Gap opening beyond dead zones by photoevaporation

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ABSTRACT

We propose a new hypothesis for the origin of protoplanetary discs with large inner holes (or gaps), so-called transition discs. Our gas disc model takes into account layered accretion, in which poorly ionized low-viscosity dead zones are sandwiched by high-viscosity surface layers, and photoevaporative winds induced by X-rays from the central stars. We find that a gap opens at a radius outside a dead zone, if the mass-loss rate due to photoevaporative winds exceeds the mass accretion rate in the dead zone region. Since the dead zone survives even after the gap opens, mass accretion on to the central star continues for a long time. This model can reproduce large gap sizes and high mass accretion rates seen in observed transition discs.

Key words: methods: numerical – protoplanetary discs.

1 INTRODUCTION

Spatial distribution of dust in protoplanetary discs is measured from disc continuum spectra in near-infrared to millimetre wavelengths whereas the gas density is measured directly by line emission such as from CO and indirectly from Hα emission which is used for estimations of gas accretion rates on to central stars. Infrared excess due to dust emission disappears in 3 Myr for roughly a half of discs and for almost all discs in 10 Myr (Haisch, Lada & Lada 2001). Gas in inner discs disappears in similar time-scales (Fedele et al. 2010), but the lifetime of gas in outer discs is not clearly known.

Recent observations, such by the Spitzer infrared space telescope, the Submillimeter Array and the Subaru Telescope, revealed discs in the dispersal phase, so-called transition discs (Merín et al. 2010; Thalmann et al. 2010; Andrews et al. 2011). They have optically thick outer discs whereas inner discs with sizes up to ~70 au are optically thin. This indicates depletion of dust in the inner discs. Some of the transition discs show near-infrared excess, indicating formation of gaps instead of holes, while others have weaker mid-infrared emission, indicating optically thinner outer discs (Muzerolle et al. 2010). The fraction of transition discs in protoplanetary discs increases with time (Currie & Sicilia-Aguilar 2011): 15–20 per cent at 1–2 Myr and more than 50 per cent at 5–8 Myr. A puzzling thing is that a large fraction (75 per cent; Merín et al. 2010) of transition discs exhibit gas accretion on to their central stars and accretion rates are close to those for classical T Tauri stars, ~10−8 M⊙ yr−1 (Hartmann et al. 1998).

Three explanations are proposed for the origin of transition discs but all of them do not seem to be fully satisfactory (Andrews et al. 2011; Williams & Cieza 2011). (1) Gap opening by photoevaporative winds (Gorti, Dullemond & Hollenbach 2009; Owen, Ercolano & Clarke 2011). If the mass-loss rate of photoevaporative winds exceeds the mass accretion rate of viscous evolution, a gap can open. However, before a gap opens, the mass accretion rate largely decreases and becomes much less than 10−8 M⊙ yr−1. This also occurs for X-ray photoevaporation having mass-loss rate as high as 10−6 M⊙ yr−1 (Owen, Ercolano & Clarke 2011). The sizes of the inner holes due to photoevaporation cannot be larger than 20 au when mass accretion on to the central star still remains. (2) Dust growth (Dullemond & Dominik 2005; Tanaka, Hime & Ida 2005). This is expected particularly in inner discs as the models show that the dust growth rate has a strong dependence on distance from the central star. However, dust growth alone cannot be responsible for transition discs, because the dust growth models predict smooth opacity changes with radius, whereas observed transition discs show clear gaps of dust. (3) Gap opening by giant planets. Zhu et al. (2011) show that multiple giant planets can open a gap as wide as the largest holes observed. However, depletion of the surface density in the gap results in a large decrease of the mass accretion rate.

The most probable source of the disc viscosity is the turbulent viscosity caused by the magnetorotational instability (MRI; Balbus & Hawley 1991). Since the ionization rate in the thick inner disc is not high enough, a poorly ionized layer with a low viscosity, called a dead zone, forms near the disc midplane sandwiched by MRI-active layers (Gammie 1996; Zhu, Hartmann & Gammie 2010). This type of accretion is called layered accretion. In this paper, we develop a gas disc model which takes into account layered accretion and photoevaporative winds. Layered accretion has not been taken into account in previous works of photoevaporation. As we will show, our disc model can reproduce some of the important properties of observed transition discs, such as large gap sizes and high mass accretion rates.
In Section 2, we introduce our gas disc model. In Section 3, results are shown for both discs with and without layered accretion over a wide range of parameters. In Section 4, implications for transition discs are discussed. In Section 5, a summary of this study is given.

