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The dispersal of circumstellar discs: the role of the ultraviolet switch

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ABSTRACT

We explore ultraviolet switch models for the dispersal of circumstellar discs in T Tauri stars that involve both photoevaporation by the central star *and* viscous evolution. We show that in combination these processes generate the observed 'two timescale' behaviour for the dispersal of such discs, whereby the disc is rapidly dispersed at the end of its life on a timescale that is a small fraction of the disc lifetime. This switch is activated when the accretion rate through the disc declines to the low level (a few times $10^{-10} M_{\odot}$ yr^{-1}) such that it roughly matches the rate of photoevaporative mass loss from the disc outside $5-10$ A.U.. At this point, the inner disc is deprived of further replenishment from larger radii and empties on to the central star on its own short viscous timescale. This causes the rapid ($\sim 10^5$ year) decline in accretion rate on to the central star and in all disc related emission shortward of 10μm. We discuss the implications of this model for the detection of mm emission around Weak Line T Tauri stars, and also point out the consequences of such a sudden draining for planet formation in the inner regions of circumstellar discs.

Key words: accretion discs- circumstellar matter - stars:accretion

1 INTRODUCTION

The processes responsible for dispersing the discs around young stars are not well understood at present. This issue is important inasmuch as it impacts on the time available for planet formation in circumstellar discs. Possible mechanisms that have been discussed include viscous draining onto the central star (Hartmann et al 1998; henceforth HCGA), interaction with a stellar magnetosphere (Armitage, Clarke and Tout 1999), the effect of a stellar wind (Elmegreen 1979), the role of encounters in a cluster environment (Clarke and Pringle 1991; Armitage and Clarke 1997; Scally and Clarke 2001), photoevaporation by the ultraviolet radiation field of the central star (Hollenbach et al 1994; Yorke and Welz 1996; Richling and Yorke 1997) or neighbouring stars (Johnstone et al 1998; Storzer and Hollenbach 1999) and the consumption of gas and solid material in planet formation (e.g. Brandner et al 2000; see also the review by Hollenbach et al 2000).

Empirical studies of disc dispersal are hampered by difficulties in observationally calibrating the ages of young stars, particularly below ages of $\sim 10^6$ years (see, for example, Tout, Bonnell and Livio 1999 and Siess et al 2000). Nevertheless, a secure conclusion from such studies is that there appear to be *two* timescales associated with disc dispersal. The first, the mean disc lifetime, appears to lie in the range $5 \times 10^6 - 10^7$ years (Strom et al 1989). However, the timescale for the *transition* between disc possessing and discless status is apparently substantially smaller than this (with typical estimates of a few times 10^5 years; Skrutskie et al 1990, Hartigan et al 1990). Note that the *ratio* of these timescales is independent of any absolute age calibration and simply reflects the fraction of T Tauri stars observed as transition objects.

Most of the mechanisms listed above do not at first glance appear promising candidates for generating this 'dual timescale' behaviour. The best studied of these, viscous draining onto the central star, gives a roughly power law decline of disc quantities with time (HCGA) - in other words, the timescale for decline by order unity from any given state is in this case of order the system's lifetime to date. Magnetospheric models appeared more promising for promoting a swift demise of the disc since they involve a feedback whereby the stellar field can clear out the inner disc more effectively once it is weakened by viscous draining. However, it turns out that although this process indeed produces the

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desired decline in the near infrared emission associated with the inner disc ($<$ a few $\times 0.1$ A.U.) intercepted by the putative magnetosphere, it has only a minor effect on disc emission at 10μm and longer (Armitage, Clarke and Tout 1999). This behaviour is at odds with the distribution of T Tauri stars in the K-L, K-N two colour plane, which indicates a nearly simultaneous decline in disc emission in the $2-10\mu$m range (Kenyon and Hartmann 1995); ISOCAM observations in Chamaeleon I also indicate that this simultaneous decline extends at least out to 14μ m (Persi et al 2000). Likewise, although close stellar encounters can weaken the inner disc so that, in magnetospheric models, the 2μm flux declines dramatically, the shaved remnant disc then viscously re-expands so that longer wavelength emission then declines on the, substantially longer, viscous timescale at larger radii (Armitage and Clarke 1997). This viscous re-expansion following one-off encounters implies that even very close encounters (e.g. at a few A.U.) cannot promote the rapid decline of emission at 5μm and longer unless the mass of the remnant disc is very low. Finally, planet formation has been invoked as a means of promoting the swift decline of disc emission, since the timescale on which grains can agglomerate, and hence remove opacity in the corresponding wavelength range, is indeed short (e.g. Weidenschilling and Cuzzi 1993). The rarity of millimetre emission in systems lacking disc emission in the infrared (Duvert et al 2000), however requires a process that acts simultaneously on spatial scales of $0.1-100$ A.U., involving the removal of dust grains whose sizes span three orders of magnitude. It remains questionable whether planet formation can achieve such global changes in the disc properties.

