Mon. Not. R. Astron. Soc. **000**, 000–000 (0000) Printed 15 January 2001 (MN LaTeX style file v1.4)

Episodic accretion in magnetically layered protoplanetary discs

Philip J. Armitage[1] ⋆, Mario Livio[2] and J.E. Pringle[2,3]
[1] *Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Str. 1, D-85741 Garching, Germany*
[2] *Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD21218, USA*
[3] *Institute of Astronomy, Madingley Road, Cambridge, CB3 0HA, UK*

15 January 2001

ABSTRACT

We study protoplanetary disc evolution assuming that angular momentum transport is driven by gravitational instability at large radii, and magnetohydrodynamic (MHD) turbulence in the hot inner regions. At radii of the order of 1 AU such discs develop a magnetically layered structure, with accretion occurring in an ionized surface layer overlying quiescent gas that is too cool to sustain MHD turbulence. We show that layered discs are subject to a limit cycle instability, in which accretion onto the protostar occurs in $\sim 10^4$ yr bursts with $\dot{M} \sim 10^{-5} M_\odot \mathrm{yr}^{-1}$, separated by quiescent intervals lasting $\sim 10^5$ yr where $\dot{M} \approx 10^{-8} M_\odot \mathrm{yr}^{-1}$. Such bursts could lead to repeated episodes of strong mass outflow in Young Stellar Objects. The transition to this episodic mode of accretion occurs at an early epoch ($t \ll 1$ Myr), and the model therefore predicts that many young pre-main-sequence stars should have low rates of accretion through the inner disc. At ages of a few Myr, the discs are up to an order of magnitude more massive than the minimum mass solar nebula, with most of the mass locked up in the quiescent layer of the disc at $r \sim 1$ AU. The predicted rate of low mass planetary migration is reduced at the outer edge of the layered disc, which could lead to an enhanced probability of giant planet formation at radii of 1 – 3 AU.

Key words: accretion, accretion discs — MHD — stars: pre-main-sequence — stars: formation — solar system: formation — planets and satellites

1 INTRODUCTION

The structure and evolution of protoplanetary discs depend upon the rate at which gas can shed its angular momentum and thereby flow inwards. Two widely applicable physical mechanisms are known to lead to the required outward angular momentum transport. If the gas is coupled to a magnetic field, instabilities that inevitably arise in differentially rotating discs (Balbus & Hawley 1991; Chandrasekhar 1961; Velikhov 1959) lead to turbulence and angular momentum transport (Stone et al. 1996; Brandenburg et al. 1995; for a review see e.g. Hawley & Balbus 1999). If the disc is massive enough, gravitational instability leads to additional transport (Toomre 1964; Laughlin & Bodenheimer 1994; Nelson et al. 1998; Pickett et al. 2000).

Applying these findings to the construction of protoplanetary disc models leads to the structure shown schematically in Fig. 1 (after Gammie 1996). In the inner disc, MHD turbulence transports angular momentum. However, at larger radii of $r \sim 1$ AU, where the temperature is typically a few hundred K, magnetic field instabilities are suppressed by the low ionization fraction (Matsumoto & Tajima 1995; Gammie 1996; Gammie & Menou 1998; Livio 1999; Wardle 1999; Sano & Miyama 1999; Sano et al. 2000). This leads (Gammie 1996) to the formation of a *layered* disc structure, in which the gas near the disc midplane is cold, shielded from ionizing high energy radiation, and quiescent (non-turbulent). Turbulence and accretion occurs only in a thin surface layer that is ionized by cosmic rays. Moving still further outwards the entire thickness of the disc again become viscous, either at the radius where the surface density is small enough for cosmic rays to penetrate to the midplane, or where the onset of disc self-gravity provides an alternative non-magnetic source of angular momentum transport.

The predictions of a static layered disc model for the accretion rate and spectral energy distribution of T Tauri stars were discussed by Gammie (1996), and are broadly consistent with observations (e.g. with the accretion rate for Classical T Tauri stars measured by Gullbring et al. 1998). In this paper we consider the evolution of the layered disc, which cannot be in a steady state (Gammie 1996, 1999; Stepinski

⋆ Present address: School of Physics and Astronomy, University of St Andrews, North Haugh, St Andrews KY16 9SS

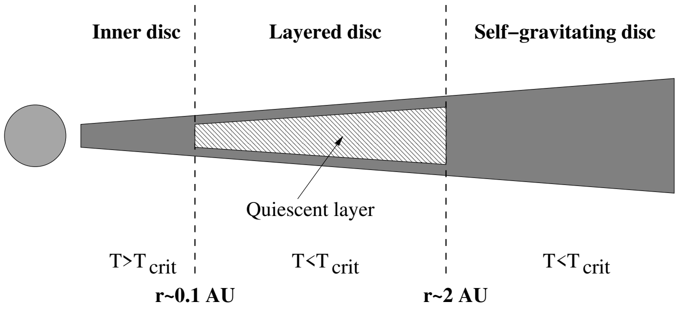

Figure 1. Illustration of the radial structure of the disc in the layered disc model. At small radii, the central temperature exceeds $T_{\rm crit}$, the temperature above which MHD turbulence provides an efficient source of angular momentum transport. In the intermediate, layered region, the central temperature is too low for the disc to support MHD turbulence. Accretion occurs through a surface layer which is kept ionized by cosmic rays, while the disc near the midplane is quiescent. At larger radii, the entire thickness of the disc is again viscous, with angular momentum transport being driven by self-gravity.

