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No wide spread of stellar ages in the Orion Nebula Cluster

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ABSTRACT
The wide luminosity dispersion seen for stars at a given effective temperature in the Hertzsprung-Russell diagrams of young clusters and star forming regions is often interpreted as due to significant ($\sim 10\,$Myr) spreads in stellar contraction age. In the scenario where most stars are born with circumstellar discs, and that disc signatures decay monotonically (on average) over timescales of only a few Myr, then any such age spread should lead to clear differences in the age distributions of stars with and without discs. We have investigated large samples of stars in the Orion Nebula Cluster (ONC) using three methods to diagnose disc presence from infrared measurements. We find no significant difference in the mean ages or age distributions of stars with and without discs, consistent with expectations for a coeval population. Using a simple quantitative model we show that any real age spread must be smaller than the median disc lifetime. For a log-normal age distribution, there is an upper limit of $< 0.14\,$dex (at 99 per cent confidence) to any real age dispersion, compared to the $\simeq 0.4$ dex implied by the Hertzsprung-Russell diagram. If the mean age of the ONC is 2.5 Myr, this would mean at least 95% of its low-mass stellar population has ages between 1.3–4.8 Myr. We suggest that the observed luminosity dispersion is caused by a combination of observational uncertainties and physical mechanisms that disorder the conventional relationship between luminosity and age for pre main-sequence stars. This means that individual stellar ages from the Hertzsprung-Russell diagram are unreliable and cannot be used to directly infer a star formation history. Irrespective of what causes the wide luminosity dispersion, the finding that any real age dispersion is less than the median disc lifetime argues strongly against star formation scenarios for the ONC lasting longer than a few Myr.

Key words: stars: formation – stars: pre-main-sequence – stars: variables, T-Tauri, Herbig Ae/Be – open clusters and associations: individual: M42

1 INTRODUCTION

When stars are newly born and emerge from their natal clouds onto the pre main-sequence (PMS), they can be placed in the Hertzsprung-Russell (HR) diagram. Low-mass stars ($\leqslant 2\,M_{\odot}$) take $> 10\,$Myr to descend their Hayashi tracks, commence hydrogen burning and settle onto the zero age main sequence. During this time the luminosity and effective temperature ($T_{\rm eff}$) of a PMS star can, in principle, be used to determine a unique, although model-dependent, age.

This technique has been used in many young clusters and star forming regions (SFRs) as the basis for inferring the age distribution and hence the star formation history. Examples range widely; from nearby, comparatively sparse clusters (Palla & Stahler 1999), to very rich and dense clusters within our own Galaxy (Beccari, G. et al. 2010), or even individual clusters in the Magellanic clouds (Da Rio et al. 2010). A significant luminosity spread, of an order of magnitude or more at a given $T_{\rm eff}$, is almost invariably found and this has been used to infer age spreads of order 10 Myr within a cluster or SFR (Palla & Stahler 2000).

Others dispute the reality of such large age spreads and debate whether the effects of unresolved binarity, differential extinction, the contribution of accretion luminosity, photometric variability, varying accretion histories over millions of years and observational uncertainties in spectral types and magnitudes could all contribute to the observed luminosity dispersion to some extent (Hartmann 2001; Burningham et al. 2005). Hillenbrand et al. (2008) showed that it may be difficult to verify or quantify age spreads unless the observational uncertainties are small and the size and distribution of the astrophysical sources of scatter are well understood. Jeffries (2007) showed that for the Orion Nebula Cluster (ONC – see below), there is a spread of radius at a given $T_{\rm eff}$, consistent with the luminosity spread observed. However, this paper also cautions that a spread of radius may not imply a spread in age. For example, some models suggest that co-eval stars with differing early accretion histories can still have significantly different radii several million years later (Tout, Livio & Bonnell 1999; Baraffe, Chabrier & Gallardo 2009).

Resolving this issue is important because ages from the HR diagrams of young SFRs are used to investigate different star formation scenarios, calculate star formation rates and set the clock for the dispersal of circumstellar material and the formation of planetary systems. For example, the inference of a large age spread in SFRs has been taken (by some) as evidence against a "fast" mode of star formation governed by the rapid dissipation of supersonic turbulence (Elmegreen 2000; Hartmann et al. 2001; Vázquez-Semadeni et al. 2005), and used instead to support a "slow" mode of star formation, where collapse is regulated by the ambipolar diffusion of strong magnetic fields (Tassis & Mouschovias 2004; Tan et al. 2006).

The ONC is one of the best-studied nearby SFRs (Jones & Walker 1988; Hillenbrand 1997). Palla & Stahler (1999) used the HR diagram to deduce that star formation in the ONC began at least 10 Myr ago and has accelerated up to the present day. Huff & Stahler (2006) extended this work to show that the inferred star formation history is similar in both the outer and inner parts (the Trapezium) of the ONC and for stars of all masses. These authors hypothesize that the ONC formed from a cloud supported by mildly dissipative turbulence, which collapsed globally in a quasi-static, but accelerating fashion over 10 Myr. Contrary to this, Fűrész et al. (2008) and Tobin et al. (2009) argue that the close agreement between the kinematics of the stars and molecular gas in the ONC implies that the ONC is younger than a crossing time ($\leqslant 1$ Myr). The ONC HR diagram has recently been updated and improved by Da Rio et al. (2010) (hereafter referred to as DR10), who present revised determinations of luminosities and $T_{\rm eff}$ and derive the distribution of members in the mass-age plane using evolutionary models. They found a mean age of 2–3 Myr, but with a very similar dispersion in luminosity, and hence inferred age spreads, to the earlier studies.

If the ONC is very young and undergoing rapid collapse, that would be difficult to reconcile with the age spread and mean age found on the basis of the HR diagram by Palla & Stahler (1999) and DR10. In this paper the reality of the ONC age spread is re-examined using the crude, but independent clock afforded by the time-dependent dispersal of circumstellar material around young PMS stars. In Section 2 the methods and the observational material are explained. The results are presented in Section 3 and examined with a simple interpretive model in Section 4. Section 5 discusses the results and their implications for PMS age determinations. Section 6 provides a summary.

2 METHODS AND OBSERVATIONAL DATA

2.1 Disc dispersal as an independent clock

It is well known that at the earliest ages, most, if not all, PMS stars are surrounded by optically thick circumstellar discs. These can be revealed either by the infrared flux emitted by warm dust in the disc, or the signatures of gas accretion from the disc onto the star. Groups of stars in young clusters and SFRs can be used to determine the timescale for the dispersal of inner disc material, traced by near-infrared excesses. Plotting the fraction of stars with a K-band excess versus the mean age (deduced from the HR diagram) of clusters, suggests that half of PMS stars lose their inner discs in about 3 Myr and that the timescale for almost all stars to lose their discs is about 6 Myr (Hillenbrand 2005). Observations at these relatively short wavelengths may not produce a complete census of discs (see the discussion in Lada et al. 2000), however whilst Haisch et al. (2001) found somewhat higher disc frequencies using $K-L$ excess as a disc indicator, the derived disc dispersal timescale was similar.

This work has now been expanded extensively using more sensitive Spitzer data, but with little change in the overall conclusion. There is a good correlation between $K-L$ excesses at wavelengths of 2.0–3.5 μm and excesses at the longer 3.6–8.0 μm wavelengths probed by Spitzer. Additional data from more clusters (e.g. see Hernández et al. 2008; Kennedy & Kenyon 2009) has strengthened the conclusion that the fraction of stars with primordial discs declines with age, such that most discs have dispersed after 5 Myr, although a few per cent of stars maintain some circumstellar material in clusters with an age of $\simeq 10$ Myr.

