They grow up so fast

- Stellar accretion in a starburst cluster -

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1 Introduction

1.1 The birth of T Tauri stars

In 1945, Alfred H. Joy coined the term "T Tauri variable", as a new group of optically variable stars. Stars in the night sky that showed variability in their light curves had been known and reported on since the early 1800s (e.g. Pigott 1805). Possible causes for this variability had been suggested, including a rotating star with non-uniform surface brightness, a non-spherical stellar shape, and what would in today's nomenclature would be referred to as an eclipsing binary (Muller & Kempf 1903). The stars grouped together by Joy presented enough observational differences from these well known variable stars, that he considered them truly distinct, and that their variability may require an entirely new explanation. The criteria initially employed by Joy to classify T Tauri variable stars were the following:

- Rapid irregular light-variations of about 3 mag.
- Spectral type F5-G5, with emission lines resembling those of the solar chromosphere, particularly in the great strength of H and K of calcium
- Low luminosity
- Association with dark or bright nebulosity.

Some of these criteria would turn out to be strongly influenced by observational limitations of the time, while others remain today as key features of T Tauri stars. The final criterion is worth noting, that T Tauri stars are associated with either bright or dark clouds of material. It is interesting that from the very inception of the T Tauri star class, one of their defining features was how they relate to their external environment.

The physical nature of T Tauri stars was not immediately known following the pioneering work of Joy (1942, 1945, 1949). In a comprehensive review of the current understanding of T Tauri stars, Herbig (1962) summarised what he referred to as the three phases of study of T Tauri stars. Beginning with their discovery and subsequent follow up studies from Joy (1945, 1949), T Tauri stars were studied and their observational signatures described without a physical picture being suggested. The second phase began with the notion that T Tauri stars were main-sequence field stars that happened to be passing through a region of nebulosity and cloud material was being accreted onto the star (e.g. Greenstein 1948). This was a mechanism being suggested in the formation of massive stars (Bondi & Hoyle 1944), and was naturally adopted as an explanation since T Tauri stars were exclusively found within or near nebulosity. The third phase was based on the idea that T Tauri stars are in fact young stars, still in the process of gravitational collapse (e.g. Ambartsumian 1954). At the time of Herbig's review in 1962, a consensus had already formed around this notion, and it was generally accepted that T Tauri stars represented young, contracting pre-main-sequence (PMS) stars. In figure 1.1, we show the original photographic plate spectra observed by Joy (1945) of the first T Tauri stars. In the bottom panel of this figure we show a modern 1D spectrum of T Tau observed with the Space Telescope Imaging Spectrograph on the Hubble Space Telescope (HST)

A number of additional observational signatures had also been discovered

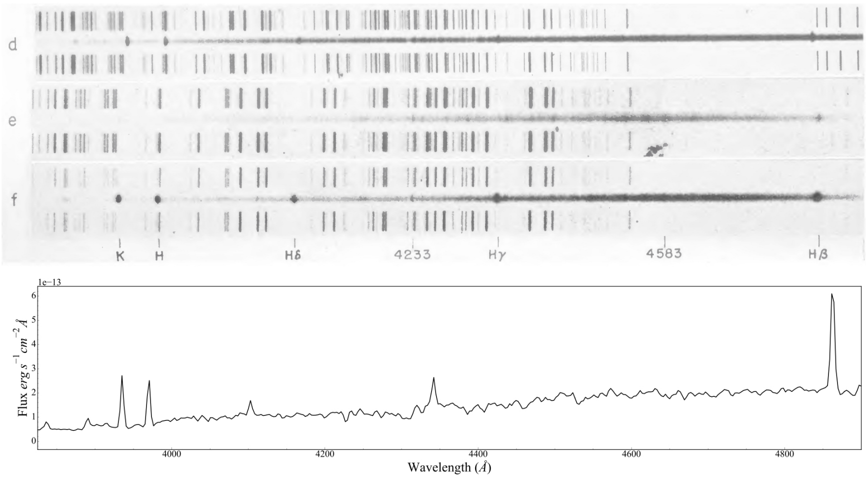

Figure 1.1: (Top) Photographic plate spectra of T Tauri stars from Joy (1945). Spectrum D corresponds to the eponymous T Tau. (Bottom) Modern 1D spectrum of T Tau obtained from HST. The wavelengths are coarsely aligned between the photographic plate spectra and 1D spectrum. The strong circumstellar emission lines are Calcium H (λ = 3933 Å) and K lines (λ = 3969 Å). H_δ (λ = 4101 Å). H_γ (λ = 4340 Å). H_β (λ = 4861 Å)

by this time which further separated T Tauri stars from other types of variables. These included excess emission at ultra-violet (UV) wavelengths (e.g. Varsavsky 1960), leading to unexpectedly negative U-B colours for a given spectral type. In the blue-optical range, absorption lines were seen to be "washed out" due to the presence of some unaccounted for extra, non-stellar continuum emission, an effect that today is known as "veiling". A similar effect was seen in infrared (IR) photometry (Mendoza & Eugenio 1966, 1968), with observations in JHKLM filters well in excess of the expected stellar black-body curve. P-Cygni profiles had also been observed

for a number of stars, typically in H_α and Calcium H and K emission lines. Here, a strong emission line was superimposed over a blue-shifted absorption line, interpreted as originating from outflowing material.
As observational studies progressed, so too did theoretical work attempting to explain the stellar evolution of T Tauri stars, as well as the source of their emission lines and continuum excess. In the foundational work of Hayashi et al. (1962), the temperature and luminosity evolution of young stars across the Hertzsprung-Russel Diagram (HRD) was described, showing that T Tauri stars first become visible to us as cool, luminous and fully convective stars, travelling down their "Hayashi track" until the core of the star is hot enough for radiative transport of energy to become important. The star then moves slowly along the equilibrium radiative track until it arrives at the zero-age main-sequence (ZAMS).
One of the primary challenges of observing stars during these early stages of their evolution is extinction. It is not a coincidence that the most well studied T Tauri stars and star forming regions are nearby, where the compounding effect of extinction is less severe. Likewise, it is for this same reason that T Tauri stars were observed before their preceding evolutionary stage, protostars, which are still heavily embedded and extinguished in their natal molecular cloud. As will be discussed in the following section however, extinction, while troublesome, can also provide important diagnostics about the star forming region, and initial conditions of planet formation.

1.2 Interstellar extinction

‘*in the very early stages, the star-to-be may not only be exceedingly faint at ordinary wavelengths, but will probably be heavily obscured by surrounding dust[...]Thus there appears to be little hope that study of the later phases, which are susceptible to observation, will tell us very much about the stage that preceded them*’

George Howard Herbig, 1962, The properties and problems of T Tauri stars and related objects

Light that passes through the interstellar medium (ISM) experiences extinction, a combination of absorption and scattering of photons. Dark patches observed in the night sky, originally referred to as ‘holes in the heavens’ by Herschel (1785), were determined to be clouds of interstellar dust, attenuating and reddening light that passed through (Trumpler 1930). Dust grains absorb and scatter light most effectively for wavelengths comparable to their size (e.g. Greenberg 1963; Li & Greenberg 1997; Li 2005). UV and optical light experience significantly more extinction compared to IR wavelengths. This immediately implies that interstellar dust grains tend to be $< 1\mu m$ in size, and this has indeed been found from observations (e.g. Mathis et al. 1977). Additionally, given that wavelengths spanning from the UV to the IR experience measurable extinction, it also suggests that there must be a range of interstellar dust grain sizes, spanning from angstroms to micrometers.

Although from certain perspectives extinction is simply a nuisance that must be corrected, it has been realised that valuable information about the size and composition of dust can be obtained based on the extinction curve that dust grains produce. The composition and grain size distribution within a star forming region has immediate implications for planet formation in protoplanetary discs, given that rocky planets and the cores of gas giants are primarily composed of dust. Dust is the main source of opacity in protoplanetary discs, regulating the heating, cooling and ionisation rate within the disc. Chemical reactions take place on the surface of dust grains (Tielens & Charnley 1997), and it is argued that complex organic molecules originate from these reactions (Bisschop et al. 2007). The dominant mass assembly mechanism for planet formation is still debated. Dust grain sizes are important in distinguishing between various planet formation theories such as gravitational instabilities or pebble accretion (Birnstiel 2024). Determining the initial grain size distribution in the parent molecular cloud is therefore necessary to understand the evolution of the size distribution of dust grains in the disc. Information on the dust grain composition can also be obtained from their extinction curves. Although extinction curves are generally smooth, there are a number of features due to specific dust species. This includes sharp, relatively weak features due to diffuse interstellar bands (DIBs) at optical and NIR wavelengths (e.g. Herbig 1995). However, the most prominent extinction curve feature is in the UV portion of the extinction curve, the 2175 Å bump. This feature is thought to originate from carbonaceous grains (Draine 2003). The feature is notably absent in the extinction curves of the Small Magellanic Cloud (SMC) (Savage & Mathis 1979). The reason for its absence is still debated, but clearly demonstrates that the dust properties are different in the SMC compared to the Milky Way, particularly with respect to the C/H ratio. This has natural implications for the composition of planets in the SMC.

