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Herschel/SPIRE observations of the TWA brown dwarf disc 2MASSW J1207334−393254★

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ABSTRACT

We present *Herschel*/SPIRE observations for the 2MASS 1207334−393254 (2M1207) system. Based on radiative transfer modelling of near-infrared to submillimetre data, we estimate a disc mass of $3 \pm 2\,M_{\rm Jup}$ and an outer disc radius of 50–100 au for the 2M1207A disc. The *relative* disc mass for 2M1207A is similar to the T Tauri star TW Hya, which indicates that massive discs are not underabundant around substellar objects. In probing the various formation mechanisms for this system, we find that core accretion is highly uncertain mainly due to the large separation between the primary and the companion. Disc fragmentation could be a likely scenario based on analytical models, and if the disc initially was more massive than its current estimate. Considering that the TW Hydrae Association (TWA) is sparsely populated, this system could have formed via one of the known binary formation mechanisms (e.g. turbulent fragmentation of a core) and survived disruption at an early stage.

Key words: brown dwarfs – circumstellar matter – stars: individual: 2MASSW J1207334−393254 – stars: low-mass.

1 INTRODUCTION

The brown dwarf 2MASSW J1207334−393254 (2M1207) was discovered by Gizis (2002, hereafter G02) and was confirmed to be a TW Hydrae Association (TWA) member by Scholz et al. (2005a) based on its proper motion. This is a system consisting of a $25\,M_{\rm Jup}$ primary (2M1207A) and a $\sim 5\,M_{\rm Jup}$ secondary (2M1207B) that lies at a projected separation of ∼55 au (Chauvin et al. 2004). At an age of 10^{+5}_{-2} Myr (Barrado y Navascués 2006), 2M1207A is currently the oldest known brown dwarf to harbour a circumstellar disc (Riaz, Gizis & Hmiel 2006). It is also known to be undergoing accretion that varies between $10^{-10.1}$ and $10^{-9.8}$ $M_\odot\,{\rm yr}^{-1}$ (Scholz, Jayawardhana & Brandeker 2005b; Stelzer, Scholz & Jayawardhana 2007). The disc has a flat structure and lies close-in to the central substellar source, with no clear signs of inner disc dissipation observed (Riaz & Gizis 2007). The *Spitzer* colour excesses for the disc are found to be similar to the optically thick primordial disc sources in the younger ∼1–3 Myr clusters, which suggests that the 2M1207A disc is still in its primordial phase (Riaz et al. 2012a).

We present ESA *Herschel Space Observatory* (Pilbratt et al. 2010) SPIRE (Griffin et al. 2010) observations at 200–500 μm for the 2M1207 system. *This is the first submillimetre (submm) detection for this system.* The main advantage of submm observations is to obtain better constraints on the disc mass and the outer disc radius. Considering that the 2M1207A disc still seems to be in its youth, it is of interest to determine if brown dwarf disc masses show any decline with the age of the system. More interestingly, obtaining a better constraint on the disc mass will allow us to investigate if the $5\,M_{\rm Jup}$ secondary may have formed in the primary's disc.

2 OBSERVATIONS

We obtained SPIRE photometric observations in the 250, 350 and 500 μm bands using the small map mode (Obs ID: 1342223257). The small map mode covers a 5 arcmin diameter circle, with a fixed scan angle of 42°.4 and a fixed scan speed of 30 arcsec s^{-1}. We requested a set-up of 25 repetitions, resulting in a total on-source integration time of 925 s. 2M1207 was detected in the 250 and 350 μm bands at a signal-to-noise ratio of ∼10–15. The detection in the 500 μm band is confusion delimited. Data analysis was performed using the rectangular sky photometry task provided in the *Herschel* Interactive Processing Environment (HIPE version 8.0.1). We have worked on the final pipeline processed data (the 'Level 2' products). The rectangular photometry task applies aperture photometry for a circular target aperture and a rectangular sky aperture. We used an

★*Herschel* is an ESA space observatory with science instruments provided by European-led Principal Investigator consortia and with important participation from NASA.
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aperture radius of 2 pixel for the target and a 30 pixel rectangular area to estimate the sky intensity. The sky intensity was estimated using the median sky estimation algorithm. Since the sky intensity could vary with location, we selected four different background regions around the target (each of 30 × 30 pixel area) and measured the sky-subtracted source flux for each sky region. The source flux values varied by less than 1 mJy as measured using the different sky locations. The final source flux and the flux error at 250 and 350 μm listed in Table 1 are the mean and the standard deviation of these four flux measurements. The flux errors are consistent with the values obtained at the source location from the 'error' image provided in the Level 2 products.

