Evolutionary constraints on the planetary hypothesis for transition discs

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ABSTRACT

We assume a scenario in which transition discs (i.e. discs around young stars that have signatures of cool dust but lack significant near-infrared emission from warm dust) are associated with the presence of planets (or brown dwarfs). These are assumed to filter the dust content of any gas flow within the planetary orbit and produce an inner ‘opacity hole’. In order to match the properties of transition discs with the largest (∼50 au scale) holes, we place such ‘planets’ at large radii in massive discs and then follow the evolution of the tidally coupled disc–planet system, comparing the system’s evolution in the plane of mm flux against hole radius with the properties of observed transition discs. We find that, on account of the high disc masses in these systems, all but the most massive ‘planets’ (100 Jupiter masses) are conveyed to small radii by Type II migration without significant fading at millimetre wavelengths. Such behaviour would contradict the observed lack of mm bright transition discs with small (<10 au) holes. On the other hand, imaging surveys clearly rule out the presence of such massive companions in transition discs. We conclude that this is a serious problem for models that seek to explain transition discs in terms of planetary companions unless some mechanism can be found to halt inward migration and/or suppress mm flux production. We suggest that the dynamical effects of substantial accretion on to the planet/through the gap may offer the best prospect for halting such migration and that further long-term simulations are required to clarify this issue.

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

1 INTRODUCTION

In recent years, space-based infrared observations have permitted the identification of a large sample of transition discs (e.g. Najita, Strom & Muzerolle 2007; Cieza et al. 2008, 2010; Kim et al. 2009; Espaillat et al. 2010; Merin et al. 2010; Muzerolle et al. 2010), young stars with spectral evidence for cool circumstellar dust but which lack diagnostics of warm dust. The standard interpretation is that transition discs contain a (at least partially) cleared inner cavity and that the temperature at the cavity wall sets the wavelength beyond which a strong spectral excess is detected.

The current census of transition discs totals more than a hundred, which is large enough to permit some examination of trends and correlations within the sample (e.g. Alexander & Armitage 2009; Kim et al. 2009; Owen, Ercolano & Clarke 2011; Owen & Clarke 2012; Owen, Clarke & Ercolano 2012). A number of authors have noted that cooler transition discs (i.e. those with a spectral up-turn longwards of 24 μm, corresponding to cavity walls at around 100 K) are associated with systematically higher accretion rates onto the star and systematically higher millimetre fluxes than warmer (small-hole) transition discs. A number of star-forming regions have now been uniformly surveyed at mm wavelengths (for example Chamaeleon, Henning et al. 1993; Lupus, Nuernberger, Chini & Zinnecker 1997; Taurus and Rho Ophiuchus, Andrews & Williams 2005, 2007; IC 348, Lee, Williams & Cieza 2011; Upper Scorpius, Mathews et al. 2012) so that the correlations between millimetre flux and the shape of the spectral energy distribution (SED) – as a diagnostic of cleared regions in the disc – are not likely to be set by observational biases. Owen & Clarke (2012) demonstrated that if one divides the transition disc sample at a mm flux that is equal to the median for young disc bearing stars, then the mm bright subsample has distinctly different properties, i.e. larger hole radii (>20 au) and higher accretion rates compared with the mm faint sample (which is dominated by small holes and a wide range of accretion rates). Given that there appears to be no correlation between these properties and the mm flux within each of the two subsamples, Owen & Clarke (2012) suggested that these may represent two distinct
populations of transition discs. They also noted that the properties of the mm faint subsample were consistent with discs that were being cleared at late times as a result of X-ray photoevaporation.

The properties of the mm bright subsample are clearly incompatible with disc clearing (e.g. by photoevaporation) at a late evolutionary stage. Indeed, the high mm fluxes imply disc masses that are in several cases $\sim 10$ per cent of the stellar mass (Andrews et al. 2011); this places them in the regime that is believed to correspond to the early stages of disc evolution and such discs may even be self-gravitating.

