Rapid evolution of the innermost dust disc of protoplanetary discs surrounding intermediate-mass stars

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Accepted 2014 May 20. Received 2014 May 19; in original form 2013 September 26

ABSTRACT
We derived the intermediate-mass (∼1.5–7 M⊙) disc fraction (IMDF) in the near-infrared JHK photometric bands as well as in the mid-infrared (MIR) bands for young clusters in the age range of 0 to ∼10 Myr. From the JHK IMDF, the lifetime of the innermost dust disc (∼0.3 au; hereafter the K disc) is estimated to be ∼3 Myr, suggesting a stellar mass (M*) dependence of K-disc lifetime ∝ M*0.7. However, from the MIR IMDF, the lifetime of the inner disc (∼5 au; hereafter the MIR disc) is estimated to be ∼6.5 Myr, suggesting a very weak stellar mass dependence (∝ M*0.2). The much shorter K-disc lifetime compared to the MIR-disc lifetime for intermediate-mass (IM) stars suggests that IM stars with transition discs, which have only MIR excess emission but no K-band excess emission, are more common than classical Herbig Ae/Be stars, which exhibit both. We suggest that this prominent early disappearance of the K disc for IM stars is due to dust settling/growth in the protoplanetary disc, and it could be one of the major reasons for the paucity of close-in planets around IM stars.

Key words: planets and satellites: formation – protoplanetary discs – circumstellar matter – stars: pre main-sequence – stars: variables: T Tauri, Herbig Ae/Be – infrared: stars.

1 INTRODUCTION
Understanding protoplanetary discs is not only essential for understanding the star formation process, but it is also critical for understanding planet formation (e.g. Lada & Lada 2003). The lifetime of protoplanetary discs is one of the most fundamental parameters of a protoplanetary disc because it directly restricts the time for planet formation (e.g. Williams & Cieza 2011). Many studies that derive the lifetime of protoplanetary discs are now available. In a pioneering work, Strom et al. (1989) studied the frequency of disc-harbouring stars with known ages in the Taurus molecular cloud that have a K-band excess and suggested that the disc lifetime is in the range from ≤3 Myr to ∼10 Myr. Subsequently, a more direct method using the ‘disc fraction’, which is the frequency of near-infrared (NIR) or mid-infrared (MIR) excess stars within a young cluster with an assumed age, has been widely adopted to study the disc lifetime following the work by Lada (1999) and Haisch, Lada & Lada (2001b). Using the disc fraction that monotonically decreases as a function of cluster age, the disc lifetime is estimated at about 5–10 Myr in the solar neighbourhood (Lada 1999; Haisch et al. 2001b; Hernández et al. 2008; see also Yasui et al. 2010). Mamajek (2009) compiled disc fractions for about 20 clusters and derived the characteristic disc decay time-scale (τ) of 2.5 Myr, assuming the disc fraction[percent] ∝ exp(−[r/Myr]/τ).

These estimated disc lifetimes were mainly derived from the disc fraction with all detected cluster members and thus the estimated lifetime has been primarily for low-mass (LM) stars (<2 M⊙), considering the characteristic mass of the initial mass function(IMF, ∼0.3 M⊙; Elmegreen 2009) and the typical stellar mass detection limit (∼0.1 M⊙). However, a number of assessments of the effect of the stellar mass dependence of the disc lifetime have recently suggested a shorter disc lifetime for the higher mass stars (e.g. Hernández et al. 2005; Carpenter et al. 2006; Kennedy & Kenyon 2009). Although the existence of discs of high-mass stars (>8 M⊙) is still under debate (e.g. Fuentes et al. 2002; Mann & Williams 2009), the discs of intermediate-mass (IM) stars have been extensively studied and are well characterized (Hernández et al. 2005, 2007a, 2008). IM stars with optically thick discs are known as Herbig Ae/Be (HAeBe) stars. They were originally discovered with strong emission lines by Herbig (1960). After Hernández et al. (2004) established the method for selecting HAeBe stars using the spectral energy distribution (SED) slope from the V band to the IRAS 12 μm band, Hernández et al. (2005) derived the HAeBe-star disc fraction for six clusters in the age range of 3–10 Myr. They showed that...
the disc fraction is lower compared to the previously derived disc fraction for LM stars, in particular by a factor of \(~10\) lower at \(~3\) Myr.

Recently, the disc fraction studies have shifted to longer wavelengths (MIR or submm) mainly because of the interest in tracing the outer disc, where most of the disc mass resides (Williams & Cieza 2011). However, the disc fractions can also be estimated using only \(JHK\) data, in particular, for the IM stars. Originally, the disc lifetime was estimated with disc fractions derived by using the colour–colour diagram based on imaging in the \(JHK\) and \(JHKL\) photometric bands (e.g. Lada 1999; Haisch et al. 2001b). After the advent of the Spitzer Space Telescope, the SED slope (\(\alpha = d \ln \lambda F_\lambda /d \ln \lambda\)) in the MIR wavelength range (3.6, 4.5, 5.8, and 8.0 \(\mu\)m) is used for selecting disc-harbouring stars (e.g. \(\alpha \geq 2.0\); Lada et al. 2006). However, the derived disc fractions and disc lifetime with \(\text{Spitzer}\) data were found to be almost the same as those with \(\text{JHKL}\) data (see Sicilia-Aguilar et al. 2006; Hernández et al. 2008), and even with \(\text{JHK}\) data (Lada 1999; Yasui et al. 2010). Although the NIR disc fractions are known to show values systematically smaller and with a larger uncertainty due to contamination of the non-disc-harbouring stars on the colour–colour diagram (Haisch, Lada & Lada 2001a; Yasui et al. 2010), Hernández et al. (2005) showed that the \(\text{JHK}\) colour–colour diagram can clearly distinguish disc-harbouring IM stars from non-disc IM stars. The \(\text{JHK}\)-disc fraction value is robust both because of the large infrared excess and the higher stellar effective temperature of the IM stars, compared to LM stars.

In this paper, we derived the \(\text{JHK}\) intermediate-mass disc fraction (IMDF) using the Two Micron All Sky Survey (2MASS) Point Source Catalog of a large number \((\approx 20)\) of well-established nearby \((D \lesssim 1.5\,\text{kpc})\) young clusters with an age span of \(0\) to \(~10\) Myr in order to quantitatively and comprehensively study the lifetime of protoplanetary discs surrounding IM stars \((\approx 1.5–7 \, \text{M}_\odot)\). In particular, we included as many clusters as possible with ages \(\approx 5\) Myr. To securely identify IM cluster members, we made use of the spectral types of each cluster member from the literature, assuming a single age for each cluster. With the derived \(\text{JHK}\) IMDFs for a large number of younger clusters \(\approx 5\) Myr, we estimated the disc lifetime of the IM stars. We then estimated the stellar mass dependence of the disc lifetime by comparing the lifetime of IM stars to that of LM stars. We also derived the MIR IMDFs with \(\text{Spitzer}\) data in the literature to compare them to the \(\text{JHK}\) IMDFs. We found that the derived \(\text{JHK}\) IMDFs are significantly lower than the MIR IMDFs, in particular at younger ages \((\approx 3\) Myr\)), which results in shorter lifetime of the \(K\) disc than the MIR disc. This suggests a potentially larger fraction of ‘transition discs’ for IM stars compared to those for LM stars. We discuss the implications of these results for dust growth and planet formation.

Because the sample clusters and the selection of the IM stars are critical for this paper, we discuss these in detail in Section 2. The definition and derivation of the \(\text{JHK}\) IMDF and the MIR IMDF are described in Sections 3 and 4, respectively. Before interpreting the results of the IMDFs, the definition of the disc lifetime is discussed in Section 5. Section 6 then discusses the results for \(\text{JHK}\) IMDFs. The \(\text{MIR}\)-disc fraction is discussed in Section 7. Subsequently, Section 8 discusses the large difference between \(\text{JHK}\) and \(\text{MIR}\) IMDFs found in this study and potential disc evolution consequences for IM stars. Finally, Section 9 discusses the possible physical mechanisms of this rapid evolution of the \(K\) disc. At the end, in Section 10, we briefly discuss possible implications for planet formation. Section 11 summarizes this paper.

## 2 Target Clusters and Selection of IM-Star Samples

### 2.1 Target clusters

We selected our target clusters from previous studies of the disc fraction/evolution (Haisch et al. 2001b; Hernández et al. 2005, 2008; Gáspár et al. 2009; Kennedy & Kenyon 2009; Mamajek 2009; Fedele et al. 2010; Roccatalia et al. 2011). For estimating the disc lifetime with acceptable accuracy, it is necessary to derive the IMDFs for as many as young clusters as possible, ideally more than \(10\). We thus selected our target young clusters from the above papers, but with the following criteria: (1) cluster ages are spaced from \(0\) to \(~10\) Myr, to cover the time period of disc dispersal. (2) The cluster membership is well defined from a variety of observations (astrometry, radial velocity, variability, Hz, X-ray, NIR excess, MIR excess, optical spectroscopy, NIR spectroscopy, etc.). This criterion naturally leads to clusters in the solar neighbourhood (distance < 1.5 kpc). (3) The spectral types of a large number of cluster members are available by spectroscopy. (4) Well-defined NIR and MIR photometry of the cluster members with \(M_{\text{lim}} \approx 1 \, \text{M}_\odot\) is published in a widely available catalogue, such as 2MASS. (5) At least three IM stars are available per cluster for IMDF derivation.

