A discontinuity in the low-mass IMF – the case of high multiplicity

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ABSTRACT

The empirical binary properties of brown dwarfs (BDs) differ from those of normal stars suggesting BDs form a separate population. Recent work by Thies & Kroupa revealed a discontinuity of the initial mass function (IMF) in the very low mass star regime under the assumption of a low multiplicity of BDs of about 15 per cent. However, previous observations had suggested that the multiplicity of BDs may be significantly higher, up to 45 per cent. This contribution investigates the implication of a high BD multiplicity on the appearance of the IMF for the Orion Nebula Cluster, Taurus–Auriga, IC 348 and the Pleiades. We show that the discontinuity remains pronounced even if the observed mass function (MF) appears to be continuous, even for a BD binary fraction as high as 60 per cent. We find no evidence for a variation of the BD IMF with star-forming conditions. The BD IMF has a power-law index $\alpha_{BD} \approx +0.3$ and about two BDs form per 10 low-mass stars assuming equal-mass pairing of BDs.

Key words: binaries: general – stars: low-mass, brown dwarfs – stars: luminosity function, mass function – open clusters and associations: general.

1 INTRODUCTION

The origin of brown dwarfs (BDs) remains the subject of intense discussions. There are two broad ideas on their origin: (1) the classical star-like formation scenario of BDs (e.g. Adams & Fatuzzo 1996; Padoan & Nordlund 2004), and (2) BDs and some very low mass stars (VLMSs) form as a separate population (hereafter named BD-like besides the classical star-like population) with a different formation history than stars, e.g. as ejected stellar embryos (Reipurth & Clarke 2001; Kroupa & Bouvier 2003b) or as disrupted wide binaries (Goodwin & Whitworth 2007; Stamatellos, Hubber & Whitworth 2007). Additionally, the formation of BDs from Jeans instabilities in high-density filaments near the centre of a massive star-forming cloud has been recently suggested implying such BDs to be preferentially located in clusters with strong gravitational potentials (Bonnell, Clark & Bate 2008).

The star-like formation scenario fails to reproduce the observed different binary properties of BDs and stars. Especially the truncation of the semimajor axis distribution between 10 and 20 au for BDs and the different mass-ratio distribution of BDs and stars (Bouy et al. 2003; Burgasser et al. 2003; Close et al. 2003; Kroupa et al. 2003; Martin et al. 2003), as well as the BD desert (McCarthy, Zuckerman & Becklin 2003; Grether & Lineweaver 2006), are difficult to account for if BDs form indistinguishably to stars. This implies the need of treating BDs as a separate population to stars. The assumption of two separate populations would then require two separate initial mass functions (IMFs) of the individual bodies of a star cluster. Although the observed mass function may appear approximately continuous from the lowest mass BDs up to the highest mass stars (Lodieu et al. 2007), a discontinuity in the IMF may be present but be masked by ‘hidden’ (unresolved) binaries only emerging if the observed mass function (MF) is corrected for unresolved multiplicity. This issue has been discussed in greater detail in Thies & Kroupa (2007, hereafter TK07) for the case of a low multiplicity of 15 per cent of the BD-like population. However, a higher BD multiplicity between 20 and 45 per cent had been reported by some authors, e.g. Jeffries & Maxted (2005), Basri & Reiners (2006). This raises the need, dealt with this contribution, for including higher multiplicities as well as for an analysis of the general effects of a high multiplicity on the IMF and on the BD-to-star ratio.

In Section 2 we review the evidence for a separate BD-like population. Section 3 briefly introduces the mathematical method of calculating the IMF including unresolved binaries. In Section 4 the new results are presented and compared to those of TK07. The summary follows in Section 5.

2 BROWN DWARFS AS A SEPARATE POPULATION

2.1 Motivation

It may be argued that by treating the BDs as a separate population this forces an IMF discontinuity near the stellar/substellar mass limit by construction. Indeed, the semimajor axis data and binary
fraction (here used as a simplification for the multiplicity, neglecting multiples of higher order; Goodwin et al. 2007) as a function of the primary mass can be interpreted to be continuous with no evidence for BDs being a separate population (Burgasser et al. 2007).