In principle the declining disc fraction with age seen in an ensemble of clusters could be used as a means of constraining any age spread within a single cluster. However, it is not clear to what extent the fraction of stars with discs in a single cluster is determined by the disc lifetime or a spread of ages within that cluster. A disc fraction that decreases with mean cluster age could be produced by a range of disc lifetimes in increasingly elderly but strictly coeval cluster populations. On the other hand, the trend in disc fraction could also be explained if the cluster populations had a spread of ages, with clusters of increasing mean age possessing larger proportions of stars older than some unique disc lifetime. These two possibilities would have different signatures in the present-day HR diagram and in the comparative age distributions of stars with and without discs. For the first possibility we would expect to see no luminosity spread in the HR diagram beyond that contributed by astrophysical scatter (binarity, variability etc.) and observational uncertainties, and no correlation between the presence of a disc and HR diagram position. However, for the second possibility we would expect a clear distinction in the HR diagram and inferred age distributions between young stars with discs and older stars that had lost their discs. For a more general case between these two extremes (i.e. an age spread *and* a range of disc lifetimes) we would expect to see a strong correlation between age determined from the HR diagram and the presence of a disc whenever the age spread becomes comparable to, or exceeds the mean disc lifetime.

To illustrate this argument, Fig. 1 shows a simulation using a model that is explored in more detail in Section 4. It is assumed (for the purposes of demonstration) that the

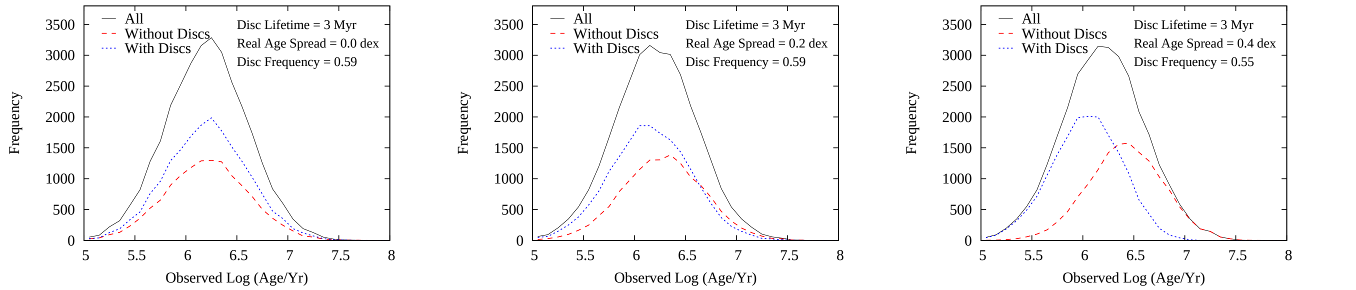

Figure 1. The apparent age distributions of stars with and without discs generated for simulated populations of 30 000 stars in a cluster with a mean log age (in years) of 6.2, an observed dispersion in log age of 0.4 dex and an exponential disc decay lifetime of 3 Myr. The three panels show cases where the real dispersion of age in the stellar population (as opposed to dispersion caused by observational uncertainties etc.) is increased from zero (a coeval population) to 0.2 dex (a mix of effects) to 0.4 dex (where the entire observed age dispersion is due to a real age dispersion). These plots show the differences expected in the age distributions of stars with and without discs once there are significant numbers of stars that are older than the mean disc lifetime.

observed distribution of ages from the HR diagram can be represented as log-normal in age (a reasonable approximation for the ONC discussed further in Section 4) with a mean log age of 6.2 (in years), a dispersion $\sigma = 0.4$ dex, and that this dispersion is formed from the quadrature sum of observational uncertainties, binarity, variability (etc.) and a separate contribution due to a *real* dispersion in age. It is further assumed that all stars begin their lives with a disc and that the disc lifetime is drawn from an exponentially decaying distribution with a characteristic timescale of 3 Myr. Different functional forms for these distributions are possible and will be explored in Section 4. The three panels of Fig. 1 show, for simulated populations of 30 000 stars, how the observed (or apparent) age distributions for stars with and without discs become clearly separated when the dispersion in real ages becomes large enough that there are many stars older than 3 Myr that have a high probability of having lost their discs.

There have been a number of previous attempts to identify this phenomenon with mixed outcomes. Strom et al. (1989) found that there was considerable overlap of stars with and without near-infrared excess in the HR diagram of the Taurus-Auriga association, but that the stars presumed to be discless were older on average. Subsequently, Hartigan et al. (1995) and Bertout et al. (2007) found that classical T-Tauri stars (CTTS) with veiling and accretion discs were systematically younger than their discless, weak-lined T-Tauri star (WTTS) counterparts in the Taurus-Auriga association. These samples were relatively small and it is likely that X-ray selected foreground field stars contaminated the WTTS samples, making them appear older. Fang et al. (2009) observed CTTS and WTTS in the L1630 and L1641 clouds, finding some evidence for a decrease with age in disc frequency determined from infrared excesses, and a 97 per cent signficance result that CTTS and WTTS were not drawn from the same age distribution. On the other hand Herbig (1998), Herbig & Dahm (2002), Dahm (2005) and Rigliaco et al. (2011) all found no difference in the age distributions of CTTS and WTTS in the IC 348, IC 5146, NGC 2264 and σ Orionis clusters respectively.

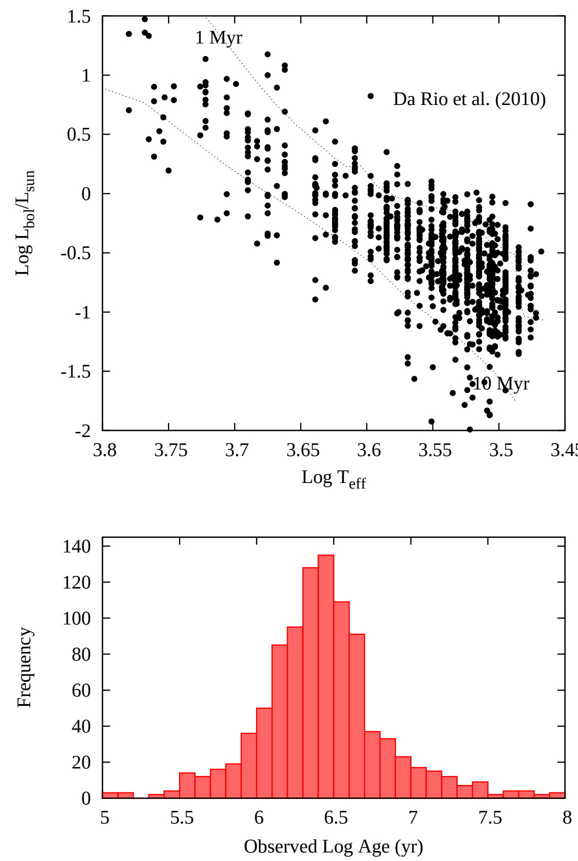

Figure 2. (Top) The Hertzsprung-Russell (HR) diagram for stars in the Orion Nebula cluster included in the catalogue compiled by Da Rio et al. (2010b). The dashed loci are 1 and 10 Myr isochrones from Siess et al. (2000). (Bottom) The inferred distribution of log age (in years).

2.2 Observations of the ONC

The goal of this investigation is to search for differences in the age distributions of stars with and without discs in a large and homogeneous sample from the ONC, and thus estimate the extent of any real age spread. The observational basis is the optical catalogue and HR diagram of the

ONC produced by DR10. This improves on earlier work by Hillenbrand (1997) and is the largest homogeneous catalogue of photometry and spectral types for stars in the ONC. DR10 simultaneously used photometry and spectroscopy to estimate extinction and accretion luminosity and hence find the intrinsic bolometric luminosity and effective temperature for each source. The sample of ONC stars was filtered to exclude possible non-members with membership probabilities based on proper motion that were smaller than 50%.[1] The overall level of non-member contamination remaining in the catalogue was estimated to be 2–3%.