2 METHODS

2.1 Basic equations

We assume that mass accretion from a molecular cloud core has already completed and that the mass of the central star is fixed during disc evolution. Time evolution of the surface density $\Sigma$ is derived from the mass and angular momentum conservation equations:

$$\frac{\partial \Sigma}{\partial t} = \frac{1}{2\pi r} \frac{\partial M}{\partial r} - \Sigma \omega, \quad (1)$$

$$\frac{\partial (\Sigma j)}{\partial t} = \frac{1}{2\pi r} \frac{\partial}{\partial r} (M j + J_{vis}) - \Sigma j, \quad (2)$$

where $M$ is the mass accretion rate (assumed to be positive for inward accretion), $\Sigma$ is the mass-loss flux of photoevaporative winds, $j = r^2 \Omega$ is the specific angular momentum with $\Omega$ being the Keplerian frequency, and $J_{vis} = 2\pi r^2 \Sigma v d\Omega/dr$ is the angular momentum flux transferred by the disc viscosity, $v$. From equations (1) and (2), the mass accretion rate is obtained as

$$\dot{M} = -2\pi r \Sigma v_i = 6\pi^{1/2} \frac{\partial}{\partial r} \left( \Sigma v r^{1/2} \right), \quad (3)$$

where $v_i$ is the radial velocity. Substituting this equation into equation (1), we obtain the well-known diffusion equation (Lynden-Bell & Pringle 1974):

$$\frac{\partial \Sigma}{\partial t} = \frac{3}{r} \frac{\partial}{\partial r} \left( r \frac{\partial}{\partial r} (\Sigma v r^{1/2}) \right) - \Sigma \omega. \quad (4)$$

2.2 Disc viscosity

Using the viscosity parameter $\alpha$ (Shakura & Sunyaev 1973), the viscosity is given as

$$v = \alpha ch = \frac{\alpha RT}{\mu \Omega}, \quad (5)$$

where $c$ is the isothermal sound velocity at the disc midplane and $h = c/\sqrt{\Sigma}$ is the vertical scale height of the disc. The isothermal sound velocity is given as $c = (RT/\mu)^{1/2}$, where $R$ is the gas constant, $T$ is the disc temperature at the midplane, and we take the mean molecular weight as $\mu = 2.33$ g mol$^{-1}$. For models without dead zones, $\alpha$ is radially constant. For models with dead zones, the $\alpha$ parameters for active surface layers and dead zones are defined to be $\alpha_a$ and $\alpha_d$, respectively. Then, the effective disc viscosity parameter is given as

$$\alpha = \frac{\Sigma \alpha_a + (\Sigma - \Sigma_a) \alpha_d}{\Sigma}, \quad (6)$$

where $\Sigma_a$ is the sum of the surface densities of both sides of active layers. In simulations, we adopt $\alpha_a = 0.01$. The surface density $\Sigma_a$ is modelled after Suzuki, Muto & Inutsuka (2010):

$$\Sigma_a = \min \left\{ \Sigma_{CR} + \Sigma_X \left( \frac{r}{1 \text{ au}} \right)^{-2}, \Sigma \right\}, \quad (7)$$

where $\Sigma_{CR}$ is the surface density of layers ionized by cosmic rays and $\Sigma_X$ is the surface density of layers ionized by X-rays from the central star at 1 au. Equations (6) and (7) indicate that $\alpha \ll \alpha_a$ if $\Sigma \gg \Sigma_a$. On the other hand, if $\Sigma \leq \Sigma_{CR} + \Sigma_X (r/1 \text{ au})^{-2}$, the region is entirely MRI active ($\Sigma = \Sigma_a$) so that $\alpha = \alpha_a$.

The surface densities $\Sigma_{CR}$ and $\Sigma_X$ particularly depend on the dust amount in the disc, as recombination of ions and electrons occurs on the dust surface (Sano et al. 2000; Bai 2011). For example, Suzuki, Muto & Inutsuka (2010) use $\Sigma_{CR} = 12$ g cm$^{-2}$ and $\Sigma_X = 25$ g cm$^{-2}$, whereas Gammie (1996) adopts nominal values as $\Sigma_{CR} = 200$ g cm$^{-2}$ and $\Sigma_X = 0$. The value of $\Sigma_{CR}$ adopted in Gammie (1996) comes from the attenuation length of cosmic rays ($\approx 96$ g cm$^{-2}$; Umebasyashi & Nakano 1981). If the dust abundance is negligible, MRI is sustained in the layers as thick as the attenuation length (Sano et al. 2000). On the other hand, in the magnetohydrodynamic (MHD) simulations of Suzuki et al. (2010), they adopt the ionization degree calculated in Sano et al. (2000) and Inutsuka & Sano (2005) assuming that the dust-to-gas ratio is 0.01. In this study, we vary $\Sigma_{CR}$ as a parameter. We fix $\Sigma_X$ to be 25 g cm$^{-2}$, as we find that $\Sigma_X$ is less important than $\Sigma_{CR}$ for overall disc evolution, in particular for $\alpha_d \gtrsim 10^{-3}$. MHD simulations show that dead zones have non-zero viscosities (Fleming & Stone 2003; Suzuki et al. 2010), and the value of $\alpha_d$ is of the order of $\sim 10^{-5}$–$10^{-3}$.