The resultant 19 target clusters are summarized in Table 1 along with the age, distance, and references for the disc fraction study. Almost all young \(\approx 5\) Myr clusters in the references (Table 1) are included, though three young clusters (MBM 12, NGC 6231, and NGC 7129) are excluded. This is because it appears that no IM stars are present in MBM 12 (Luhman 2001), and the spectral types of stars in NGC 6231 and NGC 7129 are limited only to brightest members (OB, A stars), and are not adequate to cover the entire IM-star mass range down to \(1.5 \, \text{M}_\odot\). Some older clusters \((> 5\) Myr\), mostly those from Fedele et al. (2010), are excluded because they do not satisfy the above criterion. For several well-known clusters within the target clusters (Trapezium, Ori OB1a, Ori OB1bc, Per OB2), we could derive only \(\text{JHK}\)-disc fractions because we could not find published \(\text{Spitzer}\) MIR data for the IM stars, probably because of saturation. As a result, we obtained the \(\text{JHK}\) IMDF for 19 clusters and the MIR IMDF for 13 clusters.

### 2.2 Selection of IM stars

Although the original definition of mass for HAeBe is \(\approx 2–10 \, \text{M}_\odot\) with spectral types of B and A (and in a few cases F; Herbig 1960), the presence of discs around stars earlier than B5 \((\approx 6–7 \, \text{M}_\odot)\) in the main-sequence phase) is not well established since the disc lifetime of high-mass stars is very rapid, e.g. \(\approx 1\) Myr (Fuente et al. 2002; Zinnecker & Yorke 2007). Also, the number of high-mass stars \((\approx 6–7 \, \text{M}_\odot)\) is very small because of the IMF, and the number stochastically fluctuates from cluster to cluster. Therefore, we set the upper mass limit as \(7 \, \text{M}_\odot\) in this paper. This is also a good match with the mass range of the isochrone model by Siess, Dufour & Forestini (2000, \(M_{\text{max}} = 7 \, \text{M}_\odot\)), which is used throughout this paper. As for the lower mass limit, we employed \(1.5 \, \text{M}_\odot\), which corresponds to spectral type ‘F1’ for main sequences, following past comprehensive works of discs for IM stars by Hernández et al. (2005) and Kennedy & Kenyon (2009). The latter defined a mass range bin of 1.5–7 \(\text{M}_\odot\), which can be directly compared to our results.

The IM-star selection is a critical item for this study. Ideally, stellar mass and the age of each cluster member are determined from the
HR diagram with the extinction-corrected luminosity and spectroscopically determined effective temperature through an isochrone model. However, this requires a time-consuming observational programme, and thus the number of target clusters is limited as in the previous studies. Even if we had the complete observational data, the value of mass and age depends on the isochrone model, and could strongly depend on the extinction correction with different \( R_V \) (e.g. Hernández et al. 2004, 2005). Another approach is to use a limited number of parameters, such as only the spectral type, to pick up cluster members in a broad mass range, such as IM or LM stars, and to use a larger number of clusters. Although sacrificing the accuracy of the mass estimate, a study including a larger number of clusters is possible. Although some past studies, in fact, focus on targets of certain spectral types (e.g. earlier than F1) to pick up cluster members without considering differential extinction. This method enables IM-star selection only with the spectral type of the members without considering differential extinction. This method could strongly depend on the extinction correction with different \( R_V \). We assume that the cluster age is the age of the members in the selection of the IM stars.

The choice of the isochrone model is critical for the mass estimate. Although a number of recent isochrone models are available (e.g. Siess’s isochrone is also critical for comparison with the previous studies which used Siess’s isochrone in most cases (e.g. Kennedy & Kenyon 2009)). We take particular note of the fact that the age spread of young clusters in the solar neighbourhood is in many cases small enough so that a single age can be assumed for each cluster (see Table 1). Therefore, the boundary masses of the IM stars (7 and 1.5 \( M_\odot \)) theoretically correspond to a unique spectral type for each cluster, which enables IM-star selection only with the spectral type of the members without considering differential extinction. This method should be effective, in particular, for IM stars because most of the time they evolve along the Hayashi track, which is roughly horizontal on the HR diagram, and even when the IM stars are on the Hayashi track before switching to the Henyey track, the spectral type does not change because the track is almost vertical on the HR diagram.

HR diagram. Table 2 shows the unique spectral types corresponding to the boundary masses for each cluster age based on the isochrone model by Siess et al. (2000).

However, there are several points to take note for using the above method in selecting the IM stars. First, each spectral type, in particular the later spectral type (G7–K5), corresponds to a slightly broader mass range as shown in the third column of Table 2. For example, the boundary spectral type K5 corresponds to 1.2–1.5 \( M_\odot \) for the age of 2 Myr. Therefore, the sampling by spectral type naturally leads to the inclusion of stars with a mass of slightly lower than the nominal 1.5 \( M_\odot \). Hillenbrand & White (2004) also noted that the introduction of new isochrone models tends to bring new systematic uncertainty and should be used with caution. For this study, using Siess’s isochrone is also critical for comparison with the previous studies which used Siess’s isochrone in most cases (e.g. Kennedy & Kenyon 2009).

The disc evolution of intermediate-mass stars

**Table 1. Summary of target clusters.**

| Cluster       | Age\(^a\) (Myr) | Distance\(^b\) (pc) | References for the disc fraction study\(^c\) |
|---------------|------------------|---------------------|---------------------------------------------|
| NGC 1333      | 1 ± 1 (He08)     | 318 (LL03)          | He08, Ma09, Ro11                            |
| Trapezium     | 1 ± 1 (Mu02)     | 450 (LL03)          | Ha01, He08, Ma09                            |
| ρ Oph         | 1 ± 1 (Fe10)     | 125 (LL03)          | Fe10                                        |
| Taurus        | 1.5 ± 1.5 (He08) | 140 (El78)          | He01, He08, Ke09, Ma09, Fe10, Ro11          |
| Cha I         | 2 ± 1 (Ro11)     | 170 (Lu08)          | He01, He08, Ke09, Ma09, Fe10, Ro11          |
| NGC 2068/71   | 2 ± 1.5 (Ro11)   | 400 (LL03)          | He08, Ma09, Ro11                            |
| IC 348        | 2.5 ± 0.5 (He08) | 320 (Ha01a)         | He01, He08, Ke09, Ma09, Fe10, Ro11          |
| σ Ori         | 3 ± 1 (Ro11)     | 440 (He07a)         | He08, Ma09, Fe10, Ro11                      |
| NGC 2264      | 3 ± 1 (He08)     | 760 (Da08a)         | He01, He08, Ma09                            |
| Tr 37         | 4 ± 1 (He08)     | 900 (Si05)          | He08, Ke09, Ma09, Ro11                      |
| Ori OB1b      | 4 ± 3 (He05)     | 443 (He05)          | He05, He08, Ke09, Ma09, Ga09, Fe10, Ro11    |
| Upper Sco     | 5 ± 1 (Pr02)     | 144 (He05)          | He05, He08, Ke09, Ma09, Ga09, Fe10, Ro11    |
| NGC 2362      | 5 ± 1 (He08)     | 1500 (Da08b)        | Ha01, He08, Ke09, Ma09, Fe10, Ro11          |
| γ Vel         | 5 ± 1.5 (He08)   | 350 (He08)          | He08, Ma09, Ro11                            |
| λ Ori         | 5 ± 1 (He08)     | 450 (He09)          | He08, Ma09                                  |
| Per OB2       | 6 ± 2 (He05)     | 320 (He05)          | He05                                        |
| η Cham        | 7 ± 1 (He08)     | 100 (Ma09)          | He08, Ma09, Ga09, Fe10, Ro11                |
| Ori OB1a      | 8.5 ± 1.5 (Br05) | 350 (He05)          | He05, He08, Ke09, Ma09, Ga09                |
| NGC 7160      | 11 ± 1 (He08)    | 900 (Si05)          | He08, Ke09, Ma09, Ro11                      |

\(^a\)Adopted age with reference in parentheses.
\(^b\)Distance with reference in parentheses.
\(^c\)References for disc fraction study in the past. Note that some references show different cluster names (e.g. 25 Ori, which is named as Ori OB1a in our list).
cluster may cause contamination of lower mass stars in our IM-star samples in the case where the age of the star is older than the cluster age. Table 2 also shows the possible mass range for an age spread of $\Delta t = 2$ Myr, which is the maximum possible age spread in most cases (typically $\Delta t = 1$ Myr; see Table 1). Although the ages of most stars are within the age spread of 2 Myr, there are $\approx 15$ per cent stars at most which are older than the age spread and are actually lower mass stars (see figs 1–5 in Palla & Stahler 2000). Lastly, the distance uncertainties of target clusters may also influence the selection of the IM stars. The typical uncertainties of distance are about 10 per cent for the clusters in the solar neighbourhood (Reipurth 2008a,b). For the clusters studied by Hernández et al. (2005), the uncertainties are even smaller (less than 5 per cent) with Hipparcos data. For deriving the mass and age of a star on the HR diagram, the effective temperature is independent of the distance because it is derived from spectroscopy, while luminosity is directly affected. However, the luminosity can differ by only 0.2 mag with the assumed distance uncertainties, which then cause a mass difference of $\lesssim 0.1 \, M_\odot$ around the lower mass limit of this study, $1.5 \, M_\odot$, from the isochrone models by Siess et al. (2000) in the target age range of this paper ($\lesssim 11$ Myr). Because this mass uncertainty is very small, the distance uncertainties for the selection of IM stars do not affect our results. The above three points (or any other unconsidered uncertainties) might mask the possible lifetime difference between IM and LM stars. However, if we find any significant difference, it is likely to be real and should be clearly seen with better selected IM-star samples in the future. Note that contamination of higher mass stars can occur, but that should not affect the lifetime differences between the discs of IM and LM stars. We discuss the effect of IM-star selection on the derived IMDF in Section 8.1.2.

