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Photoevaporation of circumstellar discs

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Abstract. Models which couple viscous evolution and photoevaporation have the potential to explain the observed rapid dispersal of discs around T Tauri stars. However the source of the ionizing radiation required to drive the photoevaporation was poorly constrained. We have investigated a number of potential ionizing sources and found that emission from the chromospheres of these stars appears to be sufficient to drive the photoevaporation.

Key words. accretion, accretion discs – stars: formation – circumstellar matter – planetary systems: protoplanetary discs – stars: pre-main sequence

1. Introduction

Observations tell us that at an age of $\sim 10^6$yr most low-mass stars are surrounded by discs that are optically thick in the optical and near-infrared (Kenyon & Hartmann 1995; Haisch et al. 2001). However, by an age of $\sim 10^7$yr almost no such discs are detected. Thus the lifetimes of these discs must be of order a few million years. In addition it is well-established that the fraction of transition objects, between the disc-bearing classical T Tauri stars and discless weak-lined T Tauri stars (hereafter CTTS and WTTS), is small. This has been confirmed by observations at near-infrared (Kenyon & Hartmann 1995), mid-infrared (Persi et al. 2000) and millimetre wavelengths (Duvert et al. 2000). These observations constrain the transition time between the WTT and CTT states to be $\sim 10^5$yr, with the disc vanishing simultaneously over a radial range covering 0.1–100AU on a timescale 1–2 orders of magnitude shorter than the disc lifetime. The fact that this effect is most pronounced in low-mass star-forming regions such as Taurus-Auriga implies that it is likely due to something intrinsic to individual TTS systems, as opposed to an external effect. Most existing disc evolution models fail to reproduce this two-timescale behaviour (eg. Hartmann et al. 1998; Armitage et al. 1999), and it is unlikely that a single planet could clear the disc across such a large range in radii.

One model which has been successful in reproducing the observed rapid disc dispersal times is the so-called "UV-switch" model of Clarke et al. (2001). This model couples viscous evolution of the disc to a photoevaporative disc wind. Photoevaporative winds occur when ultraviolet (UV) photons from the star produce a thin, ionized layer on the surface of the disc. Beyond some gravitational radius (5–10AU for TTS) this 10^4K material is no longer bound to the star and escapes as a disc wind. Models of this process were first constructed by Hollenbach et al. (1994) (see also the review by Hollenbach et al. 2000). The mass-

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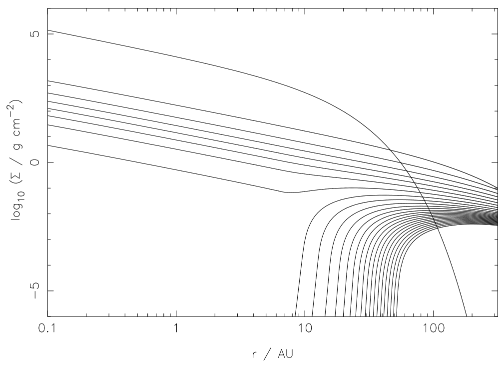

Fig. 1. Disc surface density in a simple photoevaporating disc model. Snapshots of the surface density are plotted every 2×10^6yr. Note the rapid draining of the inner disc at an age of 1.4×10^7yr. (Figure adapted from Clarke et al. 2001.)

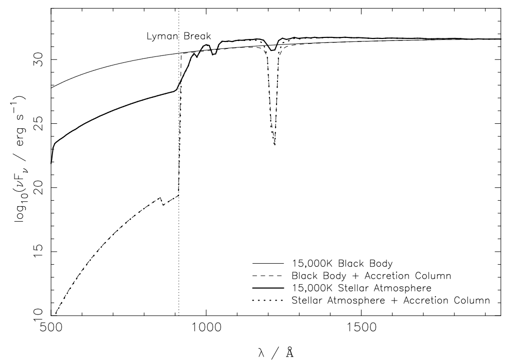

Fig. 2. Spectra of light incident on and emitted by a typical accretion column. Note the precipitous drop in the emitted spectra at the Lyman break, due to photoabsorption by HI. (Figure from Alexander et al. 2004a.)