In this paper we investigate the dispersal of circumstellar discs in T Tauri stars due to photoionisation by the ultraviolet radiation from the central star. We rely heavily on parameterisations of photoevaporative mass loss derived from the models of Hollenbach et al 1994 and incorporate this mass loss as sink terms in standard viscous evolution models. The integrated mass loss rate for typical T Tauri stars (a few $\times 10^{-10} M_\odot \mathrm{yr}^{-1}$) implies that this process can only by itself disperse a rather low mass disc (comparable to the minimum mass solar nebula) within $\sim 10^7$ years. We show, however, that in conjunction with viscous draining, this mechanism provides the desired 'switch' whereby the inner disc and its associated diagnostics fade on a 10^5 year timescale.

In Section 2 we describe the time dependent disc model and its parameters. Section 3 describes our results and provides a comparison with observations. In Section 4 we discuss the level and origin of the photoionising radiation in T Tauri stars and how uncertainties in this regard affect the viability of the model. We conclude in Section 5 by summarising the virtues and potential problems of the model.

2 PHOTOEVAPORATIVE VISCOUS MODEL

2.1 Viscous model

In order to be able to isolate the effect of photoevaporative mass loss on the viscous evolution of the disc, we employ parameters for the viscous evolution that are identical to the similarity solutions explored by HCGA (see also Lynden-Bell and Pringle 1974). These authors focus on the case that the kinematic viscosity in the disc is a linear function of the radius, R, at all times. Thus our initial surface density profile is of the form:

$$\Sigma = \frac{M_d(0)}{2\pi R_1^2 r} exp[-r] \quad (1)$$

where $r = R/R_1$, R_1 is a radial scale factor and $M_d(0)$ the initial disc mass. [Note that the significance of R_1 is that the fraction of the disc mass initially outside this radius is e^{-1}]. If the value of the viscosity is parameterised by ν_1 at radius R_1, the initial value of the accretion rate at the origin is given by

$$\dot{M}_0(0) = \frac{3M_d(0)\nu_1}{2R_1^2} \quad (2)$$

Thus the viscous evolution of each model is completely specified by the three parameters, $M_d(0)$, R_1 and $\dot{M}_0(0)$. Note that in such models the viscous scaling time is given by

$$t_s = \frac{M_d(0)}{2\dot{M}_0(0)} \quad (3)$$

and that for times much larger than t_s, the accretion rate at the origin and the disc mass both show an approximately power law dependence on time:

$$\dot{M}_0 \propto t^{-3/2} \quad (4)$$

$$M_d \propto t^{-1/2} \quad (5)$$

2.2 Photoevaporation model

Our parameterisation of the photoevaporative mass loss follows closely that set out (the 'weak stellar wind' case) by Hollenbach et al 1994. These authors assume that material is lost from the disc surface at radii beyond

$$R_g = \frac{GM_*}{a^2} \sim 10^{14} \tilde{M} cm \quad (6)$$

where M_* is the stellar mass, a is the sound speed of photoionised gas and $\tilde{M}$ is the stellar mass in solar mass units. This radius represents the maximum extent of the region within which photoionised gas (temperature $\sim 10^4$ K) can remain bound to the central star. Beyond this radius the rate of mass loss per unit area is given by:

$$\dot{\Sigma}_w = 2an_0(R)m_H \quad (7)$$

where $n_0(R)$ is the number density at the base of the photoevaporating flow, m_H the mass of a hydrogen atom and the factor 2 takes account of mass loss from both sides of the disc. The base density $n_0(R)$ is determined by detailed photoionisation calculations and for $R > R_g$ is parameterised by

$$n_0(R) = n_0(R_g)\left(\frac{R}{R_g}\right)^{-5/2} \quad (8)$$

where

$$n_0(R_g) = 5.7 \times 10^4 \Phi_{41}^{1/2} R_{g14}^{-1.5} cm^{-3} \quad (9)$$

Here R_{g14} is the gravitational radius in units of 10^{14}cm and Φ_{41} the ionising photon luminosity of the central star in units of 10^{41} s^{-1}. The above prescription corresponds to a total wind mass loss rate of

$$\dot{M}_{dw} = 4.1 \times 10^{-10} \Phi_{41}^{1/2} \tilde{M}^{1/2} M_{\odot} yr^{-1} \tag{10}$$

2.3 Model evolution

The viscous evolution of the disc subject to photoevaporative mass loss is computed using a standard first order explicit scheme, equispaced in $R^{1/2}$ over the dynamic range $9 \times 10^{-3} R_1$ to $250 R_1$. Zero torque boundary conditions are applied at the inner and outer boundaries. For ease of comparison with HCGA, the spectral energy distribution is generated by assuming that the disc temperature is a fixed power law function of radius, subject to a minimum temperature T_{min}. (This fixed temperature distribution was justified as approximately representing a disc in which the main heating agent is reprocessing of stellar radiation, though even in this case this condition would be modified once the disc became optically thin to the incident radiation, as well as by the luminosity evolution of the central star). In order to reproduce the observed spectral index in T Tauri stars, the form :

$$T_d \propto R^{-1/2} \tag{11}$$

is adopted. The spectral energy distribution is then generated by assuming that at every radius the disc radiates as an isothermal slab at temperature $T_d(R)$ (equation 44 of HCGA), with a dust opacity described by

$$\kappa_\nu = 0.1(\nu/10^{12} Hz) gcm^{-2} \tag{12}$$

2.4 Summary of parameters

The model is uniquely described by the following parameters.