### Table 2. Adopted spectral type for the boundary masses of IM stars.

| $t^a$ (Myr) | $7 \, M_\odot$ | $1.5 \, M_\odot$ | Boundary mass with $\Delta t^b$ |
|-------------|----------------|------------------|-------------------------------|
| $7 \, M_\odot$ |                | $7 \, M_\odot$   | $7 \, M_\odot$ ($\Delta t = \pm 2$ Myr) |
| $1$       | B2.5           | K5 (1.5–1.6 $M_\odot$) | $\gtrsim 7 \, M_\odot$ | $1.2–1.5 \, M_\odot$ |
| $1.5$      | B3             | K5 (1.2–1.5)    | $\gtrsim 7 \, M_\odot$ | $1.2–<2.2 \, M_\odot$ |
| $2$        | B3             | K5 (1.2–1.5)    | $7$                   | $1.2–<2.2 \, M_\odot$ |
| $2.5$      | B3             | K5 (1.2–1.5)    | $6–7$                 | $1.2–1.8 \, M_\odot$ |
| $3$        | B3             | K4 (1.5–1.6)    | $>6–7$                | $1.2–1.6 \, M_\odot$ |
| $4$        | B3             | K4               | $7$                   | $1.4–1.8 \, M_\odot$ |
| $5$        | B3             | K4 (1.4–1.5)    | $7$                   | $>1.4–1.6 \, M_\odot$ |
| $6$        | B3             | K3               | $7$                   | $1.4–1.6 \, M_\odot$ |
| $7$        | B3             | K2               | $7$                   | $1.4–1.7 \, M_\odot$ |
| $8.5$      | B3             | K1               | $7$                   | $1.4–1.7 \, M_\odot$ |
| $10$       | B2             | K2               | $\sim 7$              | $1.3–1.5 \, M_\odot$ |
| $11$       | B3             | G7               | $7$                   | $>1.3–<1.7 \, M_\odot$ |

$^a$Age of cluster.

$^b$Spectral type for the boundary mass ($7$ and $1.5 \, M_\odot$) based on the isochrone model by Siess et al. (2000). The range of stellar mass corresponding to the spectral type is shown in the parentheses when the range covers more than $\Delta M > 0.1 \, M_\odot$.

$^c$The possible shift of boundary mass for the age spread of $\pm 2$ Myr based on the isochrone model by Siess et al. (2000).

2.3 Selected samples

We searched the literature to gather all of the available spectral type information for the stars in the sample clusters. We then made a list of all the IM stars by selecting cluster members by spectral type earlier than that of the lower mass boundary and also later than that of the higher mass boundary. The clusters chosen are shown in column 1 and the references to the papers from which the IM stars were selected are shown in column 2 of Table 3. Following the fifth criterion in Section 2.1, we removed any target clusters for which less than three IM stars can be identified. Also, because IMDFs for clusters with age of $>5$ Myr are found to be $\approx 0$ per cent as discussed in the following sections, we obtained IMDFs for only about 10 clusters. Disc fractions for clusters with age of $\leq$ 5 Myr are the most useful for studying stellar mass dependence of disc dispersal (cf. Kennedy & Kenyon 2009).

As a result, the total number of stars used for deriving $JHK$ and MIR IMDF becomes 799 and 365, respectively. In Appendix , the IM-star samples for all clusters are summarized in tables as well as in colour–colour diagrams. For the following five clusters, the spectral type information for lower mass stars in the literature is incomplete, and we could not reach to the mass limit of $1.5 \, M_\odot$: γ Vel (F5: $2 \, M_\odot$), λ Ori (G0: $2 \, M_\odot$), Per OB2 (G8: $1.8 \, M_\odot$), OB1bc (G3: $2.2 \, M_\odot$), and OB1a (G6: $1.7 \, M_\odot$). Although it is desirable to set exactly the same mass limit, such as $2 \, M_\odot$, we used $1.5 \, M_\odot$ as the lowest mass for the other clusters in order to obtain as many IM stars as possible.

3 $JHK$ IMDF

The optical–NIR SED difference between stars with and without discs is more prominent for IM stars than LM stars (Lada & Adams 1992; Carpenter et al. 2006). This is mainly because the stellar SED
for stars with higher masses peaks at the shorter wavelength side of the $U$ and $B$ bands (e.g. $\sim 0.3 \mu m$ for AO stars, with mass of $\sim 3 M_\odot$ and $T_{\text{eff}}$ of 9790 K; Cox 2000) compared to the disc SED that peaks near the $K$ band ($\gtrsim 2 \mu m$). HAeBe stars also have a large infrared excess from the optically thick disc 'wail', which arises from the inner edge of the discs and where dust disc is so hot as to evaporate (Dullemond, Dominik & Natta 2001; Luhman et al. 2004). Therefore, even in the case of using only $JHK$ photometry, IM stars with discs can be much more easily and more accurately selected than LM stars, disc fractions of various young clusters have been derived from those for classical Be (CBe) stars based on the modelling of the disc emission. CBe stars show NIR excess from gaseous free–free emission and are often confused with HAeBe stars, but the disc excess from HAeBe stars is much larger. After Hernández et al. (2005) defined the locus of HAeBe stars on the intrinsic $JHK$ colour–colour diagram, Wolff, Strom & Rebull (2011) identified HAeBe stars of IC 1805 using their definition. Comerón et al. (2008a)

### Table 3. IM-star selection and $JHK$/MIR IMDF of target clusters.

| Cluster   | Membership ref$^a$ | Age (Myr) | SpT$^b$ | SpT ref$^c$ | $JHK$ IMDF$^d$ (%) | MIR Ref$^e$ (%) | MIR IMDF$^f$ (%) |
|-----------|---------------------|-----------|----------|-------------|-------------------|----------------|----------------|
| NGC 1333  | S76, As97, Wi04     | 1 ± 1     | B2.5–K5  | Win10, Co10, SB | 17 ± 17 (1/6)    | Gu09          | 100 ± 50 (4/4) |
| Trapezium | Hi97                | 1 ± 1     | B2.5–K5  | Hi97        | 9 ± 3 (8/89)      | –             | –             |
| ρ Oph     | Wi08                | 1 ± 1     | B2.5–K5  | Wi08        | 0 ± 5 (0/20)      | W08           | 80 ± 20 (4/5)  |
| Taurus    | Fu06, Fu11          | 1.5 ± 1.5 | B3–K5    | Fu06, Fu11   | 31 ± 10 (9/29)    | Fu06, Lu06    | 72 ± 16 (21/29) |
| Cha I     | Lu04                | 2 ± 1     | B3–K5    | Lu04        | 29 ± 13 (5/17)    | Lu08          | 60 ± 35 (3/5)  |
| NGC 2068/71 | Fi08                | 2 ± 1.5   | B3–K5    | Fi08        | 15 ± 11 (2/13)    | Fi08          | 69 ± 23 (9/13) |
| IC 348    | Lu03                | 2.5 ± 0.5 | B3–K5    | Lu03        | 0 ± 3 (0/34)      | Lu06          | 21 ± 8 (7/34)  |
| η Ori     | He07a               | 3 ± 1     | B3–K4    | Ca10, Re09, SB | 0 ± 4 (0/23)    | He07a         | 17 ± 9 (4/23)  |
| NGC 2224  | Re02                | 3 ± 1     | B3–K4    | Re02        | 0 ± 2 (0/55)      | –             | –             |
| Tr 37     | Si05                | 4 ± 1     | B3–K4    | Si05, SB    | 3 ± 2 (2/69)      | Si05, Si06    | 22 ± 10 (5/23) |
| Ori OB1bc | He05                | 4 ± 3     | B3–K4    | He05        | 4 ± 2 (4/94)      | –             | –             |
| Upper Sco | Ca06                | 5 ± 1     | B3–K4    | Ca06        | 0 ± 1 (0/94)      | Ca06          | 2 ± 2 (2/94)$^b$ |
| NGC 2362  | Da07                | 5 ± 1     | B3–K4    | Da07        | 0 ± 5 (0/19)      | Da07          | 0 ± 5 (0/19)   |
| γ Vel     | He08                | 5 ± 1.5   | B3–K4    | He08, SB    | 0 ± 6 (0/17)      | He08          | 0 ± 6 (0/17)   |
| λ Ori     | He09                | 5 ± 1     | B3–K4    | He09        | 8 ± 8 (1/13)      | He09          | 4 ± 4 (1/27)   |
| Per OB2   | He05                | 6 ± 2     | B3–K3    | He05        | 0 ± 3 (0/31)      | –             | –             |
| η Cham    | Me05                | 7 ± 1     | B3–K2    | Me05        | 0 ± 33 (0/3)      | Me05          | –             |
| Ori OB1a  | He05                | 8.5 ± 1.5 | B2–K1    | He05        | 2 ± 1 (2/98)      | –             | –             |
| NGC 7160  | Si05                | 11 ± 1    | B3–G7    | Si05        | 0 ± 1 (0/82)      | Si06          | 3 ± 2 (2/78)   |

$^a$References from which the members of the clusters were picked up. The IM stars that were used for deriving the $JHK$ IMDF were obtained from these references. For the Trapezium Cluster, members are selected from Hi97, but only those whose stated membership probability is more than 50 per cent were used.

$^b$The range of spectral type for the target mass range (1.57 M_\odot$) for the cluster age listed in the third column. † shows cluster for which the observed spectral types of cluster members do not completely reach to the boundary spectral type for the lowest mass (see the main text).

$^c$References from which the spectral types in the clusters were obtained. For some clusters for which the spectral type listing in the published papers is incomplete, we supplement the spectral type information with those listed in the SIMBAD data base at http://simbad.u-strasbg.fr/simbad/ (denoted as SB).

$^d$Derived $JHK$ IMDF and uncertainties based on Poisson errors. Numbers in parentheses show the number of disc-harbouring members over total number of members. For the treatment of Poisson errors for zero detection, see the main text.

$^e$References for the MIR photometric data.

$^f$/Derived MIR IMDF and uncertainties based on Poisson errors. Numbers in the parentheses show the number of disc-harbouring members over total number of members. For the treatment of Poisson errors for zero disc-harbouring members, see the main text.

$^g$/The clusters for which $Spitzer$ MIR data are unavailable.