loss rate is low, of order 10^{-10}M$_\odot$yr^{-1}, and is initially negligible by comparison to the accretion rate through the disc. However the accretion rate falls with time, and eventually drops to a level comparable to the wind rate. At this point the disc cannot be resupplied inside the gravitational radius, and the inner part of the disc drains on a viscous timescale. Thus after a disc lifetime of $\sim 10^7$yr the inner disc is dispersed on a timescale of $\sim 10^5$yr, satisfying the two-timescale constraint demanded by observations (Clarke et al. 2001, see also Fig.1).

However a number of problems and caveats still exist, which we seek to address. In order for the model to succeed TTS must sustain ionizing fluxes of order 10^{41}photons s^{-1}, and it is not clear if TTS can produce such large ionizing fluxes. Here we consider three potential sources: excess UV produced by accretion, coronal X-rays and UV from the stellar chromosphere.

2. Ionizing photons from the accretion shock

One possible source of ionizing photons is the "accretion shock" produced when accreting disc material strikes the stellar surface. Previous studies have modelled this process to explain the observed emission at both UV (1000-3000Å) and visible (4000-7000Å) wavelengths (Calvet & Gullbring 1998; Gullbring et al. 2000). However the emission shortward of the Lyman break at 912Å cannot be studied directly. We have constructed simple models of the accretion shock and column, treating the accretion shock as a hotspot beneath a column of accreting material. We have found that while the hotspot can in principle produce a high ionizing flux for high accretion rates, attenuation of the ionizing flux due to absorption by neutral hydrogen in the column is severe. In fact, the ionizing flux that escapes the accretion column is less than that expected from the stellar photosphere. As the photospheric level is some 10 orders of magnitude too small to drive the UV-switch model, we conclude that UV from the accretion shock is not a significant factor in disc evolution (Alexander et al. 2004a, see also Fig.2).

3. X-ray driven disc winds?

Another possible source of disc heating is X-rays. Both CTTS and WTTS are known to be strong X-rays sources, with typical X-ray luminosities of order 10^{28}–10^{30}erg s^{-1} (Feigelson & Montmerle 1999). The energy emitted in X-rays is comparable to the energy required in the UV in order to drive the photoevaporative wind, and so we have investigated whether X-rays can drive a disc wind. In contrast to the case of UV-heating, where the recombination (diffuse) field dominates, when soft X-rays are incident on the material in a circumstellar disc recombinations are negligible and only the direct field is important. We have used simple X-ray physics to model the effect of X-ray heating on disc structure.

As a first iteration we construct a simple 1-D model. Here we make the approximation that the disc can be divided into a series of concentric, non-interacting annuli. We adopt an initial steady disc model and treat the disc as being in hydrostatic equilibrium. Then, using the CLOUDY photoionization code, we study what happens at each radius R when the disc is irradiated from above by X-rays. We find that the resultant disc structure can be well-modelled by a two-component structure, with a heated region above the cold disc midplane. We also find that for radii $\gtrsim 100\mathrm{R}_\odot$ attenuation of the X-ray flux by heated disc material at smaller radii is significant. Thus a 1-D model will not suffice, and we extended our analysis to create a simple 2-D model.

In our 2-D model we assume that the X-rays penetrate the disc along a given line-of-sight to a constant value of the ionization parameter

$$\xi = \frac{L_X J_h}{nd^2} \tag{1}$$

where n is the local particle number density, d the distance along the line-of-sight to the source and where the factor J_h accounts for the attenuation of the flux due to absorption along the line-of-sight (Krolik & Kallman 1983; Glassgold et al. 1997). We evaluate the attenuation factor numerically by integrating the column along the line-of-sight, and solve for the structure of the disc self-consistently (see Fig.3). We are able to make a crude estimate of the mass-loss that can be driven by X-rays by evaluating the mass-loss per unit area as ρc_s, at the base of the heated column at the gravitational radius. Our model is designed so that this value is an upper limit, yet the resulting mass-loss rate is still smaller than that for the fiducial UV disc wind of Hollenbach et al. (1994). Thus we find that X-rays are unlikely to drive a disc wind at a rate that can be significant within the framework of viscous evolution models (Alexander et al. 2004b).