One possibility for creating a transition disc at this stage is via the formation of a giant planet/brown dwarf at large radius, which then tidally truncates the disc just beyond the orbit of the planet (Kraus & Ireland 2012; Nayakshin 2013). Although the time-scale for planet formation by core accretion is long in the outer disc, this is a region where massive discs can undergo gravitational fragmentation on account of their low ratio of cooling to dynamical time-scale (Rafikov 2005; Stamatellos & Whitworth 2008; Clarke 2009). In order to reproduce the observed high accretion rates in these systems, it is necessary that some gas can leak inwards past the planet. On the other hand, in order to produce the spectral signature of a transition disc, this leakage flow has to be depleted in dust. Rice et al. (2006) and Pinilla, Benisty & Birnstiel (2012) have suggested that such ‘transparent accretion’ can be affected via trapping of dust grains at the inner edge of the tidally truncated disc. Although many details of the mechanism are still to be quantified, an orbiting companion provides a qualitatively attractive scenario for explaining these objects.

In this Letter, we provisionally assume that the mm bright transition discs are indeed created by embedded planets. We then investigate how such systems (i.e. planet plus outer disc plus leaky accretion flow) would evolve over the subsequent lifetime of the disc. For this simple experiment, we neglect the possible role of photoevaporation; see Armitage et al. (2002), Matsuyama, Johnstone & Murray (2003), Alexander & Armitage (2009) and Rosotti et al. (2013) for a modelling of combined photoevaporation and planet formation. We also assume that the level of the leaky accretion flow from the outer disc is around 10 per cent of the viscous accretion rate in the outer disc, though – as we discuss in Section 2 below – this value, and its influence on planet migration, is not currently well calibrated numerically. We furthermore assume that the dust filtration mechanism works for all companion masses and at all orbital radii.

We do not attempt a detailed population synthesis of transition disc properties, due to the large number of model assumptions and degeneracies in fitting the data. Moreover, we do not require that evolution of the mm bright transition discs (whose properties provide the initial conditions for our experiment) can necessarily account for all mm faint transition disc objects, since some of these may well have a quite different origin (e.g. photoevaporation). What we do require is that the model evolution does not populate ‘forbidden’ regions of parameter space. Specifically, we need to (a) avoid the production of large numbers of mm bright sources with small (warm) holes and (b) avoid the production of mm faint large holes among conventional transition discs (i.e. those without stellar mass companions). We add this proviso concerning binary companions since discs in wide stellar binaries have typical mm fluxes that are at least an order of magnitude fainter than those of transition discs without binary companions (Kraus et al. 2011, 2012; see fig. 11 of Andrews et al. 2011). We therefore require that our model generates large mm faint holes only in the limit of high companion masses.

2 A SIMPLE MODEL FOR COUPLED DISC/PLANET EVOLUTION

We model the evolution of the disc according to the viscous diffusion equation

$$\frac{\partial \Sigma}{\partial t} = \frac{1}{R} \frac{\partial}{\partial R} \left[ 3 R^{1/2} \frac{\partial}{\partial R} (\nu_i \Sigma R^{1/2}) \right],$$

where $\Sigma$ is the disc surface density and $\nu_i$ is the kinematic viscosity which we model phenomenologically as a power law of radius following Lynden-Bell & Pringle (1974) and Hartmann et al. (1998); here we adopt $\nu_i \propto R$ (noting that this implies that in steady state the disc surface density profile scales as $R^{-1}$ – cf. Hartmann et al. 1998; Andrews et al. 2009). We model the coupled evolution of disc and planet through the disc’s inner boundary condition (see below); a free outflow condition is imposed at the disc’s outer edge. The equation is integrated using a standard explicit finite difference method, equispaced in $R^{1/2}$; we typically employ 1000 radial grid points over the range 1–3200 au. We have experimented with values of the outer boundary in order to ensure that the disc mass leaving the outer boundary is a small fraction of the initial disc mass (a few per cent or less) and that the evolution is independent of the outer boundary location in this case.

