The Photoevaporation of Discs Around Young Stars in Massive Clusters

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ABSTRACT

We present models in which the photoevaporation of discs around young stars by an external ultraviolet source (as computed by Adams et al 2004) is coupled with the internal viscous evolution of the discs. These models are applied to the case of the Orion Nebula Cluster, where the presence of a strong ultraviolet field from the central OB stars, together with a detailed census of circumstellar discs and photoevaporative flows, is well established. In particular we investigate the constraints that are placed on the initial disc properties in the ONC by the twin requirement that most stars possess a disc on a scale of a few A.U., but that only a minority (< 20%) are resolved by HST at a scale of 50 A.U.. We find that these requirements place very weak constraints on the initial radius distribution of circumstellar discs: the resulting size distribution readily forgets the initial radius distribution, owing to the strong positive dependence of the photoevaporation rate on disc radius. Instead, the scarcity of large discs reflects the relative scarcity of initially massive discs (with mass > 0.1M⊙). The ubiquity of discs on a small scale, on the other hand, mainly constrains the timespan over which the discs have been exposed to the ultraviolet field (< 2Myr). We argue that the discs that are resolved by HST represent a population of discs in which self-gravity was important at the time that the dominant central OB star switched on, but that, according to our models, self-gravity is unlikely to be important in these discs at the present time. We discuss the implications of our results for the so-called proplyd lifetime problem.

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

1 INTRODUCTION

The Orion Nebula Cluster (ONC) provides a unique opportunity to measure the size distribution of discs around young stars. Whereas in other regions, resolved discs are observed in emission - and therefore the deduced sizes are sensitive to factors such as the disc temperature profile or the depletion or dissociation of molecular tracers - the bright nebular background of the ONC allows discs to be observed in silhouette. In this case, the edges of observed discs represent uniform contours in optical extinction and hence, assuming standard dust:gas ratios, uniform contours of gas column density. Silhouette discs therefore provide the best opportunity to measure disc size distributions with the fewest input assumptions about conditions in the disc.

Disc sizes are of interest inasmuch as they provide information about the initial angular momentum of the natal gas (Burkert and Bodenheimer 2000), about the possibility of disc truncations by dynamical interactions (Armitage and Clarke 1997, Bate, Bonnell and Bromm 2003) and about the magnitude of the viscosity driving disc spreading (Hartmann et al 1998). Disc sizes evidently also limit the range of separations over which planets can potentially form. Most importantly, the lifetime of an isolated disc is determined by the viscous timescale at its outer edge, which is almost certainly an increasing function of disc outer radius. The disc size distribution is thus intimately linked with the large range of lifetimes of circumstellar discs and probably holds the key to understanding the mixture of disc possessing and discless systems seen in stars of a given age (Armitage, Clarke and Palla 2003, Alexander and Armitage 2006, Dullemond et al 2006).

However, the ONC is not a good environment in which to use disc sizes as a diagnostic of viscous spreading, since disc sizes in Orion are shaped, in addition, by photoevaporation by the FUV continuum of the cluster’s central OB stars (particularly its most massive member, the O6 star θ1C). Direct evidence for the effect of photoevaporation on disc sizes is provided by the fact that relatively few silhouette discs in Orion have been resolved by HST at a size scale of 50 A.U.
(McCaughrean and Rodmann, in preparation), whereas in Taurus-Auriga (which lacks massive stars), the majority of discs are resolved by submillimetre studies at a scale of 100 A.U. or more (Kitamura et al 2002, Andrews and Williams 2007). In Orion, photoevaporative flows are manifest as proplyds, cometary shaped ionisation fronts that are associated with a number of stars in the inner regions of the ONC, both those with and without resolved silhouette discs (O’Dell et al 1993, O’Dell and Wen 1994. O’Dell and Wong 1996, McCaughrean and O’Dell 1996, Bally et al 1998a), Bally et al 2000). In the standard, and highly successful, models for proplyds, the FUV radiation field in Orion creates a layer of warm outflowing gas, fed by the disc, into which ionising photons can only penetrate to within a couple of disc radii of the central star (e.g. Johnstone et al 1998, Störzer and Hollenbach 1999). The mass loss rate deduced from these models - independently confirmed by spectroscopic measurements (Henney & O’Dell 1999) - are high (∼ 10⁻⁷ M⊙ yr⁻¹) thus raising the issue of the longevity of circumstellar discs in this environment.