DR10 used the evolutionary models of Palla & Stahler (1999) and Siess et al. (2000) to assign masses and ages from the resultant HR diagram and to study their distributions. They preferred the models of Siess et al. (2000) as they produced a smaller apparent age spread and a mean age that was independent of stellar mass. The catalogue is incomplete due to (a) lack of photometry or spectral types, which becomes severe at $V > 18$ and (b) crowding in the inner parts of the ONC. This affects stars at all magnitudes, but is more serious for fainter objects. For similar extinctions this of course means that incompleteness becomes greater for less luminous objects (see Fig. 19 of DR10) and, for the purposes of this investigation, biases the sample against "older" stars (where "older" means as judged from position in the HR diagram).

The 976 stars from the catalogue of DR10, that have ages deduced from the model isochrones, are plotted in a HR diagram in Fig. 2a. The inferred age distribution is shown as a histogram in Fig. 2b. The overall age distribution can be approximated as log-normal, with a mean of 6.42 and a dispersion (1-sigma) of 0.43 dex, although there is some kurtosis and it could be argued that some sort of core plus halo distribution is more appropriate (see Section 4.1). The mean and median masses of this sample are $0.50\,M_{\odot}$ and $0.32\,M_{\odot}$ respectively, and there is no significant correlation between mass and age.

The catalogue of DR10 was cross-correlated against three independent catalogues of ONC data that enable a judgement as to whether the stars possess a circumstellar disc. These catalogues are:

(i) Stars in the ONC with measurements of near-infrared excess in the $I-K$ colour (Hillenbrand et al. 1998). The cross-matched catalogue contains 535 stars spread over about 700 square arcminutes, with some concentration towards the central Trapezium region. The same criterion used by Hillenbrand et al. (1998) was adopted to signal the presence of a disc; namely that $I-K$ is more than 0.3 mag redder than expected from the photospheric spectral type. Using this criterion there are 295 stars with discs and 240 without. This sample is subsequently referred to as the "K-band sample".

(ii) Stars in the central regions of the ONC with a measurement of near infra-red excess using $JHKL$ data (Lada et al. 2000). The cross-matched catalogue in this case consists of 150 objects in a much smaller 36 square arcminute region surrounding the Trapezium. Discs are identified in the $J-H$ versus $K-L$ diagram using the same criterion adopted by Lada et al. (2000); namely that the star's $K-L$ colour lies redward of a reddening line extending from the intrinsic colours of a low-mass main-sequence star (defined by Bessell & Brett 1988). Using this criterion there are 115 stars with discs and 35 without. This sample is subsequently referred to as the "L-band sample".

(iii) Stars in the ONC with measurement of infrared excess using the Spitzer [3.6]-[8.0] colour (Megeath et al. in prep.). The cross-matched catalogue contains 425 objects spread over about 1300 square arcminutes, with no obvious concentration in the central Trapezium region. The relatively simple criterion of whether the [3.6]-[8.0] colour is greater than 0.7 mag is adopted to diagnose the presence of a disc (see Cieza & Baliber 2006). Using this criterion there are 290 stars with discs and 135 without. This sample is subsequently referred to as the "Spitzer sample".

Each of these samples is subject to a variety of selection effects, which are discussed further subsequently, but all three have a high fraction of stars less massive than the Sun (86%, 77% and 84% respectively).

3 COMPARISON OF STARS WITH AND WITHOUT DISCS

Figure 3 shows the HR diagrams and inferred "age distributions" using the three sources of information on disc presence. In each case, the stars with and without discs are identified and the parent sample from the catalogue of DR10 that share the same spatial extent as each survey is shown to illustrate completeness. Table 1 reports the means and standard deviations of the distributions of log age for each subsample as well as the median mass derived by DR10.

The K-band and Spitzer samples contain stars down to lower masses than the L-band sample because they are more sensitive in absolute terms in detecting stellar photospheres. Paradoxically, Fig. 3 shows that the L-band sample is almost complete in terms of providing data for the parent sample of stars from the DR10 catalogue, whereas there is some incompleteness at fainter magnitudes and lower luminosities in the K-band and Spitzer samples. The reason for this is that the DR10 sample is also more incomplete for faint stars near the centre of the ONC where the L-band sample is, but achieves greater sensitivity in the outer regions where most of the K-band and Spitzer sample stars are.

It is clear from Fig. 3 and Table 1 that the age distributions of stars with and without discs are similar using each of the three methods of identifying discs. The means and variances of the disc/no-disc subsamples are judged to be not significantly different in each case, using T-tests and F-tests respectively (see Press et al. 1992), although there are small differences in the overall mean age between the three samples.

Whether the age distributions of stars with and without discs are drawn from the same parent distribution, was tested with two-sided Kolmogorov-Smirnov (K-S) tests on the cumulative age distributions (Press et al. 1992). Similar tests were performed on the cumulative mass distributions. The results of these are reported in Table 1 in terms of a probability that the null hypothesis (that the two distributions are drawn from the same population) can be rejected.

[1] As discussed in DR10, there are very few objects with membership probabilities between 10% and 90%, so the exact choice of membership criterion is not important

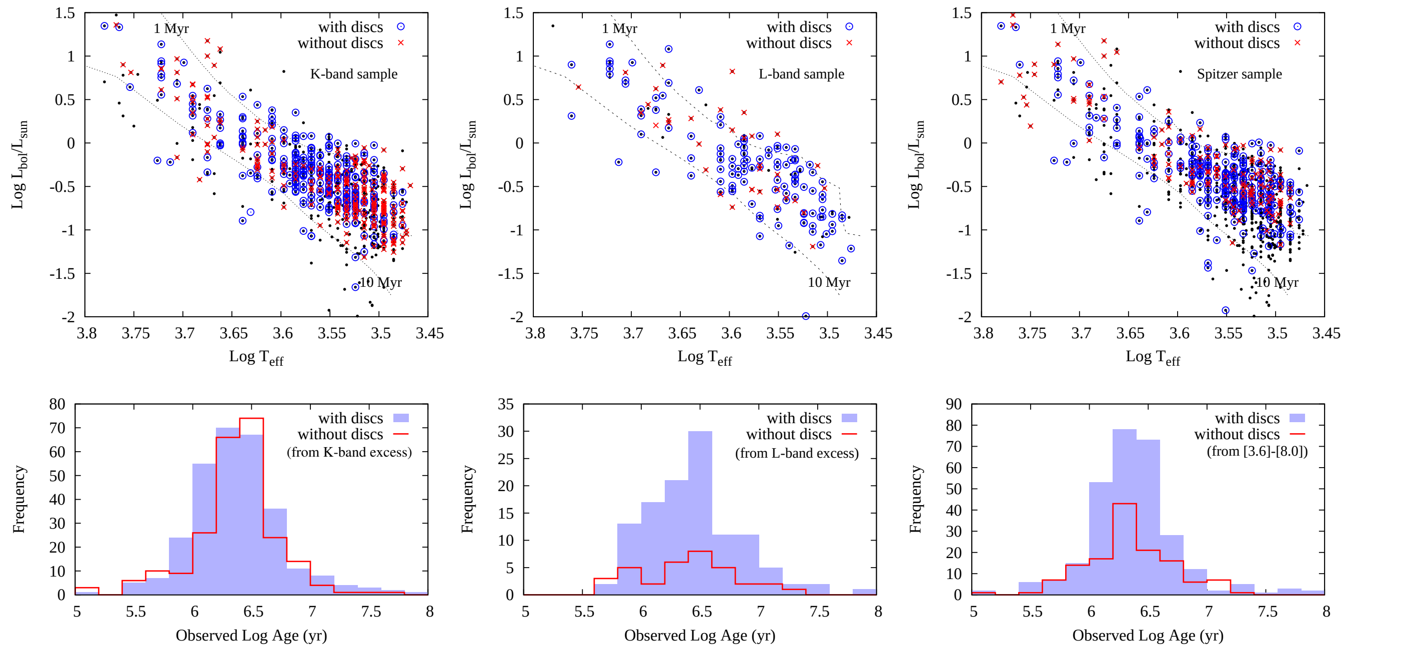

Figure 3. (Top row): Hertzsprung-Russell (HR) diagrams showing the locations of stars with and without discs, diagnosed using three different methods. Isochrones at 1 and 10 Myr are shown from the models of Siess et al. (2000). To demonstrate the level of completeness, the parent sample stars from Da Rio et al. (2010b) that lie within the area covered by each of the infrared surveys is shown with small dots. (Bottom Row:) Histograms of the age distributions inferred from the HR diagrams for stars with and without discs.

