Dispersion in the lifetime and accretion rate of T Tauri discs

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ABSTRACT

We compare evolutionary models for protoplanetary discs that include disc winds with observational determinations of the disc lifetime and accretion rate in Taurus. Using updated estimates for stellar ages in Taurus, together with published classifications, we show that the evolution of the disc fraction with stellar age is similar to that derived for ensembles of stars within young clusters. Around 30 percent of stars lose their discs within 1 Myr, while the remainder have disc lifetimes that are typically in the 1-10 Myr range. We show that the latter range of ages is consistent with theoretical models for disc evolution, provided that there is a dispersion of around 0.5 in the log of the initial disc mass. The same range of initial conditions brackets the observed variation in the accretion rate of Classical T Tauri stars at a given age. We discuss the expected lifetime of discs in close binary systems, and show that our models predict that the disc lifetime is almost constant for separations \( d \gtrsim 10 \) au. This implies a low predicted fraction of binaries that pair a Classical T Tauri star with a Weak-lined T Tauri star, and is in better agreement with observations of the disc lifetime in binaries than disc models that do not include disc mass loss in a wind.

Key words: accretion, accretion discs — stars: pre-main-sequence — planetary systems: protoplanetary discs — open clusters and associations: general

1 INTRODUCTION

Observations of young stars in star forming regions such as Taurus Aurigae show that there is a wide dispersion in the lifetimes of circumstellar discs, in the range 1-10 Myr (Strom et al. 1989; Haisch, Lada & Lada 2001). Although disc lifetimes of this order are consistent with the meteoritic evidence from our own Solar System (Russell et al. 1996), the reason for the large dispersion in the disc lifetime remains unknown. The obvious controlling parameter would be the stellar mass, but in fact observations of low mass stars in young clusters show little correlation between mass and disc lifetime (e.g. Rebull et al. 2002).

The simplest disc models also fail to reproduce other properties of circumstellar discs. One problem is to match the rapid dispersal of the disc. An accretion disc evolves on a single, viscous timescale, which in order to reproduce the aforementioned disc lifetimes needs to be of the order of \( 10^6 \) yr. Dispersal of the disc on this timescale would lead to the prediction of a substantial class of objects with properties intermediate between accreting Classical T Tauri stars (CTTS) and discless Weak-lined T Tauri stars (WTTS) (Armitage, Clarke & Tout 1999). In fact, few stars are caught in the act of clearing their discs, which constrains the disc dispersal time to be short — of the order of \( 10^5 \) yr (Simon & Prato 1995; Wolk & Walter 1996; Duvert et al. 2000).

A second problem is that disc evolution is largely indifferent to the presence or absence of close binary companions. The viscous timescale increases with the characteristic radius of the disc, so discs hemmed in by close binary companions ought to evolve more rapidly than discs around relatively isolated stars. Although examples are known of binaries that appear to have dissipated their discs at an early epoch (Meyer et al. 1997), surveys suggest that binary companions as close as 10 au generally have little effect on the lifetime or mass accretion rate of the disc surrounding the primary (Simon & Prato 1995; Bouvier, Rigaut & Nadeau 1997; Ghez, White & Simon 1997; White & Ghez 2001).

Recently, Clarke, Gendrin & Sotomayor (2001) have shown that models which include mass loss from the disc lead to a dispersal timescale that is much shorter than the viscous evolution timescale, reproducing the two-timescale
behavior required by the observations. In this paper we demonstrate that the same class of models, when combined with a modest range of initial disc parameters, are quantitatively consistent with the wide dispersion in disc lifetimes. In Section 2 we set out the disc model and show that when mass loss is included, the evolution of the accretion rate depends mainly on the initial disc mass and viscous timescale at large radius, and only weakly on the radial dependence of disc parameters such as the surface density and viscosity. In Section 3, we experiment with the range of initial conditions that are required to reproduce the observed age distributions of CTTS and WTTS in Taurus-Aurigae, and show that this range also reproduces the observed scatter in accretion rates in CTTS inferred by Gullbring et al. (1998). In Section 4, we apply the model to binary star systems, and show that due to the wind mass loss from large radii in the disc, the disc lifetime may increase with decreasing disc binary separation over the binary separation range 10−100 au. Section 5 summarizes our conclusions.

