

The long-term evolution of photoevaporating transition discs with giant planets

Giovanni P. Rosotti,^{1,2,3★} Barbara Ercolano^{3,4} and James E. Owen^{5†}

¹*Institute of Astronomy, Madingley Rd, Cambridge CB3 0HA, UK*

²*Max-Planck-Institut für extraterrestrische Physik, Giessenbachstraße, D-85748 Garching, Germany*

³*Universitäts-Sternwarte München, Scheinerstraße 1, D-81679 München, Germany*

⁴*Excellence Cluster Universe, Boltzmannstr. 2, D-85748 Garching, Germany*

⁵*Institute of Advanced Study, Einstein Drive, Princeton, NJ 08540, USA*

Accepted 2015 September 8. Received 2015 September 8; in original form 2015 April 15

ABSTRACT

Photoevaporation and planet formation have both been proposed as mechanisms responsible for the creation of a transition disc. We have studied their combined effect through a suite of 2D simulations of protoplanetary discs undergoing X-ray photoevaporation with an embedded giant planet. In a previous work, we explored how the formation of a giant planet triggers the dispersal of the inner disc by photoevaporation at earlier times than what would have happened otherwise. This is particularly relevant for the observed transition discs with large holes and high mass accretion rates that cannot be explained by photoevaporation alone. In this work, we significantly expand the parameter space investigated by previous simulations. In addition, the updated model includes thermal sweeping, needed for studying the complete dispersal of the disc. After the removal of the inner disc, the disc is a non-accreting transition disc, an object that is rarely seen in observations. We assess the relative length of this phase, to understand if it is long lived enough to be found observationally. Depending on the parameters, especially on the X-ray luminosity of the star, we find that the fraction of time spent as a non-accretor greatly varies. We build a population synthesis model to compare with observations and find that in general thermal sweeping is not effective enough to destroy the outer disc, leaving many transition discs in a relatively long lived phase with a gas-free hole, at odds with observations. We discuss the implications for transition disc evolution. In particular, we highlight the current lack of explanation for the missing non-accreting transition discs with large holes, which is a serious issue in the planet hypothesis.

Key words: hydrodynamics – planet–disc interactions – protoplanetary discs.

1 INTRODUCTION

Disc dispersal is a crucial problem in understanding planetary formation. In particular, the time for the survival of gas in protoplanetary discs sets important constraints on the time available for the formation of gas-rich planets. This is particularly relevant for the core accretion scenario, where the time-scale of giant planet formation (Pollack et al. 1996) is predicted to be of the same order as the lifetime of discs.

Discs have a typical lifetime of a few Myrs (Haisch, Lada & Lada 2001; Mamajek 2009; Fedele et al. 2010; Ribas et al. 2014). For most of their time, the redistribution of angular momentum dominates their evolution and a simple analytical relation (e.g.

Lynden-Bell & Pringle 1974) can be used to describe the observed decline of the mass accretion rate with the age of the system (e.g. Hartmann et al. 1998) and their surface density profiles (Andrews et al. 2009). The exact nature of the source of viscosity is still matter of debate, although the magnetorotational instability is the most plausible candidate (Turner et al. 2014). Observations of star-forming regions also reveal a particular class of discs, called ‘transition discs’ (TD; Strom et al. 1989; Skrutskie et al. 1990; Espaillat et al. 2014). These discs show a dip in their spectral energy distributions (SED) at near-infrared (NIR) wavelengths, which is usually interpreted as a deficit of warm dust in their innermost regions (i.e. a few astronomical units; Calvet et al. 2005; Lada et al. 2006; Currie & Kenyon 2009; Cieza et al. 2010; Espaillat et al. 2010; Muzerolle et al. 2010). This is not expected in the viscous evolution framework, and it shows that, while viscosity is certainly a main ingredient of disc evolution, another process must also be at play. This is further reinforced by the fact that the viscous time-scale in

* E-mail: rosotti@ast.cam.ac.uk

† Hubble fellow.

Table 1. Parameters varied.

Parameter	Values
M_{disc}	[15, 30, 45, 60] M_{jup}
R_{p}	[20, 40] au
L_{X}	$[4 \times 10^{29}, 7.5 \times 10^{29}, 10^{30}, 2.5 \times 10^{30}, 4 \times 10^{30}] \text{erg s}^{-1}$

the outer regions of protoplanetary discs ($\gtrsim 100$ au) is $\gtrsim \text{Myr}$, which implies that some other process must drive disc dispersal at these radii. Observations currently show that approximately 10 per cent of all observed discs (Kenyon & Hartmann 1995; Koepferl et al. 2013) are TDs. If all discs go through the TD phase, this implies that this phase must be short lived (of order of 10^5 years), implying that disc evolution observes a ‘two-time-scale behaviour’. TD have also been imaged by sub-mm interferometers (Piétu et al. 2006; Brown et al. 2009; Andrews et al. 2011; Isella, Pérez & Carpenter 2012), confirming the presence of huge (tens of au) cavities in the mm-dust.

Photoevaporation (Hollenbach et al. 1994; Font et al. 2004; Alexander, Clarke & Pringle 2006) is an ideal candidate to explain, together with viscous evolution, the observed IR colour evolution of discs. Clarke, Gendrin & Sotomayor (2001) showed that when the mass accretion rate becomes comparable with the mass loss by photoevaporation, a gap opens at around a few astronomical units, rapidly shutting down accretion (the so-called UV switch) and producing a TD. The outer disc left is quickly eroded from the inside out by photoevaporation, which agrees with observational findings (Ercolano, Clarke & Hall 2011; Koepferl et al. 2013). While this explains *some* TDs, it does not explain *all* of them. In particular, these models predict that discs with large holes should not be accreting, which is at odds with observations. Recent observational work has remeasured accurately the accretion rates of a specific sample of TDs, selected to be highly accreting and with large holes (Manara et al. 2014), confirming the values of the accretion rates and finding that, from the point of view of accretion, these discs show the same properties of normal discs.

In recent years, other heating mechanisms have been proposed for driving a photoevaporative wind, namely the far ultraviolet (FUV) and soft X-rays (Ercolano et al. 2008; Gorti & Hollenbach 2009; Owen et al. 2010). These models predict significantly higher mass-loss rates, which can create TDs with higher accretion rates. It is still unclear however which heating mechanism is the dominant one. Direct evidence of the presence of a low-velocity, ionized disc wind has been given through observations of blueshifted forbidden emission lines such as [Ne II] (Pascucci & Sterzik 2009; Sacco et al. 2012). The shape of these lines agrees very well with the predictions of photoevaporation, although it is unfortunately unable to discriminate between the existing models. For what concerns X-ray heating, it has also been recognized that, after hole opening, when the disc is directly exposed to the X-ray radiation from the star, a ‘thermal sweeping’ instability can develop, that rapidly destroys the leftovers of the disc (Owen, Clarke & Ercolano 2012; Owen et al. 2013). This contributes to explaining why non-accreting TDs with large holes are not observed, as they are destroyed before reaching this state. The revised X-ray-driven rates provide a way of explaining the observed correlation between mass accretion rates and star masses (Ercolano et al. 2014), confirming that photoevaporation is a fundamental ingredient of disc evolution. Roughly 50 per cent of TDs can be directly explained by photoevaporation alone (Owen, Ercolano & Clarke 2011; Owen et al. 2013) in the X-ray framework,

but despite all efforts the subset of strongly accreting TD with large inner holes mentioned above remains unexplained.

