The frequency of large variations in the near-infrared fluxes of T Tauri stars

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ABSTRACT

Variability is a characteristic feature of young stellar objects (YSOs) and could contribute to the large scatter observed in Hertzsprung–Russell (HR) diagrams for star-forming regions. For typical YSOs, however, the long-term effects of variability are poorly constrained. Here we use archived near-infrared photometry from Two Micron All Sky Survey (2MASS), UKIDSS and DENIS to investigate the long-term variability of high-confidence members of the four star-forming regions ρ-Oph, ONC, IC348 and NGC 1333. The total sample comprises more than 600 objects, from which ∼320 are considered to have a disc. The data set covers time-scales up to 8 yr. About half of the YSOs are variable on a 2σ level, with median amplitudes of 5–20 per cent. The fraction of highly variable objects with amplitudes >0.5 mag in at least two near-infrared bands is very low – 2 per cent for the entire sample and 3 per cent for objects with discs. These sources with strong variability are mostly objects with discs and are prime targets for follow-up studies. A transition disc candidate in IC348 is found to have strong K-band variations, likely originating in the disc. The variability amplitudes are largest in NGC 1333, presumably because it is the youngest sample of YSOs. The frequency of highly variable objects also increases with the time window of the observations (from weeks to years). These results have three implications. (1) When deriving luminosities for YSOs from near-infrared magnitudes, the typical error introduced by variability is in the range of 5–20 per cent and depends on disc fraction and possibly age. (2) Variability is a negligible contribution to the scatter in HR diagrams of star-forming regions (except for a small number of extreme objects), if luminosities are derived from near-infrared magnitudes. (3) Accretion outbursts with an increase in mass accretion rate by several orders of magnitudes, as required in scenarios for episodic accretion, occur with a duty cycle of >2000–2500 yr in the Class II phase.

Key words: accretion, accretion discs – stars: activity – brown dwarfs – stars: low-mass – stars: pre-main-sequence.

1 INTRODUCTION

Before T Tauri stars were recognized as young stellar objects (YSOs) they were known primarily for their characteristic photometric variability. T Tauri itself, first seen by Hind (1852), was described in a paper by Knott (1891) as a ‘remarkable variable star’ with ‘a magnitude range from 9.4 to 13.5 or 14’ (see also the discussion in Barnard 1895). About 50 years later, Joy (1945) defined the class of T Tauri variables based on this prototype and a number of objects with similar light curves, including RW Aur, R CrA, RU Lup, RY Tau and UX Tau – today some of the best studied YSOs. They exhibit large-scale (>1 mag), irregular variations in visual bands on time-scales ranging from hours to years. This type of variability can be attributed to the process of accretion from the circumstellar disc on to the newly formed star (e.g. Appenzeller & Mundt 1989; Herbst et al. 1994; Bouvier et al. 1995).

Nowadays, most of the YSOs with discs are identified by other means, primarily from their mid-infrared colour excess due to hot dust in the inner disc or from optical/near-infrared emission lines originating in the accretion flow or in the wind. It is well established that a large fraction of YSOs show variability on time-scales of days to weeks with light curve rms of typically <0.2 mag (e.g. Lamm et al. 2004). In many cases this moderate variability is periodic and can be explained by cool spots and/or hotspots corotating with the objects (Herbst et al. 2007). In addition, it is known that at least some T Tauri stars exhibit stable long-term variations with large amplitudes of up to several magnitudes (e.g. Grankin et al. 2007). More recently, it has been established that these two types of variability occur over a wide range of stellar masses,
Figure 1. $K$-band variability versus colour variability for YSOs in $\rho$-Oph. The left-hand panel shows variations on time-scales of $\sim 6$ yr; the right-hand panel shorter time-scales of $< 2$ yr. Different symbols are used for various combinations of data sets: circles – 2MASS versus UKIDSS; crosses – 2MASS versus DENIS epoch 1; plusses – 2MASS versus DENIS epoch 2; squares – DENIS epoch 1 versus epoch 2.

The near-infrared bands employed by the three surveys are similar, but not identical. We converted the DENIS magnitudes to the 2MASS system using the transformations given by Carpenter (2001). The UKIDSS photometry was shifted into the 2MASS system using the conversion equations published by Hewett et al. (2006). Many YSOs in highly extinct regions have near-infrared colours for which these transformations are not properly calibrated; this could lead to colour-dependent offsets between the two photometric systems. In some of the figures (see in particular Figs 1 and 2), the cumulation of objects around the origin appears elongated, which could be caused by such systematic errors.