2 DISC MODEL

2.1 Evolution equation

The evolution of the surface density, $\Sigma(r, t)$, of a geometrically thin accretion disc is described by (Lynden-Bell & Pringle 1974; Pringle 1981),

$$\frac{\partial \Sigma}{\partial t} = \frac{3}{r} \frac{\partial}{\partial r} \left[ r^{1/2} \frac{\partial}{\partial r} \left( \nu \Sigma r^{1/2} \right) \right] + \dot{\Sigma}_{\text{wind}}(t),$$

where the term $\dot{\Sigma}_{\text{wind}}$ represents the rate of mass loss per unit surface area of the disc in the equatorial plane. We assume that any mass lost leaves the disc with Keplerian specific angular momentum, and thus does not drive radial inflow or outflow in the remaining disc gas. For the kinematic viscosity $\nu$ we adopt a simple power-law in radius,

$$\nu = \nu_0 r^\beta,$$

with $\nu_0$ and $\beta$ constants. Within the context of $\alpha$ disc models (Shakura & Sunyaev 1973), the viscosity in a protoplanetary disc is determined by the intrinsic efficiency of angular momentum transport (i.e. the value of $\alpha$); by the relative contribution of viscous heating and stellar irradiation; and by the opacity which controls the vertical disc structure. A passive irradiated disc, in which both the central temperature and the surface temperature decline with radius as $T_c \propto r^{-1/2}$, has a viscosity (assuming a constant $\alpha$) which scales as $\nu \propto r$. More elaborate calculations of protoplanetary disc structure – though still within the $\alpha$ disc formalism – likewise yield $\beta \sim 1$ (e.g. Bell et al. 1997; D’Alessio et al. 1998). Only limited observational constraints are available at the (small) radii of interest, though $\beta = 1$ is consistent with VLA observations of TW Hydrae by Wilner et al. (2000).

In a steady-state, the surface density profile corresponding to a given accretion rate $\dot{M}$ is,

$$\nu \Sigma = \frac{M}{3r} \left( 1 - \sqrt{\frac{\Sigma_{\text{in}}}{\Sigma}} \right),$$

where we have assumed standard zero-torque boundary conditions at $\Sigma_{\text{in}}$, the inner edge of the disc.

Equation (1) is a diffusion equation for the surface density. Provided that the surface density evolution is controlled by angular momentum transport rather than mass loss, the characteristic timescale for evolution is the viscous time,

$$t_v = \frac{r^2}{\nu}.$$  \hspace{1cm} (4)

Since the viscous timescale increases with radius, the evolution of a disc described by equation (1) speeds up at late times if the outer edge of the disc is truncated by mass loss.

Standard numerical methods (e.g. Pringle, Verbunt & Wade 1986) are employed to solve equation (1) on a non-uniform radial mesh. We use zero-torque ($\Sigma(r_{\text{in}}) = 0$) boundary conditions at the inner edge of the disc. The spatial domain is large enough that the outer boundary condition has no influence upon the results. Formally, we set the radial velocity $v_r = 0$ at this boundary.

2.2 Disc mass loss

Observations provide direct evidence for the existence of two types of disc outflow, jets and photoevaporative flows. Of these, photoevaporative flows, which lead to mass loss from the outer regions of the disc, are the most obviously promising for producing two-timescale disc evolution and rapid disc dispersal (Clarke, Gendrin & Sotomayor 2001; Matsuyama, Johnstone & Hartmann 2002). We consider mass loss via photoevaporation exclusively in this paper, while noting that almost identical behaviour is also possible in models of magnetically driven outflows in which mass loss extends beyond the inner few au of the disc (e.g. Ostriker 1997).

Photoevaporative flows are thermal winds that occur when the disc surface is heated by exposure to ultraviolet radiation (Hollenbach et al. 1994; Johnstone, Hollenbach & Bally 1998; Hollenbach, Yorke & Johnstone 2000; Richling & Yorke 2000). The heated gas can escape at radii $r > r_g$, where the critical radius $r_g$ is given (approximately) by the condition that the sound speed $c_s$ of the hot gas exceeds the local escape velocity,

$$r_g \sim \frac{GM}{c_s^2}.$$  \hspace{1cm} (5)

For parameters appropriate to T Tauri stars, $r_g \sim 5−10$ au. The flux of photoevaporating radiation can be external, as in Orion where UV radiation from massive stars is responsible (Churchwell et al. 1997; Johnstone, Hollenbach & Bally 1998; Scally & Clarke 2001; Henney et al. 2002). Alternatively, a lower level of mass loss can result from the UV and X-ray flux of the low mass star itself (Shu, Johnstone & Hollenbach 1993).