Given this argumentation, it is essential to describe the methodology applied in our analysis: we seek one mathematical formulation which is a unification of the binary population for G, K, M dwarfs and VLMSs and BDs. This is found to be possible for G, K and M dwarfs: thus, for example, G dwarfs have mostly K- and M-dwarf companions, and the period-distribution functions of G-, K- and M-dwarf primaries are indistinguishable. Further, the mass-ratio and period-distribution functions for G-, K- and M-dwarf primaries derive from a single birth mass ratio and period distribution which does not differentiate according to the mass of the primary (Kroupa et al. 2003). One single mathematical model can therewith be written down which treats G, K and M dwarfs on exactly the same footing – one can say that G-, K- and M-dwarf stars mix according to one rule (random pairing from the IMF at birth).

If BDs are to be introduced into a similar mathematical formulation which does not differentiate between BDs and stars, then the model fails, because it leads to (1) a too wide BD period-distribution function, (2) too many BD binaries, (3) far too many stellar–BD binaries and (4) far too few star–star binaries (Kroupa et al. 2003). Lafreniere et al. (2008) show that the mass ratio of binaries depends on the primary-star mass in a way that results in an almost constant lower mass limit of the companions near 0.075 M⊙ for the Chamaeleon I star-forming region (see the figs 7 and 12 in their paper). This distribution can be reproduced by random pairing over the stellar mass range, while global random pairing over BDs and stars yields a different distribution, as shown in Fig. 1. In order to avoid these failures, and in particular, in order to incorporate the BD desert (‘stars and BDs do not mix, while G, K and M dwarfs do mix’) into the mathematical formulation of the population, it is unavoidable to invent special mathematical rules for the BDs. That is, stars and BDs must be described separately.

TK07 show that this necessarily implies a discontinuity in the IMF, given the observational data. We emphasize that the observational mass distributions lead to this conclusion, once the correct mathematical description is incorporated consistently. However, TK07 assume a rather low binary fraction of the BD-like population of 15 per cent. Some papers (Guenther & Wuchterl 2003; Kenyon et al. 2005; Joergens 2006) that report the discovery of close BD binaries instead conclude that these may imply a significantly higher binary fraction between 20 and 45 per cent (Jeffries & Maxted 2005; Basri & Reiners 2006), the latter being similar to that of stars in dynamically evolved environments (Kroupa 1995b). It is therefore useful to re-address the problem TK07 posed by incorporating a larger BD binary fraction into the analysis.

2.2 A short review of binarity analysis

This contribution is, like TK07, part of a series on the theoretical interpretation of observational stellar cluster data. Kroupa, Gilmore & Tout (1991), Kroupa, Tout & Gilmore (1993) and Kroupa (2001) showed for the first time that the true individual-body stellar IMF is changed significantly by correcting for the bias due to unresolved binary stars. A detailed study in Kroupa (1995a,b,c), in Kroupa, Petr & McCaughrean (1999) and in Kroupa, Aarseth & Hurley (2001) of the observed binary properties of field stars, stars in the Orion Nebula Cluster (ONC), the Pleiades and the Taurus–Auriga (TA) association led to a thorough understanding of the energy distribution of binary systems. This work established that simply taking observed distributions can lead to wrong interpretations, unless the counting biases and stellar–dynamical evolution is treated systematically and consistently; the basis of the argument being that Newton’s laws of motion cannot be ignored. In a recent paper Reipurth et al. (2007) have supported the predictions made by Kroupa et al. (1999) concerning the binary population in the ONC, by uncovering a radially dependent binary fraction in nice agreement with the theoretically expected behaviour. The late-type stellar binary population is therewith quite well understood, over the mass range between about 0.2 and 1.2 M⊙. The above work has also established the necessity to correctly dynamically model observed data in order to arrive at a consistent understanding of the physically relevant distribution functions.

BDs, which extend the mass scale down to 0.01 M⊙, have been added into the theoretical analysis in Kroupa & Bouvier (2003a,b) and Kroupa et al. (2003). This theoretical study of observational data (Bouy et al. 2003; Close et al. 2003) showed that BDs cannot be understood as being an extension of the stellar mass regime (as is often but wrongly stated). The hypothesis of doing so leads to incompatible statistics on the star–star, star–BD and BD–BD binary fractions, and on their energy distributions. This work showed that
BDs must be viewed as a separate population, and the theoretical suggestion by Reipurth & Clarke (2001), that BDs are ejected stellar embryos, is one likely explanation for this. In fact, their proposition logically implies different binary properties between stars and BDs, because ejected objects cannot have the same binding energies as not-ejected objects. Likewise, the model of Goodwin & Whitworth (2007), according to which BDs are born in the outer regions of massive accretion discs, implies them to have different pairing rules than stars.

