three scenarios to determine how binarity may affect outflows from young systems.

The scaleheight of the discs in our simulations is $z_H = 25 \text{ AU}$. Analysis of the outflows from the systems is carried out by measuring the outflowing mass where $|z| \geq 2z_H = 50 \text{ AU}$. The momentum and angular momentum carried in the outflowing gas is also calculated. We decide to measure outflows from two scaleheights from the disc to exclude most of the disc material. Within the measuring regions outflow mass is defined as any mass in cells with $v_z > 0$ for $z > 0$ and $v_z < 0$ for $z < 0$. From the outflow mass, the angular momentum and linear momentum of the outflows is calculated. The linear momentum is calculated from the magnitude of the velocity and the outflow mass. The angular momentum is calculated about

the centre of mass of the systems.

The outflow measurements of the three cases are shown in Figure 2.3. In all cases *Single Star* is the most efficient at transporting mass, momentum and angular momentum, while *Wide Binary* is the least efficient in transporting those same quantities. In all cases there is already some outflow material by the time the sink particle forms.

To compare the overall outflow efficiency of these quantities we calculate the time averaged values of the quantity using:

$$\langle q \rangle = \frac{\int_0^T q(t) dt}{\int_0^T dt}, \quad (2.12)$$

where q is mass, momentum and angular momentum and $T = 2500$ yr.

Single Star is the most efficient at carrying mass in its outflows. The time averaged values of the outflow mass for *Tight Binary* and *Wide Binary* are $\sim 71\%$ and $\sim 50\%$ of *Single Star*, respectively.

The outflow of *Single Star* carries the greatest linear momentum. This is due to a combination of having the most massive outflows along with the highest outflow velocities. Similarly the outflows of *Wide Binary* carry the least amount of linear momentum due to the same reasons. The time averaged values of the linear momentum for *Tight Binary* and *Wide Binary* are $\sim 66\%$ and $\sim 33\%$ of *Single Star*, respectively.

Single Star is the most efficient at transporting angular momentum via its outflows. It is expected that *Single Star* is more efficient at transporting angular momentum from the disc compared to *Wide Binary* because a binary star system has higher angular momentum than a single star with the same total mass. This is because greater angular momentum is necessary in order to maintain the binary orbit. The larger the binary separation, the greater the angular momentum necessary to maintain the orbit. As *Tight Binary* has a very small separation, angular momentum of the system is comparable to *Single Star*, hence the outflowing angular momentum of *Tight Binary* converges towards the quantities measured in *Single Star*. The time averaged values of the angular momentum for *Tight Binary* and *Wide Binary* are $\sim 87\%$ and $\sim 42\%$ of *Single Star*, respectively.

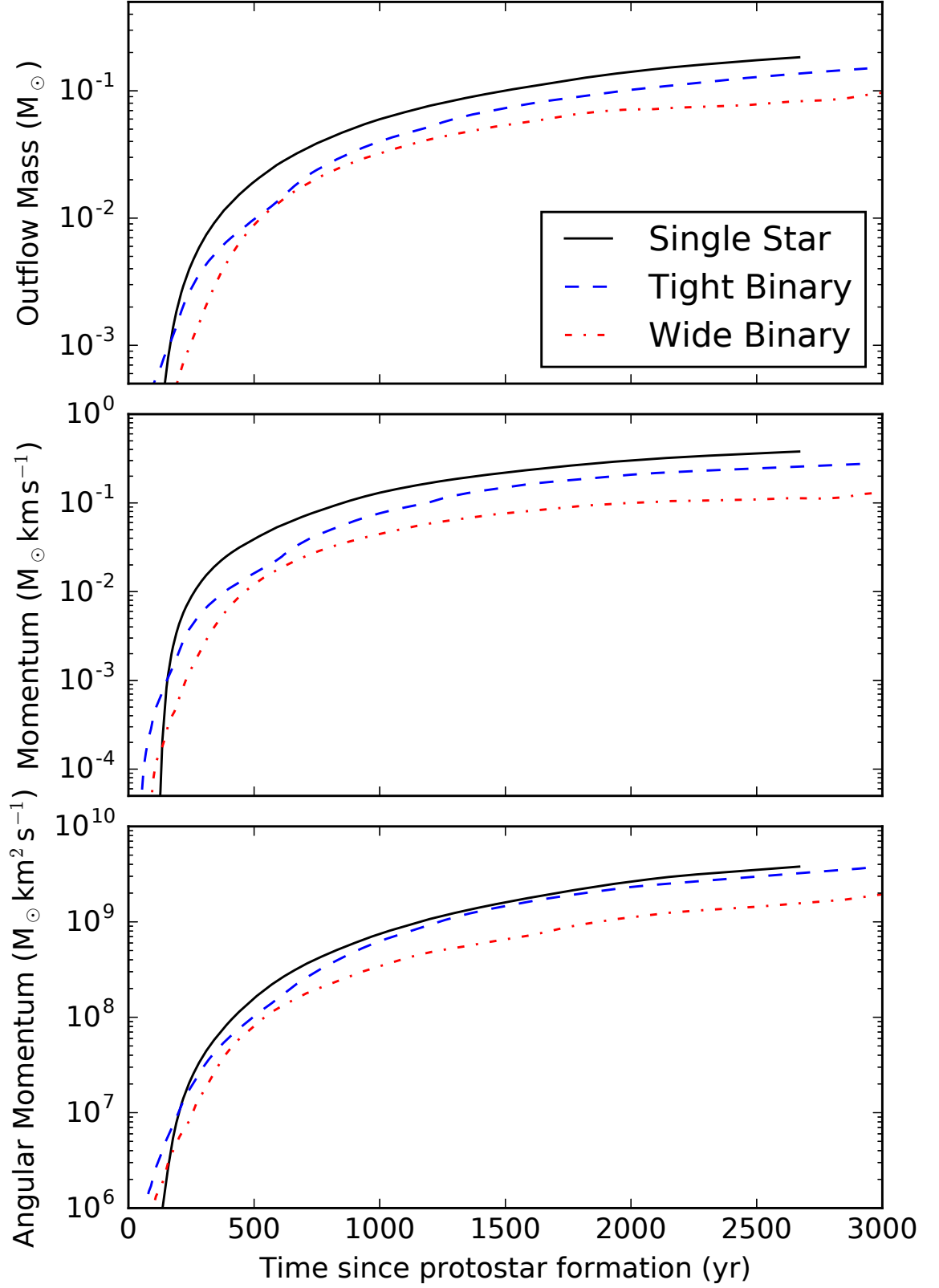


Figure 2.3: Time evolution of the outflow quantities measured from outflowing material greater than two scaleheights from the disc mid-plane (i.e. $|z| \geq 2z_{\text{H}} = 50 \text{ AU}$). *Top*: outflowing mass, defined as mass within cells with v_z away from the disc. *Middle*: linear momentum of the outflowing gas. *Bottom*: angular momentum of the outflowing gas calculated around the centre of mass of the system.

2.4.4 Evolution of the accreted mass

From the outflow analysis in Figure 2.3 we have determined that the binary cases are less efficient at transporting mass and momentum. Since the outflows are less efficiency in the binary cases compared to *Single Star*, we expect that the binaries may have accreted more mass. Figure 2.4 shows the total mass accreted by the sink particles in our three simulations. We see that the binary star cases have a greater star formation efficiency (fraction of accreted mass) than *Single Star* at all times. Figure 2.4 shows that 3000 yr after sink particle formation, the tight and wide binaries have respectively accreted $\sim 10\%$ and 20% more mass than the *Single Star*. Moreover, the time evolution of the binary cases between 2500 and 3000 yr after protostar formation indicates that the accretion rate increases compared to the *Single Star*. However, we cannot predict the final mass of the stars, because it is impossible to run these simulations until the stars stop accreting mass, due to the limited amount of compute time currently available.

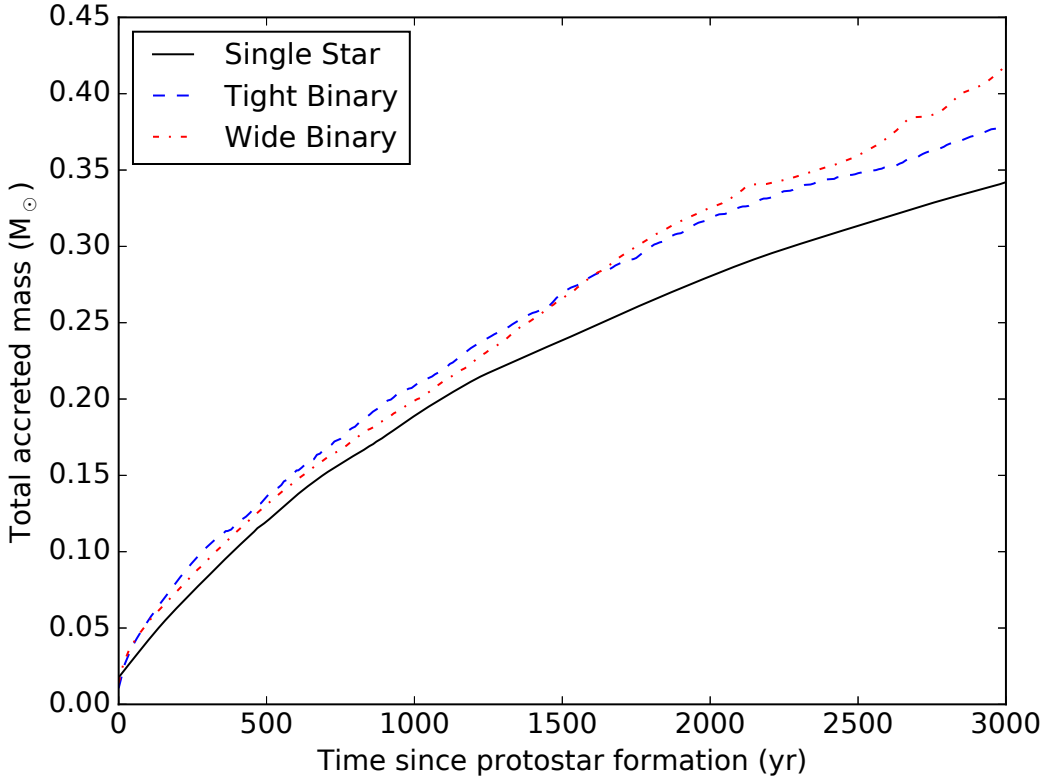


Figure 2.4: The total mass accreted by the sink particles in *Single Star* (solid line), *Tight Binary* (dashed line) and *Wide Binary* (dash dotted line). At all times the binary cases have accreted more mass compared to *Single Star*, which is likely the result of the respectively lower efficiency of the outflows in the binary cases compared to *Single Star* (c.f. Figure 2.3).

2.4.5 Disc structure

In Figures 2.5, 2.6 and 2.7 we present slices along the mid-plane of the density and relative Keplerian velocity for our three simulations at 1000 yr intervals. In the figures, the top panels show streamlines annotating the magnetic field. For clarification, the magnetic field exactly in the mid-plane is perpendicular to the slice. Here the annotated field is taken slightly off-centre from the mid-plane. We also show mass-weighted radial profiles of the relative Keplerian velocity. It should be noted that the data presented is very early in the evolution of the systems and we do not expect large Keplerian discs to be established so soon after protostar formation.

The formation of large Keplerian discs in ideal MHD simulations has been problematic due to the magnetic breaking catastrophe (Hennebelle & Teyssier 2008). Ideal MHD simulations of the collapse of magnetized cores of mass-to-flux ratios smaller than ~ 5 (Hennebelle & Teyssier 2008; Mellon & Li 2008; Joos et al. 2012) do not produce Keplerian discs due to the magnetic field carrying away angular momentum very efficiently. This is despite observations indicating the presence of Keplerian discs around class 0 objects (Murillo et al. 2013) with radii of ~ 100 AU. Various solutions to this problem have proposed such as non-ideal MHD effects (Duffin & Pudritz (2009), see Section 2.5.2) and turbulence (Seifried et al. 2013, 2015). Our simulations have an initial mass-to-flux ratio of ~ 4.8 which is near this threshold of ~ 5 and we produce small Keplerian discs of a few AU. Other factors such as the initial angular momentum of the cloud core can contribute to the ability to produce Keplerian discs and the mass-to-flux threshold of ~ 5 should not be taken as a rigorous criterion for establishing rotationally supported discs or not.

Because there are multiple centres about which the calculation of the Keplerian velocity can be taken (e.g. the centre of mass of the system and the individual sink particles), we find the Keplerian velocity about each possible centre. The final Keplerian velocity is taken to be the mean of the relative Keplerian velocity calculated about the centre of mass of the system and around the sink particles. The relative Keplerian velocity (v_{rel}) is:

$$v_{\text{rel}} = \frac{v_{\phi}}{v_{\text{kep}}}, \quad (2.13)$$

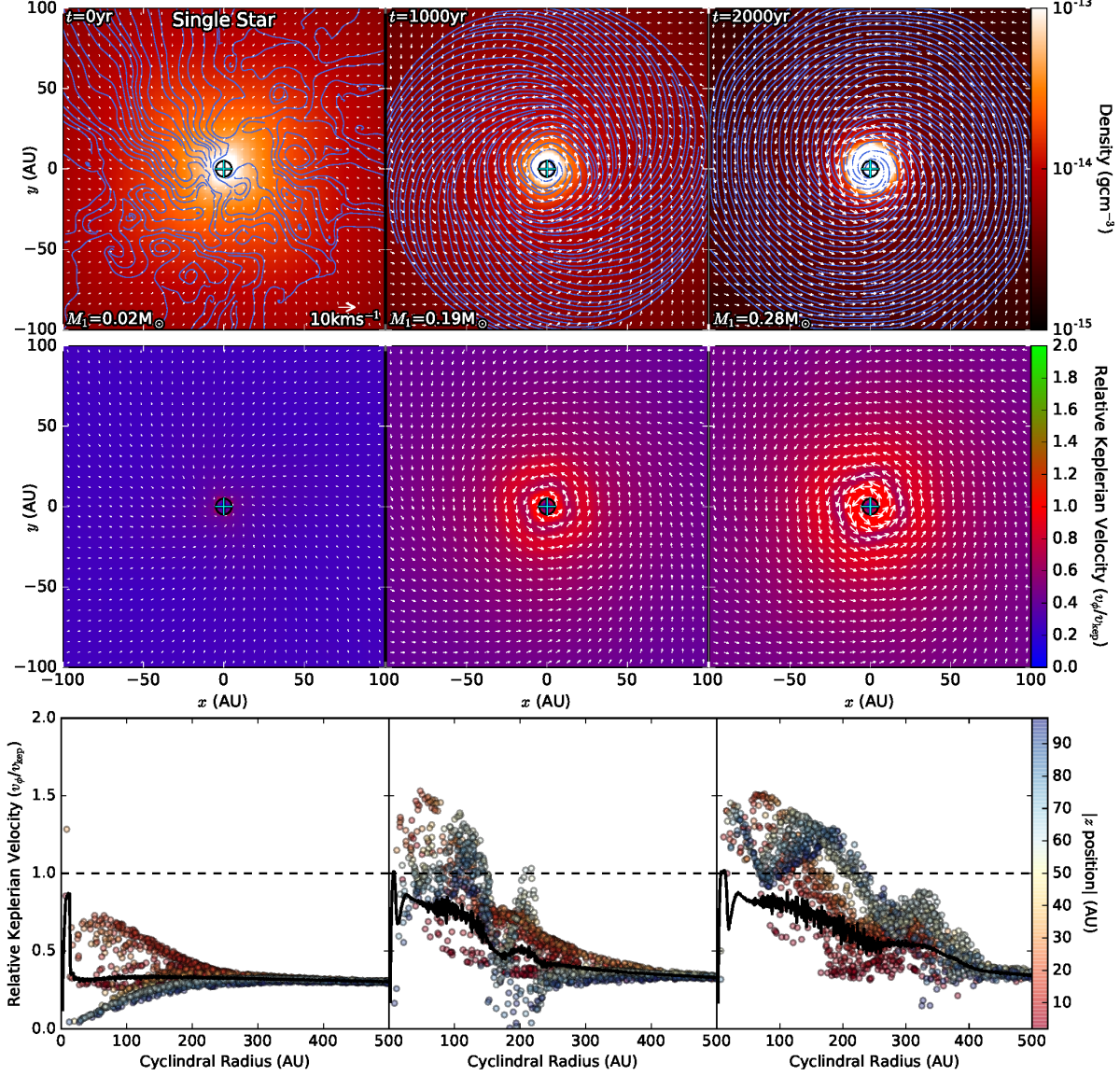


Figure 2.5: *Top*: slice plots of density for *Single Star* in the disc mid-plane. The thin lines show the magnetic field, and the arrows indicate the velocity field. The centre of the cross marks the position of the sink particle, and the circle marks the accretion radius of the particle. Although the magnetic field in the xy plane changes sign in the vicinity of the mid-plane, the streamline structure at 1000 and 2000 years has a near identical (spiral) structure just above and just below the mid plane. *Middle*: slice plots of the relative Keplerian velocity defined in Equation 2.13. *Bottom*: The solid black line is the mass-weighted radial profile of the relative Keplerian velocity for a cylindrical volume of radius 500 AU and thickness 200 AU centred on the centre of mass. The points are randomly selected cells in the volume at various distances from the mid-plane. Each column progresses at steps of 1000 yr.

where v_ϕ is the tangential velocity to the radial direction and v_{kep} is the Keplerian velocity, given by:

$$v_{\text{kep}} = \sqrt{\frac{GM_{\text{enc}}}{r}}, \quad (2.14)$$

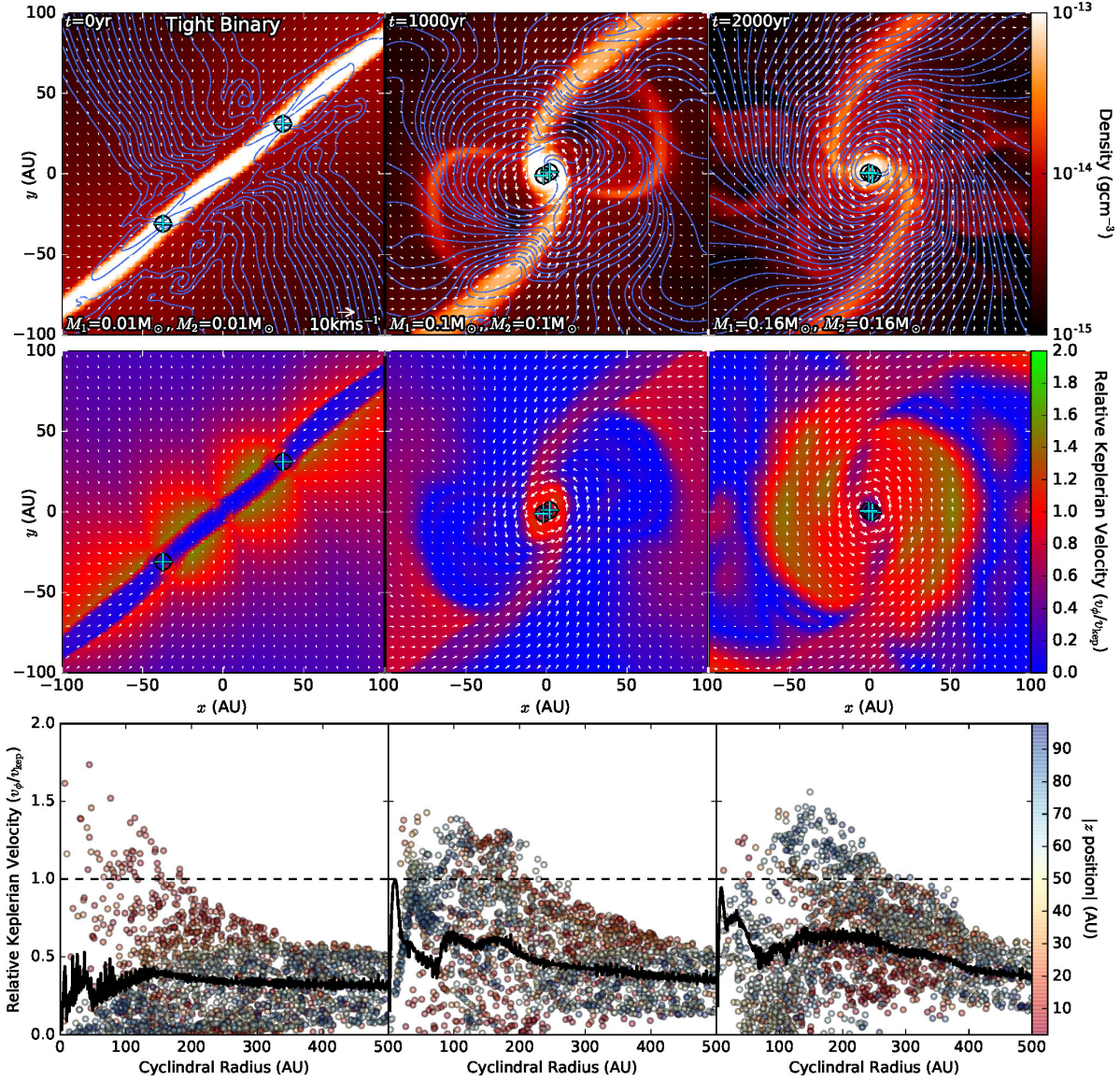
where M_{enc} is the mass enclosed in a sphere with radius r from the chosen centre (either the centre of mass, or sink particle position).

For *Single Star* the centre of mass is essentially the particle, therefore we do not expect these values to vary significantly when calculating the relative Keplerian velocity around the centre of mass and the sink particle. With the binary cases, the values may vary significantly close to the sink particles, but further out as the gravitational potential of the binary system begins to look like that of a single star, the values will converge. For each calculation of the Keplerian velocity the enclosed mass is the sum of the gas and sink particles within r .

The mass-weighted profiles (solid black line in bottom panel of Figure 2.5) are calculated over a cylinder of radius 500 AU and thickness 200 AU centred on the centre of mass of the systems. 1 AU bins are used to produce these profile plots. Along with the radial profile, randomly selected cells are plotted to show any variation in relative Keplerian velocity perpendicular to the disc.

In *Single Star* (Figure 2.5) the evolution of the disc density is axially symmetric. In the density slices we clearly see that the magnetic field is disorganised at time 0 yr, but it coils around the sink particle as the system evolves. In the relative Keplerian velocity slices we see the material around the sink particle is Keplerian out to ~ 50 AU (red colour) by 2000 yr. The profile plot from time 0 yr shows that material above and below the mid-plane (blue scatter points) is severely sub-Keplerian compared to the material near the mid-plane (red scatter points) at the same radius. This indicates material is falling onto the circumstellar disc. After the jets and outflows are launched we see an inversion of the material in the mid-plane and the material above and below the disc. At time 2000 yr we see the material further away from the mid-plane has greater Keplerian velocity compared to that in the mid-plane. This is showing the infall of material along the mid-plane, while the material further away from the disc is leaving via outflows.

In *Tight Binary* (Figure 2.6) and *Wide Binary* (Figure 2.7) a dense bar forms


 Figure 2.6: Same as Figure 2.5, but for *Tight Binary*.

due to our strong density perturbations similar to the bar fragmentation described by Machida et al. (2004) and Machida et al. (2005). Along this dense bar two sink particles form to create the binary systems that we analyse here.

In *Tight Binary* (Figure 2.6) we see that the particles form and fall in along the dense stream. As the sink particles orbit each other, tendrils of material are flung away from the binary. At time 1000 yr the dense material nearest the sink particles is Keplerian in an elliptical disc extending to ~ 15 AU. The material in the streams is near Keplerian indicating that the mass is accreted onto the binary tangentially. The region outside the inner disc, barring the streams, is severely sub-Keplerian. At time 2000 yr the Keplerian to near super-Keplerian region has extended outwards

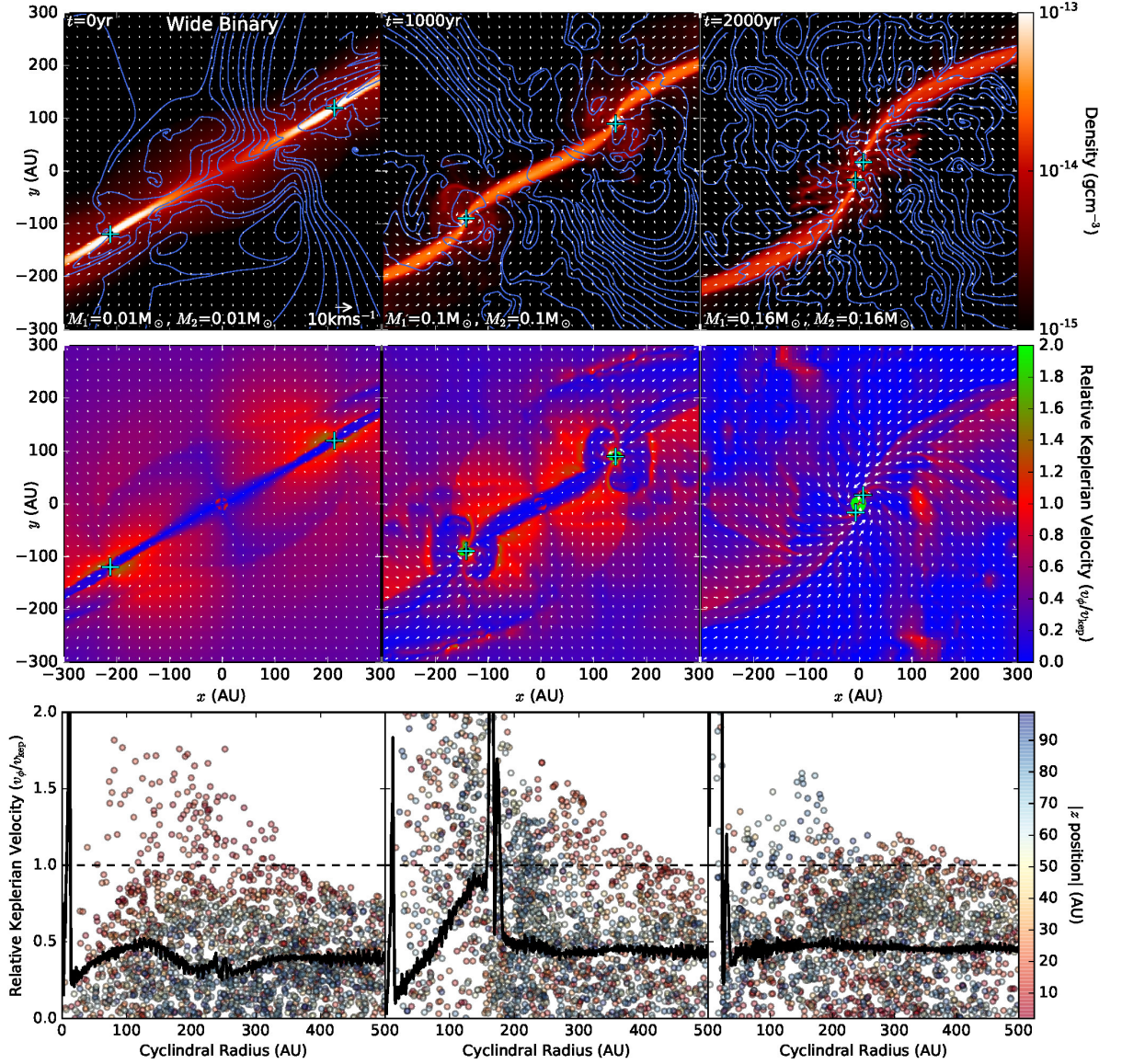


Figure 2.7: Same as Figure 2.5, but for *Wide Binary* zoomed-out to capture both sink particles.

to ~ 50 AU. This region does not correlate with any near-uniform density region, therefore it is difficult to determine whether a disc has been established.

In *Tight Binary*, when the sink particles initially form, the magnetic field is predominantly perpendicular to the dense stream. When the sink particles have established a steady binary, we see that the magnetic field also coils around the binary system like that seen in *Single Star*.

The profile plot of the *Tight Binary* does not show a gradient between material in the mid-plane, and above and below the disc. At time = 0 yr the material above and below the disc (blue scatter points) is predominantly sub-Keplerian. This indicates infall of material onto the disc.

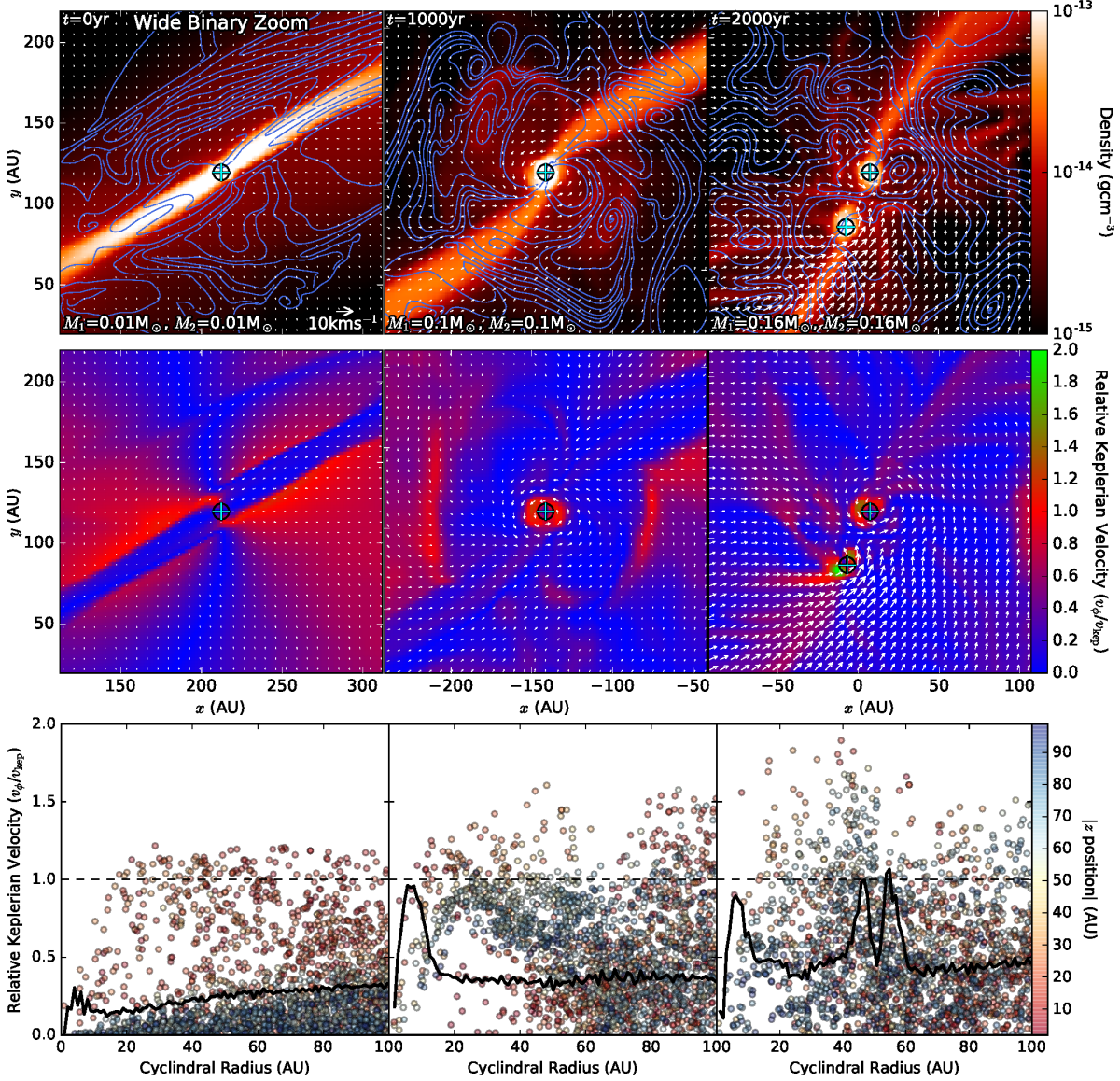


Figure 2.8: Same as Figure 2.5 for *Wide Binary*, but centred on one sink particle.

In *Wide Binary* (Figure 2.7) the sink particles form and fall in along a dense stream as in *Tight Binary*. As the sink particles fall towards each other we see dense discs near the particles. These discs are confirmed in the zoomed in relative Keplerian velocity plot shown in Figure 2.8, with the disc extending to ~ 10 AU. In Figure 2.8 the relative Keplerian velocity that is plotting in the second row is calculated just around the particle that the plots are centred on. These circumstellar discs are disrupted when the sink particles first pass by each other. Over the course of the *Wide Binary* evolution the magnetic field remains mostly random and disorganised. The streams that the sink particles fall along are severely sub-Keplerian similar to *Tight Binary*.

2.5 Discussion

2.5.1 Jet launching mechanisms

Here we look at the outflow morphology and magnetic field structure to discuss how the outflows are launched in our three simulations.

From *Single Star* we see one strong jet being produced. In *Tight Binary* we also get one jet being produced. Blandford & Payne (1982) describe magnetocentrifugally driven winds from protoplanetary discs which requires the winding up of magnetic fields around the protostar. In the top row of Figure 2.5 and in the first panel of Figure 2.9 we see that the magnetic field lines are tightly wound about the sink particle at times 1000 yr and 2000 yr. This suggests that this outflow is magnetocentrifugally driven. We also believe that the outflow from the *Tight Binary* is driven in the same way. In the top row of Figure 2.6 we also see that the magnetic field does wind around the binary system at time 1000 yr and 2000 yr, but not as tightly as *Single Star*.

The magnetic field structure in the *Wide Binary* is mostly disorganised compared to the other two cases. We do not see in Figure 2.7 large-scale winding up of the magnetic field that would indicate the presence of a circumbinary disc. However, *Wide Binary* does have individual circumstellar discs which launch individual jets as seen in Figure 2.2. If the outflows from these individual discs are launched by the same mechanism that launches the outflows of the other two cases, we would expect greater launching velocities. But this scenario has the lowest outflow velocities.

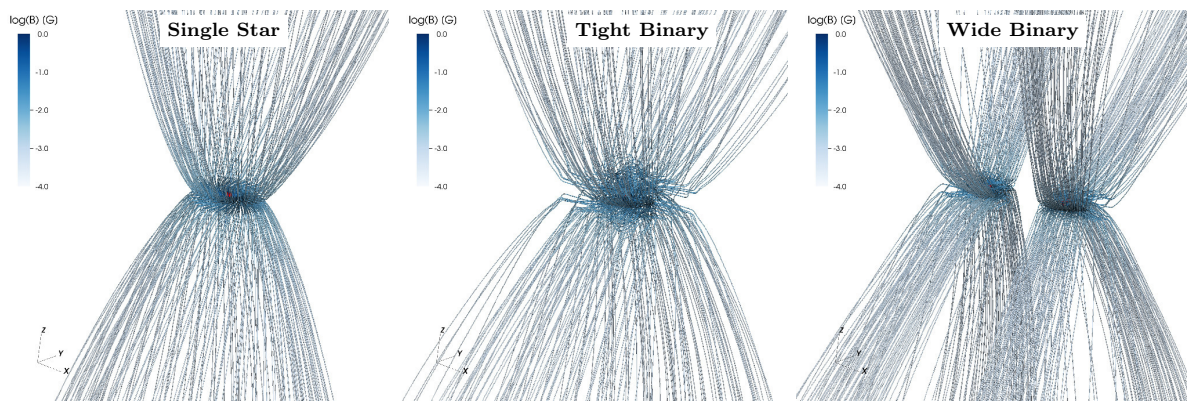


Figure 2.9: 3D streamline plots of the magnetic field structure around *Single Star* (left), *Tight Binary* (middle) and *Wide Binary* (right). The colour bar shows the magnitude of the magnetic field.

Lynden-Bell (2003) describes outflows launched due to magnetic pressure gradients. Magnetocentrifugally driven outflows also require a magnetic pressure gradient which is provided by the tight winding of magnetic fields in the disc creating a denser magnetic field. Because we do not see the winding up of the magnetic fields around the individual sink particles in *Wide Binary* in Figure 2.8, we suggest that the outflows are launched from a general magnetic pressure gradient, weaker than that produced by the other two cases.

A stronger force due to the magnetic pressure gradient compared to the gravitational force is an indication of the strength of the outflow. To measure this for the three cases we calculate the ratio of the force due to magnetic pressure and the gravitational force in a cylindrical measuring volume of radius 25 AU centred on a sink particle, extending to 1000 AU above and below the disc. The direction of the acceleration is naturally in the opposite direction to the pressure gradient, which in our case is away from the disc. The magnetic pressure described by Equation 2.6 gives the magnetic pressure acceleration to be:

$$\ddot{z}_{\text{mag}} = -\frac{1}{8\pi\rho} \frac{d|\mathbf{B}|^2}{dz}, \quad (2.15)$$

where $\ddot{z}, \rho, |B|$ is acceleration in the z -direction, mass density and magnitude of the magnetic field. The gravitational acceleration is given by:

$$\ddot{z}_{\text{grav}} = -\frac{GM_{\text{enc}}}{z^2}, \quad (2.16)$$

where M_{enc} is the enclosed mass. In our case the enclosed mass is calculated in spherical coordinates centred on the centre of mass.