UKIDSS is deeper than 2MASS and DENIS, but also affected by saturation at the bright end. The effects of saturation are clearly visible when plotting magnitude differences between 2MASS and UKIDSS; above a certain limit UKIDSS underestimates the fluxes of the stars. When identifying variable sources, a magnitude cut-off was implemented to avoid bright stars for which saturation plays a role.

For all archives no additional cuts on signal-to-noise ratio were implemented, i.e. all objects with valid flux and error measurements were used for the analysis (e.g. the 2MASS quality flags A–E). The objects that turn out to be highly variable and are listed in Table 1

2 DATA

The photometric data used for this study come from the three projects 2MASS, UKIDSS and DENIS. 2MASS$^1$ is an all-sky survey carried out from 1997 to 2001 in the $J$, $H$ and $K$ bands (Skrutskie et al. 2006). The 10$\sigma$ depth is approximately 16, 15 and 14 mag in these three filters.

UKIDSS is a seven-year survey programme started in 2005 (Lawrence et al. 2007), carried out with the United Kingdom Infrared Telescope (UKIRT) Wide-Field Camera (Casali et al. 2007) in the five bands $Y$, $Z$, $J$, $H$ and $K$ (Hewett et al. 2006). The project comprises five different survey components; for this paper we use the 6th data release of the Galactic Cluster Survey (GCS) (for $\rho$-Oph, ONC and IC348) and the Galactic Plane Survey (GPS) (for NGC 1333, Lucas et al. 2008). For more information on UKIDSS see for example Dye et al. (2006) and Hambly et al. (2008).

DENIS is a survey of the southern sky in two near-infrared bands ($J$ and $K$) and one optical band (Gunn-I), carried out between 1996 and 2001 (Epchtein et al. 1999). For this paper we use the third data release from 2005 September.

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$^1$2MASS is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by the National Aeronautics and Space Administration and the National Science Foundation.

Figure 2. $K$-band magnitude change as a function of time-scale for YSOs in $\rho$-Oph. The plot uses data from 2MASS, DENIS and UKIDSS. Symbols are the same as in Fig. 1. The solid line shows the 90th percentile for the epoch bins $< 40$ d, 60–100 d, 200–800 d and 1000–3000 d.
Table 1. Sources with strong variability in the regions ρ-Oph, ONC, IC348 and NGC 1333. Most were found by comparing 2MASS and UKIDSS photometry (time window 6–8 yr); the two exceptions come from the DENIS versus 2MASS comparison and are marked.

| α (J2000) | δ (J2000) | K2M (mag) | dK (mag) | dH (mag) | dJ (mag) | Disc | SIMBAD names | Comments |
|-----------|-----------|-----------|----------|----------|----------|------|--------------|----------|
| 16 26 17.23 | −24 23 45.4 | 12.251 | +0.515 | +0.882 | − | Y | ISO-Oph-21 | Faint in 2MASS |
| 16 26 44.19 | −24 34 48.3 | 11.603 | −0.137 | −1.510 | − | Y | ISO-Oph-65, [GY92] 111 | − |
| 16 27 11.8 | −24 40 46.7 | 10.196 | −0.786 | −0.804 | − | Y | ISO-Oph-112, [GY92] 224 | − |
| 16 27 17.59 | −24 05 13.7 | 10.727 | +0.910 | +0.695 | +0.632 | Y | ISO-Oph-123 | − |
| 16 27 26.94 | −24 40 50.8 | 9.745 | −0.650 | −0.713 | − | Y | ISO-Oph-141, [GY92] 265 | Companion |
| 05 35 18.78 | −05 18 02.6 | 10.974 | −0.635 | − | −0.546 | ? | COUP 990, [H97b] 5058 | − |
| 05 35 29.46 | −05 18 45.8 | 10.825 | +0.639 | +1.235 | ? | COUP 1425, [H97b] 3042 | − |
| 05 35 05.38 | −05 24 10.5 | 9.616 | −0.505 | − | −0.687 | Y | COUP 236, [H97b] 265 | M0, DENIS |
| 03 44 31.36 | +32 00 14.7 | 10.636 | −0.784 | −0.771 | −0.752 | Y | CI* IC 348 LRL 55 | M0.5 |
| 03 28 58.42 | +31 22 17.7 | 11.849 | −1.227 | −0.737 | − | Y | [LAL96] 166, MBO 38 | Class I |
| 03 29 03.13 | +31 22 38.2 | 11.323 | −0.620 | −0.828 | −0.581 | Y | [LAL96] 189, MBO 31 | Class II |
| 03 29 20.05 | +31 24 07.6 | 12.042 | −1.555 | −2.128 | − | Y | [LAL96] 296, MBO 46 | Class II |

have 2MASS photometry flags A or B – signal-to-noise ratio ≥7 – in the analysed bands.