n	κ_0	a	b	$T_{\rm max}$ / K
1	1.0×10^{-4}	0	2.1	132
2	3.0×10^{0}	0	-0.01	170
3	1.0×10^{-2}	0	1.1	377
4	5.0×10^{4}	0	-1.5	389
5	1.0×10^{-1}	0	0.7	579
6	2.0×10^{15}	0	-5.2	681
7	2.0×10^{-2}	0	0.8	964
8	2.0×10^{81}	1	-24	1572
9	1.0×10^{-8}	2/3	3	3728
10	1.0×10^{-36}	1/3	10	10330
11	1.5×10^{20}	1	$-5/2$	45060
12	0.348	0	0	—

Table 1. Opacity regimes in ascending order of temperature, fitted by analytic functions of the form $\kappa = \kappa_0 \rho^a T^b$. We have used fits provided by Bell & Lin (1994), as modified for low temperatures by Bell et al. (1997). The maximum temperature $T_{\rm max}$ for each regime is quoted for a typical disc density of 10^{-9} gcm^{-3} (where specification of the density is necessary).

1999), and examine the implications for the outflow history of young stars and for the predicted disc mass. The most significant changes to the disc structure occur at the radii of greatest interest for planet formation (Reyes-Ruiz & Stepinski 1995), and we discuss the implications for the migration of low mass planets, and for the eccentricity of massive planets interacting with the disc.

2 LAYERED PROTOPLANETARY DISC EVOLUTION

2.1 Equations

Describing the evolution of the surface density $\Sigma(r,t)$ and midplane temperature $T_c(r,t)$ of a layered disc requires only minor modifications to the usual time-dependent equations for thin accretion discs. We denote the surface density of the 'active' (viscous) disc by Σ_a. If,

$$T_c > T_{\rm crit} \tag{1}$$

or,

$$\Sigma < 2\ \Sigma_{\rm layer} \tag{2}$$

then the disc is viscous throughout its thickness and $\Sigma_a = \Sigma$. Otherwise only the surface layers are viscous and $\Sigma_a = 2\Sigma_{\rm layer}$. The values of these parameters are determined by the requirement that the disc be sufficiently ionized to support MHD turbulence (Gammie 1996). We adopt $T_{\rm crit} = 800$ K, and $\Sigma_{\rm layer} = 10^2$ gcm^{-2}. For a Keplerian disc, the angular velocity is $\Omega = \sqrt{GM_*/r^3}$, where M_* is the stellar mass. The surface density evolution is then described by,

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

where ν is the kinematic viscosity and $\dot{\Sigma}(r,t)$ is the rate of change of the surface density due to infall onto the disc.

For the energy equation, we adopt a simplified form of that used by Cannizzo (1993),

$$\frac{\partial T_c}{\partial t} = \frac{2(Q_+ - Q_-)}{c_p \Sigma} - v_r \frac{\partial T_c}{\partial r}. \tag{4}$$

Here c_p is the disc specific heat, which for temperatures $T_c \sim 10^3$ K is given by $c_p \simeq 2.7\mathcal{R}/\mu$, where $\mathcal{R}$ is the gas constant and $\mu = 2.3$ is the mean molecular weight. Q_+ represents local heating due to viscous dissipation, given by,

$$Q_+ = \left(\frac{9}{8}\right)\nu\Sigma\Omega^2 \tag{5}$$

if the entire disc is viscous and

$$Q_+ = \left(\frac{9}{8}\right)\nu\Sigma_{\rm layer}\Omega^2 \tag{6}$$

otherwise. For Q_-, the local cooling rate, we assume that each annulus of the disc radiates as a blackbody at temperature T_e, so that

$$Q_- = \sigma T_e^4, \tag{7}$$

where σ is the Stefan-Boltzmann constant. Finally, we include an advective term in the energy equation, which depends on the vertically averaged radial velocity,

$$v_r = -\frac{3}{\Sigma r^{1/2}}\frac{\partial}{\partial r}\left(\nu\Sigma r^{1/2}\right), \tag{8}$$

and the radial temperature gradient.

2.2 Vertical structure

Completing the model requires specification of both the viscosity ν and the vertical structure, which sets the relation between the central temperature T_c and the surface temperature T_e. We adopt the simplest, vertically averaged approach, for which,

$$T_c^4 = \frac{3}{8}\tau T_e^4, \tag{9}$$

where $\tau = (\Sigma/2)\kappa$ is the optical depth for a given opacity $\kappa(\rho_c, T_c)$. When an annulus makes the transition to the layered state, we crudely account for this by replacing $(\Sigma/2)$ in the expression for τ by $\Sigma_{\rm layer}$. Note that this means that we do not attempt to treat the vertical structure *during* the transition consistently.

Analytic expressions for low temperature Rosseland mean opacities are given by Bell et al. (1997). The behaviour of the disc depends primarily on the opacity near the transition temperature $T_{\rm crit}$, for which the fit is,

$$\kappa = 2 \times 10^{-2} T_c^{0.8} \ {\rm cm}^2 \ {\rm g}^{-1}. \quad (10)$$

The full list of opacities used is quoted in Table 1. These fits have been taken from Bell & Lin (1994), with the modifications for low temperatures quoted in Bell et al. (1997).