This has led to the hypothesis that TDs might actually consist of two different families (Owen & Clarke 2012), created by different physical processes. Photoevaporation can explain the class of low accretors, that also happen to have a lower mm-flux, while another process would be needed to explain the other ones. Note that in this picture, discs belonging to this second class need not necessarily represent the final phases of protoplanetary disc evolution and they do not need to be necessarily short lived; it is perfectly plausible that only some of the discs are subject to this phase. Specifically, Owen & Clarke 2012 speculated that TDs with large holes and high accretion rates were rare and long lived. The theoretical difficulty in explaining them resides in having to simultaneously explain objects with large holes, almost perfectly clear in the mm-resolved images, which sustain a very high mass accretion rate, meaning that they contain large quantities of gas near the central star (although see Rosenfeld, Chiang & Andrews 2014 for an alternative explanation).

Disc gaps carved by giant planets may represent a viable alternative explanation for the class of TDs with large holes and high accretion rates. If this were true, such discs would represent indirect evidence for the presence of young planets in discs. The model envisaged by Paardekooper & Mellema (2006) and Rice et al. (2006), is that a planet, if massive enough to dynamically open a gap in the disc, produces a pressure maximum outside its orbital radius. Dust grains with Stokes numbers ~ 1 , which for the parameters of such discs correspond to particle sizes ~ 1 mm, are trapped at this radius by gas drag on a short (\ll viscous) time-scale. Recent observations support this idea; for example van der Marel et al. (2013) recently imaged a dust trap in Irs 48 with Atacama Large Millimeter/submillimeter Array (ALMA). While this scenario certainly constitutes a promising avenue, it is still faced with the problem of small grains in the disc. Small grains ($\lesssim 1 \mu\text{m}$) are strongly coupled to the gas and do not remain trapped at the pressure maximum, thus they flow through the gap and replenish the inner disc. Even if the mass contained in the small grains is small, they provide most of the opacity in the mid-infrared. For example, Zhu et al. (2012) needed to invoke grain growth in the inner disc to remove these small grains which would otherwise produce too much (unobserved) emission in the MIR. Indeed, de Juan Ovelar et al. (2013) presented models including also the effect of grain coagulation, that in some cases can successfully clear the inner disc of the small dust. Recently, another scenario was proposed by Owen (2014), who investigated the effect of radiation pressure from the accretion luminosity on the planet on the dust grains. In this case, provided there is gas accretion on to the planet, the radiation pressure acts to keep the small dust outside of the gap. The process depends sensitively on the mass of the planet and accretion rate; if this is too small, this effect is not strong enough, and the small dust will flow in the gap. This is consistent with several existing observations, which show a hole at mm wavelength, but have the SED of a primordial disc (Andrews et al. 2011).

The goal of this study is to investigate what evolutionary path may lead to the creation of TDs with large holes and high accretion rates. While considerable theoretical effort has been invested in understanding what process may be responsible for the creation of a TD, relatively little has been done to understand their time evolution (but see for example Alexander & Armitage 2009, although the holes there are much smaller, and Clarke & Owen 2013). In this work, we will just assume that a planet is a sufficient condition to produce a TD, and we explore what happens when such a system is allowed to evolve. As viscous evolution and photoevaporation

are thought to be the main drivers of disc evolution, these are the ingredients that we consider to follow the evolution in time of the disc. Specifically, we want to address the issue that very few (if any) TDs with low mass accretion rates and large holes are observed. Naively, one would expect to see the mass accretion rate of these discs going down with time as they age. If this decay happens in a power-law fashion, as it is the case for viscously evolving discs not in transition, then we should see more and more discs at low rates, contrary to the observations.

Thermal sweeping, which is included in our modelling, may explain the deficiency in the observations of weakly TDs. In this work, we shall investigate whether this mechanism is effective enough in destroying the leftovers of TDs. In a previous paper (Rosotti et al. 2013), we studied the evolution of the inner disc, finding that the presence of a planet can trigger its dispersal at times significant earlier than what would have happened otherwise. After the dispersal of the inner disc, the outer disc is directly exposed to the X-ray radiation, and can be prone to the thermal sweeping instability. As this phase is short lived, it is then unlikely to observe it, and we would expect to observe only TDs that are accreting at higher rates. One goal of this study is to quantify how effective this process may be.

This paper is structured as follows. In Section 2, we explain our numerical procedure. In Section 3, we present our results, and finally we present our conclusions in Section 4.

2 NUMERICAL MODEL

We refer the reader to Rosotti et al. (2013), where the details of our model are reported. Here, we summarize the most important points, and describe the addition of thermal sweeping.

Our model consists of a protoplanetary disc undergoing viscous evolution and X-ray photoevaporation. We follow the evolution in time of the disc using the publicly available hydrodynamical code `FARGO` (Masset 2000), which we modified to include the effect of mass removal by photoevaporation. At a time t_{creation} we assume that a planet forms in the disc with an initial mass of $M_p = 0.7M_{\text{jup}}$. Similar to many other works found in the literature that studied the long-term disc evolution or planet–disc interaction (e.g. Nelson et al. 2000; Armitage et al. 2002; Alexander & Armitage 2009; Zhu et al. 2011), we do not model the formation of the planet itself. The simulated radial extent of the disc is $[0.1r_p, 10r_p]$, where r_p is the planet orbital radius. We employ a resolution of $n_\phi = 256$ cells in the azimuthal direction and $n_r = 188$ logarithmically spaced cells in the radial direction, which gives approximately square cells. Our choice of resolution privileges the possibility of running for times comparable to the viscous one. Computational time is saved by modelling the evolution of the disc until the moment of planet insertion in 1D, since the disc is azimuthally symmetric up to that point. Our viscous code uses a flux-conserving donor-cell scheme, implicit in time. Details about the implementation can be found in Birnstiel, Dullemond & Brauer (2010). The computational grid of the 1D code covers $[0.0025 \text{ au}, 2500 \text{ au}]$, and it is comprised of 1000 grid points. The mesh is uniform in a scaled variable $X \propto R^{1/2}$.

We assume that the planet accretes material from the surrounding circumplanetary disc, as prescribed by Kley (1999). In `FARGO`, this is controlled by a free parameter, f_{acc} , that expresses the time-scale over which the planet accretes material from the surrounding in terms of the dynamical time-scale, i.e. $t_{\text{acc}} = 1/f_{\text{acc}}\Omega^{-1}$. We set $f_{\text{acc}} = 1$ in all of our models, which means that we are working in the ‘disc-limited’ regime where the planet is able to accrete all the material the disc gives to it. Such a regime is expected by the

core accretion model (Pollack et al. 1996) after reaching the critical mass, i.e. effectively after becoming a giant planet.