In a recent elaboration of disc photoevaporation theory, Adams et al (2004) have constructed models in which discs lose mass mainly through their outer rims. These models couple hydrodynamic flow equations to the complex relationship between temperature and column density provided by detailed PDR modeling. In essence, the flow resembles a Parker wind solution in that material leaves the disc edge in a subsonic flow and is accelerated by thermal pressure gradients to sonic velocities at a location close to the point where the flow becomes marginally unbound. Unlike the classic Parker wind solution, however, this flow is not isothermal - material is injected into the base of the PDR at a few hundred K and is heated to a few thousand K as it flows away from the disc edge, due to its increasing exposure to the incident ultraviolet radiation field. The results of Adams et al suggest that although discs experience large mass loss rates if they are extended to > 100 A.U., this rate drops strongly for more compact discs. For example, they find mass loss rates of ∼ 10⁻⁸ M⊙ yr⁻¹ for discs of radius 40 A.U. and ∼ 10⁻⁹ M⊙ yr⁻¹ for outer radius of 20 A.U., under conditions where the mass loss rate exceeds (10⁻⁷ M⊙ yr⁻¹) for large (> 100 A.U.) discs. The reason for this steep dependence on disc outer radius is that material at the disc outer edge is more tightly bound in the case of more compact discs. It therefore has to be heated to higher temperatures to initiate the flow, and these higher temperatures can only be achieved if the flow is lower in density.

In this paper we use the apparatus set up by Adams et al to study the evolution of discs that are subject to photoevaporative and internal viscous evolution. Our time dependent models employ a variety of assumptions about the initial mass and radius of the discs and we examine how these parameters are constrained by two key observations: the observed high fraction of stars with discs on the scale of an A.U. or less, and the much lower fraction possessing discs resolved on a scale of 50 A.U. or more. Section 2 sets out the method and assumptions, Section 3 describes the nature of the evolution and Section 4 examines what constraints are placed on the initial masses and radii of discs in the ONC. Section 5 discusses the results in relation to the proplyd lifetime problem and the role of self-gravity in circumstellar discs. Section 6 summarises the conclusions.

2 METHOD

2.1 Treatment of gas

We model the disc as a viscous accretion disc subject to photoevaporative mass loss at its outer edge. For the viscous evolution of the disc we follow a number of authors (e.g. Hartmann et al 1998, Clarke et al 2001, Armitage et al 2003) in assuming that the disc viscosity is proportional to radius in the disc. Such a parameterisation is equivalent to a disc with a constant α - viscosity (Shakura & Sunyaev 1973) and a mid-plane temperature that declines with radius as ∝ r⁻¹/₂, and implies that the steady state surface density distribution declines as r⁻¹. (See Hartmann et al 1998 for arguments in favour of such a viscosity law).

A convenient aspect of viscosity laws that are power laws in radius is that there are similarity solutions for the disc evolution (Lynden-Bell and Pringle 1974). For viscosity ∝ r, this takes the form:

\[ \Sigma = \frac{M_d(0)}{2\pi R_d^2} \exp\left(-\frac{x}{T}\right)T^{-1.5} \]  (1)

where \( M_d(0) \) is the initial disc mass, \( R_d \) is the initial disc scaling radius, \( x = r/R_d \) and \( T = 1 + t/t_a \) where \( t_a \) is the viscous timescale \((r^2/3\nu)\) at \( r = R_d \). Such a \( \Sigma \) profile implies that the accretion rate through the disc may be written:

\[ \dot{M} = \frac{1}{2} \frac{M_d(0)}{t_a} \exp\left(-\frac{x}{T}\right)T^{-1.5}(1 - \frac{2x}{T}) \]  (2)

This means that the accretion flow is inwards for \( x < T/2 \) and that the rate of outflow reaches a maximum at \( x = 3T/2 \), where the outward accretion flow is equal to its instantaneous value at small radii \( x < \) multiplied by a factor \( 2e^{-1.5} \). The quantity \( TR_d \) therefore controls the radius in the disc separating inflowing and outflowing regions at any time.