In Taurus, there are no massive stars which could generate a strong external flux of photoevaporating radiation. We therefore adopt a simple mass loss prescription appropriate for the case where the mass loss is driven by local irradiation (Hollenbach et al. 1994). The mass loss per unit area of the disc, $\dot{\Sigma}_{\text{wind}}$, is a function of radius but not of time, and is given by,

$$\dot{\Sigma}_{\text{wind}} = 0, \quad r < r_g$$

1 Implicitly, this assumes that the photoevaporating flux is not tied to the accretion rate. Models by Matsuyama, Johnstone & Hartmann (2002) show that photoevaporation driven solely by the star-disc accretion shock fails to disperse the disc quickly enough.
The accretion rate (upper panel) and the surface density profile (lower panel, plotted at $t = 0.5$ Myr) for disc models with $\beta = 3/2$ (solid line), $\beta = 1$ (short dashes), and $\beta = 1/2$ (long dashes). The other parameters of the models are as given in Table 1. Models with very different viscosity laws and surface density profiles can yield almost identical accretion rate histories.

$$\dot{\Sigma}_{\text{wind}} \propto r^{-5/2} , \quad r > r_g .$$

We express the normalization of the mass loss via the parameter $M_{\text{wind}}$, which is defined as the total mass loss rate if the disc extends to 25 au. The instantaneous mass loss rate will therefore differ from this depending upon the outer disc radius. We take $r_g = 5$ au.

### 2.3 Model parameters

The model described above is defined by two parameters describing the disc physics ($v_0$ and $\beta$), two describing the wind ($M_{\text{wind}}$ and $r_g$), and two for the initial conditions ($M_{\text{init}}$ and the initial disc mass)$^2$. Sensible values for most of these parameters can be estimated from existing observations. We adopt $M_{\text{init}} = 5 \times 10^{-8} M_\odot \text{yr}^{-1}$, since most T Tauri stars have accretion rates of this order or lower (Gullbring et al. 1998). With this initial accretion rate, a disc lifetime of 1-10 Myr mandates an initial disc mass of $\approx 0.1 M_\odot$. After 2 Myr of evolution, this initial disc mass has declined (see Table 1) to a few hundredths of a Solar mass, a value which is broadly consistent with estimates of T Tauri disc masses (Beckwith & Sargent 1991). The assumption that mass loss is driven by photoevaporation fixes $r_g$ to be 5-10 au, and the requirement that this mass loss drives rapid dispersal of the disc suggests that $M_{\text{wind}}$ be no more than a couple of orders of magnitude smaller than $M_{\text{init}}$ (Clarke, Gendrin & Sotomayor 2001).

Determining the parameters for the disc viscosity is more difficult. We have already noted that theoretical models for protoplanetary discs favour values for $\beta$ around unity, but no-one would claim that this parameter is as yet accurately determined. We have therefore chosen for our fiducial models combinations of $v_0$ and $\beta$, shown in Table 1 along with the other parameters of the disc model, that yield a disc lifetime of approximately 5 Myr. This choice of disc lifetime fixes the viscous time at a radius of around 10 au, but does not constrain either $v_0$ or $\beta$ individually. Indeed, as shown in Figure 1, disc models that include a disc wind have only a limited period during which the accretion rate drops as a power-law defined by the value of $\beta$ in the viscosity law. As a consequence of this, models with different choices of $\beta$ can be constructed that yield almost identical evolution of the disc accretion rate, even though they have entirely different surface density profiles. This degeneracy implies that it is not possible to discriminate observationally – even if we had perfect data – between models with different $\beta$, using only measurements of the evolution of the accretion rate with time. We cannot, therefore, use the accretion rate evolution measured by Gullbring et al. (1998) to constrain our models in the same way as was done for disc models without mass loss by Hartmann et al. (1998) and Stepien (1998). In the following discussion, we will leave $\beta$ as an unconstrained parameter, and consider the three models outlined in Table 1 as equally valid possible descriptions of the disc.