2.3 Viscosity

We adopt an alpha prescription (Shakura & Sunyaev 1973) for the viscosity,

$$\nu = \alpha \frac{c_s^2}{\Omega}, \quad (11)$$

where $c_s = \sqrt{\mathcal{R} T_c / \mu}$ is the midplane sound speed and α a dimensionless parameter measuring the efficiency of angular momentum transport. Numerical simulations of MHD turbulence in discs suggest that $\alpha \approx 10^{-2}$ (Stone et al. 1996; Brandenburg et al. 1995).

2.4 Self-gravity

An immediate consequence of the layered disc structure is that the accretion rate through the surface layer is a fixed, increasing function of radius (Gammie 1996). Inevitably, therefore, material builds up in the quiescent layer over time, until the surface density becomes high enough that self-gravity of the disc becomes important. The condition for this is that the Toomre Q parameter (Toomre 1964), given by,

$$Q = \frac{c_s \Omega}{\pi G \Sigma}, \quad (12)$$

is less than some critical value $Q_{\rm crit}$, which is of the order of unity. Here, we adopt $Q_{\rm crit} = 2$. When $Q < Q_{\rm crit}$, non-axisymmetric instabilities set in and act to transport angular momentum outwards. In doing so, the surface density evolves in such a way that the stability of the disc generally increases, thereby self-regulating the violence of the instability.

In a local approximation, the efficiency of angular momentum transport due to self-gravity can be determined by the requirement that viscous heating balances radiative losses (Gammie 1999). This approach, in which the cooling time directly determines α, is most appropriate for discs whose thermal balance is determined by viscous heating. Even in this limit, global effects may be important (Balbus & Papaloizou 1999). A global redistribution of surface density, driven by self-gravity, can also occur even if the disc temperature is set externally (for example by irradiation). This is the limit that has been studied extensively using isothermal or polytropic simulations (e.g. Laughlin & Bodenheimer 1994). For protoplanetary discs, models suggest that both viscous heating and irradiation can be important at different epochs and radii (Bell et al. 1997).

Given the above complications, it is evident that attempts to include the effects of self-gravity into one dimensional disc models can only be approximate. We adopt the form suggested by Lin & Pringle (1987, 1990), and use a variant of equation (11) along with an effective gravitational 'α', $\nu_{\rm grav} = \alpha_{\rm grav} c_s^2 / \Omega$, with

$$\begin{aligned} \alpha_{\rm grav} &= 0.01 \left(\frac{Q_{\rm crit}^2}{Q^2} - 1 \right) \quad \text{if } Q < Q_{\rm crit} \\ \alpha_{\rm grav} &= 0 \quad \text{otherwise.} \end{aligned} \quad (13)$$

Operationally, we solve equations (3) and (4) using an explicit finite difference method, and include the self-gravity as an additional sweep over the grid using $\nu_{\rm grav}$ and the full surface density Σ in the diffusive part of equation (3), and as an additional heating term in the energy equation.

3 RESULTS

For our numerical calculations we adopt $M_* = M_\odot$, an inner disc radius $r_{\rm in} = 3.5 \times 10^{11}$ cm (5 $R_\odot$), and an outer disc radius $r_{\rm out} = 6.0 \times 10^{14}$ cm (40 AU). The computational grid of 120 radial mesh points is uniform in a scaled radial variable $X \propto r^{1/2}$. A zero torque boundary condition is imposed at $r_{\rm in}$, while at $r_{\rm out}$ we prevent outflow by setting the radial velocity, v_r, to zero. When mass is added to the disc (representing infall of further material from the molecular cloud), we take $\dot{\Sigma}$ to be a Gaussian centered at 10 AU with a width of 1 AU. This is exterior to the layered section of the disc that we are interested in studying, so the details of how mass is added are unimportant here. We add mass assuming that it has the same specific angular momentum and temperature as the local disc material.

3.1 Steady infall models

To demonstrate the evolution of the layered disc model, we first take the infall rate onto the outer disc $\dot{M}_{\rm infall}$ to be a constant. We take $\alpha = 10^{-2}$, as suggested by numerical simulations of MHD disc turbulence, and allow the disc to evolve from an initially low mass (10^{-2} $M_\odot$) until either a steady state or a limit cycle has developed.

Figure 2 shows the accretion rate onto the star for a range of mass infall rates between 5×10^{-7} $M_\odot {\rm yr}^{-1}$ and 3×10^{-6} $M_\odot {\rm yr}^{-1}$. For the highest infall rate, the disc is able to transport gas steadily onto the star. The inner region, in which $T_c > T_{\rm crit}$, is able to be supplied by an outer disc in which $Q < Q_{\rm crit}$ and the angular momentum is transported by self-gravity. Q is typically around 1.5 in this region, with the transition occurring at a radius of ≈ 3 AU.

For lower infall rates such steady accretion is not possible. After an initial phase in which the disc mass increases steadily, a limit cycle is obtained in which outbursts, with a peak accretion rate $\dot{M} \approx 10^{-5}$ $M_\odot {\rm yr}^{-1}$, alternate with quiescent intervals where $\dot{M} \approx 10^{-8}$ $M_\odot {\rm yr}^{-1}$. Both the duration of the outbursts, and the recurrence time, vary with the rate at which gas is supplied to the outer disc. However, to order of magnitude, for $\dot{M}_{\rm infall} \lesssim 10^{-6}$ $M_\odot {\rm yr}^{-1}$ we find $t_{\rm outburst} \sim 10^4$ yr, and $t_{\rm recur} \sim 10^5$ yr.