Extinction is typically parametrised with three terms: (1) $A(V)$, the absolute extinction measured in magnitudes in the Johnson V band ($\lambda = 0.551\mu m$), (2) $E(B-V)$, the colour-excess, which measures the extinction in the B band compared to the V band. For this reason it is also sometimes referred to as reddening or differential extinction. (3) $R(V) = \frac{A(V)}{E(B-V)}$, the total-to-selective extinction ratio (Cardelli et al. 1988, 1989, CCM88, CCM89). The average value of $R(V)$ in the diffuse interstellar medium is

~ 3.1 (Wang & Chen 2019). In dense star forming regions however, it tends to be higher at $\sim 4-5$ (e.g. Weingartner & Draine 2001). The over all shape of the extinction curve in the optical-UV varies considerably for different lines of sight. In CCM89 they found that they could reasonably reproduce a wide range of observed extinction curves with their parameterisation, in which the only free parameter is $R(V)$. This made correcting observations for extinction straightforward for a wide range of environments. Another major result from this work was the discovery that $R(V)$ tends to increase with increasing dust grain size. It is argued in CCM89 that grain-grain collisions leading to accretion and coagulation may explain why grain sizes are typically larger in dense environments. The effect of larger grains, and hence a higher value of $R(V)$, is a flatter extinction curve, with weaker wavelength dependence. This is clearly apparent in Figure 1.2.

Unlike at optical and UV wavelengths, the extinction curve in the IR was

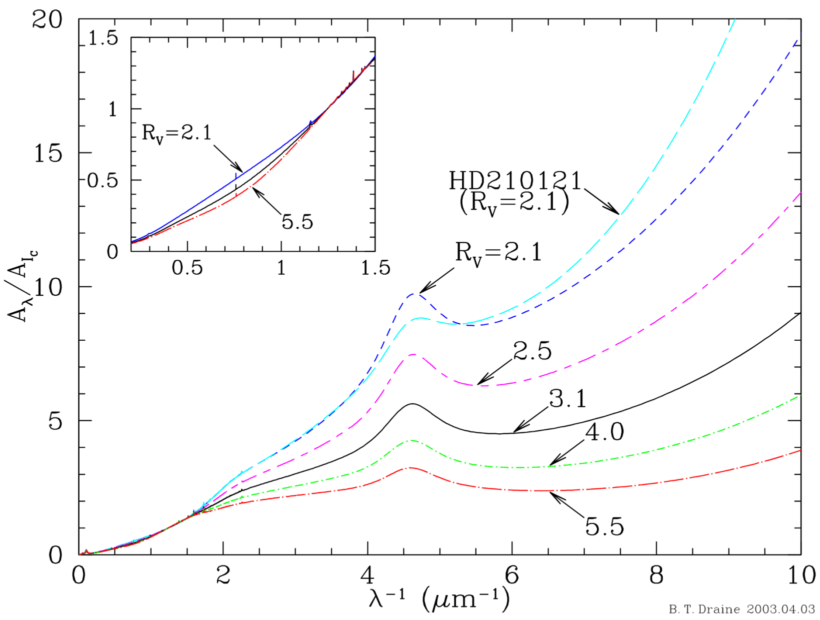

Figure 1.2: Extinction curves from Fitzpatrick (1999) for a variety of values of $R(V)$. The 2175Å($\sim 4.6\mu m^{-1}$) bump is clearly the most prominent feature. Much smaller bumps due to absorption of diffuse interstellar bands can be seen in the insert. This figure has been taken from Draine (2003).

seen to remain remarkably constant across different lines of sight. This led to the idea that the NIR extinction curve was universal, and could be expressed as a simple power law $A(\lambda) \sim \lambda^{-\beta}$, where β was typically $\sim 1.6-1.8$

(e.g. Mathis 1990). More recent observations have challenged this notion. While it is now accepted that the NIR extinction law can be modelled as a power-law, a single exponent is not consistent with detailed observations. (Fitzpatrick & Massa 2009, FM09) used spectrophotometric observations of high mass stars to determine the shape of the NIR extinction curve. They found that a variable exponent in their NIR power-law, which they call α, was required to fit their observations. They also found that the best fitting value for α changed depending on the wavelength range used during the fitting procedure. This latter result indicates that extrapolating extinction curves to longer or shorter wavelengths without observations is not reliable. The result of a variable exponent in the NIR extinction curve was confirmed by Schlafly et al. (2016), who employed tens of thousands of stars observed in the Pan-STARRS1 survey. Sight lines towards dense regions including the Galactic centre have found values of α that differ significantly from the canonical ~ -1.6, with Fritz et al. (2011) finding $\alpha = -2.11 \pm 0.06$.
Advances in our understanding of interstellar extinction have made it possible to exploit extinction curves to learn about the dust properties of different environments, as well as to perform reliable extinction corrections to observations. This is a crucial step when observing young forming stars, particularly in the context of accretion, which is directly observed in the form of UV radiation, and therefore highly susceptible to extinction.

1.3 The origin of emission lines. Infall versus outflow

1.3.1 Accretion

'*It had been known for some time that the colors of T Tauri stars were not normal for their absorption line spectral types, in the sense that the blue and particularly ultraviolet regions were too bright.*'

George Howard Herbig, 1962, The properties and problems of T Tauri stars and related objects

Emission lines from T Tauri stars were originally thought to arise predominantly from winds (Kuhi 1964). This was supported by the presence of P-Cygni profiles in optical spectra tracing outflowing material. Additionally, forbidden emission lines were observed towards T Tauri stars, indicating emission from gas with particularly low density. Such conditions can occur as a result of outflows punching cavities into the interstellar medium (ISM). Many attempts were made at modelling the expected wind. These models were successful in reproducing the over all flux of the lines, as well as the presence of a blue-shifted absorption component. However, as the number of observations and P-Cygni profile detections increased, theoretical wind models proved incapable of explaining the entire line profile (Calvet 1997, references therein). This suggested that additional line emission mechanisms may be relevant besides winds.

Line profiles had been observed towards a number of T Tauri stars showing a variation of the P-Cygni profile. In these cases, called P-Cygni type II, the absorption component, which was normally seen blue shifted well away from the emission line peak, was seen to sit in the middle of the emission line, presenting itself as a central depression of the line profile. This morphology, which is also referred to as a "central reversal", could not be explained with a wind. Ulrich (1976) showed that broad agreement could be found between observed P-Cygni type II profiles and modelled emission lines if an infall model was assumed. Ulrich pointed out that in a paper published two year prior, Lynden-Bell & Pringle (1974) had demonstrated that accretion discs were also capable of producing emission lines, but these generally symmetric, double peaked lines did not match the majority of observations of T Tauri stars, and so his own infall model was favoured over winds or an accretion disc.

Around the same time, "inverse P-Cygni" profiles began to be observed towards T Tauri stars. As the name suggests, the inverse P-Cygni profile presented an emission line profile superimposed over red-shifted absorption, rather than blue-shifted absorption. This provided additional evidence that infalling material played an important role in T Tauri stars.

In the following years, increased attention would be given to whether accretion discs existed around T Tauri stars based on combined efforts from both observations and theory. It was already speculated that a disc would form around a star during its formation as the angular momentum of material from the parent molecular cloud would be too high to fall directly onto the star (Cassen et al. 1985). In a series of papers, Hartmann & Kenyon (1985, 1987) successfully employed an accretion disc model to explain the significant increase in luminosity seen towards a subclass of T Tauri stars known as FUors, arguing that the increased brightness was a result of enhanced accretion from the disc. An IR classification scheme was developed by Lada (1987) (Class I, II, III), to describe the evolution of T Tauri stars under the assumption that their IR emission was dominated by a circumstellar envelope and disc. A nearly edge on disc around the well studied T Tauri star HL Tau had been inferred from numerous observational campaigns (Appenzeller & Mundt 1989, references therein). It was Sargent & Beckwith (1987) who unambiguously proved the existence of a large molecular disc around HL Tau based on ^{13}CO interferometric observations. By the beginning of the 1990s, it was generally accepted that T Tauri stars were surrounded by an accretion disc (Bertout et al. 1988; Calvet & Hartmann 1992; Shu et al.