The acceleration is calculated in 1000 bins along the z axis. The force is then calculated using $F = m\ddot{z}$, where m is the mass in the bin. The ratio of the magnetic force to the gravitational force for the three cases at time 0 yr, 500 yr, 1000 yr and 2000 yr is shown in Figure 2.10. We see that *Single Star* has the largest force ratios near the disc. *Tight Binary* and *Wide Binary* have weaker force ratios. In each case we see spikes in the ratio that occur at greater distances from the disc at later times. These spikes in the force ratio are following the shock fronts of jets.

The ratio of the magnetic force to the gravitational force provides information on the velocity of the outflows but says little about the morphology of the outflows.

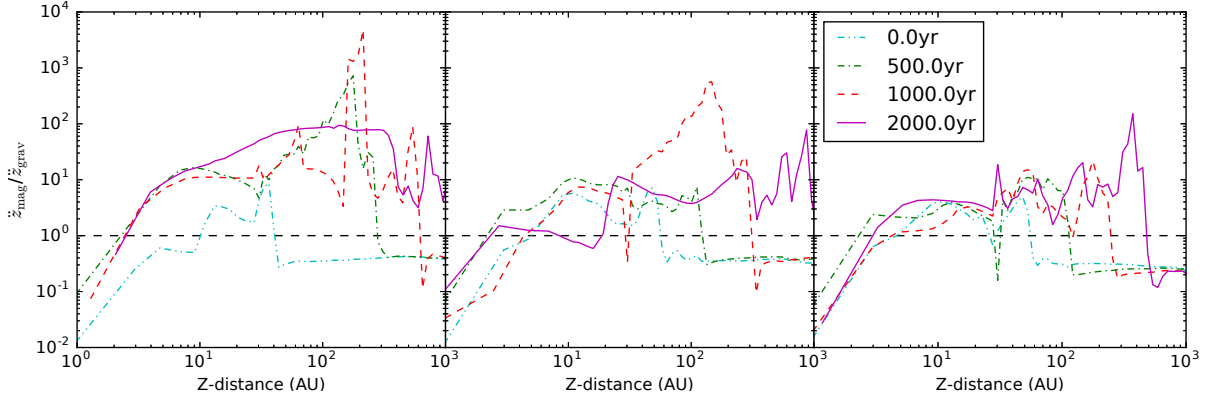


Figure 2.10: Ratio of the acceleration due to magnetic pressure and gravitational potential for *Single Star* (left), *Tight Binary* (middle) and *Wide Binary* (right) at times 0 yr (dash-dash-dot cyan line), 500 yr (dash-dot green line), 1000 yr (dashed red line) and 2000 yr (solid purple line) after sink particle formation.

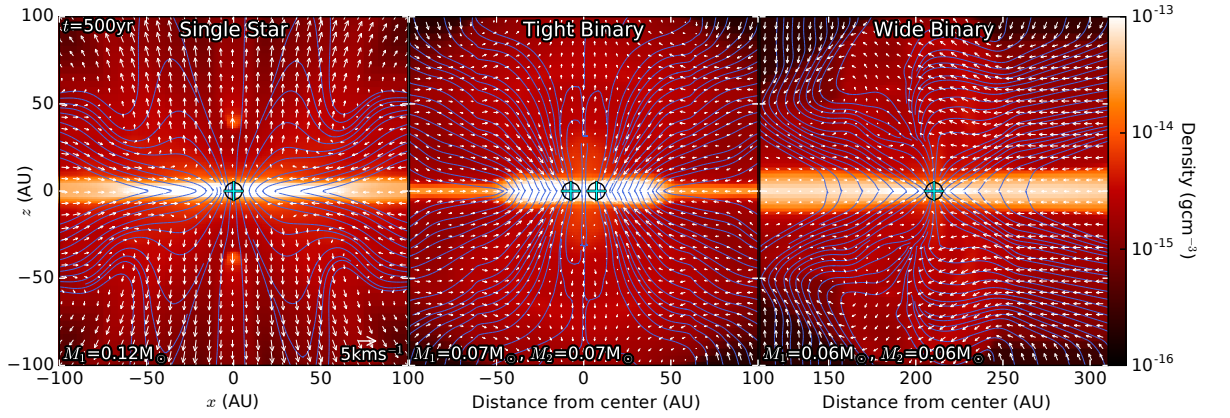


Figure 2.11: Zoomed in plots of the slices of Figure 2.2 at time 500 yr after sink particle formation.

In Figure 2.11 we show zoomed-in side-on plots of the three simulations at time $t = 500$ yr soon after outflows are beginning to be launched. The zoom in of *Single Star* and *Tight Binary* are centred on the centre of the simulation domain, while the zoom in of *Wide Binary* is centred on one of the sink particles. We see in *Single Star* and *Tight Binary* that the magnetic field structure is symmetric about the rotation axis, while *Wide Binary* is asymmetric with a magnetic field density gradient from larger radii to smaller radii. The symmetry of the magnetic field in *Single Star* and *Tight Binary* likely contribute to the symmetry of the outflow. From Figure 2.2 we see that the velocity of the outflows are skewed towards the rotation axis of the system. This may be due to the magnetic field gradient seen across the sink particle pushing the outflows towards the rotation axis.

From these results we conclude that the structure of the magnetic fields contributes significantly to the symmetry and morphology of the outflows. The varying ratio of the magnetic force to the gravitational force between the three cases also support our hypothesis about the magnetocentrifugal launching produces a stronger magnetic pressure gradient, leading to a greater acceleration of the outflows.

2.5.2 Caveats

Numerical resolution

In Appendix A we show the results of our resolution study. Federrath et al. (2014) find that fully converged values require a level of refinement of $L \gtrsim 17$ for a computational domain the same size as that used in our simulations (giving the highest resolution cells a length of $\Delta x = 0.06$ AU). A level of refinement of 17 is very computationally intensive, therefore we used a lower level of refinement. The primary goal of this paper is to relatively compare our three scenarios, therefore we are not concerned about being fully converged.

We use a level of refinement of $L = 12$, which gives the smallest cell size to be ~ 1.95 AU. This causes some issues resolving structure near the sink particles. In *Tight Binary* we only discuss outflows originating from the circumbinary disc. This is because our simulations could not fully resolve individual circumstellar discs around the sink particles. Following the results of Artymowicz & Lubow (1994), if *Tight Binary* had individual circumstellar discs they would be no larger than 1 AU in radius.

Using a higher level of refinement would allow us to resolve the structure nearest to the sink particles in the disc and would lead to resolving greater launching velocities of the outflow.

Radiation effects

We do not explicitly calculate radiative transfer in our simulations, however the equation of state that we use approximates some of these radiative effects on the local cell scale as described in Section 2.3.1.

Radiative feedback is most important when considering massive stars and their radiation driven winds as well as accretion heating. Kuiper et al. (2016) find that radiative feedback is reduced when the protostar initially forms with low luminosity

and when outflows clear bipolar cavities. However, Stamatellos et al. (2012) ran smoothed particle hydrodynamic (SPH) simulations of episodic accretion onto low-mass stars with radiative feedback and found that fragmentation of the disc was suppressed. However, provided there was sufficient time between accretion events (≥ 1000 yr) and a low quiescent accretion rate ($\sim 10^{-7} M_{\odot} \text{ yr}^{-1}$) the discs could fragment to produce companions.

There have been plenty of previous simulations concerning binary star formation that have included radiative transfer and feedback (Offner et al. 2010; Bate 2012; Bunttemeyer et al. 2016; Kuiper et al. 2016). Offner et al. (2010) found that the inclusion of radiative transfer in the flux-limited diffusion approximation in hydrodynamic simulations leads to binary stars forming predominantly from core fragmentation rather than disc instabilities. Our initial conditions are designed such that our binary star systems form from core fragmentation, in agreement with the results of Offner et al. (2010). Bate (2012) ran radiation hydrodynamical simulations of star cluster formation and conclude the main physical processes involved in determining the properties of multiple stellar systems are gravity and gas dynamics.

There have already been works considering both radiative feedback and ideal MHD mostly concerning cluster formation (Offner et al. 2009; Price & Bate 2009; Myers et al. 2013, 2014; Krumholz et al. 2016). These works found that radiation mainly contributed to the suppression of fragmentation of the cloud. Bate (2012) and Krumholz et al. (2016) found that radiation greatly hindered the formation of brown dwarfs of $\sim 0.01 M_{\odot}$. This is because the surrounding material is likely to be accreted as thermal pressure in the vicinity of the protostar prevents further fragmentation. This could also contribute to why low-mass binary star systems are less common than high-mass binary star systems.

Overall the effect that radiative feedback may have on our simulations is that it would help suppress fragmentation. The effects should be investigated in future work.

Non-ideal MHD effects

Non-ideal MHD effects are most important where partial ionisation fractions would occur such as in protoplanetary discs. The non-ideal effects of Ohmic resistivity, the Hall effect and ambipolar diffusion are important at ~ 1.5 , $2-3$ and ≥ 3 scaleheights

respectively (Wardle 2007; Salmeron & Wardle 2008; Königl & Salmeron 2011). At greater scaleheights the surface layers of discs are expected to be ionized by stellar radiation in the FUV and the ideal MHD limit is a reasonable approximation (Perez-Becker & Chiang 2011).

These non-ideal MHD effects on star formation have been studied in detail (Duffin & Pudritz 2008, 2009; Gressel et al. 2015; Wurster et al. 2016; Bai & Stone 2017; Wurster et al. 2017). Wurster et al. (2016) conducted a comprehensive study of individual non-ideal MHD effects on the collapse of cloud cores with SPH. Ohmic resistivity had no major effect on the morphology of the outflows or size of the protoplanetary disc. The Hall effect allowed for a jet component to form, but suppressed the formation of a disc if the initial angular momentum vector ($\mathbf{L}_0$) and the magnetic field ($\mathbf{B}_0$) were aligned ($\mathbf{L}_0 \cdot \mathbf{B}_0 > 0$). However, if $\mathbf{L}_0 \cdot \mathbf{B}_0 < 0$ the formation of an outflow was suppressed in their simulations, but a large disc was established. Ambipolar diffusion created a less dense jet and disc component, and changed the shape of the jet’s head compared to the ideal MHD case. In the case including all non-ideal MHD effects, for $\mathbf{L}_0 \cdot \mathbf{B}_0 > 0$ (like that in our simulations) their simulations created a less dense jet and disc because ambipolar diffusion was the most dominant non-ideal MHD effect. This is likely because the regions where ambipolar diffusion is most important (large heights from the disc mid-plane) are the most resolved in these simulations. This is supported by Gressel et al. (2015) who also found that ambipolar diffusion contributed the most to the outflows in their disc simulations which included Ohmic resistivity and ambipolar diffusion. The simulations of Gressel et al. (2015) with only Ohmic resistivity produced results similar to ideal MHD.

There has already been some work looking at non-ideal effects specifically on binary star formation. Machida et al. (2009) looked at the influence of Ohmic resistivity on outflows from the circumbinary disc around a tight $\sim 5\text{--}10$ AU binary. They found that Ohmic resistivity weakens the magnetic field strength near the protobinary but accumulated in the circumbinary disc where they are launched. Duffin & Pudritz (2009) and Wurster et al. (2017) found that these effects do not have significant impact on the overall early evolution of the binary stars. Wurster et al. (2017) found that when Ohmic resistivity, the Hall effect and ambipolar diffusion

were all included in their simulations of binary star formation, more massive discs were formed and the binary forms on a wider orbit. They also found that non-ideal MHD effects were amplified by the binary interaction near periastron, but overall non-ideal effects have little influence on binary formation and the initial conditions played the dominant role.

Our work does not consider non-ideal MHD effects because we are mainly concerned with the comparison between the formation of a single star and binary stars. Given the results of previous studies on binary star formation and outflows produced from accretion discs, the relative differences between *Single Star*, *Tight Binary* and *Wide Binary* determined here, are not expected to change significantly with the inclusion of non-ideal MHD effects. The relative differences between these cases are not expected to change significantly with the inclusion of non-ideal MHD effects.

2.6 Summary and conclusion

We ran and analysed MHD simulations of the formation of a single star, a tight binary and wide binary star system. We quantified the accretion, the outflow mass, momentum and angular momentum as well as the morphology of the outflows in these three simulation cases. We find the following main results.

Outflow Morphology: Our simulations produce jets and outflows not only from our single star case (as shown in previous simulations), but also from both our binary star cases. *Single Star* and *Tight Binary* produce a single jet, whereas the *Wide Binary* simulation produces two distinct outflows. The morphology of the *Single Star* and *Tight Binary* outflows look similar apart from the *Tight Binary* having low outflow velocities (c.f. Figure 2.2).

Outflow efficiencies: The *Single Star* simulation produces outflows with the greatest efficiency in terms of transporting mass, linear momentum and angular momentum away from the sink particle and disc system. *Tight Binary* produces outflows carrying angular momentum with efficiencies that converge towards that measured in *Single Star*. *Wide Binary* has the weakest outflow efficiencies in mass, linear and angular momentum (c.f. Figure 2.3). However, as a result of having weaker efficiencies the binary star cases have accreted more mass than *Single Star* (c.f. Figure 2.4). This implies that the star formation efficiency is greater in the

binary star cases than in *Single Star*.

Launching mechanisms: Based on the winding up of magnetic fields around the sink particles in *Single Star* and *Tight Binary* we suggest that the outflows are launched via a magnetocentrifugal mechanism. The magnetic field winding up in the circumbinary disc in *Tight Binary* leads to the production of only one jet from this system. By contrast, the structure of the magnetic field in *Wide Binary* is disorganised, not showing the strong evidence of winding up seen in the other two cases. As a result we suggest the outflows in *Wide Binary* are launched by a general magnetic pressure gradient (c.f. Figures 2.5–2.8).

Overall, when looking at morphology of outflows a tight binary star system may look like a single protostar but the outflows are weaker and less efficient.

2.7 Acknowledgments

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3

Turbulence and disc formation in binary star systems

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3.1 Abstract

Most stars form in binaries and the evolution of their discs remains poorly understood. To shed light on this subject, we carry out 3D ideal MHD simulations with the AMR code **FLASH** of binary star formation for separations of 10 – 20 AU. We run a simulation with no initial turbulence (NT), and two with turbulent Mach numbers of $\mathcal{M} = \sigma_v/c_s = 0.1$ and 0.2 (T1 and T2) for 5000 yr after protostar formation. By the end of the simulations the circumbinary discs in NT and T1, if any, have radii of $\lesssim 20$ AU with masses $\lesssim 0.02 M_\odot$, while T2 hosts a circumbinary disc with radius 70 – 80 AU and mass $\sim 0.12 M_\odot$. These circumbinary discs formed from the disruption of circumstellar discs which harden the binary orbit. Our simulated binaries launch large single outflows. We find that outflows of NT carry the most mass, and linear and angular momentum from the system. T2 produces the least efficient outflows concerning mass, momentum and angular momentum (~ 61 per cent, ~ 71 per cent, ~ 68 per cent of the respective quantities in NT). We conclude that while

turbulence helps to build circumbinary discs which leads to the restructuring of magnetic fields for efficient outflow launching, too much turbulence may disrupt the ordered magnetic field structure required for magneto-centrifugal launching of jets. We conclude that the role of turbulence in building large circumbinary discs may explain some observed very old (> 10 Myr) circumbinary discs. The longer lifetime of circumbinary discs may increase the likelihood of planet formation.

3.2 Introduction

A significant fraction of stars are born in binary star systems (Raghavan et al. 2010; Moe & Di Stefano 2017) and in the last two decades a number of planets have been discovered orbiting in binary star systems (e.g. γ Cephei Ab (Neuhäuser et al. 2007), HD 196885 Ab (Chauvin et al. 2007), Kepler-47b and c (Orosz et al. 2012), PH-1 (Schwamb et al. 2013), ROXs 42Bb (Kraus et al. 2014) and OGLE-2007-BLG-349L(AB)c (Bennett et al. 2016)). Planet formation models have historically only been concerned with formation around single stars. However, given the frequency of binary stars and the discovery of planets in binaries, this picture is insufficient. Therefore, in order to fully understand planet formation, environments around young binary stars must be considered.

Kraus et al. (2016) find that the frequency of planets orbiting in binary star systems drops for separations of $a \sim 40$ AU (Kraus et al. 2016). However, this work is based on current planet statistics and mostly concerned planets in S-Type orbits, where the planet is orbiting one component in a binary. To date, we only know of ~ 20 circumbinary planet, thus, we are not able to conduct significant studies of population statistics on these types of planets. In order to understand planet statistics around binary stars we can look at the discs from which these planets would form.

Multiplicity may affect the disc lifetime and as a result can also affect the likelihood of planet formation. The presence of a companion can truncate circumstellar discs leading to the disc material being accreted faster, on the order of ~ 0.3 Myr (Williams & Cieza 2011). A shorter circumstellar disc lifetime is implied by binaries of separation < 40 AU being half as likely to host circumprimary/circumsecondary discs than binaries with separations $40 - 400$ AU (Cieza et al. 2009; Duchêne 2010;

Kraus et al. 2012), and by close binaries having less sub/millimetre flux due to the absence of an inner disc (Jensen et al. 1994, 1996; Andrews & Williams 2005).

Harris et al. (2012) and Cox et al. (2017) also found that circumstellar discs in binaries produced faint millimetre flux suggesting they are relatively small. However, they also observed circumbinary discs produced at least an order of magnitude higher millimetre flux densities compared to circumstellar discs around binaries of the same separation. This implies that circumbinary discs are larger and have more material than circumstellar discs in similar binaries to form planets. There also exist circumbinary discs that are considerably older than the typical lifetime of protoplanetary discs of ~ 3 Myr (Haisch et al. 2001; Mamajek 2009). Examples include AK Sco (18 ± 1 Myr, Czekala et al. 2015), HD 98800 B (10 ± 5 Myr, Furlan et al. 2007), V4046 Sgr ($12 - 23$ Myr, Rapson et al. 2015) and St 34 (also known as HBC 425, ~ 25 Myr, Hartmann et al. 2005). If circumbinary discs have a significantly longer lifetime than discs around single stars, it would increase the likelihood of forming planets (Kuruwita et al. 2018).

The mechanisms that determine the lifetime of a disc are: 1. accretion of material, 2. jets and outflows, 3. photo-evaporation of the disc, 4. dynamical interactions. Here we investigate how turbulence influences accretion, outflows and the dynamical evolution of discs during binary star formation and evolution. The work in this paper is a continuation of the work of Kuruwita et al. (2017) which found circumstellar discs were disrupted during the evolution of a young binary star system of separation ~ 45 AU, creating a hostile environment for planet formation. In this work we add turbulence to the initial conditions, and run turbulent magnetohydrodynamical simulations of binary star formation to study the evolution of the discs in these systems.

In Section 3.3 we describe the simulation code used, how protostar formation is modelled, our simulation set-up and implementation of turbulence. The results are presented and discussed in Section 3.4, where we analyse the evolution of the binary systems, the outflows produced and the evolution of the discs. Section 3.5 discusses the limitations and caveats of this study. Our conclusions are summarised in Section 3.6.

3.3 Method

3.3.1 FLASH

The simulations are carried out with **FLASH** which is a magnetohydrodynamic (MHD) adaptive mesh refinement (AMR) code (Fryxell et al. 2000; Dubey et al. 2008). **FLASH** integrates the ideal MHD equations. We use the HLL3R Riemann solver for ideal MHD (Waagan et al. 2011). The gravitational interactions of the gas are calculated using a Poisson solver (Wünsch et al. 2018).

Our simulations use a piecewise-polytropic equation of state, given by:

$$P_{\text{th}} = K\rho^\Gamma, \quad (3.1)$$

where K is the polytropic constant and Γ is the polytropic index. For our simulations Γ is defined to be:

$$\Gamma = \begin{cases} 1.0 & \text{for } \rho \leq \rho_1 \equiv 2.50 \times 10^{-16} \text{ g cm}^{-3}, \\ 1.1 & \text{for } \rho_1 < \rho \leq \rho_2 \equiv 3.84 \times 10^{-13} \text{ g cm}^{-3}, \\ 1.4 & \text{for } \rho_2 < \rho \leq \rho_3 \equiv 3.84 \times 10^{-8} \text{ g cm}^{-3}, \\ 1.1 & \text{for } \rho_3 < \rho \leq \rho_4 \equiv 3.84 \times 10^{-3} \text{ g cm}^{-3}, \\ 5/3 & \text{for } \rho > \rho_4. \end{cases} \quad (3.2)$$

These values were determined by radiation-hydrodynamical simulations of molecular core collapse by Masunaga & Inutsuka (2000). These values of Γ approximate the gas behaviour during the initial isothermal collapse of the molecular core, adiabatic heating of the first core, the H_2 dissociation during the second collapse into the second core and the return to adiabatic heating.

The formation of sink particles indicates the formation of a protostar (Federrath et al. 2010, 2011, 2014). A second-order leapfrog integrator is used to update the particle positions using a velocity and acceleration to calculate a variable time step. To prevent artificial precession of the sink particles a sub-cycling method is implemented (Federrath et al. 2010). The interactions between sink particles and the gas are computed using N -body integration.

For further details about **FLASH** and sink particles, refer to Kuruwita et al. (2017)

and references therein.

3.3.2 Simulation setup

The simulations methods are identical to Kuruwita et al. (2017), except for adding turbulence (see details in Equation (3.3)). Here we only summarise the main elements of the method and refer the reader to Kuruwita et al. (2017) for the details. We simulate the formation of a binary star with turbulence and without turbulence for comparison of outflow quantities and evolution of environment around the protostars.

The size of the computational domain is $L_{\text{box}} = 1.2 \times 10^{17} \text{ cm}$ ($\sim 8000 \text{ AU}$) along each side of the 3D computational domain. On the highest level of refinement of the AMR grid the resolution is $\sim 1.95 \text{ AU}$. At this resolution the accretion radius of the sink particles is $r_{\text{sink}} \sim 4.9 \text{ AU}$.

Our simulations begin with a spherical cloud of mass $1 M_{\odot}$, and radius $\sim 3300 \text{ AU}$ placed in the centre of the simulation domain. In the non-turbulent case the cloud is given solid body rotation with angular momentum of $1.85 \times 10^{51} \text{ g cm}^2 \text{ s}^{-1}$. With this angular momentum, the product of the angular frequency and the free-fall time of the cloud is $\Omega \times t_{\text{ff}} = 0.2$ (see Banerjee & Pudritz (2006) and Machida et al. (2008)). A magnetic field of 10^{-6} G is also threaded through the cloud in the z -direction. This gives a mass-to-flux ratio of $(M/\Phi)/(M/\Phi)_{\text{crit}} = 5.2$ where the critical mass-to-flux ratio is $487 \text{ g cm}^{-2} \text{ G}^{-1}$ as defined in Mouschovias & Spitzer (1976).

The cloud is initially given a uniform density of $\rho_0 = 3.82 \times 10^{-18} \text{ g cm}^{-3}$ and then a density perturbation is imposed on the cloud. This is to seed the formation of a binary star system. Previous works of multiple star formation from a single molecular core suggest that cloud fragmentation is a more likely pathway of multiple star formation rather than disc fragmentation (Offner et al. 2010). This is due to radiation feedback increasing the Jeans length within discs, suppressing fragmentation. Our initial conditions are designed such that our binary star systems form from core fragmentation in agreement with previous results. The density perturbation in our simulations is described by:

$$\rho = \rho_0(1 + \alpha_p \cos\phi), \quad (3.3)$$

Simulation name	σ_v (km s ⁻¹)	$\mathcal{M}$	E_{turb} (erg)
NT	0.0	0.0	0.0
T1	0.02	0.1	4.0×10^{39}
T2	0.04	0.2	1.6×10^{40}

Table 3.1: Summarises the simulations. The left column gives the simulation name. The right column gives the amount of initial turbulence (σ_v) as described by Equation 3.4.

where ϕ is the angle about the z -axis and α_p is the amplitude of the perturbation. For our simulations $\alpha_p = 0.50$. This perturbation is a standard method of seeding binary star formation within simulations of molecular cores (Boss & Bodenheimer 1979; Bate & Burkert 1997).

In order to prevent the cloud from expanding rapidly, the spherical cloud is in pressure equilibrium with the surrounding material. This is set by giving the surrounding material a gas density of $\rho_0/100$ with an internal energy such that the cloud and surrounding material is in pressure equilibrium. Inflow/outflow boundary conditions are used at the edge of our computational domain.

Adding turbulence

Stars form in turbulent cores inside molecular clouds (Ferrière 2001; Mac Low & Klessen 2004; Padoan et al. 2014). In order to simulate this effect, we add turbulence to the initial conditions of our cores. The purpose of this work is to investigate the role of turbulence on disc evolution during binary star formation. Therefore to isolate the effect of turbulence all simulations in this work have the same initial conditions bar the level of turbulence introduced to the initial velocity field of the cloud.

For our simulations we derive a ball-park value for the velocity dispersion by setting the turbulent energy to a fraction of the rotational energy. The turbulent energy is given by the following:

$$E_{turb} = \frac{1}{2} M \sigma_v^2, \quad (3.4)$$

where M is the initial mass of our cloud i.e. $1 M_\odot$ and σ_v is the velocity dispersion. The initial rotational energy of the cloud in our simulations is $E_{rot} = 3.4 \times 10^{40}$ erg. Here we study $\sigma_v = 0, 0.02$ and 0.04 km s^{-1} or Mach 0.0, 0.1, and 0.2

which corresponds to $E_{turb}/E_{rot} = 0.0, \sim 0.12$ and ~ 0.46 . This is consistent with mild, subsonic levels of turbulence expected to be present in star-forming cores and discs. Hereafter, the simulations with turbulence of $\mathcal{M} = 0.0, 0.1$ and 0.2 are referred to as NT, T1 and T2 respectively. The simulations are summarised in Table 3.1.

The mixture of solenoidal and compressible modes is set such that the velocity field only contains solenoidal modes initially, i.e., the velocity field is divergence-free (Federrath et al. 2010). The spectrum of initial turbulent velocities follows a Kolmogorov (1941) spectrum with a spectral slope of $k^{-5/3}$ (this is the expected power-law slope for the mildly compressible regime of turbulence relevant here; see Federrath (2013)), populated in the wavenumber range $k = [2, 20]$, where k is in units of $2\pi/L_{\text{box}}$.

The random seed for the turbulence is the same for all simulations. The turbulence is not driven in our simulations, it is only applied to the initial velocity field of the gas during the set-up.

3.4 Results and discussion

Our simulations were run and we followed the system evolution. Side-on and top-down slices of the resulting simulations are shown in Figure 3.1 and Figure 3.2. Figure 3.1 shows side-on gas density slices of thickness 300 AU at 1000 yr intervals since the formation of the first sink particle. Figure 3.2 shows top-down gas density slices of thickness 100 AU at 1000 yr intervals since the formation of the first sink particle. The orientation of the side-on slices in Figure 3.1 is aligned along the dense accretion streams we see in Figure 3.2.

3.4.1 Time evolution of the binary star system

As the simulations progress, the spherical cloud collapses and sink particles are created in collapsing regions (c.f. Section 3.3.1). Sink particles form at separations between 400 – 500 AU and fall towards the centre of the initial dense core as shown in Figure 3.2 and the top plot of Figure 3.3. The initial separation and delay between the formation of the first and second sink particle is dependent upon the strength of the turbulence of the initial velocity field (c.f. Equation (3.3)). In the non-turbulent NT simulation the sink particles form sooner and at the same time because the

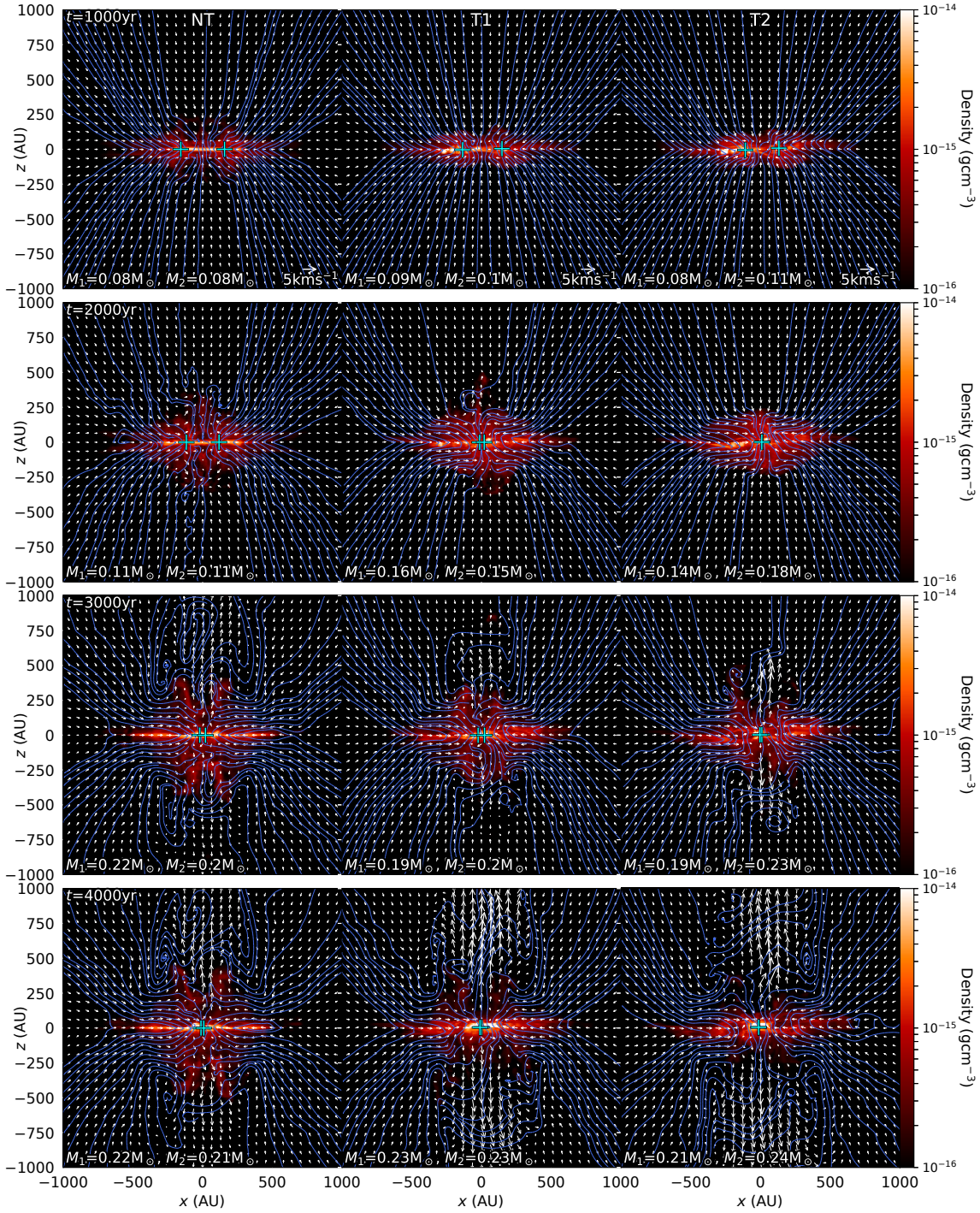


Figure 3.1: 300 AU thick volume-weighted slices orientated along the dense accretion streams such that the slice captures the dense material and two sink particles for NT (left), T1 (middle) and T2 (right). Each row progresses at 1000 yr intervals since the first protostar formation. The thin lines show the magnetic field, and the arrows indicate the velocity field. Crosses show the position of the sink particles. The mass accreted by the sink particles in the simulations is indicated on the bottom left of each panel.

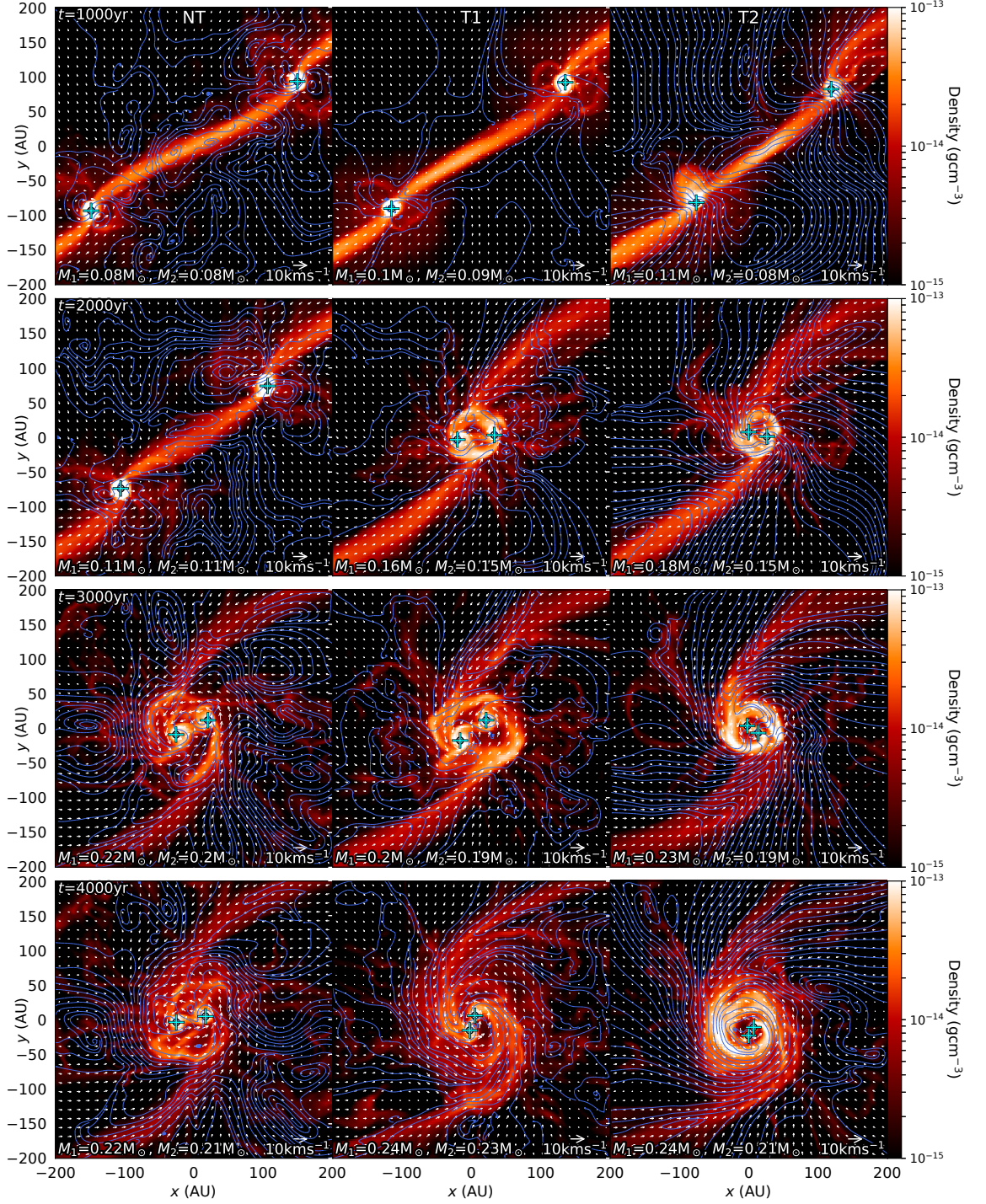


Figure 3.2: Same as Figure 3.1, but for 100 AU thick slices along the $z = 0$ plane of the simulation box.

density perturbation is symmetric. In T1 and T2, the turbulence washes out some of the initial $m=2$ density perturbation (refer to α_p in Equation 3.3) and the sink particles form at later absolute simulation times as a result. The turbulence in T1 and T2 also introduces asymmetries to the initial density perturbation creating a delay between the formation of the sink particles, producing binary systems with unequal mass components. The stronger the turbulence the greater the delay between formation of the sink particles. Our binary systems are evolved for 5000 yr after formation of the first sink particle. This ensured that the binary was able to complete many orbits to form an established binary system of semi-major axis between $\sim 10 - 20$ AU. The dashed line in Figure 3.3 (top panel) indicates the accretion radius of our sink particles (which is $r_{\text{sink}} = 4.9$ AU) to demonstrate that the separation of the binaries is not limited by numerical resolution. The binary systems begin to establish their orbits approximately ~ 2000 yr after the formation of the first sink particle in all cases. We see that T2 has fully circularised approximately ~ 4000 yr after the first sink particle formation, while in NT and T1, circularisation is still ongoing after 5000 yr. This orbital shrinkage after protostar formation has also been seen in other MHD simulations of binary star formation and is caused by magnetic braking of the infalling gas (Zhao & Li 2013).