The mechanism for these outbursts is shown in Figure 3, which plots the central temperature during the quiescent interval leading up to an outburst. Following the end of one outburst, there is an extended layered region of the disc between ≈ 0.3 AU and ≈ 3 AU. This region is stable against gravitational instability, and supports only the small quiescent accretion rate. Gas flowing inwards from the more

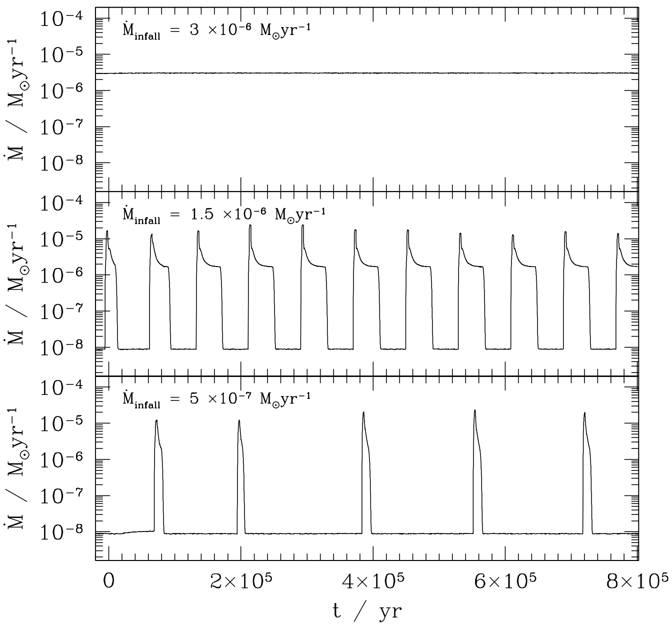

Figure 2. Protostellar accretion for models with a constant rate of infall onto the outer disc. From top down, the panels show models with $\dot{M}_{\rm infall} = 3 \times 10^{-6}\ M_{\odot}{\rm yr}^{-1}$, $\dot{M}_{\rm infall} = 1.5 \times 10^{-6}\ M_{\odot}{\rm yr}^{-1}$, and $\dot{M}_{\rm infall} = 5 \times 10^{-7}\ M_{\odot}{\rm yr}^{-1}$ respectively. All models are shown after initial transients have decayed. Steady accretion occurs for sufficiently high accretion rates through the outer disc. At lower accretion rates, the mass flow onto the star is strongly time-dependent.

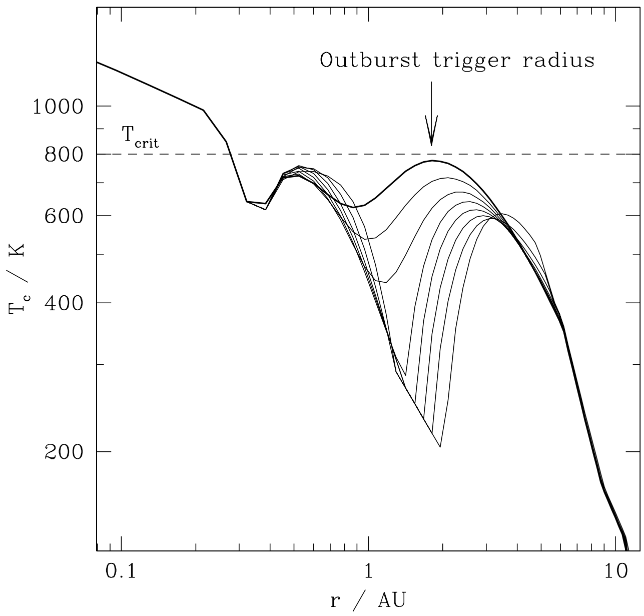

Figure 3. Evolution of the disc central temperature during quiescence. An outburst is triggered when the central temperature in the layered region first exceeds $T_{\rm crit}$ (dashed line), the temperature at which the disc is well enough ionized to support MHD turbulence. The curves show temperature profiles plotted at intervals of 10^4 yr, with the earliest timeslice having the lowest temperature at 2 AU. The final timeslice, shown as the upper, bold curve, immediately precedes the start of an outburst.

active self-gravitating region of the disc thus accumulates in the quiescent region, and the transition radius where the disc becomes self-gravitating moves inward. At the same time, the greater dissipation rate in the self-gravitating disc creates a local peak in the disc temperature, which also moves inwards. A new outburst is triggered when this peak first exceeds $T_{\rm crit}$, thereby satisfying the condition for MHD turbulence to be restarted. Once the outburst begins thermal energy is rapidly advected inwards, triggering a transition of the entire inner disc into a hot turbulent state with high accretion rate. This continues until the reservoir of accumulated mass has been depleted, whereupon a cooling wave sweeps through the disc and returns it to the quiescent, layered, state.

The derived outburst durations are consistent with the expected viscous timescale in protoplanetary discs at radii of a few AU. For an outburst triggered at a radius of approximately 2 AU, the viscous timescale once the disc is in outburst, given by

$$t_\nu \simeq \frac{r^2}{\nu} = \frac{1}{\alpha\Omega}\left(\frac{h}{r}\right)^{-2}, \tag{14}$$

where h is the disc scale height, is approximately,

$$t_\nu \approx 2 \times 10^4 \left(\frac{\alpha}{10^{-2}}\right)^{-1} \left(\frac{r}{2\ {\rm AU}}\right)^{3/2} \left(\frac{h/r}{0.05}\right)^{-2} {\rm yr}. \tag{15}$$

This is only a rough estimate, but it is of the correct order of magnitude to match the numerical model.