2.3 Disc temperature

As heat sources of discs we take into account viscous heating, irradiation from the central star and background irradiation. We simply suppose all contributions which are independently modelled:

$$T^4 = T_{vis}^4 + T_{in}^4 + T_{amb}^4, \quad (8)$$

where $T_{vis}$, $T_{in}$ and $T_{amb}$ are the temperatures contributed from viscous heating, irradiation from the central star and background irradiation, respectively. If only viscous heating is considered, the radiative cooling from both sides of the disc balances with the viscous heating as

$$2\sigma_{SB} T_{vis, eff}^4 = \frac{9}{4} \Sigma v r \Omega^2, \quad (9)$$

where $T_{vis, eff}$ is the effective disc surface temperature. The relation between the midplane temperature $T_{vis}$ and the effective temperature is given by Hubeny (1990) as

$$T_{vis}^4 = \tau_{eff} T_{vis, eff}^4, \quad (10)$$

with

$$\tau_{eff} = \left[ \frac{3\tau}{8} \left( 1 + \frac{\Sigma}{\Sigma_a} - \frac{\alpha_a \Sigma_a}{\alpha \Sigma} \right) + \sqrt{\frac{3}{4} + \frac{3}{4\tau}} \right]^{-1}, \quad (11)$$

where $\tau = \kappa \Sigma/2$ is the optical depth at the midplane. Equation (11) is applicable to all cases. For pure MRI-active regions without dead zones, we set $\Sigma = \Sigma_a$ and $\alpha = \alpha_a$. For the dead zone region with $\alpha_d = 0$, we set $\Sigma \alpha = \Sigma_a \alpha_a$ so that equation (10) becomes the same as equation (7) of Gammie (1996) for $\tau \Sigma / \Sigma_a \gg 1$. A detailed derivation of the first term in the square bracket of the right-hand side of equation (11) is given in Wünsch et al. (2006). The opacity $\kappa$ is represented by $\kappa = \kappa_0 T^{\beta}$, where $\kappa_0$ is a constant. We use $\kappa$ from Stepinski (1998) shown in Table 1. Results of the present study do not sensitively depend on opacity law.

The disc effective temperature irradiated by the central star is given by (Ruden & Pollack 1991)

$$T_{in, eff}^4 = T_s^4 \left[ \frac{2}{3\pi} \left( \frac{r_s}{r} \right)^3 + \frac{1}{2} \left( \frac{r_s}{r} \right)^2 \left( \frac{h}{r} \right) \left( \frac{\ln h}{\ln r - 1} \right) \right], \quad (12)$$

where $T_s$ and $r_s$ are the photospheric temperature and radius of the central star, respectively. We adopt $T_s = 4000$ K and $r_s = 3 r_\odot$. 

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The scale height $h$ used in equation (12) is the photospheric disc scale height, which we simply assume to be the same as the pressure scale height. Following Hueso & Guillot (2005), we assume $d \ln h / d \ln r = 9/7$. This is validated as $T \propto r^{-3/7}$ at large radii, where irradiation from the central star is usually the dominant heat source. The midplane temperature, $T_{\text{irr}}$, irradiated by the central star is calculated using the vertical temperature structure derived by Malbet & Bertout (1991) (see also Malbet, Lachaume & Monin 2001):

\[
T_{\text{irr}}^4 = T_{\text{irr},\text{eff}}^4 \left\{ \frac{3}{4} \mu_0 \left[ 1 - \exp \left( -\frac{\tau}{\mu_0} \right) \right] + \frac{1}{2} \right\} + \frac{1}{4 \mu_0} \exp \left( -\frac{\tau}{\mu_0} \right),
\]

(13)

Here, $\mu_0$ is the averaged cosine of the incident angle of the central star given as

\[
\mu_0 = -\frac{H_0}{\sqrt{r}},
\]

(14)

with the zeroth and first-order moments, $J^0$ and $H^0$, of the incident intensity at the uppermost layer:

\[
J^0 = \frac{\sigma_B T^4}{4\pi} \left\{ 1 - \left[ 1 - \left( \frac{\tau}{r} \right) \right]^{1/2} \right\},
\]

(15)

\[
H^0 = -\frac{\sigma_B T_{\text{irr},\text{eff}}^4}{4\pi}.
\]

Equation (13) shows that $T_{\text{irr}}$ of an optically thick disc is lower than $T_{\text{irr},\text{eff}}$ by a factor of $2^{1/4}$, as the uppermost layers emit half of the received energy towards the midplane. In the optically thin limit ($\tau \to 0$), the third term in the bracket dominates and we obtain $T_{\text{irr}} = T_{\text{irr}}^* (r_s/r)^{3/8}$, which corresponds to the equilibrium temperature irradiated by the half hemisphere of the central star without any obstacle. The temperature at $\tau \to 0$ should be higher by a factor of $2^{1/4}$, but this difference does not affect our results as the stage with a low surface density is very short with photoevaporative winds.