The magnitude differences between the various surveys comprise (a) variability, (b) photometric uncertainties and (c) systematic effects (saturation and band offsets). The photometric uncertainties in 2MASS and DENIS range from a few per cent up to 0.2 mag for the objects investigated here; for UKIDSS these numbers are significantly smaller. Systematic effects can contribute up to 0.1–0.2 mag. Thus, any magnitude difference >0.5 mag can safely be attributed to a variable source. In this paper, we focus mostly on these strongly variable objects which can unambiguously be identified from the two to three epochs available in the surveys. To exclude spurious detections, we require that an object shows this level of variation in at least two bands.

As the main diagnostic to identify variables and explore possible causes of their variability, we plot the magnitude difference between two surveys in the K band versus the colour difference (either in H − K or in J − K). These diagrams (see Figs 1, 3, 4 and 5) show the trends in the evolution of the brightness (brighter/fainter) and colour (redder/bluer). Depending on the origin of the variability, objects will appear in different quadrants: hotspots due to accretion will make the objects brighter and bluer (upper-right quadrant) or fainter and redder (lower-left quadrant). Cool spots due to magnetic activity will have the same, albeit much smaller effect. Variable extinction, for example due to inhomogeneities in the disc, would again make the sources either brighter and bluer or fainter and redder. In contrast, variable emission from the disc would cause variability towards brighter and redder (upper-left quadrant) or fainter and bluer (lower-right quadrant). Whatever the origin of the variations, it is expected that the sign of the magnitude change is the same in all bands, which serves as an additional sanity check. For a more detailed discussion of the variability causes and their effects on magnitudes and colours see Carpenter, Hillenbrand & Skrutskie (2001) and Scholz et al. (2009).

To identify the objects with discs in the samples in ρ-Oph and IC348, we made use of the ‘HREL’ photometry catalogues from the ‘Cores to Disks’ (C2D) Spitzer Legacy Program (Evans et al. 2009).

Figure 3. K-band variability versus colour variability for YSOs in the ONC. The left-hand panel shows variations on time-scales of ~6 yr; the right-hand panel shows variations on shorter time-scales of 2–5 yr. Different symbols are used for various combinations of data sets: circles – 2MASS versus UKIDSS; crosses – DENIS versus 2MASS.
3 IDENTIFYING VARIABLE STARS

3.1 ρ-Ophiuchus

ρ-Ophiuchus (ρ-Oph) is a region of star-forming activity at a distance of ∼130 pc. The area is visible from the Northern and Southern hemispheres and was covered by 2MASS, DENIS and UKIDSS/GCS. According to the census given in Wilking, Gagné & Allen (2008), the main cloud of ρ-Oph, L1688, harbours at least 300 YSOs, confirmed by their X-ray emission, infrared excess emission, Li absorption, Hα emission or other signs of youth. Due to its high extinction, the cloud effectively acts as a screen, i.e. the sample should be clean from background contamination. The median age of YSOs in L1688 is often cited as <1 Myr, but a fraction of the YSOs in this area might actually belong to an older population associated with the UpSco star-forming region (age 2–5 Myr). For more information, see Wilking et al. (2008).

We start with the list of 316 members with 2MASS counterparts from Wilking et al. (2008). For the comparison between UKIDSS and 2MASS, we select the 223 objects with photometry in the $H$ and $K$ bands in the two surveys. In the $J$ band, many objects are undetected in 2MASS due to the high extinction. In the UKIDSS data set, all objects with $H < 11$ and $K < 9$ are affected by saturation; this brings the number of usable objects down to 144.

In Fig. 1, left-hand panel, we show the $K$-band variability $dK$ versus the colour variability $d(H - K)$ for the UKIDSS/2MASS comparison. In this plot, objects in the upper-right and -left and lower-right and -left quadrants became bright-blue and -red, respectively. The average epoch difference between 2MASS and UKIDSS is ∼6 yr. Eight objects in this sample show $K$-band variations of $dK > 0.5$ mag; two of them have $dK \sim 1$ mag. The maximum amplitude in the $H$ band is $dH = 1.5$ mag. Five out of eight have >0.5 mag variations in at least two bands and are listed in Table 1.