We evolve the viscous diffusion equation for such a disc using a standard explicit finite difference method, equally spaced in \( x \) and \( t \) and \( \tau = 100 \) for most of the grid. The disc extends from the disc edge to a value of \( x = 10 \). The steady state surface density profile \( \Sigma(x) \) is parametrised by \( \Sigma = M_d(0)/(2\pi R_d^2) \exp(-x/T)T^{-1.5} \), where \( M_d(0) \) is the initial disc mass, \( R_d \) is the initial disc scaling radius, \( x = r/R_d \) and \( T = 1 + t/t_a \). This profile implies that the accretion rate through the disc may be written:

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In what follows, we will simply assume that the dust follows the evolution of the gas. Although this is unlikely to be true in detail (see discussion below) we are motivated to do this because the disc edges in our photoevaporating simulations are extremely sharp and because the optical depth of the disc just inside this edge is enormous (> $10^4$ for a standard grain mixture and dust to gas ratio). This means that the gas disc’s edge is well defined and that the edge of the dust disc will also be well defined unless the dust to gas ratio differs from standard values by a very large factor.

A number of studies have however shown that it is likely that the micron sized grains (which dominate the opacity at optical wavelengths: Miyake and Nakagawa 1993) are well coupled to the gas, both in the case of pure disc flows and in the case of photoevaporation (Takeuchi et al 2005, Alexander and Armitage 2007). One possible route to creating a gas poor outer dust disc is if the gas and associated small grains are photoevaporated, and then small dust is replenished by collisions between residual large bodies in the disc (Throop and Bally 2005). If the gas and dust did not trace each other, however, one would not expect to see the observed correlation between the size of discs embedded in ionised objects (proplyds) and the offset of the ionisation fronts (Johnstone and Bally 1998, Vicente and Alves 2005).

In summary, although the study of dust evolution in discs subject to external photoevaporation is an issue that could repay further study, it is unlikely that such studies would contradict our assumption here, i.e. that the sizes of the gas discs derived from our models can be directly compared with the observed sizes of silhouette discs.

3 RESULTS: PORTRAIT OF THE EVOLUTION

We find that, depending on the initial disc parameters, there are two qualitatively distinct evolutionary patterns. If the initial accretion rate at the inner edge ($\dot{M}_{in}$) is substantially larger than $\dot{M}_{wind}(R_1)$ (Figure 2), the disc will self-adjust to a quasistatic configuration with radius ($> R_1$) such that the outward viscous flow rate at $r_d$ just matches $\dot{M}_{wind}(r_d)$. This situation can be sustained over a time $T \sim (\dot{M}_{in}/\dot{M}_{wind}(r_d))^{2/3}$, over which the accretion rate on to the star declines by viscous evolution to a level $\sim \dot{M}_{wind}(r_d)$. (Note that over this stalled period, the density profile in the region of $r_d$ self-adjusts so as to continue to deliver the required viscous flow of material to re-supply the wind). However, once the accretion rate on to the star drops to below $\dot{M}_{wind}(r_d)$, the disc is unable to sustain the viscous outflow at $r_d$ that is required to hold $r_d \sim$ constant. Subsequently, the disc outer edge moves inwards on its instantaneous viscous timescale. (Note that in ordinary viscous evolution, a fluid element at radius $r$ moves inwards on its viscous timescale ($t_v(r)$) but that the surface density at $r$ evolves on the generally much longer timescale of the viscous timescale at the outer edge, due to re-supply of material from larger radius. In the present case, as fluid moves in on a timescale $t_v$, the wind prevents re-supply of material from larger radius and hence $t_v$ is in this case the timescale for the shrinkage of the disc’s outer edge.) We note that in this second evolutionary stage, the disc is drained by a mixture of accretion onto the star and photoevaporation. Since the viscous timescale scales as $r$ for our viscosity prescrip-

![Figure 1. Assumed photoevaporative mass loss rate as a function of outer disc radius (equations (3)-(6)). Adapted from Adams et al 2004 for the case $M_\ast = 1M_\odot$ and ultraviolet radiation field intensity $G_0 = 3000$.](image-url)
tion, one may understand that the resultant evolution during this stage involves the disc moving in at roughly constant velocity ($\sim R_1/t_s$; see Figure 4).

