

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

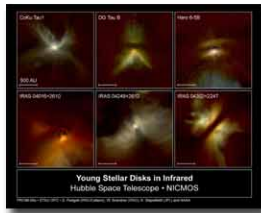
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Abstract

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-time-scale' behaviour for the dispersal of such discs, whereby the disc is rapidly dispersed at the end of its life on a time-scale that is a small fraction of the disc lifetime. We discuss the implications of this model for the detection of millimetre 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.

Introduction

The processes responsible for dispersing the discs around young stars are not well understood at present. Possible mechanisms that have been discussed include viscous draining on to the central star, interaction with stellar magnetosphere, the effect of a stellar wind, the role of encounters in a cluster environment, photoevaporation by the ultraviolet radiation field of the central star or neighbouring stars and the consumption of gas and solid material in planet formation.



A secure conclusion from empirical studies is that there appear to be **two time-scales associated with disc dispersal**. The first, the mean disc lifetime, appears to lie in the range 5×10^4 - 10^5 yr. However, the time-scale for the transition between disc possessing and discless status is apparently substantially smaller than this.

Most of the mechanisms listed above do not at first glance appear promising candidates for generating this 'dual time-scale' behaviour. In this work we investigate the dispersal of circumstellar discs in T Tauri stars owing to photoionization by the ultraviolet radiation from the central star. We rely heavily on parametrizations of photoevaporative mass loss derived by Hollenbach et al.⁴ and incorporate this mass loss as sink terms in standard viscous evolution models.

Photoevaporative Viscous Model

Viscous: we employ parameters that are identical to the similarity solutions explored by Hartmann et al.⁵ These authors focus on the case that the kinematic viscosity (ν) in the disc is a linear function of the radius, R , at all times. The viscous evolution can be described using

$$d\Sigma/dt = 3/R \times d/R + (R^{10} \times d/R) (\nu \times \Sigma \times R^{12})$$

where Σ is the surface density. It can be shown that most of the mass moves inwards losing energy and angular momentum as it does so, but a tail of matter moves out to a larger radii in order to take up the angular momentum. This viscous mechanism gives a roughly power-law decline of disc quantities with time.

Photoevaporative: our parametrization of the photoevaporative mass loss follows closely that set out by Hollenbach et al.⁴ These authors assume that material is lost from the disc surface at radii beyond

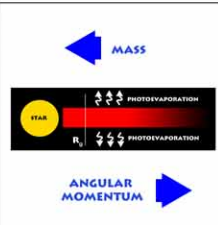
$$R_{\text{ph}} = G_{\text{M}} / a^2 \sim 10^{14} M_{\odot}^{-1} \text{ cm.}$$

where M_{\odot} is the stellar mass, 'a' is the speed of sound of photoionized gas and M_{\odot} is the stellar mass in units of solar mass. Beyond this radius the rate of mass loss per unit area is given by

$$d\dot{M}_{\text{ph}}/dt = 1.4 \times 10^{-10} \text{ am}_{\odot} / 10^{14} (R/R_{\text{ph}})^{-3/2} (R/R_{\text{ph}})^{3/2}$$

where ϕ is the ionizing photon luminosity of the central star and m_{H} is the mass of a hydrogen atom.

The viscous evolution of the disc subject to photoevaporative mass loss is computed using a standard first-order explicit scheme.



Results

Fig. (a) illustrates snapshots of the surface density profile for our photoevaporative viscous model ($M_{\odot}=1$, $\phi = 10^{41}$ M_{\odot} , $0 \leq t \leq 1$ Msun), while Fig (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 au for the photoevaporative case. At time $t = 1.02 \times 10^5$ yr the photoevaporative viscous model develops a pronounced dip in the surface density profile in the vicinity of R_{ph} . The following snapshots illustrate the very rapid subsequent decline of Σ inward of R_{ph} on a time-scale of $\sim 10^4$ yr. At radii slightly beyond R_{ph} the disc profile is scarcely modified on this time-scale. Following the viscous emptying of the inner disc, the remaining disc is then progressively dispersed from the inside out on a time-scale that is comparable to, though somewhat less than, the age of the system when rapid draining of the inner disc set in.