We first describe the set-up in the absence of leakage from the outer disc. If the planet is located at grid point $i$, the inner edge of the disc is located at grid point $i + 1$, where we impose a zero mass flux boundary condition. We then record the increase in angular momentum of the disc resulting from this boundary condition until the total angular momentum acquired by the disc is equal to the difference in angular momentum of the planet in the Keplerian orbit at grid points $i$ and $i + 1$. (Note that in recording the increase of angular momentum of the disc we also include the angular momentum that is advected through the outer boundary, where a zero torque boundary condition is applied.) At this point, the planet is moved to grid point $i + 1$, the inner edge of the disc to grid point $i$ and the process repeated. This simple approach ensures that the angular momentum of the system is conserved to machine accuracy and does not – as in the approach more usually adopted – rely on a parametrization of the torque between the disc and planet. We do not expect our method to model the detailed structure of the disc in the region where it is tidally sculpted by the planet and this will have some effect on the mm emission (although probably not greater in magnitude than the effect of varying the dust-to-gas ratio in this region, which is an effect that we do explore). Since we are interested in the orbital evolution of the planet and the global evolution of the disc (insofar as this affects the mm fluxes), our simple angular momentum conserving approach is sufficient for our purposes.

In addition, we implement a leakage flow from the outer disc. Other phenomenological modelling exercises (e.g. Alexander & Armitage 2009; Alexander & Pascucci 2012) have used a prescription in which the leakage flow rises with decreasing planet mass to attain a maximum of around a third of the mass flow rate through the outer disc for planets of around a Jupiter mass. The appropriate values are however rather uncertain based on the existing simulation data (Veras & Armitage 2004; Lubow & D’Angelo 2006): as discussed below, in the cases where the leakage flow (and accretion on to the planet) is significant, there is considerable uncertainty about the consequences for planet orbital migration inasmuch as this would deviate from the Type II planetary migration induced purely by interaction with the outer disc. In order to avoid these uncertainties (and because the focus of our investigation will end
up being in the more massive planetary regime where leakage is expected to be fairly minor), we simply assume that the leakage flow is around 10 per cent of the flow in the outer disc for all companion masses. We cannot rule out that the leakage flow might not become much more significant in the case of planets of much lower planet mass and return to this issue in Section 5.

The leakage has three consequences for the system: (a) it implies a finite accretion rate on to the star, (b) it modifies the disc evolution by depleting the outer disc and (c) it affects the planetary migration, both via (b) and via the torques imparted to the planet from the planetary accretion stream and the flow to the inner disc. Note that the efficiency factor of the leakage flow (ε, i.e. the ratio of the leakage flow to the accretion rate in the outer disc) critically determines the accretion rate on to the star for all values of ε; leakage is also significant in reducing the millimetre flux from the disc (b). However (c) is only mildly affected by leakage for low values of ε such as the value of ε (=0.1) adopted here. This is fortunate given the uncertainties in (c). Calculation of (c) involves knowledge of the change in specific angular momentum of fluid elements that are either directly accreted on to the planet or are able to cross the planetary orbit into the inner disc. In addition, the finite angular momentum possessed by material in the latter category is eventually passed back to the planet via tidal torques at the outer edge of the inner disc. Since we are not modelling either the inner disc or the detailed trajectories of the material crossing the planet’s orbit or accretion on to the planet, we simply assume that the entire angular momentum of the material leaving the inner edge of the outer disc is added to the planet. For ε = 0.1, relaxation of this assumption makes negligible difference to the orbital migration of the planet which is set almost entirely by the transfer of angular momentum to the outer disc.

We use the instantaneous properties of the disc to compute the mm flux, adopting standard opacity values:

\[ \kappa_\nu = 0.1 \left( \frac{v}{10^{11} \text{ Hz}} \right) \text{ cm}^2 \text{ g}^{-1} \]  

such that \( \kappa_\nu = 0.02 \text{ cm}^2 \text{ g}^{-1} \) at 1.3 mm and compute the luminosity density (for a face-on disc) as

\[ L_\nu = 4\pi \int_{R_{in}}^{R_{out}} dR 2\pi R B_\nu(T(R))(1-e^{-\tau_\nu(R)}) \]  

(Beckwith et al. 1990), where \( B_\nu \) is the Planck function and \( \tau_\nu (= \kappa_\nu \Sigma) \) is the optical depth. We adopt a simple power-law parametrization of the disc temperature:

\[ T(R) = 100 \left( \frac{R}{1 \text{ au}} \right)^{-0.5} \]  

which is motivated by typical parameters that have been found to provide a fit to the SEDs of circumstellar discs (Beckwith et al. 1990; Andrews & Williams 2005, 2007; Andrews et al. 2011).