The ambient temperature is simply assumed to be $T_{\text{amb}} = 20$ K.

### 2.4 Mass-loss due to photoevaporation

Of the various types of photoevaporations, the photoevaporation induced by X-rays from the central star is the strongest and most important for gas disc evolution in the planet formation region (Ercolano, Clarke & Drake 2009; Owen et al. 2010, 2011), unless discs are close to very massive external stars (Adams et al. 2004; Mitchell & Stewart 2010). The total mass-loss rate from a disc to X-ray photoevaporation is estimated by Owen et al. (2011) as

\[
M_\nu = 6.4 \times 10^{-9} A \left( \frac{L_X}{10^{30} \text{erg s}^{-1}} \right)^{1.14} \text{M}_\odot \text{yr}^{-1},
\]

(17)

where $A$ is a constant of the order of unity (we fix it to be unity) and $L_X$ is the X-ray luminosity from the central star. For sub-solar to solar mass protostars, $L_X$ is $10^{29} - 10^{31}$ erg s$^{-1}$ (Güdel et al. 2007). Numerical simulations of Owen et al. (2010) show that $\Sigma_w$ is roughly proportional to $r^{-3/2}$ (their fig. 13). Thus, we give the mass-loss rate per unit area as

\[
\Sigma_w = \frac{M_\nu}{4\pi \left( r_{\text{out}}^{1/2} - r_{\text{in}}^{1/2} \right)} r^{-3/2} \text{(for } r_{\text{in}} \leq r \leq r_{\text{out}} \text{)},
\]

(18)

where $r_{\text{in}}$ and $r_{\text{out}}$ are the inner and outer edges, respectively, of the range where mass-loss occurs. We take $r_{\text{in}} = 1$ au and $r_{\text{out}} = 70$ au from Owen et al. (2010). Outside $r_{\text{out}}$, other mechanisms such as extreme ultraviolet or far-ultraviolet photoevaporation (Gorti, Dullemond & Hollenbach 2009) may work, although these effects are not taken into account in this work. Results of disc evolution do not depend sensitively on $r$-dependence of $\Sigma_w$, as similar results are obtained even if we vary the power-law index between $-1$ and $-2$.

In some test simulations, we also adopt the mass-loss due to MRI disc winds (Suzuki et al. 2010). The mass-loss rate of MRI disc winds at a given radius is proportional to the surface density. We find that gas depletes very rapidly even near the inner edge, and that the mass accretion rate on to the central star becomes less than $10^{-8}$ M$_\odot$ yr$^{-1}$ within 1 Myr, as shown in Suzuki et al. (2010). This accretion rate appears too low compared with those for typical discs around classical T Tauri stars (Hartmann et al. 1998). Probably, the mass-loss rate of MRI disc winds is much smaller, but this mechanism may still play an important role in disc evolution.

### 2.5 Numerical procedures

We numerically solve equation (4) using the method described in Bath & Pringle (1981), in which the radial grid size is proportional to $\sqrt{T}$. We use 1000 grids between 0.03 and 3000 au. These numbers give the innermost grid size of 0.02 au. At the inner boundary, $\Sigma$ is fixed to be zero, and at the outer boundary we adopt the outward mass flux given by $-3\pi \Sigma v$. We find that the evolution of the total mass is nearly the same even with larger outer boundary radii, whereas artificial mass-loss from the outer boundary is not negligible with smaller outer boundary radii. The temperature is calculated by the Newton–Raphson method.

For all simulations, the mass of the central star is the solar mass, M$_\odot$, the initial mass of the disc is 0.1 M$_\odot$, and the initial surface density is proportional to $r^{-1}$ with the outer edge of 20 au. The adopted time-step size is 1 yr. A single simulation for $\sim 10$ Myr takes roughly one CPU day. We conduct eight runs for discs with radially constant $\alpha$ values and 18 runs for discs with dead zones.