1994).
As pointed out by Appenzeller & Mundt (1989) in their review on T Tauri stars, a particular area of uncertainty in the accretion disc model was how the inner edge of the disc relates to the central star. The disc was expected to be in Keplerian rotation, while T Tauri stars were seen to rotate well below this rate. How could disc material fall onto the star without transferring angular momentum onto the star, causing it to spin-up? There must be a transition zone where a significant amount of angular momentum and gravitational energy from the disc is dissipated, but the details of this transition zone were not well understood. As we will see, addressing this particular aspect of the puzzle would prove vital in developing a consistent theory of accretion discs.
Appenzeller & Mundt (1989) went on to comment that the subclass of T Tauri stars known as YY Ori stars exhibit rather dramatic inverse P-Cygni profiles in their spectra, indicative of free-falling material onto the star from at least several stellar radii, to account for the significantly red-shifted absorption component.
It was Koenigl (1991) who connected the accretion disc to magnetic activity of the star, providing the first framework for magnetospheric accretion (MA) for T Tauri stars. Königl's work was an adaptation of the accretion disc model described by Ghosh & Lamb (1979) for neutron stars. This physical picture could naturally explain all of the puzzling observational features seen towards T Tauri stars. In the MA paradigm, the magnetic field of the

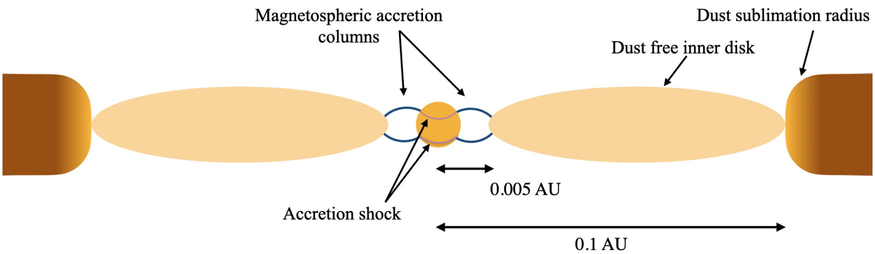

Figure 1.3: Schematic view of the inner disk and magnetospheric accretion zone for a T Tauri star.

central star is strong enough that it reaches out from the stellar surface and into the disc, truncating the disc at several stellar radii. This requires a magnetic field strength in the kilogauss. The inclusion of the stellar magnetic field was necessitated by the apparent discrepancy between the slow rotation of the star with respect to the Keplerian rotation of the disc. A strong stellar magnetic field can reach into the disc across a range of distances. The spin-up effect of field lines located within the corotation radius r_{co} is perfectly balanced by the spin-down effect of field lines located outside of r_{co}. This balance allows for accretion to take place while maintaining the observed low stellar rotation rates. The magnetic field lines act as a funnel through which disc material can fall onto the star. This structure of falling material is referred to as the accretion flow, or accretion column. Material in the column moves in near free-fall, reaching supersonic velocities, leading to a shock at the stellar surface. This shock raises the surface temperature to $\sim 10^6$K, leading to strong x-ray emission. The stellar surface absorbs the bulk of this radiation and re-radiates it at longer wavelengths. This post-shock emission can be modelled as a black-body with a temperature of 10 000K and is readily explained as the source of the UV and blue-optical excess emission commonly observed towards T Tauri stars (Hartmann et al. 2016). The accretion column is expected to contribute significantly to the observed line emission, with temperatures of $8000 - 10\,000$K (Muzerolle et al. 1998), though this notion has been challenged more recently with local excitation calculations from the circumstellar environment (Kwan & Fischer 2011). The observed inverse P-Cygni profiles can be explained as coming from the accretion flow as it recedes from the observer. Hot dust in the inner disc, heated up by the central star, as well as through accretion, can account for the excess emission seen at longer wavelengths in the IR. Figure 1.3 shows a schematic representation of the inner accretion disk and MA zone of a T Tauri star.

The MA theory rests upon the assumption that T Tauri stars can have strong and ordered magnetic fields. Using the Zeeman line splitting technique, the magnetic field strength was measured towards numerous T Tauri stars, indeed finding typical values of $1 - 3\ kG$ (Johns-Krull et al. 1999; Symington et al. 2005; Johns-Krull 2007). Further evidence of magnetically driven accretion came from Muzerolle et al. (1998), who modelled emission lines generated in the MA zone, finding good agreement between observed and modelled lines in both the optical and IR.

Unambiguous proof that T Tauri stars accrete material magnetically from a circumstellar disc came from the observational work of Bouvier et al. (2007). In this study, the authors employed time-series photometry as well as high spectral resolution time-series spectroscopy, observing the well known nearly edge-on disc AA Tau. Their aim was to compare the modulation of the central star's luminosity with accretion related emission lines and photospheric absorption lines. This type of analysis was only possible with a near edge-on disc, as the reason for the photometric and line variability was believed to

be due to occultation of the star by the magnetically warped inner disc and MA column, rotating around the star. The reader may recall that an early explanation for variable stars was from occultation of a companion star, which is intriguingly close to the mechanism being investigated by Bouvier et al. (2007). From their observations, the authors showed that the star's luminosity was modulated with a period of 8.22 days. The Balmer lines also exhibited modulation, in particular the red-shifted absorption component of the inverse P-Cygni profiles. The period of this modulation was also found to be 8.22 days. The veiled photospheric absorption lines were also seen to change in strength due to a modulation in the veiling, again with a period of 8.22 days. With these results, the star, disc and accretion flow were firmly tied together for the first time, proving beyond a shadow of a doubt that the T Tauri variable star could be understood via magnetically channelled accretion onto a young pre-main sequence star from a circumstellar disc.
While the accretion process around stars was being understood, another problem lingered for all types of accretion discs, around stars, black holes and active galactic nucleii (AGN). In order for disc material to accrete onto the star, it needs to somehow lose energy/angular momentum. It was first proposed in the landmark paper of Shakura & Sunyaev (1973) that disc viscosity was responsible for transferring angular momentum outwards, in the context of black hole accretion discs. By redistributing angular momentum from the inner disc to the outer disc, material could fall onto the star to be accreted, while the outer parts would spread out, becoming thinner and thinner. This idea was adopted to explain accretion from circumstellar discs, though the source of the viscosity itself was not known. Balbus & Hawley (1991) demonstrated that magnetic fields threading accretion discs could lead to drag forces between differentially rotating layers of the disc, leading to the extraction of angular momentum from inner regions to outer regions. This process was dubbed the magnetorotational instability (MRI). MRI requires that a certain fraction of the disc is ionised, so that the moving charges can generate a sufficient magnetic field. A limited number of observations have revealed that the degree of ionisation in circumstellar discs does not appear to be high enough to be consistent with MRI as the dominant process driving accretion (e.g. Perez-Becker & Chiang 2011). Thus, a new mechanism was sought to power accretion. A promising explanation would come by considering not just the infall of disc material, but also the outflow via winds.

1.3.2 Winds

'*If current theoretical dogma and our intuition are correct, then the evolution of [protostars] should be dominated by* ***collapse and infall****...However, extensive studies of these objects during the first half of the present decade* *have produced the unexpected result that most are sources of energetic* ***outflow*** *of molecular cloud material.*'

Charles J. Lada, 1987, Star formation: from OB associations to protostars.

While the MA paradigm was being developed, the important role of winds as well as collimated jets from T Tauri stars was acknowledged. It was generally thought that most permitted atomic emission lines originated from the accretion flow, but forbidden lines such as [OI] and [FeII] were thought to trace outflowing material. These lines were consistently detected from stars with discs, indicating that outflows were as ubiquitous as accretion flows.

It was Hartigan et al. (1995) who connected these wind tracing forbidden lines to accretion, showing a remarkably strong correlation between the mass accretion rate ($\dot{M}_{acc}$) of a sample of T Tauri stars with the strength of [OI]. This provided the first piece of evidence that outflows from T Tauri stars were intimately connected to accretion, with the assumption being that the outflows were somehow powered by accretion.

Around the same time, powerful collimated jets were observed in optical forbidden emission lines (Hirth et al. 1994b,a, 1997; Lavalley et al. 1997). Evidence of strong collimation provided a significant constraint on the launching mechanism of these outflows, as only one process was known that could produce the observed morphology, a magnetohydrodynamic (MHD) wind.