- Stellar parameters:
  - mass of star ($\tilde{M}$),
  - ionising photon flux (Φ_{41}).
- Disc parameters:
  - initial disc mass ($M_d(0)$),
  - initial accretion rate in inner disc ($\dot{M}_0(0)$),
  - initial scaling radius (R_1),
  - dust temperature at R_1 (T_1)
  - and minimum dust temperature (T_{min}).

From the above parameters, the initial viscous time, t_s, the gravitational radius R_g, the wind mass loss rate $\dot{M}_{dw}$ and run of temperature in the disc can be calculated using equations 3,6,10 and 11.

3 RESULTS

3.1 Standard model

We start by describing the main features of a 'standard' photoionisation model with parameters: $\tilde{M} = 1, \Phi_{41} = 1, R_1 = 10 A.U., M_D(0) = 0.1 M_\odot, \dot{M}_0(0) = 4.2 \times 10^{-7} M_\odot$ yr^{-1}. In this model the initial viscous evolution timescale is 1.1×10^5 years, the gravitational radius (beyond which wind loss occurs) is 10^{14}cm and the total wind mass loss rate is $4 \times 10^{-10} M_\odot$ yr $^{-1}$.

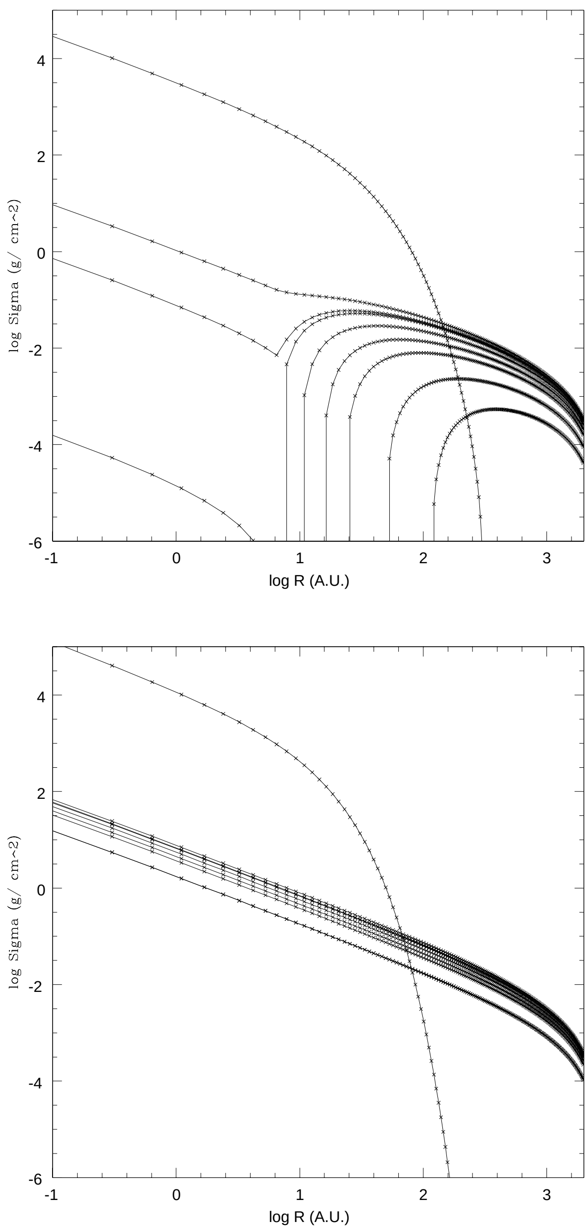

Figure 1. Snapshots of the surface density distribution in the disc a) for the standard model (see 3.1) and b) for the corresponding model with no photoevaporative mass loss. The curves represent (from the top down), $t = 0, 1.3 \times 10^7, 1.41 \times 10^7, 1.43 \times 10^7, 1.6 \times 10^7, 1.8 \times 10^7, 2.0 \times 10^7, 2.4 \times 10^7, 2.8 \times 10^7$ years. Note the precipitous decline of the inner disc in a) over the 2×10^5 year timescale between the third and fourth snapshots.