TK07 and this contribution are a logical extension of the above findings. Here we repeat parts of the analysis of TK07 with assumed BD-like binary fractions up to 60 per cent as an upper limit. The clusters we analyse are the ONC (Muench et al. 2002), TA (Luhman et al. 2003a; Luhman 2004), IC 348 (Luhman et al. 2003b) and the Pleiades based on data by Dobbie et al. (2002) and Moraux et al. (2003) and the Prosper and Stauffer Open Cluster Database.\(^1\) The aim is to check whether our previous results are still valid for a higher binary fraction, and how robust they are for different accounting of unresolved binary masses.

### 3 IMF BASICS AND COMPUTATIONAL METHOD

The IMFs are constructed from power-law functions similar to that proposed by Salpeter (1955),

\[
\xi(m) = \frac{dn}{dm} = km^{-\alpha},
\]  

or in bi-logarithmic form

\[
\xi_L(\log_{10} m) = \frac{dn}{d\log_{10} m} = \ln(10) m \xi(m) = k_L m^{1-\alpha},
\]  

where \(k\) is a normalization constant and \(k_L = \ln(10) k\). While Salpeter found \(\alpha \approx 2.35\), the canonical stellar IMF, \(\xi_{\text{star}}\), is constructed as a two-part power law after Kroupa (2001), with \(\alpha_1 = 1.3\) for a stellar mass \(m < 0.5\, M_\odot\) and \(\alpha = 2.3\) for higher masses. The substellar IMF, \(\xi_{\text{BD}}\), is taken to be a single power law with cluster-dependent exponent \(\alpha_{\text{BD}}\).

The basic assumption is that a large fraction of binaries remains unresolved since cluster surveys are often performed with wide-field surveys with limited resolution. One may be tempted to use the observed IMF (hereafter IMF\(_{\text{obs}}\)) as a direct representation of the true IMF of individual bodies (simply the IMF hereafter). However, IMF\(_{\text{obs}}\) can differ largely from the IMF, especially at the low-mass end of the population which contains most of the stellar companions. If the companion has a much lower mass than its primary, then its light does not contribute much to the combined luminosity and spectral type, and thus the derived mass is essentially that of the primary. If, however, both components have near-equal masses (as expected from random pairing for very low primary masses), the low-mass region of the IMF\(_{\text{obs}}\) may be depressed even further, since the combined luminosity can be up to twice the luminosity of the primary alone. Therefore, a fraction of unresolved low-mass binaries is counted as single stars, maybe even of higher mass, while their companions are omitted, attenuating the IMF\(_{\text{obs}}\) at the lower mass end.

Possible approximations to the IMF\(_{\text{obs}}\) are the system IMF (IMF\(_{\text{sys}}\)), that is the IMF as a function of system mass (see equations 6 to 8 in TK07), and the primary body IMF (IMF\(_{\text{prim}}\)), the IMF as a function of the primary object mass, \(m_{\text{prim}}\),

\[
\xi_{\text{prim}}(m_{\text{prim}}) = f_{\text{tot}}N_{\text{bod}} \int_{m_{\text{min}}}^{m_{\text{max}}} \xi(m)\xi(m) dm,
\]  

where \(N_{\text{bod}}\) is the total number of objects, \(m_{\text{min}}\) is the minimum mass of an individual body in the given population, \(f_{\text{tot}} = N_{\text{bod}}/(N_{\text{tot}} + N_{\text{bod}})\) is the total binary fraction and \(\xi(m) = \xi(m)/N_{\text{bod}}\) is the normalized individual-body IMF.

In TK07 the IMF\(_{\text{obs}}\) has been used for the fitting process. However, one may argue that the mass derived from the system luminosity is closer to the mass of the primary star since the luminosity is mainly given by the primary object and the spectral features of the companion are outshone by those of the primary. Therefore, the IMF\(_{\text{prim}}\) has been used as the workhorse in the current contribution.