This framework, first theorised by Blandford & Payne (1982) to explain radio jets from AGN, proposed that a combination of magnetic and centrifugal forces were responsible for the observed jets, employing the now well known "beads on a wire" analogy to visualise the process. In this picture, the centrifugal force of the disc lifts material upwards along unconnected magnetic field lines, like a bead sliding up a taught, rotating wire. Material is accelerated to high velocities before ultimately being ejected entirely from the star+disc system. As material is lifted by the magnetic field, it exerts a drag, winding up the field lines in the process. This produces a strong toroidal component to the field that collimates the outflowing material into a jet. Based on conservation of angular momentum, the twisted field lines above the disc should naturally rotate more slowly than the field lines at the disc surface, due to their larger distance to the centre of rotation (i.e. the star). However, the magnetic field lines are anchored, meaning that the field lines rotate with the disc. This forces the field lines at large distances above the disc to co-rotate. This exerts a torque, or braking force on the disc, leading to a transfer of angular momentum from the disc to the field lines, causing disc material to slow down and spiral inwards, while wind material is accelerated away and ejected. Figure 1.4 builds upon Figure 1.3, adding the MHD wind and jet to the inner disk.

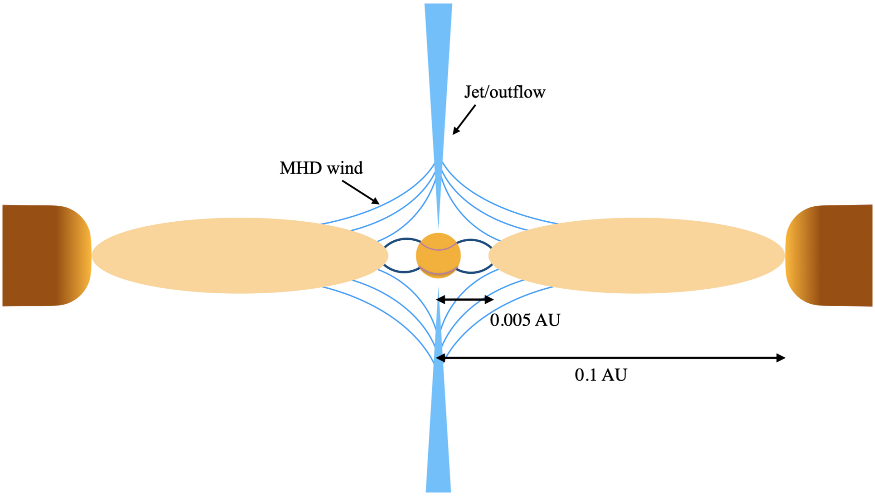

Figure 1.4: Building upon our previous schematic, the MHD wind and collimated jet emerging from the inner disk of a T Tauri star have been introduced to the picture.

The MHD wind has become the leading theory to explain young stellar outflows, as it is able to explain several disc phenomena at once: the launching of accelerating outflows; the formation of jets; and crucially, the shedding of angular momentum from the disc to facilitate accretion. Although initially thought that winds from young stars were powered by accretion, it was realised that the relationship is in fact the other way around, accretion is powered by winds.

1.4 Herbig AeBe stars

Up until now, star formation and disc evolution has been discussed in the context of T Tauri stars. However, in the 1960s, the higher mass counterparts of T Tauri stars had already been identified and discovered. First discussed by Herbig (1960), these young stars were named after their founder - Herbig AeBe stars. The "A" and "B" are spectral types, which correspond to surface temperatures of $>$ 7000K. The "e" refers to the fact that these are emission line stars, just like T Tauri stars. Following the description of Brittain et al. (2023), Herbig AeBe stars are young PMS stars with spectral types B, A and sometimes F. They exhibit emission lines, including H_α, and are often associated with nebulosity, and exhibit an IR excess.
It is known that the magnetic field produced by T Tauri stars comes from an

internal dynamo, generated by convective layers of the stellar surface (e.g. Johns-Krull 2007). For the hotter surface temperatures of Herbig AeBe stars, these layers have transitioned from convective to radiative, raising questions on the nature of magnetic fields around Herbig AeBe stars, and as such, on their accretion mechanism.

Magnetic fields have been measured towards a number of Herbig AeBe stars. Their field strengths were collated by Mendigutía (2020). In general, it appears that magnetic fields are present, but weaker for Herbig AeBe stars, and likely more complex, deviating from a simple dipole structure. This more complex morphology adds to the difficulty of measuring field strengths, as some field components cancel each other out, leading to an apparently weaker global field. The radius at which the magnetic field truncates the disc is also expected to be closer to the star. Since magnetic fields are not expected to be generated by the star itself, it has been theorised that "fossil fields" may exist, inherited either from the original molecular cloud from which the star formed, or from an earlier, convective stage of stellar evolution (e.g. Hamidouche et al. 2008).

In general, the emission lines observed towards Herbig AeBe stars are comparable to T Tauri stars, and MA models are able to successfully reproduce these line profiles (Muzerolle et al. 2004). For Herbig Ae stars, infalling signatures in the form of inverse P-Cygni profiles have been observed, particularly from He I 1.083 μm. Interestingly, these profiles are not detected towards Herbig Be stars. Smoking gun evidence for MA for Herbig AeBe stars has yet to be found, as it was by Bouvier et al. (2007) for T Tauri stars. However, a picture is emerging that Herbig Ae stars likely accrete similarly to T Tauri stars, albeit with weaker magnetic fields truncating the disc at smaller radii. For Herbig Be stars, there appears to be a meaningful difference in their accretion properties.

Wichittanakom et al. (2020) measured the accretion rates of 163 Herbig AeBe stars, and presented the relationship between their accretion rates and stellar luminosity, along with a sample of T Tauri stars from the literature. As shown in figure 1.5, the relationship is consistent between the T Tauri stars and Herbig Ae stars, but becomes noticeably flatter for Herbig Be stars, beginning at spectral type B7/B8. This suggests that the accretion mechanism may change for Herbig Be stars, but the exact nature of this change remains unknown.

It has been proposed that boundary layer (BL) accretion may take place for Herbig Be stars, as well as higher mass stars with spectral type O. BL accretion was considered in the original accretion disc model of Lynden-Bell & Pringle (1974). In this picture, the accretion disc continues up to the stellar surface, as there is no magnetic field to truncate it. Disc material is transferred onto the star via a BL, in which a significant release of kinetic energy occurs as the material is decelerated and accreted. The accretion energy itself comes from this release of kinetic energy. This is one

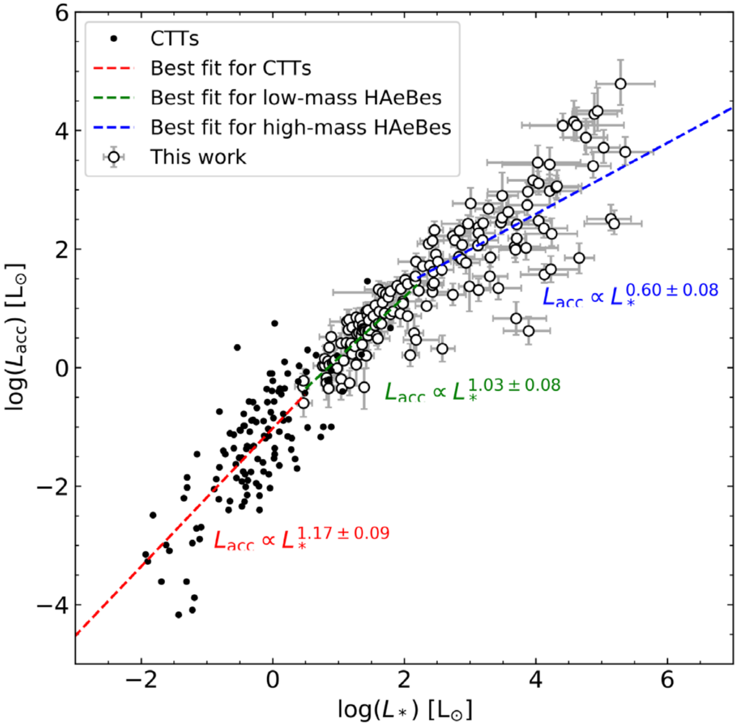

Figure 1.5: Relationship between L_* and L_{acc} for a sample of T Tauri, Herbig Ae, and Herbig Be stars. This figure has been taken from Wichittanakom et al. (2020).

of the fundamental differences between MA and BL accretion. In the MA paradigm, it is the gravitational potential energy of the infalling material that is released, and converted into heat/radiation. As such, $\dot{M}_{acc}$ determined for a given source is dependent on which accretion model is assumed. For instance, the blue-optical excess emission due to accretion is predicted to be consistently higher for a given $\dot{M}_{acc}$ in a MA model compared to a BL model. Assuming MA, this would equate to an underestimate of the true $\dot{M}_{acc}$ if BL accretion was in fact taking place. Given the extremely small spatial scales involved (the BL would extend out to $\sim 1\ R_*$), it remains unclear whether BL takes place for Herbig Be stars.