### Table 1. Rosseland mean opacity from Stepiniski (1998).

| Applicability | $\kappa_0$ (cm$^2$g$^{-1}$) | $\beta$ |
|---------------|----------------------------|--------|
| $T < 150$ K   | $2 \times 10^{-4}$         | 2      |
| $150$ K $< T \leq 180$ K | $1.15 \times 10^{18}$ | -8     |
| $180$ K $< T \leq 1380$ K | $2.13 \times 10^{-2}$ | 3/4    |
| $1380$ K $< T$   | $4.38 \times 10^{44}$   | -14    |

### Table 2. Input parameters for simulations of discs without dead zones.

| Run ID | $L_X$ (10$^{30}$ erg s$^{-1}$) | $\alpha$ |
|--------|--------------------------------|---------|
| N1     | 1.0                            | 10$^{-2}$|
| N2     | 1.0                            | 10$^{-3}$|
| N3     | 3.0 $\times 10^{-4}$          | 10$^{-4}$|
| N4     | 1.0                            | 10$^{-4}$|
| N5     | 3.0                            | 10$^{-2}$|
| N6     | 3.0                            | 10$^{-3}$|
| N7     | 3.0 $\times 10^{-4}$          | 10$^{-4}$|
| N8     | 3.0                            | 10$^{-4}$|

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The input parameters are shown in Tables 2 and 3 for simulations of discs without and with dead zones, respectively.

3 RESULTS

Results for all simulations are summarized in Table 4.

3.1 Discs without dead zones

Fig. 1 shows time evolution of the surface density $\Sigma$, the temperature $T$, and the mass accretion rate $\dot{M}$ for a disc with a radially constant $\alpha$ (run N2). As the disc spreads with time, $\Sigma$ and $T$ decrease. The kinks seen in the $T$ profile correspond to the opacity transition temperatures (150, 180 and 1380 K) and the corresponding kinks are also seen in $\Sigma$. The direction of the radial gas motion is inwards in the inner disc and outwards in the outer disc, and the zero radial velocity radius expands with disc expansion. The accretion rate $\dot{M}$ is independent of $r$ in the inner disc and is equivalent to the mass accretion rate on to the central star $M_*$, as long as $\dot{M}$ is sufficiently larger than the mass-loss rate due to photoevaporation $\dot{M}_e$. When $M_*$ becomes less than $M_*\Sigma$ rapidly decreases and eventually a gap opens at slightly beyond 1 au, as well as

Table 4. Summary of disc properties.

| Run ID | $M_*$ (1 Myr) | $t_d$ (Myr) | $t_{\text{at}}$ (Myr) | $r_{\text{gap}}$ (au) | $M_{\text{gap}}$ ($10^{-3} M_\odot$) | $M_{\text{gap, out}}$ ($10^{-3} M_\odot$) | $M_{\text{s, gap}}$ (10^{-9} M_\odot yr^{-1}) |
|--------|---------------|-------------|-----------------------|----------------------|----------------------------------|--------------------------------------------|-----------------------------------------------|
| N1     | 7.73          | 2.40        | -                     | 2.40                 | 1.47                            | 10.23                                      | 5.27 $\times$ 10^{-4}                       |
| N2     | 9.19          | 6.12        | -                     | 6.01                 | 1.34                            | 10.72                                      | 2.58 $\times$ 10^{-2}                       |
| N3     | 6.73          | 10.21       | -                     | 9.08                 | 60.37                           | 6.85                                       | 0.17                                         |
| N4     | 3.22          | 16.02       | -                     | 14.90                | 1.34                            | 2.65                                       | 3.21 $\times$ 10^{-2}                       |
| N5     | 1.27          | 1.11        | -                     | 1.09                 | 1.22                            | 12.63                                      | 5.86 $\times$ 10^{-2}                       |
| N6     | 6.80          | 2.84        | -                     | 2.63                 | 60.37                           | 5.46                                       | 0.20                                         |
| N7     | 5.31          | 4.58        | -                     | 4.12                 | 1.34                            | 5.62                                       | 5.59                                         |
| N8     | 2.56          | 6.46        | -                     | 5.12                 | 1.34                            | 14.29                                      | 7.99 $\times$ 10^{-2}                       |
| D1     | 2.89          | 12.17       | 12.11                 | 4.36                 | 47.55                           | 47.37                                      | 2.87                                         |
| D2     | 5.61          | 8.01        | 7.92                  | 3.71                 | 31.18                           | 34.79                                      | 4.77                                         |
| D3     | 2.89          | 6.58        | 6.54                  | 1.48                 | 54.58                           | 57.09                                      | 2.12                                         |
| D4     | 5.61          | 5.08        | 5.03                  | 1.66                 | 42.27                           | 44.84                                      | 3.94                                         |
| D5     | 3.48          | 9.39        | 9.39                  | 5.52                 | 57.02                           | 34.43                                      | 1.85                                         |
| D6     | 6.89          | 6.24        | 6.18                  | 5.37                 | 45.32                           | 10.98                                      | 3.17                                         |
| D7     | 18.31         | 3.69        | 3.46                  | 3.68                 | 2.05                            | 7.11                                       | 7.11                                         |
| D8     | 3.26          | 5.40        | 5.37                  | 1.30                 | 61.23                           | 63.56                                      | 1.03                                         |
| D9     | 6.53          | 3.97        | 3.94                  | 1.62                 | 57.02                           | 48.91                                      | 2.10                                         |
| D10    | 17.71         | 2.51        | 2.47                  | 1.83                 | 45.32                           | 20.08                                      | 4.10                                         |
| D11    | 30.85         | 1.50        | 1.37                  | 1.49                 | 2.54                            | 8.19                                       | 1.89 $\times$ 10^{-2}                       |
| D12    | 3.55          | 14.32       | 14.15                 | 14.29                | 28.20                           | 1.66                                       | 1.65                                         |
| D13    | 7.00          | 9.01        | 8.28                  | 9.00                 | 1.22                            | 4.32                                       | 4.32                                         |
| D14    | 18.49         | 6.50        | 4.07                  | 6.49                 | 1.10                            | 5.75                                       | 5.75                                         |
| D15    | 17.37         | 4.10        | 3.95                  | 4.09                 | 2.05                            | 6.40                                       | 6.40                                         |
| D16    | 15.84         | 2.62        | 2.58                  | 2.02                 | 52.18                           | 14.87                                      | 2.98                                         |
| D17    | 19.99         | 2.83        | 2.20                  | 2.83                 | 1.47                            | 9.51                                       | 9.51                                         |
| D18    | 15.31         | 1.56        | 1.48                  | 1.55                 | 2.72                            | 8.17                                       | 8.17                                         |