We assume a fixed profile for viscosity and temperature. The sound speed is a fixed function of radius, and is chosen to give a mildly flaring disc (i.e. $H/R \propto R^{1/4}$); the normalization is chosen so that at 1 au the aspect ratio $H/R = 0.0333$. We evaluate the viscosity using the well-known relation $\nu = \alpha c_s H$ (Shakura & Sunyaev 1973), where we set $\alpha = 1.5 \times 10^{-3}$. All the discs have the same initial conditions, that are taken from Owen et al. (2011), who showed that the scatter in the X-ray luminosity alone can account for the scatter in the properties of observed discs. The surface density is assumed to initially have a self-similar profile (Lynden-Bell & Pringle 1974):

$$\Sigma(R, 0) = \frac{M_d(0)}{2\pi R R_1} \exp(-R/R_1), \quad (1)$$

where $M_d(0)$ is the initial mass of the disc and R_1 a scale radius describing the exponential taper of the disc’s outer region. We set a value of $R_1 = 18 \text{ au}$ and an initial disc mass of 10 per cent the mass of the star, which is fixed to be $0.7M_*$.

The details of the photoevaporation profile assumed can be found in the appendix of Owen et al. (2012). In our simulations, we do not allow the planet to migrate, as Rosotti et al. (2013) found migration to have little impact. While we have run a number of extra simulations in the new parameter space to confirm this assumption, due to excessive computational costs our tests can unfortunately not be considered comprehensive.

2.1 Thermal sweeping

By means of 2D hydrodynamic simulations, Owen et al. (2012) showed that photoevaporating discs are subjected to thermal sweeping, an instability that can rapidly destroy the disc. In particular, thermal sweeping is triggered when the width of the X-ray heated layer becomes comparable with the vertical scaleheight of the layer. If this condition is satisfied, a slight readjustment in the vertical direction causes the X-rays to penetrate slightly more, heating a wider layer. This causes a runaway effect that was found to effectively destroy the disc on a time-scale $\lesssim 10^4$ years. Owen et al. (2013) presented a relation for the critical surface density threshold at the inner edge of the disc for the instability to set in based on the above argument. They found that thermal sweeping sets in when the surface density is lower than:

$$\begin{aligned} \Sigma_{\text{TS}} = & 0.14 \text{ g cm}^{-2} \left(\frac{L_X}{10^{30} \text{ erg s}^{-1}} \right) \left(\frac{T_{1\text{au}}}{100 \text{ K}} \right)^{-1/2} \\ & \times \left(\frac{M_*}{0.7 M_\odot} \right)^{-1/2} \left(\frac{R_{\text{hole}}}{10 \text{ au}} \right)^{-1/4} \\ & \times \exp \left[\left(\frac{R_{\text{hole}}}{10 \text{ au}} \right)^{1/2} \left(\frac{T_{1\text{au}}}{100 \text{ K}} \right)^{-1} \right] \end{aligned} \quad (2)$$

where L_X is the X-ray luminosity of the star, $T_{1\text{au}}$ is the temperature at 1 AU and R_{hole} is the size of the hole. We use equation (2) to determine the stability of the outer disc of our simulations. At each snapshot, we monitor if the inner disc is still present or if it has already dispersed. We experimented with using a criterion based on the total column of material in the midplane, ensuring that it is less than 10^{22} cm^{-2} , which is the penetration depth of $\sim 1 \text{ keV}$ X-rays, and checking that the mass in the inner disc is a factor of a few (we typically use 5) above the value it had if the disc had the floor surface density everywhere. Apart for some specific cases where manual intervention was required, we find the two criteria to yield little difference in practice. When the inner disc is no longer present, we

inspect the maximum of the azimuthally averaged surface density outside the planet orbital radius. If this is smaller than the threshold at that radius, then we assume that the disc is going to be rapidly destroyed by thermal sweeping and we stop the simulation.

2.2 Parameters varied

We vary the following parameters: disc mass (which corresponds to the age of the disc at the moment of planet creation), X-ray luminosity and planet location. Unfortunately, we cannot perform a true population synthesis model, as not all the distributions of the parameters are known. In particular, neither the formation time of planets is known, neither the distribution of planet orbital radii, as very little is known about planets at distances of tens of au. Only recently surveys (Brandt et al. 2014; Chauvin et al. 2015) are starting to put constraints on the fraction and distribution of planets in wide orbits. However, it is difficult to relate the properties of these planets around main-sequence stars to the putative ones present in TDs, as significant migration might have happened (Clarke & Owen 2013). Rather, the purpose of this investigation is to get a handle on the possible outcomes in different regions of the parameter space. It is also not clear whether planets can form at all at such large radii. Core accretion models (e.g. Ida & Lin 2004) predict that planets form closer to the star (~ 5 au) where the relevant time-scales are short enough that significant growth happens over the disc lifetime. Gravitational instability could be possibly another candidate for the formation of those planets (e.g. Rafikov 2005; Stamatellos & Whitworth 2008; Clarke 2009), although no statistical comparison with the theories has been conducted so far to the best of our knowledge. Nevertheless, there is a growing consensus about the presence of planets in TDs as detailed in the introduction. If observations will prove conclusively that planets really exist at large radii, a revision of the theories of planet formation will be needed to account for this observational evidence. For the time being, we assume the *working hypothesis* that a planet at large radii is responsible for the formation of the cavity in the dust.

We explore values of 4×10^{29} , 7.5×10^{29} , 10^{30} , 2.5×10^{30} , 4×10^{30} erg s⁻¹ for the X-ray luminosity. Such values are chosen in order to sample appropriately the Taurus X-ray luminosity function (Güdel et al. 2007): the minimum and maximum value chosen are roughly at 16 and 84 percentile, i.e. roughly 1σ (if the distribution were Gaussian) from the median, which is 10^{30} erg s⁻¹. Therefore these values bracket most of the possible outcomes, depending on the level of X-ray luminosity. We experiment with planet locations of 20 and 40 au. For the disc mass at planet creation, we used values of 15, 30, 45, 60 M_{Jup} . Table 1 summarizes the parameter used.

3 RESULTS

3.1 Classification scheme for comparison with observations

As already mentioned, we assume that the presence of a planet is a sufficient condition to produce a TD and we do not include any modelling of the dust component in our simulations. Therefore, we cannot directly relate the outcomes of our simulations to continuum images or SEDs. Rather, the observational proxies that we would like to compare with are the following:

- (i) the presence of significant gas in the cavity of TDs;
- (ii) the presence of a detectable mass accretion rate.

We stress that, although we consider the presence of a planet as a *sufficient* condition, we do not consider it as *necessary* for the cre-

ation of a TD. As remarked in the introduction, roughly half of the known TDs can be explained by photoevaporation alone, without the need to invoke the presence of a planet. However, here we are concerned with the discs that *cannot* be explained by photoevaporation (those with huge cavities and high accretion rates), and that is why we explore the consequences of the presence of a planet.

While some unsuccessful attempt to detect gas in the cavity was done with the previous generation of interferometers (Dutrey et al. 2008; Lyo et al. 2011), ALMA has now the sensitivity and the spatial resolution necessary to accomplish this goal (Rosenfeld et al. 2012; Casassus et al. 2013; Bruderer et al. 2014; Zhang et al. 2014). As measurements of this kind are becoming routinely available, it is of primary importance for models of TDs to provide predictions for the gas content. This quantity is much ‘cleaner’ from the hydrodynamical side, in contrast to the dust that can be observed in the continuum. The dust has a much more complicated dynamics, as it interacts differently with the gas depending on its size. In addition, dust grains have a distributions of sizes, and processes of coagulation and fragmentation happening in the disc introduce other uncertainties and make it difficult to predict the dust distribution. However, observations of the gas are also not straightforward, as H_2 , the most abundant molecule, is essentially invisible. Nevertheless, observations of other molecules (particularly CO) and modelling of their chemistry has now advanced to a point where it is possible to compute the expected emission in the gas lines from a given gas surface density.