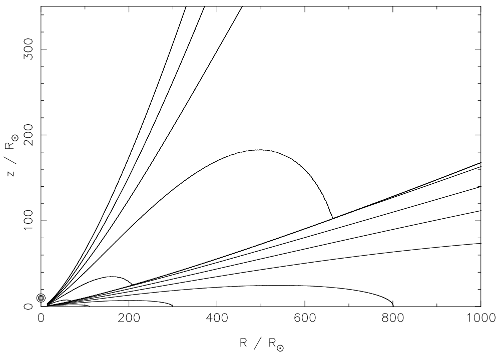

Fig. 3. Structure of an X-ray heated disc evaluated by the 2-D model. Density contours are drawn at $n = 10^{15}$, 10^{14}, $10^{13}\ldots 10^{3}\mathrm{cm}^{-3}$. (Figure from Alexander et al. 2004b.)

4. Ionizing photons from the chromosphere

A third possible source of Lyman continuum photons from TTS is the stellar chromosphere. Some authors have argued that a chromosphere that resembles a "scaled-up" solar chromosphere seems likely for TTS (eg. Costa et al. 2000). This would in principle satisfy the demands of the UV-switch model, and so we have sought to quantify the chromospheric emission from TTS.

In order to achieve this goal we have first made use of an emission measure (EM) analysis. We model the chromosphere as an optically thin plasma, using EMs from the literature (Brooks et al. 2001) and the CHIANTI spectral synthesis code to produce synthetic spectra for 5 TTS chromospheres. This results in values that are somewhat uncertain, due primarily to reddening uncertainties, but that lie in the range $\sim 10^{41}$–10^{43} photons s^{-1}. This is more than is necessary to drive the UV-switch model.

In addition the UV-switch model demands that the ionizing flux remains approximately constant as the TTS evolve. In our plasma model we note that most of the lines in the observed UV spectra (1200-1900Å) are reproduced well by the model. However the He II 1640Å line is not reproduced at all by the model, and we suggest that it is radiatively excited. As such it should provide a diagnostic of the ionizing flux emitted by the central objects. In addition, the C IV 1550Å line traces the total power radiated by TTS chromospheres (Brooks & Costa 2003). Thus we propose that the HeII:CIV line ratio should provide a normalised, reddening-independent diagnostic of the ionizing flux emitted by TTS, and confirm this correlation for the 3 objects whose the spectra permitted a robust EM analysis. By studying the behaviour of this line ratio in a large sample of TTS (from the *IUE* archive, Valenti et al. 2000) we can investigate its behaviour against a number of evolutionary indicators.

We find no evidence for any decline in the line ratio, and thus the ionizing flux, as TTS evolve. Thus the Lyman continuum emitted by TTS chromospheres appears sufficient to drive the UV-switch model of disc dispersal (Alexander et al. 2004c).

5. Summary

Models which couple viscous evolution and photoevaporation have the potential to explain the observed rapid dispersal of TTS discs. However the source of the ionizing radiation required to drive the photoevaporation was poorly constrained. We have investigated the ionizing flux produced by accretion shocks, coronal X-rays and chromospheres. We find that the chromospheric Lyman continuum appears sufficient to drive photoevaporation at the rate required by the model, and thus conclude that photoevaporative models may indeed explain the dispersal of TTS discs. Number statistics for observed brown dwarf discs are not yet available, but there is no *a priori* reason why this dispersal mechanism should not apply to brown dwarf discs also.

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