The other type of evolution (illustrated in Figure 3, where the disc mass is unchanged compared with Figure 1, but where the scaling radius and viscous timescale is an order of magnitude larger and the initial accretion rate hence an order of magnitude smaller) occurs in systems where $\dot{M}_{\text{wind}}(R_1) > \dot{M}_{\text{in}}$. In this case, the outer disc radius never stalls, but instead moves in on a timescale set by the photoevaporative mass loss, i.e. by the fulfillment of the condition on $r_d(t)$ that:

$$\int_0^t \dot{M}_{\text{wind}}(r_d(t')) dt' = M_{\text{di}}(r > r_d(t))$$

where $M_{\text{di}}(r > r_d(t))$ is the initial disc mass outward of $r_d(t)$. (Note that this condition assumes the photoevaporation of a static disc and hence neglects the minor role of viscous evolution). During this time, the accretion rate on to the central star remains roughly constant, provided that the time to photoevaporate the disc to radius $r_d$ is less than the disc’s viscous timescale at $r_d$. Since, $\dot{M}_{\text{wind}}(r_d)$ is decreasing monotonically as $r_d$ shrinks, whereas $\dot{M}_{\text{in}}$ is constant, the two mass flow rates eventually become comparable and thereafter the disc drains on a viscous timescale through a mixture of photoevaporation and accretion.

The one to one correspondence between wind mass loss and disc outer edge radius (Figure 1) means that the dashed curves in Figure 2 and 3 may be readily converted into plots of the evolution of the disc outer edge. We display this evolution (in linear rather than logarithmic time units) in Figure 4 and draw attention to the fact that the late time evolution of the two models (which share the same value of initial disc mass but which differ in $R_1$ - and hence initial accretion rate - by a factor of 10) are very similar. The models differ in their early evolution inasmuch as the extended (low accretion rate) model (dashed in Figure 4) initially loses mass mainly through photoevaporation, whereas the compact, high accretion rate model initially drains by accretion. At late times, however, both models converge on the same evolutionary path, with mass being drained by accretion and photoevaporation in nearly equal measure. We note that the stalling of the outer edge in the compact case (which can be inferred from the evolution of the wind mass loss rate in Figure 2) is not very significant when plotted against time in linear units, since stalling occurs at early times when the disc expands out to its maximum extent.
4 COMPARISON WITH OBSERVED DISC SIZE DISTRIBUTION

We will now attempt to constrain the permitted distribution of initial disc parameters using observations of the observed size distributions of discs in the ONC. The key observations are as follows: (i) the majority of stars close to the centre of the ONC exhibit ionised outflows; within the central 0.15 pc in projection, the fraction of sources exhibiting such flows is 80% (Bally et al 2000), which is compatible with all the stars within this region in three dimensions being subject to such flows (Scally and Clarke 2001). (ii) out of a sample of 150 sources exhibiting ionised outflows, only 25 contained discs that were resolvable by HST; the minimum disc radius that could be extracted in this study varied over the range 20 – 50 A.U.; thus the fraction of discs with radius greater than 50 A.U. is considerably less than 20% (Rodmann 2002, McCaughrean and Rodmann in preparation). (iii) essentially all sources exhibiting ionised outflows however exhibit thermal infrared emission indicative of disc material at a radius of an A.U. or less (Lada et al 2000). From this we may conclude that stars in the core of the ONC are a) overwhelmingly likely to be subject to photoevaporation (so that the models here will be applicable to them), b) possess reservoirs of disc material (as required by models of disc photoevaporation), but c) rather rarely (i.e. in less than 20% of cases) exhibit discs on a scale of 50 A.U. or more. For the subset of ionised outflow sources exhibiting resolved discs (i.e. 25 objects) the size distribution in the regime \( r > 50 \) A.U. may be described as a power law of the form \( n(r) \propto r^{-2} \) (McCaughrean and Rodmann, private communication).

It is evidently impossible to use such information to reconstruct the parameter distribution of initial disc radii and masses in the ONC, owing to the considerable degeneracy in the problem. On the other hand, we can derive interesting constraints by considering what are the aspects of the observational data that are going to be hard to reproduce by the sort of models we have constructed. We can get a hint of this from Figure 4: evidently in both these models (which share a common initial disc mass but in which the size and initial accretion rate differ by an order of magnitude), the sources spend > 50% of their lives with radii greater than 50 A.U.. If star-disc systems are created at a steady rate during the time that the photoionising source is ‘on’, the observed fraction of systems with resolved discs then requires that sources should spend < 20% of their lives with \( r > 50 \) A.U., in clear contradiction of the models.