In the sample of 144 objects shown in Fig. 1, left-hand panel, 80 have Spitzer/IRAC colour excess ($[5.8 \mu m] - [8.0 \mu m] > 0.3$ mag, $[3.6 \mu m] - [4.5 \mu m] > 0.2$ mag), interpreted as evidence for a disc; among them five are highly variable sources.

ρ-Oph was covered twice by DENIS, with epoch differences of −1 to +2 yr relative to 2MASS. From the initial sample of 316 members, 82 have usable photometry in 2MASS and DENIS, epoch 1, 194 in 2MASS and DENIS, epoch 2, and 78 in the two epochs of DENIS. In Fig. 1, right-hand panel, we show the $dK$ versus $d(J - K)$ plot for the three possible combinations from these data sets, covering time-scales <2 yr. Three objects exhibit magnitude

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**Figure 4.** $K$-band variability versus colour variability in $H - K$ (left-hand panel) and $J - K$ (right-hand panel) for YSOs in IC348 on time-scales of ∼8 yr. The plots use data from 2MASS and UKIDSS.

**Figure 5.** $K$-band variability versus colour variability in $H - K$ (left-hand panel) and $J - K$ (right-hand panel) for YSOs in NGC 1333 on time-scales of ∼7 yr. The plots use data from 2MASS and UKIDSS.
changes of $dK > 0.5 \text{mag}$, two of them with discs, but only one in more than one band. This one, however, is at the detection limit of 2MASS in the $J$ band with the signal-to-noise ratio of only 4. Therefore we do not list any new objects from this search in Table 1.

The five highly variable sources from the UKIDSS versus 2MASS comparison are listed in Table 1 and were verified in the survey images. One of them is close to the sensitivity limit of 2MASS, although the photometric uncertainties are still well below 0.5 mag. One more has a companion which is not well resolved in the 2MASS images; hence, it appears fainter in UKIDSS with its better resolution. Thus, the total fraction of sources in $\rho$-Oph that are highly variable on time-scales of $\sim 6 \text{yr}$ is three to five out of 144 in the total sample (2–3 per cent), and three to five out of 80 with discs (4–6 per cent).

One of the five $\rho$-Oph objects listed in Table 1, ISO-Oph-112, has already been identified by Alves de Oliveira & Casali (2008) as highly variable on time-scales of up to 1 yr (for reference, the number in their table 4 is 58). Similar to the results presented here, Alves de Oliveira & Casali (2008) find relatively few objects with $H$- or $K$-band amplitudes exceeding 0.5 mag.

In Fig. 2 the absolute $K$-band variability is plotted against the epoch difference, combining the data from all three surveys. With this figure we aim to test whether the variations depend on the time-scale or not. The fraction of objects with $dK > 0.5$ is $0.8 \pm 0.3$ for epoch differences $< 1000 \text{d}$ and $5.6 \pm 1.2$ for epoch differences $> 1000 \text{d}$ (errors are $1 \sigma$ binomial confidence intervals). We also overplot the 90th percentile for four bins in epoch difference: $< 40 \text{d}$, $60–100 \text{h}$, $200–800 \text{d}$ and $1000–3000 \text{d}$. These values increase from 0.13 on the shortest time-scales to 0.37 on the longest. This result is robust within the statistical uncertainties of these percentiles.

We conclude that high-level variations in the near-infrared are more frequent on time-scales of years than on time-scales of weeks to months.

### 3.2 ONC

The ONC is a massive cluster of YSOs in the Orion star-forming region with an age of about 1 Myr. The cluster has been observed by 2MASS in 2000, by UKIDSS/GCS in 2005–2006 and by DENIS between 1996 and early 1999, although the coverage by UKIDSS and DENIS is incomplete. A good starting point for a cluster census is the list of point sources in the X-ray catalogue from the COUP project (Getman et al. 2005a). Among those >1600 objects 918 are with optical and near-infrared counterpart. As argued by Getman et al. (2005b), these can be assumed to be safe members of the cluster. The sample is dominated by K–M stars, but also includes some more massive objects.

Due to the limited coverage of UKIDSS, only 198 have $J$- and $K$-band photometry in 2MASS and UKIDSS, from which 188 are unaffected by saturation ($J > 11, K > 9$). With $H$ and $K$ the numbers are even lower. As can be seen in Fig. 3, left-hand panel, three sources are strongly variable with $dK > 0.5 \text{mag}$. Two of them show this level of variability in two bands; they are listed in Table 1.