The importance of winds from Herbig AeBe stars has been recognised in explaining the emission lines observed towards them. Using high spatial resolution NIR interferometry, the exact location of line emission has been probed for a number of Herbig AeBe stars (Kraus et al. 2008; Mendigutía et al. 2015; Tambovtseva et al. 2016; Kreplin et al. 2018). In general, it ap-

pears that line emission is more diverse for Herbig AeBe stars, coming from a wider variety of mechanisms. Disc winds appear to be a more important contributor of emission lines, with strong extended emission having been measured towards a number of nearby sources. Compact emission more consistent with MA has also been observed, but it appears to be a less important source of emission compared to T Tauri stars. For accretion rates above $\sim 10^{-8}\ M_{\odot}\ \mathrm{yr}^{-1}$, the inner disc is expected to become optically thick and become an important source of line emission (Muzerolle et al. 2004).
Given that Herbig AeBe discs tend to be larger and brighter than equally distant T Tauri discs, several important discoveries were made based on observations of Herbig AeBe stars. The nature of the inner disc has been historically challenging to characterise due to the small spatial scales involved ($\leq 1\ AU$). NIR excess emission has been referenced a number of times in this chapter, being a defining characteristic of both T Tauri and Herbig AeBe stars. The source of this excess was initially thought to arise from a spherical shell of material surrounding the star which reprocesses stellar light to longer wavelengths. With the success of the accretion disc theory, a new explanation emerged that dust located in the inner disc close to the star becomes heated by radiation from the central star, producing NIR continuum emission, with a characteristic temperature of $\sim 1500K$ (e.g. Hillenbrand et al. 1992). This is approximately the dust sublimation temperature of ISM-like dust. Advances in NIR interferometry in the early 2000s made it possible to test this theory directly by resolving the inner regions of large Herbig AeBe discs. The most compelling and direct piece of evidence for inner disc dust emission came from 'aperture-masking', a form of interferometry in which a mask is placed in the optical beam of a single telescope. Light passes through numerous sub-apertures within this mask resulting in interference. This mimics having many small individual telescopes. Two Herbig Be stars were imaged in this way, revealing unambiguous, asymmetric disc structures (Tuthill et al. 2001; Danchi et al. 2001). This proved that the NIR excess originated from a disc, and not a spherical shell of material surrounding the star, as had been previously thought. These images also revealed an inner cavity where no dust emission was detected, as expected for material within the dust sublimation radius.
As it was becoming clear that NIR excess emission originated from dust in the inner disc, attempts were being made to model the SEDs of T Tauri and Herbig AeBe discs. While the distinct NIR bump could be reasonably produced by adding a 1500K black-body to an appropriate photospheric spectrum, more physically motivated models were being developed that attempted to incorporate the structure and density of the inner disc and the radiative transfer that occurs within it. These models initially assumed a sharp vertical wall located at the dust sublimation radius, inside which all dust is destroyed. However, given this geometry, strong asymmetries were predicted for the brightness of the wall depending on the inclination angle.

For face-on discs, no emission from the wall should be detected at all. Observations of discs with the Infrared Optical Telescope Array (IOTA) three-telescope interferometer showed that very few discs exhibited the asymmetries expected from this vertical wall model (Monnier et al. 2006). This suggested that the transition from the dusty to dust free disc may be more gradual. A rounded inner wall was able to better explain these observations, and this was supported by subsequent models, which showed that the dust sublimation temperature was a function of density, which changes significantly with disc scale height (Tannirkulam et al. 2007), with higher sublimation temperatures for dust in the midplane of the disc compared to the surface layers. Figure 1.3 illustrates the rounded wall and higher temperatures of the inner dust disc.

Thus, it is thanks in large part to Herbig AeBe stars that our understanding of the inner disc underwent so much progress in the first decade of this century. These insights have been extrapolated to T Tauri discs, providing constraints on planet formation occurring within these inner regions.

1.5 From circumstellar discs to protoplanetary discs

Following the significant progress made in understanding the accretion and ejection processes of young stars and their circumstellar discs, increasing attention was paid toward the planets that were presumably forming within these discs. Around the mid-1980s, the term 'protoplanetary disc' began to be used in place of circumstellar discs, denoting more importance on planet forming processes of these discs, rather than their role in star formation. With the first exoplanet being discovered by Wolszczan & Frail (1992), the field of exoplanet and planet formation research is still extremely young. Understanding the planet formation process requires an understanding of the disc, as this is the site where planets form, and the properties of the disc create the initial conditions of planet formation.

A major boom in planet formation studies resulted from advancements in sub-mm telescope capabilities, particularly with the commissioning of the Submillimetre Common-User Bolometer Array (SCUBA) on the James Clerk Maxwell Telescope (JCMT). In the sub-mm, emission from both gas and dust can be studied over a large extent of the disc's surface, including optically thin dust emission, which enables the determination of the dust mass of the disc. From this the gas mass can be determined based on a dust-to-gas mass ratio, typically assumed to be 0.01, as this is the value found in the ISM.

Surveys were undertaken for nearby, low mass star forming associations to examine well known T Tauri stars and discs from the perspective of sub-mm observations (Andrews & Williams 2005, 2007a,b; Andrews et al. 2009, 2010). These surveys revealed for the first time the typical disc masses ($0.004\ M_\odot$), disc-to-star mass ratio (0.9%) and characteristic dust temperatures ($\sim 20K$) in these nearby discs.

A major revolution in protoplanetary disc studies occured with the construction of the Atacama Large (sub)Millimetre Array (ALMA) in 2011, becoming fully operational in 2013. ALMA consists of 66 telescopes, observing wavelengths between 0.32 to 3.6mm, with a maximum baseline of 16km, capable of achieving $0.01''$ resolution. ALMA represented an enormous leap forward in sub-mm interferometry, with superior resolution, sensitivity, and flexibility in terms of baseline length compared to previous generation sub-mm telescopes such as the JCMT or Institut de Radio Astronomie Millimétrique (IRAM).

Observations of nearby spatially extended protoplanetary discs with ALMA immediately revealed an apparent ubiquity of substructures, including spirals, rings, and asymmetries (e.g. van der Marel et al. 2013; Isella et al. 2013; Pérez et al. 2014). Substructures are often interpreted as an indication of planet formation in the disc, though substructures are also often required to enable planet formation (e.g. Pinilla et al. 2012), leading to a chicken and egg scenario. Regardless of this paradox, substructures in discs are widely sought after as signposts of ongoing planet formation. The DSHARP survey provided the first high resolution overview of a large sample of nearby discs (Andrews et al. 2018a). Many of these discs exhibit dramatic substructures, most notably ring shaped gaps, thought to have been carved out by a forming planet. Only a single disc to date has been unambiguously shown to

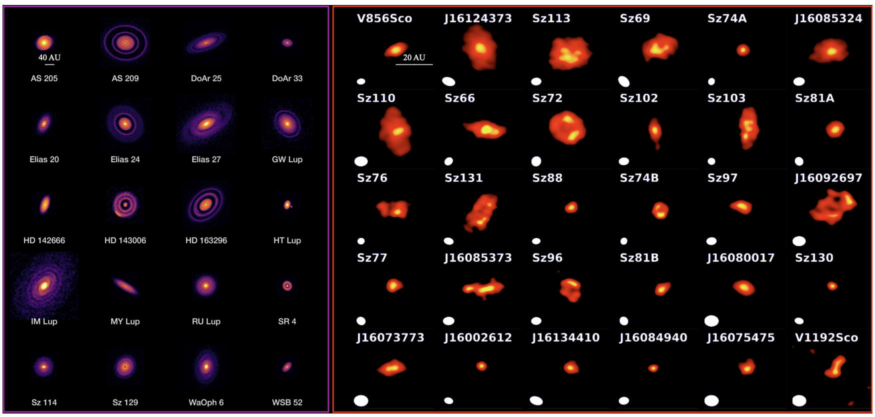

Figure 1.6: (Left) The original DSHARP discs from Andrews et al. (2018b). (Right) Sample of disks from Guerra-Alvarado et al. (2025). Scaling for each image is indicated with a white bar.

possess substructures as a result of planet formation, PDS 70 (Keppler et al. 2018; Haffert et al. 2019). A recent large ALMA program, exoALMA, is attempting to exploit the presence of disc substructures in order to make direct inferences about the suspected protoplanets causing them (Teague et al. 2025).