Table 1. A comparison of the bulk properties of the parent sample of ONC stars from the Da Rio et al. (2010b) catalogue with subsamples that have the presence of discs diagnosed by three different methods. For each of the three subsamples the table also shows the probability (judged by a two-tailed Kolmogorov-Smirnov test) that the null hypotheses, that the age and mass distributions of stars with and without discs are drawn from the same parent distribution, can be rejected.

Sample	Size	log Age (years)			Mass ($M_{\odot}$)		
		Mean	Std. Dev.	Median	Mean	Std. Dev.	Median
Dario et al. (2010b) parent sample	976	6.42	0.43	6.41	0.50	0.47	0.32
K-band sample, Hillenbrand et al. (1998)							
All with $I-K$	535	6.37	0.38	6.38	0.57	0.53	0.36
With Discs	295	6.37	0.38	6.37	0.59	0.48	0.42
Without Discs	240	6.36	0.37	6.40	0.55	0.58	0.30
Null KS Probability With vs Without			0.90			>0.9999	
L-band sample, Lada et al. (2000)							
All with $JHKL$	150	6.42	0.42	6.41	0.80	0.63	0.56
With Discs	115	6.45	0.40	6.43	0.72	0.62	0.46
Without Discs	35	6.34	0.47	6.41	0.84	0.57	0.56
Null KS Probability With vs Without			0.73			0.90	
Spitzer sample, Megeath et al. (in prep.)							
All with [3.6]-[8.0]	425	6.35	0.41	6.34	0.60	0.56	0.37
With Discs	290	6.36	0.42	6.36	0.55	0.50	0.36
Without Discs	135	6.33	0.39	6.33	0.70	0.66	0.39
Null KS Probability With vs Without			0.51			0.96	

The age distributions are indistinguishable in the cases of the L-band and Spitzer samples and are only marginally different at a 90 per cent confidence level in the case of the K-band sample. The mass distributions are not significantly different for stars with and without discs diagnosed in the L-band, are marginally different for the Spitzer samples (the median masses are similar but there is an excess of tail of higher mass stars in the discless population), but there is a highly significant difference in the mass distributions of stars with and without discs in the K-band sample – the stars with discs have a higher median mass. It is worth noting that the K-S tests we use are very insensitive to outliers in the distributions (see Press et al. 1992).

The K-band disc census is likely to be quite incomplete. It is well known (see Hillenbrand et al. 1998; Lada et al. 2000) that the effectiveness of K-band excess measurements reduces with decreasing mass because the contrast between the photosphere and warm dust diagnosed in the K-band becomes smaller. This probably accounts for the lower disc frequency in the K-band sample compared to the L-band and Spitzer samples, and likely accounts for the differing mass distributions of the stars with and without discs. Such incompleteness could also bias the comparison of the age distributions, because the disc lifetime for lower mass stars may be longer (Carpenter et al. 2006; Kennedy & Kenyon 2009). In this case the average age of stars with discs would be biased downwards by being unable to detect longer-lived discs in the lower mass stars, whilst the average age of stars without discs (or at least appearing to have no disc) would consequently be biased upwards. This selection effect is likely to be much weaker for discs detected by excesses in the L-band or at 8 μm and in any case the mass distributions of stars with and without discs in these samples are not very different.

Irrespective of these complications we have found no significant evidence (even using K-band excesses) that stars with discs are younger than stars without discs, which is consistent with the highly overlapping locations of of these samples in the HR diagrams (see Fig. 3). This appears to contradict the idea that most stars are born with discs and then lose them on timescales that are comparable to or shorter than the claimed spread of ages in the ONC and is instead consistent with the idea that the stellar population has an age spread smaller than a typical disc lifetime. However, a quantitative treatment needs to consider the influence of observational uncertainties and any other physical mechanisms that might cause scatter in the HR diagram.

4 AN INTERPRETIVE MODEL

Having established that the mean ages and age distributions of stars with and without discs in the ONC are not significantly different, this Section develops a simple model to interpret the results quantitatively and to set limits on the age spread that could be present in the population and yet still be consistent with the observational data.

Table 2. Results from modelling the age distributions of stars with and without discs and the fraction of stars with discs in the three samples discussed in the text. In each case the mean age is set to the observed value from Table 1 and the rows list the adopted apparent age spread, the derived best-fit real age spreads and exponential disc lifetimes and the 99 per cent confidence upper limit to any real age spread.

	K-band	L-band	Spitzer
Apparent age spread (dex)	0.3	0.42	0.3
Best-fit real age dispersion (dex)	$0.09^{+0.02}_{-0.02}$	$0.05^{+0.12}_{-0.05}$	$0.04^{+0.06}_{-0.04}$
Best-fit exponential disc lifetime (Myr)	4 ± 1	11 ± 3	6 ± 1
99 per cent upper limit to real age spread (dex)	< 0.16	< 0.25	< 0.14

4.1 Model Construction and Parameter Estimation

The basic model is similar to that described in Section 2.1. The distribution of stellar ages, as measured in the HR diagram, is assumed to be log-normal, with an overall dispersion consisting of the quadrature sum of two components – a real age spread and another dispersion term representing uncertainties in the observations or other sources of astrophysical scatter in the observed luminosity at a given age. The mean age and overall dispersion were chosen to match the combined apparent age distribution of stars both with and without discs. The real age dispersion was left as a free parameter. The additional observational dispersion was not a free parameter; it was varied so that when combined with the real age dispersion, the observed age dispersion was recovered. The other main component of the model is a prescription for the disc lifetime. Our most basic assumption is that most stars begin life with a circumstellar disc that betrays its existence via the infrared diagnostics we have discussed. The fraction of stars exhibiting these disc signatures is then assumed to decay monotonically (on average) with age. Initially we assumed that all PMS stars begin with a disc and that the disc lifetime obeys a probability distribution that decays exponentially, with a mass-independent decay timescale that was a free parameter.