At 500 μm, we have no bright source detection at 2M1207 location, as can be seen in the images shown in Fig. 1. The flux level at the target location is the same as found in some of the confusion noise dominated regions seen in the image. We selected three locations from the 250 μm image where there is no clear source detection, and measured the flux at these locations in the 500 μm image using the same method as discussed above. The flux values are found to be between ∼10 and 13 mJy. If we consider this as the 1σ confusion noise in the 500 μm observation, then the flux measured at the location of 2M1207 (16 mJy) is just above the confusion noise level. We have therefore considered the 500 μm measurement as an upper limit.

We note that we are observing the primary+disc+secondary in these submm bands, since the *Herschel* resolution (6, 10 and 14 arcsec in the 250, 350 and 500 μm bands, respectively) is not high enough to resolve the disc or the emission from the companion. If we consider a $T_{\rm eff}$ of ∼1000 K for the secondary object (e.g. Barman et al. 2011), then its photospheric emission would be ∼3 per cent of 2M1207A's photospheric flux. The photospheres for both A and B are too faint to be detected at SPIRE wavelengths, and we are therefore mainly observing the disc emission around the primary at these wavelengths.

3 DISC MODELLING

We have used the 2D radiative transfer code by Whitney et al. (2003) to model the disc around 2M1207A. Detailed discussion on the fitting procedure and the variations in the model SEDs is provided in Riaz & Gizis (2007). Here we have provided a brief description of the best model fits obtained, based on the lowest χ^2 value. Fig. 2 shows the best model fit obtained for 2M1207A. We have adopted a trigonometric parallax of 18.75 ± 0.37 mas (53.3 ± 1 pc) by taking the weighted average of the values measured by Gizis et al. (2007), Biller & Close (2007) and Ducourant et al. (2008).

Table 1. 2M1207A observations.

Band	Flux (mJy)	Reference	Date of Obs
J	10.10 ± 0.89	2MASS (G02)	1999 May
H	11.35 ± 1.0	2MASS (G02)	
K	11.12 ± 0.98	2MASS (G02)	
3.6 μm	8.49 ± 0.32	Riaz et al. (2006)	2005 June
4.5 μm	7.15 ± 0.26	Riaz et al. (2006)	
5.8 μm	6.36 ± 0.06	Riaz et al. (2006)	
8.0 μm	5.74 ± 0.21	Riaz et al. (2006)	
24 μm	4.32 ± 0.03	Riaz et al. (2006)	
70 μm	9 ± 4	Riaz & Gizis (2008)	2007 August
250 μm	35 ± 2	This work	2011 July
350 μm	23.5 ± 2	This work	
500 μm	16 (UL)	This work	

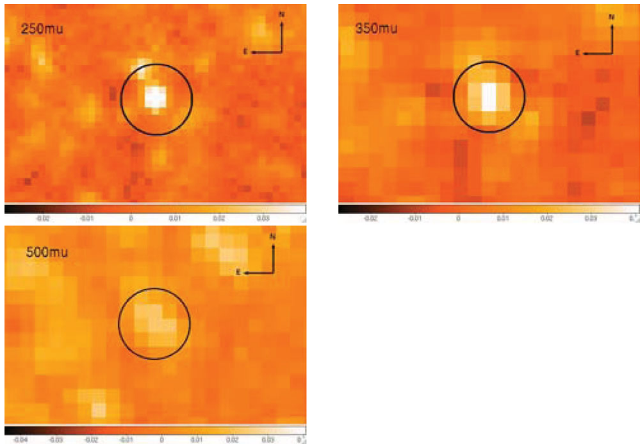

Figure 1. The *Herschel*/SPIRE images for 2M1207. The image sizes are 260 × 170 arcsec^2 for 250 μm, 210 × 130 arcsec^2 for 350 μm and 280 × 180 arcsec^2 for 500 μm. The colour bar in units of MJy sr^{-1} is shown at the bottom.