The involvement of disc self-gravity means that relatively large disc masses are required for the limit cycle to operate. In our models, $M_{\rm disc}$ fluctuates between 0.2 and 0.3 $M_{\odot}$. During an outburst, only a small fraction of the disc mass — around 20% — is accreted. In more realistic evolutionary models, in which the mass infall rate declines with time, the disc will therefore be able to produce a handful of outbursts, with a few hundredths of a solar mass of gas accreted during each, before settling into a permanent quiescent state.

3.2 Relation to FU Orionis events

The most striking variability observed in pre-main-sequence stars occurs in FU Orionis events (e.g. Kenyon 1995; Hartmann & Kenyon 1996), which are large amplitude outbursts in the system luminosity originating in the accretion disc. The statistics of these events are subject to considerable uncertainty, but the peak accretion rate during outbursts is of the order of $10^{-4}\ M_{\odot}{\rm yr}^{-1}$, while the duration is generally thought to be around 10^2 yr.

The most popular explanation for FU Orionis events is in terms of a disc thermal instability (e.g. Bell & Lin 1994; Kley & Lin 1999, and references therein), akin to that used to model dwarf novae (e.g. Cannizzo 1993). In the protostellar case, a thermal instability can only operate at extremely small disc radii, typically at less than 0.1 AU. Matching the observed timescales then requires small values of α (10^{-3} to 10^{-4}), with correspondingly large values for the disc surface density. As noted by Gammie (1999), it would be attractive to dispense with the need for a thermal instability by invoking an alternative limit cycle of a layered disc. This might be possible *if* the transition to the outburst state was triggered at the extreme inner edge of the layered region. Whether this happens depends on where in the quiescent layer mass preferentially accumulates, and the outcome is therefore sensitive to the detailed, and rather uncertain, physics of the layered disc. In our model, in which matter is being added to the layered region primarily at large radius, the triggering occurs at the outer edge of the layered region, and the timescales are inconsistent with those of FU Orionis events. We note, however, that the accretion rates of $(1-10)\times 10^{-5} M_{\odot}\mathrm{yr}^{-1}$ that we obtain during our outbursts fall into the thermally unstable regime. The long outbursts obtained here could then feed shorter FU Orionis event of the sort calculated by Bell & Lin (1994).

3.3 Protostellar accretion history

Continuous replenishment of the disc mass from infall is not a realistic model for protostellar accretion. To explore how the accretion rate onto the star may evolve with time, we adopt a simple model for the infall of gas onto the disc. The details are model-dependent (see e.g. Larson 1969; Shu 1977; Basu 1998), but at early times the infall rate is expected to be of the order of $\dot{M}_{\mathrm{infall}} \sim c_s^3/G$, where c_s is the sound speed in the collapsing cloud. For cloud temperatures $T \sim 10$ K, this implies an infall rate of $\sim 10^{-5}$ $M_{\odot}\mathrm{yr}^{-1}$. We take an initial infall rate of 2×10^{-5} $M_{\odot}\mathrm{yr}^{-1}$, and assume that this declines exponentially on the free fall timescale, $t_{\mathrm{ff}} = (3\pi/32G\rho_{\mathrm{cloud}})^{1/2}$, where ρ_{cloud} is the cloud density. We take $t_{\mathrm{ff}} = 10^5$ yr. Other input parameters are as described earlier.

With these parameters, Fig. 4 shows the accretion rate for the layered disc model. For comparison, we also show the results from a viscous disc model which has identical parameters, but which has no layered region. This control model would be appropriate, for example, if angular momentum transport was driven by a purely hydrodynamic mechanism whose efficiency was independent of the disc temperature. We compute the control model by using the same code and infall history, but with T_{crit} set to zero.

Initially, when the infall rate is higher than around 2×10^{-6} $M_{\odot}\mathrm{yr}^{-1}$, both models support an accretion rate onto the star which tracks that with which matter is being added to the disc. Subsequently, accretion through the layered disc occurs in outbursts with properties similar to those described earlier, but with increasing intervals between events. For this model, the last outburst before the disc became permanently quiescent occurred after 2 Myr. The accretion rate onto the star in the control model, on the other hand, declines smoothly with time. Similar results are obtained using other functional forms for the mass infall rate as a function of time.

The timescales of variability predicted by the model are much longer than any direct observational record. Indirect evidence for long timescale variability of young stars, however, is provided by studies of protostellar outflows, since the rate of mass outflow via jets is widely believed to track the accretion rate. For example, observations by Reipurth, Bally & Devine (1997) suggest that large amplitude variations in the outflow rate occur not only on the 10^2 yr timescales characteristic of FU Orionis events, but also on much longer