As the binary evolves the sink particles accrete mass. The bottom panel of Figure 3.3 shows the mass accreted by the sink particles in our three simulations. The thick solid lines show the total accreted mass and the mass of the individual sink particles is indicated by the thin transparent lines. The mass ratio ($M_{\text{secondary}}/M_{\text{primary}}$) is lowest for the most turbulent simulation. This is primarily due to the time delay between the formation of each component. We see that the turbulent cases have a greater star formation efficiency (fraction of accreted mass) than NT at all times, but the amount of accreted mass does not vary significantly. 5000 yr after sink particle formation, T1 and T2 have respectively accreted $\sim 8\%$ and 3% more mass than NT. We cannot predict the final mass of the stars, because it is impossible to run these simulations until the stars stop accreting mass, due to the limited amount of compute time currently available.

Initially the accretion rate is very high, but steadily falls over the course of our simulations. All simulations show episodes of increased accretion rate around

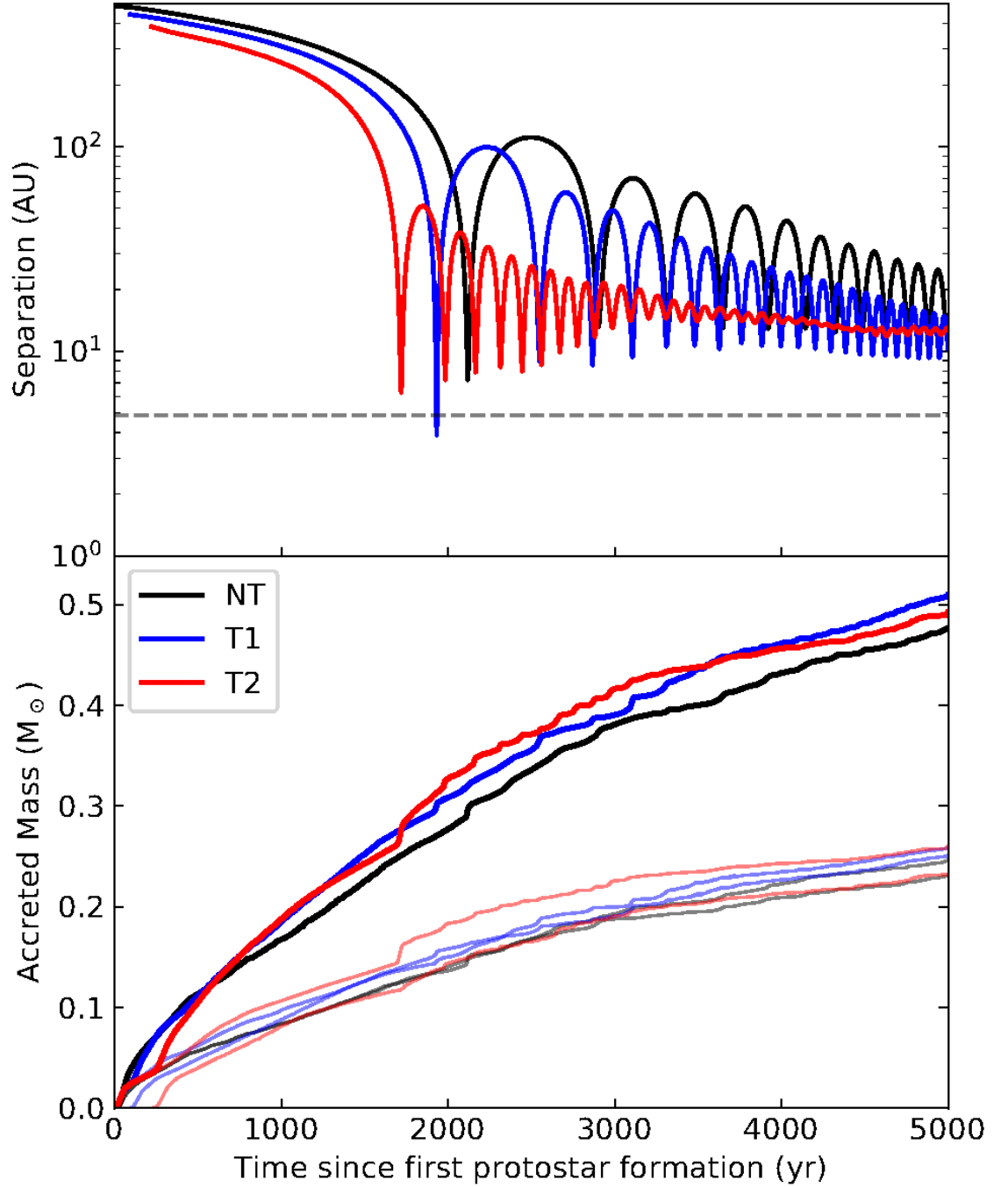


Figure 3.3: Shows the evolution of the binary separation (top), and accreted mass (bottom) since protostar formation of the first sink particle for the NT, T1 and T2 cases in black, blue and red respectively. In the plot of the accreted mass, the transparent thin lines trace the mass of the individual components and the thick opaque lines trace the total accreted mass.

the first few periastron passages. This supports the binary trigger hypothesis for accretion events leading to FU Ori type outbursts (Green et al. 2016; Tofflemire et al. 2017).

The accretion rate of NT decreases significantly after the third periastron passage at ~ 3000 yr. We see from Figure 3.2 that the circumstellar discs of NT are heavily disrupted and are smaller at times after 3000 yr. The circumstellar discs help funnel gas onto the sink particles. Because these discs are disrupted, the accretion rate onto the sink particles is reduced.

In contrast, we also see the average accretion rate of T2 decreases at approximately the time when the binary system has circularised between 3000 – 4000 yr. We see from Figure 3.2 that for T2, a dense circumbinary disc is building up and the magnetic field is coiling up in this disc, while a cavity appears to open near the binary stars at times after 3000 yr. The establishment of the circumbinary disc helps circularise the binary system by removing angular momentum from the binary orbit and transporting it through the disc. The reduced eccentricity of the orbit also means the cross-section in which mass must exist to be accreted is reduced. The low density of material near the sink particles at later times also affects the accretion rate.

We now turn to analysing the properties of the outflows/jets launched from these binary-star systems.

3.4.2 Morphology of outflows and launching mechanism

Figure 3.1 qualitatively shows the outflow morphology in the three cases. In NT the outflows from the sinks are launched at the same time and remain symmetric over the course of the simulation. T1 produces asymmetric outflows because the turbulence induces asymmetric density perturbations. There is even greater delay between the formation of the first and second sink particle in T2, however in this case we do not see jets from the individual sink particles. This may be due to the stronger turbulence creating an unordered magnetic field reducing the magnetic pressure gradient required for efficient launching.

Individual jets from young proto-binaries have been observed, such as L1551 IRS5 (Wu et al. 2009). The morphology of the outflows from this system is similar

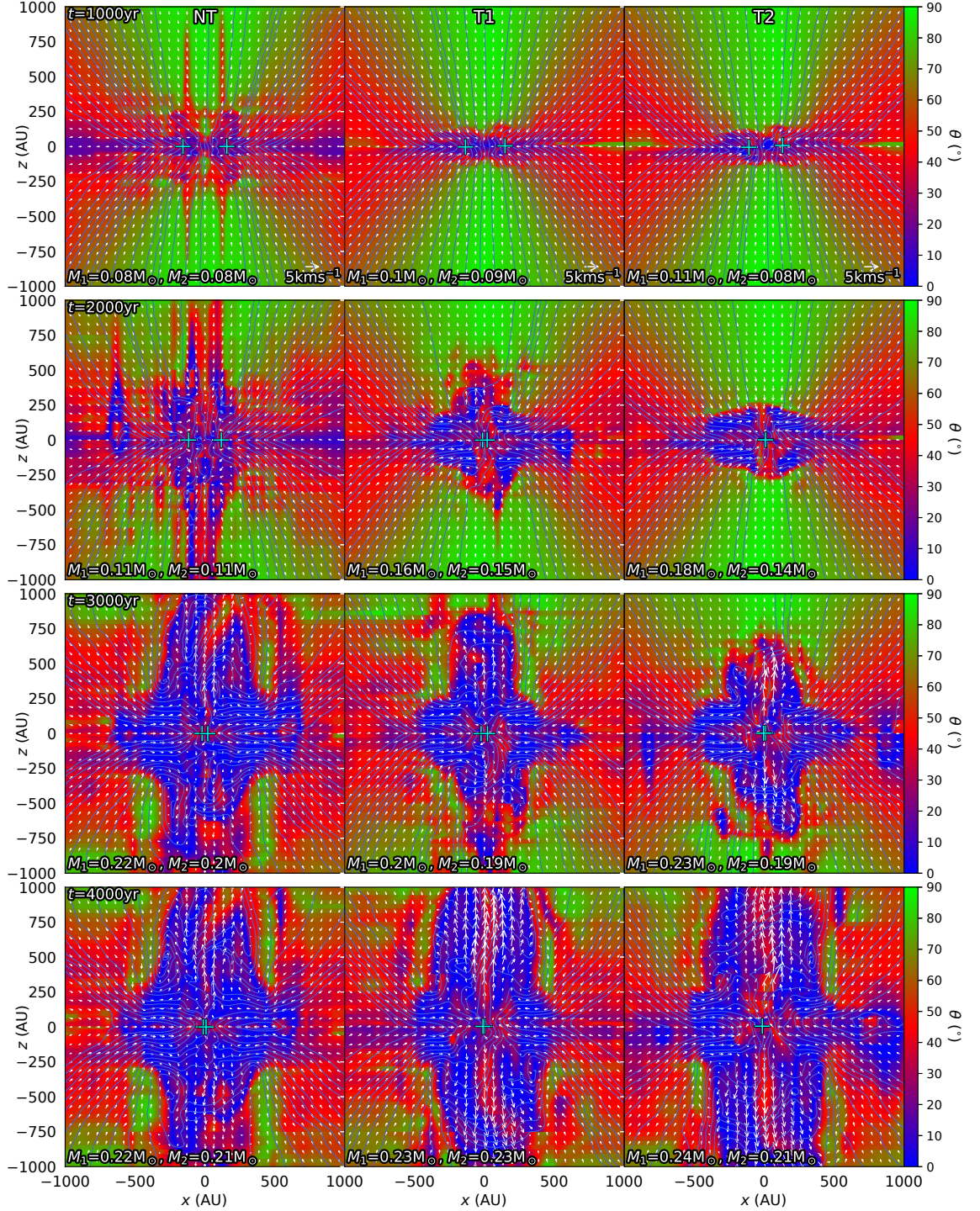


Figure 3.4: Same as Figure 3.1, but shows volume-weighted slices of the magnetic field angle to the xy -plane.

to those produced by the NT and T1 cases. The duration of the individual jets from our simulations depends on the separation and coalescence time of the binary star system. The duration of the individual jets in our simulations is of the order of 1000 – 2000 yr. The L1551 IRS5 system has a separation of ~ 42 AU (Bieging & Cohen 1985) which is 2–3 times larger than the binaries produced in our simulations. This system could be in-spiralling and the duration of these individual outflows is also limited by the time taken for the circumstellar discs to be disrupted by dynamical interactions. The duration of these individual outflows can be assumed to depend on the separation of the binary system and the detection of these double outflows can help trace recent binary star formation. However, binaries formed in more turbulent environments may be harder to detect in the early stages of formation as individual jets are not produced as shown by T2. This would mean that binary star formation in very turbulent environments can be obscured from observations.

In all cases, once the binary has been established after many orbits the system produces a single outflow. The speed of the outflows increases at later times, with the more turbulent cases producing greater bulk outflow speeds.

Based on the magnetic field structure in the simulations we attribute the driving force of the outflows to the magneto-centrifugal mechanism. Blandford & Payne (1982) calculated that gas can be launched centrifugally along magnetic field lines if the poloidal component of the magnetic field (B_{pol}) subtends an angle of less than 60° from the disc surface. Once an outflow is launched, the toroidal component of the magnetic field (B_{tor}) becomes important and collimates the outflow. To test this we calculate both the angle of the magnetic field to the xy -plane (θ) and the ratio of the poloidal to toroidal magnetic field components. Slices of the magnetic field angle and the poloidal to toroidal ratio are shown in Figures 3.4 and 3.5.

From Figure 3.4 we see at early times the magnetic field angle is shallow in the mid-plane ($< 30^\circ$) and is steep away from the disc ($> 60^\circ$). As the simulations progress the transition region where the magnetic field angle transitions from $> 60^\circ$ to $< 60^\circ$ follows the outflow fronts seen in Figure 3.1. From Figure 3.5 we also see at early time the poloidal component dominates the magnetic field structure. However, at later times after the outflows are launched, we find that the toroidal component grows and begins to dominate the magnetic field around the outflows.

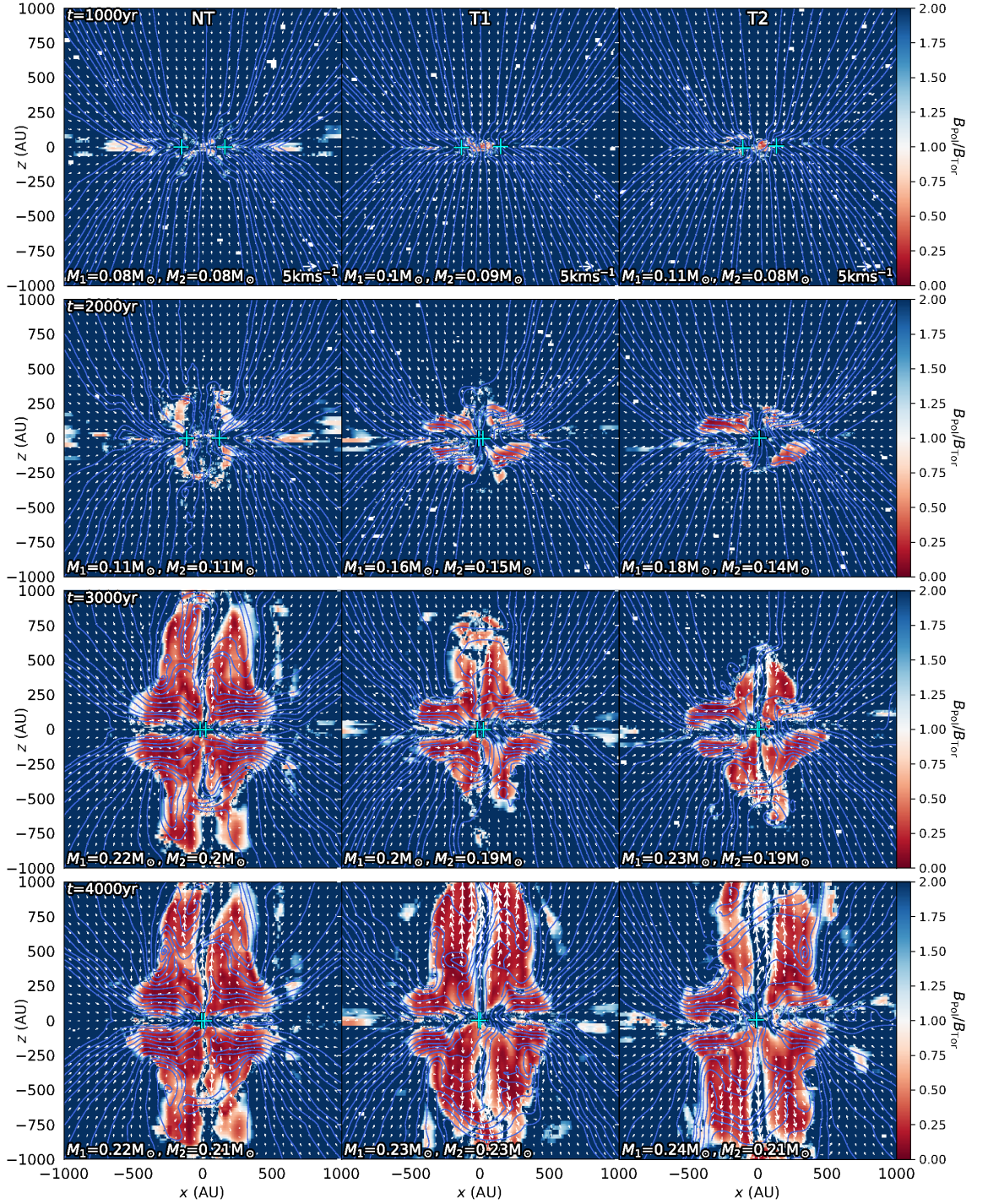


Figure 3.5: Same as Figure 3.1, but shows volume-weighted slices of the ratio of the poloidal component (B_{pol}) to the toroidal component (B_{tor}) of the magnetic field.

It is this toroidal field that collimates the outflows. We also see that the poloidal field is the primary component in the disc mid-plane. These results indicate that these outflows are launched via the magneto-centrifugal mechanism and are in line with other simulations that also show this (Banerjee & Pudritz 2006).

3.4.3 Measurement of the outflows

Mass, momentum, and angular momentum can be carried away from protostellar systems via outflows. Here we measure these outflow quantities in our three scenarios to determine how turbulence may affect outflows from young binary star systems.

The scale height of the discs is approximately $z_H \approx 25$ AU in the non-turbulent case. Analysis of the outflows from the systems is carried out by measuring the outflowing mass within two measuring cylinders placed above and below the $z = 0$ plane. The face of the cylinder nearest the discs is placed $|z| \geq 4z_H = 100$ AU from the $z = 0$ plane. This height is selected to capture the outflow material, while avoiding measuring turbulent material in the warped discs in T1 and T2. The radius and height of the measuring cylinders is 500 and 3300 AU, respectively, to capture and track outflowing material. Within the measuring regions outflow mass is defined as any mass in cells with $v_z > 0$ for $z > 0$ and $v_z < 0$ for $z < 0$. From the outflow mass, the angular momentum and linear momentum of the outflows is calculated, as well as the maximum outflow speed. The linear momentum is calculated from the magnitude of the velocity from the centre of mass and the outflow mass. The angular momentum is calculated about the centre of mass of the systems.

The outflow measurements of the three cases is shown in Figure 3.6. Most of the measured quantities reach a plateau as the quantity flowing into the measuring volumes is equal to the amount of the quantity leaving the volumes. From Figure 3.6 we see that the outflows of NT reach the measuring volume the fastest. This is also confirmed in the bottom plot of Figure 3.6 where NT has the highest initial outflow velocity. While these curves shown in Figure 3.6 illustrate the rate at which these quantities are carried in the outflows, to compare the overall outflow efficiency of these quantities we calculate the time averaged values of the quantity using:

$$\langle q \rangle = \frac{\int_0^T q(t) dt}{\int_0^T dt}, \quad (3.5)$$

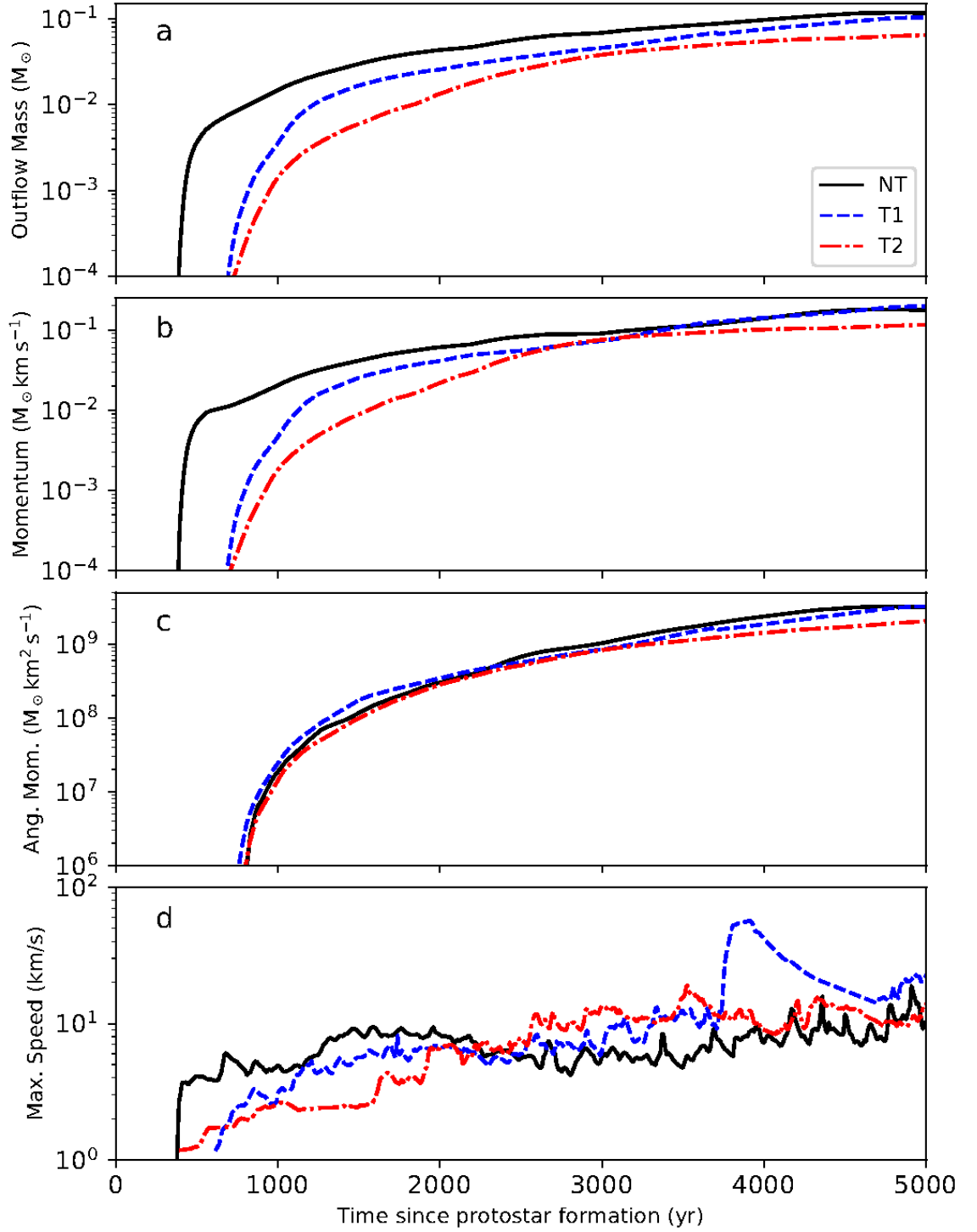


Figure 3.6: Time evolution of the outflow quantities measured from cylinders of radius 500 AU and height 500 AU placed at 100 AU above and below the disc $z = 0$ plane. Panel a: outflowing mass, defined as mass within cells with v_z away from the disc. Panel b: linear momentum of the outflowing gas. Panel c: angular momentum of the outflowing gas calculated around the centre of mass of the system. Panel d: the speed of the cell with the maximum speed within the measuring volume.

where q is mass, linear momentum, and angular momentum, and $T = 5000$ yr.

Panel a of Figure 3.6 shows the mass carried in the outflows. We see that NT is the most efficient at transporting mass via outflows and T2 is the least efficient. T1 falls between the other two cases with respect to the outflow mass. The time averaged values of the outflow mass for T1 and T2 are $\sim 90\%$ and $\sim 61\%$ of NT, respectively.

Initially the outflow of NT carries the greatest linear momentum. This is mostly due to having the most massive outflows and faster outflow velocities. However, at later times T1 converges towards NT. This may be due to increased outflow velocities. The outflows of T2 carry the least amount of linear momentum over the course of the entire simulation due to having the least massive outflows and have lower outflow velocities. The time averaged values of the linear momentum carried in the outflows for T1 and T2 are $\sim 111\%$ and $\sim 71\%$ of NT, respectively.

All the simulations show similar outflow behaviours for angular momentum. The time averaged values of the angular momentum carried in the outflows for T1 and T2 are $\sim 102\%$ and $\sim 68\%$ of NT, respectively.

The maximum outflow varies between the three cases. In NT the maximum outflow speed remains relatively steady over the course of the entire simulation, sitting at the level of $3 - 10 \text{ km s}^{-1}$. There are bursts in the outflow velocity for NT which happen around the time of periastron passage as seen in Figure 3.3. The maximum outflow velocity of T1 grows to a steady state by ~ 1000 yr, with speeds in the same range as the NT case. At ~ 3800 yr there is a sharp rise in the outflow velocity. From Figure 3.2, between times 3000 and 4000 yr, we see that the magnetic field structure in T1 has become mostly organised, coiling around the binary. This ordering of the magnetic field is also tied with the establishment of a circumbinary disc. We conclude the increased outflow velocity of T1 is due to this building-up of a circumbinary disc which then leads to the restructuring of the magnetic field to allow for efficient launching of outflows. In T2 the outflow velocities grow slowly before reaching a steady state at ~ 3000 yr. From Figure 3.2, we see that the building of a circumbinary disc begins at earlier times for T2, with an extensive disc already visible at ~ 3000 yr.

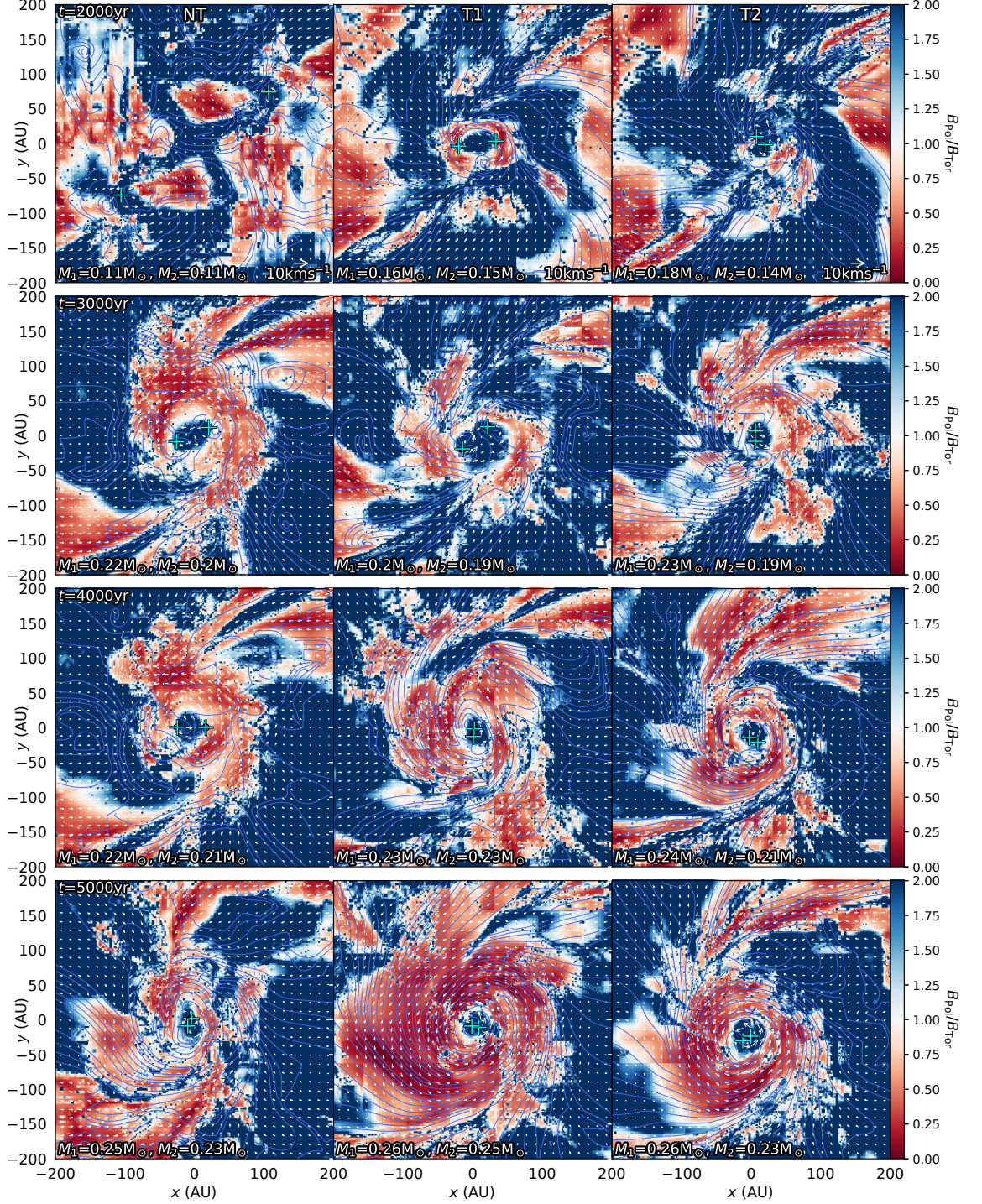


Figure 3.7: Same as Figure 3.2, but shows volume-weighted slices of the ratio of the poloidal component (B_{pol}) to the toroidal component (B_{tor}) of the magnetic field.

3.4.4 Disc structure

We see from Figure 3.2 that all the cases have the sink particles form and fall in along dense streams. As the sink particles fall towards each other we see dense circumstellar discs near the stars. As the binary systems in all the cases pass periastron the circumstellar discs are disrupted. As the circumstellar discs are disrupted, material is thrown outwards. Over the course of our simulations the turbulent cases appear to establish a large circumbinary disc. We see from Figure 3.2 at later times (≥ 3000 yr) that the turbulent simulations show the strong coiling of the magnetic field around the binary system as well as a dense circumbinary disc. The circumbinary disc is denser in T2 than in T1. The non-turbulent case does not appear to establish a circumbinary disc over the course of our simulation however, it might do so at later stages. As discussed in the previous section, the turbulence makes the disc more coherent. The formation of the disc restructures the magnetic field which then leads to the magnetic field also becoming more coherent. In Figure 3.7 we show the ratio of the poloidal component to the toroidal component of the magnetic field for times 2000, 3000, 4000 and 5000 yr. As the simulations progress we see that the toroidal component dominates within the disc. The poloidal component seen at the mid-plane in Figure 3.5 is a result of the toroidal field changing direction. The size of the cavity that is predominately the poloidal component is approximately twice that of the binary star separation. The poloidal component is necessary for efficient launching of outflows and a strong toroidal component is needed for collimating the launched outflows via the magneto-centrifugal mechanism (Blandford & Payne 1982).

We determine how the relative Keplerian velocity of these circumbinary discs evolve to see if near-rotationally supported discs are created and how turbulence may influence this evolution. Rotationally supported gas discs can rotate at slightly sub-Keplerian velocities as the gas pressure contributes to supporting the disc against rapid infall (Adachi et al. 1976; Weidenschilling 1977). Studying the velocity structure throughout the discs provides details on mass transport around the forming binary star systems.

In Figures 3.8, 3.9 and 3.10 we present 200 AU thick volume-weighted projections along the $z = 0$ plane of the gas discs of the density and density-weighted for the

relative Keplerian velocity for our three simulations at 1000 yr intervals. We also show density-weighted radial profiles of the relative Keplerian velocity. The relative Keplerian velocity (v_{rel}) is:

$$v_{\text{rel}} = \frac{v_{\phi}}{v_{\text{kep}}}, \quad (3.6)$$

where v_{ϕ} is the tangential velocity to the radial direction and v_{kep} is the Keplerian velocity, given by:

$$v_{\text{kep}} = \sqrt{-\Phi_{\text{tot}}}, \quad (3.7)$$

where Φ_{tot} is the total gravitational potential, i.e. the potential from the gas and the sink particles.

The density-weighted profiles (solid black line in bottom panel of Figures 3.8, 3.9 and 3.10) are calculated over a cylinder of radius 150 AU and height 200 AU centred on the centre of mass of the systems. The normal vector to this measuring cylinder is the angular momentum vector of the gas in the simulation domain. As most of the gas is within the discs this vector is perpendicular to the plane of the discs. 2 AU cylindrical radius bins are used to produce these profiles. Along with the radial profile, randomly selected cells are plotted to show any variation in relative Keplerian velocity perpendicular to the disc.

In NT (Figure 3.8), the evolution of the system is messy despite having no initial turbulence. At 2000 yr after formation of the first sink particle, the two stars have not passed the first periastron and they maintain their own circumstellar discs. At later times as the two stars interact, their circumstellar discs are disrupted and matter is ejected from the discs during the interaction. At time 5000 yr there is some circumbinary material that could hint at the formation of a circumbinary disc, however, only a very small one at this stage.

In the density projections, we clearly see that the magnetic field is disorganised at time 2000 yr, but it begins to coil around the binary as the system evolves.

In the relative Keplerian velocity projections, we see most of the material in the vicinity is sub-Keplerian with a few patches of near Keplerian gas. The structure of the Keplerian material does not appear to follow the density structure closely.

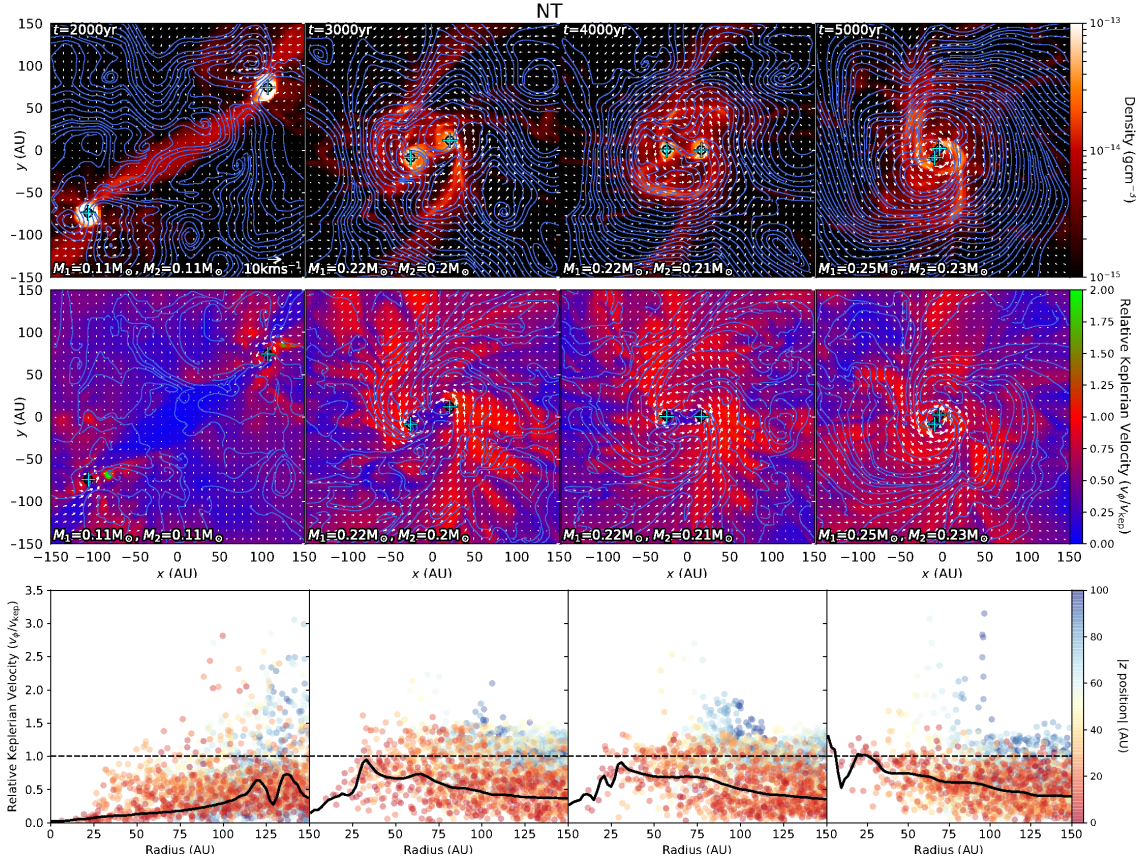


Figure 3.8: Top and middle: 200 AU thick volume-weighted projection plots of density and density-weighted projection plots of relative Keplerian velocity (described by Equation 3.6) for NT. The thin lines show the magnetic field, and the arrows indicate the velocity field. The centre of the cross marks the position of the sink particle, and the black circle marks the accretion radius of the particle. Bottom: The solid black line is the density-weighted radial profile of the relative Keplerian velocity for a cylindrical volume of radius 150 AU and thickness 200 AU centred on the centre of mass. The points are randomly selected cells in the volume at various distances from the $z = 0$ plane. Each column progresses at steps of 1000 yr. The black dashed line highlights where material is Keplerian.

The density-weighted profile plot from time 3000 and 4000 yr show the velocity structure of the gas after the binary has completed a few orbits. At these times we see that the density-weighted profile is mostly sub-Keplerian, demonstrating that material is still in-falling. The material closest to the mid-plane (the red scatter points) is very sub-Keplerian, while material that is further away from the mid-plane (the blue scatter points) is more Keplerian to super-Keplerian. This is demonstrating the building up of the circumbinary environment by showing that gas falls into the system along the mid-plane and other gas is being carried away in the outflows. At later times it appears that material is being launched at radii up to 100 AU.