There are mainly six parameters related to the disc emission which can be varied to obtain a good fit (Table 2). The disc scale height varies as $h = h_0(\varpi/R_*)^\beta$, where h_0 is the scale height at R_* and β is the flaring power. 2M1207A shows a nearly flat SED shape between ∼24 and 250 μm (Fig. 2). This required a slight increase in h_0 and β, and the best fit is obtained using $h_0 = 0.1$ and $\beta = 1.2$. From a range in viewing angles, we find inclination angles between 57° and 69° to provide the best model fit. We have varied the inner disc radius $R_{\rm min}$ in multiples of $R_{\rm sub}$, which is the dust sublimation radius. We have obtained good fits for $R_{\rm min}$ between 1 and 3$R_{\rm sub}$, with a peak at 1$R_{\rm sub}$ (based on a χ^2 value comparison). This implies an absence of an inner hole in the disc since it would have to be larger than the dust sublimation radius.

There are three grain models supplied by the code: 'large' grains with a size distribution that decays exponentially for sizes larger than 50 μm up to 1 mm, the 'medium' sized grains of sizes with $a_{\rm max}$ ∼ 1 μm, and 'small' interstellar medium (ISM) like grains with $a_{\rm max}$ ∼ 0.25 μm. The dust opacity at 200–500 μm is ∼1 cm^2 g^{-1} for the large grain model and ∼0.1 cm^2 g^{-1} for the smaller sized grains (Whitney et al. 2003). For 2M1207A, we have used the large grain model in the disc mid-plane and the medium-sized grains in the disc atmosphere. Since this disc shows no silicate emission at 10 μm (Riaz & Gizis 2008), grains larger than the ISM are required to fit the flat silicate feature. We have varied both the outer disc

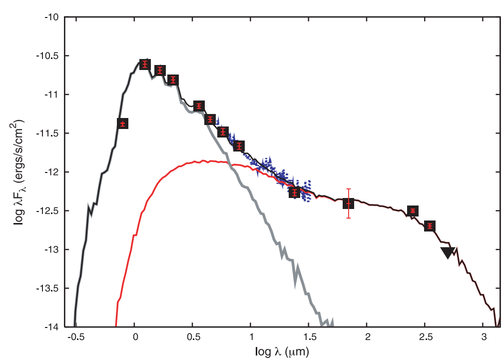

Figure 2. The best model fit for 2M1207A disc (black line). Also shown is the contribution from the disc (red) and the stellar photosphere (grey). The *Spitzer*/IRS spectrum is shown in blue.

Table 2. Stellar and disc parameters.

Parameter	Value
M_*	$0.025\,M_\odot$
R_*	$0.24\,R_\odot$
T_*	2550 K
d	53.3 ± 1 pc
β	1.2 ± 0.01
h_0	0.3 ± 0.1
$R_{\rm min}$	$1\,R_{\rm sub}$ ($\sim 3R_*$)
$R_{\rm max}$	50–100 au
$M_{\rm disc}$	$3 \pm 2\,M_{\rm Jup}$
i	57°–69°

radius, $R_{\rm max}$, and the disc mass, $M_{\rm disc}$, in order to obtain a good fit to the submm points. $M_{\rm disc}$ is the total mass of the disc (dust + gas). We have obtained good fits to the full observed SED using a disc mass between 1 and $5\,M_{\rm Jup}$, and an outer disc radius between 50 and 100 au. The models for smaller $R_{\rm max}$ of 30 or 10 au result in flatter slopes longward of ~70 μm, and cannot fit the 250 and 350 μm points. Increasing the disc mass to fit these smaller $R_{\rm max}$ models results in flattening the disc further at wavelengths longward of ~500 μm, and still cannot fit the 250 and 350 μm points. On the other hand, slightly increasing β or h_0 for these smaller $R_{\rm max}$ models can fit the submm points, but the optical depth then is too large to fit the 24 and 70 μm observations. This shows the advantage of having several points at far-infrared and submm wavelengths which can better tweak the model fits. Reducing the disc mass to values smaller than $1\,M_{\rm Jup}$ results in lower fluxes than the observed 250–500 μm points, while increasing the disc mass to values higher than $5\,M_{\rm Jup}$ results in larger optical depth and misses the 350 and 500 μm points. From these various combinations, we estimate that a disc mass of $3 \pm 2\,M_{\rm Jup}$ and an outer disc radius of 50–100 au can provide good fits to the 2M1207A disc emission.