To illustrate how the results depend upon some of the other model parameters, we show in Fig. 2 how the accretion rate evolves with time for different choices of the initial disc mass, initial accretion rate, and disc mass loss rate. We start with a disc of mass $M_{\text{disc}}$, and accretion rate $\dot{M}_{\text{init}}$. The disc has an initial surface density profile defined by equation (3) out to the radius where the enclosed mass is $M_{\text{disc}}$, and $\Sigma = 0$ at greater radii. As is obvious from Fig. 2, the two-timescale behaviour discussed by Clarke, Gendrin & Sotomayor (2001) occurs in a range of disc models which incorporate mass loss. The decline of the accretion rate steepens dramatically in all models at the epoch when mass loss in the disc wind becomes important.

### 3 THE DISC FRACTION IN TAURUS

In a recent study, Haisch, Lada & Lada (2001) determined (using $JHKL$ band photometric surveys) the fraction of stars possessing discs as a function of the previously published mean cluster age. They found an evolution in the disc fraction shown in the lower panel of Figure 4. However, since the spread in stellar ages can be comparable to the mean age for clusters that are only $\sim 10^5$ yr old, it is not immediately obvious whether the smooth decline in disc fraction with ‘age’ seen in the Haisch, Lada & Lada (2001) sample reflects primarily,

- A true dispersion in the lifetime of circumstellar discs.
- A convolution of a constant disc lifetime with an extended epoch of star formation in each cluster.
The evidence suggests that for low mass stars there is a significant intrinsic dispersion in disc lifetime. To distinguish between these possibilities, it is necessary to date the stars within young clusters on a star by star basis. We present such an analysis below, and show that in Taurus the evidence suggests that for low mass stars there is a significant intrinsic dispersion in disc lifetime.

### 3.1 Data

To study the evolution of the disc fraction with stellar age, we make use of data compiled for a study of star formation in Taurus by Palla & Stahler (2002). The sample of 151 stars includes approximately 10 stars from Wichmann et al. (2000) whose pre-main-sequence status is confirmed by lithium observations, and which fall within the boundaries of the $^{12}$CO map that contains the bulk of the Taurus-Auriga population. ROSAT All Sky Survey sources that fall at larger distances have not been included. Of this sample, 67 stars are classified as CTTS, and 57 are WTTS. For 27 stars discovered in more recent surveys we were unable to find published classifications, and these are excluded from further analysis.

For each of the stars in the CTTS and WTTS samples, we have estimated ages using the evolutionary tracks of Palla & Stahler (1999). In general, age estimates for pre-main-sequence stars are subject to considerable uncertainty, due to different assumptions as to the initial conditions and accretion history (Tout, Livio & Bonnell 1999; Hartmann 2001; Baraffe et al. 2002). In the specific case of Taurus, Hartmann (2003) has argued that the ages of the higher mass stars (with masses $\gtrsim 1 M_\odot$) are especially uncertain, due to different treatments of the stellar birthline (e.g. Hartmann, Cassen & Kenyon 1997; Palla & Stahler 1999) and possible foreground contamination. We therefore further restrict the sample under consideration to those stars with effective temperatures $T_e \lesssim 4350$ K, leaving a final sample of 57 CTTS and 41 WTTS. With the effective temperature cut, these are all low mass stars.

Figure 3 shows histograms of the age distribution of the low mass CTTS and WTTS in Taurus. The most immedi-
Figure 3. Distribution of the ages of stars classified as Classical T Tauri stars (upper panel) and Weak-Lined T Tauri stars (lower panel) in Taurus. Only stars with effective temperature $T_e \leq 4350$ K are included in the histograms. At least obvious conclusion to be drawn from the Figure is that there is substantial overlap in the derived ages of the CTTS and the WTTS. However, there is also evidence that the WTTS are significantly older as a class. A KS test reveals that the age distributions of the WTTS and CTTS samples differ at more than the $2\sigma$ level (the probability that the distributions are the same is approximately 0.03).

Although the empirical conclusion that the WTTS are significantly older than the CTTS falls short of statistical proof, the evidence is consistent with our expectations if CTTS turn into WTTS. Indeed, if no such difference were found, one would either have to posit no evolutionary link between the two (thus begging the question of what CTTS should turn into) or else appeal to contrived models in which the lifetime of discs were shorter in the case of stars born more recently. We shall show below that the Taurus data is instead compatible with the simple hypothesis that CTTS turn into WTTS, but that the clock for this process varies from star to star. In Chamaeleon I, by contrast, it has been claimed that the age distribution of CTTS and WTTS is indistinguishable (Lawson, Feigelson & Huenemolder 1996). It is now known, however, that this dataset was missing a number of young CTTS (Persi et al 2000), and a more complete census of this region may not ultimately yield an answer different from the Taurus result reported here.