$^h$/For MIR-disc classification of this cluster, we use the slope between [4.5] and [8] rather than [3.6] and [8] because Carpenter et al. (2006) do not list photometry data in [3.6]. However, Kennedy & Kenyon (2009) confirm that use of [4.5] instead of [3.6] does not change the classification.

$^i$/MIR IMDF was not derived because of the small number of sample IM stars ($<3$).

References:
As97: Aspin & Sandell (1997); Ca06: Carpenter et al. (2006); Ca10: Caballero, Albacete-Colombo & López-Santiago (2010); Co10: Connelley & Greene (2010); Da07: Dahm & Hillenbrand (2007); Fi08: Flaherty & Mazurello (2008); Fu06: Furlan et al. (2006); Gu09: Gutermuth et al. (2009) He05: Hernández et al. (2005); He07a: Hernández et al. (2007a); He08: Hernández et al. (2008); He09: Hernández et al. (2009); Hi97: Hillenbrand (1997); Ho78: Houk (1978); Lu06: Lada et al. (2006); Lu03: Luhan et al. (2003); Lu04: Luhan (2004); Lu06: Luhan et al. (2006); Lu08: Luhan et al. (2008); Me05: Megeath et al. (2005); Re02: Rebull et al. (2002); Re09: Renson & Manfroid (2009); Si05: Sicilia-Aguilar et al. (2005); Si06: Sicilia-Aguilar et al. (2006); Si07: Strom, Vrba & Strom (1976); Wi04: Wilking et al. (2004); Wi08: Wilking, Gagné & Allen (2008); Win10: Winston et al. (2010).

#### 3.1 Identification of IM stars in the colour–colour diagram

On the $JHK$ colour–colour diagram, the stars with discs are known to be lying in the infrared excess region that is separated from the region of stars without discs (e.g. Lada & Adams 1992). For LM stars, disc fractions of various young clusters have been derived using the $JHK$ colour–colour diagram (Lada 1999; Yasui et al. 2010; see also Hillenbrand 2005). For IM stars, Lada & Adams (1992) showed that HAeBe stars occupy completely separated regions even from those for classical Be (CBe) stars based on the modelling of disc emission. CBe stars show NIR excess from gaseous free–free emission and are often confused with HAeBe stars, but the disc excess from HAeBe stars is much larger. After Hernández et al. (2005) defined the locus of HAeBe stars on the intrinsic $JHK$ colour–colour diagram, Wolff, Strom & Rebull (2011) identified HAeBe stars of IC 1805 using their definition. Comerón et al. (2008a)
defined the disc excess region for HAeBe stars on the JHK colour–colour diagram (non-intrinsic) by using a line that passes through $(H - K, J - H) = (0.11, 0)$ and is parallel to the reddening vector as a border line between the HAeBe stars and CBe stars.

In Fig. 1, we plot the observed colours of the HAeBe stars (filled circles) and the CBe stars (open circles) for all the samples in Hernández et al. (2005, Upper Scorpius, Per OB2, Lac OB1, Ori OB1a, and Ori OB1b) and are shown with the dot-dashed line; the grey dot–dashed line shows the definition by Comerón et al. (2008a) while the black dot–dashed line shows our definition. The region to the right of the border line (orange colour) is defined as the ‘IM-disc excess region’.

3.2 Determination of the IMDF

We used the 2MASS Point Source Catalog$^3$ (Skrutskie et al. 2006) to obtain the $JHK$ magnitudes of all the sample IM stars. We rejected all IM stars that do not have an ‘A’ photometric quality flag (signal-to-noise $\geq 10$ for all $JHK$ bands) in the 2MASS catalogue. We then obtained the IMDF of the IM stars from the $JHK$ colour–colour diagrams of each target cluster.

From previous studies of the disc fractions for LM stars, the systematic errors of the disc fraction are known to be less than the statistical errors when using data with small photometric uncertainties (Liu, Najita & Tokunaga 2003; Yasui et al. 2009). The present data should be in the same situation in view of the small uncertainties in $JHK$ photometry of the IM-star samples. For estimating the statistical errors of the disc fraction, we assumed that the errors are dominated by Poisson errors ($\sqrt{N_{\text{disc}}}/N_{\text{disc}}$) for the $1\sigma$ uncertainty of the disc fraction, where $N_{\text{disc}}$ is the number of stars with optically thick discs ($=\text{HAeBe stars}$) and $N_{\text{all}}$ is the number of all cluster members, respectively. However, if the number of HAeBe stars is zero, the statistical error was calculated assuming one HAeBe star in the examined target cluster to give a $1\sigma$ uncertainty of $1/N_{\text{all}}$ (e.g. Hernández et al. 2005). Table 3 summarizes the derived $JHK$ IMDFs for all the target clusters.

4 MIR IMDF

In the previous studies utilizing the data from the Spitzer Space Telescope, the SED slope ({$\alpha = d \ln \lambda F_{\lambda}/d \ln \lambda$;} Adams, Lada & Shu 1987) in the MIR wavelength range (3.6, 4.5, 5.8, and 8.0 $\mu$m) is used for selecting disc-harbouring stars (e.g. $\alpha \geq -2.0$; Lada et al. 2006; Hernández et al. 2007b). The number of such IM stars should be precisely determined with this method since discs show a large flux excess compared to the central star continuum in the MIR. For the derivation of the MIR IMDF, we made use of the published Spitzer photometric results in the literature because of the signal-to-noise and uniformity across target clusters.

For the definition of the MIR-disc fraction, we followed the procedure by Kennedy & Kenyon (2009), who derived $\alpha$ using the SED slope of Spitzer’s Infrared Array Camera (IRAC) [3.6] to [8] and regarded those with $\alpha > -2.2$ as cluster members with MIR dust discs. We estimated $\alpha$ of the IM stars only in the cases where reliable photometry in all four IRAC bands is available. However, for the derivation of $\alpha$, we used only [3.6] and [8.0] because those two bands determine $\alpha$ for almost all cases. For several clusters (e.g. IC 348, which shows moderate extinction), we cross-checked our $\alpha$ values with those in the literature (Hernández et al. 2008) and confirmed that they are almost the same. Following Kennedy & Kenyon (2009), we set the boundary at $\alpha = -2.2$ to separate all the IM stars into the categories of ‘with disc’ and ‘without disc’.

For the target clusters with published Spitzer data (13 clusters out of 19 target clusters; see Table 3), we estimated $\alpha$ for the IM stars. Unfortunately, the MIR Spitzer photometry of some IM stars in the nearby star-forming regions could not be obtained because they are too bright for Spitzer. Therefore, the number of IM stars for the MIR IMDF is, in most cases, less than those for the $JHK$ IMDF (e.g. Tr 37). In some cases, we have more sample stars for

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$^3$ http://www.ipac.caltech.edu/2mass/releases/allsky/doc/sec6_2.html
the MIR than those for JHK (e.g. λ Ori) because some of the MIR stars do not have good JHK photometry with 2MASS. In this case, we calculated the MIR IMDF by rationing the number of stars with discs by the total number of stars in each MIR sample. The results are summarized in Table 3. The treatment of uncertainty is similar to that for the JHK IMDF, as described in Section 3.

5 DEFINITION OF THE DISC LIFETIME

Different terms have been used for the disc dispersal time-scale: e.g. disc lifetime (Lada 1999; Haisch et al. 2001b; Hernández et al. 2008), disc decay time-scale (Mamajek 2009), and disc dissipation time-scale (Fedele et al. 2010). These terms are based on the observed cluster age–disc fraction plot with age on the horizontal axis and disc fractions on the vertical axis. However, these terms are not consistently used. Moreover, the value of disc fraction at zero age has not been considered with care because these studies are performed mainly for LM stars and all LM stars are thought to initially have discs in the standard picture of LM star formation (Shu, Adams & Lizano 1987). Since this may not be the case for IM stars, we define these terms explicitly in this section.

To fit with a single function to the disc fraction evolution curve, an exponential function is appropriate. The ‘disc decay time-scale’ \( \tau \) is defined as DF[percent] \( \propto \exp(-t/\tau) \) (e.g. Mamajek 2009). The decay time-scale is proportional to the slope of the curve on a semilog plot, log (IMDF)–age plot (Fig. 2). On the other hand, the most often used term ‘disc lifetime’ \( \tau_{\text{life}} \) is originally defined as the x-intercept of the cluster age–disc fraction plotted as a linear function. However, fitting with a linear function does not appear appropriate to describe the shape of disc fraction evolution, which appears to decrease and level out at about 5–10 per cent (Hernández et al. 2008). Therefore, we define the disc lifetime to be the time when the disc fraction is 5 per cent (\( \tau_{\text{life}} \)) and use this for the discussion throughout this paper.

We define the ‘initial disc fraction’ (DF\(_0\)) as the disc fraction at \( t = 0 \). Fig. 2 shows two possible cases: DF\(_0\) = 100 per cent and DF\(_0\) < 100 per cent for the same \( \tau_{\text{life}} \). The value of DF\(_0\) = 100 per cent (the dark grey line in Fig. 2) means that all stars initially have discs, while that of DF\(_0\) < 100 per cent (the light grey line in Fig. 2) means that all stars do not necessarily have discs from the beginning or that some discs disappear quickly within a very short time-scale that is not recognized within the accuracy of the age determination. Note that if DF\(_0\) is constant, then the disc lifetime is proportional to the disc decay time-scale.

6 EVOLUTION OF THE K DISC

The stellocentric distance of the K disc (\( r_K \)) for HAeBe stars has a wide range, ~0.1–1.0 au for HAe stars to ~1–10 au for HBe stars (Millan-Gabet et al. 2007). However, because a large part of the IM stars in this paper are HAe stars, \( r_K \) of ~0.3 au is taken to be the nominal radius in this paper. The JHK IMDF derived in this paper is the fraction of the HAeBe stars whose discs at a stellocentric distance of \( r_K \) of ~0.3 au are optically thick with a temperature of \( \sim 1500 \) K (see e.g. fig. 2 in Millan-Gabet et al. 2007).