4 DISCUSSION AND CONCLUSIONS

4.1 A massive brown dwarf disc

Fig. 3(a) compares the *relative* disc mass for 2M1207A with younger brown dwarf discs in the Taurus (~1 Myr) and IC 348 (~2 Myr) star-forming regions. The Taurus and IC 348 disc mass measurements are from Scholz, Jayawardhana & Wood (2006) and Klein et al. (2003), respectively. Fig. 3(a) suggests a possible trend of a rise in the relative disc mass towards lower object masses. We also do not find any decline in the relative disc masses with the age of the system. Even if we consider the lower limit of $1\,M_{\rm Jup}$ for the 2M1207A disc mass, its disc-to-star mass ratio is still comparable to the most massive discs in Taurus. Disc dissipation time-scales are found to be longer for brown dwarfs compared to higher mass stars (e.g. Riaz & Gizis 2008), which could explain the absence of any underabundance of massive discs around such older systems. A confirmation of these trends requires larger samples of brown dwarfs across a wide range in ages.

Fig. 3(b) compares the relative disc mass for 2M1207A with other low-mass disc sources in the TWA (using data from Calvet et al. 2002; Low et al. 2005; Andrews et al. 2010). TW Hya is known to be a strong accretor, with $\dot{M}$ of $4 \times 10^{-10}\,M_\odot\,{\rm yr}^{-1}$, compared to 0.8–$1.6 \times 10^{-10}\,M_\odot\,{\rm yr}^{-1}$ for 2M1207A (Muzerolle et al. 2000; Stelzer et al. 2007). The SED for TW Hya shows a highly flared disc, with no hint of turning over even out to 160 μm (Calvet et al.

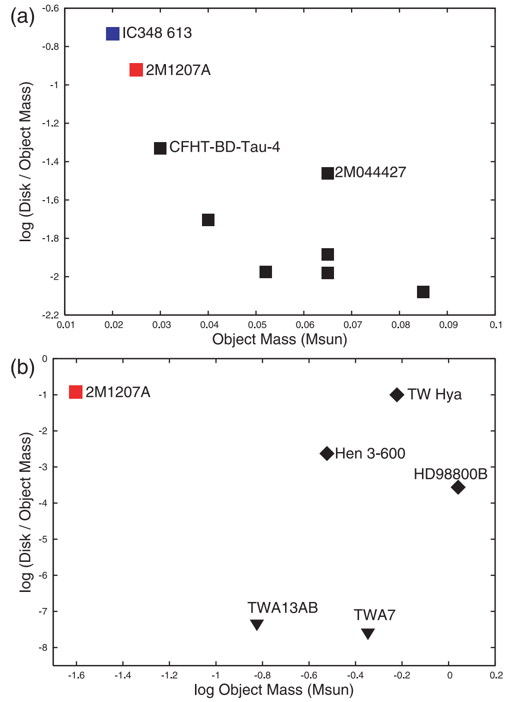

Figure 3. (a) A comparison of 2M1207A relative disc mass with other known brown dwarf discs in Taurus and IC 348. (b) Relative disc masses versus object mass for TWA discs.

2002; Low et al. 2005). Hen 3−600 is a weaker accreting source ($0.5 \times 10^{-10}\,M_\odot\,{\rm yr}^{-1}$), while the other disc sources in TWA are non-accretors (e.g. Muzerolle et al. 2000). TW Hya is a rare case in the TWA, as it still harbours an optically thick primordial disc at ~10 Myr which is actively accreting. This is in contrast to nearly 70 per cent of the low-mass stars which have transitioned to the debris phase by this age (e.g. Low et al. 2005). 2M1207A is a similarly rare primordial case among the substellar members of the TWA, and may be considered as a TW Hya analogue. 2M1207A also has a similar fractional disc luminosity ($L_{\rm IR}/L_*$) as TW Hya; the value is 0.27 for TW Hya (Low et al. 2005) compared to 0.3 for 2M1207A. It is thus interesting to find comparable relative disc masses for these two systems, which further signifies that massive discs are not underabundant around substellar objects.