Figure 4 shows the CTTS fraction in Taurus as a function of stellar age. We have binned the data into 5 bins, evenly spaced in the log of the estimated stellar age. Most of the transition between CTTS and WTTS occurs for ages between 1 Myr and 10 Myr. At the youngest inferred ages, CTTS are dominant, but there is still a significant admixture of WTTS. We note, however, that for such young ages – less than a Myr – theoretical uncertainties in the age are probably comparable to the age itself (Baraffe et al. 2002). Any conclusions we might draw as to the evolution of the CTTS fraction prior to 1 Myr should therefore be treated with caution.

Figure 4 also shows the evolution of the disc fraction as measured by Haisch, Lada & Lada (2001) in a sample of 6 young clusters with estimated ages ranging between 0.3 Myr and 30 Myr. Within the errors, which are substantial (arising both from the limited number of stars, and from the uncertainty in cluster age which is not shown in the Figure), the same trend with age is seen as for the Taurus data.

3.2 A model for the dispersion in disc lifetime

A dispersion in the disc lifetime could be caused by several factors, including different disc initial conditions or varying rates of mass loss. For photoevaporation, the mass loss rate is predicted to vary only weakly (as the square root) with the ionizing flux. We have therefore explored whether the data shown in Fig. 4 can instead be explained as arising from different initial conditions for the discs. We focus on the effect of different initial disc masses, as Fig. 2 indicates that the disc lifetime changes markedly as we vary this parameter.

Figure 5 shows how the disc lifetime varies with the initial disc mass. We define the disc lifetime as the time at which the accretion rate first drops below $10^{-10} \, M_{\odot} \, yr^{-1}$ (once this epoch is reached, as shown in Figure 1, mass loss in the wind dominates the evolution, and the accretion rate is dropping precipitously). Apart from changing $M_{\text{disc}}$, the...
Figure 5. The disc lifetime as a function of the initial disc mass, for models with $\beta = 3/2$ (solid line), $\beta = 1$ (short dashes), and $\beta = 1/2$ (long dashes). The initial accretion rate is assumed constant for all models.

Figure 6. Evolution of the disc fraction predicted by models with $\beta = 3/2$ (upper solid line), $\beta = 1$ (short dashes), and $\beta = 1/2$ (long dashes), assuming in each case that there is a dispersion of 0.5 in the log of the initial disc mass. Better, but ad hoc fits to the data (lower curves), are obtained by assuming that $\approx 30\%$ of stars lose their discs via other processes within the first Myr.

other parameters are kept fixed at the values shown in Table 1 (i.e. we change the initial conditions for the disc, but keep the parameters describing the disc viscosity and disc wind constant). For all three disc models, the disc lifetime has an approximately power-law dependence upon the initial disc mass, with an index of $\approx 0.5$.

Figure 5 shows the predicted disc fraction as a function of age, under the assumption that log($M_{\text{disc}}$) is distributed as a Gaussian around the central values given in Table 1. We find that the general trend in the plot of disc fraction with age can be reproduced provided that there is a 1 sigma dispersion of approximately 0.5 in the log of the initial disc mass. A dispersion in initial disc mass of this magnitude leads to almost all stars losing their discs between 1 Myr and 10 Myr, as required to fit the evolution of the CTTS fraction in Taurus, and the evolution of the disc fraction in the clusters studied by Haisch, Lada & Lada (2001).

Although the models do a reasonable job in reproducing the width of the transition seen in Fig. 5, they fail in that they predict a 100\% disc fraction for the youngest stars, those with ages less than a Myr. Indeed, from Fig. 6 we find that a disc lifetime as short as (say) 0.5 Myr requires an initial disc mass that is very small — of the order of few $\times 10^{-3}$ $M_{\odot}$. As noted previously, one possibility is simply that the ages of the youngest WTTS have been underestimated. We find, however, that the spatial distribution of these young WTTS, relative to the cluster gas, is more consistent with the distribution of the young CTTS (Palla & Stahler 2002) than of the older stars. Another possibility is that these objects, classified as WTTS on the grounds of their equivalent width in H$_\alpha$, have highly variable line emission, and have thus been classed as WTTS even though they are not bona fide discless objects. However, we find that these systems are also lacking significant excesses both in the near and far infrared, thus confirming their discless status. These considerations support the contention that the apparently young, discless stars really are young and discless, and constitute a separate population which have lost their discs at a earlier epoch due to processes that do not affect the majority of stars. An ad hoc model in which 30\% of stars lose their discs within a Myr, while the rest evolve in the way which we have modelled, is shown in Fig. 6, and is consistent with the available observations.