In this section, we discuss the evolution of the K disc of IM stars traced by K-band excess emission and on the JHK IMDF change with cluster age.

6.1 Disc lifetime

By making use of the method described in Section 3, the JHK IMDFs of ~20 clusters are derived for the first time, in particular for clusters at ages <3 Myr. Fig. 3 shows the derived IMDF as a function of ages (black filled circles). The JHK IMDF is found to show an exponentially decreasing trend with increasing cluster age as seen in previous studies. There is a large scatter with many upper limits at 1–3 Myr. In view of the upper limit points, we used the astronomical survival analysis methods (Isobe, Feigelson & Nelson 1986). These terms are based on the...
6.3 Stellar mass dependence of the disc lifetime

The stellar mass dependence of the disc lifetime can be a strong constraint on the disc dispersal mechanism and the theory of planet formation, as discussed by Kennedy & Kenyon (2009). They compared the disc fraction for different mass bins, $\sim 1 \, M_\odot$ (0.6–1.5 $M_\odot$) and $\sim 3 \, M_\odot$ (1.5–7 $M_\odot$), in seven clusters and suggested that their data are more consistent with $t_{\text{KK09}} \propto M^{-0.8\pm0.7}$ than with $\propto M^{-1/4}$. $t_{\text{KK09}}$ is the disc decay time-scale defined by their model, in which the discs are dispersed when the accretion rate drops below the wind-loss rate. However, only four clusters appear to be the main contributors to the resultant mass dependence (see fig. 9 in Kennedy & Kenyon 2009) – the H$_\alpha$ disc fraction for three clusters and the MIR-disc fraction for one cluster. Although Hernández et al. (2005) and Carpenter et al. (2006) found similar stellar mass dependence for clusters with ages $>3$ Myr, the dependence is uncertain because of an insufficient number of clusters, in particular those with ages $<3$ Myr. Obviously, it is necessary to increase the number of data points to clarify the mass dependence. Also, the large uncertainty in previous studies might be the result of differences in the evolution of the $K$ and MIR discs. Thus, studying of only the $JHK$ disc (or only the MIR disc) might show a clearer mass dependence.

The stellar mass dependence of the disc lifetime can be quantitatively estimated by combining the time-scales for the two mass ranges. For the IMDF, stars with mass of 1.5–7 $M_\odot$ are used in this paper. Considering the larger number of lower mass stars with the typical universal IMF (e.g. Kroupa 2002), the characteristic mass is set as 2–3 or 2.5 $M_\odot$. We estimated the stellar mass dependence with a characteristic mass from 2–3 $M_\odot$, but no significant difference was found within the uncertainties. The characteristic mass of 0.5 ± 0.5 $M_\odot$ (0.1–1 $M_\odot$) for the LMDF is set by considering the IMF and mass detection limit ($\sim 0.1 \, M_\odot$) for clusters used to derive disc fractions. Assuming the stellar mass dependence of the disc lifetime as a power-law function of stellar mass, we find $t_{\text{JHK}} \propto M^{-0.8\pm0.7}$ using the survival fitting. These results are tabulated in Table 4. Our result is consistent with the results by Kennedy & Kenyon (2009), who found that $t_{\text{KK09}}$ is proportional to about $M^{-0.5}$. However, note again that our results are derived only from the $K$-disc data, while Kennedy & Kenyon (2009) used mostly data from the MIR disc or the H$_\alpha$ gas disc. We discuss the difference of disc lifetimes of the $K$ disc, MIR disc, and gas accretion disc in Section 8.

### Table 4. Summary of disc lifetime.

| Mass          | $t_{\text{JHK}}$ (Myr) | Binning $^b$ | $t_{\text{MIR}}$ (Myr) | Binning $^b$ |
|--------------|------------------------|--------------|-----------------------|--------------|
| Intermediate | $2.5 \, M_\odot$       | Survival     | $2.8 \pm 2.4$         | Survival     |
| Low          | $0.5 \, M_\odot$       | 9.7 ± 1.1    | $3.3 \pm 0.9$         | Survival     |
| Mass dependence | $M_\odot^{-0.8\pm0.7}$ |               | $6.1 \pm 4.2$         |               |

$a$Characteristic mass for the mass range (see details in the main text).
$^b$See Section 8.1 for the definition of this fitting.

7 EVOLUTION OF THE MIR DISC

In this section, we discuss the evolution of the inner disc of IM stars traced by the MIR excess emission and using the results on the MIR IMF derived in Section 4.
7.3 Stellar mass dependence of the disc lifetime

The results of the lifetimes for the MIR discs of both IM and LM stars are summarized in Table 4. We derived the stellar mass dependence of the MIR-disc lifetime as $t_{\text{KIN9}} \propto M_{\ast}^{0.2}$, assuming a power-law function and using the characteristic masses for the two mass ranges as for the $\text{HJK}$-disc lifetime (Section 6.2) and the results for the survival fitting. These results are tabulated in Table 4.

Our results show no significant stellar mass dependence of the disc lifetime, which is apparently inconsistent with Kennedy & Kenyon (2009), who derived a steeper stellar mass dependence of $\tau_{\text{KK09}} \propto M_{\ast}^{-0.5}$. However, note that their results are based on the lifetime of both dust and gas discs. The strong dependence appears to be mainly contributed from the inclusion of the gas disc. They suggested an $M_{\ast}^{-0.5}$ dependence rather than $M_{\ast}^{-0.25}$ dependence mostly based on the data for three clusters [Taurus (H$\alpha$), Tr 37 (H$\alpha$ and MIR), and OB1bc (H$\alpha$); see their fig. 9], but the existence of the discs is based mostly on the H$\alpha$ gas disc for those three clusters. Using their data, we attempted to estimate the mass dependence and confirmed that $\tau \propto M_{\ast}^{-0.5}$ is obtained in the case of using only the H$\alpha$ disc lifetime for the eight clusters in their list except for OB1a/25Ori, while $\tau \propto M_{\ast}^{-0.2}$ is obtained in the case of using only the MIR-disc fraction for the same eight clusters. Therefore, we conclude that there is no mass dependence of the lifetime of an MIR disc within the uncertainties.

8 DIFFERENCE IN THE EVOLUTION OF $K$ AND MIR DISCS

In the previous sections, we discussed the disc lifetime of the $K$ disc, which traces the innermost dust disc, and the MIR disc, which traces the inner disc outside of the $K$ disc. In this section, we compare the $K$ and MIR-disc fractions and discuss the evolution of the $K$ disc and the MIR disc. We also discuss the relation of the MIR disc to the inner gas disc, which is traced by accretion signatures, such as the H$\alpha$ emission line.

8.1 Comparison of the $K$ disc and the MIR disc

8.1.1 LM stars

Before discussing the case for the IM stars, we take a look at the case for the LM stars as a reference. Fig. 5 (right) shows the comparison of the $\text{HJK}$ LMDF (red) and the MIR LMDF (blue). The derived lifetime for the $K$ disc (9.7 ± 1.1 Myr) and that for the MIR disc (8.6 ± 0.7 Myr) are identical within the uncertainties (see Table 4), which suggests that the $K$ disc and the MIR disc disperse almost simultaneously in the discs of LM stars. This is consistent with the recent view of disc dispersal that the entire disc disperses almost simultaneously for LM stars ($\Delta t \lesssim 0.5$ Myr; Andrews & Williams 2005).

8.1.2 IM stars

We compared $\text{HJK}$ and the MIR IMDFs in Fig. 5 (left). The filled circles showing IMDFs and the arrows showing upper limits are labelled with the cluster numbers in Table 1. This figure immediately suggests that the MIR IMDFs are systematically larger than the $\text{HJK}$ IMDFs. The MIR IMDF appears to be almost as high as 100 per cent for all the clusters (Section 6.1). Using their data, we attempted to estimate the mass dependence and confirmed that $\tau \propto M_{\ast}^{-0.5}$ is obtained in the case of using only the H$\alpha$ disc fraction for the eight clusters in their list except for OB1a/25Ori, while $\tau \propto M_{\ast}^{-0.2}$ is obtained in the case of using only the MIR-disc fraction for the same eight clusters. Therefore, we conclude that there is no mass dependence of the lifetime of an MIR disc within the uncertainties.
Comparison of $JHK$-disc fraction (red) to MIR-disc fraction (blue) as a function of cluster age. The left figure is for intermediate-mass stars (IMDF), while the right figure is for low-mass stars (LMDF). For the IMDF, the red filled circles show the $JHK$ IMDF from Section 6 (Table 3), while the blue filled circles show the MIR IMDFs from the same table. The arrows show the upper limits. Both circles and arrows are labelled with the cluster numbers in Table 1. The lines show the fits with survival analysis including the upper limits. For the LMDF, red filled circles are from Yasui et al. (2009, 2010), while blue filled circles are mainly from Roccatagliata et al. (2011, see the text for the details).

Comparison of $JHK$ IMDF to MIR IMDF for 13 target clusters for which both $JHK$ and MIR IMDFs are available (see Table 3). The smaller $JHK$ IMDF is a unique property of the IM-star disc lifetimes compared to those of the LM stars. The significantly lower disc fraction of the $K$ discs means they disappear much earlier than the MIR discs. The lifetime difference is about 3 Myr ($6.1 - 2.8 = 3.3$ Myr; see Table 4).

As suggested in Section 2.2, possible contamination of LM stars in selecting IM stars may affect the above discussion. Therefore, it is safer to set the lower limit mass for IM stars as $2 M_\odot$, which is slightly larger than the nominal mass limit in this paper ($1.5 M_\odot$). With this lower limit mass, we derived the $JHK$/MIR IMDFs in the same way as in Sections 2–4. As a result, the derived IMDFs do not largely differ, and the estimated lifetimes of $K$ and MIR discs are $2.7 \pm 3.6$ and $6.0 \pm 6.1$ Myr, respectively, which are very close to the results for the lower mass limit of $1.5 M_\odot$, although the uncertainties for both disc fractions and disc lifetimes become larger. Therefore, we conclude that the effect of possible contamination of LM stars on our IM-star samples is very small, and that it does not change the conclusion.