4.2 Formation mechanism of 2M1207A and 2M1207B

4.2.1 Core accretion

There have been speculations about the formation of the planetary mass secondary in the primary's disc. In the core accretion model (Pollack et al. 1996), a rocky core of a few Earth masses forms in the disc, followed by accretion from the surrounding gaseous material. Payne & Lodato (2007) have investigated the potential for planet formation via core accretion around substellar objects. Their simulations indicate that the growth of Earth-mass planetary cores is at a much slower rate around brown dwarfs compared to solar-type stars, and so none of the rocky cores formed grows quickly enough or massive enough to start accreting gas before it dissipates. Giant planet formation is thus inhibited in the case of brown dwarfs. Core accretion is unlikely at large distances, since the typical core accretion time increases with radius and can be >10 Myr at radii >20 au (e.g. Goldreich, Lithwick & Sari 2004). At a projected separation of ~55 au, 2M1207B is unlikely to have formed through core accretion, mainly because the separation is too large and the surface density of solids at those distances would be too small ($\leq 0.023\,\mathrm{g\,cm^{-2}}$; Lodato, Delgado-Donate & Clarke 2005).

4.2.2 Disc fragmentation

Disc instability requires a relatively cool massive disc that becomes gravitationally unstable, thus developing spiral arms that sweep up gaseous material into dense condensations, resulting in the formation of protoplanets (e.g. Stamatellos & Whitworth 2009). This mechanism is more efficient at forming planets at larger radii (>25–50 au; e.g. Rafikov 2005), since the gas in the inner warm disc regions cannot cool quickly enough to allow a gravitationally unstable disc to fragment. It has been argued for the case of 2M1207 that if the disc mass was at least 20 per cent of the stellar mass ($M_{\rm disc} > qM_\star$, $q = 0.2$), then the disc could fragment to form the secondary (Lodato et al. 2005). This limit would be $M_{\rm disc} > 5\,M_{\rm Jup}$, which is the upper limit to the estimated disc mass range. A similar estimate can be obtained using the analytical model of Rafikov (2005), who estimates, as a function of the main parameters, a minimum surface density $\Sigma_{\rm inf}$ for the disc to satisfy simultaneously the requirements of being linearly unstable and of cooling quickly enough. Following equation (6) of Rafikov (2005), assuming a disc composed of molecular hydrogen (with mean molecular weight $\mu = 2.3$), a critical Toomre parameter $Q_0 = 1.2$ (Cossins, Lodato & Clarke 2009) and a critical cooling time $\zeta = t_{\rm cool}\Omega = 5$ (e.g. Rice, Lodato & Armitage 2005), the minimum disc mass required for fragmentation is

$$M_{\rm d} = \pi \Sigma_{\rm inf} R^2 \approx 3.5\,M_{\rm Jup} \left(\frac{M_\star}{25\,M_{\rm Jup}}\right)^{7/10} \left(\frac{R}{50\,{\rm au}}\right)^{1/10}. \quad (1)$$

The minimum fragment mass can be obtained recalling that the Jeans length for a marginally stable disc is of the order of the disc thickness $H \approx 0.1R$:

$$M_{\rm frag} = \pi \Sigma_{\rm inf} H^2 = M_{\rm d} \left(\frac{H}{R}\right)^2 \approx 0.035\,M_{\rm Jup}. \quad (2)$$

Such a low-mass fragment can then rapidly grow through accretion from the disc to become the $5\,M_{\rm Jup}$ observed, as suggested by Lodato et al. (2005). The initial disc mass would have to be at least a factor of ∼2 higher than its current estimate, in order to form a $5\,M_{\rm Jup}$ object and still retain a $5\,M_{\rm Jup}$ disc. We can then consider a scenario wherein the initial mass of the disc was much higher, say 10–20 $M_{\rm Jup}$, which then quickly fragmented to form the secondary and then dissipated, resulting in a remnant $5\,M_{\rm Jup}$ disc at ∼10 Myr. Even for the younger brown dwarf discs in Taurus (∼1 Myr), the disc masses range between 0.5 and 2.5 $M_{\rm Jup}$ (Scholz et al. 2006). Thus, if fragmentation is a possibility, then it must have occurred during the very early stages of formation of this system (<1 Myr).