Note that no band transformation was carried out for the UKIDSS photometry in Fig. 3 because not all objects in this plot have the required colour information. This causes some additional scatter around the zero-point in the diagram, but does not affect the selection of strongly variable objects.

151 objects have usable $J$- and $K$-band photometry in 2MASS and DENIS, which is plotted in Fig. 3, right-hand panel. Four of them exceed $dK = 0.5 \text{mag}$; two of them have also $dJ > 0.5$ and are included in Table 1.

The ONC is a crowded area, and all of the objects listed in Table 1 might be affected by close neighbours, particularly in the 2MASS and DENIS images. Thus, some of these objects might not be variable. Re-observations with good resolution are necessary to clarify their nature.

For the ONC we cannot probe the mid-infrared excess for the sample. The Spitzer data for this region have not been published yet, and the region is not covered by the preliminary data base from the Wide-field Infrared Survey Explorer (WISE). Instead, we use the near-infrared excess $\Delta(I-K)$ from Hillenbrand et al. (1998) to identify the discs. In the sample plotted in Fig. 3, left-hand panel, 82 objects have a measured $\Delta(I-K)$; 40 of them with colour excess $> 0.3 \text{mag}$, considered to be a safe disc detection by Hillenbrand et al. (1998). For the right-hand panel, 84 have a $\Delta(I-K)$ measurement, 44 of them $> 0.3 \text{mag}$. Thus, the disc fraction in the samples plotted in Fig. 3 is in the range of 50 per cent.

For two of the four variables from Table 1 the near-infrared excess is available in Hillenbrand et al. (1998). One of them clearly has a disc (COUP 236), and the other does not (COUP 64). Lack of near-infrared excess does not necessarily imply the lack of circumstellar material, i.e. COUP 64 might still harbour a disc. Three of the four objects listed in Table 1 – COUP 1425, 64 and 236 – are also identified as variables by Carpenter et al. (2001).

In summary, the total fraction of objects with strong near-infrared variability on time-scales of several years for the ONC is in the range of 1 per cent for all objects and 2 per cent for objects with discs.

### 3.3 IC348

For IC348, an $\sim 3 \text{Myr}$ old cluster in the Perseus star-forming region, we start with the list of 288 spectroscopically confirmed cluster members published by Luhman et al. (2003). Most of these objects are low-mass stars with spectral types K–M. The cluster was covered by 2MASS from late 1998 to early 1999 and by UKIDSS/GCS in late 2006, i.e. the typical epoch difference is $\sim 8 \text{yr}$.

249 objects have photometry in the $H$ and $K$ bands in the two surveys; 201 of them are not affected by saturation in UKIDSS ($H > 11$ and $K > 10.5$). In Fig. 4, left-hand panel, we plot the $K$-band versus $H-K$ colour variability. Two objects show $K$-band variations $> 0.5 \text{mag}$, one of them with $dK = 0.8 \text{mag}$ and $dH = 0.8 \text{mag}$. This object is included in Table 1.

The right-hand panel in Fig. 4 shows the same plot using $J-K$ instead of $H-K$. Here 247 objects have photometry in the two surveys, 208 without effects of saturation ($J > 11$ and $K > 10.5$). Again, there are two objects with $dK > 0.5 \text{mag}$, the same as those in the left-hand panel.

From the samples shown in the figure, 63 have mid-infrared excess due to the presence of discs based on the IRAC colours ($[5.8 \text{um}] > [8.0 \text{um}] > 0.45 \text{mag}$, $[3.6 \mu m] > [4.5 \mu m] > 0.15 \text{mag}$). Among them is one of the two highly variable objects listed in Table 1. The second one ($\alpha = 03^h44^m22.57, \delta = +32^01^'33.7$, SIMBAD name Cl* IC 348 LRL 72) has $[5.8 \mu m] - [8.0 \mu m] = 0.44 \text{mag}$ and $[3.6 \mu m] - [4.5 \mu m] = 0.01 \text{mag}$. It also has strong excess at $24 \mu m$ with $[8.0 \mu m] - [24 \mu m] = 4.8 \text{mag}$, which is more than that of most objects with discs in IC348. Thus, this source clearly has circumstellar material, but it might have an inner hole in the disc and therefore little excess at $3–8 \mu m$, a so-called transition disc. Indeed, the object was previously classified as a ‘transition disc candidate’ (Muzerolle et al. 2010) and is an
interesting target for further monitoring. Since the variability for this source is mostly seen in the K band, it is likely to originate in the disc.

The fraction of highly variable sources, as defined in this paper, is thus 1/208 for the total sample (1 per cent) and 1/63 for objects with discs (2 per cent).