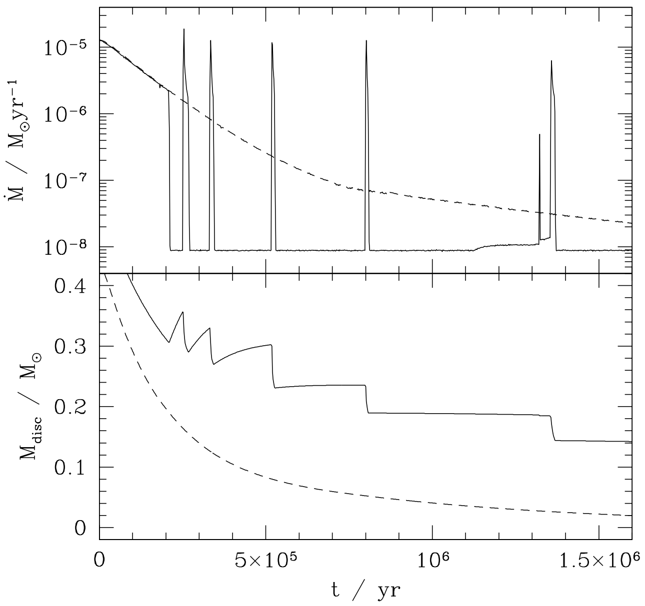

Figure 4. Accretion rate and disc mass as a function of time. The solid curves are for layered disc models in which the mass infall rate onto the outer disc declines exponentially. For comparison with these, the dashed curves show the evolution of a model without a layered structure. This model has identical parameters, except that the disc is assumed to be viscous at all radii and central temperatures.

timescales of 10^4 yr or greater. These longer timescales are characteristic of processes occurring at larger disc radii than thermal instabilities, and are consistent with instabilities, of the kind discussed here, originating in the layered disc region.

The *outburst* accretion rate in the layered disc model is several orders of magnitude higher than that in the equivalent fully viscous disc model at $t \sim 10^6$ yr. However, the time averaged accretion rate is substantially lower, so that at late times the disc mass in the layered model substantially exceeds that in the viscous model. We find that $M_{\mathrm{disc}} \gtrsim 0.1$ $M_{\odot}$ after 1 – 2 Myr. By this time the mass of the fully viscous disc has dropped to only 10^{-2} $M_{\odot}$. As shown in Fig. 5, most of this extra mass is tied up in the quiescent layer at radii of the order of 1 AU, where the surface density exceeds the minimum mass solar nebula estimate (Hayashi, Nakazawa & Nakagawa 1985) by about two orders of magnitude.

3.4 Compatibility with observations of protoplanetary discs

A disc mass of a few tenths of a solar mass at early times is consistent with the upper end of the disc mass distribution inferred from mm-wavelength observations (Beckwith et al. 1990; Osterloh & Beckwith 1995). However, the layered disc model predicts that a substantial mass – at least a few hundredths of a solar mass – remains in the disc throughout most of the typical Classical T Tauri disc lifetime (Strom 1995). Although recent measurements of the mass of H_2 in debris discs indicate that several Jupiter masses of gas can

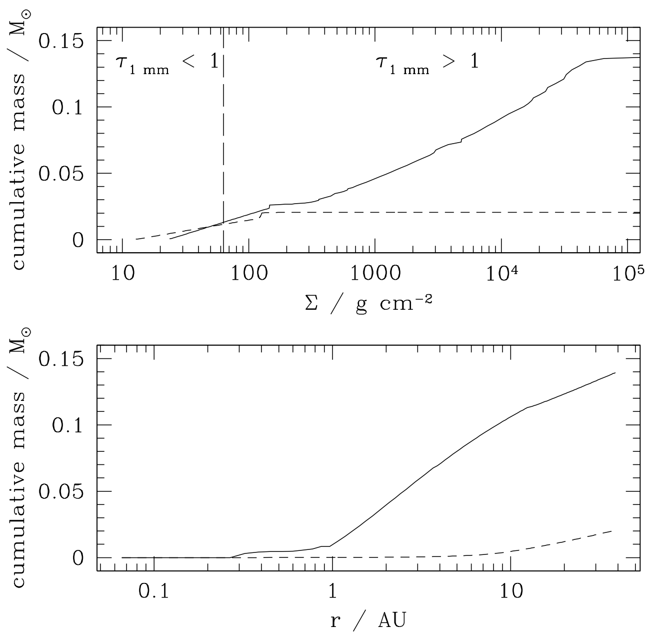

Figure 5. Cumulative disc mass as a function of (upper panel) surface density Σ and (lower panel) radius. The solid curve shows the layered disc model at $t = 1.5 \times 10^6$ yr. For comparison, the dashed curve shows results for the fully viscous model at the same time. The vertical dashed line in the upper panel shows the approximate surface density below which the disc would be optically thin at $\lambda = 1$ mm. Essentially all the additional mass present in the layered disc is locked up in highly optically thick regions at small radii. The amount of mass at $r > 10$ AU is comparable in both the layered and the fully viscous model.

persist beyond 10 Myr (Thi et al. 2001), our predicted disc masses are in apparent contradiction with mm observations of many systems with disc masses estimated at $10^{-3}\ M_\odot$ or smaller.

To check whether this is a serious problem for the layered disc model, we plot in Fig. 5 the cumulative distribution of disc mass as a function of surface density. Most of the 'additional' mass in the layered disc, compared to the equivalent fully viscous control model, is locked up in the quiescent layer at small radii and high surface density. This material is highly optically thick, and thus would not contribute to the observed emission at mm wavelengths. For a range of dust models, the opacity of dust at $\lambda = 1$ mm is thought (Menśhchikov & Henning 1997; Beckwith et al. 1990) to be in the range $0.3\ \mathrm{cm^2g^{-1}} \lesssim \kappa \lesssim 10\ \mathrm{cm^2g^{-1}}$ (note that this is per gram of *dust*). For a gas to dust ratio of 100, this implies that an optical depth of unity at 1 mm is attained for $\Sigma \sim 10^2\ \mathrm{gcm^{-2}}$. At this surface density threshold, the masses of optically thin gas in the layered and non-layered disc models are very similar. The masses of protoplanetary discs inferred from mm-wavelength measurements could thus substantially underestimate the true disc masses.