We have explored this further by considering a grid of models parameterised by the initial disc scaling radius \( R_0 \) (see Section 2) and initial disc mass \( (M_d) \). We assume a viscosity law of the form \( \nu \propto r \) and have normalised different models such that the viscous timescale at a given radius is the same for all models (in terms of \( \alpha \)-viscosity theory, this implies that \( \alpha \) and the disc aspect ratio are the same in all models). This means that in different models, the initial accretion rate always scales with the disc mass within a fixed radius. Since the initial surface density distribution implies that the enclosed mass within radius \( r \) scales as \( r/R_0 \) (provided \( r < R_1 \)), this means that the initial accretion rate scales as \( M_0/R \). We normalise our models such that the viscous timescale at 10 A.U. is always 1.1 \( \times 10^5 \) years.

For such a grid of models, we then ask how long each disc spends with \( r > 50 \) A.U. as a fraction of the total lifetime of the disc. We find that there are essentially no credible models that can match the data. In most models, the system spends considerably longer with radius larger than 50 A.U. than with radius less than 50 A.U.. If we want to reverse the situation, then it is difficult to change significantly the time that the disc spends at small radii, given that the erosion of the inner disc is always set roughly by its viscous timescale (which we have not allowed to vary between models). On the other hand, we can change the balance of small and large discs (i.e. < and > 50 A.U.) by ensuring that the outer disc is eroded extremely rapidly: this is favoured by low total disc mass and by large scaling radius. However, even in the case of very extreme parameters (e.g. initial disc mass of \( 3 \times 10^{-3} \)M\(_\odot\), \( R_1 = 200 \) A.U.), the time spent by the system at small radius never much exceeds the time spent at large radius; moreover, in this case, all the ‘large discs’ are at radii only slightly exceeding 50 A.U., whereas the data shows a smoothly declining distribution out to an observed maximum of > 150 A.U.\(^2\).

We then consider another scenario: i.e. that stars are not being created at a steady rate but that instead star formation ceased at the point that the photoionising source switched on, at a time \( t_{uv} \) ago. This assumption is not unreasonable given the evidence from radio maps for the escape of ionised gas from the core of the ONC (Wilson et al 1997), together with the theoretical expectation that ionising radiation and stellar winds should clear the star forming gas from the vicinity of young massive stars (see, for example, Figure 16 of Dale et al 2005). We find that if \( t_{uv} \) were much in excess of 1.5 Myr then the majority of discs would already have drained away due to a mixture of photoevaporation and accretion, in contradiction to the near ubiquity of sources with a near infrared excess in the core of the ONC.\(^3\)

Figure 5 is a plot of the disc edge radius as a function of \( R_1 \), with models of the same initial disc mass being con-

\(^1\) Note that this points to the importance of photoevaporation in pruning discs in the ONC, since in Taurus, which lacks photoionising sources, discs are considerably larger; according to Kitamura et al 2002, about half the classical T Tauri stars in Taurus were imaged in millimetre emission at a scale of 100 A.U. or more, whereas the recent study of Andrews and Williams (2007) estimates a median disc radius in Taurus of about 200 A.U..

\(^2\) We have also experimented with changing the radial dependence of the viscosity law, considering also the case that \( \nu \propto r^{1.5} \) (i.e. where the steady state surface density profile scales as \( r^{-1.5} \)). Such models predict faster viscous evolution at large radius than the standard models and also faster erosion by photoevaporation at large radius, due to the lower disc mass at large radius. Although these changes work in the direction of increasing the fraction of compact (> 20 A.U.) sources, they are still not close to satisfying the observational constraints, and so we consider that changing the viscosity law is unlikely to solve this problem.

\(^3\) In the case of a source switching on (and suppressing subsequent star formation), the distribution of disc parameters should of course be thought of as representing those of a population of stars at the moment of ultraviolet switch on, rather than being necessarily a set of initial parameters.
Figure 5. Disc radius as a function of initial disc scaling radius ($R_1$). The dashed (solid) lines link models of fixed initial disc mass after $t_{uv} = 0.5$ (1) Myr of exposure to the photoionising source. Initial disc masses for each pair of $t_{uv}$ values are listed on the right hand side of the plot.

connected by dashed and solid lines for the cases $t_{uv} = 0.5$ and 1 Myr. It is immediately evident that although there is a mild trend of increasing $r_{edge}$ with $R_1$ at a given $M_d$ and $t_{uv}$, the main determinant of disc radius ‘now’ (i.e. time $t_{uv}$ after switch on) is the initial disc mass. This can be simply understood in that a disc that is initially more extended will suffer stronger photoevaporative mass loss and therefore will also shrink much faster: the convergence of the models shown in Figure 4 demonstrates the same effect.