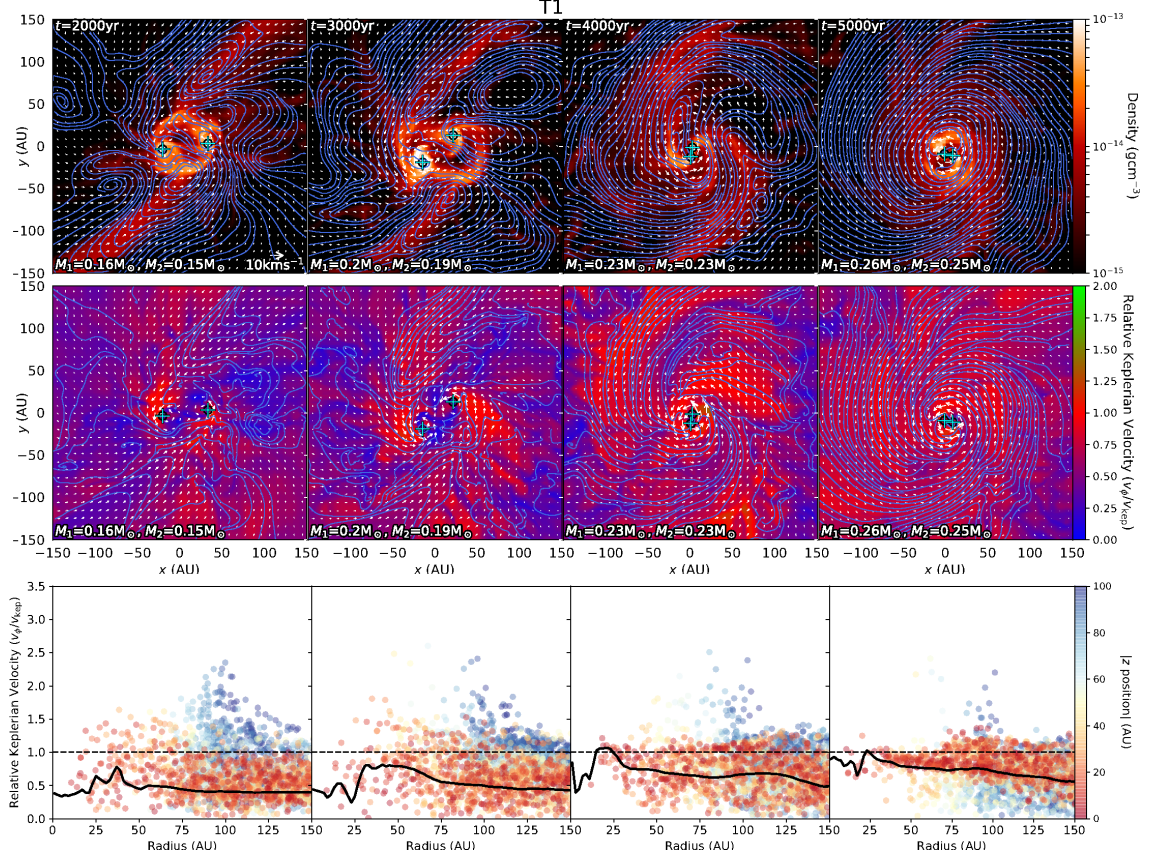


Figure 3.9: Same as Figure 3.8, but for T1.

The density-weighted profile at time 5000 yr shows that there is a Keplerian disc out to ~ 30 AU. This rotationally supported disc may grow at later times.

In T1 (Figure 3.9), the sink particles fall in towards each other faster than NT, and have already passed the first periastron by 2000 yr. As the sink particles orbit each other material is thrown outwards and a circumbinary disc is beginning to build up at around 4000 yr. By 5000 yr we see a circular circumbinary disc that has been built. The evolution of the magnetic field structure in this case is more pronounced compared to NT. By 4000 yr we see the beginning of the circumbinary disc forming, and the magnetic field is orientated along the dense spiral arms that feed the disc. By 5000 yr the magnetic field has coiled around the binary system tightly. This restructuring of the magnetic field plays an important role in the magneto-centrifugal launching of outflows and in the increased outflow velocities discussed in Section 3.4.2 for the T1 case.

The relative Keplerian velocity slices for T1, like NT, show that most of the material in the vicinity of the stars is sub-Keplerian with a few patches of near

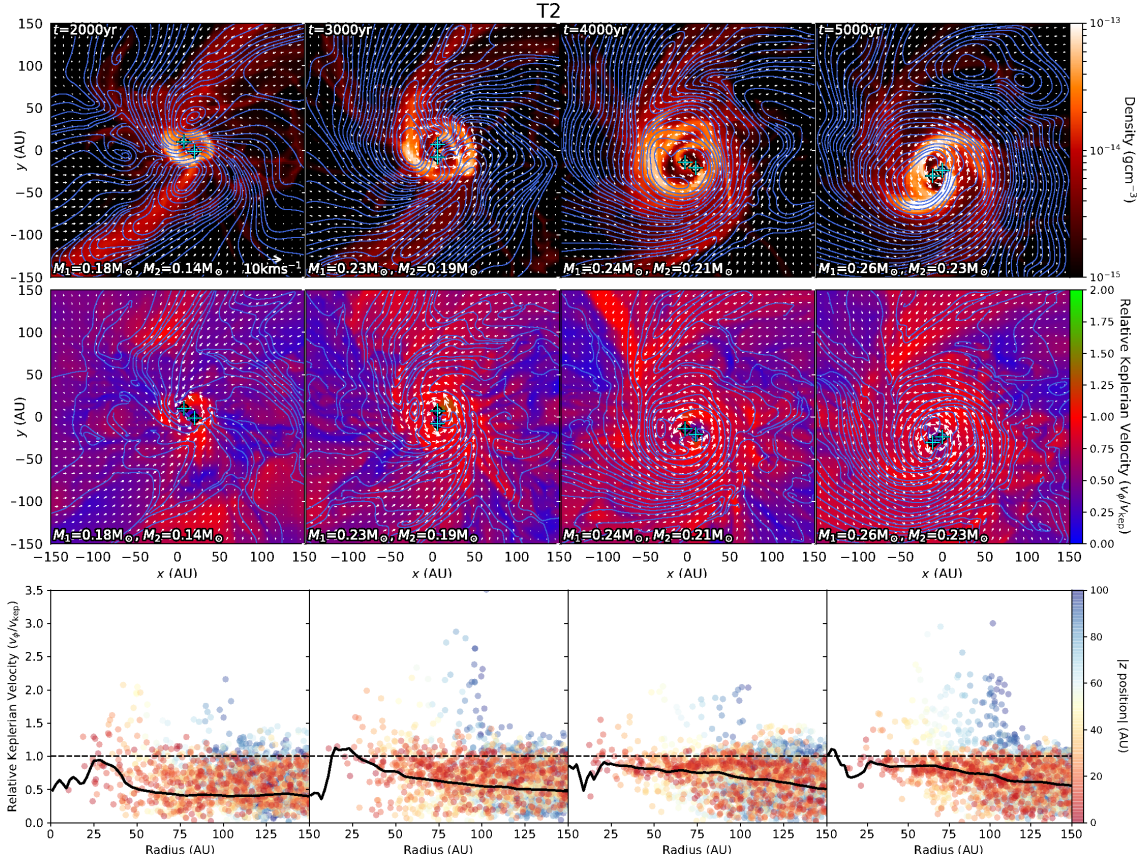


Figure 3.10: Same as Figure 3.8, but for T2.

Keplerian gas at times before the establishment of the circumbinary disc. However at later times we see at large radii the denser material is very sub-Keplerian, and the gas in the disc is near Keplerian.

The density-weighted profiles for T1 begin sub-Keplerian and grow towards being near Keplerian. We see a gradient between sub-Keplerian mid-plane gas and Keplerian to super-Keplerian gas at larger $|z|$, similar to the NT case at these same times. At time 5000 yr, the gas near the mid-plane is clustered near Keplerian out to ~ 80 AU. This is also the extent to which the circumbinary disc can be seen. Like NT, we see that material is being launched at radii up to 100 AU.

In T2 (Figure 3.10), the circumbinary disc begins forming at earlier times compared to the other two cases. At time 3000 yr, we see that a circumbinary disc has formed and continues to grow over the course of the simulation. We also see that the magnetic field coils about the binary system, but not as tightly as that seen in T1.

The density-weighted profiles for T2 follow the same trends as the other two

cases. We see at later times that the mid-plane gas is sub-Keplerian to near Keplerian, and gas at large heights becomes more super-Keplerian. From the profile plot, the mostly Keplerian mid-plane extended to 80 – 100 AU. Also like the previous cases we see material being launched at radii up to 100 AU.

Measuring disc sizes

To compare the extent of circumbinary material we calculated radial profiles of the volume-weighted density, H₂ column density and cumulative gas mass shown in Figure 3.11. Density profiles are shown for 1000 yr intervals since 2000 yr after the formation of the first sink particle for our three cases. The measuring volume used to calculate the density profiles is the same used to calculate the relative Keplerian velocity profiles shown in Figures 3.8, 3.9 and 3.10.

From the overall shapes of the density profiles we see that the circumbinary material of NT does not show any significant growth over the course of the simulation after 3000 yr. In T1 within 80 AU the disc size oscillates, growing larger or smaller between the times plotted. Beyond 80 AU we see that the density of the material oscillates out of phase to the growing and shrinking seen within 80 AU. This behaviour may hint at bulk movement of material at larger radii falling inwards. T2 is the only simulation that shows a clear inside-out growth of the circumbinary material, with the disc size steadily growing over the course of the simulation.

We also calculated H₂ column density radial profiles to produce quantities measurable by observations. These are shown in the middle panels of Figure 3.11. The H₂ column density radial profiles are calculated from projection plots with the same thickness as the measuring volume used to calculate the relative Keplerian velocity and density profiles. The column density profiles also include the contribution of material above and below the bulk disc material (within ± 100 AU), which would also add to the line-of-sight density observed.

NT shows little growth after 3000 yr, similar to what is shown by the density profiles. In T1, the column density increases between 2000 and 3000 yr, but then proceeds to decrease over the rest of the simulations. From Figure 3.6 it was between 3000 and 4000 yr that the outflow velocities increase suddenly for T1. It is also between these times that we see the greatest decrease in column density. This is likely due to the increased outflow velocities suddenly clearing a cavity, reducing the

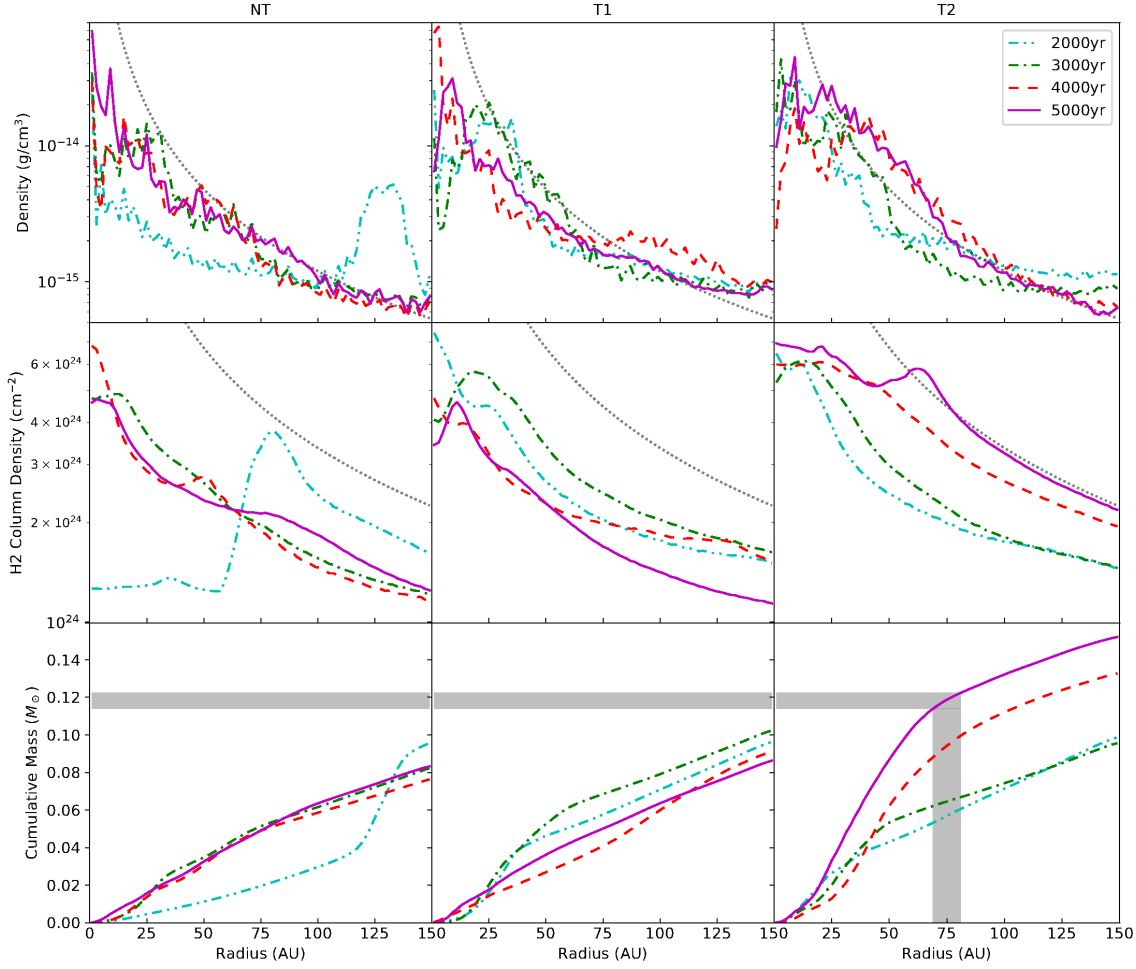


Figure 3.11: Radial profiles of the volume-weighted mean gas density (top), integrated H2 column density (middle), as well as the cumulative gas mass (bottom) for the NT case (left), T1 case (middle) and T2 case (right) at times 2000 yr (dash-dash-dot cyan line), 3000 yr (dash-dot green line), 4000 yr (dashed red line) and 5000 yr (solid purple line) after sink particle formation. The dotted grey line in the top and middle panels highlight a r^{-2} and r^{-1} drop off in density and column density respectively. The grey region highlights the approximate radius and mass of the circumbinary disc in T2

column density. T2 is the only simulation that shows a clear inside-out growth in the column density of the circumbinary material, much like that seen in the density profiles. In the inner ~ 75 AU we see perturbations (clumps, asymmetries) in the density / column density. These are the most prominent in the T2 case for the column density profile at 5000 yr where profile shows many features before dropping off beyond 75 AU. Features like these seen in observations can be indicative of turbulence producing rings, spiral arms and other disc characteristics (Hull et al. 2017; Avenhaus et al. 2018; Cox et al. 2018; Esplin et al. 2018; Sanna et al. 2018; Tychoniec et al. 2018).

Determining the extent of the circumbinary disc is ambiguous, therefore in this work we look at the shape of the density and column density profiles. We approximate the disc radii to be where the profiles turn from showing features to dropping off smoothly with either a r^{-2} profile for the density or r^{-1} profile for the column density as seen in observations (Avenhaus et al. 2018). Such power laws are indicated in Figure 3.11 by the dotted grey lines in the top and middle panels. From this we estimate the radii of the circumbinary discs at time 5000 yr to be $\lesssim 20$ AU, for NT and T1, and ~ 70 -80 AU for T2.

In order to estimate the mass of the circumbinary discs we have also calculated cumulative gas mass profiles, shown in the bottom panel of Figure 3.11. From these profiles, at the radii estimated above, we find the circumbinary disc masses to be $\lesssim 0.02 M_{\odot}$ for NT and T1, and $\sim 0.12 M_{\odot}$ for T2. The cumulative mass profiles show the same evolution described by the other profiles above.

Figures 3.2, 3.9 and 3.10 also shows that at later times a minor inner hole in the circumbinary disc has been cleared by the binaries in the turbulent cases. The size of these inner holes is smaller or comparable in size to the semi-major axis of the binaries given by Figure 3.3. This does not follow the prescription of Artymowicz & Lubow (1994) who find the inner disc location to fall between $1.8a - 2.6a$, where a is the semi-major axis of the binary system. However these discs are still in the very early stages of formation.

3.5 Limitations and caveats

3.5.1 Numerical resolution

The level of refinement used in our simulations does not resolve the regions closest to the actual protostar where high velocity outflows are launched. In our work, the resolution on the highest level of refinement ($L = 12$) produces a cell size of $\Delta x \sim 1.95$ AU. Federrath et al. (2014) find that to have fully converged results for a simulation box size the same as that used in our work requires a level of refinement of $L = 17$. This level of refinement produces cell sizes of $\Delta x = 0.06$ AU. Running simulations with this level of refinement is very computationally intensive and impractical. This is the motivation for using $L = 12$ for our work, as the primary goal is to compare relatively the influence of turbulence on binary star evolution.

Kuruwita et al. (2017) find using a level of refinement of $L = 12$ is enough to resolve the larger scale outflows, while also allowing the simulations to evolve for a long time.

The evolution of accretion and the disc formation process is also sensitive to the initial and boundary conditions (Machida et al. 2014; Kuffmeier et al. 2017, 2018). Machida et al. (2014) find that the initial density distribution can affect the disc sized up to an order of magnitude. This was tested with a uniform density sphere and Bonner-Ebert profile. Kuffmeier et al. (2017, 2018) also find from zoom-in simulations that the density of the surrounding medium can affect the infall and accretion of the forming protostars. As our work is concerned with the relative influence of turbulence on the evolution of discs in binaries, our results would not vary significantly as the initial and boundary conditions are consistent between all cases.

All of the binary star systems that formed in our simulations have separations of ~ 10 -20 AU, which is resolved over ~ 5 -10 cells. Following the prescription of Artymowicz & Lubow (1994), if the sink particles host circumstellar discs, they would have a radius of ~ 5 AU. These discs would be resolved over approximately 5 cells. The contribution from these circumstellar discs is therefore, not well characterised at later times in our simulations. However, we are mostly concerned with the global evolution of these binary systems and the establishment of circumbinary discs. Using a higher level of refinement would allow us to resolve circumstellar discs around our sink particles, and understand more about their contribution to the global evolution of these binary systems.

3.5.2 Radiation effects

Our simulations do not explicitly calculate radiation transfer, however our EOS accounts for some radiative effects on the local cell scale (see section 3.3.1).

Radiation plays an important role in the initial collapse of molecular cores as it suppresses fragmentation (Krumholz et al. 2007; Offner et al. 2009; Bate 2012; Federrath et al. 2017). Fragmentation of these cloud cores is one of the pathways in which binary stars and multiple star systems may form, therefore we should consider mechanisms that can influence fragmentation. Magnetic fields can also help

suppress fragmentation by magnetically supporting the cloud (Price & Bate 2008; B urzle et al. 2011; Peters et al. 2011; Federrath & Klessen 2012; Federrath 2015, 2016). However radiation-MHD simulations such as those conducted by Myers et al. (2013), Federrath et al. (2017), and Cunningham et al. (2018) find that radiation plays the most dominant role in fragmentation suppression in molecular cores.

Another pathway in which multiple star systems may form is via gravitational instability in discs. Simulations of binary star formation via this pathway find that even in relatively massive discs ($0.22 M_{\odot}$) that once stellar cores form, the radiative feedback can suppress further disc fragmentation (Bate 2012). Despite this radiative feedback effect, Bate (2012) also conclude that gravity and gas dynamics are the main physical processes involved in determining the properties of multiple star systems.

From hydrodynamic simulations of star formation with radiative transfer in the flux-limited diffusion approximation Offner et al. (2010) found that binary stars form predominantly via core fragmentation rather than disc instabilities. Therefore, of the two competing pathways in which binary systems may form, core fragmentation seems to be the more likely.

While most work on radiation feedback has focused on massive stars, some work has been done on low-mass stars. Hansen et al. (2012) ran 3D AMR radiation hydrodynamic simulations of low-mass star formation within a turbulent molecular core. This work also found that stellar outflows dominate feedback reducing protostellar masses and accretion rates. A consequence of this is that the radiation pressure from the protostar is insignificant for low-mass stars, but radiation still suppresses fragmentation within the turbulent cloud by heating feedback.

Simulations of cluster formation incorporating both radiative feedback and ideal MHD have been carried out (Offner et al. 2009; Price & Bate 2009; Myers et al. 2013, 2014; Krumholz et al. 2016). Krumholz et al. (2016) found that the formation of brown dwarfs of $\sim 0.01 M_{\odot}$ is greatly hindered by radiation. This is because thermal pressure in the vicinity of the protostar is increased due to accretion luminosity preventing further fragmentation (Federrath et al. 2017; Guszejnov et al. 2018). This may explain why low-mass binary stars are less frequent than high-mass binary stars.

Overall the effect that radiation may have on our simulations is that it would help suppress fragmentation. We believe the inclusion of radiation would not change the results of our simulations significantly because the stars formed are low-mass. However, the influence of radiative feedback should be investigated to fully understand how the evolution of discs in binaries differs to disc evolution in single stars.

3.5.3 Non-ideal MHD effects

Non-ideal MHD effects are most important where partially ionised gas would exist such as in protoplanetary discs. The non-ideal effects are Ohmic resistivity, the Hall effect and ambipolar diffusion, and they are important at ~ 1.5 , $2 - 3$ and ≥ 3 scale heights from the disc-mid-plane respectively (Wardle 2007; Salmeron & Wardle 2008; Königl & Salmeron 2011; Tomida et al. 2015; Marchand et al. 2016). At scale heights greater than 3 the ideal MHD limit is a reasonable approximation. This is because the surface layers of discs are ionised by FUV stellar radiation (Perez-Becker & Chiang 2011).

The motivation to investigate non-ideal MHD effects on star formation is due to the magnetic breaking catastrophe, where magnetic fields are too efficient at breaking the rotation of the core in ideal MHD, suppressing the formation of circumstellar discs around young stars. Various works have found that non-ideal MHD effects can weaken the magnetic field strength and angular momentum transport helping to overcome magnetic breaking (Mellon & Li 2009; Krasnopolsky et al. 2011; Li et al. 2011; Dapp et al. 2012; Tsukamoto et al. 2015; Wurster et al. 2016; Vaytet et al. 2018; Zhao et al. 2018). Because these non-ideal effects help to remove magnetic flux, magnetically sub-critical cores are able to collapse (Machida et al. 2018). Wurster et al. (2018) also find that the inclusion of all three non-ideal MHD effects along with radiation produced longer lived hydrostatic cores and second core phases. Applying this result to our simulations would delay the formation of sink particles. Despite delaying the collapse of molecular cores, non-ideal effects are also found to not significantly change the mass and radius of the first hydrostatic cores (Masson et al. 2016).

While most work on non-ideal MHD effects on star formation has mostly focused on single stars, there has been work on binary star formation (Duffin & Pudritz

2009). Machida et al. (2009) found that Ohmic resistivity weakens the magnetic field strength near proto-binaries of separation $5 - 10$ AU, but accumulated in the circumbinary disc where they are launched. Wurster et al. (2017) found that the inclusion of Ohmic resistivity, the Hall effect and ambipolar diffusion in their simulations produced wider binaries with more massive discs. While they found that near periastron, non-ideal MHD effects were amplified, overall the initial conditions played the dominant role during binary star formation.

Our work does not consider non-ideal MHD effects because we are mainly concerned with the influence of turbulence on disc evolution in binary star systems. Given the results of previous studies on binary star formation the results of this study are not expected to change significantly with the inclusion of non-ideal MHD effects. There is numerical diffusion in our simulations which weakens the magnetic field. In the turbulent cases we see circumbinary discs building up, which implies that turbulence plays a dominant role in angular momentum transport compared to the magnetic fields. Due to this, non-ideal MHD is not expected to significantly alter our main conclusions.

3.6 Summary and conclusion

We ran and analysed MHD simulations of binary star formation with varying levels of turbulence. We quantified the accretion, the outflow mass, momentum and angular momentum as well as the morphology of the outflows in three simulation cases: no turbulence (NT), Mach 0.1 turbulence (T1) and Mach 0.2 turbulence (T2). We also determined the evolution of the discs in these systems, in particular the building up of circumbinary discs. We find the following main results.

Orbital Evolution: Turbulence produces asymmetric binaries. Stronger turbulence delays the absolute time taken for sink particles to form. This is likely due to the effective Jeans mass being greater with greater turbulence. Stronger turbulence also delays the formation of the secondary component of the binaries. The binary system formed in T2 circularises which is likely tied to the evolution of the associated circumbinary disc. While turbulence controls the star formation rate and efficiency on molecular cloud scales (Federrath & Klessen 2012; Krumholz et al. 2012; Hennebelle & Chabrier 2013; Padoan et al. 2014), we find here that it does

not significantly influence the accretion rate of the stars inside the discs. We also see evidence for episodic accretion correlated with the periastron passage of the binary components (cf. Figure 3.2 and 3).

Outflow Morphology: All our simulations produce jets and outflows. The circumstellar discs around the protostars in NT and T1 launch individual jets before the stars complete a few orbits. The protostars in the most turbulent simulation fails to launch individual jets. This is likely due to the stronger turbulence disrupting the initial magnetic field structure, therefore producing a more unordered field, which does not allow for the magneto-centrifugal mechanism to work efficiently. At later times all systems produce a single outflow with the turbulent simulations producing outflows that appear bulkier and faster (cf. Figure 3.1).

More turbulent binary star formation can fail to launch individual outflows before coalescing. This may have interesting implications for observations because outflows are used as indicators of recent protostar birth. Because turbulent systems would not produce individual jets, the formation of binary systems in turbulent environments may be obscured to observations. However, this likely depends on the initial separation of the binary. Wider separation binaries formed in turbulent environments may produce individual outflows, however, this is outside the scope of this study.

Outflow Efficiency: The non-turbulent simulation produced the most massive outflows, while the most turbulent simulation has the least massive outflows. However concerning linear and angular momentum transport, T1 produced outflow efficiencies comparable or more efficient than the non-turbulent case, while the most turbulent simulation was significantly less efficient at transporting momentum via outflows. Maximum outflow speeds remain relatively steady for the non-turbulence case, while the turbulent cases have maximum outflow speeds that grow by at least an order of magnitude over the course of the simulations (cf. Figure 3.6)

Disc Evolution: All binaries host small circumstellar discs (approximately with a radius of 10 AU) which are destroyed as the system passes periastron and reform shortly thereafter. In the non-turbulent case the circumstellar discs do not survive long and the surrounding circumbinary material is diffuse and has little structure.

In the turbulent cases the interaction of the binary stars redistributes angular momentum, such that a circumbinary disc can form faster than in the NT case. In the turbulent cases we also see that the magnetic fields coil up in the circumbinary discs (cf. Figure 3.2). This is what then primarily drives the outflows at late times. The T2 simulation produces the largest circumbinary disc (cf. Figure 3.11). The circumbinary discs produced are rotationally supported.

Overall, we find that turbulence helps to build up larger circumbinary discs, from which planets may form more easily than without the presence of turbulence.

3.7 Acknowledgements

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4

Survivability of discs in binary star systems

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4.1 Abstract

We present observations of disc-bearing stars in Upper Scorpius (US) and Upper Centaurus-Lupus (UCL) with moderate resolution spectroscopy in order to determine the influence of multiplicity on disc persistence after 5 – 20 Myr. Discs were identified using infra-red (IR) excess from the Wide-field Infra-red Survey Explorer (*WISE*) survey. Our survey consists of 55 US members and 28 UCL members, using spatial and kinematic information to assign a probability of membership. Spectra are gathered from the ANU 2.3m telescope using the Wide Field Spectrograph (WiFeS) to detect radial velocity variations that indicate the presence of a companion. We identify 2 double-lined spectroscopic binaries, both of which have strong IR excess. We find the binary fraction of disc-bearing stars in US and UCL for periods up to 20 years to be $0.06^{+0.07}_{-0.02}$ and $0.13^{+0.06}_{-0.03}$ respectively. Based on the multiplicity of field stars, we obtain an expected binary fraction of $0.12^{+0.02}_{-0.01}$. The determined binary

fractions for disc-bearing stars does not vary significantly from the field, suggesting that the overall lifetime of discs may not differ between single and binary star systems.

4.2 Introduction

In the age of *Kepler* and other planet finding surveys a number of planets have been discovered around binary star systems. Some of these planets are in S-Type orbits where the planet orbits one star in the binary system (e.g. γ Cephei Ab (Neuhäuser et al. 2007) and HD 196885 Ab (Chauvin et al. 2007)) and others are in P-Type, or circumbinary orbits, where the planet orbits both stars (e.g. Kepler-47b and c (Orosz et al. 2012), PH-1 (Schwamb et al. 2013) and ROXs 42Bb (Kraus et al. 2014)). When considering planet formation, current models mostly focus on single star systems. This picture is, however, insufficient, given that a large fraction of stars are in binary star systems (Raghavan et al. 2010) and therefore a complete understanding of planet formation must take these environments into account.

Current planet occurrence rates around binary stars show that the frequency drops for systems with separations $a \sim 40$ AU (Kraus et al. 2016), which might indicate that it is difficult for planets to form around binaries of this separation. Could this be because the disc material from which the planets would form is destroyed faster in binary star systems than around single stars? There are various mechanisms that contribute to the dispersal of protoplanetary discs such as accretion, photoevaporation, and outflows. How these mechanisms change and affect the discs in binary star systems has been investigated using simulations (e.g. Artymowicz & Lubow 1994; Kuruwita et al. 2017) which find that circumstellar discs are truncated to $r_{disc} \sim a/3$ and outflows from binary star systems are less efficient at carrying away mass and momentum compared to single star counterparts.

Harris et al. (2012) and Cox et al. (2017) found that circumstellar discs in binaries were smaller and fainter, suggesting that they may be dispersed faster. On the surface it seems that discs have a shorter lifetime around stars in binary systems, and as a result shorten the time in which planets may form. However, they also found that circumbinary discs have at least an order of magnitude higher millimetre flux densities compared to circumstellar discs around binaries of the same separation,

suggesting they are larger and have more material in the circumbinary disc to form planets. There is also a handful of other considerably old circumbinary discs (e.g. AK Sco (18 ± 1 Myr, Czekala et al. 2015), HD 98800 B (10 ± 5 Myr, Furlan et al. 2007), V4046 Sgr ($12 - 23$ Myr, Rapson et al. 2015) and St 34 (also known as HBC 425, ~ 25 Myr, Hartmann et al. 2005)) compared to the typical lifetime of protoplanetary discs of 3 Myr (Haisch et al. 2001; Mamajek 2009). If circumbinary discs always have a significantly longer lifetime than discs around single stars, it would provide a greater opportunity for planets to form in these systems.

In this work we aim to determine what fraction of disc-bearing stars are in binary star systems in the OB associations Upper Scorpius (US) and Upper Centaurus-Lupus (UCL). These OB associations are part of the larger Scorpius-Centaurus-Lupus-Crux (Sco-Cen) association which is the nearest region of recent massive star formation at a distance of ~ 140 pc (Zeeuw et al. 1999). The subgroups of the Sco-Cen association show a well-known age gradient from ~ 5 Myr at high galactic latitudes to ~ 26 Myr in the galactic plane (Pecaut & Mamajek 2016), making this region an ideal place to study evolution of pre-main sequence stars and protoplanetary discs. The ages of US and UCL sub-groups in the Sco-Cen association are ~ 11 Myr (Pecaut et al. 2012) and ~ 17 Myr (Mamajek et al. 2002) respectively. These regions are expected to have $\sim 10^4$ G/K/M pre-main sequence stars based on typical initial mass functions. Many studies have looked to discover and characterise this low mass population (e.g. Zeeuw et al. 1999; Preibisch & Zinnecker 1999; Mamajek et al. 2002; Rizzuto et al. 2011, 2015). Previous work on the presence of discs around these members (Luhman & Mamajek 2012; Rizzuto et al. 2012; Pecaut & Mamajek 2016) show a general increase in disc fraction with later spectral types. This is consistent with previous studies showing that protoplanetary disc lifetime is short around higher mass stars (Ribas et al. 2015). However, none of these works investigated the binary fraction of these disc-bearing members. Work on binary fractions in the Sco-Cen region have primarily focused on the higher mass B/A/F stars (Kouwenhoven et al. 2005, 2007) finding binary fractions of $> 70\%$.

In order to investigate the influence of binarity on disc lifetime, we look for radial velocity variation in selected disc-bearing stars in US and UCL to determine the

binary fraction. The Upper Scorpius and Upper Centaurus-Lupus regions are relatively old considering the typical protoplanetary disc lifetime, but it is at these older ages that we believe any variation in disc fractions between single and binary stars would be amplified. Section 4.3 describes identification of US and UCL members, the target selection criteria, observations, and how radial velocities are determined. In Section 4.4 we discuss our estimated binary fractions and Bayesian analysis. In Section 4.5 we discuss our results and caveats of our work.

4.3 Method and observations

Section 4.3.1 and 4.3.2 describe how the targets for our survey are selected. The observations and instrument specifications are detailed in Section 4.3.3. as well as how radial velocities are obtained from the observations.

4.3.1 Upper Scorpius and Upper Centaurus-Lupus membership probability

We selected candidate Upper Scorpius and Upper Centaurus-Lupus members using kinematic and photometric data from UCAC4, 2MASS, USNO-B and APASS (Zacharias et al. 2013; Skrutskie et al. 2006; Monet et al. 2003; Henden et al. 2012) using the Bayesian membership selection method of Rizzuto et al. (2011) and Rizzuto et al. (2015), which uses kinematic and spatial information to assign membership probabilities. We took the proper motions from the UCAC4 catalogue (Zacharias et al. 2013) and photometry from 2MASS and APASS (Skrutskie et al. 2006; Henden et al. 2012, summarised in Table B1), and used the photometry and a 15 Myr pre-main sequence isochrone (Siess et al. 2000) to estimate each candidate member’s distance. We then treated the proper-motion and estimated distance together to calculate the membership probability by comparing to both the model association velocity (Rizzuto et al. 2011) and Galactic thin disc velocity distributions (Robin et al. 2003). This selection was magnitude limited, and covered all stars in the UCAC4 catalogue with $10 < V < 16$, and comprised of several thousand candidate members with membership probability greater than 25%. These candidates were then searched for disc-indicating IR excesses at 12 and 24 μm (see Section 4.3.2). While a purely kinematic selection on the UCAC4 proper motions and photometric

distances alone would not be sufficient to assign high probability membership to G,K, and M-type stars, in combination with an infrared excess indicating the presence of a primordial or debris circumstellar disc these members can be considered robust.

4.3.2 IR excess to identify discs

Discs around young stars are often identified with IR observations, as an excess emission at these wavelengths can be detected when compared with the expected stellar photosphere flux of the star alone. The wavelength of IR emission correlates with the distance from the central star/stars with shorter wavelength emission originating at smaller radii and longer wavelengths originating from larger radii. This is due to the thermal profile of the discs (Lada & Wilking 1984).

The Wide-field Infra-red Survey Explorer (*WISE*) telescope carried out an all-sky survey in 4 wavelength bands: W1 ($3.4\ \mu\text{m}$), W2 ($4.6\ \mu\text{m}$), W3 ($12\ \mu\text{m}$) and W4

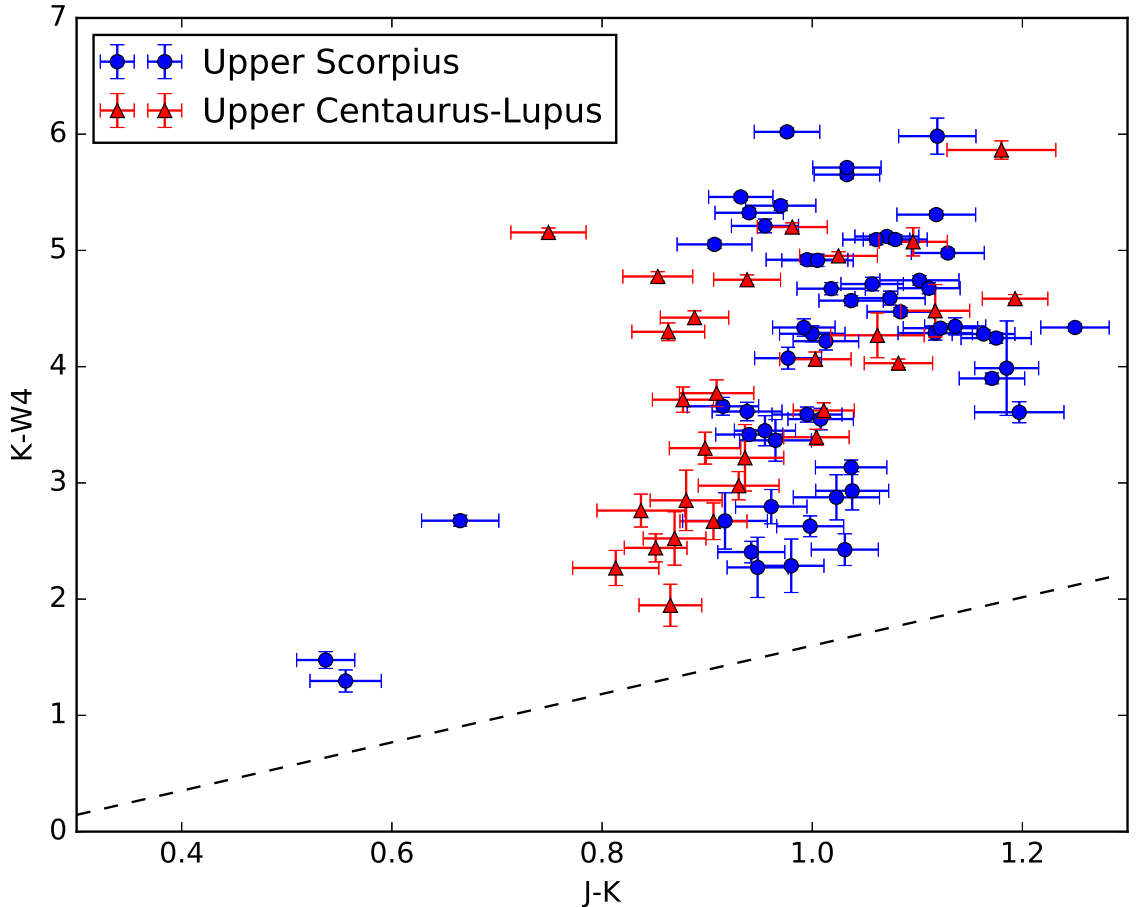


Figure 4.1: Colour-colour plot of $K - W4$ against the $J - K$ colours. The dashed line shows the expected $K - W4$ colour based on the photospheric sequence.