Something to note on the study of disc substructures is that the samples are strongly biased towards the nearest, largest and brightest discs. Recent work with a more representative sample of 73 faint discs in Lupus, including 33 new high resolution observations, show that 2/3 discs are compact (< 30 AU), and exhibit no visible substructures (Guerra-Alvarado et al. 2025). The DSHARP survey discs and a subset of those from Guerra-Alvarado et al. (2025) are shown side by side in Figure 1.6. While the DSHARP discs are spectacular, most discs do not appear to exhibit such striking features. This type of work highlights the need for representative samples if conclusions are to be applied to the population as a whole. On this note, it is crucial to emphasise that the majority of stars and planets in the Milky Way, and indeed the Universe, have not formed in regions like Taurus or Lupus. They formed in large stellar clusters with hundreds to thousands of members, including OB stars which strongly irradiate their environment (Lada & Lada 2003). Even studies that attempt to obtain representative samples of protoplanetary discs usually focus on nearby low mass star forming regions (SFRs) where discs can be spatially resolved. These regions tend to lack the strong environmental influences found in large clusters, which may be critical to the star and planet formation process.

1.6 The external environment

Paradigms of star and planet formation developed over the last several decades are centred around internal processes. These are processes that occur within, and are driven by, the star+disc system, such as the previously discussed magnetically driven accretion and MHD disc winds. It is generally thought that fully formed stars and the planetary systems that they host have been shaped and influenced predominantly by these internal processes (Alexander et al. 2013). This assumption has in part been motivated and validated by the fact that the vast majority of detailed observational star and planet formation studies have been conducted for nearby low-mass SFRs, where there is less interaction between stars, discs, and their environment. The T Tauri star was first discovered, as the name suggests, in the low-mass SFR of Taurus. This region has subsequently become the most well studied site of star formation in the Galaxy, with other similarly nearby, low mass regions like Ophiuchus, Lupus and Chamaeleon I following behind. This is despite only $10 - 30\%$ of stars in the Galaxy forming in regions like this (Lada & Lada 2003). In clusters, a number of important differences exist in the external environment compared to low mass SFRs, including the UV radiation field and interstellar gas and dust density. The picture of star and planet formation that has been built through observations of these low-mass SFRs may not actually represent how the majority of stars and planets in the Milky Way formed. The role of the external environment has yet to be fully addressed. Doing so requires observations towards more distant, massive clusters.

1.6.1 External irradiation

Clusters are defined by Lada & Lada (2003) as groups of 35 or more stars with an observed stellar mass volume density of $\rho_* \geq 0.1 M_\odot pc^{-3}$. Of the clusters surveyed by Lada & Lada (2003), which extended to regions within 2kpc of the solar system, 75% still contain massive stars. The presence of massive stars introduces important environmental feedback, including UV radiation, strong, line driven stellar winds, and eventually supernovae explosions. Observations of the Orion Nebula Cluster (ONC) obtained with the then recently launched HST (Burrows et al. 1991) revealed numerous unexpected structures. Large cocoons of gas were seen surrounding discs in the ONC. The cocoons possessed a 'tadpole' morphology, with a round head and elongated tail. The head of these cocoons were brightly in emission, and seen to consistently face towards the massive stars in the cluster, while the tails pointed away in the opposite direction. Objects exhibiting this peculiar morphology were dubbed 'proplyds' (O'dell et al. 1993; O'dell & Wen 1994). An example of a proplyd from the ONC is shown in figure 1.7. It was immediately thought that these unusual objects were discs that had become ionised due to strong external irradiation from the nearby massive stars, particularly from the most massive member of the Trapezium cluster, θ^1 Ori C, with a spectral type of O6. The radiation field intensity is commonly measured in units of the Habing field (Habing 1968), denoted by G_0. This is the value of the average interstellar radiation field between 912 and 2400 Å. Most stars in low-mass SFRs experience a G_0 of 1-10. The proplyds in the ONC experience a G_0 of about 10^5 (Tielens & Hollenbach 1985). This irradiation leads to significant mass loss due to a strong pressure gradient between the disc and surrounding H II region. This mass loss process is known as external photoevaporation. Henney & O'dell (1999) determined the mass loss rates for four proplyds, finding typical values of $0.4 \times 10^{-6} M_\odot$ yr^{-1}. These mass loss rates imply disc dispersal timescales of $\sim 10^5$ yrs, dramatically shorter than average disc lifetime in low UV environments of ~ 5 Myrs. This raises questions on whether planets have enough time to form in these discs (though there is increasing evidence that planet formation begins very early, possibly during the class 0 stage (Nixon et al. 2018)).

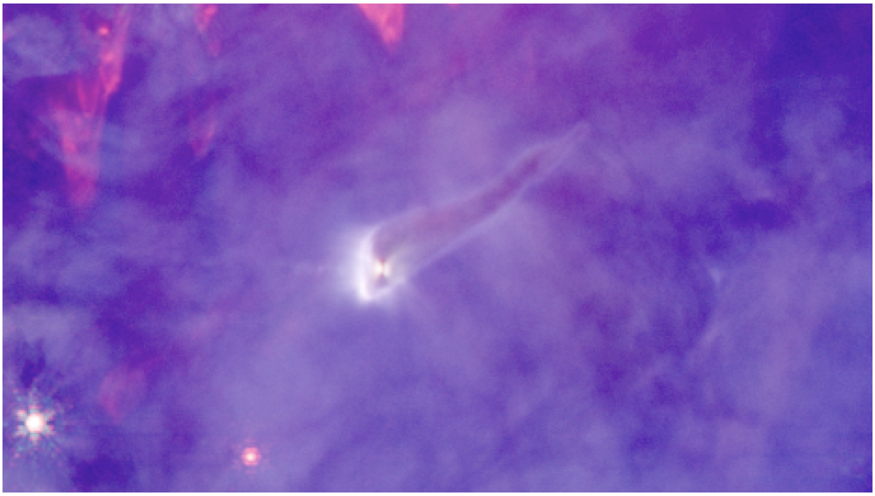

Figure 1.7: The spectacular ONC proplyd 142-301, observed recently with JWST NIRCam. The bright ionised head and elongated tail are clearly visible. We have adapted this image, taken from ESA Webb, based on observations by McCaughrean & Pearson (2023).

In figure 1.8, we continue building upon our schematic diagram of the inner disc, now including the presence of nearby massive stars, and their intense UV radiation impinging on the disc.

It is now thought that mass loss due to external photoevaporation is dominated by far-UV (FUV) photons with ($6 \leq h\nu \leq 13.6\ eV$) (Johnstone et al. 1998). This leads predominantly to mass loss at large radii $5 - 10\ AU$ and remains significant at even larger distances $> 100\ AU$. As such, much of the outer disc is eroded, leading to disc truncation. This effect was shown by Mann et al. (2014), where the disc luminosity of proplyds in the ONC was seen to decrease with decreasing distance to θ^1 Ori C.

External irradiation is also expected to impact disc chemistry, as FUV photons both destroy molecules via dissociation while also opening new chemical pathways (Walsh et al. 2012, 2013; Gross & Cleeves 2025; Zannese et al. 2024). The outer disc is expected to be impacted more than the inner regions as FUV photons penetrate deeper into the disc at large radii where the density is lower. However, observations of externally irradiated inner discs in the NIR are still rare, and sensitive surveys are required to address to what extent the inner disc is affected by external irradiation. Recent work using JWST MIRI has revealed the presence of the methyl cation CH_3^+ from a proplyd in Orion (Berné et al. 2023), thought to be an important catalyst for gas-phase organic chemistry. This was the first detection of CH_3^+ outside of the solar system, suggesting that external irradiation may be im-

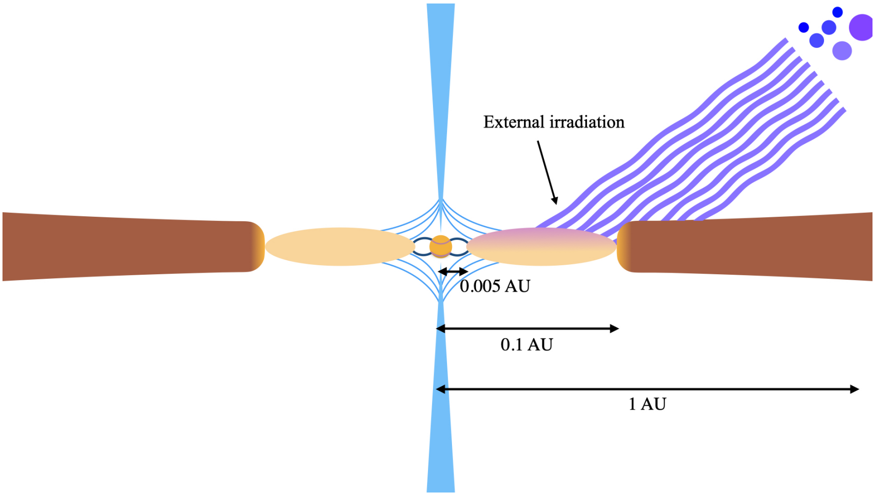

Figure 1.8: Massive stars now strongly irradiate the disc, potentially driving external photoevaporation from the outer disc. The impact of harsh external irradiation on the inner disc is not well understood.

portant in the formation of this molecule. More work is needed specifically targetting the inner discs of externally irradiated discs, for which JWST observations are extremely well suited. In the coming years a number of large surveys will characterise the proplyds in the ONC from $1 - 28\mu m$ (Rogers et al. 2024; Schroetter et al. 2025), providing key constraints on the impact of UV photons on disc chemistry.