For a given real age spread (characterised by a Gaussian sigma in log age) and disc decay timescale, the model predicts the *apparent* age distributions of stars with and without discs and the fraction of stars that still possess discs, within a total population with a given observed mean age and apparent age dispersion. Separate K-S tests were performed for the cumulative apparent age distributions of the stars with and without discs versus their respective model distributions, and a chi-squared test was performed between the observed and modelled fraction of stars that still possess a disc. The product of the three probabilities arising from these tests was used to estimate the overall probability that the data were drawn from a population described by

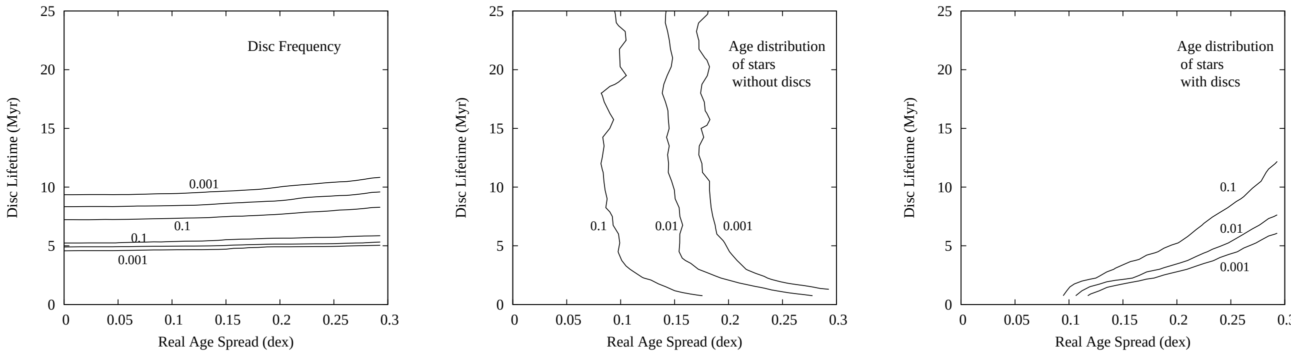

Figure 4. Contour plots of probability that the models described in Section 4.1 provide a good fit to the properties of the Spitzer sample (plots for the other two samples are qualitatively similar): the disc frequency (left); the apparent age distribution of stars without discs (centre); and the apparent age distribution of stars with discs (right). In each plot the contours represent probability levels of 0.1, 0.01 and 0.001 respectively.

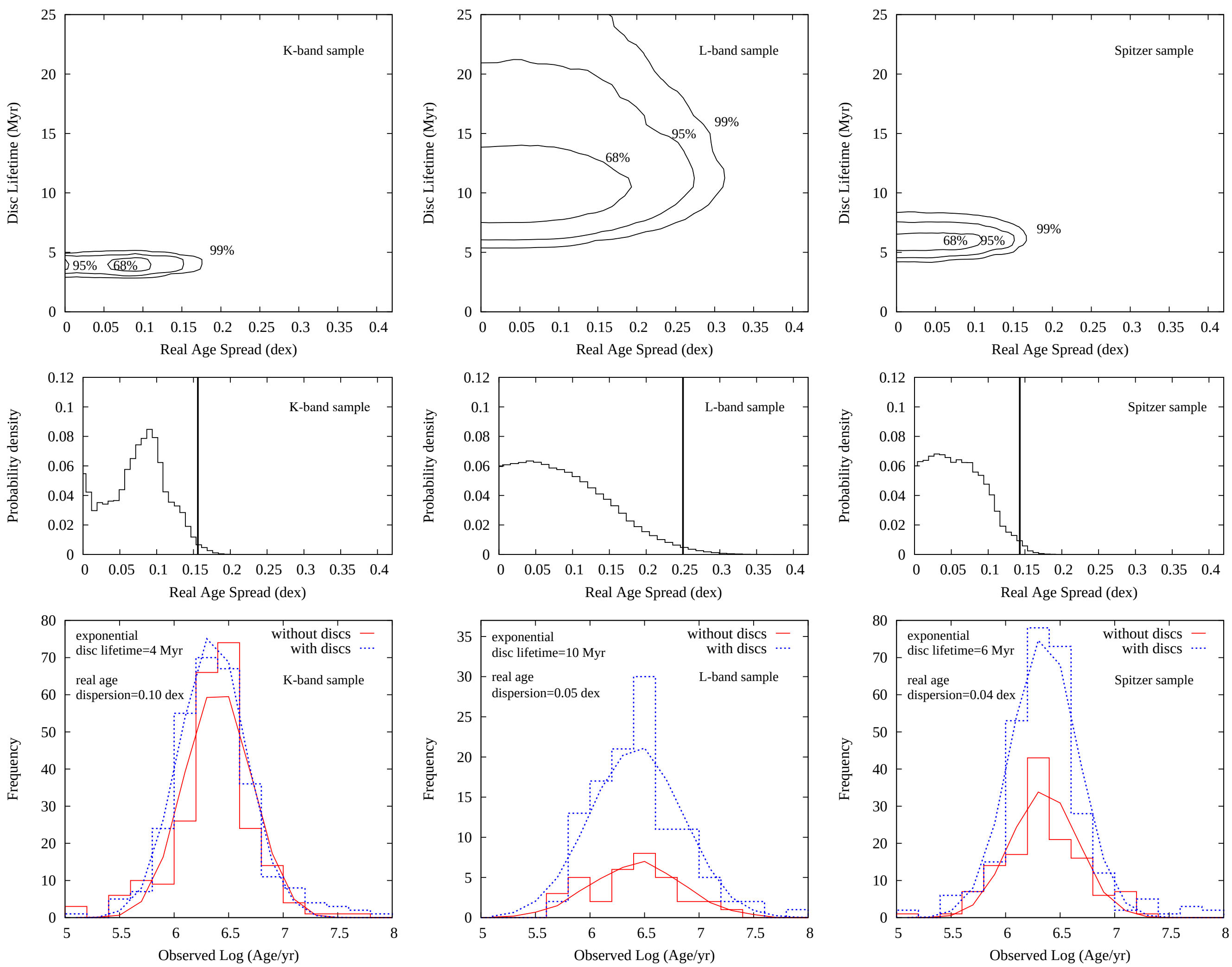

Figure 5. (Top row): A grid of relative probability for combinations of exponential disc lifetime (on the y-axis) and real age dispersion (on the x-axis). The contours enclose 68, 95 and 99 per cent of the probability. (Middle row): The integral of the probability distribution over the full range of possible disc lifetimes, yielding the probability distribution for the real age dispersion. 99 per cent of the probability distribution lies to the left of the vertical lines (note that we integrated over a larger range of disc lifetimes than displayed in the top plots). (Bottom row): The most probable age distributions for stars with and without discs. In each row the leftmost plot corresponds to discs diagnosed by a K-band excess, the middle plot corresponds to discs diagnosed by a L-band excess and the rightmost plot corresponds to discs diagnosed with Spitzer.

the model. This probability was calculated over a large, two-dimensional grid of possible values for the real age spread and disc decay timescale. Examples are shown in Fig. 4, calculated by comparison with the Spitzer sample.

For small sample sizes (the L-band sample), the relatively crude initial assumption of a log-normal age distribution was reasonable and we found areas of parameter space that gave satisfactory fits to the data. The larger K-band and Spitzer samples revealed deficiencies in this simple model – the observed log-normal age distributions in these samples have a significant kurtosis of 2.43 ± 0.21 and 4.84 ± 0.24 respectively, and are more peaked than a simple Gaussian, with extended wings. The broad Gaussians required to match the overall age dispersion are not a good fit near the observed distribution medians and thus result in very low K-S probabilities. To counter this, and provide a slightly more conservative (i.e. larger) upper limit to the possible real age dispersion, we allowed the input dispersion of the apparent age distribution to vary from the observed values of 0.38 dex and 0.41 dex (see Table 1), finding that a smaller value of 0.3 dex gave a much more probable model in both cases. This represented the core of the apparent age distribution quite well (see bottom row of Fig. 5). The derived parameters (and limits) are in fact rather insensitive to this procedure, because of the very low weight that is attached to objects in the tails of the apparent age distribution by K-S tests.[2] The nature of these outliers and whether they offer any support to the idea of a real age spread is discussed further in Section 5.3.

Confidence intervals on the model parameters were estimated by renormalising the probability grid so that the sum over all possible parameter combinations was unity. Contours containing arbitrary fractions of the probability distribution were calculated from this grid. Integrating the grid over one or other of the parameter axes gave estimated confidence intervals in one parameter. The extent of the probability grids were larger along the disc lifetime axis (typically up to 100 Myr) than displayed in Fig. 5 to ensure that all probability was accumulated.