We explore four model discs, in all cases adjusting the normalization of the surface density profile in order that the initial disc has a 1.3 mm flux (scaled to the distance of Taurus, i.e. 140 pc) of around 100 mJy; thus, in each case the initial disc has properties that are typical of the mm bright transition discs with large holes. (We emphasize that throughout we only consider the mm flux from material that is still in the outer disc, assuming that dust filtration suppresses the mm emission from the leakage flow.) None of the results presented here depend on the normalization of the viscosity (since this determines the time-scale of evolution rather than the relationship between millimetre flux and hole size that we explore here). It is however worth noting that if we normalize the viscosity such that the initial accretion rate on to the star is \( \dot{M} = 10^{-8} M_\odot \text{ yr}^{-1} \), as observed, then the time-scale on which the hole size shrinks to 10 au is a few Myr. We also note that the models do not involve the mass of the star except inasmuch as this would, in practice, affect the temperature normalization of the disc profile (which we have taken directly from observations; Andrews et al. 2009).

We list the inner and outer disc radii and total disc mass for each model (designated E, N, P1 and P2) disc in Table 1. The extended (E) and narrow (N) simulations share the same inner (‘cavity’) radius but differ in their outer radii; the mean emissivity per unit mass is higher in the narrow model (on account of its higher mean temperature) and thus the total disc mass required for a fixed mm flux is somewhat lower. In addition, we compute a couple of variant prescriptions for the mm emission, motivated by the results of recent simulations by Pinilla et al. (2012). These relax the assumption of a constant gas-to-dust ratio and follow the evolution of the grain size distribution and spatial variation of the dust in the case of a disc whose gas density profile is sculpted by a planet. Dust is concentrated in the resulting structure within a pressure bump located at about twice the orbital radius of the planet, with the disc being strongly depleted in dust at radii interior to this pressure bump (we however note that these dust calculations are run for a small fraction of a viscous time and thus – since the disc has not evolved into a steady state – the results should be regarded as somewhat provisional). We model this situation by two crude approximations that are intended to bracket the simulation results. In model P1, the planet orbital radius is halved with respect to the default model (i.e. 25 au compared with 50 au), and the region between 50 and 25 au is filled with dust-free gas with a surface density profile that is an extrapolation of the power-law profile; this increases the total gas mass by a factor of 2 with respect to model N (which shares the same outer radius). The gas hydrodynamics and planetary orbital migration are modelled exactly as before; as the planet migrates, it is assumed that the inner edge of the dusty disc remains at twice the instantaneous planet orbital radius. In model P2, the disc gas is again extrapolated to the planet location (25 au); emission is again only calculated from outwards of the cavity radius (i.e. twice the instantaneous radius of the planet) and the initial outer radius is again 75 au. In this case, however, the flux contribution from dust that would have been located between the planetary radius and twice this radius is calculated as optically thin emission at the temperature of the cavity radius. Placing of additional emission at the cavity radius increases the total disc mass required for a fixed mm flux somewhat.

In summary, each of these models is designed to reproduce observational parameters (cavity size of 50 au and mm flux of \( \sim 100 \text{ mJy} \)) that are typical of large-hole (mm bright) transition discs. We then evolve the coupled disc–planet system for a range of different planet masses and track the evolution of the system in the plane of mm flux versus cavity radius. We emphasize that at this stage we

| Model | \( R_{in} \) (au) | \( R_{out} \) (au) | \( M_{disc} \) |
|-------|-----------------|-----------------|-------------|
| E     | 50              | 150             | 50\( M_{Jup} \) |
| N     | 50              | 75              | 40\( M_{Jup} \) |
| P1    | 25              | 75              | 80\( M_{Jup} \) |
| P2    | 25              | 75              | 30\( M_{Jup} \) |
generically describe the companions as ‘planets’ even though we shall include companions with masses up to 100 Jupiter masses. We do not extend our calculations to higher masses on the grounds that Type II migration theory (which places the centre of mass of the system at the primary star) becomes inapplicable at higher mass ratios. Thus, we cannot directly address the disparity in mm fluxes between large-hole transition discs and stellar binaries.