An alternative approach was tried to confirm these results. To increase the statistical significance, we binned all of the disc-harbouring stars and cluster members in the cluster age range from 1 to 5 Myr with 1 Myr bins and 1 Myr steps and computed both the $JHK$ and MIR IMDFs. To have enough clusters, all the members of the four clusters in the 6–11 Myr range are accumulated to estimate a binned IMDF at $8.5 \pm 2.5$ Myr for the $JHK$ IMDF. Because we have only one data point at $t = 11$ Myr for the MIR IMDF, we simply used it without binning. This ‘binning’ process effectively reduces the number of upper limit points, and the disc fraction curve becomes clearer with less scatter.

The results are plotted in Fig. 7, which suggests the disc fraction offset between the $JHK$ and the MIR IMDFs as well as the lifetime difference. The fitting results for the $JHK$ IMDFs are as follows: disc lifetime ($t_{\text{life}}(\text{IM},JHK)$) of $3.3 \pm 0.9$ Myr with DF$_{0/JHK}$ of $35 \pm 13$ per cent.
appears to be the only unique property of the IM stars compared to the LM stars.

8.3 Comparison with the Hα gas disc

Another question we investigated is how the dust disc evolution is synchronized with the gas-disc evolution. We compared the disc fraction and lifetime of the K and MIR discs with those of the innermost gas disc traced by the Hα emission as has been comprehensively studied by Fedele et al. (2010). They used spectroscopy of the Hα emission for the clusters in the solar neighbourhood. Because the Hα emission was not observed for many IM stars, we used the Hα disc fractions from Kennedy & Kenyon (2009, their 1.5–7 M☉ samples for IMDF and all mass range samples for LMDF) and directly compared them with those of K and MIR discs. This is shown in Fig. 8. The left-hand panel includes eight clusters (Taurus, Cha I, IC 348, Tr 37, Ori OB1bc, Upper Sco, NGC 2362, and NGC 7160), and the right-hand panel includes an additional cluster (OB1a/25Ori).

In the right-hand panel of Fig. 8, the Hα LMDF closely traces JHK and MIR LMDFs, and this shows the co-evolution of the dust and gas discs for LM stars. This is consistent with the results of Fedele et al. (2010), who found that the time-scale of Hα mass accretion is almost the same as that of the dust disc. In the left figure, however, the Hα IMDF shows a different cluster age dependence compared to the IMDF of the dust disc. We note that (1) it overlaps the MIR IMDF at younger ages (<5 Myr), and (2) it is systematically larger than the JHK IMDF at younger ages with a longer lifetime than the K disc. While the first point suggests the co-evolution of the gas and dust disc, which is suggested by Fedele et al. (2010), the second point has not been noted before. Only the K disc appears to have a unique cluster age dependence among the different disc components of the IM stars.

8.4 Long transition disc phase for IM stars

In summary, for the IM stars there appears to be the following lifetime sequence for the various stellocentric radii: $\nu(\text{IM}) < \nu(\text{K}) \approx \nu(\text{MIR}) < \nu(\text{Submm})$. On the other hand, all these time-scales are nearly the same for the LM stars (Andrews & Williams 2005, 2007; Mathews et al. 2012). The above result suggests that for the IM stars the K disc has a shorter time-scale and an evolutionary history that is different from that of the LM stars. The observed longer lifetime with larger stellocentric distance is qualitatively consistent with the recent view of the disc dispersal sequence for protoplanetary discs of LM stars (Williams & Cieza 2011). However, the lifetime difference between the K and MIR discs for the IM stars (~3–4 Myr) is significantly longer than that suggested previously for LM stars ($\Delta t \lesssim 0.5$ Myr; e.g. Williams & Cieza 2011).

That a time lag is clearly seen only for the IM stars gives us a clue to the mechanism of disc evolution. The time-lag between K- and MIR-disc lifetimes can be interpreted as a transition disc phase, in which the innermost K disc disappears while the outer MIR disc remains. Discs with no Hα excess emission and with MIR excess are called ‘classical’ transition discs (Muzerolle et al. 2010), while the original definition of ‘transition disc’ is a disc that has no or little excess emission at $\lambda < 10 \mu$m and a significant excess at $\lambda \geq 10 \mu$m (Strom et al. 1989; Wolk & Walter 1996). The two significant processes, disc dispersal (e.g. Muzerolle et al. 2010) and planet formation (e.g. Calvet et al. 2002), are thought to happen during this phase. Therefore, our finding suggests that such critical evolutionary events can be clearly recognized in the transition disc.

Figure 7. Comparison of the JHK IMDF (red) to the MIR IMDF (blue) as a function of age. Same as the left figure of Fig. 5, but the data are binned in the age axis direction (see Section 8.1 for details). The straight lines show the fits to the data points with the upper limit at 3 Myr excluded from the fitting of JHK IMDF.

with $\chi^2$ of 1.0 with degree of freedom of 3. The derived lifetime is, in fact, very close to the results without binning (2.8 Myr). Note that the data point at $t = 3$ Myr was not used because it remains an upper limit due to many upper limits in this age bin. As for MIR IMDF, a disc lifetime $t_{\text{IM}}^{(\text{JHK})}$ of 6.7 ± 1.1 Myr with DFM(104 ± 26 per cent with $\chi^2$ of 2.2 with degree of freedom of 4 was obtained. In summary, these ‘binning’ fitting results (see Table 4) confirm the survival analysis results without binning although there are very few data points in the binning fitting and we should be cautious of any unknown biases. The stellar mass dependence for this binning analysis is also listed in Table 4 and is consistent with previous results. Therefore, we conclude that there is a lifetime difference of ~3–4 Myr between K and MIR discs.

8.2 Comparison with the submm disc

To investigate further the dependence on stellocentric distance, we also compared the disc fraction and lifetime of the K and MIR discs with that of the outer cold (~10 K) dust disc traced by the submm and mm continuum. There are a number of studies of submm observations of IM stars in Taurus (1.5 Myr), $\rho$ Oph (2 Myr), and Upper Sco (5 Myr) (Andrews & Williams 2005, 2007; Mathews et al. 2012). We confirmed that the MIR disc is well correlated with the submm disc for the IM stars. Out of the observed 20 B-, A-, F, and G-type stars in the above papers, 19 stars are detected with MIR and submm discs, and only one star, HIP 76310 in Upper Sco, lacks an MIR disc but has a submm disc. The strong correlation clearly suggests that the MIR inner disc and submm outer disc disperse almost simultaneously for the IM stars. This behaviour is similar to that for LM stars (Andrews & Williams 2005, 2007; Mathews et al. 2012). Thus, the early disappearance of the innermost K disc again
phase for IM stars as a time lag between the dispersal of the $K$ disc and the dispersal of the MIR disc, while both events happen nearly simultaneously for the LM stars ($\Delta t \lesssim 0.5 \text{ Myr}$).

9 PHYSICAL MECHANISM OF THE DISC EVOLUTION OF IM STARS

In this section, we discuss the implications of the observed timescales of the gas/dust discs on the mechanism of disc evolution of the IM stars. Although there are many detailed processes related to disc evolution, we focus on discussing the following two categories, which are not intended to be comprehensive but broadly cover basic processes related to disc evolution: (1) the disc dispersal processes, such as mass accretion and dissipation due to photoevaporation, and (2) the dust settling to the disc mid-plane and dust growth, which could be connected to planetesimal formation and planet formation. We suggest that the latter process is more likely for the early disappearance of the $K$ discs.

Before discussing the detailed evolution mechanisms, we first remark on the radial configuration of the dust disc in the steady state. If we consider an optically thick disc for discs with IR excess, the radius ($R$) with a temperature ($T$) is given by $R = (L_*/4\pi T^4 \sigma)^{1/2}$, where $L_*$ is the stellar luminosity and $\sigma$ is the Stefan–Boltzmann constant. The dust temperature is about 1500 K for the $K$ disc and ~500 K for the MIR disc as inferred from the peak wavelength of the blackbody emission. From those typical temperatures, the stellocentric distances to those disc regions are estimated to be $r_K \sim 0.3 \text{ au}$, $r_{\text{MIR}} \simeq 5 \text{ au}$ for IM stars (with the characteristic mass $M_* \sim 2.5 M_\odot$) and $r_K \simeq 0.1 \text{ au}$, $r_{\text{MIR}} \simeq 1 \text{ au}$ for LM stars (with the characteristic mass $M_* \sim 0.5 M_\odot$) (see Fig. 9), considering the effective temperatures of the central star (see Millan-Gabet et al. 2007). Because the radius $R$ of an optically thick disc with IR excess is expressed with $R = (L_*/4\pi T^4 \sigma)^{1/2}$, $R$ is proportional to $M_*^2$ with the mass–luminosity relation of $L_* \propto M_*^4$ (Siess et al. 2000). Therefore, $r_K$ and $r_{\text{MIR}}$ should be roughly proportional to $M_*^2$.

9.1 Disc dispersal?

The disc dispersal process consists of two kinds of processes: mass accretion on to the central star and dissipation into interstellar space (Hollenbach, Yorke & Johnstone 2000). The combination of mass accretion and dissipation due to photoevaporation (e.g. the so-called UV-switch model; Alexander 2008) is thought to be one of the major mechanisms of overall disc dispersal (Williams & Cieza 2011), because this can explain the almost simultaneous dispersal of the entire disc ($\Delta t \lesssim 0.5 \text{ Myr}$), and thus the short transition disc phase as implied in Fig. 8 (right). Although there are a number of other proposed dispersal mechanisms (e.g. stellar encounter, disc wind), our discussion here focuses on the dispersal due to photoevaporation.