It is straightforward to know in our models if CO emission would be observed from a cavity of a TD, as the region sampled by ALMA is in our computational grid. Bruderer (2013) showed that ALMA has the sensitivity to detect through observations of the CO 3–2 transition in Band 7 up to a few Earth masses of gas in the cavity. Measuring how much mass is present involves more complicated modelling using different isotopologues of the molecule. For the sake of simplicity, we restrict ourselves here to explore only if there is going to be a detection, rather than focusing on the strength of the expected emission. Note that we are more concerned with the detection of the rotational transitions of the CO molecule rather than the observations of the fundamental rovibrational transition at $4.7 \mu\text{m}$. The reason is that this transition does not trace the bulk of the gas mass inside the cavity, but rather the warm gas (roughly between 100 and 1000 K) up to distances of several astronomical units.

Unfortunately, it is not straightforward to derive mass accretion rates from our simulations, as the disc inner boundary is not resolved in our simulations. We assume that for the first part of the evolution the inner disc just readjusts its structure in order to supply the star with the same mass accretion rate that we have at the inner boundary of our grid. This assumption is justified by the fact that the viscous time in the inner region that we do not simulate is smaller than the one in the region that we simulate. When photoevaporation mass-loss rates are coupled with viscous evolution (Clarke et al. 2001; Ruden 2004; Owen et al. 2010), it is found that when the mass accretion rate goes below the photoevaporation rate, a gap opens in the disc, at a radius around 1 au (for a solar type star). We assume that the clearing of this inner region (that is, disc 1 in Fig. 1) is independent of what happens in the outer region of the disc. We thus use 1D models of the whole disc to complement our 2D simulations. We monitor the mass accretion rate at which a gap opens in the disc in our 1D models, and we assume that the same happens in the disc we do not resolve when the mass accretion rate at the inner boundary of the grid reaches this threshold. Subsequently, we take the evolution in time of the mass accretion rate of the 1D

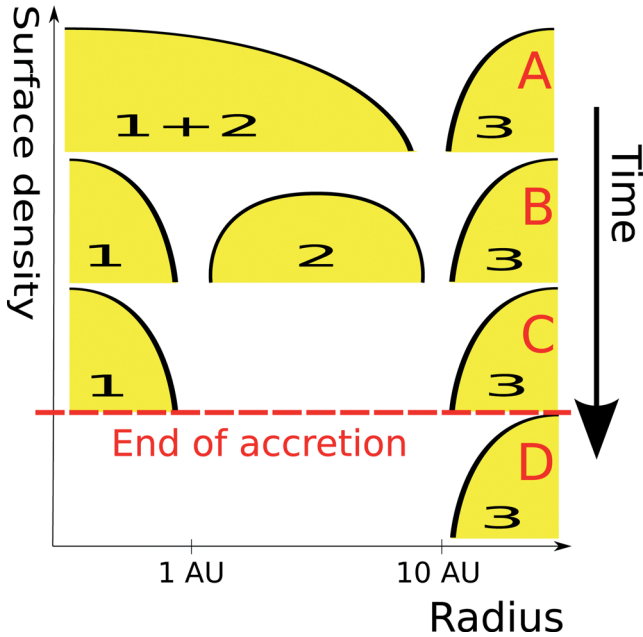


Figure 1. Classification scheme used to separate the lifetime of a TD in different phases. Phase A and phase B correspond to accreting TDs with gas in the cavity, phase C is an accreting TD without gas in the cavity, and phase D is a non-accreting TD without gas in the cavity.

model as the mass accretion rate on to the star. Note that this is not the same as what was done by Rosotti et al. (2013), who matched the 1D and 2D models monitoring the radius of the inner hole in the 2D grid. However, this assumes that the disc resolved in the 2D simulations always clears from inside out. We decided to switch to this new criterion because in some of our simulations, which cover a larger region of the parameter space than what was done by Rosotti et al. (2013), the central disc clears from the outside in, and therefore the criterion used by Rosotti et al. (2013) would trigger the opening of a photoevaporation gap at slightly later times.

The qualitative behaviour that we have described can be summarized in four phases, which are shown in Fig. 1. Initially, only the dynamical gap created by the planet is present (phase A), and the disc is otherwise continuous. As the disc ages and mass accretes on to the star, the mass accretion rate will decrease up to the point where photoevaporation is able to open a gap in the innermost region of the disc. We note that, as Rosotti et al. (2013) reported, this will happen at earlier times for discs with a planet, as this partially cuts out the inner from the outer disc, where most of the mass is. Thus, we assume that the disc will have two gaps (phase B), dividing the disc in three regions. Disc 2 is cleared on a relatively short phase (typically less than 10^5 years) by photoevaporation, leaving only discs 1 and 3 (phase C). This disc will not show emission from the cavity in the CO rotational lines, which trace the bulk of the cold mass, but will still have a measurable accretion on to the star due to the presence of disc A. Finally, disc 1 cannot last longer than 10^5 years (its viscous time-scale), and in the last phase (phase D) only the outer disc will be present. Observationally, this is a non-accreting TD without gas in the cavity. Non-accreting TDs are rarely seen in observations, and the main goal of this paper is exactly to quantify how long lived this phase may be before the set in of thermal sweeping.

As in every classification scheme, we do not expect it to hold necessarily for all discs; rather, we are interested that it catches the majority of the behaviour. We inspected visually the results of our

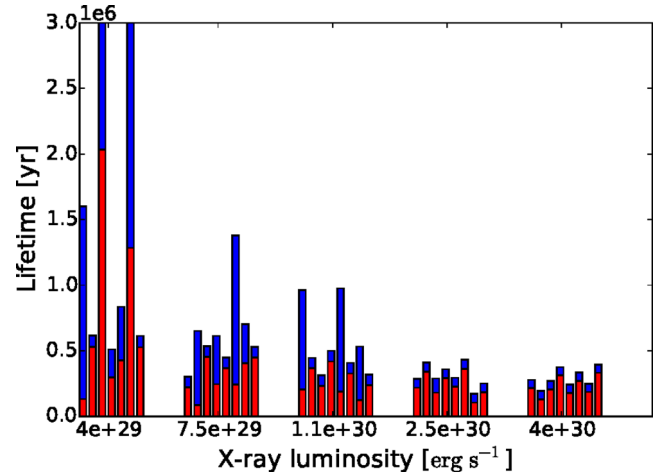


Figure 2. Total lifetime of each simulation, decomposed in accreting (red) and non-accreting phase (blue).

simulations and confirm that this is the case. Differences are found in the way disc 2 clears, which happens sometimes from inside in and sometimes from inside out. Since, as said before, the clearing of this disc is quite fast, this different behaviour is unlikely to have an observational impact.