The accretion rates inferred for Classical T Tauri stars can also provide a test. In the simplest version of the layered disc model, the accretion rate during quiescence does not change over the lifetime of the protostellar phase. This rate is consistent with the order of magnitude inferred for accreting Classical T Tauri stars (Gullbring et al. 1998). There have also been suggestions that the observationally inferred accretion rate declines with increasing stellar age (Hartmann et al. 1998). Although currently the scatter in measured accretion rates at a given assumed age is very large, and the age estimates themselves are subject to substantial uncertainties (Tout, Livio & Bonnell 1999), this observation poses difficulties for the simplest layered disc model (Stepinski 1998). We note, however, that changes in the quiescent accretion rate with time would be expected in more complete models, for example if the opacity from dust decreased with time due to grain growth. Including heating of the disc from the changing stellar radiation would also lead to a decline in the quiescent accretion rate.

4 PLANET FORMATION

The environment which a layered disc presents for planet formation differs in several respects from both previous viscous disc models (e.g. Lin & Pringle 1990), and from static models such as the minimum mass solar nebula. At radii between a few tenths of an AU, and several AU, the gas near the disc midplane is almost always quiescent, unless the settling of cm sized particles itself drives additional instabilities (Goldreich & Ward 1973; Cuzzi, Dobrovolskis & Champney 1993). The low viscosity of the disc in this region would reduce the rate at which massive planets migrate inwards, and may allow planet-disc interactions to excite significant eccentricity (Papaloizou, Nelson & Masset 2001).

Other differences include the disc at large radii remaining mildly unstable to gravitational instability for a relatively long time – around a Myr – because the reduced time-averaged accretion rate leads to a larger disc mass at late times when compared to viscous disc models. Outbursts, which persist for a substantial fraction of the disc lifetime, mean that much of the inner disc is expected to be subject to rapid heating and cooling episodes. However, we find no evidence that these cooling waves drive the disc into a state where gravitational collapse ($Q \lesssim 1$) would occur.

The survival of solid bodies in protoplanetary discs is limited by the rate at which they migrate inwards relative to the gas. Migration can be rapid both for cm-sized bodies (e.g. Godon & Livio 1999, and references therein), and is particularly problematic for low mass planets, for which migration occurs due to the influence of gravitational torques (Goldreich & Tremaine 1979). In standard disc models, the migration timescale for Earth mass planets at a few AU can be as short as $10^4 - 10^5$ yr, which leaves little time to assemble the cores of giant planets before the putative building blocks are consumed by the star. The rate of migration depends only very weakly upon the surface density profile (Ward 1997), but *is* sensitive to the gradient of the central temperature, and can be halted if there exists a region of the disc where $T_c \propto r$. During the quiescent phase, the models we have discussed here possess such a non-monotonic central temperature profile at radii of 1-3 AU (Fig. 3), leading to the possibility of an enhanced probability of giant planet formation at those radii (Papaloizou & Terquem 1999). Current radial velocity surveys are sensitive to massive planets at radii $r \lesssim 3$ AU, i.e. within this region. If migration is as rapid as currently suspected, a consequence of the layered disc model would probably be fewer planets at larger radii than would be expected from an extrapolation from the current data.

5 SUMMARY

In this paper, we have presented models for the evolution of magnetically layered protoplanetary discs. Given our present understanding of angular momentum transport in discs, this model represents the best guess for the structure of protoplanetary discs at radii of the order of 1 AU, where the gas is cool and poorly coupled to the magnetic field. The evolutionary models presented here suggest a number of important differences with non-layered viscous disc models.

(i) The disc cannot be in a steady state for outer disc accretion rates in the range $10^{-8}\ M_\odot \mathrm{yr}^{-1} \lesssim \dot{M} \lesssim 2\times 10^{-6}\ M_\odot \mathrm{yr}^{-1}$. A limit cycle is obtained, in which heating when the layered region of the disc becomes self-gravitating periodically restarts MHD turbulence, leading to outbursts of accretion onto the star. All calculations to date of layered discs obtain strongly episodic accretion, despite variations in the physical processes included in the models (Gammie 1999; Stepinski 1999). This is the most robust prediction of the model.

(ii) The duration of outbursts depends on where in the quiescent disc they are triggered. In our model, the outbursts are long, with duration $\sim 10^4$yr. They could drive repeated strong episodes of mass outflow from the inner disc, resulting in 'pulsing' of the observed jets.

(iii) The time-averaged accretion rate is reduced due to the bottleneck created by the layered region of the disc. As a result, the disc mass at late times is large, typically $\approx 0.1 M_\odot$ at 1-2 Myr. Most of this mass is locked up in the quiescent layer of the disc at small radii.

(iv) The central temperature is strongly modified, and often *increases* with radius, near the transition between the layered disc and the outer self-gravitating region. This could slow the otherwise rapid rate of low mass planetary migration at radii $r \sim 1-2$ AU.

(v) A low viscosity in the layered region of the disc affects the migration rate and eccentricity evolution of massive planets at the radii currently probed by radial velocity surveys.