4.2 Model Results

The results of comparing the models with the three ONC data samples are tabulated in Table 2 and illustrated in Figs. 4 and 5. Fig. 4 demonstrates to what extent the derived model parameters are sensitive to each of the observational constraints using the example of the Spitzer sample. It can be seen that the disc lifetime is very strongly constrained by the observed fraction of stars with discs. The real age spread is strongly constrained by the age distribution of stars that have lost their discs, whereas the age distribution of stars with discs rules out parameter space featuring large age spreads and short disc lifetimes.

The outcome is a consistent interpretation from all three samples, varying in statistical significance as expected from the different data set sizes. Figure 5 shows that the lack of any difference in the observed age distributions of the stars with and without discs constrains the real age spread to be much lower than the observed age spread and formally consistent with zero for all three samples. The most constraining dataset is the large Spitzer sample, which demands that the real age spread be < 0.14 dex with 99 per cent confidence. Even the smaller L-band sample provides a 99 per cent upper limit to the real age spread of < 0.25 dex. The disc lifetime, as parameterised in this model, is also well constrained in the two larger datasets at about 4 ± 1 Myr (K-band sample) or 6 ± 1 Myr (Spitzer sample), corresponding to a half-life of 3–4 Myr. It is larger for the L-band sample at 11 ± 3 Myr, due to the higher L-band disc frequency.

4.3 Sensitivity of the Results to Model Assumptions

The sensitivity of the conclusions to various model assumptions has been investigated. In particular, the possibilities of salvaging a real age spread that is anywhere near comparable with the observed age spread were explored in detail. Figure 6 shows plots equivalent to those in Fig.5, applied to the Spitzer sample, corresponding to the following model alterations.

(i) In column 1 of Fig. 6 the input value of the apparent age spread is increased to its observed value of 0.41 dex. As discussed in Section 4.1, the model is a poorer fit to the age distributions of stars with and without discs and the upper limit to the real age spread is almost unaltered, at < 0.15 dex.

(ii) In the initial models we assumed all stars started with discs. A lower initial disc frequency would imply that even at "zero age" there are some stars without discs. This has the effect of allowing much longer disc lifetimes, because fewer stars need to lose their discs to explain the observed disc frequency at a later time, and it simultaneously relaxes the constraint on any real age spread because even quite old stars could have a similar probability to young stars of being discless. Presumably, the initial disc fraction cannot be lower than the currently observed disc fractions. Considering the Spitzer sample with an observed disc frequency of 0.68, then if we adopt an initial disc fraction of 0.75, this allows a 99 per cent upper limit to the real age spread of 0.28 dex, which is an appreciable proportion of the observed age spread, although the best-fitting model still has a very small real age dispersion. This is achieved at the expense of a very long disc lifetime of > 20 Myr (see column 2 of Fig. 6).

(iii) A different functional form for the disc lifetime distribution may also allow longer disc life times. Rather than an exponential decay, the disc lifetimes could be distributed normally in log age in a similar way to the observed ages of the stars. If the dispersion of this normal distribution is smaller than the observed age spread (i.e. < 0.4 dex), then the results are very similar to those shown in Fig. 5. However, if the dispersion in disc lifetimes is made much wider around some median value, then there can be a significant probability that an older star would have kept its disc and likewise that a younger star had lost its disc. This means that the apparent age distributions of stars with and without discs could be quite similar even in the presence of a real age spread. Column 3 of Fig. 6 shows an extreme example

[2] We have experimented with clipping out 10–20 per cent of the sample as outliers (both in the data and models) and find almost no quantitative difference from the results in Section 4.2 where all the data were included.

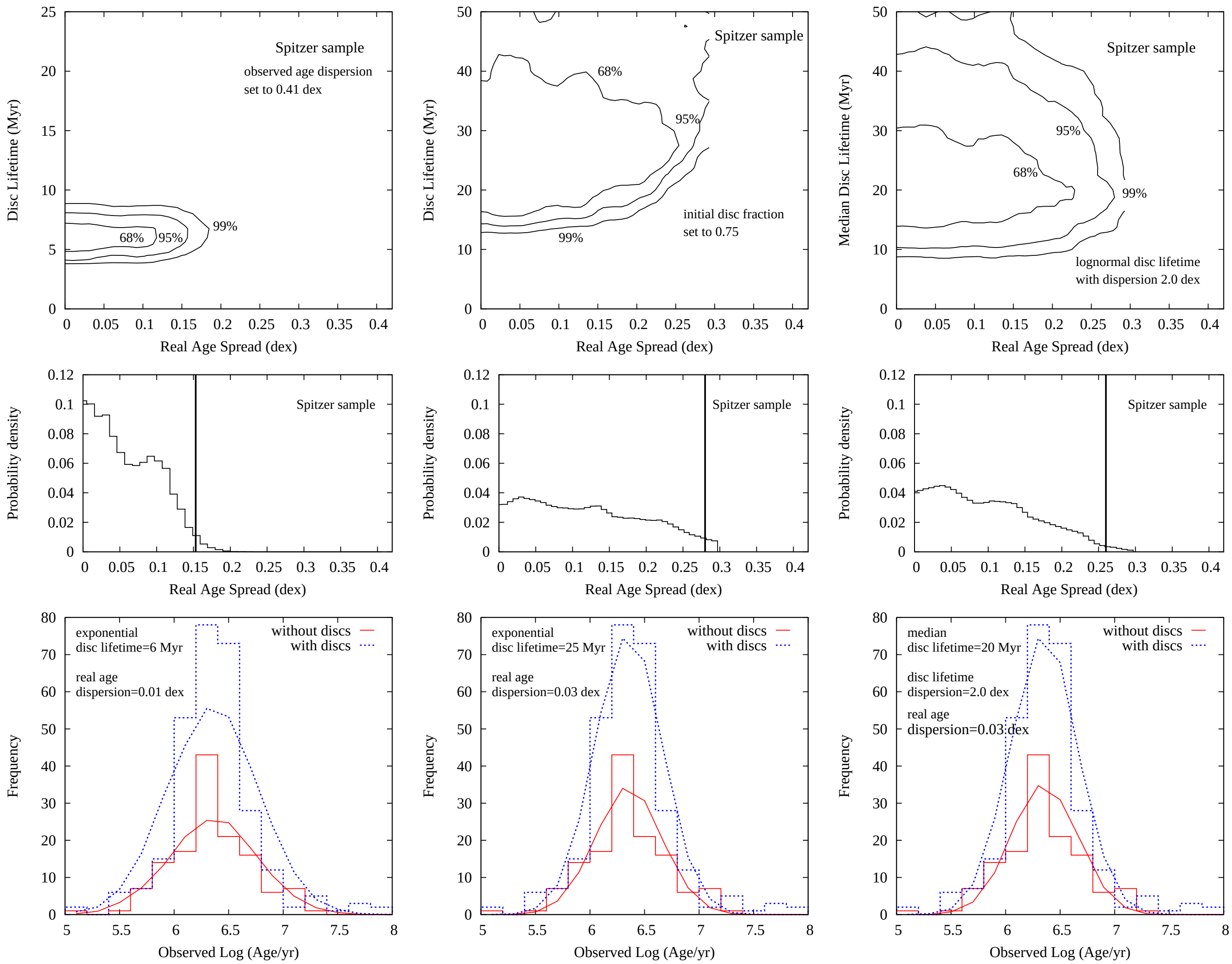

Figure 6. Exploring sensitivity to key model assumptions. These plots illustrate results for the Spitzer sample and are analogous to the third column of Fig. 5. The results for the K-band and L-band samples are qualitatively similar. (Column 1): As per Fig. 4, but the apparent age dispersion was fixed at the observed value of 0.41 dex rather than 0.3 dex (as in Fig. 5). The best model is a poorer fit to the age distributions than those in Fig. 5 (see bottom plots), but the upper limit to any real age spread remains similar. (Column 2): As per Fig.5, but the initial disc fraction was set to 0.75 instead of 1.0. This leads to longer inferred disc lifetimes and allows a larger real age spread compared to Fig. 5. (Column 3): As per Fig. 4, but the disc lifetime distribution is log-normal in age with a dispersion of 2.0 dex. The y-axis of the top plot now corresponds to the median disc lifetime of this distribution. This model demands a longer median disc lifetime which then also permits a larger real age spread than in Fig. 5, but which is still less than the total observed age spread of 0.41 dex.