In two simulations (the parameters are $L_X = 10^{30} \text{ erg s}^{-1}$, $R_p = 20 \text{ au}$, $M_{\text{disc}} = 45M_{\text{jup}}$ and $L_X = 4 \times 10^{29} \text{ erg s}^{-1}$, $R_p = 20 \text{ au}$, $M_{\text{disc}} = 60M_{\text{jup}}$) out of the 40 we have run, disc 2 is eroded briefly from inside out, but then the erosion by photoevaporation reaches an equilibrium with the material filtering through the gap. In one case, disc 2 is very long lived (almost 1 Myr), creating a TD without accretion (as disc 1 cannot be so long lived, being cut out from the mass resupply) but with cold gas in the cavity (although the mass is very small: just a few Earth masses, at the limit of detectability with ALMA). We remove this disc from what follows, as it might falsify the results.

3.2 Lifetimes

The main result that we extract from each simulation consists in the length of each phase that was introduced in Section 3.1.

In Fig. 2 we show a bar chart that decompose the life of each disc in the accreting and non-accreting phase. The discs are grouped together based on their X-ray luminosity. The figure clearly shows the importance of X-ray luminosity on the total lifetime of the discs. The lifetime of the disc can range from a few 10^5 years to several Myrs, and there is a significant trend for higher X-ray luminosities to yield shorter lifetimes. The average values are respectively roughly 1.5 Myr, $6.5 \times 10^5 \text{ yr}$, $5.5 \times 10^5 \text{ yr}$, $3 \times 10^5 \text{ yr}$ and $2 \times 10^5 \text{ yr}$, from the lowest to the highest X-ray luminosity. This result is expected, since the photoevaporation rates are higher for higher X-ray luminosities.

When looking at the relative length of the accreting and non-accreting phases in Fig. 2, it can be seen that some discs almost never go through the non-accreting phase. As soon as their outer disc is directly exposed to the X-ray radiation from the star, it is prone to the thermal sweeping instability. This depends very sensitively from the X-ray luminosity; we note that indeed all the discs we run at high X-ray luminosity go through this behaviour, as well as some of the ones at the median luminosity. In contrast, all the discs at low X-ray luminosity experienced a significant non-accreting phase before being dispersed. This has important consequences on the expected

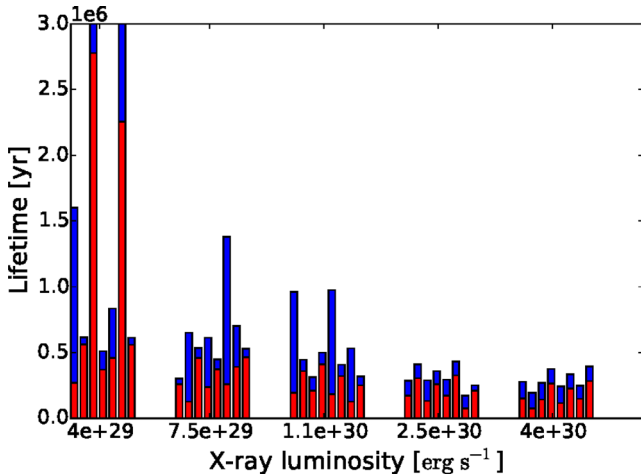


Figure 3. Total lifetime of each simulation, decomposed in phase with (red) and without (blue) cold gas in the cavity.

population of TDs found by observations. We can take, inside each X-ray luminosity bin, the fraction of discs that would be expected to be accreting. This is done by computing

$$f_{\text{acc}} = \frac{\sum t_{\text{acc}}}{\sum t_{\text{total}}}, \quad (3)$$

that is, the mean duration of accretion divided by the mean lifetime. This calculation assumes that, save for the X-ray luminosity, the other two parameters have a uniform distribution. Although this is probably not true, their true distribution is not known; the purpose of the calculation is to get a handle on the result, and not to get an accurate statistical prediction. The fraction of accretors is found to be roughly 55 per cent for the first three X-ray luminosity values, and nearly 80 per cent for the last two cases. It is interesting that in the high X-ray luminosity case the fraction of accretors is quite high. Since only a handful of TDs with large holes have been observed up to now (roughly 20 in the compilations of Owen & Clarke 2012 and Manara et al. 2014), such a high fraction would explain why only few non-accreting discs (for example, two in the compilation of Manara et al. 2014) have been observed. However, already in the median X-ray luminosity case the fraction goes down to one half. Clearly, a better statistical treatment is needed to extract a predicted value, which we will discuss in the next section.

Fig. 3 shows again the lifetime of each simulations, but this time decomposed in the two phases with and without cold gas in the cavity. There is practically no difference with the accretion for the median X-ray luminosity case; the fraction of discs expected to have cold gas in this case is 56 per cent, which should be compared with the 57 per cent of discs expected to be accreting. As explained in Section 3.1, the cold gas in the cavity and the presence of accretion have almost the same lifetime; some difference is due only to phase C, where the disc is still accreting but disc 2 has been already dispersed. However, phase C is so short that is practically unobservable. More interesting are the two cases with high X-ray luminosity; here the fraction of discs with cold gas in the cavity is respectively 64 and 58 per cent, and thus the difference with the fraction of time spent accreting is more significant. This is due to the fact that all the other phases are faster with a high X-ray luminosity, so that the relative importance of phase C increases and the difference is larger. Although still unlikely given the number of observed TDs, this predicts that one could in principle observe a disc that is still accreting, but no longer has cold gas in the cavity. Future

observations with ALMA may be able to tell if such discs exist. Finally, also the lowest X-ray luminosity case is interesting. Here, the fraction of discs with cold gas rises to almost 70 per cent, which is puzzling to explain in the framework we presented up to now. The reason is that in this case there is a long phase where the disc is accreting (that is, it is still in phase A or B), but the accretion rate is under the current observational limits (we used $10^{-11} M_{\odot} \text{ yr}^{-1}$ as threshold), whereas ALMA will have the capability of detecting cold gas in the cavity down to very low masses. We thus classify such a disc as a non-accretor; hence, the lower time spent as an accretor compared to the time spent with gas in the cavity. As in the previous case, future observations will be able to tell if such discs exist.

3.3 Observational prediction: the fraction of accreting discs

We can use the results of our runs to estimate what would be the fraction of accreting TDs found in observations. This involves creating a population synthesis model. We stress again that, for the purposes of this exercise, the term ‘TD’ has a narrower meaning than what is normally meant. Here, it designates a disc containing a giant planet, and the purpose of this exercise is investigating whether we can explain the lack of non-accreting TDs with large holes. We generate a population of N_{disc} discs. We assign a random X-ray luminosity to these discs, distributed according to the X-ray luminosity function of Güdel et al. (2007). We assume that a fraction $f_{\text{TD}} = 0.1$ of these discs become at a certain point of their life TDs via the formation of a giant planet. We draw randomly the initial location of this planet between 20 and 40 au, and we also assign a random formation time t_{cr} , uniformly distributed between $t_{\text{min}} = 10^5$ and 3×10^6 yr. Note that we assume that there is no correlation between the formation time-scale and the X-ray luminosity, i.e. that the planet formation process is independent from the disc dispersal process. Since the assumed time-scale of planet formation is of the same order as the disc lifetime (see Introduction), some of our discs will be dispersed before they have a chance to form a planet. This highlights that, although the quantity that we are seeking to compute involves *only transitional discs*, what the *total* population of discs does is still relevant, as it selects which discs will form planets. In particular, this means that discs with higher X-ray luminosity are less likely to become TDs via the formation of a planet. Being short lived, they are more likely to have been already dispersed when they go in transition.