3 RESULTS

As the planet and disc inner edge migrate inwards, the mm flux changes due to three effects: redistribution of material in radius (and hence temperature), optical depth effects and mass-loss from the outer disc due to the leakage flow to the inner disc (which is assumed not to contribute to the mm flux). The two latter effects both result in a reduction in mm flux. The former can change the mm flux in either direction since viscous evolution results in material spreading both inwards and outwards – i.e. into both hotter and cooler regions. In practice, we find that the net effect is either rough constancy of the mm flux or a gentle fading as the planet migrates inwards. We find that these two outcomes depend on the relative masses of the planet and the disc. In the case of a planet that is comparable to or less massive than the disc, the planet is conveyed inwards as though it were a representative fluid element in the disc; the disc structure upstream of the planet is not significantly modified by the planet’s presence, and the mm flux is nearly constant as the planet and associated disc hole move inwards. This behaviour is seen in models 100 P1, 40 N and 10 N in Fig. 1 (where the number refers to the planet mass – in Jupiter masses – and the model designation is defined in Table 1). On the other hand, in models where the ‘planet’ is more massive than the disc (such as 100 E, 100 N and 100 P2 in Fig. 1), the behaviour is somewhat different since the finite inertia of the planet impedes the free viscous migration of the disc inner edge (Lin & Papaloizou 1986; Syer & Clarke 1995; Ivanov, Papaloizou & Polnarev 1999). The slower migration means that there is time for a significant depletion of the outer disc by the leakage flow and more than half the initial disc mass has leaked past the planet in these models by the time it reaches 10 au. The mm flux declines by more than a factor of 2 over this time, with additional fading resulting from the disc’s expansion to large radii where the temperature – and associated mm emission – is low.

Fig. 1 plots observed transition discs in the plane of mm flux (scaled to a distance of 140 pc) versus hole size (see Owen & Clarke 2012, for details of the mm data which are mainly obtained from the mm surveys of Andrews & Williams 2005, 2007; Henning et al. 1993; Nuernberger et al. 1997). In the minority of objects that lack 1.3 mm fluxes, this is converted from 800 μm data using the prescription of Cieza et al. (2008). The open circles denote systems that have been imaged by Brown et al. (2009) and Andrews et al. (2011) and which therefore represent the systems with the largest holes and highest mm fluxes. For the remaining unresolved objects, the hole radius is either obtained from detailed SED modelling (Calvet et al. 2002, 2005; Espaillat et al. 2007, 2010; Najita et al. 2007; Kim et al. 2009; Merin et al. 2010; Andrews et al. 2011: shown as open symbols) or, in the case of filled symbols, is simply estimated from the ‘turn-off wavelength’ listed in Cieza et al. (2010); the hole radius is thus more uncertain in these latter systems. The squares and triangles distinguish mm detections from upper limits.

Fig. 1 illustrates that there is a lack of mm bright objects (with flux >30 mJy at the distance of Taurus) with hole sizes <10 au. Although such objects are obviously not the targets of mm imaging studies, they would have been readily picked up in photometric mm surveys and there are likewise no reasons why such objects would not be identifiable as transition discs from their SEDs (see Owen & Clarke 2012). This observational constraint defines the range of models that provide an acceptable fit to observations. Evidently, it is only models with a rather large planet-to-disc mass ratio (a factor of 2 or more) that avoid evolving into the forbidden region with high mm flux and small hole size. Furthermore, we emphasize that those models that remain mm bright at 10 au spend a comparable time with hole sizes in the ranges 50–10 and 10–1 au. We thus cannot appeal to rapid inward migration at <10 au in order to explain the observed lack of objects in the forbidden zone. Given the requirement that the disc has to be massive enough to generate the observed mm fluxes of large-hole, mm bright systems (~100 mJy), this in practice rules out systems in which the ‘planet’ is less than ~100 Jupiter masses (i.e. it excludes all companions in the planetary mass or brown dwarf regime).