Figure 1a) illustrates snapshots of the surface density profile while b) provides, for comparison, an equivalent model with no photoevaporative mass loss. At early times, the evolution of the two models is similar, though with a somewhat more rapid decline in Σ inward of around 30 A.U. for the wind case. At time $t = 1.41 \times 10^7$ years, (which we denote t_w in the discussion below) the wind model develops a pronounced dip in the surface density profile in the vicinity of R_g. The following snapshots illustrate the very rapid subsequent decline of Σ inward of R_g on a timescale t_{inner} of $\sim 10^5$ years. At radii slightly beyond R_g the disc profile is scarcely modified on this timescale. Following the viscous emptying of the inner disc, the remaining disc is then

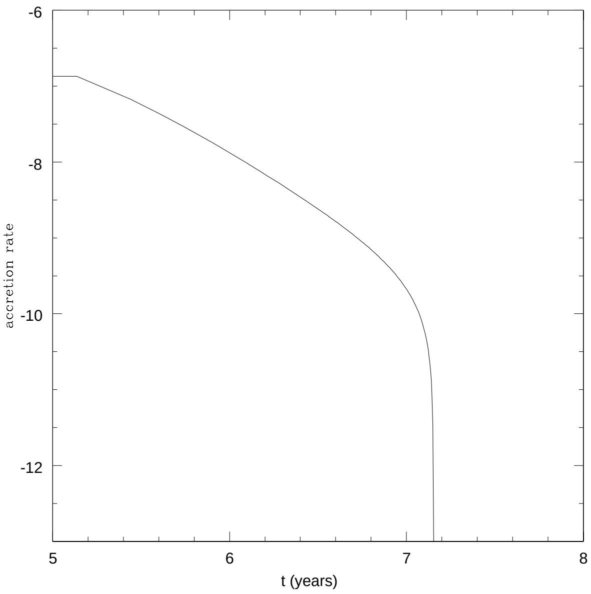

Figure 2. Evolution of the accretion rate onto the central star for the standard wind model. Note the abrupt turn down in $\dot{M}$ once it declines to a level comparable with $\dot{M}_{dw}$.

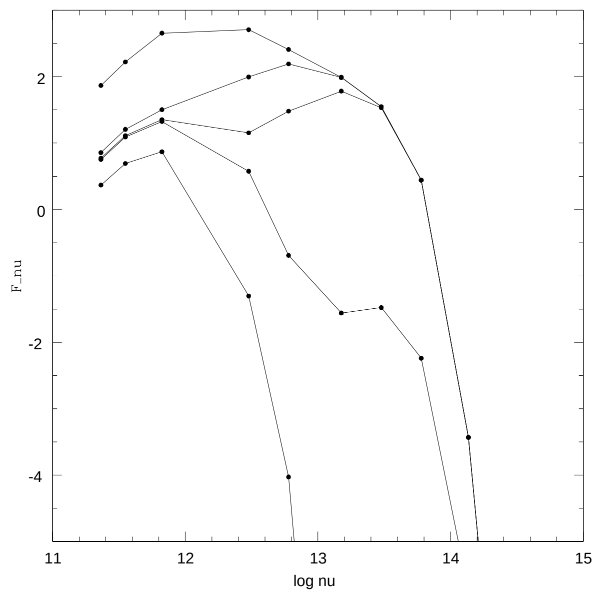

Figure 3. Snapshots of the spectral energy distribution for the standard model at times (from the top down) of $t = 0, 1.3 \times 10^7, 1.41 \times 10^7, 1.43 \times 10^7, 2.0 \times 10^7$ years. Plotted points correspond to wavelengths of 1.3 mm, $850, 450, 100, 50, 20, 10, 5$ and 1.6μm.

progressively dispersed from the inside out. The timescale for this dispersal (t_{outer}) is much greater than t_{inner} and is within a factor of a few of t_w: in other words, the outer disc is dispersed on a timescale that is comparable, though somewhat less, than the age of the system when rapid draining of the inner disc set in.

This behaviour is readily understood since at early times the accretion rate through the disc is much larger than $\dot{M}_{dw}$ and hence the effect of photoevaporative mass loss is small. As $\dot{M}$ in the disc declines due to viscous draining on to the central star, it eventually attains a level comparable with $\dot{M}_{dw}$ (see Figure 2) . At this point, a substantial fraction of the accretion flow in the outer disc is blown away in the vicinity of R_g. (Note that the mass loss rate per unit area scales as $R^{-5/2}$ so that mass loss is concentrated in a region rather close to R_g). In consequence, the fraction of the accretion flow that is available to resupply the inner disc ($R < R_g$) falls precipitously. The inner disc is then effectively starved and empties on to the central star on a timescale that is the viscous timescale at R_g.