9.1.1 Accretion on to the central star?

The first possible mechanism for the short $K$-disc lifetime of the IM stars is the faster mass accretion on to the central star for higher mass stars. Mendigutía et al. (2011) suggested a very strong mass dependence of the mass accretion rate from observations of UV Balmer excess. However, our results suggest that the gas accretion disc has a longer lifetime than the $K$ disc (Fig. 8, left), about equal to that of the MIR disc. Therefore, more rapid accretion and the resultant deficiency of material are not likely to be the cause of the faster destruction of the $K$ disc.

9.1.2 Photoevaporation?

Photoevaporation is another strong candidate for the dispersal mechanism that may cause the short $K$-disc lifetime. Photoevaporation is known to be effective for outside of the gravitational radius, $r_g$, where the thermal energy balances the gravitational potential. This radius scales with the stellar mass as $r_g \sim G M_*/c^2$ (Alexander 2008), and $r_g$ for IM stars ($2.5 M_\odot$) and LM stars ($0.5 M_\odot$) are ~25 and ~5 au, respectively. The corresponding $K$-disc radii ($r_K$) for IM and LM stars are only ~0.3 and ~0.1 au, respectively, which are less than $1/50$ of $r_g$. Similarly, the corresponding MIR-disc radii
Figure 9. Proposed disc evolution sequences for LM stars (left) and IM stars (right) as discussed in Section 9. The radius in the horizontal direction is roughly shown with a logarithmic scale. $r_K$, $r_{\text{MIR}}$, and $r_g$ denote the K-disc radii, MIR-disc radii, and photoevaporation radii, respectively. Blue arrows show the dispersal of gas/dust. Black dots and the cyan region show the dust and gas distribution, respectively, while Jupiter-mass planets are shown by circles with cyan and black. K, MIR, submm, and Hα emissions are shown by arrows with wavy lines. After 4–5 Myr, the entire gas/dust disc disperses before the dust settling is completed for LM stars (left), while the entire gas/dust disc disperses after dust settling is completed in the K disc for IM stars (right). After the dispersal, the Jupiter-mass planets are left (bottom). It is known that a larger number of Jupiter-mass planets are distributed at $<2.5$ au for IM stars than for LM stars. The thin vertical lines at $r = 0.5$ au show the inner region where close-in planets are rarely found for IM stars (see Section 9.3). Note that this is intended to describe the typical case and is not applicable to all stars.

are $\sim 5$ and $\sim 1$ au, respectively. Although all these radii change with the stellar mass (from 1.5 to 7 M$_\odot$ for IM stars), the relative magnitude of the radii, $r_K < r_{\text{MIR}} < r_g$, should not change for both IM and LM star mass ranges, even considering the scaling with the stellar mass mentioned above. Therefore, photoevaporation is not likely the main cause of the fast K-disc dispersal for IM stars.

9.2 Dust settling, dust growth, and planet formation

The transition disc phase is now interpreted as the most important phase in the standard planet-formation scenario, and now much observational effort has been put into characterizing this phase (Williams & Cieza 2011). In this interpretation, the early disappearance of the innermost dust disc compared to other portions of disc is due to dust settling to disc mid-plane (Kenyon & Hartmann 1987; Dullemond & Dominik 2005) and/or dust growth (Weidenschilling 1997; Dullemond & Dominik 2004). We discuss those possibilities in the following section with a schematic picture shown in Fig. 9.

9.2.1 Dust settling and growth

From the basic equations of protoplanetary discs in equilibrium, the radial dependence of the dust settling time can be analytically shown to be proportional to the Kepler rotation period, which is proportional to $r^{3/2} M_*^{-1/2}$ (Nakagawa, Nakazawa & Hayashi 1981). Although there are many new simulations incorporating more physical processes to show the dust settling time with a different $r$ or $M_*$ dependence (e.g. Tanaka, Himeno & Ida 2005), we compare our results with this base relationship by Nakagawa et al. (1981) as an initial consistency check.

First, as for the radius $r$ dependence, the shorter K-disc lifetime than that of MIR disc for the IM stars (Fig. 9, right, Table 4) is qualitatively consistent with the base relationship in that the dust settling/growth is occurring more effectively in the inner disc. Although the observed results ($\rho_{\text{disc}} \sim 3$ Myr at $r_K \sim 0.3$ au and $\rho_{\text{disc}} \sim 6–7$ Myr at $r_{\text{MIR}} \sim 5$ au) do not quantitatively follow the base $r^{3/2}$ relation and instead show a much weaker $r$ dependence, this can be interpreted as that the turbulent process or some other processes that prevent the dust settling/growth have the opposite $r$ dependence to reduce the $r$ dependence of dust settling/growth (e.g. Dullemond & Dominik 2005). For the LM stars, on the other hand, the lifetimes of the inner K, MIR, and the outer submm discs do not show any significant difference (see discussions in Sections 8.1.1 and 8.2). This is even more inconsistent with the base $r^{3/2}$ relation than the IM stars. Most likely this means that the disc disperses before dust is totally settled in the entire disc, although dust settling/growth is
reported for some LM stars (e.g. Pinte et al. 2008). In this case, the dust in the upper disc layer is dissipated in the process of mass accretion and photoevaporation (Fig. 9, left), and the disc lifetime (~9–10 Myr) sets the lower limit of the dust setting/growth timescale for most of the LM stars. However, it should be noted that the above discussion is intended to describe the typical case and is not applicable to all stars. The time-scale of transition disc is still under debate, short (~0.2 Myr; e.g. Luhan et al. 2010) or long (~ a few Myr; e.g. Currie & Sicilia-Aguilar 2011), although the discrepancies among these studies are largely due to differing definitions of the transition disc and how to estimate the total disc lifetime (Espaillat et al. 2014).

Next, as for the stellar mass M∗ dependence, the much shorter K-disc lifetime of the IM stars than that of the LM stars (t_{\text{IM}} \sim 3 Myr, while t_{\text{LM}} \sim 9–10 Myr; see Table 4; Fig. 5, left) is apparently consistent with the base relation in that dust settling/growth occurring effectively for higher mass stars. However, if we also consider the r dependence, the characteristic IM stars (M_r = 2.5 M⊙, r_K = 0.3 au) are expected to have longer settling time-scale (about twice) than the characteristic LM stars (M_r = 0.5 M⊙, r_K = 0.1 au) which shows the opposite tendency compared to the observed timescales. This might suggest that turbulence of the innermost disc is much weaker for the IM stars than for the LM stars so that the dust growth/settling occurs quickly. Although the larger disc mass (surface density) for stars with higher mass (Andrews & Williams 2005) might cause such a situation, the physical process is unknown.

9.2.2 Planet formation

Planetesimal and planet formation results from the dust settling/growth processes according to the standard core-accretion model (Lissauer & Stevenson 2007). For IM stars, the quick dust settling/growth processes in the presence of gas may cause effective planetesimal formation (Hubickyj, Bodenheimer & Lissauer 2005). This results in effective Jupiter-mass planet formation (e.g. Ida & Lin 2004a; Laughlin, Bodenheimer & Adams 2004; Robinson et al. 2006), which could accelerate the disappearance of the innermost disc with clearing by migration (Lin, Bodenheimer & Richardson 1996; Trilling et al. 1998; Trilling, Lunine & Benz 2002). Such a scenario is consistent with the trend of a higher probability of Jupiter-mass planets with a larger stellar mass for stars in the mass range of 0.2–1.9 M⊙ for semimajor axes of 0.3 au (Johnson et al. 2010). However, the mass range for IM stars (1.5–7 M⊙) has only a small overlap with this trend. This trend is generally interpreted as a result of larger disc mass (high surface density) for larger stellar mass, which enables the rapid formation of Jupiter-mass planets (e.g. within 1 Myr; Ida & Lin 2004b).

9.2.3 Summary

In summary, dust settling/growth (and some planet formation) can generally explain the shorter K-disc lifetime of IM stars, although the specific physical processes are not known. This interpretation is summarized in the schematic pictures shown in Fig. 9 (right): (1) The K disc (r_K \sim 0.3 au): dust settling/growth works very efficiently from the beginning of disc evolution (cluster age = 0) and is almost completed in \sim 3 Myr. Because there is no leftover IR-emitting grains even in the upper disc layer, no NIR continuum is emitted, (2) The MIR disc (r \sim 5 au): a significant amount of dust grains is in the upper disc layer due to the turbulence and gives rise to the MIR continuum emission. After \sim 4–5 Myr, dust settling has occurred, or dust in the upper layer of the MIR disc is dissipated, resulting in no emission of MIR-thermal continuum emission. If this picture is correct, the lifetime difference of JHK and MIR IMDFs constrains the timescale of this settling process in the K disc to about \sim 4 Myr (Section 8.1.2) (Table 4). The low initial value of the JHK IMDF (~50 per cent) might also be naturally explained with the effective settling in the inner disc. Future MIR spectroscopy of the silicate emission lines and the SED slope (Furlan et al. 2006) of those IM stars with and without the K disc will test the idea that the disappearance of the K disc is due to dust settling/growth.

10 IMPLICATIONS FOR PLANET FORMATION AROUND IM STARS

Two remarkable trends are known for the Jupiter-mass planets around IM stars: (1) the lack of close-in planets with semimajor axes of \langle 0.5 au orbiting stars with masses M > 1.5 M⊙ (such planets are common for stars with M < 1.2 M⊙), and (2) the higher probability of having planets with semimajor axes of \langle 2.5 au compared to LM stars. In this section, we discuss these trends in the context of our disc fraction lifetime results.