We therefore conclude that the fact that < 20% of ionised flows contain discs with radii > 50 A.U. is in fact that chiefly constrains the initial masses of circumstellar discs, rather than their initial radii. From our models, the predominance of ‘small’ (less than 50 A.U.) discs simply translates into a predominance of discs with initial masses < 0.1$M_\odot$ (if $t_{uv} = 1.5$ Myr) or with initial masses < 0.03$M_\odot$ (if $t_{uv} = 1$ Myr). This predominance of smaller mass discs is at least compatible with the submillimetre results of Andrews and Williams (2005) for the current (as opposed to initial) masses of discs in Taurus Auriga.

5 DISCUSSION

Our models have shown that the common occurrence of stars with optically thick inner discs in the ONC implies that the ultraviolet source (presumably $\theta_1$C) switched on less than 1 – 2 Myr ago, and that there has been little star formation since that time. In the alternative scenario (where stars form continuously in the presence of a constant ultraviolet field), the preponderance of small discs (radius < 50 A.U.) in the observed distribution would imply that discs were formed with implausibly low masses (much less than the minimum mass solar nebula).

Given the scenario that discs are exposed to the ultraviolet field for a finite time, the main parameter that affects their present day size distribution is the distribution of initial disc masses. The present day size distribution is in fact remarkably insensitive to the initial distribution of disc radius: at a given disc mass, an extended disc suffers stronger photoevaporative mass loss and so shrinks to radii similar to discs of much smaller radius initially.

The relative scarcity of discs larger than 50 A.U. imposes upper limits on the initial disc masses for the bulk of the population in the range 0.03 – 0.1$M_\odot$. These upper mass limits are in no way unexpected; what is possibly more interesting is the fact that 20% of ionised flows do contain larger discs, and therefore must have larger initial disc masses. In fact, the initial disc masses that are required in order to produce the largest (i.e. resolved) discs are in the range where disc self-gravity was almost certainly important. [Recall that a measure of the importance of disc self-gravity is provided by the Toomre Q criterion, and can be re-expressed as the approximate condition $M_d/M_* > H/R$. Since $H/R$ (the aspect ratio of the disc) is typically ~ 10% in models of circumstellar discs, the disc masses that we are invoking as ‘initial’ conditions for the resolved disc population are clearly close to, or in, the self-gravitating, regime.] The fact that ~ 20% of the discs were probably self-gravitating at the time that the ultraviolet source switched on implies that at least 20% of discs pass through a self-gravitating phase and would also be consistent with all discs spending 20% of their lifetimes in the self-gravitating state. However, according to our models, the resolved discs are not self-gravitating now (i.e. after exposure to the ultraviolet field for 1 – 2 Myr) since they have been significantly eroded in the meantime.

How do these results affect an understanding of the so-called proplyd lifetime problem? This problem stems from estimating the exhaustion timescale ($t_{exh}$) for a disc as simply the ratio of the disc mass to the photoevaporation rate. Since estimates of disc masses have (until the recent work of Eisner and Carpenter 2006: see below) been uniformly low (Mundy et al 1995, Bally et al 1998b) whereas mass loss rates (both from modeling and from spectroscopic measurements; Henney & O'Dell 1999) are high, the resulting values of $t_{exh}$ are low (< 10$^5$ years), i.e. much less than the mean stellar age in the ONC (> 1 Myr; Falle and Stahler 1999). This has been interpreted as implying a requirement that discs have been only very recently exposed to the ultraviolet flux of the central OB stars: either because their orbits only take them briefly into the cluster core (Störzer and Hollenbach 1999) or due to the recent switch on of the ionising stars. However, Scally and Clarke (2001) argued against the former hypothesis on the grounds that it proved impossible to find plausible dynamical models of the ONC whose orbital structure could solve the proplyd lifetime problem.