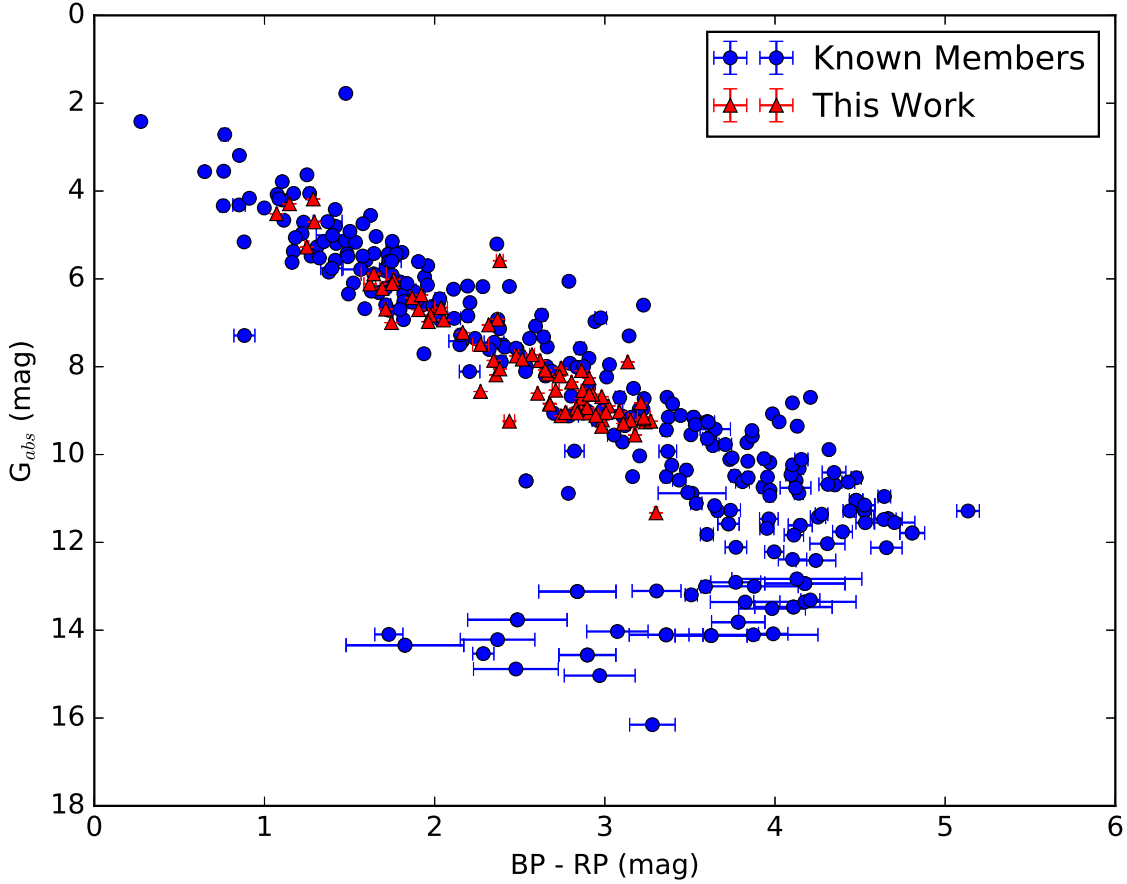


Figure 4.2: Colour-magnitude of our targets (red) against previously known members of the Scorpio-Centaurus star forming region (blue). Magnitudes are taken from Gaia (G Mag) and the colour is determined from the Gaia Blue band (BP) and Red band (RP) photometry (Gaia Collaboration et al. 2016, 2018). Known members are shown in blue and are taken from Pecaute & Mamajek 2016; Luhman & Mamajek 2012; Aarnio et al. 2008; Preibisch et al. 1998; Chen et al. 2011; Martín et al. 2004; Meyer et al. 1993; Köhler et al. 2000; Martín et al. 1998; Bouvier & Appenzeller 1992; Kraus & Hillenbrand 2009; Lodieu et al. 2006; Erickson et al. 2011; Slesnick et al. 2006; Wilking et al. 2005; Oliveira et al. 2010; Cieza et al. 2010; Luhman & Rieke 1999; Doppmann et al. 2003; Natta et al. 2002; Elias 1978; Walter et al. 1994; Ardila et al. 2000; Lodieu et al. 2011; Martín et al. 1998; Lodieu et al. 2008; Preibisch et al. 2002; Herbig & Bell 1988; Vieira et al. 2003.

($22\ \mu\text{m}$) (Wright et al. 2010). We cross-matched our objects with *WISE* IR objects from the AllWISE Source Catalogue. IR excesses in the W2 and W3 bands can indicate the presence of an inner disc and excess in the W4 band would indicate the presence of a colder outer disc. An excess is determined relative to the 2MASS (Skrutskie et al. 2006) K-band magnitude. The expected $K - W4$ colours based on photospheric sequence of stars without discs is taken to be $(K - W4) = 2.08(J - K) - 0.48$, where the J and K magnitudes are taken from the 2MASS catalogue (Rizzuto et al. 2015). An object is taken to have an excess if the $K - W4$ colour

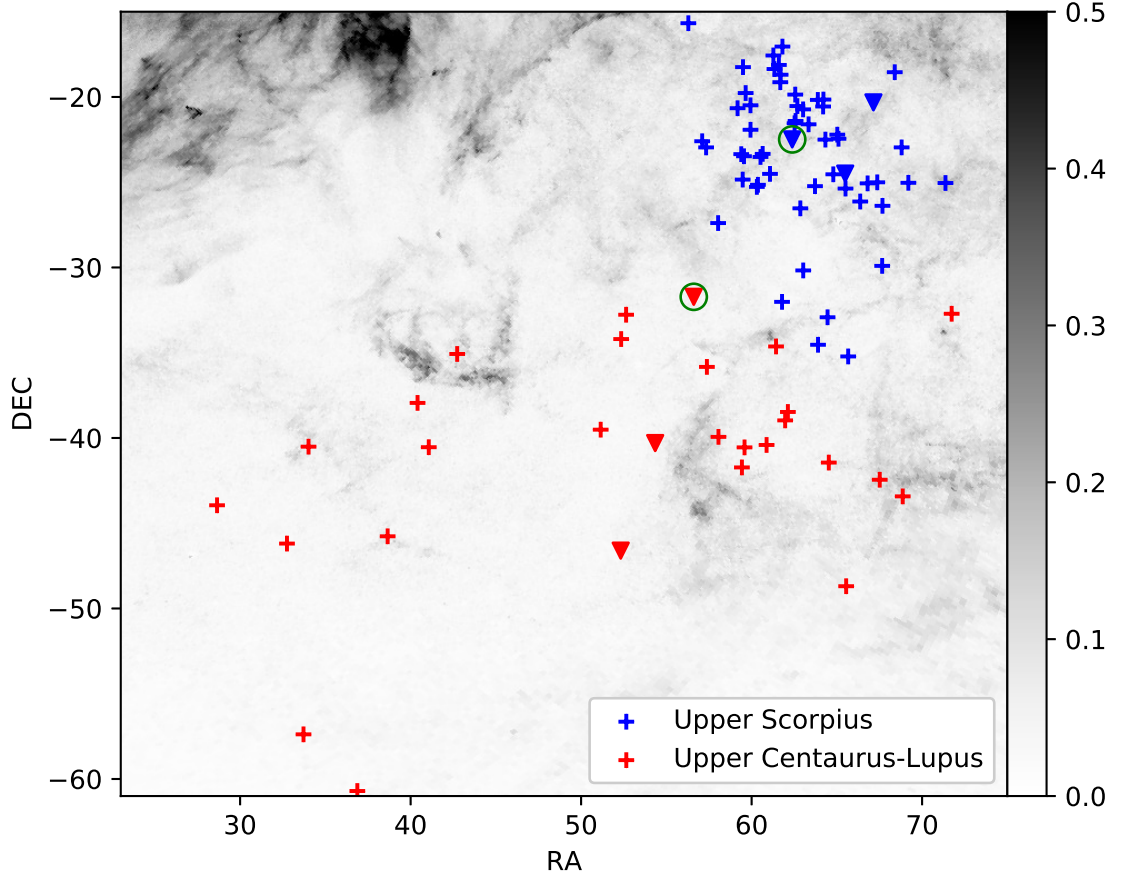


Figure 4.3: A map of the candidate disc-bearing stars in Upper Scorpius (US, the *blue* markers) and Upper Centaurus-Lupus (UCL, the *red* markers) that we consider in this study. The background image is an extinction map compiled by Schlafly et al. (2014). The triangle markers indicate objects that we believe to be binary star systems because they have Bayes factor (described by Equation 4.9 in Section 4.4.2) greater than 300. The circled triangles highlight two double-lined spectroscopic binaries found in this work (described in Figure 4.3)

is at least 3σ greater than the expected value. These colours are plotted for our targets in Figure 4.1 and their W4 magnitudes are tabulated in Table B1.

IR excess is searched for in our target members of Upper Scorpius and Upper Centaurus-Lupus. These targets were visually inspected on the IRSA *WISE* image service to check for obscuration by a cloud or contamination by a nearby IR bright object. Some objects were discarded and the final survey used 55 US targets and 28 of UCL targets found to exhibit IR excesses. The targets are plotted in a colour-magnitude diagram against other known Scorpio-Centaurus members in Figure 4.2. The colour-magnitude diagram is produced using magnitudes from Gaia (Gaia Collaboration et al. 2016, 2018) and summarised in Table B1. This shows

that our targets are consistent with membership of the Sco-Cen star forming region. The positions of our targets are also plotted in Figure 4.3 and are summarised in Table B2. Our targets have large angular separations from the Lupus star-forming clouds. Therefore, we believe it is unlikely that we have interlopers from this significantly younger association in our sample. After our disc-bearing targets had been identified they were observed to search for radial velocity (RV) variation which may indicate the presences of a companion.

4.3.3 Spectroscopic observations to obtain radial velocities

WiFeS observations

To obtain spectroscopic data to determine the radial velocities of our targets, we used the Wide Field Spectrograph (WiFeS, Dopita et al. 2007). WiFeS is an integral field spectrograph on the Australian National University 2.3 m Telescope at Siding Spring Observatory. We used this instrument to search for radial velocity variation over time for our targets. The instrument consists of a blue camera with spectral range 329 – 558 nm and red camera with spectral range 529 – 912 nm.

Data for our targets was collected from June of 2013 to July of 2017. Our observations included Ne-Ar arc exposures every 15-30 minutes to characterise the wavelength scale variation of the instrument over the night due to temperature fluctuations. The WiFeS $R \sim 7000$ grating was used to perform radial velocity measurements. We observed radial velocity standards with well characterised velocities of various spectral types. Radial velocity standards were selected from Nidever et al. (2002) and Soubiran et al. (2013) (detailed in Table 4.1). Observations of radial velocity standards were bracketed by arc lamp exposures and further correction to the calibrations was applied using oxygen B-band atmospheric absorption lines (static with respect to the observer). The calibration using the oxygen B-band lines is dependent on stellar type and signal-to-noise of each individual target. Data are reduced using the PyWiFeS pipeline¹ (Childress et al. 2013).

Radial velocity precision based on RV standards

Radial velocity standards of spectral types varying from G1 through to M3.5 (see Table 4.1) were observed with WiFeS to create spectral templates. These templates

¹available at <http://pywifes.github.io/pipeline/>

RV Standard	v_r (km/s)	Sp. Typ.	Approx. Mass ($M_\odot$)
HD35974	76.683	G1V ^a	1.40
HD144585	-14.067	G2V ^b	1.38
HD145809	21.146	G2V ^c	1.38
HD141885	-16.160	G3V ^a	1.37
HD1461	-10.166	G3V ^b	1.37
HD189625	-28.218	G5V ^d	1.35
HD19034	-20.344	G5V ^e	1.35
HD198802	-3.171	G5V ^e	1.35
HD153458	0.641	G5V ^e	1.35
HD37213	12.464	G5V ^a	1.35
HD128428	-42.074	G6IV ^e	1.34
HD196761	-41.987	G7.5IV-V ^b	1.32
HD283	-43.102	G9.5V ^c	1.29
HD156826	-32.634	K0V ^e	1.26
HD114783	-12.012	K1V ^e	1.23
HD32147	21.552	K3+V ^c	1.15
HD2025	3.241	K3V ^c	1.15
HD130992	-57.160	K3.5V ^c	1.12
HD170493	-54.752	K4V ^e	1.10
HD120467	-37.806	K6Va ^b	0.90
GJ173	-6.768	M1V ^g	0.55
GJ433	17.973	M1.5 ^f	0.50
GJ2066	62.205	M2V ^h	0.45
GJ382	7.932	M2V ⁱ	0.45
GJ357	-34.581	M2.5V ^c	0.40
GJ273	18.216	M3.5V ⁱ	0.20
GJ729	-10.499	M3.5Ve ^j	0.20

Table 4.1: Radial velocity standards used as templates to obtain radial velocities of our observed targets. Standards are selected from the Nidever et al. (2002) and Soubiran et al. (2013) catalogues. ^aHouk (1982), ^bKeenan & McNeil (1989), ^cGray et al. (2006), ^dHouk & Smith-Moore (1988), ^eHouk & Swift (1999), ^fHenry et al. (2002), ^gStephenson (1986), ^hAlonso-Floriano et al. (2015), ⁱKirkpatrick et al. (1991), ^jDavison et al. (2015). The approximate masses are derived from the Baraffe et al. (2015) pre-main sequence evolution models based on spectral type at age $\log_{10}(t_{age}) \sim 7.1$.

are cross-correlated with our targets to determine their radial velocity using the post-processing tools developed for WiFeS². Obtained radial velocities are corrected to be in the heliocentric velocity frame.

The radial velocity standards were observed using the settings described in Section 4.3.3. After the observations of the RV standards were reduced, their wavelength scale was shifted to the rest frame. This product was used as the template from

²available at <http://github.com/PyWiFeS/tools>

which the radial velocity of the targets is obtained.

Tests of retrieving the radial velocity of the RV standards after creating templates of the observed spectra were run. This was done by cross-correlating the reduced spectra of the observed RV standards with created templates, ensuring that the standard was not cross-correlated with itself. We found that the retrieved radial velocities had a relatively large spread from the actual radial velocity of the RV standards with standard deviation of 3.0 km s^{-1} (top panel of Figure 4.4). We believe this is because the WiFeS instrument may vary on a shorter time-scale than 15-30 minutes. The wavelength scale solution is the linear interpolation between that derived from nearby arcs, as done by the PyWiFeS pipeline, was therefore not accurate enough for the purposes of our work.

In order to improve our radial velocity precision, we use the oxygen B-band atmospheric absorption lines and sky emission. Using the oxygen B-band absorption lines we could determine the offset from the wavelength solution derived from PyWiFeS. The precision of retrieving the radial velocity of the RV standards with the added correction from the B-band is shown in the middle panel of Figure 4.4. We see that the precision is increased significantly for the G standards, but is decreased for K and M standards. This is not surprising as K and M type stars have emission in the wavelength region of the oxygen B-band absorption, which makes it difficult to determine a velocity.

In addition to using oxygen B-band absorption lines to improve radial velocity precision, emission from skylines was also tested. This proved to not be useful because the RV standards are very bright, therefore not enough signal-to-noise is obtained to confidently retrieve a radial velocity.

Based on the results of this investigation, we decided to only apply calibrations to the G type RV standards by correcting the radial velocity from the shift measured in the B-band absorption. The resulting precision is shown in the bottom panel of Figure 4.4. The overall standard deviation of the precision using this combination of velocity calibrations is 0.9 km s^{-1} , which is a slight increase from applying the B-band absorption correction to all RV standards, but the standard deviation per spectral type is improved. The standard deviation per spectral type is summarised in Table 4.2.

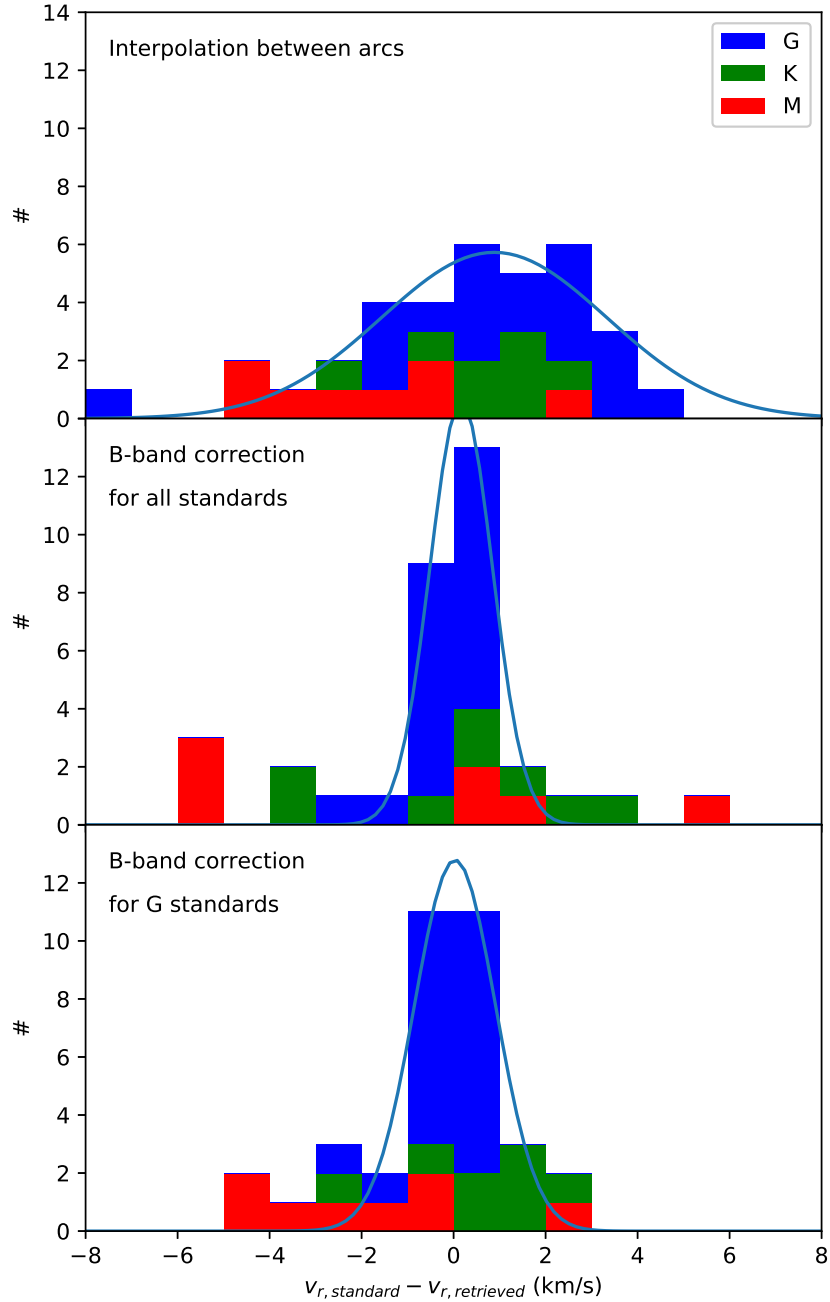


Figure 4.4: Precision in retrieving the radial velocity of RV standards. The x-axis is the difference between the radial velocity of the RV standard and the retrieved radial velocity using our pipeline. The blue, green, and red histograms show the precision of the G, K, and M-type RV standards respectively. *Top*: precision when only using the wavelength solutions produced by linear interpolation between arcs (as produced by PyWiFeS). *Middle*: precision when the oxygen B-band absorption lines are also used to further calibrate the wavelength scale. *Bottom*: precision when the oxygen B-band absorption lines are only used for further calibration on the G-type RV standards.

Obtaining radial velocity of targets

To obtain the radial velocity of our targets, observations are cross-correlated with all the RV standards in an initial step. In order to cross-correlate the target spectra with

RV standard spectral type	σ (km/s)
G	0.7
K	1.4
M	2.3

Table 4.2: Precision of retrieving RV standard radial velocity per spectral type.

the template spectra the $H\alpha$ region had to be masked out because most of our targets have strong $H\alpha$ emission (discussed further in Section 4.3.4). Each object is then set a preferred RV standard template to make sure all epochs are cross-correlated with the same template. In the initial step an object will mostly cross-correlate the best with the same template over all epochs or with templates of similar spectral type. An object's preferred template is the template that it correlates the best with over most of the epochs.

After a preferred template is selected, radial velocities are determined again, with all epochs cross-correlating with the same template. Correction using the oxygen B-band absorption is also applied to the obtained radial velocities. The added correction from the absorption lines does show an improvement on the radial velocity precision. When plotting a histogram of radial velocity variation, we expect a large fraction of objects to possess a variation near 0 km s^{-1} , which are the objects that are single stars. From our observations, the radial velocity variation is taken to be the difference between the objects last, nth, epoch ($v_{r,n}$) and the objects mean radial velocity over all epochs ($\langle v_r \rangle$), i.e.

$$\Delta v_r = v_{r,n} - \langle v_r \rangle. \quad (4.1)$$

A histogram of radial velocity variation for our targets is shown in Figure 4.5. The full-width-half-maximum (FWHM) of this histogram can be taken as a precision of the radial velocity measurements. We see that the reduces precision from 3.40 km s^{-1} to 2.37 km s^{-1} when corrections using the oxygen B-band absorption is applied (Figure 4.5).

We identify two double-lined spectroscopic binaries (SB2s). RIK-96 is found in Upper Scorpius and UCAC4-161328427 in Upper Centaurus-Lupus. Cross-correlations at two epochs for each of the SB2s are shown in Figure 4.6. Both objects show very strong IR excesses, which likely indicate the presences of a large circumbinary disc.

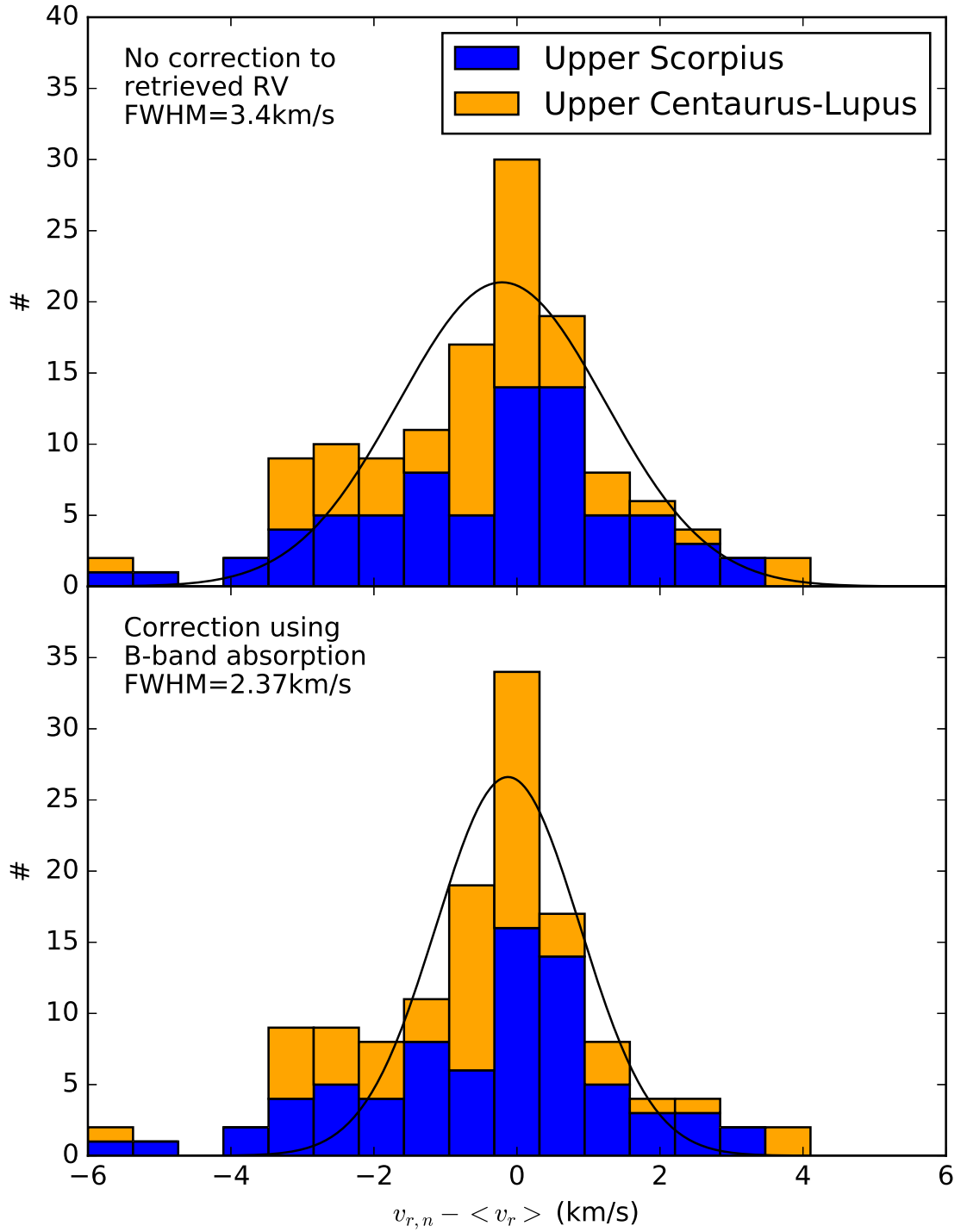


Figure 4.5: Radial velocity variation distributions for observed objects calculated as the difference between the radial velocity of the objects last, n th, epoch ($v_{r,n}$) and the objects mean radial velocity over all epochs ($\langle v_r \rangle$). *Top*: shows the distribution without correction from the absorption lines. The full-width-half-maximum of the fitted gaussian is 3.40 km s^{-1} . *Bottom*: shows the radial velocity variation with the added correction from the absorption lines. The full-width-half-maximum of the fitted gaussian is 2.37 km s^{-1} .

We carried out two dimensional cross-correlations with templates for these objects to estimate the spectral type and flux ratio of the components. We find for RIK-96 the primary and secondary to be of spectral type M1.5 and M2.5, respectively, with a flux ratio of ~ 0.71 . We find for UCAC4-161328427 that both components fit best to M2.5 templates, with a flux ratio of ~ 0.98 . Information about these two objects is summarised in Table 4.3.

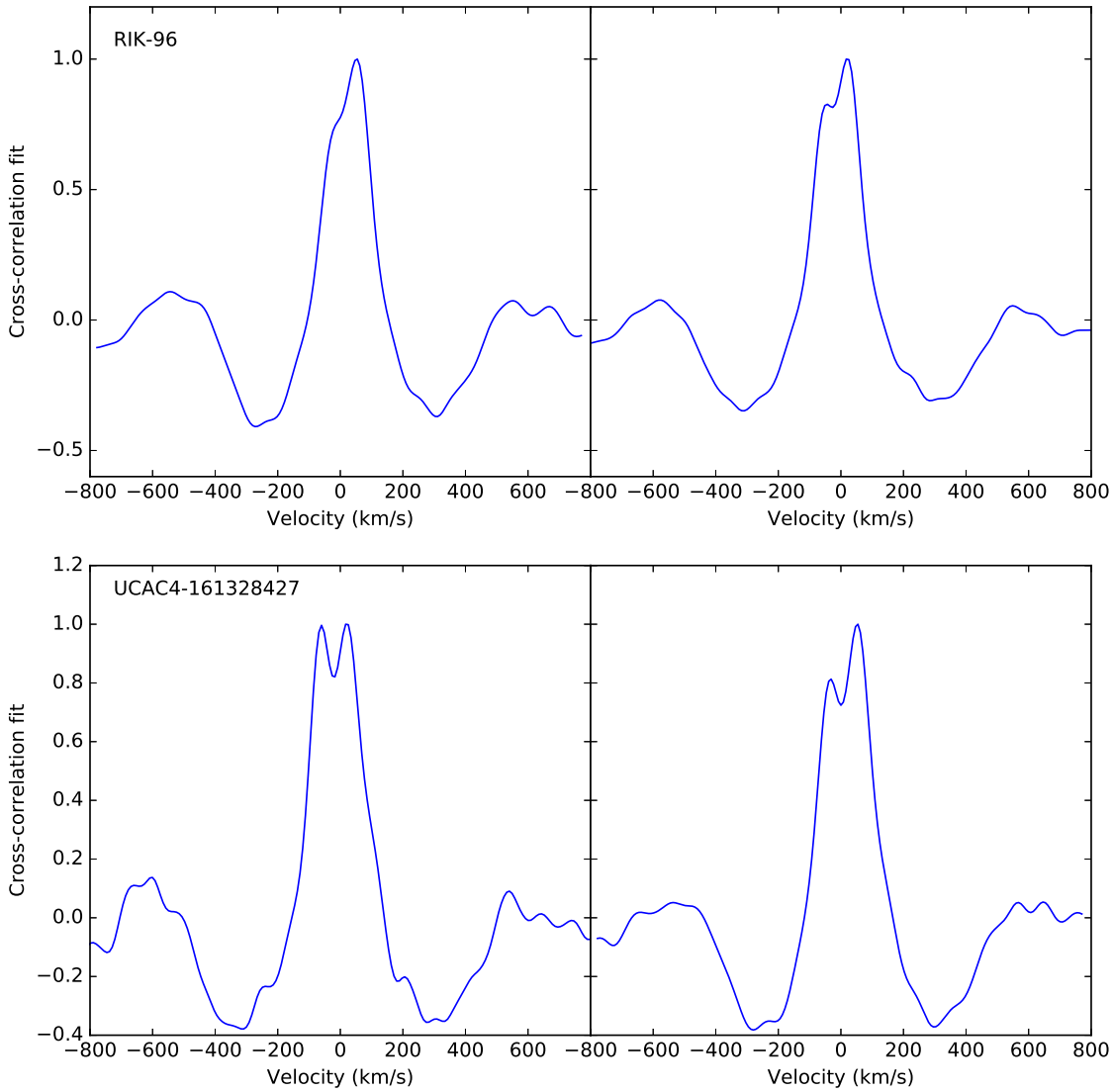


Figure 4.6: Cross-correlations of the two SB2s found. The y-axis has arbitrary units of a measure of fit. The top two panels show cross-correlations for RIK-96 and the bottom two show cross-correlations for UCAC4-161328427 at two different epochs.

4.3.4 $H\alpha$ as a youth indicator

As mentioned in Section 4.3.3 the observed targets showed $H\alpha$ emission that hindered cross-correlations with template spectra. The $H\alpha$ emission is believed to be

	RIK-96	UCAC4-161328427
RA	16 09 31.66	15 46 25.81
DEC	-22 29 22.4	-31 43 19.3
$J - K$	0.995	0.863
$K - W4$	4.922	4.305
SpT of Primary	M1.5	M2.5
SpT of Secondary	M2.5	M2.5
Flux ratio	0.71	0.98
Epoch 1		
$v_{r,\text{left}}(\text{km/s})$	-57.5 ± 0.3	-63.4 ± 0.9
$v_{r,\text{right}}(\text{km/s})$	26.5 ± 0.2	24.3 ± 1.0
$v_{\text{heliocentre}}(\text{km/s})$	16.9	23.1
Epoch 2		
$v_{r,\text{left}}(\text{km/s})$	-31.3 ± 1.0	-39.5 ± 0.7
$v_{r,\text{right}}(\text{km/s})$	57.9 ± 0.7	56.7 ± 0.7
$v_{\text{heliocentre}}(\text{km/s})$	-10.2	-5.9

Table 4.3: Summary of the SB2s found. The assigned spectral type of the components is based on the best fitting template. We also tabulate the heliocentric velocity correction to demonstrate that neither SB2 peak is due to uncorrected telluric lines.

caused by accretion of disc material onto the stars. In Figure 4.7, we display the measured $\text{H}\alpha$ equivalent widths for the targets. The majority of the target members show some level of $\text{H}\alpha$ emission, with a clear sequence of increasing emission with spectral type. Rizzuto et al. (2015) uses the combination of lithium and $\text{H}\alpha$ emission as indicator of youth for the identified RIK objects. Of our 55 US and 28 UCL targets, $\sim 82\%$ and $\sim 70\%$ show $\text{H}\alpha$ emission with $\text{EW}(\text{H}\alpha) < -1\text{\AA}$. Of the members that do not show or show weak $\text{H}\alpha$ emission, most are earlier than M0 spectral type based on the template spectra used for cross-correlation.

4.4 Results and statistical analysis

Using a hard cut of 5σ significance on the radial velocity variation for the fraction of binaries in Upper Scorpius and Upper Centaurus-Lupus we get 15% and 10%, respectively. The fractions produced from this criterion only find the closest binaries, which produce the greatest radial velocity variation. In order to better characterise the binaries that we do not detect we must use Bayesian statistics to explore the parameter space.

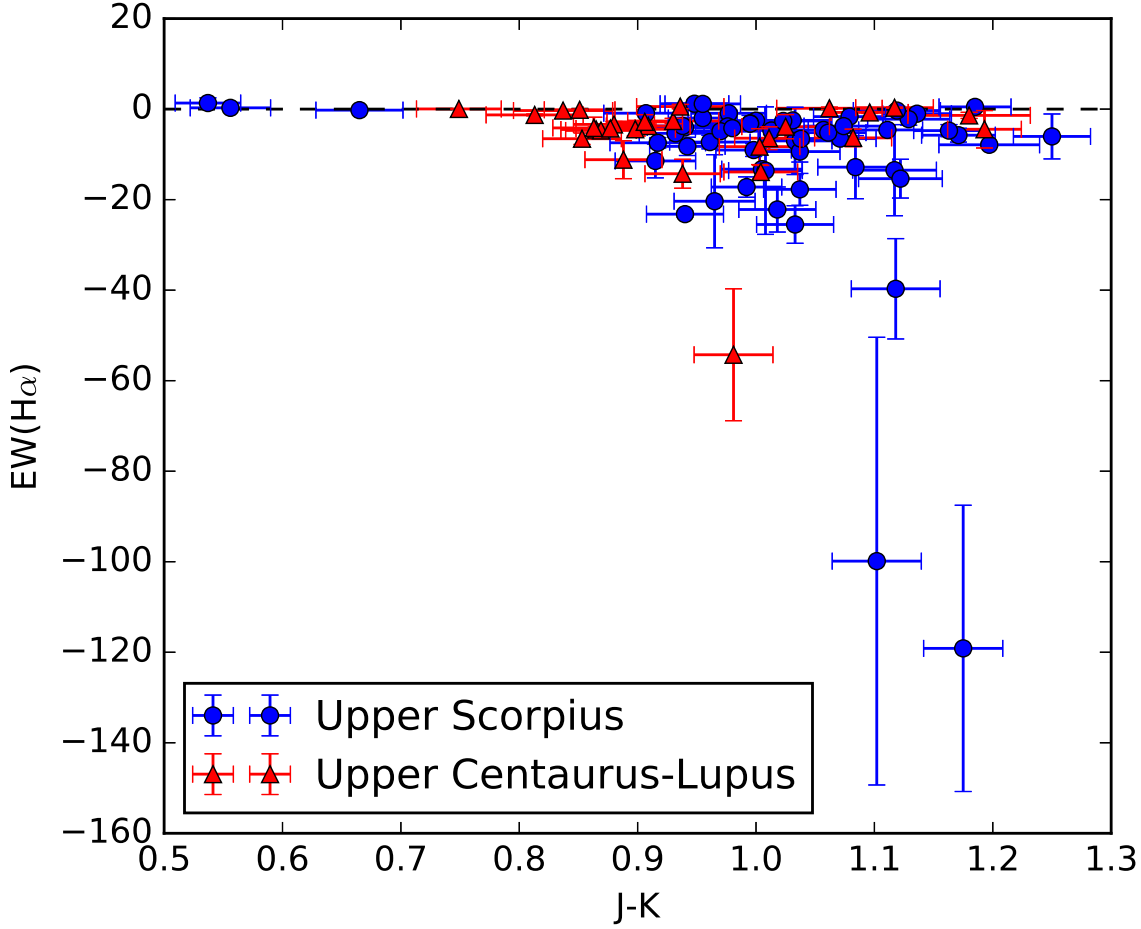


Figure 4.7: Mean $H\alpha$ equivalent width for our targets measured over all epochs. The error bars is the standard deviation of the measured equivalent width over all epochs.