If stars form in isolation, then it is hard to understand why a significant fraction of them should lose their discs very early. Rapid early accretion onto the star is expected to cease when the disc first becomes gravitationally stable, at a mass of the order of 0.1 $M_\star$, after which time slower ‘viscous’ evolution continues. Within this framework, initial disc masses that are smaller than average by one to two orders of magnitude are puzzling. In an environment where stars are strongly sub-clustered at birth (Scally & Clarke 2002), however, close encounters between stars can efficiently reduce the disc mass, both directly by unbinding disc material (Clarke & Pringle 1993), and indirectly by reducing the outer disc radius and hastening viscous evolution (Armitage & Clarke 1997). Recent simulations of clustered star formation (Bate, Bonnell & Bromm 2003) show that the required interactions may well be extremely common. In the Bate et al. (2003) calculation, most stars have encounters with another star with a minimum separation distance of a few au or smaller. The young WTTS seen in Taurus may simply be
the fraction of those stars which fail to accrete a significant new disc following their last close flyby.

3.3 Evolution of the accretion rate of CTTS
With the caveats noted above, the evolution of the disc fraction in Taurus is consistent with a theoretical model in which differences in disc lifetime are ascribed to differences in the initial disc mass. A 1σ dispersion of around 0.5 in the log of the initial disc mass is required to reproduce typical disc lifetimes of 1-10 Myr. Figure 7 shows how this model compares with observations of the accretion rate of CTTS in Taurus. We plot estimates of $\dot{M}$ by Gullbring et al. (1998) (as tabulated in Hartmann et al. 1998) against our own revised determinations of the stellar ages. The vertical error bars show Hartmann et al.’s (1998) best estimate of the error in determining the accretion rate, which is 0.6 in log($\dot{M}$). Against this data, we plot theoretical curves for the $\beta = 3/2$ disc model. We show the predicted evolution of $\dot{M}$ for the central estimate of the initial disc mass of $0.1 M_\odot$, and for the models with initial disc masses differing by $\pm 1\sigma$.

From the Figure, it is clear that the $\pm 1\sigma$ curves bracket the observed range of CTTS accretion rates at a given age. The dispersion in initial disc mass required to reproduce the observed range in disc lifetimes also produces roughly the correct spread in accretion rates. Since we can reproduce the same result with other choices of $\beta$, our interpretation is that the Hartmann et al. (1998) plot of $\dot{M}$ against $t$, shown in a modified form as Figure 7, tells us more about the variation in the initial conditions for discs than it does about the internal physics governing their evolution.

4 THE INFLUENCE OF BINARY COMPANIONS
Most T Tauri stars are found in binary systems (Leinert et al. 1993; Ghez, Neugebauer & Matthews 1993; Simon et al. 1995), which can affect the evolution of circumstellar discs in several ways. First, gravitational torques from the companion act to truncate the disc (Paczynski 1977), and prevent it from expanding freely. Second, if the binary is sufficiently close, it will limit the reservoir of gas available to be accreted. Both of these effects would be expected to reduce the lifetime of discs in binary systems as compared to single stars. A substantially reduced disc lifetime in binaries is not, however, observed (Simon & Prato 1995; Bouvier, Rigaut & Nadeau 1997; Ghez, White & Simon 1997; White & Ghez 2001).

Fig. 8 shows how binaries alter the predicted disc lifetime in our models. We have assumed that the only effect of the binary on the initial surface density distribution is to truncate the disc at a radius $r_t = d/3$, where $d$ is the binary separation. The initial accretion rate in the binary models is therefore the same as for the isolated disc models. At $r_t$, we model the torques from the companion using a $v_r = 0$ boundary condition. Parameters for the disc wind and the disc viscosity remain unchanged.