The requirement that the discs in the ONC are only exposed to the ultraviolet radiation field of the central stars over a timescale < 10$^5$ years is much more stringent than what we have found in our models, which can readily accommodate the exposure of discs for a Myr or more. In order to understand this, we must look in more detail at the model predictions: the bulk of the population in the models is composed of discs that are compact and low in mass, with correspondingly low photoevaporative mass loss rates (see Figure 1). On the other hand, the large (resolved) discs in the models have both higher masses and higher photoevaporative mass loss rates. In both types of model systems, $t_{exh}$ is relatively long (~ a Myr).
The reason that the models do not exhibit a ‘proplyd lifetime problem’ is thus chiefly because those models that spend a reasonable time with large disc radii ($\sim 100$ A.U.) have correspondingly large disc masses at that stage ($\sim 0.1 M_\odot$). At first sight, this would appear to contradict the low disc masses (and upper limits) obtained from submillimetre studies of proplyd discs. Disc masses of around $0.02 M_\odot$ have been measured in a handful of proplyd systems (i.e. 182-413 (HST 10) by Bally et al 1998b) and 163-317, 170-337, 171-334 and 171-340 by Williams et al 2005). Crucially, these studies assumed optically thin emission. Thus, using the opacities assumed by these authors, one may calculate a lower limit to the emitting area of the disc, in order for the assumption of optically thin emission to be correct. It is however notable that in the subset of systems for which the disc size and inclination is known through optical imaging (i.e. 182-413, 170-337 and 171-340), the disc emitting area is remarkably close to this lower limit: in other words, the observed fluxes are close to that expected for optically thick emission for discs of this size scale. In this case, the observed fluxes only impose a lower limit on the disc mass. This surmise is supported by the recent detection at 3mm of a relatively massive ($\sim 0.13 M_\odot$) disc in 182-413, as well as in a handful of other proplyds (Eisner and Carpenter 2006). The mean disc masses inferred in undetected sources is likewise higher in the case of the 3mm measurements than those derived from submillimetre observations, which is again compatible with the notion that some of the sources may be optically thick in the latter case. A possible way of exploring this issue further would be to concentrate on proplyds containing the most spatially extended discs (e.g. those detailed by Vicente and Alves 2005).

6 CONCLUSIONS

Our modeling of the photoevaporation of viscously evolving discs in the Orion Nebula Cluster, combined with observational data on the observed size distribution of discs in the cluster, has allowed us to draw a number of conclusions about the properties of the discs and the history of irradiation by the cluster’s dominant OB star ($\theta_1$C).

1) The fact that most stars in the core of the ONC possess discs but that the majority (> 80%) of such discs are compact (< 50 A.U. in radius) is incompatible with a model in which star-disc systems are continuously created in the steady ultraviolet field of $\theta_1$C. Instead, we require that $\theta_1$C has been ‘switched on’ for no more than 1 – 2 Myr, in which case the bulk of discs have been formed by prior photoevaporation to their present day compact state.

2) We find that the present day sizes of discs that are subject to a mixture of photoevaporation and viscous evolution are very insensitive to their initial sizes. This is because discs that are more extended initially suffer stronger photoevaporative mass loss and thus shrink back to sizes similar to systems that were initially much more compact. The main parameter affecting present day disc sizes is the disc mass at the stage that the photoionising source switched on.

3) The bulk of discs in the ONC, which are not resolved by HST, have radii less than 20 – 50 A.U. and must, in our models, correspond to systems with disc masses, when the photoionising source switched on, of less than $0.03 – 0.1 M_\odot$ (the range in these upper limits depending on the duration of exposure to the photoionising field).

4) The minority (around 20%) of discs in the ONC that are more extended (i.e. with radius > 20 – 50 A.U. and hence resolvable by HST) correspond to a population of more massive discs at the stage that the photoionising source switched on. Such discs were almost certainly self-gravitating at this stage, but, following 1 – 2 Myr of photoevaporation, would not be expected to be self-gravitating currently.

5) In our models, discs are photoevaporated on a timescale of $\sim 10^6$ years and so do not imply any conflict with the existence of discs in the ONC. We suggest that the much shorter, observationally based, photoevaporation timescales quoted in the literature (which are associated with the ‘proplyd lifetime problem’) may result from an underestimate of disc masses in systems that are optically thick at submillimetre wavelengths. In order to avoid ambiguities due to optical depth, it is desirable that future measurements concentrate on proplyds containing the most spatially extended discs.

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