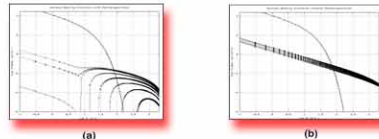


Fig (a) & (b) Snapshots of the surface density distribution in the disc (a) for the photoevaporative viscous model and (b) for the corresponding model with no photoevaporative mass loss. The curves represent (from top down): $t = 0$, 0.9×10^4 , 1.02×10^5 , 1.04×10^5 , 1.2×10^5 , 1.4×10^5 , 1.6×10^5 , 1.8×10^5 , 2.0×10^5 yr. Note the precipitous decline of the inner disc in (a) over the 2×10^4 yr time-scale between the third and fourth snapshots.

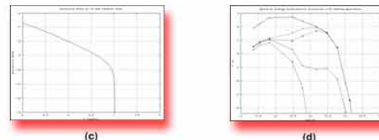


Fig (c) Evolution of the accretion rate on to the central star for our photoevaporative viscous model. Note the abrupt turn down in the accretion rate once it declines to a level comparable with the photoevaporative mass-loss rate.

Fig (d) Snapshots of the spectral energy distribution for the photoevaporative viscous model at times (from top down) of: $t = 0$, 0.9×10^4 , 1.02×10^5 , 1.04×10^5 , 1.2×10^5 , 1.4×10^5 , 1.6×10^5 , 1.8×10^5 , 2.0×10^5 yr. Plotted points correspond to wavelengths of 1.3 mm, 850, 400, 100, 50, 20, 10, 5 and 1 μm .

This behaviour is readily understood since at early times the accretion rate through the disc ($4.2 \times 10^{-5} M_{\odot} \text{ yr}^{-1}$) is much larger than the photoevaporative mass-loss rate ($4 \times 10^{-10} M_{\odot} \text{ yr}^{-1}$). As the accretion rate in the disc declines owing to viscous draining on to the central star, it eventually attains a level comparable with photoevaporative mass-loss rate. At this point, a substantial fraction of the accretion flow in the outer disc is blown away in the vicinity of R_{ph} . Consequently, the fraction of the accretion flow that is available to resupply the inner disc falls precipitously. The inner disc is then effectively starved and empties on to the central star on a time-scale that is the viscous time-scale at R_{ph} .

Fig (d) shows snapshots of the resulting spectral energy distribution for the case that the disc temperature at 100 au is 10 K and where the minimum is set at 7 K. This clearly illustrates that the rapid ($\sim 10^4$ yr) emptying of the inner disc produces a corresponding fall in the radiative output of the disc at those (short) wavelengths predominantly produced within ~ 10 au.

Discussion & Conclusions

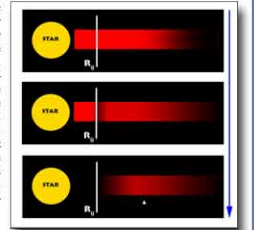
• We have shown that a low level of photoevaporative mass loss from the disc in the region 5-10 au can promote the eventual rapid 'switch off' of the disc inward of this radius, and an associated rapid decline of diagnostics associated with this region (i.e. spectroscopic accretion indicators, infrared emission at 10 μm 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 radii that had hitherto replenished it. Thus starved of its exterior supply, the inner disc rapidly empties on the viscous time-scale at ~ 5 au.

• 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 10 μm , as required by the distribution of T Tauri stars in the infrared two-colour plane.

• There are two potential problems for the model. First, although it predicts the rapid dispersal of the inner disc, emission from larger radii should decline over a considerably longer time-scale (see figure). The second potential problem concerns what is the magnitude and the origin of the ionizing radiation in T Tauri stars. 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.

• 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.⁶ In their discussion of the impact of photoevaporation on planet formation. These authors envisaged that the primary depletion of the surface density of the disc would occur outside the critical radius for photoevaporative 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. This type of behaviour should be borne in mind in future analyses of planet formation in photoevaporating discs.



References & Acknowledgments

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- Further reading: C. J. Clarke, A. Gendrin, M. Sotomayor, MNRAS 328, 485-491 (2001)
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