We further use the results of our simulations to compute the time-scales over which a newly formed TD will accrete and after which it will be dispersed by thermal sweeping. At any given time, we are thus able to compute how many discs have not been dispersed yet, how many are in transition, and how many of them are accreting. The key quantity that we want to compute from our models is the fraction of TDs that we would expect to see accreting. The observations gather together discs that come from different star formation regions, rather than looking at a specific moment in time of a single region. In addition, it is commonly assumed that stars in the same region have an age spread between them (although the exact amount of this spread is debated). For this reason, we need to time average the fraction that we compute, under the assumption that the observations are sampling uniformly enough the timespan of disc lifetimes, and that there is a constant star formation rate in the neighbourhood of the Earth. Finally, we weight the fraction with the total number of discs that have not been dispersed yet, as observations are more likely to detect discs where there is more of them. In other words, we compute the time average of the number

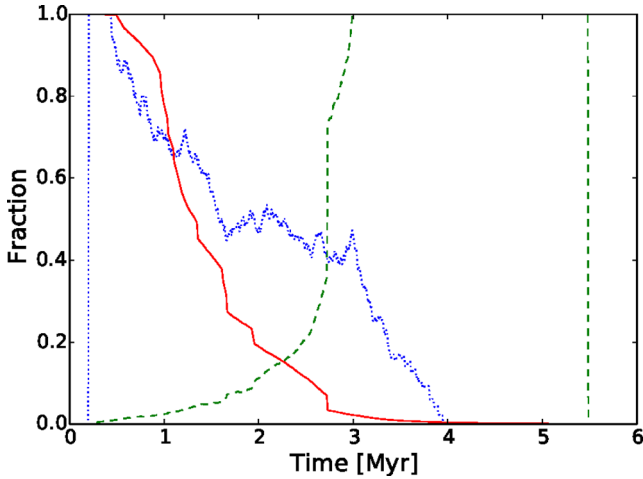


Figure 4. The three quantities that appear in equation 4, namely $S_{\text{disc}}(t)$ (red solid line), $f_{\text{TD}}(t)$ (green dashed line) and $f_{\text{TD,acc}}(t)$ (blue dotted line).

of TDs that are still accreting, rather than the time average of the fraction. Mathematically, we compute the quantity

$$\frac{\int_0^{t_{\text{max}}} S_{\text{disc}}(t) f_{\text{TD}}(t) f_{\text{TD,acc}}(t) dt}{\int_0^{t_{\text{max}}} S_{\text{disc}}(t) f_{\text{TD}}(t) dt} \quad (4)$$

where $S_{\text{disc}}(t)$ is the survival function of the discs at time t (that is, the fraction that is still alive), $f_{\text{TD}}(t)$ is the fraction of TDs across the whole disc population, and $f_{\text{TD,acc}}(t)$ is the fraction of TDs that are accreting.

Fig. 4 shows the three quantities that appear in equation (4) as a function of time, namely $S_{\text{disc}}(t)$, $f_{\text{TD}}(t)$ and $f_{\text{TD,acc}}(t)$. The number of discs (red solid line) decreases roughly exponentially, as expected for a disc dispersal model. Conversely, the number of TDs (green dashed line) increases with time: as planets form, some of the discs are converted into TDs. Some of the TDs formed can be very long lived, as phase D can be very long. The sharp cut-off around 6 Myr is a numerical consequence of the fact that we run the 2D hydro simulations only for 3 Myr at most. We note that this makes our estimate of the fraction of TDs accreting an upper limit, and the predicted fraction should be even lower. Finally, the plot shows also the fraction of accreting TDs (blue dotted line). This is not necessarily a monotonic function: as time passes, the number of already existing TDs that are still accreting can only decrease, but new TDs are formed, and all of them will initially be accreting. Overall though, the net effect is that the fraction is decreasing, that is, TDs stop accreting at a faster rate than they are created.

Fig. 5 shows the numerator and the denominator of equation (4) as a function of time (note that the absolute normalizations of these functions are arbitrary). We note that the TD number is initially zero, as no disc has formed a planet yet. After t_{min} the discs start to be in transition, and for a while all of them are accreting. This can be seen by looking at the number of TDs that are accreting, which initially overlaps with the other curve. The number of TDs keep increasing until 3×10^6 yr, when planets are not formed any more. Note also that after $\sim 5 \times 10^5$ yr some TDs stop accreting, and the number of accreting TDs is lower than the overall number of TDs. After $\sim 4 \times 10^6$ yr, no more TDs are accreting, and after $\sim 6 \times 10^6$ yr all the transition discs have been dispersed. These absolute time-scales are obviously dependent on the assumed time-scale of planet formation.

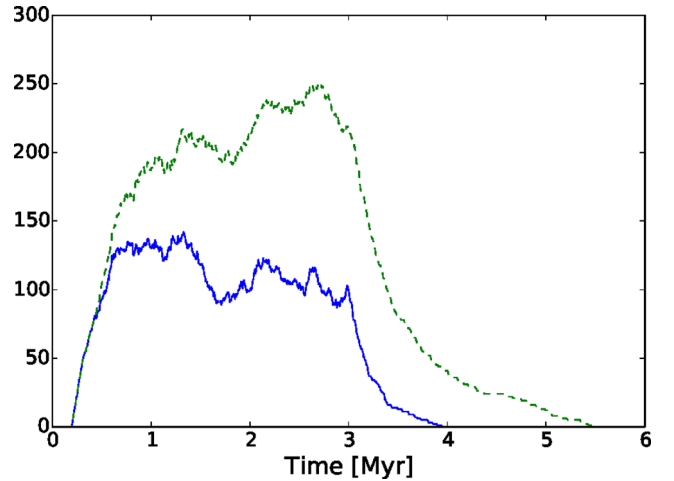


Figure 5. The numerator (blue solid line) and the denominator (green dashed line) of equation (4) as a function of time, that is, respectively the fraction of accreting TDs and the total number of TDs (note that the normalization is arbitrary).

The final result of this section is that the time averaged value of the fraction of accretors is ~ 0.48 . Therefore, in our model we do not expect the majority of TDs to be seen accreting.

4 DISCUSSION AND CONCLUSIONS

We have run 2D hydrodynamical simulations of photoevaporating protoplanetary discs with a giant planet embedded. We have followed the evolution in time of such a system, which we called ‘TD’, until the final dispersal of the outer disc by thermal sweeping. Our results show that the effectiveness of thermal sweeping in destroying the outer disc depends sensitively on the X-ray luminosity of the central star. When the X-ray luminosity is at the upper end of the X-ray luminosity function, the outer disc can be destroyed very rapidly. Otherwise, the outer disc is very long lived (even several Myrs).

To quantify better the implications of these results for observations, we have constructed a population synthesis model based on our simulations. We predict that only ~ 48 percent of TDs should be observed accreting at rates greater than $10^{-11} M_{\odot}$ yr.

This is at odds with observations, where the great majority of TDs with large holes are observed accreting above the mentioned rate. We discuss in the following points some of the assumptions used in this paper and possible solutions to reconcile the observations with the predictions of our model.