In IC 348 the plots indicate that there are little problems with the band correction, most likely because the extinction is on average lower than that in ρ-Oph and the ONC. Therefore it is feasible to provide quantitative limits on the variability of the general population. The median difference between 2MASS and UKIDSS photometry is 0.05, 0.04 and 0.04 mag in J, H and K for the entire sample and 0.07, 0.06 and 0.05 for the sources with discs respectively.

These numbers are still affected by the observational errors, which are dominated by the 2MASS uncertainties. The UKIDSS errors are typically lower than the 2MASS errors by a factor of 10. The fractions of objects for which the offsets are more than twice as large as the 2MASS errors (i.e. variable on a 2σ level) in J, H and K are 46, 41 and 37 per cent for all objects and 56, 52 and 60 per cent for the ones with discs, respectively. The typical 1σ binomial uncertainties in these fractions are 4 per cent for all objects and 6 per cent for the stars with discs. For these variable sources, the median difference between 2MASS and UKIDSS after subtracting the 2MASS error is 0.05, 0.06 and 0.05 mag for all objects and 0.07, 0.09 and 0.06 for those with discs, respectively.

This analysis shows that (a) about half of the YSOs in IC 348 exhibit low-level variability in near-infrared bands, typically on the level of a few per cent and (b) the level of variations is slightly enhanced in objects with discs.

### 3.4 NGC 1333

NGC 1333 is an extremely young cluster with an age of about 1 Myr and a distance of about 300 pc. As IC 348, NGC 1333 is located in the Perseus star-forming region. We use the sample of 137 Class I and II sources identified by Gutermuth et al. (2008) based on Spitzer data, which should be essentially free from contamination. As these objects are identified from the infrared excess, all are considered to have a disc (or at least circumstellar material).

The cluster has been observed by 2MASS from 1999 November to 2000 October and by UKIDSS/GPS in early 2007, i.e. the average epoch difference is 7 yr.

From the initial sample, 96 have K- and H-band photometry in the two surveys; 82 of them are unaffected by saturation. 84 have K- and J-band photometry; 72 of them are unaffected by saturation. In Fig. 5 the usual plots for the H – K colour (right-hand panel) and the J – K colour (left-hand panel) are shown.

Three objects appear in the plots at dK > 0.5, one of them in both panels. All three have dK > 0.5 mag amplitudes in one more band. These three are contained in Table 1. As indicated, all of them are considered to have discs. Compared with the other regions, the upper limit of the amplitudes is somewhat higher in NGC 1333 (1.6 in K, instead of 1.0), possibly due to the extreme youth and early evolutionary stage of the cluster. The frequency of highly variable objects is 3/82 or 4 per cent.

Some more objects have large variations in the J band up to dJ > 1, but are much less variable in the other bands. It turns out that they are close to the sensitivity limit of 2MASS in the J band and in some cases affected by neighbouring brighter stars. Although they need verification with additional epochs, at this point they are not considered to be variable.

Similar to IC 348, we determine the level of variability in the entire sample. The median difference in the three bands J, H and K is 0.09, 0.09 and 0.09 mag, respectively. The fraction of objects with 2σ variability is 47, 40 and 60 per cent, respectively. These fractions have typical binomial 1σ errors of 6 per cent. For the variable objects, the median difference between 2MASS and UKIDSS after subtracting 2MASS errors is 0.20, 0.14 and 0.11 mag in the three bands J, H and K, respectively. As noted above, all objects analysed in NGC 1333 show evidence for the presence of a disc.

The fraction of variable objects is similar to IC 348, but the typical level of variations is higher in NGC 1333 than in IC 348. For comparison, variable stars in the ONC, a cluster similar in age to NGC 1333, show median peak-to-peak amplitudes of 0.15, 0.12 and 0.11 mag in the three bands J, H and K, respectively, on time-scales of about one month (Carpenter et al. 2001). This is consistent with the values in NGC 1333, indicating that the low-level variability mostly occurs on time-scales of days to weeks, not years.

### 3.5 σ Ori

For the open cluster σ Ori, age ~3 Myr, Lodieu et al. (2009) recently published a comparison between 2MASS and UKIDSS data. They look at 263 sources with J-band magnitudes between 12 and 16. Two of them show J-band variability by dJ > 1.0, three more with dJ > 0.5. Thus the frequency of highly variable objects is in the range of 2 per cent for the total sample or, assuming a disc fraction of 30 and 6 per cent for the objects with discs. These numbers are derived for the J band, whereas the K band is used in the other regions, but they confirm that highly variable objects are rare (well below 10 per cent) in star-forming regions.