Notes. $M_{\ast,1\text{Myr}}$ is the mass accretion rate on to the central star at $t = 1$ Myr, $t_d$ is the time when $M_*$ becomes $10^{-12} M_\odot$ yr$^{-1}$, $t_{\text{at}}$ is the lifetime of the dead zone (when a disc becomes entirely MRI active for all radii), $t_{\text{gap}}$ is the time when a gap opens, $r_{\text{gap}}$ is the gap radius where $\Sigma$ becomes zero in the earliest time, $M_{\text{gap}}$ and $M_{\text{gap, out}}$ are the total disc mass and the disc mass outside $r_{\text{gap}}$ at $t = t_{\text{gap}}$, and $M_{\ast, \text{gap}}$ is $M_*$ at $t = t_{\text{gap}}$. 

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Simulations in Owen et al. (2011). Once a gap opens, the inner disc (inside the gap) disperses very quickly and mass accretion on to the central star stops. The hole size is only 1.3 au at this time. The temperature increases when the disc becomes optically thin, but this phase (with a non-zero gas density) is very short.

The gap opening slightly outside \( r_{X,\text{in}} \) is explained as follows. Let us assume that the inward mass flux due to viscous accretion at \( r_{X,\text{out}} \) is \( M_{\text{out}} \). As gas moves inwards by \( dr \), the mass flux is reduced by \( 2\pi r \Sigma_{\text{in}} dr \). Therefore, the inward mass flux decreases with increasing \( r \) and eventually becomes zero at \( r_{X,\text{in}} \) if \( M_{\text{out}} = M_{\ast} \). Thus, if \( \dot{M} \) is independent of \( r \) without photoevaporation, a gap inevitably opens near \( r_{X,\text{in}} \). Since gas takes time to radially move from \( r_{X,\text{out}} \) to \( r_{X,\text{in}} \) (the viscous time-scale at \( r_{X,\text{out}} \), \( M_{\text{out}} \) becomes much less than \( M_{\ast} \) at the time of actual gap opening (see the black curve in Fig. 1).

In some runs, large gaps can open (runs N3 and N6; see Table 4). This happens because the disc sizes are not sufficiently larger than \( r_{X,\text{out}} \) and the mass accretion rates are not radially constant near the outer edges of the discs. Even in these cases, the mass accretion rates on to the central stars at the time of gap opening are much smaller than those seen in transition discs. Overall, a large accretion rate and a large hole size are not simultaneously reproduced as long as \( \alpha \) is radially constant.

### 3.2 Discs with dead zones

#### 3.2.1 Cases with no dead zone viscosity (\( \alpha_d = 0 \))

Pictures of evolution of discs with dead zones are very different from those without dead zones. Fig. 2 shows evolution of a layered disc with \( \alpha_d = 0 \) (run D1). The mass accretion rate discontinuously drops at \( T = 150 \) K, because the opacity law changes. As a result, two dead zone regions appear. Splitting into multiple dead zones was theoretically predicted by Gammie (1996). Most of the disc mass remains in the dead zones and \( \dot{M} \) remains nearly constant as long as the dead zones exist. Since \( M \) in the dead zone region increases with \( r \), \( \Sigma \) increases with time (Gammie 1996; Zhu et al. 2010).