(i) Discs with large holes, but no accretion are indeed present, but they have not been observed yet. This is similar to the idea of ‘relic discs’ in the discussion of Owen et al. (2011). If such discs showed no signatures of accretion and no infrared excess above the stellar photosphere, they would be unlikely to be observed, and their host stars would be classified as discless. However, even with holes of several tens of au such as those we consider here the disc would have still significant emission at the *Spitzer* wavelengths of 24 and 70 μm . We checked that this is the case by inspecting the models in the Robitaille et al. (2006) grid. Therefore we exclude this hypothesis. In addition, we note that recent ALMA observations (Hardy et al. 2015) have placed strong upper limits on the masses of some relic discs, showing that they are severely depleted in gas mass. On the other hand, Espaillat et al. (2015) just added an object to the census

of TDs with large holes and no (or very low) accretion rate; the hole has been confirmed through sub-mm imaging. While this shows that some of these discs have gone unnoticed, it is unlikely that a population of lurking TDs with large holes and very low accretion rates, as numerous as the current population of TDs with large holes, is present.

(ii) It may be that ‘TDs’ created by carving of the disc by giant planets do not represent the last phase of protoplanetary disc evolution. Indeed, Andrews et al. (2011) find that the TDs of their sample are more massive than classical T Tauri discs, possibly pointing out that they are younger, leading Owen & Clarke (2012) to argue that they may be rare and long lived and not associated with disc dispersal. Note that our calculations just *assume* that a disc with a planet is a TD, but this might not be the case. It may be that the inner hole phase caused by the planet is only temporary, and the disc may later then become a normal protoplanetary disc again before being eventually dispersed. This scenario fits nicely with the recently proposed idea by Owen (2014) that TDs are created by the accretion on to the planet will only appear as ‘transition’ discs through a dip in the SED when the accretion rates are high $\sim 10^{-8} M_{\odot} \text{ yr}^{-1}$. At lower accretion rates, Owen (2014) argued that the planet was unable to trap small dust particles outside the planet’s orbit and refilled the inner cavity. In this case one would expect to see a primordial SED, but still a large cavity in the mm as the mm-size particles are still trapped by the pressure maxima (Pinilla et al. 2012). However, although such a disc will show a conventional full SED once the mass accretion rate has decreased enough, in the framework presented in this work eventually photoevaporation will remove the *gas* inner disc (and therefore the dust with it), and the disc will be in what we called phase D. It would then be again a non-accreting TD with a large hole. For the detectability of such a source, see the previous point. So, while this process can explain why we do not see TDs with huge cavities accreting at low rates, it does not explain why we do not see TDs with huge cavities that are not accreting.

(iii) The planet induced photoevaporation (PIPE) effect that we described in Rosotti et al. (2013) and in this paper for the case of X-ray photoevaporating discs (see Alexander & Armitage 2009 that first described it in the context of EUV photoevaporation) is largely due to the fact that the planet is accreting at high rates. This is necessary for example in the scenario of Owen (2014) to push the small grains out of the gap and create a TD. More fundamentally, in the core accretion framework giant planets *must* accrete gas at some stage in order to become giants. It might be speculated however that the accretion phase switches down after a while. Note that in standard core accretion this is not the case (Pollack et al. 1996), as it is the initial phase that is planet limited, while after the collapse accretion is thought to be disc limited. On the other hand, if accretion went on at disc-limited rates for a time comparable to the disc lifetime in a massive enough disc, all giant planets would end up having masses of several M_J (Szulágyi et al. 2014). Instead, studies of exoplanets have shown that such planets are extremely rare (e.g. Mayor et al. 2011). In hydrodynamical simulations like the ones that we employed here that lack the resolution to accurately model the flow inside the Hill sphere, this accretion rate is controlled by the parameter that sets the efficiency of accretion f_{acc} mentioned in Section 2. If this parameter depends on time (or on the planet mass), so that it is reduced during the lifetime of the disc, the planet does not disturb so significantly the mass flow from the outer to the inner disc and PIPE is less effective in dispersing the inner disc. For example, in the extreme case where there is no accretion on to the planet, the presence of a planet does not make any difference to the evolution

of a disc *on viscous time-scales* (e.g. Zhu et al. 2011; Dürmann & Kley 2015), and therefore huge cavities are never opened in the gas. The dispersal of the inner disc would then happen when the disc is less massive, and thermal sweeping will take less time to disperse it. Note that this effect can coexist with the one described in the previous point, namely with a TD going back to a primordial phase, possibly offering a solution to the problem presented in this paper. From the observational side, it would be extremely useful to have measurements of accretion on to the putative planets present in TDs that could inform the theory. Such searches are under way (Close et al. 2014; Zhou et al. 2014) and it is likely that more data will arrive in the next future.

(iv) Photoevaporation rates lower than the ones that we employed here would make the dispersal of the inner disc happen at later times. At this point, the mass of the disc would be lower, allowing thermal sweeping to set in on a quicker time-scale. This could happen if, for example, the dominant heating mechanism is EUV photoevaporation rather than X-rays. In addition, we note that the presence of huge cavities in the dust and of a gap created by a planet could affect the photoevaporation rate. In this paper, we assumed rates computed for a full disc up to the moment of the inner disc dispersal. In particular, given that the cavities are depleted of dust (even in the small grains), the temperature of the disc will be severely affected. This will change the density vertical structure of the disc; the density at the launching point of the photoevaporative wind, which sets the mass-loss rate, might be affected. Although X-ray photoevaporation has been shown to be quite resistant to changes in the underlying disc structure (Owen et al. 2012), it remains to be seen whether this applies also to such extreme differences. In particular, even if this effect is unlikely to change the total mass-loss rate, it will probably change the flow topology (Owen et al. 2012), which might have implications for the inner disc. More work is clearly needed in this area.

(v) Another unknown physical parameter that regulates the dispersal process is the value of α which sets the magnitude of the viscosity. Note that within a photoevaporation model, this value is usually constrained by the requirement to reproduce the observed disc lifetimes. This is the reason why we did not let it vary in our simulations. Nevertheless, we can ask ourselves what would be the effect on the relative lifetimes of the accreting and non-accreting phase. We can assume that the disc inside the orbit of the planet evolves according to a self-similar solution (Lynden-Bell & Pringle 1974; Hartmann et al. 1998) where $\nu \propto r^{\gamma}$. For the purpose of this paper, we assumed $\gamma = 1$, but the value is not constrained and suitable values are in the range 0.5–1.5 (e.g. Williams & Cieza 2011). If \dot{M}_w is the photoevaporation mass-loss rate from the inner disc, this disc is dispersed when the mass accretion rate on to the star becomes equal to \dot{M}_w . The duration of the accreting phase is thus

$$\begin{aligned} T_{\text{clear}} &= t_v \left(\frac{\dot{M}_w}{\dot{M}_0} \right)^{-(2-\gamma)/(5/2-\gamma)} \\ &= t_v^{1/(5-2\gamma)} \left(\frac{\dot{M}_w}{\dot{M}_0} \right)^{-(2-\gamma)/(5/2-\gamma)} \end{aligned} \quad (5)$$