where we have allowed the dispersion in disc lifetimes to be as large as 2.0 dex (almost a flat distribution over the entire range of observed ages). This huge range of disc lifetimes is very unlikely from other considerations (see section 5), but it could simultaneously explain the presence of "young" stars without discs and "old" stars with discs in the case of a real age spread as large as $\simeq 0.2$ dex, as long as the *median* disc lifetime is > 10 Myr.

5 DISCUSSION

Assuming that most stars are born with a disc and that the frequency of stars exhibiting disc signatures decays (on average) monotonically, then the similar apparent age distributions of stars with and without discs in the ONC imply that there is unlikely to be a large real age spread within the bulk of the population. The simple quantitative model developed in Section 4 suggests that any real age dispersion is limited to < 0.14 dex at 99 per cent confidence – a small fraction of the observed ~ 0.4 dex apparent age dispersion. This additional dispersion would therefore have to be due to observational uncertainties or other sources of astrophysical scatter in the stellar luminosities that are not related to age.

Our simple model could be criticised in that it does not provide exact fits to the observed age distributions, and the approach taken to modelling disc lifetimes is simplistic. In Section 4.3 we considered alternative disc lifetime distributions that do allow a larger fraction of the observed age spread to be real. These involve either initial disc fractions smaller than unity or a very large spread of disc lifetimes. Either is perhaps possible for the ONC, but the currently observed disc frequency would then require that median disc lifetimes be very long (> 10 Myr). A more robust qualitative statement of our conclusion for the ONC is therefore that any real age spread in the PMS population is smaller than the median disc lifetime, rather than smaller than some absolute value. The possibility of long disc lifetimes, sufficient to allow a large real age dispersion, is permitted by the ONC data alone, but unlikely in the context of infrared observations of other clusters. A median disc lifetime > 10 Myr would mean that a large fraction of stars in clusters with ages $\simeq 10$ Myr would still possess inner discs, but that is not borne out by the observational facts. Older clusters have infrared disc fractions limited to at most a few per cent (e.g. Sicilia-Aguilar et al. 2006; Hernández et al. 2008).

5.1 Selection Effects and Biases

Incompleteness could perhaps explain similar age distributions for stars with and without discs if our samples were missing either low-luminosity stars without discs or stars with discs among the more luminous, apparently young stars. The parent sample from DR10 does become increasingly incomplete for less luminous "older" stars, but this is not an issue if it applies equally to stars with and without discs. The infrared samples are also incomplete for less luminous objects, but this incompleteness will be less severe for stars with an infrared excess, because by definition these are brighter in the infrared. In principle then, "older" stars with an infrared excess are more likely to appear in these catalogues than stars of a similar age without discs. The HR diagrams in Fig. 3 allow the reader to assess how problematic this may be. It is clear that the infrared data are sampling stars from almost the full range of the HR diagram of the parent sample, although there is some evidence that fainter stars lying below the 10 Myr isochrone in the Spitzer sample are more likely to be stars with discs. This could be due to the effect we are discussing, but it could also arise from the possibility that some of these very low-luminosity sources are occulted by edge-on discs and being observed via scattered light (see Section 5.3). We do not expect either of these possibilities to significantly affect our results because the K-S tests used here are insensitive to differences in the tails of the respective apparent age distributions. In any case, the L-band sample is almost complete (in terms of having measurements for sources in the DR10 catalogue in the same area of sky – see Fig. 3) and whilst of lower statistical quality, the results from this sample do not contradict those from the Spitzer sample.

A less obvious bias might arise if incompleteness in the infrared samples affects the measured disc frequency. The K-band census of discs is likely to be incomplete towards lower masses - indeed the K-band sample disc frequency is significantly lower than the other two samples considered. A lower disc frequency leads to a smaller inferred disc dispersal timescale, which in turn means that a given age spread should produce a more marked difference in the age distributions of stars with and without discs. Thus if either the census of stars with discs is incomplete, or the subsample of stars without discs contained many contaminating non-members, then a misleadingly low disc frequency would be measured, the inferred disc lifetime would be too short, and the real age spread constrained too tightly. This bias is unlikely to be important here because stars with discs are actually more likely to be included in the infrared surveys; the samples were screened to exclude objects with low proper motion membership probabilities; and in any case if disc frequencies were higher, allowing long disc lifetimes, then this would contradict the mean disc lifetime estimates from the ensemble of young cluster observations.

5.2 What Causes the Apparent Age Spread?

If the apparent age spread in the HR diagram is not genuinely caused by a large age dispersion then how does it arise? Estimates of the uncertainties in measured luminosities have been made by a number of authors (Hillenbrand 1997; Hartmann 2001; Rebull et al. 2004; Burningham et al. 2005) and are likely to have pseudo-Gaussian dispersions in the range 0.16–0.20 dex. The well-known $L \propto t^{-2/3}$ scaling between age and luminosity on the PMS would then lead to an estimated Gaussian dispersion in the apparent age of 0.24-0.3 dex. Most recently, Reggiani et al. (2011) have shown, specifically for the ONC, that observational uncertainties and variability are unlikely to cause an apparent age dispersion beyond 0.15 dex. Thus observational uncertainties could be a component of the observed apparent age dispersion, but are unlikely to account for all of it. Supporting evidence for this point of view comes from the observed projected radii of PMS stars in the ONC (Jeffries 2007b). These exhibit a larger dispersion than can be explained by random inclination angles, implying a spread in stellar radii at a given $T_{\rm eff}$ that is consistent with the observed luminosity spread. In other words, the dispersion in luminosity appears to be genuine, with observational uncertainties playing only a minor role.

A further argument in favour of genuine dispersions in luminosity and radius, but not age, arises from the work of Littlefair et al. (2011). Here it was found that the rotation rates of high luminosity, apparently young, stars in the ONC were faster than for the low-luminosity, apparently old, stars. This contradicts the idea that the apparently older stars have evolved with time from the positions in the HR diagram currently occupied by the apparently younger stars, since in so doing they should have contracted and hence spun up. Instead Littlefair et al. (2011) suggest that both groups have a similar age but that their luminosities, radii and rotation rates have been affected by prior episodes of heavy accretion.

How could there be a genuine dispersion in luminosity, but not in age? The idea that early accretion could alter the position of a PMS star in the HR diagram making it appear younger or older has existed for some time (Mercer-Smith et al. 1984; Tout et al. 1999). This hypothesis has been revived by observations of class I young stellar objects (e.g. by Enoch et al. 2009) that suggest the main mass-building phase of a star could be characterised by transient or episodic accretion at very high rates ($\sim 10^{-4}\, M_{\odot}\,{\rm yr}^{-1}$) for brief periods of time (~ 100 yr). This episodic accretion has been modelled by Vorobyov & Basu (2006) and its consequences for PMS evolutionary tracks were explored by Baraffe et al. (2009). They find that if accreted energy can be efficiently radiated away, then a short phase of rapid accretion builds up the stellar mass, but leaves insufficient time for the star to adjust its radius before it emerges on the PMS. In the Baraffe et al. (2009) models, the consequent PMS star emerges on the HR diagram after the class I phase with a smaller radius and lower luminosity than would be otherwise predicted by non-accreting evolutionary tracks and *appears* older. A range of accretion histories could lead to a dispersion in the observed luminosities among any coeval group of stars with ages less than the Kelvin-Helmholtz timescale of ~ 10 Myr. As there may be no connection between accretion rates in the class I phase and later accretion as a class II T-Tauri star, this would effectively randomise the apparent ages determined from the HR diagram for young PMS stars.