4.4.1 Simulating systems

The radial velocity (v_r) of the primary star in a binary system can be described by:

$$v_r = K[\cos(\omega + \theta) + e \cos \omega] + v_{sys}, \quad (4.2)$$

where K is a constant described below, ω is the longitude of periastron, θ is the true anomaly (the angle between the primary star and periastron), e is the eccentricity of the system and v_{sys} is the system velocity. K is described by:

$$K \equiv \frac{2\pi}{P} \frac{a_1 \sin i}{(1 - e^2)^{1/2}}, \quad (4.3)$$

where P is the period of the system, a_1 is the semi-major axis of the primary star from the barycentre of the system and i is the inclination of the binary. a_1 for a system can be calculated for a binary when the period and component masses

are known. From the primary mass and mass ratio, the semi-major axis can be determined from Kepler's third law:

$$a = (M_1(1 + q)P^2)^{1/3}, \quad (4.4)$$

where a is the semi-major axis of the system in AU, M_1 is the mass of the primary star in $M_\odot$, q is the mass ratio between the secondary and primary components, i.e. $q = M_2/M_1$, and P is period in years. From the binary mass function, the semi-major axis of the primary component can be determined from:

$$a_1 = a \frac{q}{1 + q}. \quad (4.5)$$

There is no analytical solution to calculating the true anomaly from the period, eccentricity and time to periastron, T_0 . Therefore, we approximate the true anomaly using the series expansion:

$$\theta = \mu + (2e - \frac{1}{4}e^3) \sin(\mu) + \frac{5}{4}e^2 \sin 2\mu + \frac{13}{12}e^3 \sin 3\mu, \quad (4.6)$$

where μ is the mean anomaly given by:

$$\mu = \frac{2\pi}{P}T_0. \quad (4.7)$$

In our Bayesian analysis, we simulate radial velocity curves using ω , i , e , P , T_0 , v_{sys} , M_p and q sampled from appropriate parameter spaces described in the next section.

4.4.2 Bayesian statistics

Some of these priors are independent from the physical characteristics of the system, such as ω and i , therefore the parameter space from which these quantities are sampled is the same for all objects. The parameter spaces that the period, time of periastron passage and eccentricity are sampled from also remain the same for all objects because these quantities directly influence the shape of the radial velocity curve. The parameter space sampled for the system velocity is dependent on the observed radial velocities, therefore this space is redefined for each object, as described in Section 4.4.3.

Initially all random orbits are given an amplitude of 1 km s^{-1} , but this is scaled when considering the possible mass of the primary star and the mass ratios. For each object ω , i , P , T_0 , e and v_{sys} are sampled 10^5 times to produce radial velocity curves with normalised amplitudes. Then for each of these orbits, M_p and q are sampled 10^2 times to scale these normalised radial velocity curves. The parameter space that the primary mass is sampled is dependent on the template that the object cross-correlates with. The parameter space that the mass ratio is sampled from is the same for all objects.

Once a radial velocity curve is simulated, a likelihood of fit is calculated for each simulated orbit given by:

$$L \propto e^{-\frac{(v_{r,obs} - v_{r,sim})^2}{2\sigma_{obs}^2}}, \quad (4.8)$$

where $v_{r,obs}$ is the observed radial velocity, $v_{r,sim}$ is the simulated radial velocity, and σ_{obs} is the error on the measured radial velocity. The error of the measured radial velocity is the error derived from the cross-correlation, the error from the precision of the template used, and a standard astrophysical error added in quadrature. The standard astrophysical error accounts for variations caused by stellar activity or rotation and is set to 1 km s^{-1} . Our results are shown not to vary significantly for an astrophysical error over the range of $0.5 - 2.0 \text{ km s}^{-1}$. The error on the precision of the RV standard template is taken from Table 4.2.

Likelihoods are also calculated for fitting a single star i.e. a constant radial velocity. The velocity for a single star fit is taken to be the system velocity (v_{sys}) that is sampled for the simulated binary star orbit.

After all the radial velocity curves for the simulated orbits have likelihoods calculated, we calculate the mean likelihood of the data given our two models, $P(D|S)$ and $P(D|B)$. From these, the Bayes factor is calculated, which is given by:

$$\Upsilon = \frac{P(D|B)}{P(D|S)}. \quad (4.9)$$

From this we see that the Bayes factor is simply the ratio of the mean likelihoods of being a binary star to a being a single star. A binary model is preferred if $\Upsilon \gg 1$ and a single star model is preferred if $\Upsilon \ll 1$. Where $\Upsilon \approx 1$, either model is equally probable. We take objects with Bayes factors > 300 to be binary stars as this is

near the 3σ confidence level assuming a Gaussian probability distribution. Using this threshold we find six objects to be binary stars, including the two double-lined binaries shown in Figure 4.6 and listed in Table 4.3. The Bayes factors for every target can be found in Table B2.

Once the Bayes factor is calculated for each target we calculate the binary fraction. The likelihood of being a binary or multiple star system, $P(B)$, is complementary to the likelihood of being a single star, $P(S)$. Therefore, if we take the likelihood of being a binary to be γ , then $P(B) = \gamma$ and $P(S) = 1 - \gamma$. This is described statistically like a *Bernoulli trial*. The Jeffreys' prior to this case states that the probability of γ can be described by:

$$P(\gamma) \propto \frac{1}{\gamma(1-\gamma)}. \quad (4.10)$$

We are trying to find what the probability density function of γ is for Upper Scorpius and Upper Centaurus-Lupus. Following Bayes' Theorem, the probability of γ given our data is:

$$P(\gamma|D) = \frac{P(\gamma)}{P(D)} P(D|\gamma). \quad (4.11)$$

We can expand out the probability of the data given γ , $P(D|\gamma)$, into constituents of the probability of being a single or binary star given γ , $P(S|\gamma)$ and $P(B|\gamma)$ respectively, giving:

$$P(\gamma|D) = \frac{P(\gamma)}{P(D)} [P(D|B)P(B|\gamma) + P(D|S)P(S|\gamma)]. \quad (4.12)$$

As γ is defined as the multiplicity, $P(B|\gamma) \equiv \gamma$ and $P(S|\gamma) \equiv 1 - \gamma$ as described previously. This gives us:

$$P(\gamma|D) = \frac{P(\gamma)}{P(D)} [P(D|B)\gamma + P(D|S)(1 - \gamma)]. \quad (4.13)$$

We can express Equation 4.13 in terms of our Bayes' factor, which we calculate from our observations. The probability of γ given the data is now:

$$P(\gamma|D) = \frac{P(\gamma)}{P(D)} P(D|S) [\Upsilon\gamma + (1 - \gamma)], \quad (4.14)$$

or to simplify:

$$P(\gamma|D) \propto P(\gamma)[\Upsilon\gamma + (1 - \gamma)]. \quad (4.15)$$

where $P(\gamma)$ is our prior on the probability distribution of the binary fraction. Our initial guess is that the probability distributions of γ is uniform, meaning that every possible binary fraction is equally likely. This prior is updated with the Bayes' factor of each object. For the first object, the probability of γ given the data is:

$$P(\gamma|D)_1 \propto P(\gamma)_0[\Upsilon_1\gamma + (1 - \gamma)], \quad (4.16)$$

where $P(\gamma)_0$ is our initial guess of a uniform distribution. This is saying that we believe this object has an equal probability of being a single or binary star and it is updated with the Bayes factor of the first object. This updated prior becomes the prior for the next object. Expanding this to n objects we get:

$$P(\gamma|D) \propto P(\gamma) \prod_{i=1}^n [\Upsilon_i\gamma + (1 - \gamma)]. \quad (4.17)$$

4.4.3 Bayesian priors

The priors for our Bayesian analysis are summarised in Table 4.4. ω and i are all independent of physical characteristics of the binary star system. These quantities account for projection effects on the observed radial velocity and may have any orientation, i.e. are isotropic. We sample inclination, i , from a distribution proportional to $\sin(i)$, and sample the longitude of periastron ω , from 0° to 360° in order to uniformly sample the three-dimensional orientation of orbits.

The eccentricity of an object may be $e = 0$ for a circular orbit, up to $e = 1$ for a parabolic orbit. We sample the eccentricity from a uniform distribution as Raghavan et al. (2010) find that eccentricity follows a mostly uniform distribution up to $e = 0.6$. The lower bound for our eccentricity parameter space is $e = 0$ and the upper bound is $e = 0.95$.

The largest baseline our observations have is ~ 4 yr. With this baseline we take the largest binary orbital period that we should be able to detect to be 7300 day or ~ 20 yr. We take the shortest possible period to be 1 day. The periods are sampled from a log-normal distribution with a mean of $\mu_P = 5.03$ and standard deviation

Symbol	Parameter	Lower Bound	Upper Bound	Distribution
ω	Longitude of periastron	0°	360°	Uniform
i	Inclination	0°	90°	Sinusoidal
e	Eccentricity	0	0.95	Uniform
P	Period	1 day	7300 day	Log normal
T_0	Time of Periastron Passage	0 day	P	Uniform
v_{sys}	system velocity	$\langle v_r \rangle$ -4 km/s	$\langle v_r \rangle$ $+4 \text{ km/s}$	Gaussian
M_p	Mass of Primary	$M_{template}$ $-0.1M_{template}$	$M_{template}$ $+0.1M_{template}$	Uniform
q	mass ratio	0.05	1.0	Uniform

Table 4.4: Priors for Bayesian analysis.

$\sigma_P = 2.28$ as found by Raghavan et al. (2010). The time of periastron passage, T_0 , is essentially the phase of the radial velocity curve and is dependent on the period. All values of T_0 are equally likely, so this value is sampled from a uniform distribution from 0 day to P in days.

We aim to marginalise our probability distributions over all possible values of the centre of mass velocity, because the dispersion of velocities within our association is larger than our typical velocity precision. For computational speed, we only sample values of v_{sys} from a normal distribution centred on the mean radial velocity over all epochs of an object and with a standard deviation of 4 km s^{-1} (larger than our typical uncertainties). Sampling from a wider distribution would lower both the single and binary star probabilities roughly equally and would not noticeably affect our results.

It is reasonable to assume that the best fitting spectral template corresponds to the brighter component of a binary star system. From this assumption we sample the mass of the primary, M_p , based on the template that was used to derive radial velocities. The typical mass of a pre-main sequence star for the spectral type of the template is used as a guide for M_p . The typical spectral type mass for each template can be found in Table 4.1. M_p is sampled from a uniform distribution with lower and upper bounds being $\pm 10\%$ of the typical mass of the template. The mass ratio, q , is sampled from a uniform distribution as this is what observations have shown (Raghavan et al. 2010). For our work we set a minimum mass ratio of $q = 0.05$.

When carrying out this calculation for our objects in Upper Scorpius and Upper Centaurus-Lupus, we find that the maximum likelihood binary fractions to be

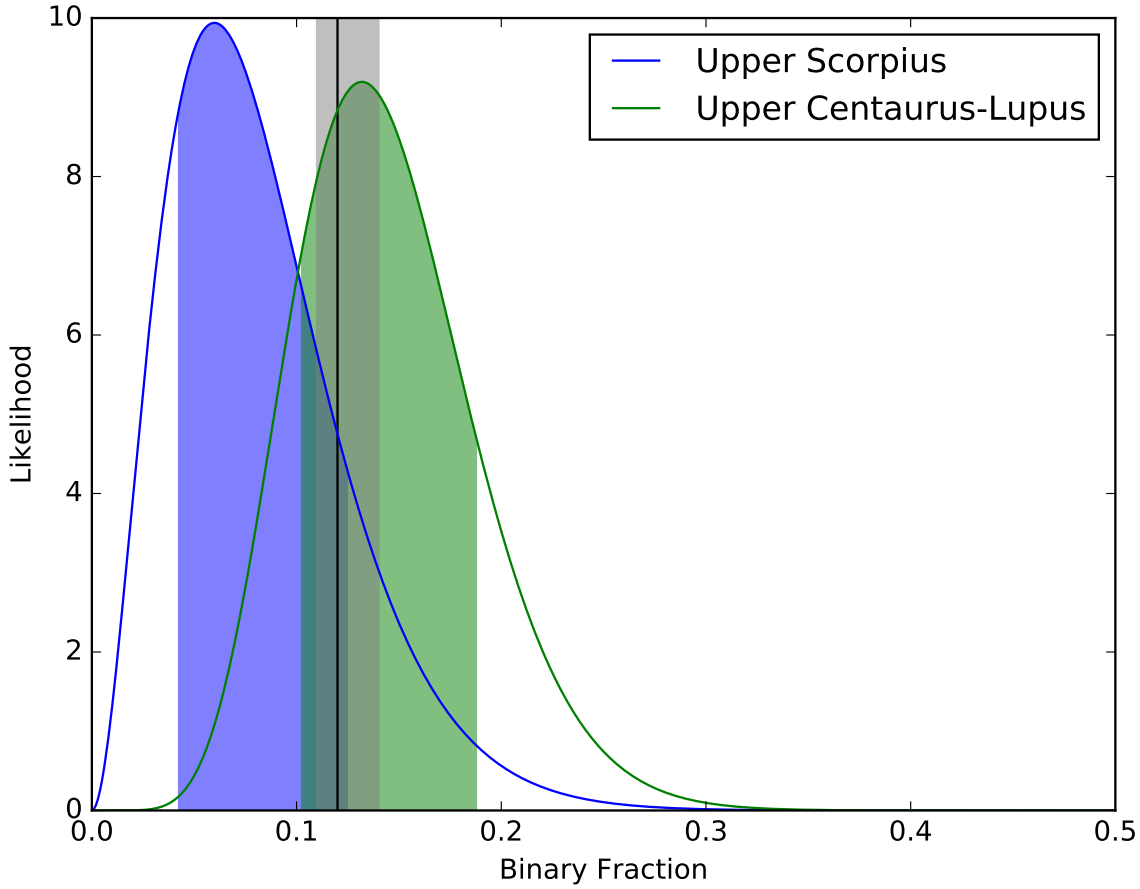


Figure 4.8: The normalised probability distribution of multiplicity for our disc-bearing stars in Upper Scorpius and Upper Centaurus-Lupus. The y-axis is in arbitrary units. The vertical line and shaded region highlights our expected binary fraction of $0.12^{+0.02}_{-0.01}$ based on the multiplicity of field stars irrespective of whether they have discs or not. The maximum likelihood fractions of US and UCL are $0.06^{+0.07}_{-0.02}$ and $0.13^{+0.06}_{-0.03}$, respectively.

$0.06^{+0.07}_{-0.02}$ and $0.13^{+0.06}_{-0.03}$, respectively. The mean likelihoods for Upper Scorpius and Upper Centaurus-Lupus are 0.08 and 0.14, respectively. The normalised posterior density functions are shown in Figure 4.8. The error bars are the 16th and 84th percentile, and are highlighted in Figure 4.8.

4.5 Discussion

4.5.1 Binary fraction and implication on disc lifetime

From our work we find that approximately one fifth of disc-bearing stars of spectral types F and later in Upper Scorpius (US) and Upper Centaurus-Lupus (UCL) are in binary star systems with periods less than 20 years.

Raghavan et al. (2010) find the multiplicity of $1.25 - 1.02 M_{\odot}$ stars to be $54\% \pm 4\%$ and $1.02 - 0.78 M_{\odot}$ stars to be $41\% \pm 3\%$. Shan et al. (2017) find a raw multiplicity of $0.9 - 0.07 M_{\odot}$ dwarfs to be $35\% \pm 3\%$. From these multiplicities found in the literature and the masses of our targets (based on the template fitted to the target, see Section 4.3.3) we calculate an expectation value for the binary fraction based on the field population. Based on the templates fit to our targets we have 6 US and 4 UCL objects $\geq 1.02 M_{\odot}$, 7 US and 8 UCL objects between $1.02 - 0.78 M_{\odot}$ and 42 US and 16 UCL objects below $\sim 0.78 M_{\odot}$. Under the assumption that binary stars of all spectral types follow the same log-normal orbital period distribution as described by Raghavan et al. (2010), we are able to detect up to 31% of all binary systems (because 31% of the log-normal period distribution is below a period of 20 years). Based on the binary fractions and the fraction of detectable binary star systems, we expect ~ 1 US and UCL target $\geq 1.02 M_{\odot}$, ~ 1 US and UCL between $1.02 - 0.78 M_{\odot}$ targets, and 5 ± 0.5 of our US and ~ 2 of our UCL objects below $0.78 M_{\odot}$ to be binaries. This gives a total expectation value of 7 ± 0.5 out of the 55 US targets and 3.5 ± 0.5 out of the 28 UCL targets to be binaries, or an expected fraction of $0.12^{+0.02}_{-0.01}$ for both regions if they followed the same binary statistics as the field stars in Raghavan et al. (2010). This is consistent with our fractions obtained from the Bayesian analysis.

Our results show that the binary fraction of our targets showing IR excess is tentatively consistent with the binary fraction of the general stellar population implying that the overall the lifetime of discs in binary star systems is comparable to single stars. Our work does not discriminate between circumbinary discs and circumstellar discs around individual components in a binary star system. There may be variations in disc lifetime depending on the configuration of the system. Damjanov et al. (2007) and Harris et al. (2012) find that binaries of separation $\lesssim 30$ AU have significantly smaller IR excess compared to other binary stars with discs, which may indicate that a close companion leads to faster disc dispersal. This is in contrast to many massive, bright circumbinary discs (Harris et al. 2012; Cox et al. 2017) which could indicate the opposite. A binary star has more angular momentum compared to a single star of the same total mass, so one would expect a binary star system to host a larger disc than its single star counterpart. The primary of a binary star

system would also accrete less rapidly than a single star of the combined mass of binary components, which would lead to a slower photoevaporation process, leading towards a longer lifetime. Daemgen et al. (2016) find that the fraction of accretion discs around binary stars is a factor of ~ 2 lower than accretion discs around single stars in the Chamaeleon I region. This may be because circumbinary discs have the gas evacuated from the inner region by a close companion, leading to lower accretion rates. This could contribute to circumbinary discs having a longer typical lifetime and explain some very old circumbinary discs. These various factors could average out over the long term leading to similar disc lifetimes in single star and binary star systems.

4.5.2 Caveats

In this work we use Bayesian statistics to account for the limited set of observations on this study. As such, we must discuss some of the caveats associated with our conclusions.

Only the two double-lined spectroscopic binaries presented in Figure 4.6 can be conclusively identified as binaries. For the remainder of our objects, binarity is determined from a combination of a detected radial velocity variation and Monte-Carlo simulations. This is because no single object has had a sufficient number of radial velocity observations to resolve a full orbit, with only 2-7 epochs, with a median of 4 epochs per target.

Additionally, given we have only two conclusively identified binary systems, our work gives a raw binary fraction which is consistent with no multiplicity in the sample. Therefore, the suggestion that discs in binary star systems are heavily hindered leading to the quick dispersal of discs in binaries of periods up to 20 years is also valid based on our data.

The $22\mu\text{m}$ emission detected by the *WISE* W4 band traces disc emission out to a few AU, whereas millimetre surveys from Harris et al. (2012) and Cox et al. (2017) trace regions that are further out. This makes comparison with previous work difficult as the infrared emission measured in this work probes a different region of the IR spectrum. Our work looks at the survival time of the inner region of discs, which may be truncated in circumbinary discs. But these same circumbinary discs

would, nevertheless, exhibit millimetre emission.

Our target sample is also biased against massive stars (i.e. greater than $\sim 1.4 M_{\odot}$). This is mainly due to a lack of absorption lines needed for precise cross-correlation with a template. This may be problematic in the context of determining multiplicity as many surveys (Raghavan et al. 2010) show that multiplicity increases with primary star mass. But the overall multiplicity of disc-bearing objects would be more sensitive to the initial mass function used and the populations of lower-mass stars. Therefore, we believe that excluding massive stars is unlikely to change our results significantly.

4.6 Summary and conclusion

We determine the multiplicity of disc-bearing stars in the ~ 11 Myr Upper Scorpius (US) and ~ 17 Myr Upper Centaurus-Lupus (UCL) for periods up to 20 years. Our sample consists of 55 US members and 38 UCL members that are shown to have an IR excess, indicating the presence of a disc. Targets are observed with the Wide Field Spectrograph (WiFeS) on the Australian National University 2.3m telescope to search for radial velocity variation.

Using Bayesian statistics we determine the binary fraction of our disc-bearing stars in Upper Scorpius and Upper Centaurus-Lupus to be $0.06^{+0.07}_{-0.02}$ and $0.13^{+0.06}_{-0.03}$, respectively. When compared to the expected binary fraction of $0.12^{+0.02}_{-0.01}$ based on our observational limits and the multiplicity of field stars, these results are consistent with disc lifetime around binary stars being similar to single stars. This implies that planet formation is equally likely around binary stars as around single stars.

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5

Conclusion

In this thesis I have studied the formation, evolution, and survivability of protoplanetary discs in binary star systems via theoretical and observational means. I summarise the conclusions of these projects in the following sections, as well as conclusions for this entire body of work. I then discuss open questions which encompass future work.

5.1 Summary of theoretical work: the early evolution of binary stars

In the introduction to this thesis I summarised the primary mechanisms that contribute to disc dispersal and lifetime: 1. Accretion; 2. Jets and outflows; 3. Photoevaporation; and 4. Dynamical interactions. In my theoretical work I looked at how binarity affected these mechanisms. This work was carried out with the adaptive mesh refinement ideal magnetohydrodynamic code **FLASH**. I simulated the collapse of molecular cores into protostars and followed the early stages of their evolution.

In Chapter 2, I presented the first theoretical project where I studied how the formation of binary stars affected the initial molecular core collapse along with outflow morphology and efficiency. I simulated the formation of a *Tight Binary* ($a \sim 2.5$ AU) and a *Wide Binary* ($a \sim 45$ AU), as well as a *Single Star* as a control scenario. This work found that the jets and outflows from the discs around binary

stars are less efficient than outflows from single stars at transporting mass, linear momentum and angular momentum, with *Wide Binary* producing the weakest outflows ($\sim 50\%$, $\sim 33\%$, $\sim 42\%$, of the respective quantities in *Single Star*, see Figure 2.3). It may be because of the outflow efficiencies that we see an inversion in the star formation efficiency. *Single Star* has accreted the least amount of mass while *Wide Binary* accreted the most (see Figure 2.4). Because these simulations only ran for ~ 3000 yr after protostar formation, is it difficult to forecast the long-term evolution of the binary.

By looking at the magnetic field structure around the protostars and analysing the ratios of magnetic force to gravitational force (see Figure 2.10), I deduced that the outflows were launched by the magnetocentrifugal mechanism (Blandford & Payne 1982) for *Single Star* and *Tight Binary*. The outflows in *Wide Binary* were likely launched by a general magnetic pressure gradient in a magnetic tower (Lynden-Bell 2003). This conclusion is drawn from the fact that the coiled up magnetic field structure was observed in *Single Star* and *Tight Binary*, which caused a steeper magnetic pressure gradient resulting in efficient launching.

The morphology of the outflows in *Tight Binary* looks similar to *Single Star*. *Tight Binary* produced a single bipolar outflow, however, the outflow velocities were lower than those of *Single Star* (see Figure 2.2). The slower outflow velocities are likely caused by the binary truncating the inner circumbinary disc where the high velocity component would be launched. *Wide Binary* produced two individual bipolar outflows that converge as the binary system fell to smaller separations. These individual outflows are launched from the individual circumstellar discs. Because the protostars in *Wide Binary* are in an initially highly eccentric orbit, when the stars pass each other at periastron, the circumstellar discs are disrupted, stopping the outflows.

It was the disruption of discs in *Wide Binary* that motivated the work presented in Chapter 3. The aim of that chapter was to study the evolution of discs during dynamical interactions, because gravitational truncation is believed to produce smaller circumstellar discs, as found by observations (Harris et al. 2012; Cox et al. 2017). In this chapter, I introduced turbulence to the initial velocity field of the simulated molecular cores, because they are observed to be turbulent (Ferrière 2001; Mac Low

& Klessen 2004; Padoan et al. 2014). I ran simulations of molecular core collapse where the initial velocity field had no turbulence (NT), as well as turbulence of levels Mach 0.1 (T1) and Mach 0.2 (T2). From these simulations we observed the disruption of circumstellar discs which later built circumbinary discs.

These simulations produced binaries that fell into orbits with semi-major axes of 10 – 20 AU after 5000 yr (see Figure 3.3). The introduction of turbulence produced weakly asymmetric binaries, and also delayed the absolute time taken for stars to form. This is likely due to the Jeans mass being larger for turbulent gas. Turbulence does not significantly influence the star formation efficiency, given all systems accreted similar mass over the course of the simulations. The simulations also show episodic accretion correlated with the periastron of the binary systems implying that the presence of a companion can trigger accretion events.

I found in the simulations from Chapter 3 that turbulence may hinder the launching of individual outflows (see Figure 3.1). In NT and T1, individual jets are launched from the circumstellar discs. The outflows from NT are symmetric while the outflows from T1 are asymmetric, with the disc around the primary component launching a jet first followed by the jet from the secondary component. T2 failed to launch individual jets which is likely due to the stronger turbulence disrupting the initial magnetic field structure. This stronger turbulence produced a less ordered field, which does not allow for the magnetocentrifugal mechanism to work efficiently. At later times, all simulations launch a single outflow with the turbulent simulations producing bulkier and faster outflows. The single outflow is launched from the circumbinary disc after the circumstellar discs have been destroyed.

NT produced the most massive outflows, while the outflows of T1 transported linear and angular momentum away from the systems most efficiently (see Figure 3.6). T2 produced the least efficient outflows. The outflow speed of NT remained relatively constant, while the outflow speed in the turbulent simulations grew by at least an order of magnitude over the course of the simulations. The low initial outflow speed in T1 and T2 is likely caused by the weakly ordered magnetic field and initially turbulent gas obstructing the outflow. At later times when a circumbinary disc is being established, the magnetic field is also being restructured, which allows for efficient launching. The regions above and below the circumbinary disc have

also been cleared by previous outflows, therefore jets can be ejected from the system easily.

All simulations had stars that hosted circumstellar discs that were later destroyed to form circumbinary discs. The circumstellar discs in the simulations had radii of ~ 10 AU. The discs are disrupted when the binary systems pass periastron and material is redistributed. In NT, the circumbinary material is diffuse and has little structure. In the turbulent simulations the interaction of the binary stars redistributes angular momentum, such that a circumbinary disc can form faster than in NT (see Figure 3.2). T2 produced the largest and most massive circumbinary disc.

The overall conclusion from these numerical projects is that, given the environment in which binary star systems form (fragmentation from turbulent molecular cores), it appears that the formation of circumbinary discs is common place. In contrast, other dynamical interactions would truncate circumstellar discs, producing smaller and harder to detect discs for smaller separation (< 40 AU as found by observations, Cieza et al. 2009; Kraus et al. 2012). It is also apparent that during the early stages of molecular core collapse binarity can hinder outflow launching, but so can other factors such as turbulence. While I showed that disc creation (circumstellar and circumbinary) is relatively easy in binary systems, we cannot draw conclusions about how long lived these discs are, because these simulations are so computationally intensive that they can only be followed for a few thousand years past protostar formation. My observational project was designed to investigate this question.

5.2 Summary of observational work: survivability of discs in binary star systems

This work aimed to gain insight into the typical lifetime of discs around binary stars. I did this by determining the multiplicity of disc-bearing stars in Upper Scorpius (US) and Upper Centaurus-Lupus (UCL). These regions were selected because they are significantly older than the typical protoplanetary disc lifetime determined from previous works (Haisch et al. 2001; Mamajek 2009), with ages of 11 Myr (Pecaut et al. 2012) and 17 Myr (Mamajek et al. 2002), respectively. The motivation is that if there were any systematic variation in disc lifetime around binary stars, compared

to single stars, this would be amplified at older ages. For a given population of disc-bearing stars, if the binary fraction was greater than that given by the field star multiplicity then this would suggest that discs around binary stars are longer lived. This is because the discs around single stars would have dispersed faster, increasing the binary fraction of disc-bearing stars. However, if the reverse was found, i.e. the binary fraction is much less than that of the field stars, then it would have suggested discs around binary stars are short lived.

I used infrared data from the *WISE* space satellite to search for IR excesses around objects in Upper-Scorpius and Upper Centaurus-Lupus. I then used the WiFeS spectrograph to search for radial velocity (RV) variation that would be caused by a binary star system. Due to the baseline of radial velocity measurements, the survey is restricted to the detection of binaries with periods up to 20 yr. The method employed to calculate radial velocities used cross-correlation with template spectra. This method also restricted the observable targets to spectral types later than F because sufficient spectral lines are needed to be able to cross-correlate with template spectra. Despite these restrictions I was able to observe 55 Upper Scorpius and 28 Upper Centaurus-Lupus members.

The median number of observations per target was four, which is not enough data to resolve a full orbit. The only targets that I could conclusively say were binary stars were the double-lined spectroscopic binaries RIK-96 and UCAC4-161328427 (see Figure 4.6). These two objects have very large IR excesses which may be indicative of these close binaries hosting large circumbinary discs. To properly determine the disc mass sub-millimetre observations would be necessary. For the other targets Bayesian statistics had to be incorporated to determine the likelihood of being a binary or a single star. From this Bayesian analysis we determined four more objects that were very likely to be binaries (UCAC4-445278523, UCAC4-447414452, UCAC4-1253626396 and UCAC4-450968247). We also identified 5 objects with Bayes factors between 1 and 10 meaning the likelihood of being a binary is greater than being a single star, but it is not at a level where we can be certain of their binarity. From the Bayes factors obtained for each object we determined the multiplicity of disc-bearing stars in Upper Scorpius and Upper Centaurus-Lupus to be $0.06^{+0.07}_{-0.02}$ and $0.13^{+0.06}_{-0.03}$, respectively. These values are consistent with our expected binary

fraction of $0.12^{+0.02}_{-0.01}$ to within one sigma (see Figure 4.8). This expectation value was calculated from the binary fraction per spectral type given from Raghavan et al. (2010). These results suggest that overall, the lifetime of discs do not differ between single and binary star systems.

Previous works looking at multiplicity and protoplanetary discs have mostly used direct imaging and this is one of the first using radial velocity to probe a parameter space not accessible by photometry: closer binaries with periods < 20 yr. Previous work, including Cieza et al. (2009); Kraus et al. (2012); Harris et al. (2012) and Cox et al. (2017), have been limited to binary separations of a few AU, maybe down to 5 AU, like Kraus et al. (2016). These surveys predominantly concerned the frequency of circumstellar discs in binary star systems, however, Harris et al. (2012) and Cox et al. (2017) do note some circumbinary discs found in their surveys. For the $1 - 2$ Myr Taurus-Auriga star forming region, Harris et al. (2012) find a multiplicity of disc-bearing stars to be $31\% - 36\%$, while Kraus et al. (2016), looking specifically at < 40 AU binaries, find a raw multiplicity of 22% . Looking at the $2 - 5$ Myr (Wilking et al. 2008) star forming region ρ Ophiuchus, Cox et al. (2017) find a raw multiplicity of disc-bearing objects to also be around one third (33%). These studies conclude that most (about $2/3$) of binaries disperse their discs within the first $2 - 3$ Myr however they have not investigated the survivability of the remaining discs which is what my observational study looked at. Previous studies have consistently concluded that there is a deficit of disc-bearing binaries for separations < 40 AU, however, this does not equate to a deficit at much smaller separations or shorter orbital periods, because these studies are unable to resolve down to these separations. Identifying whether a disc deficit persists to the shortest orbital periods is important to understanding the formation of close binaries and should make up the basis of future work.

Many works have looked at characterising the multiplicity of young stars, but have often ignored the presence of discs. Kounkel et al. (2016) looked at determining the multiplicity of stars in the $1 - 2$ Myr Orion Nebula Cloud (ONC) and $1.5 - 3$ Myr NGC 2264 for separations up to 10 AU. They find multiplicities of $5.3 \pm 1.2\%$ and $5.8 \pm 1.1\%$ for ONC and NGC 2264 respectively. My study and the study of Kounkel et al. (2016) explore the parameter space of close binaries. Given the multiplicity

of disc-bearing stars that we derive is higher than the multiplicity of stars found by Kounkel et al. (2016) is optimistic, supporting the longevity of discs in binary systems, despite the large age difference between the star forming regions observed. Kounkel et al. (2019) find a raw spectroscopic binary fraction of 8% after looking at 5007 low to intermediate mass stars ($\sim 0.05 - 1.5 M_{\odot}$) of ages between 1 – 100 Myr. However, of the 1882 disc-bearing Class II sources, they find a raw spectroscopic binary fraction of 5%, but this is for the whole sample within the large age range, therefore it is unwise to make a direct comparison with our fractions. What Kounkel et al. (2019) also find is a deficit of discs around SB2s, by around 50%, suggesting that disc material may be dispersed quicker around equal mass binaries compared to un-equal mass binaries. We find a similar deficit in my observational work, with only 2 of the 6 binaries found to be SB2s, which may suggest this deficit persists across many protostellar stages. If this is true, equal mass binaries may prove to be hostile environments for planet formation.

5.3 Summary of thesis

This thesis looked at the formation, evolution, and survivability of discs in binary star systems. My theoretical work finds that the formation of large circumbinary discs is likely to happen frequently, given the environment in which binary stars form. Binary stars form in turbulent molecular cores and turbulence assists in building large discs. The early collapse of binary stars also appears to produce weaker outflows, however other factors can also hinder the outflow efficiency, such as turbulence. Despite large circumbinary discs appearing to be easy to build, circumstellar discs find binaries to be a hostile environment due to dynamical interactions truncating the disc. I hypothesise that because circumstellar discs are disturbed by the presence of a companion star, but circumbinary discs are more common than equivalently sized discs around single stars, there is no significant difference between the lifetime of discs around single and binary stars. This is the result found by my observational work, which searched for binarity in disc-bearing objects and did not discriminate between circumstellar or circumbinary discs, because we did not have the tools to do so. The overall conclusion of this thesis is that in some scenarios binary stars produce hostile environments for planet formation via the destruction

of circumstellar discs, however, the formation of large circumbinary discs is possible which can provide a greater opportunity for planet formation.

5.4 Future work

While conducting the work that comprised this thesis more questions have been raised (as is the nature of research). Below I summarise some of the work that will continue to be investigated, as well as some other related future research projects.

5.4.1 Radiation feedback on the evolution of discs in binary systems

In previous sections I summarised the primary mechanisms that contribute to disc dispersal and lifetime as being: 1. Accretion; 2. Jets and outflows; 3. Photoevaporation; and 4. Dynamical interactions. During the work of this thesis I have neglected to investigate the effect of binarity on the radiation feedback and photoevaporation of discs. During my PhD I visited Hamburg observatory with the intent of incorporating the radiation module created by Buntmeyer et al. (2016) into **FLASH** and to study radiation feedback on star and disc formation and evolution.

This module integrates the equation of radiative transfer along a number of lines of sight (ray tracing). For a given parcel of gas, the intensity of the radiation field is described by $I(\mathbf{x}, \mathbf{n}(\theta, \phi), \nu)$ where $\mathbf{x}$ is the position of the parcel, $\mathbf{n}(\theta, \phi)$ is the direction of propagation and ν is the frequency of the radiation. The radiative transfer equation describes the change in intensities along a line of sight, which is dependent on the emission and absorption properties of the medium. It is easiest to describe the radiative transfer using the following:

$$\frac{dI(\mathbf{n})}{d\tau(\mathbf{n})} = S - I(\mathbf{n}), \quad (5.1)$$

where $I(\mathbf{n})$ and $\tau(\mathbf{n})$ are the intensity and optical depth, respectively, along the direction $\mathbf{n}$, and S is the *source function*. The source function is given as a ratio of the medium's emissivity (η_ν) and extinction coefficient (χ_ν), i.e. $S_\nu = \eta_\nu/\chi_\nu$, and allows for arbitrary contributions from thermal emission, as well as scattering. This would have a dependence on frequency, however, to save computational power, the Buntmeyer et al. (2016) module uses a 'grey' approximation which ignores any

dependence on frequency, hence why S is used instead of S_ν . The optical depth of a parcel of gas of size ds is given by the extinction coefficient of the gas by $d\tau = \chi ds$.