Figure 3 shows snapshots of the resulting spectral energy distribution for the case that the disc temperature at 100 A.U. is 10 K and where the temperature minimum is set at 7K. This clearly illustrates that the rapid ($\sim 10^5$ year) emptying of the inner disc produces a corresponding fall in the radiative output of the disc at those (short) wavelengths predominantly produced within $\sim$ 10 A.U.. In the current crude spectral model, the spectral region strongly affected extends out to $\sim 100\mu$m; we however note that in more realistic models (see, for example, Chiang and Goldreich 1997) much of the emission longward of 20μm originates beyond a radius of 10 A.U. and would thus be expected to be more mildly affected by the demise of the inner disc. In any case, the millimetre flux is expected to remain strong at this stage.

3.2 Dependence on model parameters: analytic estimates

All the photoevaporative models that we have explored are typified by the same qualitative behaviour: a decline of disc diagnostics over a period t_w, at which point the inner disc is decoupled from further supply and rapidly empties on a timescale t_{inner}. These models are thus the first models for disc clearing that demonstrate the 'two timescale' behaviour that seems to typify the evolution of T Tauri stars, and it is thus worth considering what properties control each of these timescales.

The timescale, t_w, on which the disc viscously declines to the point that the accretion rate is $\dot{M}_{dw}$ is readily obtained from the similarity solution (equation 4) as

$$t_w = t_s \left(\frac{\dot{M}_0(0)}{\dot{M}_w} \right)^{2/3} \tag{13}$$

whereas the draining timescale of the inner disc t_{inner} is just the viscous timescale at R_g (i.e. $R_g^2/\nu(R_g)$), which for this viscosity prescription is simply given by

$$t_{inner} = \left(\frac{R_g}{R_1} \right) t_s \tag{14}$$

Hence the ratio of the two timescales is simply:

$$\frac{t_w}{t_{inner}} = \left(\frac{\dot{M}_0(0)}{\dot{M}_w} \right)^{2/3} \left(\frac{R_g}{R_1} \right) \tag{15}$$

Substitution of the parameters of the standard model (where $R_1 \sim R_g$ and the initial accretion rate exceeds the wind loss rate by around three orders of magnitude) readily verifies that the two timescales are separated by two orders of magnitude as found above. Since the parameters used in this model are rather typical for characteristic disc sizes and initial accretion rates, one would thus expect that the ratio of *transition objects* (i.e. those in the process of dissipating their inner discs) to Classical T Tauri should be very small.

We may also estimate the timescale on which the outer disc is dissipated, t_{outer}. Once the inner and outer discs become decoupled (at time t_w), the residual outer disc, mass M_{outer}, is then removed by wind loss at the constant rate $\dot{M}_{dw}$. For the similarity solution considered here (as indeed in most disc models supported by observational constraints) the majority of the mass resides in the outer parts of the disc, and therefore one does not make a gross error by setting the mass of the outer disc to be blown away as just the disc mass at time t_w. If we estimate this latter quantity by simply ignoring the effect of wind mass loss on a timescale t_w, and hence use the similarity solution (equations 4,5) (which will also cause the mass to be somewhat overestimated), we obtain

$$M_{outer} = M_d(0)\left(\frac{\dot{M}_{dw}}{\dot{M}_0(0)}\right)^{1/3} \tag{16}$$

and hence

$$t_{outer} = \frac{M_{outer}}{\dot{M}_{dw}} = t_s\left(\frac{\dot{M}_0(0)}{\dot{M}_w}\right)^{2/3} \tag{17}$$

where in the latter step we have used the identity for t_s (equation 3). Comparing equations 17 and 13 we obtain the simple result that t_{outer} is always of order t_w, a result we see verified in the simulations (see Figure 1). This result can be understood more generally inasmuch as the time taken for the disc to decline to the point at which the inner and outer discs become decoupled is dominated by the ratio of disc mass to accretion rate at that time; since the wind mass loss proceeds thereafter at this constant rate, it follows that the additional time taken for the residual disc to be blown away is always comparable with the time spent reaching the point of decoupling. Below we consider possible observational problems associated with this result.

3.3 Observational constraints

As noted above, the model yields a rapid transition between objects with inner discs (out to $\sim$ 7 A.U.) and those that do not. Diagnostics that would fade on this timescale include the accretion rate on to the central object and all disc emission shortward of around 10μm. Thus unlike models considered to date (i.e. viscous clearing with or without the aid of magnetospheric effects) this model does not lead to an excessive number of objects being placed in 'forbidden' (i.e. transitional) areas of the infra-red two colour plane. In this model, by contrast, all near infrared wavelengths decline simultaneously and rapidly, producing the observed bimodal distribution of infrared colours in T Tauri stars. The onset of this rapid transition is set purely by the accretion rate in the disc falling to the low level set by photoevaporative mass loss ($\sim 4 \times 10^{-10} M_\odot \mathrm{yr}^{-1}$ for the parameters invoked by Hollenbach et al 1994). Accretion rates in stars possessing infrared signatures of inner discs have been measured down to values marginally above this (Gullbring et al 1998) whilst Muzerolle et al 2000 have recently modeled an accretion rate of $5 \times 10^{-11} M_\odot$ yr^{-1} in a T Tauri star lacking such inner disc emission. It is thus encouraging that the available data on accretion rates in T Tauri stars supports the notion