Other authors suggest that the effects of early phases of heavy accretion may not be so dramatic. The models of Hosokawa et al. (2011) show that non-accreting isochrones may only overestimate true ages for PMS stars with $T_{\rm eff} >$ 3500 K (about half of our sample). Hartmann et al. (2011) argues that the early accretion phase probably adds significant energy to the protostar, perhaps increasing rather than decreasing the radius. Nevertheless they also argue that plausible variations in initial protostellar radii and accretion histories could give rise to 0.3 dex dispersions in apparent stellar age – a significant proportion of that observed.

5.3 The Consequences for Ages, Age Spreads and Cluster Formation Timescales

If our approach and assumptions are valid then ages from the HR diagram cannot be used reliably to trace the history of star formation in the ONC as attempted by Palla & Stahler (1999) and Huff & Stahler (2006). Furthermore, our work implies that the bulk of the stars in the ONC are formed over a timescale shorter than the median lifetime of circumstellar material. Our basic quantitative model suggests that if the ONC has a mean age of about 2.5 Myr (see Table 1), then at least 95% of its stars must have ages of 1.3–4.8 Myr (based on a 1-sigma dispersion of 0.14 dex and a log normal age distribution) with a more likely range that is smaller than this. Note though that this mean age, and hence age range, are dependent on the adopted evolutionary models, which have significant systematic uncertainties at these young ages (Baraffe et al. 2002).

The ONC age has been previously estimated at 2–3 Myr using PMS isochrones and the recently revised ONC distance of $\simeq$ 400 pc (Jeffries 2007a; Sandstrom et al. 2007; Menten et al. 2007; Mayne & Naylor 2008). DR10 obtained an ONC age of 2.6 Myr based the isochrones of Siess et al. (2000). Naylor (2009) provides a uniform recalibration of young PMS ages based on fitting of the upper main-sequence, finding an age for the ONC of 2.8–5.2 Myr and there is a kinematic age of $\geqslant$ 2.5 Myr, found by tracing back three runaway stars to their estimated origin as a single stellar system in the ONC (Hoogerwerf et al. 2001). On the other hand a younger mean age would agree better with the conclusions of Tobin et al. (2009), who argued that the close similarity between the kinematic structure of the stars and gas in the ONC indicate that the cluster is no more than a crossing time old ($\sim$ 1 Myr – see also Proszkow et al. 2009). A younger age might also be indicated by the young ($\lesssim$ 1 Myr) age deduced for the high-mass stars in the Trapezium (Störzer & Hollenbach 1999; Clarke 2007; Mann & Williams 2009) Our analysis could be consistent with the adoption of any of these estimates for the mean ONC age because we only require that any age spread is smaller than the disc dispersal timescale.

Whilst the ages of individual young PMS stars derived from the HR diagram may be unreliable, this does not necessarily invalidate mean ages deduced for whole clusters, because the additional sources of luminosity scatter may be roughly symmetric. Even if they were not, there is no reason to suppose that the rank ordering by mean age of well-observed nearby clusters is incorrect and so there is no contradiction in our use of mean cluster ages to argue for a monotonic decay of disc indicators with age (although the absolute timescale must be uncertain), whilst at the same time arguing that individual stellar ages are so uncertain as to preclude using them to estimate star formation histories.

Huff & Stahler (2006) suggest that star formation began in the ONC at a low level as long ago as 10 Myr and indeed there are stars in the HR diagram that are as old or older than this. However, as our modelling is insensitive to the tails of the age distributions (see Section 4.1), it is reasonable to ask whether a small population of older stars might still be consistent with our analysis. But there is a problem with this idea when confronted with the infrared disc diagnostics, because too many of these "old" stars still possess discs. For instance, in the Spitzer sample there are 56 stars (13% of the sample) with an apparent age $>$ 5 Myr and 36 of them have discs based on their [3.6]-[8.0] colour, a fraction consistent with the overall disc fraction of 68%. If the ages of these "old" stars were accurate, then for a reasonable exponential disc lifetime of say 6 Myr (see Section 4.1), we would only expect to see 13 stars with discs – inconsistent with the observed value at very high significance. Some of the more extreme objects (in terms of their apparent age) could be examples of stars occulted by their discs and observed in scattered light (Slesnick et al. 2004). Kraus & Hillenbrand (2009) find that the components of (presumably coeval) PMS binary systems frequently exhibit apparent age differences of 0.4 dex and more, which they also attribute to systematic problems in estimating the luminosities of PMS stars with discs and accretion. A similar argument applies to the 56 stars in the Spitzer sample that are apparently younger than 1 Myr. Only 32 of these possess discs compared to the 51 expected for a disc lifetime of 6 Myr and an initial disc fraction of unity. In summary, the disc frequencies also argue against the accuracy of the ages of objects in both the young and old tails of the age distribution and, like the bulk of the population, their luminosities must too be explained in terms of observational uncertanties or physical effects that alter the luminosity-age relationship.

6 SUMMARY

Assuming that most stars are born with circumstellar material and that the infrared signatures of this material decay, on average, monotonically with time, then a wide spread of ages ($\simeq$ 10 Myr) in the ONC should manifest itself by marked differences in the age distributions of stars with and without infrared disc signatures. This hypothesis has been tested using a large, homogeneous sample from the ONC catalogue of DR10, using three independent means of diagnosing disc presence and ages derived from the HR diagram. We have found no significant evidence for differences in the apparent age distributions of stars with and without discs and their means and medians are very similar. This is consistent with the conclusion that any real age spread in the ONC must be smaller than the median lifetime of the circumstellar discs.

A simple quantitative model has been developed to interpret these results. This model suggests that for plausible disc lifetimes, the contribution of any real age spread to the apparent age dispersion inferred from the HR diagram must indeed be very small; < 0.14 dex dispersion in a log-normal age distribution at 99 per cent confidence, compared with an observed age dispersion of $\simeq 0.4$ dex. Even stars in the tails of the apparent age distribution have disc frequencies incompatible with their apparent ages and consistent with coevality with the rest of the population. These results argue strongly against cluster formation timescales longer than a few Myr. If the mean cluster age were $\simeq 2.5$ Myr, then > 95% of the population has ages between 1.3–4.8 Myr.

Instead, we suggest that the observed luminosity dispersion in the HR diagram might be explained in terms of a combination of observational uncertanties (binarity, extinction, variability etc.) or physical effects that disorder any simple relationship between luminosity and age during the early PMS. There is some evidence in the literature that observational uncertainties alone cannot explain the full extent of the apparent age dispersion, but regardless of which mechanism proves to be more important, it may be difficult to use the presently determined individual ages of PMS stars from the HR diagram to infer a star formation history for the ONC. If it does emerge that physical effects such as the early accretion history of a PMS star can significantly alter its position in the HR diagram, then even the average age of the cluster may be unreliable.

It is important to extend the type of analysis described here to other clusters, using homogeneous techniques to determine luminosity and $T_{\rm eff}$ and to diagnose the presence of discs, although few nearby clusters are rich enough to offer the clear statistical tests provided by the ONC.

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