Successfully integrating this module into **FLASH** will allow the continuation of this project to study how a binary affects all aspects of disc evolution. The radiation feedback will contribute to radiative heating on outflows, changing the outflow efficiencies, and the temperature profile of discs which will influence how accretion occurs. Radiation feedback is also important for simply modelling photoevaporation in discs. The lifetime of a disc is ultimately determined by when the photoevaporation rate overtakes the accretion rate, and then how long it takes for photoevaporation to disperse the disc material. Alexander (2012) and Shadmehri et al. (2018) argue that the observed lower photoevaporation rate and steeper temperature gradient around binary stars suggest that circumbinary discs are longer lived than discs around single stars. The dispersal of circumstellar discs for separations > 30 AU is also likely to be dominated by photoevaporation (Rosotti & Clarke 2018).

5.4.2 Episodic accretion in young binary star systems

The simulations of Chapter 3 produced episodic accretion events correlated with the periastron of the binary system, shown in Figure 5.1. Episodic accretion caused by dynamical interactions with a companion is called the ‘binary trigger hypothesis’ and has been investigated via observations (Green et al. 2016). Episodic accretion events have also been investigated via simulations (Kuffmeier et al. 2018), but theoretical work focusing specifically on accretion triggered by a companion has mostly been studied via simulations with the accretion disc already established as an initial condition (Gómez de Castro et al. 2013; Muñoz & Lai 2016). The simulations of Chapter 3 are some of the first showing accretion correlated with the periastron of the binary beginning at the collapse of the molecular core (Figure 5.1).

In order to model this episodic accretion adequately we need to consider radiation feedback (as discussed in Section 5.4.1). With the Buntmeyer et al. (2016) module the radiation from sink particles can be calculated from protostellar evolution models (Offner et al. 2009; Klassen et al. 2012). However, radiation feedback during the early stages of star formation is dominated by accretion luminosity. I want to investigate the impact episodic accretion has on outflows and feedback during binary

star formation. I also want to study why accretion events are observed at some, but not all, periastron passages.

Previous simulations of this episodic accretion have failed to reproduce the accretion evolution of these events. An example is shown in Figure 5.2 where the simulations of Muñoz & Lai (2016) fail to reproduce the accretion behaviour observed in the binaries TWA 3A (Tofflemire et al. 2017) and DQ Tau (Tofflemire

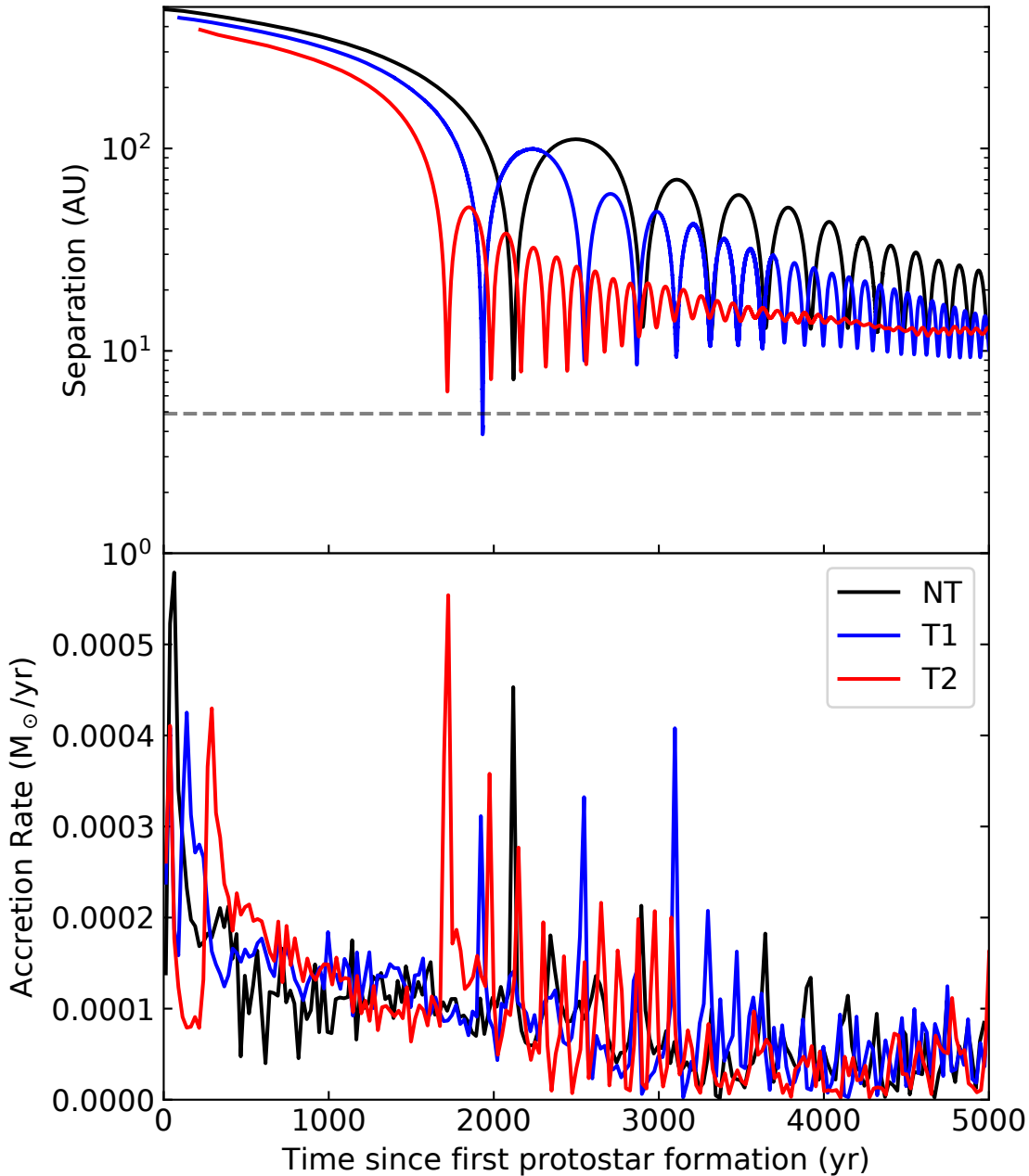


Figure 5.1: The top panel shows the separations of the binary components and the bottom panel shows the accretion rate. NT, T1 and T2 are simulations with no turbulence and turbulence of Mach 0.1 and Mach 0.2 respectively. We see accretion events correlated with the periastron of the systems formed in Chapter 3.

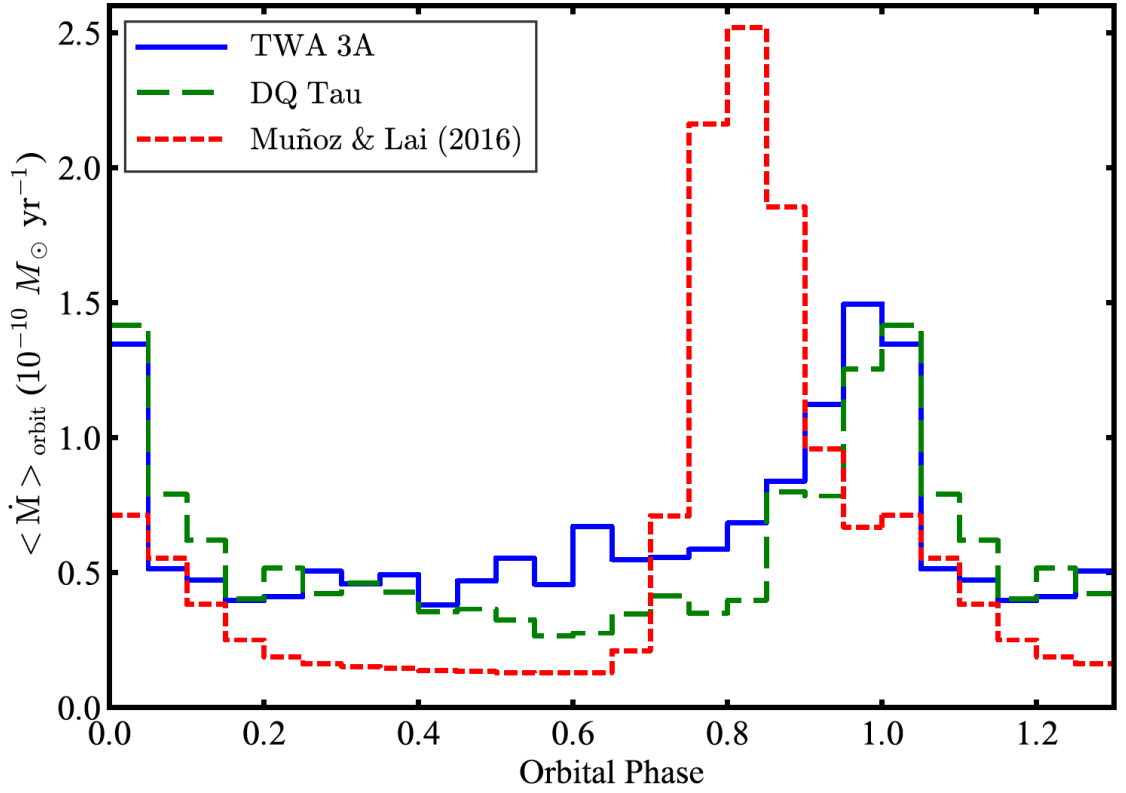


Figure 5.2: Measured accretion rate of the short period binaries TWA 3A (34.87 day, Tofflemire et al. 2017) and DQ Tau (15.8 day, Tofflemire et al. 2017) in the solid blue line and long dashed green line, respectively. This observational data is phase-folded around the orbital period of the binary. The short dashed red line shows the accretion evolution found by simulations of Muñoz & Lai (2016). Taken from Tofflemire et al. (2017).

et al. 2017). These binaries are actively accreting from a circumbinary disc and show an increased accretion rate at periastron (i.e. when orbital phase 0.0 or 1.0.). These simulations underestimate the quiescent accretion rate, while overestimating the maximum accretion rate and the time of peak accretion. This discrepancy between the simulations and observations is likely due to missing physics. The simulations of Muñoz & Lai (2016) neglect magnetic fields, which funnel material onto the stars (Koenigl 1991). Other physics such as radiation feedback could also play a role in shaping the accretion behaviour in circumbinary discs.

In this project I want to study further the episodic accretion seen in the simulations of Chapter 3 and try to replicate the behaviour observed in binaries accreting from circumbinary discs. Being able to model this accretion behaviour accurately will also enable adequate modelling of accretion luminosity and radiation feedback.

5.4.3 Disc evolution during three-body interactions

Following the hypothesis that short period binaries form via interactions with a tertiary companion (Armitage & Clarke 1997; Kiseleva et al. 1998; Reipurth 2000; Moe & Kratter 2018), I would like to investigate the survivability of discs during such dynamical evolution. Very short period binaries ($P \approx 1 - 10$ day; $a < 0.1$ AU) cannot form from cloud or disc fragmentation alone because the radius of the initial hydrostatic stellar core (~ 5 AU) is larger than the binary separation. Therefore, mechanisms such as the ejection of a tertiary companion or orbital evolution via the Kozai-Lidov mechanism are employed to explain the formation of these short period binaries (Bate et al. 2002).

While in some cases the ejection of a companion may disrupt discs in young binary systems, we know of short period binaries that host circumbinary discs. For example, the systems AK Sco and DQ Tau are two short period binaries (~ 13 and ~ 16 day respectively, Günther & Kley 2002). AK Sco and V4046 Sgr are also very old with ages of 18 ± 1 Myr (Czekala et al. 2015) and $10 - 20$ Myr (Rodriguez et al. 2010), respectively. These systems host circumbinary discs, from which they are accreting.

If these systems formed via dynamical evolution with a third body, did the circumbinary discs survive the interaction or form at later stages? The systems mentioned here may be atypical when considering dynamical interactions of young multiple systems, and in most cases, discs may be completely destroyed. Because of this I would like to better understand the survivability of discs during these interactions and determine what the impact would be on the accretion and formation of the stellar components as well as implications for planet formation.

Recent three-body interactions have also been hypothesised as triggers for protostellar outburst events. Wang et al. (2004) discovered a companion with close projected separation to the object FU Orionis (the namesake of the FUor outburst class), shown in Figure 5.3. Reipurth & Aspin (2004) suggest that a recent three-body interaction where this companion was ejected may have triggered the FUor outburst. The interaction with the third body could have deposited mass into the binary system and disrupted the discs heavily, leading to these long period outbursts. FLASH brings the computational capabilities to model multi-body interactions very

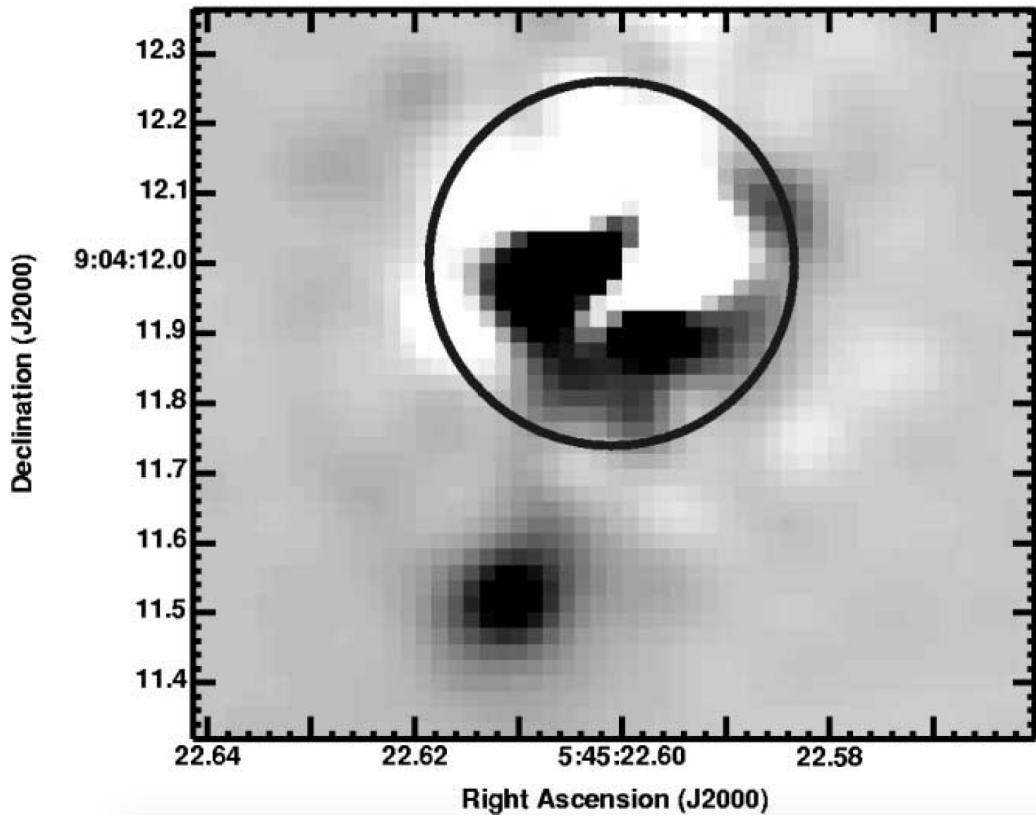


Figure 5.3: Shows an AO-assisted K' -band image obtained at Subaru for FU Orionis. The circle highlights FU Orionis which was partially subtracted by rotating the image and subtracting itself. The black object in the lower left is the companion discovered Wang et al. (2004).

accurately, because of the sub-cycling in the time-step procedure implemented in the sink particle technique (Federrath et al. 2010).

5.5 Final remarks

In the age of the *transiting exoplanet survey satellite* (TESS) and instruments such as ALMA, we are beginning to characterise the various environments that planets exist in and better resolve the discs in which they form. Through ALMA in particular we can resolve the magnetic field structure down to 10 AU scales, revealing highly complex and turbulent field geometries. However, many open questions remain such as: what is the frequency of circumbinary planets? What is the typical lifetime of discs in binary systems? And how do they build up mass and evolve?

Developing systematic methods to detect circumbinary planets is crucial to learn

about their statistics. All circumbinary planets detected to date have been discovered by chance or ‘eye-balling’ data. Archives of data from the *Kepler* space telescope are freely available and provide the ideal testing grounds for some techniques to identify circumbinary planets. However, this restricts us to systems where the binary and planets are aligned to our line of sight.

Surveys such as SOLARIS (Konacki et al. 2011) and TATOOINE (Konacki et al. 2009) use binary eclipse time variations and RV measurements of non-eclipsing, double-lined spectroscopic binaries to search for circumbinary planets. These techniques get past the need to have aligned systems (a drawback of the transit method). These detection methods will help to characterise circumbinary planets in misaligned orbits. However, neither survey has yet discovered circumbinary planets. This is probably due to the radial velocity signal of a planet being significantly weaker than that of the binary star system and precision radial velocity measurements are needed.

With better instrument sensitivity leading to higher precision RV measurements and photometry, more circumbinary planets will be discovered in the coming years, allowing us to understand the configurations they exist in.

The evolution of discs in binaries requires further investigation. Observations find discs in binaries to exist in various orientations (e.g. aligned like AK Sco (Czekala et al. 2015) or highly misaligned like IRS 43 (Brinch et al. 2016) and HD 98800 (Kennedy et al. 2019)) and simulations need to reproduce these systems. Typical simulations of discs in binaries, particularly evolution of circumbinary discs, have initial conditions where the circumbinary disc is already established, i.e. the binary has been ‘put in by hand’. Understanding the initial formation of these discs and the distribution of these discs remains an open question.

With increasing computing power, we are able to incorporate more physics into simulations, such as non-ideal MHD, radiation, and dust particles. These simulations still have to use some approximations to be able to run efficiently, but computational astrophysics is slowly improving to produce more realistic results. These simulations should be utilised to study how the temperature structures and accretion mechanisms in discs are influenced by interactions with companions. This will ultimately allow us to understand protostellar growth in multiple-star systems and

how planet formation environments vary with the presence of companions.

The work conducted in this thesis has contributed to understanding the disc evolution in binary star systems. While there are still many open questions about this topic, the future is bright. Improvements in both observations and computational power will lead to a better understanding of ‘the formation, evolution, and survivability of discs around young binary stars’.

6

Appendix

Appendix

This chapter is a compilation of appendices published in Kuruwita et al. (2017) and Kuruwita et al. (2018).

A Convergence tests for numerical simulations

Here we present the resolution study carried out prior to our research of the three scenarios in order to determine an appropriate resolution to carry out the study. Here we measured the outflow mass (Figure A1), momentum (Figure A2) and angular momentum (Figure A3) of outflow mass and maximum speed (Figure A4) of outflow mass by measuring the quantities flowing through two measuring cylinders. The cylinders have radii of 500 AU and extend to height 3300 AU from the mid-plane, and are placed 250 AU above and below the disc mid-plane. Within the volumes outflow mass is defined as any mass in cells with $v_z > 0$ for $z > 0$ and $v_z < 0$ for $z < 0$. From the outflow mass, the angular momentum and linear momentum of the outflows is calculated. The linear momentum is calculated from the magnitude of the velocity and the outflow mass. The angular momentum is calculated about the centre of mass of the systems. .

When looking at these resolution studies we see that the simulations have not converged. This is not a major issue as the overall purpose of this study is to

determine the influence binarity may have on outflow morphology and momentum transport efficiencies.

When we look at Figure A4 we see that the maximum outflow speed increases and the outflow mass reaches the measuring volume earlier with greater resolution. This is expected, because with higher resolution we are resolving the inner regions of the disc where higher velocity winds are launched. We see this trend of increasing velocity in all three cases.

When looking at the other measured quantities in this resolution study, we see that lower resolution simulation ($L_{\text{ref}} = 10, 11$) do not appear to reach a saturation level in the 3000 yr after protostar formation. However the simulations with resolution $L_{\text{ref}} \gtrsim 12$, despite not reaching a plateau in their runtimes, have converged towards the measured quantities of the previous level of refinement in the duration of the simulation.

A level of refinement of $L_{\text{ref}} = 12$ is chosen in our simulations as it allows us to run a simulation for a few thousand years after protostar formation which also resolves a strong jet component in *Single Star*.

With *Wide Binary*, when looking at the angular momentum we see a dip which is occurs when the sink particles are at periastron after sink particle formation. There is some resolution dependence on this dip because with higher resolution the sink particles form sooner and fall into each other, towards periastron at earlier times.

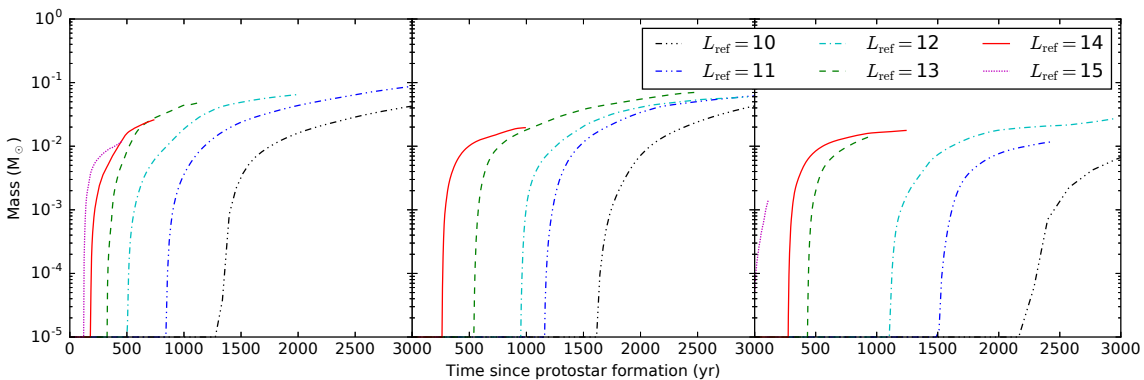


Figure A1: Outflow mass measured as described in Section 2.4.3 for *Single Star* (left), *Tight Binary* (middle) and *Wide Binary* (right). This was measured for levels of refinement of $L_{\text{ref}} = 10$ (dash-dash-dash-dot line), $L_{\text{ref}} = 11$ (dash-dash-dot line), $L_{\text{ref}} = 12$ (dash-dot line), $L_{\text{ref}} = 13$ (dashed line), $L_{\text{ref}} = 14$ (solid line) and $L_{\text{ref}} = 15$ (dotted line)

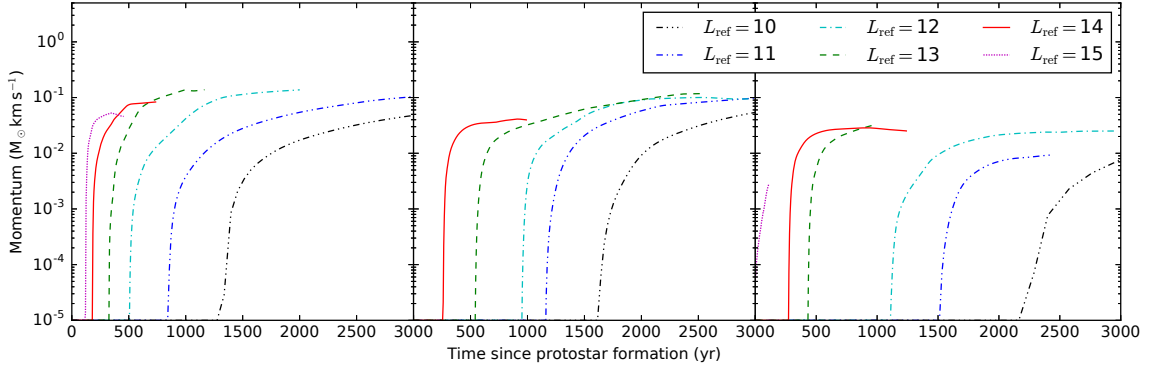


Figure A2: Same as Figure A1 but for the linear momentum carried by the outflow mass

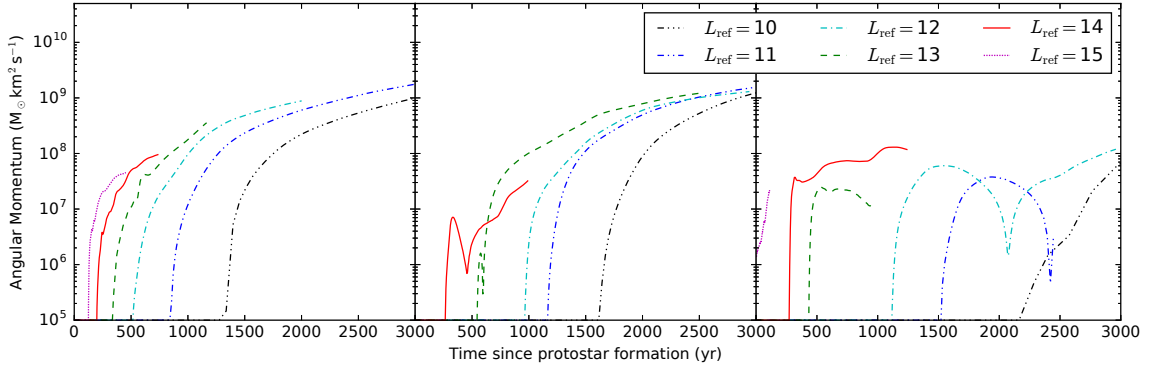


Figure A3: Same as Figure A1 but for the angular momentum carried by the outflow mass

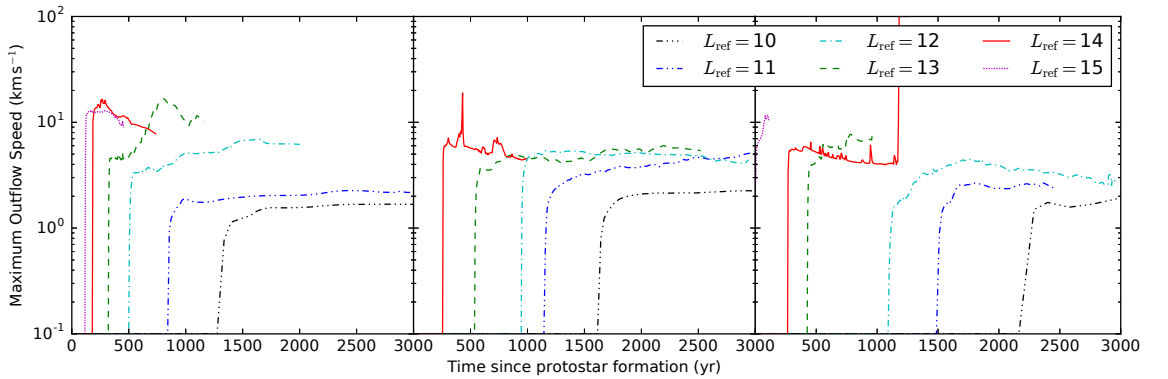


Figure A4: Same as Figure A1 but for the maximum velocity of the outflow mass.

B Summary of targets observed

Listed in Table B1 is the J and K magnitudes for our targets taken from the 2MASS survey (Skrutskie et al. 2006). The W4 magnitude is taken from the AllWISE source catalogue (Wright et al. 2010). We use Gaia (Gaia Collaboration et al. 2016, 2018) to obtain Gaia magnitudes (G Mag) as well as Blue band (BP) and Red band (RP) photometry.

Listed in Table B2 is the full list of targets observed in this survey. The probability of membership, $P(M)$, is calculated based on the calculations of Rizzuto et al. (2011) and Rizzuto et al. (2015) which uses kinematic and spatial information to assign a probability (see Section 4.3.1). Δv_r is the observed radial velocity variation over all epochs. The radial velocity variation is taken to be the difference between the epoch with the highest radial velocity and the epoch with the lowest radial velocity, (see Equation 4.1). Υ is the Bayes factor calculated as described in Section 4.4.2. A binary star model is preferred if $\Upsilon \gg 1$ and a single star model is preferred if $\Upsilon \ll 1$. Where $\Upsilon \approx 1$, either model is equally probable. We take objects with Bayes factors > 300 to be binary stars as this is near the 3σ confidence level assuming a Gaussian probability distribution.

Table B1: Magnitudes of our targets. J and K magnitudes are taken from the 2MASS survey. $W4$ magnitude is taken from the AllWISE source catalogue. The G , BP and RP magnitudes are taken from the Gaia survey.

Object	RA	DEC	J	K	$W4$	G	BP	RP
UCAC4-827387234	13 54 35.61	-43 56 48.1	11.638	10.708	7.732	14.467	15.952	13.276
UCAC4-467124593	14 10 59.69	-46 11 33.8	11.196	10.343	5.567	14.351	16.074	13.088
UCAC4-947158099	14 14 52.40	-57 22 54.0	13.262	12.2	7.93	15.941	17.135	14.865
UCAC4-382098779	14 16 03.10	-40 30 34.2	11.014	10.149	8.202	13.939	15.461	12.718
UCAC4-945204860	14 27 30.11	-60 42 18.0	12.588	11.492	6.418			
UCAC4-442012351	14 34 36.62	-45 45 59.9	11.725	10.845	7.995	14.813	16.229	13.461
UCAC4-371257082	14 41 37.66	-37 56 34.4	11.746	10.837	7.065	14.545	15.975	13.37
UCAC4-371337294	14 44 15.62	-40 32 27.3	11.654	10.766	6.344			
UCAC4-21594717	14 50 55.74	-35 04 22.9	10.892	10.055	7.293	12.948	13.802	12.056
UCAC4-365499547	15 24 35.62	-39 30 43.3	11.56	10.691	8.169	14.582	16.145	13.341
UCAC4-445278523	15 29 17.48	-46 36 28.7	12.51	11.574	8.358			
UCAC4-23251943	15 29 23.88	-34 11 54.5	11.535	10.637	7.338			
UCAC4-23288203	15 30 33.57	-32 46 19.1	11.08	10.174	7.504	13.758	14.996	12.636
UCAC4-447414452	15 37 22.69	-40 17 59.6	8.796	7.771	2.818	10.218	10.688	9.616
UCAC4-333669217	15 45 09.50	-15 40 29.0	11.808	10.795	6.576	15.126	17.031	13.793
UCAC4-161328427	15 46 25.81	-31 43 19.3	11.468	10.605	6.305	14.511	16.174	13.266
UCAC4-30196323	15 48 24.44	-22 35 49.7	11.868	10.732	6.385	15.303	17.156	13.978
UCAC4-30231541	15 49 19.76	-22 57 29.7	10.534	9.536	6.909	13.884	15.719	12.584
UCAC4-1297314504	15 49 30.74	-35 49 51.4	10.96	10.022	5.274	13.876	15.305	12.686
UCAC4-408863727	15 52 08.84	-27 23 45.8	11.996	11.019	6.946	15.294	16.951	14.045
UCAC4-1019544336	15 52 13.44	-39 56 08.2	11.705	10.828	7.112	14.595	16.079	13.402
RIK-23	15 56 42.45	-20 39 34.2	11.313	10.28	4.628	14.496	16.086	13.223
RIK-30	15 57 34.31	-23 21 12.3	9.932	8.992	5.576	12.715	13.97	11.601
UCAC4-519496506	15 57 43.61	-41 43 37.8	9.825	8.743	4.713	12.037	12.895	11.137
UCAC4-426579903	15 57 54.45	-24 50 42.4	9.51	8.578	3.118	11.776	12.518	10.899
UCAC4-404438620	15 57 58.92	-18 14 59.6	9.991	8.92	3.8	12.3	13.221	11.353
RIK-34	15 58 12.70	-23 28 36.4	8.574	8.018	6.722	10.073	10.586	9.439
UCAC4-519508031	15 58 20.40	-40 33 05.8	10.563	9.582	4.381	13.721	14.982	12.502
RIK-38	15 58 36.20	-19 46 13.5	11.697	10.721	4.701	14.878	16.626	13.605
RIK-43	15 59 44.27	-20 29 23.4	11.522	10.405	6.116	14.969	16.912	13.642
UCAC4-404466245	15 59 44.59	-21 55 25.1	11.975	11.01	7.644	15.461	17.394	14.093
RIK-56	16 01 13.99	-25 16 28.2	11.357	10.419	6.805	14.798	15.561	13.121
RIK-58	16 01 29.03	-25 09 06.9	11.186	10.084	5.341			

UCAC4-4552391	16 02 05.18	-23 31 06.9	11.73	10.673	5.962	15.057	16.919	13.768
RIK-65	16 02 35.89	-23 20 17.1	11.163	10.202	7.406	14.32	15.94	13.069
UCAC4-423900944	16 03 30.72	-40 24 34.0	11.027	10.016	6.393	14.096	15.72	12.858
RIK-77	16 04 18.93	-24 30 39.3	9.975	8.853	4.522			
UCAC4-1264898768	16 05 06.46	-17 34 02.1	11.755	10.785	5.4	15.193	16.892	13.807
RIK-78	16 05 21.57	-18 21 41.2	9.263	8.134	3.156	11.745	12.398	10.756
UCAC4-39082833	16 05 44.04	-34 37 59.0	10.572	9.721	7.28	12.631	13.444	11.753
UCAC4-415825814	16 06 23.82	-18 07 18.4	11.441	10.38	5.287	14.61	16.327	13.345
RIK-80	16 06 43.86	-19 08 05.5	10.137	9.195	6.79	12.625	13.602	11.626
RIK-81	16 06 47.94	-18 41 43.8	9.886	8.979	3.927	12.062	12.912	11.161
UCAC4-39156047	16 07 08.52	-32 01 01.1	11.22	10.141	5.047	13.704	14.95	12.603
RIK-82	16 07 14.02	-17 02 42.7	11.754	10.754	6.471	14.858	16.505	13.609
UCAC4-853813426	16 07 52.31	-38 58 06.1	11.012	10.009	5.945	14.029	15.56	12.817
UCAC4-853849672	16 08 30.70	-38 28 26.8	8.974	8.225	3.07	10.67	11.258	9.965
RIK-96	16 09 31.66	-22 29 22.4	10.143	9.148	4.228	13.08	14.475	11.903
RIK-102	16 10 05.02	-21 32 31.9	10.069	8.951	3.643	12.503	13.435	11.529
UCAC4-415948957	16 10 14.46	-19 51 37.5	11.214	10.234	7.947	14.4	16.073	13.144
UCAC4-415950015	16 10 19.04	-21 24 25.0	11.743	10.738	5.823	15.097	17.003	13.775
UCAC4-415970246	16 10 43.92	-20 32 02.6	11.401	10.204	6.596	15.141	16.81	13.581
RIK-111	16 11 26.03	-26 31 55.9	10.563	9.568	5.98	12.989	14.228	11.846
RIK-112	16 12 05.05	-20 43 40.5	10.102	9.065	5.931	12.581	13.554	11.591
RIK-113	16 12 06.68	-30 10 27.1	10.35	9.317	3.604	14.028	15.494	12.829
RIK-124	16 13 21.91	-21 36 13.7	11.014	9.977	5.409			
RIK-138	16 14 52.41	-25 13 52.4	11.492	10.454	7.522	15.036	16.465	13.459
RIK-146	16 15 32.20	-20 10 23.7	10.158	8.908	4.571			
UCAC4-39632762	16 15 35.05	-34 32 01.4	11.082	10.167	6.508	13.573	14.608	12.555
UCAC4-416216449	16 16 46.89	-20 33 32.4	11.585	10.511	5.921	14.955	16.766	13.658
UCAC4-416217728	16 16 50.82	-20 09 08.2	10.604	9.429	5.183	13.776	15.261	12.527
UCAC4-416239730	16 17 18.90	-22 30 01.7	11.327	10.309	5.638			
UCAC4-39740614	16 17 49.05	-32 55 14.6	10.107	9.023	4.551	13.332	14.181	11.911
UCAC4-1056352275	16 18 06.62	-41 26 32.5	10.67	9.666	6.273			
UCAC4-160914413	16 19 10.09	-24 32 08.9	11.345	10.234	5.559	14.792	16.69	13.478
RIK-183	16 20 06.16	-22 12 38.5	11.608	10.653	7.204	14.686	16.287	13.455
UCAC4-416359472	16 20 22.91	-22 27 04.1	11.189	10.181	6.632	14.309	15.802	13.091
UCAC4-1253626396	16 21 57.69	-24 29 43.5	8.124	7.587	6.111	9.89	10.466	9.179
UCAC4-1253629107	16 22 01.97	-25 22 20.4	13.334	12.215	6.232			
UCAC4-599700591	16 22 11.00	-48 41 38.5	12.53	11.413	6.932			
UCAC4-64946760	16 22 39.58	-35 13 06.0	11.882	10.89	6.553	15.009	16.723	13.742
RIK-223	16 25 28.81	-26 07 53.8	10.885	9.854	7.428	13.848	15.309	12.659
RIK-239	16 27 12.74	-25 04 01.8	10.553	9.382	5.483	13.546	14.904	12.39
UCAC4-450968247	16 28 34.97	-20 19 11.1	11.444	10.496	8.223	14.231	15.338	13.173
UCAC4-379613161	16 29 28.82	-25 00 25.0	13.099	11.914	7.927	16.289	17.511	15.128
UCAC4-455511949	16 30 03.71	-42 26 58.7	10.021	8.828	4.243	12.535	13.567	11.529
UCAC4-496722210	16 30 37.96	-29 54 22.4	9.05	8.385	5.71	10.567	11.139	9.89
UCAC4-60335445	16 30 42.12	-26 23 03.9	11.703	10.68	7.804	15.005	16.632	13.685
RIK-250	16 33 34.97	-18 32 53.9	11.314	10.397	7.724	14.444	16.047	13.209
UCAC4-31196367	16 35 11.73	-22 57 28.1	12.127	11.172	5.961	14.712	15.648	13.726
UCAC4-456216791	16 35 27.22	-43 25 27.9	13.843	12.663	6.799			
UCAC4-60621830	16 36 46.51	-25 02 03.3	10.062	8.899	4.618	12.825	14.05	11.733
UCAC4-1067529427	16 45 28.96	-25 02 47.7	11.214	10.274	4.95	14.423	16.055	13.146
UCAC4-431964534	16 46 56.03	-32 42 54.0	10.283	9.47	7.202	12.39	13.218	11.506

Table B2: Full list of objects observed in this survey. P(M) indicates the probability of membership to the listed region, based on Rizzuto et al. (2015) which uses proper motion and Bayesian analysis to determine a probability. An object has is given the label: N lists the number of observations obtained over the course of this survey. Temp. SpT. lists the spectral type of preferred template used to obtain radial velocities (see Section 2.3.3). $\langle v_r \rangle$ is the mean radial velocity over all epochs. Δv_r is the radial velocity variation taken to be the difference between epochs with the highest and lowest radial velocity. The Bayes' factor calculated from the Bayesian analysis described in Section 3.3. is the ratio of likelihoods of being a binary star to being a single star.