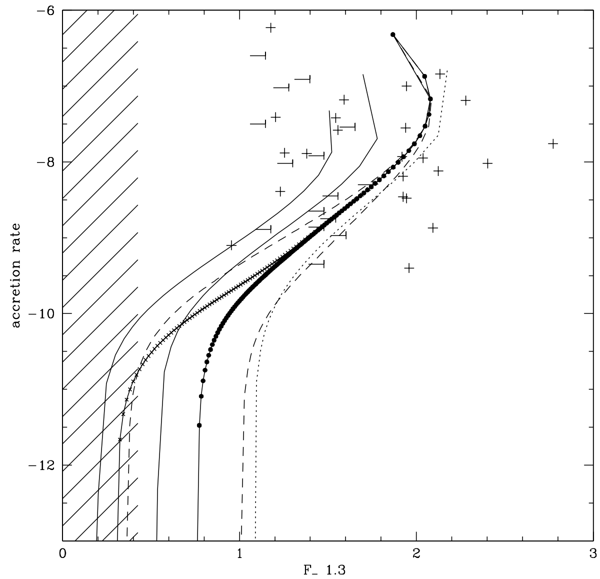

Figure 4. Evolution of various models in the plane of flux at 1.3 mm (in mJy) versus accretion rate (in $M_\odot$ yr^{-1}). The bold dots represent the standard model whereas the other two solid lines represent models that differ only in the initial disc mass ($0.01M_\odot$ and $0.03M_\odot$ for the left and right curves respectively). The dashed lines represent models that differ from the standard models only in terms of the minimum temperature imposed (3 K and 10 K for left and right respectively). The short dashed line is a more extended model with $R_1 = 30$ A.U., whereas the line marked by crosses is a low photoionising flux model with $\Phi_{41} = 0.1$. Datapoints represent detections and 3σ upper limits at 1.3 mm from Beckwith et al 1990 and Osterloh and Beckwith 1995. The hatched region represents the 3σ upper limit for non-detections of Weak Line T Tauri stars by Duvert et al 2000.

that the disc emission disappears at an accretion rate of a few times $10^{-10} M_\odot$ yr^{-1}. Although the similarity of this threshold value to that provided by photoionisation models could of course be merely coincidental, it is at least reassuring that the latter was *not* derived with this observed threshold in mind.

We have however shown above that the timescale on which the outer disc ($>$ 7 A.U.) is blown away is always considerably longer than the time for the inner disc to empty, and that this timescale is moreover always comparable with the period over which the star possesses an inner disc. There is a concern here, therefore, that we are predicting large numbers of objects that are weak on small scales but strong on large scales - in other words that we have reproduced problems with previous models but now shifted the problem out to larger radii (and hence longer wavelength emission). At first sight, the rather clear association of millimetre emission with Classical T Tauri stars, and a corresponding lack of such emission in Weak Line T Tauri stars (e.g. Andre and Montmerle 1994, Osterloh and Beckwith 1995) would appear to argue against this model. To make further progress on this issue, however, we have to make quantitative predictions and compare with available upper limits on submillimetre emission in Weak Line T Tauri stars.

Figure 4 depicts the evolution of various photoevaporation models in the plane of flux at 1.3mm versus accretion rate on to the central star, assuming sources located at a distance of 140 parsecs. When interpreting this figure, it is worthwhile recalling the spectral model, following HCGA, that we have used: that is, that the disc has a *time independent* temperature distribution, so that the evolution of the millimetre flux depends only on the disc optical depth and emitting area. Each model proceeds monotonically downwards in this diagram as the accretion rate on to the central star declines (at early times, the millimetre flux increases briefly, as viscous spreading of the initial distribution results in an increase in the emitting area of the disc that is optically thick at 1.3 mm.) At the point of decoupling of the inner disc, the accretion rate onto the central star declines precipitously, but with no corresponding decline in the millimetre flux on this timescale. The model trajectories thus become vertical at this stage. Eventually, the millimetre flux also declines and the models proceed to the left in this plane, though at accretion rates on to the central star that are so vanishingly small that this behaviour is not manifest in the diagram. Superimposed on this plot are objects for which both accretion rates and millimetre fluxes (or upper limits) have been determined. These objects are all Classical T Tauri stars, and occupy a broad region of the diagram through which all the models pass. The typical limiting sensitivity for these millimetre observations dating from the mid nineties is around $20-30$ mJy. One thus sees that by the stage that the accretion rates in the models fall to 'Weak Line' values, the anticipated millimetre flux is somewhat lower than these upper limits, so that one would not have expected such observations to be able to detect millimetre emission around Weak Line T Tauri stars.