4 DISCUSSION

Our results above imply that the model in which large mm bright transition discs are associated with a ‘planetary’ companion is viable only if the companion is in fact of stellar mass. This is simply because less massive companions are swept to small radii while the system remains mm bright, thus contradicting the observational dearth of small mm bright holes. Our initial conditions are informed by the observed high mm fluxes of large-cavity transition discs so that one cannot avoid this conclusion by simply invoking lower mass outer discs.

We noted above that we do not model the mass ratio regime of most stellar binary companions. However, our results for a 100 Jupiter mass companion do not allow us to explain the observed low mm fluxes in young stellar binaries (Kraus et al. 2011, 2012) since they do not show a strong decline of mm flux at large hole radius. This suggests that the low observed mm flux in stellar binaries may more relate to the consumption of the disc when the binary companion is formed rather than to the evolutionary effects explored here.
We find that companions of around 100 Jupiter masses provide a good fit to the observed distribution of transition discs in the plane of mm flux versus cavity radius, since such systems fade to less than 30 mJy by the stage that the hole size is ~10 au. We are not concerned that such systems would not fade to the lowest mm flux levels among transition discs with small inner holes since a separate mechanism – e.g. photoevaporation – could be invoked to explain the faintest objects.

Nevertheless, there is an unassailable objection to invoking companions of around 100 Jupiter masses: such objects would be readily detected by imaging surveys (whose current sensitivity levels extend to objects of ~10 Jupiter masses or lower (Kraus et al. 2011, 2012). The absence of such companions in transition discs, combined with the requirement demonstrated here of a rather massive companion, is a serious challenge to the notion that transition discs are associated with companions in any mass range. [See also Zhu et al. (2011, 2012) for other arguments against the planetary hypothesis for the origin of transition discs based on difficulties in reproducing the SED.]

5 CONCLUSION

We conclude that the popular planet model for large-cavity transition discs is faced with a ‘planet mobility problem’. If we set up a system with an outer disc mass that reproduces the mm flux of large-cavity transition discs and set a companion within the cavity, then the planet should migrate inwards by Type II migration and the cavity radius thus shrinks with time. We however find that both planets and brown dwarfs (i.e. objects less than ~100 Jupiter masses) are swept to small radii by Type II migration and that the mm flux of the disc does not fade significantly during this process. Thus, we would expect to see an associated population of mm bright objects with small holes (<10 au) which are not observed. We can avoid this outcome by instead invoking a more massive companion (i.e. a low-mass star). In this case, the migration is slow enough for the disc to fade at mm wavelengths before the hole shrinks to 10 au. However, such massive companions in transition discs are clearly ruled out by recent imaging surveys (Kraus et al. 2011, 2012).

In order to ‘rescue’ the planet scenario, we need some mechanism that stops the planet migrating inwards and/or suppresses the production of mm flux as the planet migrates. Photoevaporation might appear to be an attractive scenario in both respects (Rosotti et al. 2013); however, the initial conditions that are required to match the high mm fluxes of large-cavity transition discs imply massive discs, so that the photoevaporation time-scale would be long (~a Myr) even for systems with the highest X-ray luminosity. Perhaps a more likely explanation is that there is still much to learn about the secular evolution of coupled planet/disc systems. This issue is particularly acute because the low-mass planets that would be compatible with the null results from imaging surveys are in the regime where the leakage flow could play an important role in slowing planetary migration. On the other hand, it is not clear whether dust filtration – as is necessary to produce a transition disc signature – would be effective in the limit that the flow past the planet is almost unimpeded. These are issues which can only be assessed by future 2D/3D simulations exploring the secular evolution of coupled planet/disc systems.