Whether such analytical estimates are confirmed by radiative simulations of gravitationally unstable discs is still to be verified. We have performed some new simulations to check for the validity of such a scenario. Preliminary results indicate that the disc needs to have a mass of $\geq 70\,M_{\rm Jup}$ in order to undergo fragmentation (Stamatellos et al., in preparation). There is thus a discrepancy between theoretical models and simulations. A 25 $M_{\rm Jup}$ brown dwarf such as 2M1207A cannot be expected to harbour a 70 $M_{\rm Jup}$ disc. If indeed the minimum disc mass to allow fragmentation is so large (outside the typical range for protostellar discs), then this would disfavour the disc fragmentation scenario. We plan to investigate the fragmentation of a very low mass (VLM) disc in a subsequent paper.

4.2.3 Alternative mechanisms

An alternate formation scenario could be that the primary and secondary had formed independently in, e.g., small cores in filaments, and were then tidally locked together after formation. In the model discussed in, e.g., Clarke & Bonnell (2008), brown dwarfs form in filamentary structures that develop as the gas falls in the gravitational potential of the forming cluster. Such a mechanism does not require close interactions or ejections to ensure the formation of substellar cores, and so a wide binary system at low binding energy could have survived during the early formation stages. If both had instead formed via ejection from larger cores (e.g. Reipurth & Clarke 2001), then a wide system may not have survived due to experiencing multiple encounters with other stellar embryos. We can also consider the prompt fragmentation scenario, wherein both primary and secondary stars form by fragmentation of the same collapsing molecular cloud core (e.g. Bonnell & Bastein 1992).

Alternatively, these two objects could have formed by fragmentation in the disc of another star and then paired up as they are ejected from that system (e.g. Stamatellos & Whitworth 2009). Since in the case of 2M1207 the object age is around 10 Myr, the parent star could be ∼10 pc away (assuming the pair was ejected with a velocity of ∼1 $\mathrm{km\,s^{-1}}$). At the distance to TWA, 10 pc would imply about 11°.5. All of the TWA members lie within ∼12° of the cluster centre (e.g. Webb et al. 1999). The discs of the stars of TWA are not massive enough to be unstable. However, as mentioned earlier, such a scenario would work if we consider the present discs as the remnants of much more massive discs when fragmentation may have happened ∼10 Myr ago.

Also applicable could be the star–disc encounter model by McDonald & Clarke (1995), which provides a high binary fraction particularly in small groups of stars such as the sparsely populated TWA. This model is based on a disc-assisted capture, whereby discs provide a greater interaction cross-sectional area and so a star passing through the disc of another star dissipates enough kinetic energy to form a bound system. It is worth noting that the TWA is a sparsely populated association (∼0.05 objects $\mathrm{pc^{-2}}$; Riaz et al. 2012a), which would increase the probability for such wide low binding energy systems to survive disruptions during the early stages of formation.

4.3 A largely extended disc

The largely extended disc around 2M1207A ($R_{\rm max}$ = 50–100 au) argues for a star-like formation, rather than being ejected from larger cores. Recent simulations from Bate (2009) indicate that a significant fraction (10–20 per cent) of VLM objects formed via the ejection mechanism should have discs larger than 40 au in radius. Thus, 2M1207A may as well have formed via the ejection mechanism.

More interestingly, the range in the $R_{\rm max}$ values suggests that the disc around the primary extends right up to the radial distance where the secondary exists, or even farther than that distance. We thus have a possible scenario where a $5\,M_{\rm Jup}$ object is either inside or at the edge of the disc. Such a massive companion, irrespective of the formation mechanism, should open up a gap or tidally truncate the disc. We do not have the resolution or the sensitivity to probe the presence of a gap in the disc. However, we do not find any obvious 'breaks' in the observed SED, or a clear deficiency in the strength in the disc emission which would suggest the presence of a gap in the disc. Such deficiencies are clearly observed for certain brown dwarf transition discs with large inner holes (e.g. V410 X-ray 6;

Riaz et al. 2012b). The reason we do not find a clear gap could be due to continued replenishment of the gap with material from the disc. The secondary is orbiting at quite a wide orbit. At 55 au, its period is around 400 yr. If we consider a disc temperature around 10 K, then this corresponds to a sound speed of $\sim$0.2 km s^{-1}. With this velocity, a gap of, say, $\sim$5 au could be filled in with disc gas in about 60 yr. So there may be a gap just behind the companion, but not fully all around the disc. Another reason for not finding a gap could be that the disc and the companion are not coplanar, as e.g. the orbit of the companion could be highly inclined with respect to the disc. Such scenarios can be probed further once we have more knowledge of the dynamics of the system.

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