Object	Reg.	RA	DEC	P(M)	Disc?	N	Temp. SpT.	$\langle v_r \rangle$	Δv_r	Γ (binary?)
UCAC4-827387234	UCL	13 54 35.61	-43 56 48.1	77	YY	5	M2.5V	11.22	3.52	0.53(N)
UCAC4-467124593	UCL	14 10 59.69	-46 11 33.8	45	YY	5	M2.5V	9.99	4.61	0.52(N)
UCAC4-947158099	UCL	14 14 52.40	-57 22 54.0	72	YY	3	K6Va	-18.43	9.52	1.62(N)
UCAC4-382098779	UCL	14 16 03.10	-40 30 34.2	67	YY	4	M2.5V	5.42	6.06	0.65(N)
UCAC4-945204860	UCL	14 27 30.11	-60 42 18.0	73	YY	2	K3+V	-19.61	1.8	0.59(N)
UCAC4-442012351	UCL	14 34 36.62	-45 45 59.9	53	YY	4	M2.5V	13.02	7.42	0.94(N)
UCAC4-371257082	UCL	14 41 37.66	-37 56 34.4	58	NY	3	M2.5V	6.94	6.98	0.58(N)
UCAC4-371337294	UCL	14 44 15.62	-40 32 27.3	68	YY	3	M2.5V	8.51	2.26	0.54(N)
UCAC4-21594717	UCL	14 50 55.74	-35 04 22.9	25	YY	4	K6Va	5.08	2.39	0.4(N)
UCAC4-365499547	UCL	15 24 35.62	-39 30 43.3	55	YY	4	M2.5V	8.06	4.28	0.61(N)
UCAC4-445278523	UCL	15 29 17.48	-46 36 28.7	69	YY	3	G5V	2.46	70.28	>1000(Y)
UCAC4-23251943	UCL	15 29 23.88	-34 11 54.5	85	YY	4	M2.5V	6.48	2.22	0.52(N)
UCAC4-23288203	UCL	15 30 33.57	-32 46 19.1	57	YY	4	M1.5	8.36	2.82	0.51(N)
UCAC4-447414452	UCL	15 37 22.69	-40 17 59.6	70	YY	5	K0V	6.12	12.95	>1000(Y)
UCAC4-333669217	US	15 45 09.50	-15 40 29.0	83	YY	4	M2.5V	0.15	6.99	0.58(N)
UCAC4-161328427	UCL	15 46 25.81	-31 43 19.3	41	YY	4	M2.5V	5.2	76.67	>1000(Y)
UCAC4-30196323	US	15 48 24.44	-22 35 49.7	93	YY	4	M2.5V	-0.89	3.21	0.53(N)
UCAC4-30231541	US	15 49 19.76	-22 57 29.7	97	YY	4	M2.5V	0.25	4.65	0.5(N)
UCAC4-1297314504	UCL	15 49 30.74	-35 49 51.4	84	YY	4	M2.5V	3.14	4.34	0.5(N)
UCAC4-408863727	US	15 52 08.84	-27 23 45.8	87	YY	4	M2.5V	4.8	8.5	0.6(N)
UCAC4-1019544336	UCL	15 52 13.44	-39 56 08.2	81	YY	4	M2.5V	8.39	1.17	0.51(N)
RIK-23	US	15 56 42.45	-20 39 34.2	98	YY	5	M2.5V	-2.24	3.76	0.44(N)
RIK-30	US	15 57 34.31	-23 21 12.3	-1	NY	4	M1.5	-0.97	6.83	0.56(N)
UCAC4-519496506	UCL	15 57 43.61	-41 43 37.8	63	YY	4	K6Va	-0.09	2.42	0.34(N)
UCAC4-426579903	US	15 57 54.45	-24 50 42.4	85	YY	5	K3.5V	-5.24	4.73	0.37(N)
UCAC4-404438620	US	15 57 58.92	-18 14 59.6	91	YY	4	K6Va	-4.24	1.88	0.3(N)
RIK-34	US	15 58 12.70	-23 28 36.4	82	NY	6	G7.5IV-V	-4.86	1.72	0.15(N)
UCAC4-519508031	UCL	15 58 20.40	-40 33 05.8	38	YY	5	M2.5V	3.38	2.14	0.42(N)
RIK-38	US	15 58 36.20	-19 46 13.5	95	YY	4	M2.5V	0.02	5.36	0.49(N)
RIK-43	US	15 59 44.27	-20 29 23.4	88	YY	7	M2.5V	-3.14	9.08	0.54(N)
UCAC4-404466245	US	15 59 44.59	-21 55 25.1	90	YY	2	M2.5V	-2.55	2.15	0.62(N)
RIK-56	US	16 01 13.99	-25 16 28.2	-1	YY	6	M2.5V	1.27	2.76	0.41(N)
RIK-58	US	16 01 29.03	-25 09 06.9	-1	YY	6	M2.5V	-2.8	3.58	0.41(N)
UCAC4-4552391	US	16 02 05.18	-23 31 06.9	97	YY	4	M2.5V	0.18	3.56	0.53(N)
RIK-65	US	16 02 35.89	-23 20 17.1	94	YY	4	M2.5V	-1.42	0.39	0.47(N)
UCAC4-423900944	UCL	16 03 30.72	-40 24 34.0	29	YY	5	M2.5V	5.6	1.83	0.45(N)
RIK-77	US	16 04 18.93	-24 30 39.3	-1	YY	4	M2.5V	-2.42	5.28	0.5(N)
UCAC4-1264898768	US	16 05 06.46	-17 34 02.1	94	YY	3	M2.5V	0.91	5.15	0.64(N)
RIK-78	US	16 05 21.57	-18 21 41.2	79	YY	4	K6Va	-3.99	2.51	0.32(N)
UCAC4-39082833	UCL	16 05 44.04	-34 37 59.0	51	YY	4	K6Va	3.87	1.16	0.37(N)
UCAC4-415825814	US	16 06 23.82	-18 07 18.4	86	YY	4	M2.5V	-2.76	6.54	0.53(N)
RIK-80	US	16 06 43.86	-19 08 05.5	85	YY	5	K6Va	-4.83	2.53	0.27(N)
RIK-81	US	16 06 47.94	-18 41 43.8	72	YY	5	K6Va	-3.24	4.21	0.45(N)
UCAC4-39156047	US	16 07 08.52	-32 01 01.1	87	YY	4	M1.5	5.32	8.88	0.86(N)
RIK-82	US	16 07 14.02	-17 02 42.7	97	YY	4	M2.5V	-0.42	4.77	0.52(N)
UCAC4-853813426	UCL	16 07 52.31	-38 58 06.1	74	YY	4	M2.5V	2.56	3.99	0.46(N)
UCAC4-853849672	UCL	16 08 30.70	-38 28 26.8	29	NY	4	K3.5V	1.58	0.88	0.29(N)
RIK-96	US	16 09 31.66	-22 29 22.4	92	YY	6	M1.5	14.62	42.37	>1000(Y)
RIK-102	US	16 10 05.02	-21 32 31.9	91	YY	4	K6Va	-5.43	1.92	0.38(N)
UCAC4-415948957	US	16 10 14.46	-19 51 37.5	78	NY	3	M2.5V	-0.14	2.97	0.56(N)
UCAC4-415950015	US	16 10 19.04	-21 24 25.0	92	YY	3	M2.5V	-4.3	1.87	0.65(N)
UCAC4-415970246	US	16 10 43.92	-20 32 02.6	83	YY	2	M2.5V	0.16	2.18	0.71(N)
RIK-111	US	16 11 26.03	-26 31 55.9	96	YY	4	M2.5V	0.8	1.75	0.43(N)
RIK-112	US	16 12 05.05	-20 43 40.5	95	YY	4	M1.5	-1.87	4.36	0.46(N)
RIK-113	US	16 12 06.68	-30 10 27.1	73	YY	5	M1.5	1.75	2.64	0.41(N)

RIK-124	US	16 13 21.91	-21 36 13.7	93	YY	4	M2.5V	-0.61	2.41	0.49(N)
RIK-138	US	16 14 52.41	-25 13 52.4	97	YY	3	M2.5V	-0.36	2.58	0.55(N)
RIK-146	US	16 15 32.20	-20 10 23.7	-1	YY	7	M2.5V	-2.3	13.12	0.39(N)
UCAC4-39632762	US	16 15 35.05	-34 32 01.4	83	NY	4	K6Va	5.55	2.53	0.42(N)
UCAC4-416216449	US	16 16 46.89	-20 33 32.4	97	YY	3	M2.5V	-0.03	3.45	0.63(N)
UCAC4-416217728	US	16 16 50.82	-20 09 08.2	73	YY	3	M2.5V	-2.79	1.62	0.63(N)
UCAC4-416239730	US	16 17 18.90	-22 30 01.7	94	YY	3	M2.5V	-2.89	4.81	0.66(N)
UCAC4-39740614	US	16 17 49.05	-32 55 14.6	94	YY	5	M1.5	4.37	9.87	3.84(N)
UCAC4-1056352275	UCL	16 18 06.62	-41 26 32.5	82	YY	4	M2.5V	3.02	3.51	0.48(N)
UCAC4-160914413	US	16 19 10.09	-24 32 08.9	95	YY	3	M2.5V	2.05	4.09	0.6(N)
RIK-183	US	16 20 06.16	-22 12 38.5	96	YY	4	M2.5V	1.25	3.88	0.46(N)
UCAC4-416359472	US	16 20 22.91	-22 27 04.1	91	YY	3	M2.5V	-2.72	8.62	0.96(N)
UCAC4-1253626396	US	16 21 57.69	-24 29 43.5	80	NY	5	M1V	11.13	26.3	>1000(Y)
UCAC4-1253629107	US	16 22 01.97	-25 22 20.4	57	YY	3	K0V	0.67	15.0	6.31(N)
UCAC4-599700591	UCL	16 22 11.00	-48 41 38.5	77	YY	2	K3+V	-57.93	9.28	1.42(N)
UCAC4-64946760	US	16 22 39.58	-35 13 06.0	88	YY	2	M2.5V	3.32	2.1	0.62(N)
RIK-223	US	16 25 28.81	-26 07 53.8	97	NY	3	M2.5V	0.37	1.22	0.51(N)
RIK-239	US	16 27 12.74	-25 04 01.8	-1	YY	3	M1.5	-1.41	1.15	0.49(N)
UCAC4-450968247	US	16 28 34.97	-20 19 11.1	92	NY	3	G7.5IV-V	-22.0	43.28	>1000(Y)
UCAC4-379613161	US	16 29 28.82	-25 00 25.0	86	YY	3	K3V	22.72	4.87	0.58(N)
UCAC4-455511949	UCL	16 30 03.71	-42 26 58.7	59	YY	3	K6Va	-0.83	2.06	0.37(N)
UCAC4-496722210	US	16 30 37.96	-29 54 22.4	30	YY	3	K3+V	-1.53	1.48	0.36(N)
UCAC4-60335445	US	16 30 42.12	-26 23 03.9	97	YY	2	M2.5V	0.62	1.32	0.67(N)
RIK-250	US	16 33 34.97	-18 32 53.9	96	YY	2	M2.5V	-1.17	4.39	0.7(N)
UCAC4-31196367	US	16 35 11.73	-22 57 28.1	63	YY	3	G5V	3.1	5.77	1.3(N)
UCAC4-456216791	UCL	16 35 27.22	-43 25 27.9	56	YY	3	K6Va	-26.65	5.66	0.56(N)
UCAC4-60621830	US	16 36 46.51	-25 02 03.3	89	YY	4	M1.5	-1.28	3.15	0.48(N)
UCAC4-1067529427	US	16 45 28.96	-25 02 47.7	94	YY	3	M2.5V	-3.29	3.45	0.63(N)
UCAC4-431964534	UCL	16 46 56.03	-32 42 54.0	61	YY	3	K6Va	0.13	1.57	0.53(N)

C Compilation of observation epochs

Table C1: Full list of objects observed in this survey with each epoch of data. The spectral type listed is the spectral type of the preferred template used for each object. The error on the radial velocity is the error from the cross-correlation and the template precision (see Table 4.2) added in quadrature.

Object	Region	RA	DEC	Template SpT.	MJD	v_r (km/s)	σ_{v_r} (km/s)	EW(H α) (Å)
UCAC4-827387234	UCL	13 54 35.61	-43 56 48.1	M2.5V	57470.55607	10.82	2.5	-1.93
					57474.60136	13.79	1.41	-2.45
					57497.44452	10.86	1.42	-2.15
					57906.35937	10.35	2.04	-3.16
					57908.431	10.27	1.27	-3.46
UCAC4-467124593	UCL	14 10 59.69	-46 11 33.8	M2.5V	57474.62827	9.6	1.81	-6.15
					57496.52333	9.48	1.68	-6.03
					57555.43201	8.38	2.76	-4.82
					57906.36482	9.51	2.18	-8.61
					57908.44365	12.99	1.56	-7.11
UCAC4-947158099	UCL	14 14 52.40	-57 22 54.0	K6Va	57496.55327	-24.47	2.03	0.52
					57563.40438	-15.88	4.88	-0.07
					57908.35476	-14.94	2.13	0.12
UCAC4-382098779	UCL	14 16 03.10	-40 30 34.2	M2.5V	57496.58217	8.23	0.93	-4.33
					57601.34957	4.16	1.75	-3.83
					57603.53218	2.18	1.61	-4.48
					57907.45321	7.11	1.51	-5.38
UCAC4-945204860	UCL	14 27 30.11	-60 42 18.0	K3+V	57946.46472	-20.51	1.94	-0.51
					57960.45446	-18.72	1.79	-0.95
UCAC4-442012351	UCL	14 34 36.62	-45 45 59.9	M2.5V	57235.37226	8.89	1.05	-2.83
					57470.64181	16.31	1.33	-3.22
					57496.61293	15.9	1.14	-3.01
					57907.41519	10.99	1.5	-4.48
UCAC4-371257082	UCL	14 41 37.66	-37 56 34.4	M2.5V	57601.36494	2.99	3.12	-3.22
					57603.5459	9.98	3.3	-4.29
					57908.36881	7.84	1.34	-3.7
UCAC4-371337294	UCL	14 44 15.62	-40 32 27.3	M2.5V	57475.67166	8.84	1.99	-9.49
					57908.45841	9.48	1.57	-16.94
					57961.58565	7.22	2.1	-7.09
UCAC4-21594717	UCL	14 50 55.74	-35 04 22.9	K6Va	57470.63328	4.09	0.68	-0.42
					57475.69285	6.33	0.7	-0.15
					57496.66649	5.99	0.57	-0.4
					57907.47357	3.93	0.9	-0.29
UCAC4-365499547	UCL	15 24 35.62	-39 30 43.3	M2.5V	57470.67651	8.23	2.15	-4.6
					57475.70168	9.51	1.43	-4.47
					57496.67724	9.25	1.69	-4.11
					57906.44322	5.23	2.17	-5.67
UCAC4-445278523	UCL	15 29 17.48	-46 36 28.7	G5V	57496.70923	-43.13	2.81	1.24
					57907.53843	27.14	1.12	0.23
					57949.59018	23.36	2.97	0.21
UCAC4-23251943	UCL	15 29 23.88	-34 11 54.5	M2.5V	57470.70052	5.17	3.32	-3.56
					57475.71222	7.39	1.59	-3.04
					57496.71248	7.19	1.47	-6.87
					57908.48854	6.18	1.72	-4.34
UCAC4-23288203	UCL	15 30 33.57	-32 46 19.1	M1.5	57470.70624	7.35	1.22	-3.13
					57475.72232	7.06	0.94	-1.23
					57496.72613	9.16	1.02	-1.63
					57908.37974	9.88	1.78	-5.27
UCAC4-447414452	UCL	15 37 22.69	-40 17 59.6	K0V	57142.4683	-1.76	0.79	-4.5
					57236.44324	7.62	0.51	0.08
					57465.54708	11.19	0.37	-6.5
					57496.7494	10.31	0.32	-6.71
					57908.50386	3.26	0.36	-1.75
UCAC4-333669217	US	15 45 09.50	-15 40 29.0	M2.5V	57471.7143	-4.77	3.47	-3.45
					57477.65181	1.64	2.8	-4.32
					57496.78805	2.22	1.92	-5.1
					57906.46931	1.52	2.37	-6.0
UCAC4-161328427	UCL	15 46 25.81	-31 43 19.3	M2.5V	57470.73666	1.24	2.75	-6.27
					57477.57943	-32.46	1.7	-0.15
					57496.80174	7.83	1.56	-4.93

					57908.50808	44.2	1.62	-5.29
UCAC4-30196323	US	15 48 24.44	-22 35 49.7	M2.5V	57471.73511	-2.58	4.21	-0.65
					57497.52043	-0.38	1.58	0.26
					57906.48084	-1.21	2.29	-1.56
					57908.52408	0.63	2.07	-2.09
UCAC4-30231541	US	15 49 19.76	-22 57 29.7	M2.5V	57471.74415	1.14	1.72	-7.75
					57477.68273	-2.73	1.45	-9.51
					57497.53366	1.92	1.24	-7.74
					57907.59515	0.65	1.35	-11.16
UCAC4-1297314504	UCL	15 49 30.74	-35 49 51.4	M2.5V	57142.47175	4.64	1.35	-18.08
					57236.45299	0.59	0.91	-16.82
					57470.74229	2.38	1.01	-11.13
					57497.50685	4.93	0.98	-11.1
UCAC4-408863727	US	15 52 08.84	-27 23 45.8	M2.5V	57473.55232	-0.27	3.59	-0.01
					57477.69847	4.32	2.32	-1.21
					57497.56113	8.23	1.64	-1.53
					57907.48656	6.93	1.68	-0.95
UCAC4-1019544336	UCL	15 52 13.44	-39 56 08.2	M2.5V	57470.75852	9.02	2.11	-3.97
					57477.59061	8.41	1.55	-4.48
					57497.57328	8.29	1.23	-3.94
					57906.49304	7.85	1.55	-4.7
RIK-23	US	15 56 42.45	-20 39 34.2	M2.5V	56829.40365	-1.09	1.16	-21.75
					57144.53041	-4.47	4.68	-1.47
					57149.71636	-4.17	4.22	-3.25
					57497.59821	-0.77	1.3	-4.34
RIK-30	US	15 57 34.31	-23 21 12.3	M1.5	57907.50011	-0.72	1.54	-4.31
					56462.40511	-1.47	0.89	-3.99
					57235.47548	-3.91	0.72	-4.24
					57477.72126	-1.42	0.78	-4.19
UCAC4-519496506	UCL	15 57 43.61	-41 43 37.8	K6Va	57497.62018	2.92	0.85	-3.72
					57470.76585	0.23	0.54	-5.98
					57497.62503	0.64	0.57	-4.4
					57906.50465	0.55	0.58	-5.49
UCAC4-426579903	US	15 57 54.45	-24 50 42.4	K3.5V	57961.63482	-1.78	1.03	-9.56
					57472.56925	-7.75	0.6	-3.96
					57477.72767	-6.01	0.36	-6.14
					57497.62979	-3.77	0.42	-6.08
UCAC4-404438620	US	15 57 58.92	-18 14 59.6	K6Va	57906.51035	-5.65	0.44	-5.52
					57947.57933	-3.01	1.0	-5.06
					57236.42481	-4.12	0.43	-7.87
					57477.73494	-5.47	0.48	-4.91
RIK-34	US	15 58 12.70	-23 28 36.4	G7.5IV-V	57497.63388	-3.78	0.49	-6.02
					57907.63663	-3.59	0.56	-7.29
					56462.3762	-4.04	0.27	0.28
					57235.45402	-4.2	0.44	-0.0
UCAC4-519508031	UCL	15 58 20.40	-40 33 05.8	M2.5V	57497.64013	-4.83	0.31	0.31
					57603.47892	-5.7	1.0	0.36
					57908.53814	-5.76	0.35	0.27
					57942.36839	-4.65	0.38	0.48
UCAC4-404438620	US	15 57 58.92	-18 14 59.6	K6Va	57236.49687	2.56	1.24	-51.99
					57238.44218	3.12	2.03	-78.55
					57470.77231	3.81	0.97	-44.89
					57497.6434	4.7	0.85	-60.2
RIK-38	US	15 58 36.20	-19 46 13.5	M2.5V	57907.51049	2.73	1.28	-35.72
					56830.36589	0.48	2.25	-3.81
					57144.53742	-3.44	4.86	-3.26
					57149.71829	1.92	3.21	-4.16
RIK-43	US	15 59 44.27	-20 29 23.4	M2.5V	57907.52416	1.12	1.59	-4.02
					56824.62677	-3.03	4.18	-8.73
					57144.54129	-0.9	6.79	-6.76
					57149.72261	-6.58	4.32	-7.2
UCAC4-404466245	US	15 59 44.59	-21 55 25.1	M2.5V	57478.52499	-3.6	2.0	-12.86
					57497.68693	1.36	2.05	-7.35
					57908.54155	-1.51	1.93	-37.21
					57942.42496	-7.73	1.63	-14.32
RIK-56	US	16 01 13.99	-25 16 28.2	M2.5V	57497.69975	-1.48	3.14	-10.07
					57908.55466	-3.63	1.99	-30.64
					56826.60917	2.56	1.89	-5.02
					57144.54511	2.77	3.43	-3.6
					57149.72666	0.33	1.49	-2.82
					57235.52712	0.22	1.19	-2.81
					57497.71072	1.75	1.57	-3.1

					57908.56763	0.01	1.49	-5.01
RIK-58	US	16 01 29.03	-25 09 06.9	M2.5V	56830.39253	-1.69	1.68	-136.05
					57144.54974	-5.28	3.76	-150.07
					57149.7146	-1.97	4.21	-130.16
					57235.50925	-3.73	0.82	-93.85
					57478.53574	-2.13	1.43	-1.12
					57498.48848	-1.99	1.04	-87.96
UCAC4-4552391	US	16 02 05.18	-23 31 06.9	M2.5V	57478.54683	-1.92	1.95	-4.76
					57498.49994	0.77	1.69	-4.32
					57905.54177	0.24	5.04	-4.44
					57908.58114	1.64	1.54	-4.88
RIK-65	US	16 02 35.89	-23 20 17.1	M2.5V	56826.49788	-1.49	1.44	-8.39
					57145.66839	-1.36	1.46	-8.45
					57149.65538	-1.23	2.41	-4.78
					57498.51085	-1.61	1.25	-7.53
UCAC4-423900944	UCL	16 03 30.72	-40 24 34.0	M2.5V	57238.48932	4.87	1.54	-1.61
					57470.79675	6.67	1.09	-6.59
					57497.7226	5.2	1.09	-7.59
					57498.52261	6.39	1.2	-7.45
					57908.59667	4.84	1.14	-8.88
RIK-77	US	16 04 18.93	-24 30 39.3	M2.5V	57145.67724	-0.02	1.49	-10.36
					57235.49329	-5.31	1.0	-13.09
					57478.55961	-3.28	0.8	-21.89
					57498.5438	-1.09	0.87	-16.13
UCAC4-1264898768	US	16 05 06.46	-17 34 02.1	M2.5V	57473.5729	-1.55	3.58	-4.95
					57478.56847	3.6	2.14	-4.46
					57498.55261	0.67	1.65	-5.25
RIK-78	US	16 05 21.57	-18 21 41.2	K6Va	56462.42604	-2.74	0.75	-0.49
					57235.4504	-3.7	0.47	-3.17
					57478.5853	-5.24	0.39	-1.42
					57498.56468	-4.27	0.33	-3.82
UCAC4-39082833	UCL	16 05 44.04	-34 37 59.0	K6Va	57563.43617	3.53	0.49	0.01
					57601.40291	3.92	0.96	-0.03
					57947.58332	4.59	0.7	-0.33
					57961.64006	3.43	0.86	-0.24
UCAC4-415825814	US	16 06 23.82	-18 07 18.4	M2.5V	57473.58524	-5.92	2.31	-4.16
					57478.59124	-3.25	1.58	-4.19
					57498.56914	0.62	1.55	-4.65
					57907.73033	-2.49	1.61	-7.79
RIK-80	US	16 06 43.86	-19 08 05.5	K6Va	56462.43932	-3.98	0.57	-8.59
					57235.4566	-3.69	0.82	-11.32
					57478.61013	-6.05	0.56	-6.28
					57498.58745	-4.23	0.54	-9.19
					57907.7389	-6.21	0.9	-5.81
RIK-81	US	16 06 47.94	-18 41 43.8	K6Va	56462.44571	-0.97	0.54	0.03
					57145.67916	-2.81	0.84	-1.89
					57472.58833	-5.18	0.47	-0.33
					57478.61767	-4.23	0.4	-1.79
					57498.59395	-3.0	0.44	-0.53
UCAC4-39156047	US	16 07 08.52	-32 01 01.1	M1.5	57236.41859	3.56	0.89	-1.24
					57478.62577	1.31	0.83	-1.97
					57498.60217	6.2	0.94	-1.71
					57907.74872	10.19	1.4	-1.74
RIK-82	US	16 07 14.02	-17 02 42.7	M2.5V	56830.39841	1.94	2.08	-2.19
					57145.68102	-2.5	3.29	-2.64
					57478.63682	-2.83	1.83	-2.64
					57498.61399	1.72	1.53	-2.77
UCAC4-853813426	UCL	16 07 52.31	-38 58 06.1	M2.5V	57238.50914	1.7	1.98	-4.57
					57497.74736	2.08	1.12	-4.86
					57906.51835	5.23	1.31	-14.31
					57961.64449	1.24	1.44	-9.42
UCAC4-853849672	UCL	16 08 30.70	-38 28 26.8	K3.5V	57238.46447	1.42	0.87	0.06
					57465.55074	1.1	0.51	0.02
					57497.76128	1.82	0.47	0.02
					57907.68418	1.98	0.37	0.05
RIK-96	US	16 09 31.66	-22 29 22.4	M1.5	56824.69155	40.58	1.53	-4.67
					57149.57701	-0.5	1.05	-2.87
					57478.64549	5.3	0.96	-3.14
					57498.62519	39.61	0.66	-2.58
					57942.37782	4.56	1.43	-5.54
					57942.557	-1.79	1.5	-0.02
RIK-102	US	16 10 05.02	-21 32 31.9	K6Va	56829.40679	-4.41	0.95	-51.86

					57149.58541	-4.67	0.96	-49.61
					57478.654	-6.33	0.52	-27.77
					57498.63607	-6.3	0.51	-29.55
UCAC4-415948957	US	16 10 14.46	-19 51 37.5	M2.5V	56826.64646	-1.5	1.74	-4.65
					57907.69652	-0.4	1.29	-4.09
					57908.72664	1.47	1.68	-3.9
UCAC4-415950015	US	16 10 19.04	-21 24 25.0	M2.5V	57473.59428	-5.5	3.36	-12.89
					57478.66068	-3.63	2.2	-13.53
					57498.64282	-3.76	2.21	-13.39
UCAC4-415970246	US	16 10 43.92	-20 32 02.6	M2.5V	57472.60414	-0.92	2.73	-8.47
					57478.66938	1.25	2.19	-7.29
RIK-111	US	16 11 26.03	-26 31 55.9	M2.5V	56824.64743	0.75	1.63	-2.91
					57149.58719	1.5	1.33	-3.78
					57478.67785	1.19	1.03	-3.13
					57498.66452	-0.26	1.35	-3.02
RIK-112	US	16 12 05.05	-20 43 40.5	M1.5	56824.6371	0.1	1.31	-12.22
					57149.59362	-1.28	0.85	-7.23
					57478.68518	-4.26	0.86	-6.98
					57498.67318	-2.04	0.71	-11.1
RIK-113	US	16 12 06.68	-30 10 27.1	M1.5	56462.4948	2.77	0.78	-30.19
					56462.49618	2.54	0.83	-30.18
					57235.4693	0.13	0.66	-19.64
					57478.69401	1.41	0.98	-24.63
					57498.68357	1.89	0.78	-22.82
RIK-124	US	16 13 21.91	-21 36 13.7	M2.5V	56826.65497	0.75	1.3	-22.61
					57149.59856	-0.17	3.4	-18.27
					57478.70366	-1.37	1.17	-17.36
					57498.69106	-1.66	1.41	-12.69
RIK-138	US	16 14 52.41	-25 13 52.4	M2.5V	56830.4092	0.8	1.96	-5.83
					57906.53271	-0.09	1.82	-7.81
					57908.61143	-1.78	1.39	-6.05
RIK-146	US	16 15 32.20	-20 10 23.7	M2.5V	56830.54605	-1.26	1.05	-2.17
					57149.60094	-4.17	2.22	-0.34
					57235.48629	-3.96	0.9	-3.52
					57498.69961	-0.97	0.8	-1.83
					57942.39008	3.67	0.93	-9.9
					57942.40626	0.06	1.15	-14.35
					57942.57106	-9.45	1.44	-10.16
UCAC4-39632762	US	16 15 35.05	-34 32 01.4	K6Va	57472.61481	5.41	0.69	-16.1
					57478.71476	4.44	0.75	-13.1
					57498.71094	5.4	0.81	-5.88
					57907.71707	6.97	0.79	-10.74
UCAC4-416216449	US	16 16 46.89	-20 33 32.4	M2.5V	57472.7034	1.23	2.0	-3.89
					57478.72452	-2.22	1.95	-3.05
					57498.72215	0.91	1.67	-4.33
UCAC4-416217728	US	16 16 50.82	-20 09 08.2	M2.5V	57472.71465	-3.67	1.36	-77.47
					57478.7898	-2.05	1.21	-154.02
					57498.733	-2.65	1.14	-125.95
UCAC4-416239730	US	16 17 18.90	-22 30 01.7	M2.5V	57472.72121	-6.08	2.73	-28.96
					57478.77898	-1.32	1.73	-20.44
					57498.74145	-1.27	1.74	-17.14
UCAC4-39740614	US	16 17 49.05	-32 55 14.6	M1.5	57473.60631	3.14	0.96	-3.2
					57498.7916	2.01	0.93	-9.76
					57601.41439	2.54	0.99	-20.58
					57603.61091	2.28	1.47	-21.15
					57942.58642	11.88	0.86	-9.42
UCAC4-1056352275	UCL	16 18 06.62	-41 26 32.5	M2.5V	57497.76433	3.72	1.26	-12.05
					57908.6229	4.7	1.06	-16.07
					57947.59032	1.2	2.37	-13.63
					57961.66031	2.44	1.72	-13.8
UCAC4-160914413	US	16 19 10.09	-24 32 08.9	M2.5V	57473.61079	1.47	2.66	-4.25
					57498.80028	4.38	1.78	-5.55
					57601.4677	0.29	1.7	-3.99
RIK-183	US	16 20 06.16	-22 12 38.5	M2.5V	56829.55913	1.94	1.73	-2.15
					57149.6045	-0.41	2.87	-1.57
					57498.80988	3.47	1.27	-1.46
					57601.45435	0.0	1.61	-2.75
UCAC4-416359472	US	16 20 22.91	-22 27 04.1	M2.5V	57473.61945	-4.83	1.42	-7.74
					57498.82086	2.65	0.9	-0.02
					57601.44129	-5.97	1.55	-33.01
UCAC4-1253626396	US	16 21 57.69	-24 29 43.5	M1V	56462.62313	24.61	1.39	0.0
					56464.52168	17.78	1.37	2.51

					57238.56702	15.74	1.31	-0.03
					57603.62006	-1.69	1.14	1.67
					57906.72934	-0.79	1.05	2.54
UCAC4-1253629107	US	16 22 01.97	-25 22 20.4	K0V	57473.63758	-9.02	3.25	0.97
					57601.48119	5.98	2.76	-0.77
					57908.64907	5.05	1.49	-1.16
UCAC4-599700591	UCL	16 22 11.00	-48 41 38.5	K3+V	57945.57913	-53.29	1.88	0.19
					57960.50152	-62.57	1.74	0.44
UCAC4-64946760	US	16 22 39.58	-35 13 06.0	M2.5V	57473.64885	2.27	2.52	-14.97
					57906.71636	4.37	2.34	-19.47
RIK-223	US	16 25 28.81	-26 07 53.8	M2.5V	56825.36767	-0.18	1.25	-2.24
					57473.65813	0.26	1.26	-2.37
					57601.50843	1.04	1.55	-2.86
RIK-239	US	16 27 12.74	-25 04 01.8	M1.5	56829.6119	-0.65	0.86	-7.85
					57149.60884	-1.8	1.2	-4.27
					57235.47991	-1.77	0.85	-5.17
UCAC4-450968247	US	16 28 34.97	-20 19 11.1	G7.5IV-V	57940.49386	-39.24	1.08	1.77
					57961.49064	4.04	2.18	0.11
					57961.5508	-30.79	1.26	1.69
UCAC4-379613161	US	16 29 28.82	-25 00 25.0	K3V	57906.56003	25.51	2.95	0.74
					57908.66241	22.0	1.81	0.47
					57950.54517	20.64	2.56	0.25
UCAC4-455511949	UCL	16 30 03.71	-42 26 58.7	K6Va	57238.45745	-1.53	0.79	-1.08
					57497.77783	0.54	0.6	-2.0
					57951.61163	-1.5	1.04	-10.27
UCAC4-496722210	US	16 30 37.96	-29 54 22.4	K3+V	57235.59292	-1.29	0.33	-0.07
					57235.60155	-2.4	0.37	-0.2
					57951.61829	-0.91	0.49	-0.41
UCAC4-60335445	US	16 30 42.12	-26 23 03.9	M2.5V	57940.52993	1.28	2.29	-2.11
					57961.56115	-0.04	2.22	-3.12
RIK-250	US	16 33 34.97	-18 32 53.9	M2.5V	56825.58156	1.02	1.63	-8.6
					57961.47616	-3.37	4.07	-6.28
UCAC4-31196367	US	16 35 11.73	-22 57 28.1	G5V	57473.68075	0.27	1.15	0.54
					57908.67635	6.04	0.97	1.3
					57950.55867	2.98	1.21	1.63
UCAC4-456216791	UCL	16 35 27.22	-43 25 27.9	K6Va	57563.45134	-22.9	10.93	-1.53
					57601.57585	-28.49	4.58	-2.14
					57908.69006	-28.57	1.79	-0.5
UCAC4-60621830	US	16 36 46.51	-25 02 03.3	M1.5	57235.58587	0.53	0.83	-4.12
					57235.60571	-2.63	0.96	-4.44
					57906.57598	-2.6	0.93	-3.47
					57908.70287	-0.43	0.74	-6.98
UCAC4-1067529427	US	16 45 28.96	-25 02 47.7	M2.5V	57473.6928	-1.76	1.48	-22.79
					57601.58957	-5.21	2.59	-22.63
					57961.53582	-2.91	8.31	-24.2
UCAC4-431964534	UCL	16 46 56.03	-32 42 54.0	K6Va	57471.70025	-0.44	0.51	-1.34
					57477.6434	-0.3	0.56	-1.03
					57497.81589	1.13	0.5	-1.47

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