A more serious challenge may however be provided by the much lower upper limits (2.5 mJy) recently obtained by Duvert et al 2000 for a sample of Weak Line T Tauri stars. This limit is depicted as the hatched region in Figure 3. As may be seen, several of the models turn vertical in a region of the diagram to the right of this. We have calculated in these cases the time spent in the 'transition' region of the diagram (specifically, objects in which the inner disc has declined but which have millimetre fluxes greater than 2.5 mJy). We find that in these models the ratio, $f_{T/C}$, of the time spent in this region to that spent in the 'Classical T Tauri' phase (i.e. prior to the decline of the inner disc) lies in the range of $0.4-1.7$. (This result is just a re-statement of the fact that, in the case of sensitive observations, one is recovering the fact that $t_w \sim t_{outer}$; see 3.2 above).

If the ratio of Weak Line T Tauri stars to Classical T Tauri stars is $f_{W/C}$, one then derives the fraction of Weak Line Stars with mm flux detectable at the 2.5 mJy level as

$$f_{T/W} = \frac{f_{T/C}}{f_{W/C}} \tag{18}$$

Since estimates of $f_{W/C}$ vary in the range $1-10$ (Stahler and Walter 1993, Kenyon and Hartmann 1995), whereas the values of $f_{T/C}$ predicted by the models in Figure 3 lie in the range $0-1.7$, it would be premature to decide whether the low number of transition objects detected by Duvert et al (1 detection of 1.3 mm flux at the 2.5 mJy level out of 11 Weak Line T Tauris studied) represents a serious challenge to the model. We note that when we experimented with models where the steady state surface density declined more steeply with radius (and hence where the viscosity increased more steeply with radius), we found that the millimetre flux lingered at lower levels. For example, for models in which $\Sigma \propto r^{-3/2}$, most had a residual millimetre flux that was below the 2.5 mJy level; we note, however, that Hartmann et al (1998) have advanced arguments against the steady state surface density power law being much steeper than the r^{-1} law used here. What is clear, is that all ultraviolet switch models predict a lingering of the millimetre flux at its value just after the inner disc is emptied, but whether this value is greater or less than 2.5 mJy depends on the details of the spectral and viscous model, in particular the initial disc mass and radius and the minimum temperature to which the disc is allowed to cool.

4 DISCUSSION

All photoevaporative models share a common feature that makes this mechanism a highly promising one for the dispersal of discs around T Tauri stars: namely, they reproduce the observed 'two timescale' behaviour of T Tauri stars, whereby the timescale for the sudden transition between Classical and Weak Line T Tauri status is $1-2$ orders of magnitude less than the lifetime of the disc in the Classical T Tauri state. Quantities that are switched off on this $\sim 10^5$ year timescale are all those associated with the inner disc (within $5-10$ A.U.), i.e. disc emission shortward of 10μm as well as spectral diagnostics of accretion on to the central star. As discussed above, the outer disc is dispersed on a longer timescale in these models, and further sensitive searches for cool dust emission around Weak Line T Tauri stars are required before deciding if this is a serious objection to the model.

So far, we have assumed an ionising luminosity of the central star which remains invariant throughout the star's pre-main sequence lifetime. Following Hollenbach et al 2000 (see also Shu et al 1993) we have adopted an ionising luminosity of $10^{41}\mathrm{s}^{-1}$ for a solar mass central star. The assignment of an ionising luminosity that is considerably greater than that produced by the sun ($10^{39}\mathrm{s}^{-1}$) is motivated by the fact that IUE showed at least some T Tauri stars to exhibit highly super-solar activity in the ultraviolet (e.g. Gahm et al 1979, Imhoff and Appenzeller 1987): the grounds for the quantitative estimate of $10^{41}\mathrm{s}^{-1}$ are not however clear. Fortunately, the results reported above are rather insensitive to the value of the ionising flux. The associated mass loss rates scale as $\Phi_i^{1/2}$, so that if Φ_i was an order of magnitude lower, for example, one would recover qualitatively identical behaviour, but with the Classical T Tauri state persisting down to accretion rates $\sim$ a factor 3 lower, and with a longer time required to decline to this accretion rate. Once switch-off occurred, it would share the same features as for higher Φ_i models, since the timescale for emptying the inner disc, and the spectral diagnostics affected, are set purely by the gravitational radius R_g, which depends only on the stellar mass.