Proplyds in the ONC are still one of the most compelling examples of the external environment influencing the evolution of protoplanetary discs. Proplyds or proplyd-like structures have been discovered in a number of other regions (Brandner et al. 2000; Smith et al. 2003; Wright et al. 2012; Haworth et al. 2021), but since proplyds are currently identified based solely on their spatial morphology, our ability to identify proplyds is limited by the spatial resolution of current telescopes. In fact, $< 20\%$ of the discs in the ONC are spatially resolved by HST (Clarke 2007). This confines us generally to the most nearby regions, or to very large proplyds at greater distances.

1.6.2 Late stage accretion

Star formation theory generally begins with the assumption that all of the necessary material to form the star, disc, and planets is present after the pre-stellar collapse phase, and that star+disc evolution proceeds in isolation from the environment. A myriad of inconsistencies in the 'isolated' forma-

tion model are solved however, when late stage accretion is considered. This includes unresolved questions regarding disc substructures, asymmetries, as well as exoplanet orbits and exoplanet masses versus disc masses. Recent observational and modelling work are showing that it may be quite common for fresh material to be added to protoplanetary discs via infall from the surrounding ISM, a process known as late stage accretion.
Interstellar gas densities are on average higher in clusters where $n(H_2) > 10^5$ cm^{-3} than low mass SFRs with $n(H_2) \sim 10^{2-3}$ cm^{-3} (e.g. Heiner & Vázquez-Semadeni 2013). In regions of substantial nebulosity, it is possible that late stage accretion from the ISM onto the disc can occur, leading to disc replenishment (e.g. Kuffmeier et al. 2023). Late stage accretion has already been observed in a number of cases in nearby regions (Ginski et al. 2021; Gupta et al. 2023, 2024). These observational efforts demonstrate that late stage accretion occurs in low mass SFRs, and provide tentative evidence that late stage accretion signatures may be seen around as many as 50% of discs in the regions observed, based on the presence of reflection nebulae. Figure 1.9 completes our schematic of the T Tauri disc, with a stream of ISM material seen falling onto the disc, representing late stage accretion.

Complementary hydrodynamical simulations show that late stage accre-

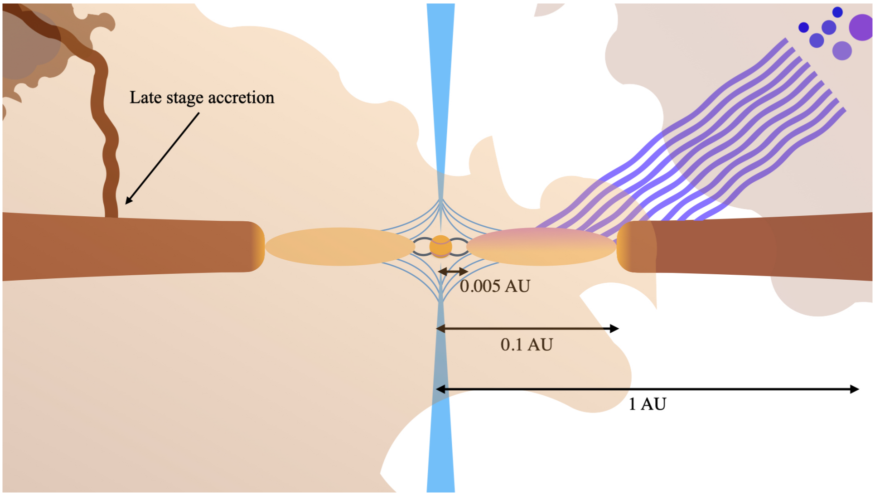

Figure 1.9: Interstellar material falls onto the disc, injecting fresh material and angular momentum in the process.

tion can commonly occur in dense environments, and can lead to significant amounts of material being added to the star+disc system. In the simulations of Kuffmeier et al. (2023) it was shown that for stars that reach the main-sequence with masses above 1 $M_\odot$, more than 50% of their mass comes

from late stage accretion. These infall events have also been offered as a potential explanation for substructures and misalignments observed in class II discs (Vorobyov et al. 2016, 2020; Kuffmeier et al. 2021).
Recently there has been a resurgence of interest in Bondi–Hoyle–Lyttleton (BHL) accretion (Hoyle & Lyttleton 1941; Bondi & Hoyle 1944) as the mechanism through which this infall occurs. The reader may recall that in the first years after the discovery of the T Tauri star, this accretion mechanism was invoked to explain the physical nature of these stars, as they are commonly found within nebulosity. Thus, a full circle moment appears to be unfolding as the community returns to BHL accretion to explain the evolution of T Tauri stars. This mechanism was successfully shown by Winter et al. (2024a) to reproduce observed disc lifetimes, masses, radii and stellar accretion rates by modelling the ISM and protoplanetary discs together. Winter et al. (2024b) showed observationally that the density of interstellar gas scales positively with $\dot{M}_{acc}$ for young stars in Lupus. Very recently, Padoan et al. (2025) showed with analytical and numerical modelling that Bondi–Hoyle accretion can explain the observed relationships between disc mass and disc angular momentum, as well as molecular cloud mass and cloud angular momentum. Their numerical simulations generate discs with masses consistent with observations, and are the first simulations to reproduce the observed scaling relationship between disc mass and stellar mass. The numerical simulation of Padoan et al. (2025) and observation of a streamer from Gupta et al. (2024) are shown in figure 1.11.

To date, only a single systematic study has taken place to search for late

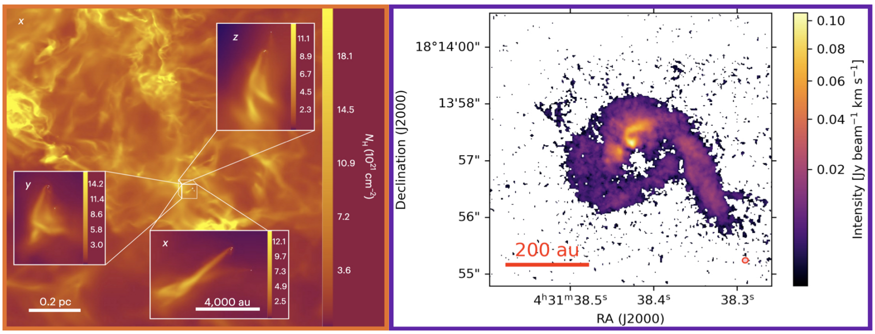

Figure 1.10: (Right) Numerical simulation showing Bondi-Hoyle accretion taking place for a number of Class II T Tauri stars. This figure has been adapted from Padoan et al. (2025). (Left) ALMA observations of a stream of material falling from the ISM onto the disc of HL Tau, a class II T Tauri star. This figure has been adapted from Gupta et al. (2024).

stage accretion onto class II protoplanetary discs (Gupta et al. 2023). This study focused again on nearby low-mass SFRs, with Orion being the only cluster included. Intuition would suggest that with higher interstellar gas densities, late stage accretion may be even more prominent and important in clusters, though the higher temperatures in these regions may hinder this process. Without dedicated observations to this problem, it remains an open question how common and important late stage accretion is in the formation of stars and planets.

1.7 Star and planet formation in the JWST era

The previous sections of this chapter have provided a brief history of star and planet formation studies. Many times throughout this history, breakthroughs were directly tied to new instruments or telescopes becoming available. A new era of star and planet formation studies has just begun with the launch of JWST in December 2021. Through sheer good fortune, my own PhD aligned perfectly with the launch of this new telescope, allowing for my entire PhD to be based on some of the first JWST observations.
Much of what we know about star and planet formation has been derived from observations of nearby regions. JWST provides several key advantages over previous generation telescopes that enable pushing farther afield to study the more distant, but more representative stellar clusters in incredible detail.
With its 6.5 meter diameter mirror, JWST is the largest space telescope ever constructed. Because of this, JWST has an angular resolution that is about 8 times better than Spitzer, the previous generation IR space telescope (Werner et al. 2004). Through a combination of its larger mirror and significant progress in IR instrumentation, JWST is able to detect objects that are about 100 times fainter in the NIR compared to Spitzer and HST. Working primarily at IR wavelengths, JWST detects photons that are less influenced by interstellar extinction. While the case has been made in section 1.2 that dust extinction can offer valuable insights into star and planet formation, it also prevents the study of distant or embedded objects at shorter wavelengths, such as young stars in distant clusters. Through its large collecting area, sensitive instrumentation, and the reduced impact of extinction, JWST is able to study objects that were simply too faint for earlier telescopes.