### 4 DISCUSSION

#### 4.1 Fraction of highly variable objects



The main result from the analysis in Section 3 is that strongly variable objects on time-scales of several years are rare among Class II YSOs. Adding ρ-Oph, ONC, IC 348 and NGC 1333, there are 11 sources with dJ > 0.5 mag variations in two near-infrared bands on time-scales of 6–8 yr, out of 620 YSOs, from which 320 have discs (here we assume a disc frequency of 50 per cent for the ONC). The fraction of such variable objects is thus 2 per cent for the full sample and 3 per cent for YSOs with discs (Class I or Class II). These low frequencies are confirmed by the independent study in σ Ori (Lodieu et al. 2009). They are much lower than the number reported in Scholz et al. (2009, 20–25 per cent). This may be due to the much smaller sample size in the previous study (only about 20 accretors) or due to an underestimation of the assumed contamination for their sample of photometrically selected YSO candidates. In the current study, only high-confidence members of star-forming regions are considered, which should provide a more reliable result.

These results have implications for the interpretation of the spread in HR diagrams that is ubiquitously observed in star-forming regions. Variability in the optical and near-infrared bands will to some extent contribute to this spread, as the luminosities are routinely estimated from I- or J-band photometry which is considered to give the best estimate of the photospheric flux. In luminosity, the spread in HR diagrams for very young regions is often as much as one order of magnitude (e.g. Luhman et al. 2003).
The results in this study indicate that the variability in the $J$ band is less than 0.5 mag for the overwhelming majority of YSOs, i.e. a factor of $<1.6$ in luminosity, which is only a minor part of the observed spread in the HR diagrams. Moreover, the typical level of variability in the $J$ band is much lower than that. About half the objects show variations of 5–20 per cent, depending on the disc fraction and possibly age; the other half is not variable within a few per cent, consistent with previous results by Carpenter et al. (2001). Variability on time-scales up to 6–8 yr can definitely cause outliers in HR diagrams and has to be taken into account when deriving fundamental parameters for individual sources, as argued in Scholz et al. (2009). For the analysis of the stellar properties of large samples, however, it is insignificant. This finding is similar to the conclusions drawn by Carpenter et al. (2001) and Burningham et al. (2005).

4.2 Nature of highly variable objects

As far as infrared data are available, 10/11 variable sources show evidence for the presence of a circumstellar disc. Since the disc fractions in the samples are high, this does not imply a statistically significant connection between variability and disc, but it gives several options to explain the nature of the variability. Without discs, only two options remain, eclipses by a companion and chromospheric flares. Both are relatively short events on time-scales of hours and thus unlikely to be detected with only two epochs. With an accretion disc, additional explanations become viable: (a) variations in the hotspots generated by an accretion shock, (b) variable circumstellar extinction, (c) variable emission from a dusty disc, and (d) eclipses by optically thick circumstellar material (Carpenter et al. 2001).

With two epochs it is not possible to unambiguously decide between these options; however, the colour of the variability gives a first hint. Hotspots and extinction cause decreasing amplitudes towards longer wavelengths, i.e. $dK < dJ$ or $dK < dH$. The reverse is the case for variable disc emission. Eclipses would cause grey absorption, i.e. similar amplitudes in different bands. As seen in Table 1, 5/13 clearly fall in the first category, 2/13 in the second and 6/13 in the third.

With reddening laws for standard dust properties, variable extinction causes $J$-band amplitudes that are 1.5 times larger than those in the $H$ band and 2.5 times larger than those in the $K$ band (Scholz et al. 2009). Three objects from Table 1 fit these requirements (ISO-Oph-21, ISO-Oph-65, MBO46). The other two with decreasing amplitude towards longer wavelength are better explained by variable hotspots, which cause less colour variations than extinction.

For a definite decision about the nature of the variability, follow-up spectroscopy and further multiband monitoring is required. As noted in Section 3, the current sample might still be affected by crowding, companions or other problems with the photometry. Particularly the six objects with almost equal amplitudes in several bands seem highly interesting for follow-up, as they might contain equivalents to KH15D (Herbst et al. 2002) which could give detailed insights into the structure of the disc.