A much more important issue than the overall level of the photoionising flux, however, is the question of the origin of this emission. It is essential for this model that it has a component that is *not* powered by accretion, because otherwise the photoionising flux would itself be turned off as the disc declined and would thus be ineffective at late times. Two recent studies (Costa et al 2000, Johns-Krull et al 2000) of archival IUE data for T Tauri stars examined the relative roles of accretion and magnetic activity as the heating source for ultraviolet emission in these objects and came to slightly different conclusions. At a purely empirical level, it is notable that in early type T Tauri stars the continuum level at 1958 A is of comparable strength in Classical and Weak Line T Tauri stars, and that these levels overlap measurements of main sequence stars of the same spectral type. In this case, it would appear clear that there is an important energy source of magnetic origin; an even stronger conclusion can be drawn in the case of Xray emission in T Tauri stars, where Weak Line systems show if anything higher levels of activity than Classical T Tauri stars (Damiani et al 1995; Stelzer 2001). Unfortunately, this conclusion cannot be tested in the ultraviolet regime for later type stars (where Classical T Tauri stars show a clear excess of emission compared with main sequence stars),owing to the rather small numbers of Weak Line systems observed by IUE.

5 CONCLUSIONS

We have shown that a low level of photoevaporative mass loss from the disc in the region $5-10$ A.U. can promote the eventual rapid 'switch off' of the disc inward of this radius, and an associated rapid decline of diagnostics associated with this region (i.e. spectroscopic accretion indicators, infrared emission at 10μm and shortwards). This switch off simply coincides with the epoch at which the accretion rate through the disc falls, as a consequence of viscous draining, to a level comparable with the photoevaporative mass loss rate. At this point, the inner disc becomes detached from the reservoir of material at larger radius that had hitherto replenished it (in other words, material flowing in from large radius is photoevaporated once it reaches the $5-10$ A.U. region, and none of it can now flow into the inner disc). Thus starved of its exterior supply, the inner disc rapidly empties on the viscous timescale at ~ 5 A.U.: using standard viscous models that correctly reproduce the overall disc lifetime, we find that this timescale is *short*, $\sim 10^5$ years. Thus photoevaporative mass loss provides the desired switch off of inner disc accretion indicators.

There are several attractive features of this model. Firstly, the switch affects a larger region of the disc than that affected by magnetospheric clearing and thus promotes the simultaneous demise of infrared emission out to wavelengths of 10μm, as required by the distribution of T Tauri stars in the infrared two colour plane. Secondly, unlike the case of one-off dynamical encounters at a similar radius, a disc that is subject to continuous photoevaporative mass loss beyond a certain radius is unable to expand outwards beyond this point. Consequently, the timescale on which the entirety of the inner disc drains away is short. It is also notable that the model predicts that the sudden switch off occurs once the accretion rate falls to several $\times 10^{-10} M_\odot$ yr^{-1}, so that Classical T Tauri stars should extend in accretion rate down to such values: this is compatible with the lowest accretion rates inferred by Gullbring et al 1998 for a sample of Classical T Tauri stars, but is comfortably larger than the upper limit recently derived for a Weak Line star (Muzerolle et al 2000).

We have also pointed out two potential problems for the model. Firstly, although it predicts the rapid dispersal of the inner disc, emission from larger radii ($> 5-10$ A.U.) should decline on a considerably longer timescale. The level at which the millimetre flux is expected to linger depends on details of the disc model (especially the initial matter distribution in the disc and the minimum disc temperature imposed). Recently, Duvert et al 2000 found that only 1 out of 11 Weak Line T Tauri stars was detectable at 1.3 mm at the very low flux limit of 2.5 mJy: some of our models predict lingering millimetre flux that is above this level and some below. It would therefore be premature to reject the model on these grounds. We merely note that the model does predict a lingering millimetre flux that is plausibly in the $1-10$ mJy range and that we would ultimately expect sensitive observations to reveal this emission in a reasonable fraction of Weak Line T Tauri stars (see discussion in 3.2).

The second potential problem concerns what is the magnitude and the *origin* of the ionising radiation in T Tauri stars. As we argue in Section 4, it is essential that this emission has an important component that is *not* accretion powered, and which therefore will not decline to insignificant levels as the disc accretion fades. Since we have shown that in other respects the photoevaporation model appears highly promising as a mechanism for disc dispersal, it is becoming increasingly desirable to have better estimates of the magnitude and origin of the ionising luminosity in these systems. We therefore urge that future analyses of the ultraviolet spectra of T Tauri stars should be used to constrain the photoionising emission rates in these systems.

Finally, we note that our time-dependent calculations have revealed a rather different evolutionary sequence for the surface density profile of the disc than that envisaged by Shu et al 1993 (see also Hollenbach et al 2000) in their discussion of the impact of photoevaporation on planet formation. These authors envisaged that the primary depletion of the disc's surface density would occur *outside* the critical radius for photevaporative mass loss, which they identified in the solar system as being the radius of the intermediate gas giant, Saturn. When photoevaporative models are combined with viscous evolution, however, we see that the most dramatic effects on the disc density profiles at late times are at all radii *inside* this radius, radii from which direct photoevaporative mass loss is not possible owing to the larger depth of the gravitational potential close to the star. These inner radii experience a more radical depletion, however, because, unlike the region from which photoevaporative mass loss occurs, they are detached from the reservoir of material at larger radius. This type of behaviour should be borne in mind in future analyses of planet formation in photoevaporating discs.

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