JWST hosts four science instruments, the near infrared camera (NIRCam), the near infrared slitless spectrograph (NIRISS) (Doyon et al. 2012), the mid-infrared instrument (MIRI) (Wright et al. 2004) and the near infrared spectrograph (NIRSpec) (Bagnasco et al. 2007). This thesis focuses on NIRSpec, using one of its observation modes, multi-object spectroscopy

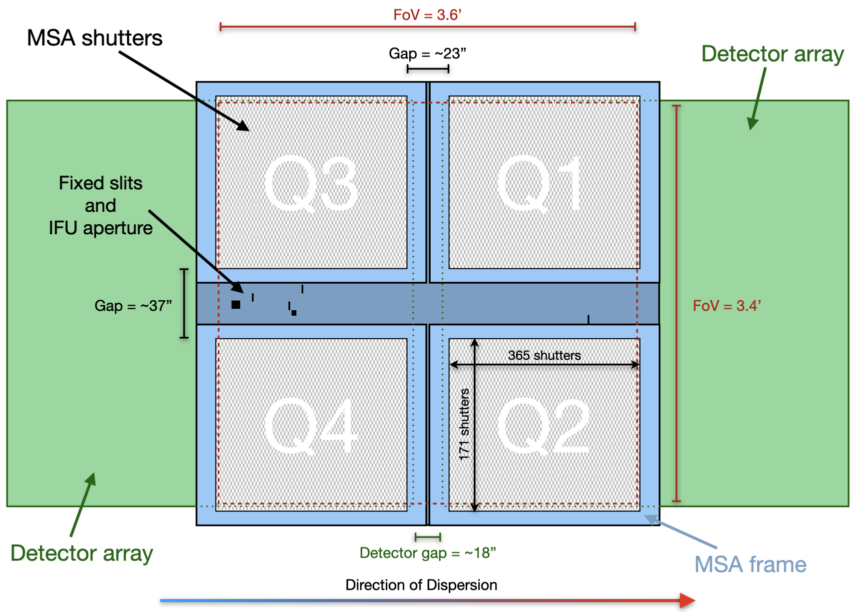

Figure 1.11: Schematic illustrating the NIRSpec MSA with respect to the NIRSpec detectors. This image has been taken from Ferruit et al. (2022).

(MOS). MOS is enabled on NIRSpec with a novel component named the micro shutter assembly (MSA). The MSA is an array of $\sim 250,000$ microscopic doors that can be commanded open or closed in a user defined configuration. The configuration is determined based on the location of targets on the sky, such that each target falls within an open micro shutter, and its light is dispersed and projected onto the NIRSpec detectors. This allows for the simultaneous observation of tens to hundreds of sources at once, depending on the specific field, and the resolving power employed. NIRSpec MOS is arguably the most efficient observing mode offered by JWST, given how many spectra can be obtained simultaneously. This is evidenced by my own PhD, which consisted of four busy years of research based on a mere four hours of observations with the NIRSpec MSA.

1.8 Thesis summary

This thesis is based on observations of young accreting stars and their protoplanetary discs in the massive Galactic star forming region NGC 3603. These sources were observed with NIRSpec onboard JWST, from a guaranteed time observations (GTO) program (PID:1225 G. De Marchi). The MSA was employed on NIRSpec, providing us with 100 stellar spectra and 600 nebular spectra. The principal goal of this project was to characterise the accretion properties of these stars, to investigate how star formation differs in clusters compared to low-mass star forming regions, as a result of differences in their environment.

Chapter 2 probes the extinction properties of NGC 3603 using hydrogen recombination lines produced by the bright nebular gas. The extinction experienced by nebular emission can be measured and characterised based on the deviation of measured line ratios predicted by Case B recombination. Each line ratio can be combined with an appropriate extinction curve to determine $E(B-V)$. The same value of $E(B-V)$ should be obtained regardless of which line ratio is chosen, but this is only true if the appropriate extinction curve is employed. We fit the nebular emission lines of each spectrum with a variety of extinction curves, varying the value of $R(V)$ until a consistent value of $E(B-V)$ was found for each ratio. To our knowledge this is the first time that this technique has been employed to iteratively fit for $R(V)$. We found a high value of $R(V) = 4.8 \pm 1.06$ for the region as a whole, with a particularly low value of $E(B-V) = 0.64 \pm 0.27$, and $A(V) = 3.1 \pm 1.5$, suggestive of significant dust grain growth occurring within this cluster. The results of this extinction analysis were used in each proceeding paper when correcting the stars for extinction.
Chapter 3 establishes for the first time an empirical relationship between the luminosity of the strong NIR hydrogen emission line L_{Pa_α} and the accretion luminosity L_{acc} of young stars. Accretion rates are measured directly from UV-optical continuum emission. Strong correlations exist between bright hydrogen emission lines and the accretion luminosity. This makes it possible to measure the accretion rate of stars based on the luminosity of hydrogen lines produced in the circumstellar environment. These lines are observationally less taxing to obtain compared to UV-optical continuum emission, and hence are an attractive alternative to measure the accretion rate. Despite the intrinsic strength of Pa_α, strong atmospheric absorption from the ground and lack of coverage from previous generation space telescopes has led to this line rarely being observed. Using a sample of 32 pre-main-sequence stars, we determined L_{acc} of each star based on the line luminosity of Br_7, a well established accretion tracer. We then compared L_{Pa_α} to L_{acc}, finding a strong relationship. We fit a line to this relationship, allowing for the conversion of L_{Pa_α} to L_{acc}.
Chapter 4 consists of a detailed analysis of the NIRSpec spectra of five stars from our sample. Three of these stars are Herbig Ae stars, with the two remaining being intermediate mass T Tauri stars. The aim of this analysis was to constrain which physical process produced the bulk of the emission

lines seen prominently in all five spectra. We considered a variety of emission line mechanisms, with an emphasis on MA, MHD winds and emission directly from the inner disc. We performed a kinematic analysis across three hydrogen spectral series (Paschen, Brackett, Pfund) to constrain the emission line origin. We found that the high excitation hydrogen lines were consistently broader than the lower excitation lines. Additionally we found that the high velocity components of the lines were optically thick, while the low velocity components were optically thin. Both of these kinematic properties are consistent with gas in the MA column or direct emission from the inner disc, but are in disagreement with gas in a MHD wind. To further discriminate between disc emission and MA, we computed the free-fall and Keplerian velocities for each source. The three Herbig Ae stars all show line widths too broad to be consistent with Keplerian rotation, and hence we favour MA as the emission mechanism. For the two intermediate mass T Tauri stars, we cannot rule out inner disc emission, due to the higher uncertainties associated with their emission lines. This kinematic analysis provides a new approach to constrain the origin of line emission for spatially unresolved observations, and offers new evidence that Herbig Ae stars accrete magnetically like their lower mass counterparts, T Tauri stars.

Chapter 5 presents an overview of the entire sample of accreting pre-main-sequence stars. Based on improvements in our methodology, we increased the number of stars that we classify as accreting from 32 to 42, mostly from improvements in the nebular background subtraction technique. The spectral type of each star was determined with a fitting procedure, incorporating HST photometry, NIRSpec spectroscopy, and a Markov chain Monte Carlo exploration. This provided the temperature, extinction, and degree of NIR veiling present in each spectrum. We placed the stars on the HRD and fit their temperature and luminosity with stellar isochrones and evolutionary tracks in order to determine their mass and age. We made use of our new $\dot{M}_{acc}$ was determined for all sources. In a number of cases we made use of our new Pa_{α} calibration, as Br_7 was not measured in those spectra. We found that $\dot{M}_{acc}$ in our sample was systematically higher compared to samples from nearby low-mass star forming regions, for a given stellar age and mass. This result suggests that something enables enhanced accretion rates in clusters compared to low-mass star forming regions. This result confirms the findings of extensive photometric surveys of accretion rates in clusters conducted with HST in the previous decade. We also discovered that sources associated with high levels of ISM H_2 exhibit accretion rates that are higher than expected given their age and mass. In line with our previous result, this suggests that the environmental conditions in clusters, i.e. high gas densities, may directly influence stellar accretion.

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