By construction, the disc lifetime for sufficiently wide

![Figure 7](image1.png)

**Figure 7.** The accretion rate of Classical T Tauri stars in Taurus, as estimated by Hartmann et al. (1998), plotted against the stellar age. The heavy central curve shows the predicted evolution of the accretion rate for the $\beta = 3/2$ disc model outlined in Table 1. The upper and lower curves show the accretion rate for models in which the initial disc mass has been increased or decreased by a factor of three.

![Figure 8](image2.png)

**Figure 8.** The predicted disc lifetime in binary systems, for models with $\beta = 3/2$ (filled triangles), $\beta = 1$ (open squares), and $\beta = 1/2$ (crosses). We assume that the disc is truncated at $1/3$ of the binary separation, and that there is no replenishment of the circumstellar discs from circumbinary material. The vertical dashed line shows the separation below which the discs suffer no mass loss.
binaries tends to the observed value of \( \approx 6 \text{ Myr} \). At smaller separations, all three disc models display similar behaviour. The disc lifetime initially increases, reaching a peak at a separation of 15 au to 100 au, depending upon the model. This increase occurs because the disc, which is prevented from expanding freely, has less area from which mass can be lost in a wind. This compensates for, and initially overwhelms, the tendency for smaller disc to have reduced viscous timescales. As a result, only very close binaries (\( d \) less than 10 au to 40 au, depending upon the model) are predicted to lead to a reduction in the disc lifetime as compared to the lifetime of an isolated disc.

In addition to asking whether the disc lifetime around the primary is a function of binary separation, we can also ask whether differential evolution of the primary and secondary disc is expected to yield ‘mixed’ binary systems that pair CTTS and WTTS. The naive expectation is that the lower mass component of the binary, whose Roche lobe encloses a smaller disc, should lose its disc and become a WTTS first. Observations, however, show that mixed pairs are rather rare. Using a sample of close binaries (most of which had projected separations between 15 au and 100 au) Hartigan & Kenyon (2002) found that only 25 percent (4 out of 16 systems) of binaries containing at least one CTTS were mixed systems. Combining these results with earlier studies (Brandner & Zinnecker 1997; Prato & Simon 1997; Duchene et al. 1999), which obtained similarly small mixed fractions, there is no evidence for a trend in the fraction of mixed systems with separation. Comparing the observations to disc models that do not include winds, this is only consistent with theoretical expectations if the initial conditions yield more massive discs around the lower mass star (Armitage, Clarke & Tout 1999).

If we assume that the initial disc accretion rate, and the mass loss rate, are the same for both stars in a binary, then the disc models presented in this paper predict a low level of mixed WTTS / CTTS binaries. For a mass ratio\( q = 0.5 \), the maximum radii of discs surrounding the primary and secondary differ by around 50 percent (Papaloizou & Pringle 1977). From Figure 8 we then estimate that an initially doubly strong (CTTS + CTTS) binary with separations of 15 au to 100 au, depending upon the model, is predicted to lead to a reduction in the disc lifetime as compared to the lifetime of an isolated disc.

5 SUMMARY

We have shown that protoplanetary disc models which include mass loss from the disc at large radius are generally consistent with observations of accretion in T Tauri stars. In particular, we can simultaneously reproduce both the rapid disc dispersal required by observations (Simon & Prato 1995; Wolk & Walter 1996; Duvert et al. 2000), and the near-independence of the disc lifetime on the binary environment (White & Ghez 2001). The evolution of the disc fraction in young clusters, which we have studied in detail for Taurus, can also be modelled within this framework, provided that we allow for a spread in initial disc masses around a central value of \( \approx 0.1 M_\odot \). We believe that the required level of variation in the initial conditions of discs is a plausible outcome of the turbulent conditions that give rise to star formation within clusters. Simulations of clustered star formation (e.g. Bate, Bonnell & Bromm 2003) show that interactions between small groups of forming stars and their discs are almost inevitable. In such a dynamic environment, we expect large star to star variations in the initial mass and angular momentum content of circumstellar material. In fact, a significant fraction of the stars formed in the Bate et al. (2003) simulation suffer encounters with other stars that are close enough to truncate circumstellar discs to sizes of au or smaller. Such interactions provide a possible origin for the otherwise puzzling observation of a population of apparently very young Weak lined T Tauri stars seen in the Taurus region.

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