Current observations provide only very limited constraints on the properties of protoplanetary discs at the radii of greatest interest for planet formation. As a result, there remains substantial uncertainty in our knowledge of how these discs evolve. Models, such as this one, that attempt to include more realistic disc physics, can lead to very different environments for planet formation and migration than the highly simplified models usually considered. The most obvious observational predictions of the model are that some very young stars should be accreting at the low 'quiescent' rate of the order of $10^{-8}\ M_\odot \mathrm{yr}^{-1}$, and that high accretion rate outbursts should continue, albeit with lesser frequency, during a substantial fraction of the Classical T Tauri phase.

ACKNOWLEDGMENTS

PJA thanks the Institute of Astronomy for their hospitality during the course of part of this work, and Charles Gammie, John Papaloizou and Henk Spruit for helpful discussions. This work was partially supported by the Training and Mobility of Researchers (TMR) program of the European Commission. ML acknowledges support from NASA Grant NAG5-6857. JEP is grateful to STScI for continuing support under their Visitors Program.

REFERENCES

Balbus S.A., Hawley J.F., 1991, ApJ, 376, 214
Balbus S.A., Papaloizou J.C.B., 1999, ApJ, 521, 650
Basu S., 1998, ApJ, 509, 229
Beckwith S.V.W., Sargent A.I., Chini R.S., Guesten R., 1990, AJ, 99, 924
Bell K.R., Cassen P.M., Klahr H.H., Henning Th., 1997, ApJ, 486, 372
Bell K.R., Lin D.N.C., 1994, ApJ, 427, 987
Brandenburg A., Nordlund A., Stein R.F., Torkelsson U., 1995, ApJ, 446, 741
Cannizzo J.K., 1993, ApJ, 419, 318
Chandrasekhar S., 1961, in Hydrodynamic and Hydromagnetic Stability, Oxford University Press, Oxford, p. 384
Cuzzi J.N., Dobrovolskis A.R., Champney J.M., 1993, Icarus, 106, 102
Gammie C.F., 1996, ApJ, 457, 355
Gammie C.F., 1999, in Astrophysical Disks, eds. Sellwood & Goodman, ASP Conf. Series, 160, p. 122
Gammie C.F., Menou K., 1998, ApJ, 492, 75
Godon P., Livio M., 1999, ApJ, 523, 350
Goldreich P., Tremaine S., 1979, ApJ, 233, 857
Goldreich P., Ward W.R., 1973, ApJ, 183, 1051
Gullbring E., Hartmann L., Briceno C., Calvet N., 1998, ApJ, 494, 323
Hartmann L., Calvet N., Gullbring E., D'Alessio P., 1998, ApJ, 495, 385
Hartmann L., Kenyon S.J., 1996, ARA&A, 34, 207
Hawley J.F., Balbus S.A., 1999, in Astrophysical Disks, eds. Sellwood & Goodman, ASP Conf. Series, 160, p. 108
Hayashi C., Nakazawa K., Nakagawa Y., 1985, in Protostars and Planets II, eds D.C. Black & M.S. Matthews, University of Arizona Press, Tuscon, p.1100
Kenyon S.J., 1995, Rev. Mex. Astron. Astrophys. Conf. Ser., 1, 237
Kley W., Lin D.N.C., 1999, ApJ, 518, 833
Larson R.B., 1969, MNRAS, 145, 271
Laughlin G., Bodenheimer P., 1994, ApJ, 436, 335
Lin D.N.C., Pringle J.E., 1987, MNRAS, 225, 607
Lin D.N.C., Pringle J.E., 1990, ApJ, 358, 515
Livio M., 1999, in Astrophysical Disks, eds. Sellwood & Goodman, ASP Conf. Series, 160, p. 33
Marcy G.W., Butler R.P., 2000, PASP, 112, 137
Matsumoto R., Tajima T., 1995, ApJ, 445, 767
Menšhchikov A.B., Henning Th., 1997, A&A, 318, 879
Nelson A.F., Benz W., Adams F.C., Arnett D., 1998, ApJ, 502, 342
Osterloh M., Beckwith S.V.W., 1995, ApJ, 439, 288
Papaloizou J.C.B., Nelson R.P., Masset F., 2001, A&A, in press
Papaloizou J.C.B., Terquem C., 1999, ApJ, 521, 823
Pickett B.K., Cassen P., Durisen R.H., Link R., 2000, ApJ, 529, 1034
Reipurth B., Bally J., Devine D., 1997, AJ, 114, 2708
Reyes-Ruiz M., Stepinski T.F., 1995, ApJ, 438, 750

Sano T., Miyama S.M., 1999, ApJ, 515, 776
Sano T., Miyama S.M., Umebayashi T., Nakano T., 2000, ApJ, 543, 486
Shakura N.I., Sunyaev R.A., 1973, A&A, 24, 337
Shu F.H., 1977, ApJ, 214, 488
Stepinski T.F., 1998, ApJ, 507, 361
Stepinski T.F., 1999, 30th Annual Lunar and Planetary Science Conference, abstract no. 1205
Stone J.M., Hawley J.F., Gammie C.F., Balbus S.A., 1996, ApJ, 463, 656
Strom S.E., 1995, Rev. Mex. Astron. Astrophys. Conf. Ser., 1, 317
Thi W.F. et al., 2001, Nature, 409, 60
Toomre A., 1964, ApJ, 139, 1217
Tout C.A., Livio M., Bonnell I.A., 1999, MNRAS, 310, 360
Velikhov E.P., 1959, Soviet JETP, 36, 995
Ward W.R., 1997, Icarus, 126, 261
Wardle M., 1999, MNRAS, 307, 849