The zero radial velocity radius is initially located at the outer edge of the outer dead zone. The direction of the radial motion of gas is outwards outside the outer dead zone, while it is inwards in the dead zone region. The absolute magnitudes of the mass fluxes in both directions are similar to each other. Since the dead zone size is \( \sim 10 \) au, most of the gas removal by photoevaporation takes place outside the dead zone region. A discussion of the gap opening due to photoevaporation is similar to the case of Fig. 1, but now the mass flux is outwards. Thus, a gap opens slightly inside \( r_{X,\text{out}} \) once \( M \) near the outer edge of the dead zone becomes less than \( M_w \).

For run D1, a gap opens roughly at 48 au when the outer dead zone disappears, because \( M \) in the outer dead zone is larger than \( M_w \) while \( M_r \) in the inner dead zone is comparable to \( M_w \). Since the inner dead zone survives for a long time, \( \dot{M}_r \) remains high even after a gap opens. The outward mass flux from the dead zone remains at \( \sim M_w \) after a gap opens, as long as the dead zone exists. Once the dead zone disappears, the inner disc quickly dissipates and mass accretion on to the central star halts.

#### 3.2.2 Cases with finite dead zone viscosity (\( \alpha_d > 0 \))

It is possible to retain a steady-state mass accretion with a finite residual viscosity in the dead zone. The condition to retain a radially constant \( M \) is given from equations (3), (5) and (6) as

\[
\frac{1}{\rho} \frac{\partial}{\partial r} \left\{ \left[ (\Sigma \alpha_d + \Sigma - \Sigma_d) \alpha_d \right] T^2 \right\} = \text{const.} \quad (19)
\]

If the radial profile of \( T \) is given, such as irradiated discs, the above condition is fulfilled when \( \Sigma \alpha_d > \Sigma \alpha_d \), so that the radial profile of \( \Sigma \) is adjusted. On the other hand, if viscous heating is the dominant heat source, the midplane temperature is given from equations (5), (6), (9) and (10) as

\[
T = \left( \frac{27}{128} \frac{R_k}{\sigma_{SB} H} \right) \Omega \left[ \left( \Sigma^2 - \Sigma_d^2 \right) \alpha_d + \Sigma^2 \alpha_d \right]^{1/(3-\beta)} \quad (20)
\]

Thus, if \( \Sigma^2 \alpha_d \gtrsim \Sigma_d^2 \alpha_d \), the radial profiles of \( T \) and \( \Sigma \) are mutually adjusted so that \( \dot{M} \) can be independent of \( r \).

Fig. 3 shows an example of evolution of a disc with \( \alpha_d = 10^{-5} \) (run D6). Since this case satisfies the condition \( \Sigma^2 \alpha_d \gtrsim \Sigma_d^2 \alpha_d \), \( M \)

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1 Without photoevaporation, the direction of radial motion of gas outside the dead zone is outwards only in the early expansion phase, but eventually turns inwards (Zhu et al. 2010), except near the outer edge of the disc. The outward flux is retained by strong photoevaporation in our simulations.
becomes almost independent of $r$ (see the orange line at 2.0 Myr in Fig. 3). Split into multiple dead zones is also suppressed. In addition to cases with $\alpha_d = 0$, a gap opens at a radius outside the dead zone.

Fig. 4 shows the radial location of a gap $r_{\text{gap}}$ for various values of $\alpha_d$, $\Sigma_{\text{CR}}$ and $L_X$. We define $r_{\text{gap}}$ as a radius where $\Sigma$ becomes zero in the earliest time while $\Sigma > 0$ in outer radii. If $M$ is independent of $r$ in the dead zone region, the condition for gap opening is given by $M_{\text{in}} \gtrsim M_*$. For small values of $\alpha_d$ and $\Sigma_{\text{CR}}$, $M_*$ can be smaller than $M_{\text{in}}$ even when a dead zone exists. Thus, a gap opens beyond a dead zone in such a case. On the other hand, for large $\alpha_d$ and $\Sigma_{\text{CR}}$, a gap opens at a small radius only after a dead zone disappears and $M_*$ becomes sufficiently small, as well as the cases with radially constant $\alpha$ values shown in Section 3.1. Not surprisingly, gap opening beyond dead zones is possible even with large values of $\alpha_d$ and $\Sigma_{\text{CR}}$ if $M_*$ (or $L_X$) is large.