10.1 Implications for the lack of close-in planets

There appears to be a lack of close-in planets with semimajor axes of \langle 0.5 au orbiting stars with masses of 1.5–3 M⊙ in planet-search surveys, while close-in planets are more frequent for lower mass stars (Wright et al. 2009). Because planets are thought to form in situ or migrate inwards in the formation phase (e.g. Lin et al. 1996), our suggestion of rapid planet formation in the K disc appears to be inconsistent with the paucity of close-in planets. However, considering the possible radial range of ‘K disc’ (from \sim 0.3 to 1 au, depending on the mass of the central star, disc mass, etc.), the higher planet occurrence for higher mass stars (Johnson et al. 2010) may reflect the rapid planet formation at r > 0.5 au. The planets that formed at r < 0.5 au may have dropped into the central stars due to migration (Papaloizou et al. 2007) because the gas disc traced by Hα still remains for about 2 Myr after the disappearance of the K disc. Or, they may have disappeared due to collisional destruction that may have effectively occurred along with grain growth (Johansen et al. 2008). In any case, more studies are necessary to understand the precise relation between disc lifetime and planet formation.

Regarding the lack of close-in planets for IM stars, two major scenarios have been proposed. The first scenario is planet engulfment caused by the stellar evolution of primary stars in the RGB phase (Villaver & Livio 2009). Another scenario is that the observed differences in orbital distribution are primordial, and they are a consequence of the planet-formation mechanism around the more massive stars (Currie 2009). In this section, we focus on the latter scenario because our results are relevant to the early stages of star formation. Currie (2009) suggests that planets around IM stars cannot migrate to inner orbits because of the shorter gas-disc lifetime for IM stars. In addition, Kretke et al. (2009) suggest that the inner edge of the dead zone in protoplanetary disc, where the dead zone is the region of the disc without magnetorotational instability (Gammie 1996), effectively determines the semimajor axes of giant planets because the dead zone traps inwardly migrating solid bodies. Thus, they suggested that the larger radius of the inner edge for higher mass stars explains the lack of close-in planets.

Our results are qualitatively consistent with Currie’s scenario in that shorter disc lifetimes are expected for higher mass stars.
We estimated that the stellar mass dependence of gas-disc lifetime \( t_{\text{disc}}^{\text{gas}} \) is about \( M_\ast^{-0.5} \) (Dullemond & Dominik, 2004, A&A, 417, 159) and \( t_{\text{disc}}^{\text{H}_2} \sim 5 \text{ Myr} \) and \( t_{\text{disc}}^{\text{H}_2} \sim 10 \text{ Myr} \) in Fig. 8. However, this dependence is not as steep as assumed in Currie (2009), \( t_{\text{disc}}^{\text{gas}} \propto M_\ast^{-\beta} \) with \( \beta = 0.75 \pm 1.5 \). In any case, migration alone may not be able to explain the observed sharp outward step in giant planet orbits as pointed out in Kennedy & Kenyon (2009).

Our results that the innermost discs of IM stars disappear at a very early time also seem to be consistent with Kretke’s dead zone model. Kretke et al. (2009) assumed a smooth stellar mass dependence of the inner edge radius of the dead zone (proportional to \( M_\ast \)) from the theoretical relationship between the radius and the mass accretion, and they compared this to the mass accretion rate derived from observations. Our results, showing the early disappearance of the innermost \( K \) disc, suggest that the radius becomes even larger because of low opacity, which makes the formation of dead zone difficult. If the critical stellar mass where the time lag between the \( K \)- and the MIR-disc dispersal is observationally determined, then this dead zone idea may be able to explain the lack of close-in planets even for the sharp cut-off at 0.5 au in the planet semimajor axes in the distribution of Jupiter-mass planets.

In addition, the difference in the planet-formation site in discs of IM stars and LM stars may explain the lack of close-in planets for the IM stars. Planets are thought to form outwards of the snow line, \( \sim 3 \text{ au} \) for LM stars and \( \sim 10 \text{ au} \) for IM stars (Kennedy & Kenyon 2008). This difference might explain the observed difference in planet location even after the smearing out by the migration processes, although this idea does not explain the sharp step in planet semimajor axes.

### 10.2 Implications for higher planet-formation probability

The probability of IM stars having Jupiter-mass planets is found to be proportional to \( M_\ast^{1.0} \) for semimajor axes \( < 2.5 M_\odot \) (Johnson et al. 2010). This observed frequency is likely to be determined by two competing effects: the tendency of shorter disc lifetimes for more massive stars reduces the likelihood of giant planets forming (Butler et al. 2006), and the tendency of higher disc masses for more massive stars increases the probability of gas-giant planet formation (Wyatt, Clarke & Greaves 2007). In Kennedy & Kenyon (2009), the stellar mass dependence of disc lifetime is estimated using the Hz disc and MIR-disc fractions as \( \tau_{K\text{KOH}} \propto M_\ast^{-1/2} \), where \( \tau_{K\text{KOH}} \) is the disc decay time-scale defined by their model. However, from our results, the disc lifetime at \( r \gtrsim r_\ast \) for IM and LM stars is not significantly different, and the stellar mass dependence of disc lifetime \( \tau_{\text{disc}} \sim M_\ast^{-0.2} \). The disc mass is known from submm observations to be roughly proportional to the stellar mass (Andrews & Williams 2005). The stellar mass dependence of the disc lifetime is negative, while the stellar mass dependence of the disc mass is positive. Therefore, the higher probability of IM stars having planets compared to LM stars seems to be due to the difference in disc mass instead of the difference in disc lifetime.

### 11 CONCLUSION

We derived and compiled protoplanetary disc fractions of IM stars (1.5–7 M\(_\odot\)) for a large number of nearby young clusters (within 3 kpc and \( \lesssim 5 \text{ Myr} \)) with the available \( \text{HJK} \) photometric data in the literature. From the results and by comparing them with those for other wavelengths (Hz, MIR, and submm), we found the following results.

1. The \( K \)-disc lifetime of IM stars \( \tau_{\text{disc}}^{\text{H}_2} \), which is defined as the time-scale of disc fraction to bottom out at 5 per cent, is estimated to be \( 3.3 \pm 0.9 \text{ Myr} \).
2. The \( K \)-disc lifetime for the IM stars, \( \tau_{\text{disc}}^{\text{H}_2} \), is one of the first-order of that for the LM stars. Assuming a power-law dependence, the stellar mass dependence of the \( K \)-disc lifetime is found to be proportional to \( M_\ast^{-0.2\pm0.5} \).
3. By comparing the \( K \)-disc (\( r \sim 0.3 \text{ au} \)) evolution to that of the MIR disc (\( r \sim 5 \text{ au} \)) for IM stars, we find that the \( K \) disc seems to disperse earlier than the MIR disc by \( \sim 3\text{--}4 \text{ Myr} \). Because the \( K \) disc and the MIR disc disperse almost simultaneously in LM stars (\( \Delta r \lesssim 0.5 \text{ Myr} \)), the long time lag may be a characteristic of IM stars, suggesting that the transition disc is the common phase in IM stars.
4. Because the disc time-scale at \( r \gtrsim r_{\text{MIR}} \) for the IM stars does not seem to be significantly different from that of LM stars, the most likely cause for the time lag seems to be early dust growth/settling and/or Jupiter-mass planet formation in the innermost disc (\( K \) disc) in IM stars.
5. Our results for the \( K \) disc of the IM stars suggest the possible reasons for the paucity of close-in planets around IM stars, but they are not conclusive. Our results also suggest that the disc mass is a more important factor for the stellar mass dependence of planet occurrence than the disc lifetime.

### ACKNOWLEDGEMENTS

We thank the anonymous referee for careful reading and thoughtful suggestions that improved this paper. This work was supported by JSPS KAKENHI Grant Number 24103509, 26800094. We also thank Taku Takeuchi, Hideko Nomura, and Masanobu Kunitomo for helpful discussions on theoretical issues.

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Table A1. NGC 1333. The α values for MIR disc are directly referred from Gutermuth et al. (2009). Though extinction is not corrected for α values in this reference, it should not affect the disc judgement because the α value is much larger than −2. The spectral type with * mark is from the SIMBAD data base.

| Name                | RA J2000 (h:m:s) | Dec. J2000 (d:m:s) | SpT  | K disc | MIR disc |
|---------------------|------------------|--------------------|------|--------|----------|
| 2MASS J03291977+3124572 | 03 29 19.77605   | +31 24 57.0474     | B8*  | X      | –        |
| 2MASS J03285720+3114189   | 03 28 57.2107    | +31 14 19.056      | B*   | X      | –        |
| 2MASS J03290575+3116396   | 03 29 05.754     | +31 16 39.69       | A3   | X      | o (−0.28) |
| 2MASS J03291037+3121591 (LZK 12) | 03 29 10.379  | +31 21 59.16       | F4–G0 | o      | o (−0.40) |
| 2MASS J03285930+3115485   | 03 28 59.306     | +31 15 48.52       | K2   | X      | o (−0.25) |
| 2MASS J03292187+3115363 (LkHA 271) | 03 29 21.873  | +31 15 36.30       | K4.0 | X      | o (−1.49) |

APPENDIX A: LIST OF SAMPLE IM STARS IN TARGET CLUSTERS

In this appendix, the IM-star samples for all 19 clusters listed in Table 3 are summarized in Tables A1–A19 as well as in colour–colour diagrams (Figs A1–A19). The complete tables and figures are available in the online version of the article.

In the tables, only RA, Dec. coordinates (in J2000) are shown in case object names are not available in the references. ‘SpT’ shows the spectral types in the literatures. The ‘K disc’ and ‘MIR disc’ columns show objects with a disc (o) and without a disc (X). The numbers in the parentheses in MIR disc column is α as defined in Section 1. The stars with K-disc emission are judged from the colour–colour diagram, in which the red and black circles show those with a K disc and without a K disc, respectively.

SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:
Appendix A. List of sample IM stars in target clusters (http://mnras.oxfordjournals.org/lookup/suppl/doi:10.1093/mnras/stu1013/-/DC1).

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