where \dot{M}_0 is the initial mass accretion rate, M_0 the initial disc mass, and we have assumed $T_{\text{clear}} \gg t_v$. This is a standard prediction of photoevaporation models (e.g. Clarke et al. 2001). Thus, T_{clear} scales with $\alpha^{-1/(5-2\gamma)}$, that is, for physically motivated values of $\gamma < 2.5$, more viscous discs are dispersed earlier, because the mass accretion rate evolves faster. The duration of the non-accreting phase is set by the time it takes to photoevaporation to remove enough

mass from the disc for thermal sweeping to kick in. In a self-similar solution, at any given time the mass of the disc $M_d \sim \dot{M}t$. Therefore the mass of the disc when the inner disc is cleared is roughly $M_d(T_{\text{clear}}) \sim \dot{M}_w T_{\text{clear}}$. If the mass needed for thermal sweeping M_{TS} is much smaller than this, the length of the non-accreting phase is $T_{\text{NA}} \sim M_d(T_{\text{clear}})/\dot{M}_w$ (in reality $T_{\text{NA}} \propto \Delta M = M_d(T_{\text{clear}}) - M_{\text{TS}}$). Substituting the expression derived for T_{clear} we conclude that also $T_{\text{NA}} \propto \alpha^{-1/(5-2\gamma)}$. To zeroth order thus the relative lengths of the accreting and non-accreting phase do not depend on the value of the viscosity, so that it is difficult that a significant dependence on the value of viscosity is present. It is possible though that a dependence is present at higher orders or due to some of the assumptions that we made not being correct, which makes it warranting further study. In particular, while in the accreting phase we have considered only the viscous evolution as responsible for mass removal, actually also photoevaporation will contribute. During the accreting phase, photoevaporation removes a mass of $M_{\text{lost}} \sim \dot{M}_w T_{\text{clear}}$, which lowers the mass at the start of the non-accreting phase with respect to our previous estimate. This effect in particular is stronger for longer viscous time-scales, or for higher mass-loss rates (despite a shorter accreting phase). This partially explains why the discs with a higher X-ray luminosity have a very short non-accreting phase, and points to the fact that the problem we described can be partially mitigated by invoking a lower value of the viscosity. In addition, if $M_d(T_{\text{clear}}) \sim M_{\text{TS}}$, the non-accreting phase can be significantly shorter than we predicted. Again, this favours higher X-ray luminosities that have higher M_{TS} , and is another reason why discs with high X-ray luminosities do not suffer from the problem of long non-accreting phases.

(vi) Up to now we assumed that the planet does not migrate. Migration could be attractive from a theoretical point of view, as it could decrease the sizes of the cavities in TDs, while at the same time the disc is decreasing in mass and mass accretion rate on to the star. If migration is fast enough, it can have reduced significantly the cavity size by the time PIPE dissipates the inner disc (that is, phase B starts) and shuts down accretion. This scenario of migrating giant planets in TDs has been considered by Clarke & Owen (2013). However, their conclusions were that planet migration is actually too fast compared to the decrease in the disc mass, so that, unless unreasonably high planet masses are considered, the planets would rapidly reduce their separation from the star. This would create TDs with small cavities, but which are still massive and therefore bright in the sub-mm, which are not observed (Owen & Clarke 2012). We note that recent results (Duffell et al. 2014; Dürmann & Kley 2015) on type II (giant) planet migration imply that planet migration could be even faster than what assumed in Clarke & Owen (2013), exacerbating even more this problem. To understand if migration is important for the models presented in this paper, we can do a check a posteriori by comparing the time-scale for migration with the lifetime of the disc. For example the time-scale for planet migration quoted by Clarke & Owen (2013), assuming a mass accretion rate of $10^{-8} M_{\odot}$ yr, is a few Myr. This is indeed long compared to the lifetime of our discs (see Fig. 2). Note however that their disc masses are a factor of a few higher, which would make the disc lifetime correspondingly longer. To remain within our models, the viscous time-scale at 20 au is $\sim 8 \times 10^5$ yr, which is marginally longer than the lifetime of most of our discs. However, note also that the planet accretes a significant amount of material during the lifetime of the simulation, so that its final mass can become as big as several M_j . In this case, type II migration is in the so-called planet-dominated regime (Syer & Clarke 1995), and will be therefore slower than the pure viscous time-scale of a factor

$\sim M_p/\pi\Sigma r^2$. For example, at 20 au, for the *initial* planet mass of $0.7M_j$, having type II migration on a viscous time-scale requires a surface density of $\sim 5\text{--}6 \text{ g cm}^{-2}$. This is significantly more than the surface density at which thermal sweeping sets in (see equation 2), meaning that there will be a long phase where migration is planet dominated. Thus, photoevaporation can efficiently disperse the disc before the planet has migrated significantly in most cases. However, for the longest lived discs in our set migration might be an important effect.

Perhaps the most important lesson to be learnt is that we should focus not only on the mechanism to create the massive TDs seen in observations, but also on their long-term evolution. Very few models have attempted to tackle this problem so far. The experiment conducted in this paper consisted in coupling the presence of a planet to models of photoevaporation, which we know is happening in discs (as mentioned in the introduction). Bearing in mind the caveats and open points discussed above, the combination of the two is not capable of explaining the lack of non-accreting TDs with large holes. We stress that this is currently an open problem, that no model has addressed so far, and is a *serious* issue in the planetary hypothesis for TDs. We are left to speculate that we are missing one of the ingredients operating in TDs. Whatever the mechanism responsible for the dispersal of TDs is, it must act on a very quick time-scale to explain the apparent lack of non-accreting sources. Moreover, taking our calculations as a *reductio ad absurdum* would lead us to conclude that one of the hypothesis that we have assumed leads to a contradiction. As there is evidence that discs are subject to photoevaporation, this poses strong constraints to scenarios in which a massive planetary companion is responsible for the creation of a TD, or, at least, in which it is the *only* culprit. Similar conclusions were reached by Clarke & Owen (2013). We also remark that, from the observational side, it would be useful to have more constraints on the ‘descendants’ of these TDs, as for example ALMA is doing for evolved discs in general (Hardy et al. 2015), and on their ‘precursors’. It is likely that in this process we will gain also more insight on the processes leading to the formation of TDs and shed more light on their nature.

Future work could investigate the effect of the inclusion of other energy sources, such as the FUV that is important at large separations from the star, in the gas heating. This might enhance the efficiency of thermal sweeping and thus produce a higher fraction of accretors.

ACKNOWLEDGEMENTS

We thank the referee, Richard Alexander, for the constructive criticism that improved this paper. GR acknowledges the support of the International Max Planck Research School (IMPRS). We acknowledge the support by the DFG Cluster of Excellence ‘Origin and Structure of the Universe’. JEO acknowledges support by NASA through Hubble Fellowship grant HST-HF2-51346.001-A awarded by the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc, for NASA, under contract NAS 5-26555. The simulations have been carried out on the computing facilities of the Computational Center for Particle and Astrophysics (C2PAP). This work has been supported by the DISCSIM project, grant agreement 341137 funded by the European Research Council under ERC-2013-ADG. We thank Marco Tazzari for discussions about the statistics of TDs. We thank Veronica Roccatagliata, Cathie Clarke and the rest of the DISCSIM group, and the ESO star formation coffee for interesting discussions.

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