REFERENCES

Alexander R., Armitage P., 2009, ApJ, 704, 989
Alexander R., Pascucci I., 2012, MNRAS, 422, L82
Andrews S. M., Williams J. P., 2005, ApJ, 631, 113
Andrews S., Williams J., 2007, ApJ, 671, 1800
Andrews S., Wilner D., Hughes A., Qi C., Dullemond C., 2009, ApJ, 700, 1502
Andrews S., Wilner D., Espaillat C., Hughes A., Dullemond C., McClure M., Qi C., Brown J., 2011, ApJ, 732, 424
Armitage P., Bonnell I., 2002, MNRAS, 330, L11
Armitage P., Livio M., Lubow S., Pringle J., 2002, MNRAS, 334, 248
Beckwith S. V. W., Sargent A. I., Chini R. S., Güsten R., 1990, AJ, 99, 924
Brown J., Blake G., Qi C., Dullemond C., Wilner D., Williams J., 2009, ApJ, 704, 496
Calvet N., D’Alessio P., Hartmann L., Wilner D., Walsh A., Sitko M., 2002, ApJ, 568, 1008
Calvet N. et al., 2005, ApJ, 630, L185
Cieza L. A., Swift J. J., Mathews G. S., Williams J. P., 2008, ApJ, 686, L115
Cieza L. et al., 2010, ApJ, 712, 925
Clarke C. J., 2009, MNRAS, 396, 1066
Espaillat C. et al., 2007, ApJ, 664, L111
Espaillat C. et al., 2010, ApJ, 717, 441
Hartmann L., Calvet N., Gullbring E., D’Alessio P., 1998, ApJ, 492, 323
Henning T., Pfau W., Zinnecker H., Prusti T., 1993, A&A, 276, 129
Ivanov P., Papaloizou J., Polnarev A., 1999, MNRAS, 307, 79
Kim K. H. et al., 2009, ApJ, 700, 1017
Kraus A., Ireland M., 2012, ApJ, 745, 5
Kraus A., Ireland M., Martinache F., Hillenbrand L., 2011, ApJ, 2011, 731
Kraus A., Ireland M., Hillenbrand L., Martinache F., 2012, ApJ, 745, 19
Lee N., Williams J., Cieza L., 2011, ApJ, 736, 135
Lin D., Papaloizou J., 1986, ApJ, 309, 846
Lubow S., D’Angelo G., 2006, ApJ, 641, 526
Lynden-Bell D., Pringle J., 1974, MNRAS, 168, 603
Mathews G., Williams J., Menard F., Phillips N., Duchene G., Pinte C., 2012, ApJ, 745, 23
Matsuyama I., Johnstone D., Murray N., 2003, ApJ, 585, L143
Merin N. et al., 2010, ApJ, 718, 1200
Muzerolle J., Allen L., Megeath S., Hernandez J., Gutermuth R., 2010, ApJ, 708, 1107
Najita J. R., Strom S. E., Muzerolle J., 2007, MNRAS, 378, 369
Nayakshin S., 2013, MNRAS, 431, 1432
Nuernberger D., Chini R., Zinnecker H., 1997, A&A, 324, 1036
Owen J., Clarke C., 2012, MNRAS, 426, 96
Owen J., Ercolano B., Clarke C., 2011, MNRAS, 412, 13
Owen J., Clarke C., Ercolano B., 2012, MNRAS, 422, 1880
Pinilla P., Benisty M., Birnstiel T., 2012, A&A, 545, 81
Rafikov R., 2005, ApJ, 631, 488
Rice W., Armitage P., Wood K., Lodato G., 2006, MNRAS, 373, 1619
Rosotti G., Ercolano B., Owen J., Armitage P., 2013, MNRAS, 430, 1392
Stamatellos D., Whitworth A., 2008, A&A, 480, 879
Syr D., Clarke C., 1995, MNRAS, 277, 758
Veras D., Armitage P., 2004, MNRAS, 347, 613
Zhu Z., Nelson R., Hartmann L., Espaillat C., Calvet N., 2011, ApJ, 729, 47
Zhu Z., Nelson R., Dong R., Espaillat C., Hartmann L., 2012, ApJ, 755, 18

ACKNOWLEDGEMENTS

We are grateful to the referee, Richard Alexander, for an insightful report which has helped us improve the Letter.

1 Note that this conclusion is qualitatively compatible with the findings of Armitage & Bonnell (2002).

This paper has been typeset from a T\textsc{e}X file prepared by the author.