4 DISCUSSION

Fig. 5 shows a comparison of observed transition discs with discs from our simulations. In the upper panel of Fig. 5, gap sizes and mass accretion rates are plotted. For simulations, we use $r_{\text{gap}}$ and the mass accretion rate on to the central star $M_{\ast, \text{gap}}$ at the time of gap opening (see Table 4). Subsequent evolution curves are also shown. As can be seen, large gap (or hole) sizes and accretion rates seen in observed transition discs are reproduced well in models with dead zones. On the other hand, models without dead zones are able to reproduce only discs with small mass accretion rates and gap sizes. In runs N3 and N6, a gap opens at $\sim 60$ au, but the mass accretion rate is small (in these runs, another gap opens at $\sim 1$ au, and the disc outside the outer gap quickly dissipates).

In the lower panel of Fig. 5, we compare disc masses from observations with our simulations. For our simulations, we take the disc mass outside the gap ($M_{\text{out}}$, Table 4), not the total disc mass, $M_{\text{total}}$. Observational data from Najita, Strom & Muzerolle (2007) are also added.

Figure 3. Same as Fig. 1 but for run D6. A layered accretion is taken into account with $\alpha_d = 10^{-5}$. Black dotted lines are initial conditions. Red, orange, blue and black solid lines are values at 0.1, 2.0, 6.0 and 6.22 Myr from the beginning, respectively. The inner disc completely disappears at 6.24 Myr.

Figure 4. Radial locations of gaps. Left: $r_{\text{gap}}$ versus $\alpha_d$ for $\Sigma_{\text{CR}} = 50$ g cm$^{-2}$ (runs D1, D3, D6, D9 and D15–D18). Asterisks and triangles are for cases of $L_X = 1.0$ and 3.0 in units of $10^{36}$ erg s$^{-1}$. The values of $r_{\text{gap}}$ for $\alpha_d = 0$ are shown at $\alpha_d = 10^{-6}$. Right: $r_{\text{gap}}$ versus $\Sigma_{\text{CR}}$ for $\alpha_d = 10^{-5}$ (runs D5–D14). Diamonds, asterisks and triangles are for cases of $L_X = 0.3, 1.0$ and 3.0 in units of $10^{36}$ erg s$^{-1}$, respectively.

Figure 5. Comparison between modelled discs and observed transition discs. Top: gap (or hole) size versus mass accretion rate on to the central star. Red squares represent observed transition discs, black and blue asterisks show all simulation results for discs without and with dead zones. Subsequent evolution curves are also shown. Small crosses represent subsequent evolution of $r_{\text{gap}}$ and $M_*$ with an interval of 10$^4$ yr only for runs N2, D1 and D6. Observed data are from Espaillat et al. (2008, 2010), Kim et al. (2009), Merín et al. (2010) and Andrews et al. (2011). Bottom: disc mass versus mass accretion rate on to the central star. Symbols are the same as those in the top panel. For simulations, we take the disc mass $M_{\text{out}}$ outside $r_{\text{gap}}$, not the total disc mass, $M_{\text{total}}$. Observational data from Najita, Strom & Muzerolle (2007) are also added.
The expected fraction of gapped discs for the cases without (left) and with (right) dead zones. Only discs with mass accretion on to their central stars are considered. The time-scales $t_{\text{g}}$ and $t_{\text{gap}}$ are the times when accretion on to the central star stops and a gap opens. The luminosity $L_X$ is 0.3 (diamonds), 1.0 (asterisks) and 3.0 (triangles) in units of $10^{30}$ erg s$^{-1}$. For runs with a dead zone, $\alpha_d = 10^{-5}$ (runs D5–D14).

Figure 6. Expected fraction of gapped discs for the cases without (left) and with (right) dead zones. Only discs with mass accretion on to their central stars are considered. The time-scales $t_{\text{g}}$ and $t_{\text{gap}}$ are the times when accretion on to the central star stops and a gap opens. The luminosity $L_X$ is 0.3 (diamonds), 1.0 (asterisks) and 3.0 (triangles) in units of $10^{30}$ erg s$^{-1}$. For runs with a dead zone, $\alpha_d = 10^{-5}$ (runs D5–D14).

5 SUMMARY

In this study, we have developed a gas disc model which takes into account layered accretion and photoevaporative winds induced by X-rays from the central stars. We found that a gap opens at a radius outside a poorly ionized dead zone, if the mass-loss rate due to photoevaporation exceeds the mass accretion rate in the dead zone region. Since the dead zone survives even after the gap opens, high mass accretion on to the central star remains for a long time.

We found good agreements between modelled and observed transition discs in regard to gap sizes and mass accretion rates. However, our model shows disc masses (we take masses outside gaps) in an order of magnitude smaller than those for the most massive transition discs observed. This may indicate that the dust-to-gas ratios are large in the outer discs of the transition discs while our model assumes a fixed dust opacity.

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