4.3 Episodic accretion

One other possible application for the results presented in this paper is to derive constraints for scenarios of ‘episodic accretion’, i.e. the hypothesis that a large fraction of the stellar mass is accreted in short episodic bursts of accretion. Episodic accretion might be the explanation for the dramatic outbursts in FU Ori-type objects, and it could also resolve the problem of the underluminosity of protostars (e.g. Hartmann & Kenyon 1996). Based on Spitzer photometry, Evans et al. (2009) find that half of the mass of T Tauri stars is accreted in only 7 per cent of the Class I lifetime, which is $\sim 0.5$ Myr. This implies that episodes with strong accretion of $> 10^{-3} M_\odot$ yr$^{-1}$ which last in total a few $10^3$ yr are interspersed with significantly longer quiescent phases with much lower accretion rates ($< 10^{-6} M_\odot$ yr$^{-1}$). These numbers are supported by the available submillimetre data from embedded protostars (Enoch et al. 2009).

There is strong interest in episodic accretion from theoretical work on star and planet formation. Numerical simulations of the gravitational cloud collapse (Vorobyov & Basu 2006; Vorobyov 2009) actually predict episodic accretion to occur, with duty cycles that are consistent with the current constraints by the observations (e.g. 1–2 per cent of protostars with accretion rates $> 10^{-4} M_\odot$ yr$^{-1}$). Models of episodic accretion can reproduce the observed luminosity spread in HR diagrams, with quiescent phases of $10^{-2}$–10$^3$ yr (Baraffe, Chabrier & Gallardo 2011). These ‘lulls’ allow for the formation of low-mass stars, brown dwarfs and planets via disc fragmentation, and their duration may be critical for the frequency of these objects (Stamatellos, Whitworth & Hubber 2011).

Episodic accretion causes variability on very long time-scales of hundreds of years or more. One way of improving the constraint on the aforementioned models is thus to monitor the brightness of large samples of accreting YSOs over long time windows, to identify possible outbursts and derive their frequency. The increase in accretion rate should be approximately proportional to the increase in bolometric luminosity, if the gravitational energy of the accreted material is fully converted to radiation.

It is difficult to assess the effect of an accretion burst on the near-infrared magnitudes and colours, without knowing the spectral energy distribution of the accretion shockfront and the effects of increased accretion on the heating and emission of the disc. In contrast to most previously detected accretion bursts, two recent events have been observed in the near-infrared and indicate $dK$ of 3–4 mag and and $dJ$ of 3–5 mag (Caratti o Garatti et al. 2011; Miller et al. 2011). Although a full characterization is still pending, these two events probably do not classify as FU Ori-type outbursts (see Kóspál et al. 2011); they are more likely to be weaker bursts with accretion rate increase of at most two to three orders of magnitude.

In the samples investigated in this paper, there are zero objects with $K$- or $J$-band magnitude increase by more than 2 mag, i.e. it is unlikely that any of them undergoes an accretion rate outburst by several orders of magnitude, as it would be required in the episodic accretion scenario. This sets a lower limit on the duty cycle of accretion bursts in YSOs. Since this study covers about 320 objects with accretion discs and time-scales of 6–8 yr, the quiescent phases with low accretion rates last at least 2000–2500 yr. We note that Carpenter et al. (2001) determined a lower limit of 5400 yr for the duty cycle of FU Ori outbursts, using a similar approach. Their sample, however, comprises the entire YSO population of Orion A, including objects without discs. Assuming that about half of their objects have discs, that time-scale drops to 2700 yr, which is very similar to our result.

While this is consistent with the constraints from the infrared luminosities of protostars (see above), it is important to point out that the majority of the objects considered here are Class II sources because the earlier stages of the protostellar evolution (Classes 0 and I) have shorter lifetimes and are heavily embedded and thus often not observable in the near-infrared. It is possible that accretion...
bursts become less frequent as the objects progress towards the Class II stage. Maybe we should expect much longer duty cycles (or possibly weaker bursts) at Class II compared with Class I stage.

Thus, the constraint given above is currently of limited use when compared with the model predictions for the earlier stages. Improving the analysis requires one of the following: (1) adding second epoch data for a number of southern star-forming regions with well-characterized YSO population not observed by UKIDSS (e.g. Chamaeleon, Lupus and Corona Australis), to increase the sample size substantially; (2) establishing a census of YSOs in star-forming region for which several epochs are already available (e.g. from Galactic plane surveys); (3) carrying out a similar analysis in the mid-infrared regime where the Class I sources are visible [e.g. based on data from Spitzer or WISE, see e.g. Morales-Calderón et al. (2011)] and (4) extending the time baseline by adding more epochs over the next decades, which becomes feasible through all-sky monitoring facilities like Pan-STARRS or LSST.

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