To obtain the true IMF from an observed mass distribution a binary correction has to be applied to each native population (i.e. a population of objects that share the same formation history) the cluster consists of. This is done here via the semi-analytical backward-calculation method and \(\chi^2\) minimization against the observational data introduced in TK07. It assumes two native populations with different IMFs, different overall binary fractions and different mass-ratio distributions (namely the two extreme cases of random pairing and equal-mass pairing for BDs while random pairing is always applied to stars). For each cluster the BD IMF slopes, the population ratio,

\[
R_{\text{pop}} = \frac{N_{\text{BD}}}{N_{\text{star}}},
\]  

and the upper mass limit of the BD-like IMF, \(m_{\text{max, BD}}\), are to be fitted, while the lower mass limit of BDs (0.01 \(M_\odot\)) and of the star-like population (0.07 \(M_\odot\)) is kept constant. Here, the number of BD-like and star-like objects is given by

\[
N_{\text{BD}} = \int \xi_{\text{BD}}(m) dm,
\]

\[
N_{\text{star}} = \int \xi_{\text{star}}(m) dm,
\]

respectively. The IMFs are then transformed into separate primary mass functions. Before being compared to the observational MFs the fitted IMF\(_{\text{prim}}\) has been smoothed by a Gaussian convolution along the mass axis in order to simulate the error of the mass determination (see TK07 for a more detailed description). This process is repeated iteratively until \(\chi^2\) reaches a minimum.

For the Pleiades the BD data do not constrain the power-law index, so fixed power laws with \(\alpha_{\text{BD}} = 0.3\) (the canonical value) and \(\alpha_{\text{BD}} = 1\) have been used here. It should be noted that the power-law indices are in rough agreement with the power-law index \(\alpha = 0.6\) deduced by Bouvier et al. (1998) and Moraux et al. (2003). Since they use BDs and low-mass stars up to 0.48 \(M_\odot\) while only BDs and VLMSs are used in our contribution these values have to be compared with caution.

The crucial point in performing the binary correction is that the assumed number and mass range of a native population largely affects the resulting IMF\(_{\text{prim}}\). If, for example, only one overall population is assumed (as in the traditional star-like scenario for BDs and stars) but there are actually two separate BD-like and star-like populations with different mass ranges, then the binarity is corrected for wrongly at the lower mass end of the star-like population since a mixing of binary components between BDs and stars is assumed that does not exist in reality. Reversely, the observed (primary) IMF

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\(^{1}\) Available at http://www.cfa.harvard.edu/~stauffer/opencl/
of a cluster may appear as being continuous while actually consisting of two populations, because the discontinuity is masked by the interference of different probability densities of the populations in the transition or overlap region on the one hand and different binary fractions on the other, as well as being smeared out by measurement uncertainties. Thus, an apparently continuous IMF$_{\text{pop}}$ or IMF$_{\text{sys}}$, may be related to a discontinuous IMF or, more precisely, a composite IMF which can only be revealed by reducing the fraction of unresolved binaries to insignificance by high-resolution observations.

The magnitude of the discontinuity, measured as the number ratio of BD-like to star-like objects at the hydrogen-burning mass limit (HBL), $R_{\text{HBL}}$, is given by

$$R_{\text{HBL}} = \frac{N_{\text{BD}}(m \approx 0.075 \, M_\odot)}{N_{\text{star}}(m \approx 0.075 \, M_\odot)}.$$  \hspace{1cm} (6)

If there is no overlap of the fitted BD-like and the star-like population (which is actually the case for the ONC and the Pleiades), $R_{\text{HBL}}$ is calculated from extrapolation of the BD-like IMF to the HBL. Since $R_{\text{HBL}}$ depends on the binary fraction among each population, the binary fraction is varied from $f_{\text{BD}} = 0$ to 0.6 in order to include even the most extreme BD binary fraction. The unresolved stellar binary fraction, $f_{\text{star}}$, is set to 0.4 for the ONC, IC 348 and the Pleiades while that of TA is assumed to be 0.8, as in TK07.

### 4 RESULTS

#### 4.1 IMF fitting parameters for different BD binary fractions

For illustration, Fig. 2 shows the fitted BD-like and star-like IMFs, $\xi_{\text{BD}}$ and $\xi_{\text{star}}$, and the resulting IMF$_{\text{pop}}$ for the ONC for an assumed $f_{\text{BD}} = 0.15$ (upper panel) and $f_{\text{BD}} = 0.45$ (lower panel), both using equal-mass pairing for BD-like binaries and random pairing for star-like ones. Random pairing means, in this context, pairing two stars selected by chance from the IMF. The discontinuity (equation (6)) between the BD-like and the star-like IMF becomes slightly smaller for higher binary fractions while the BD-like IMF slope remains almost constant. The discontinuity between both populations is, however, still present. The top panel of Fig. 3 shows the dependency of $\alpha_{\text{BD}}$ on $f_{\text{BD}}$ for the ONC, TA and IC 348 (the clusters for which $\alpha_{\text{BD}}$ has actually been calculated from $\chi^2$ minimization) for both equal-mass pairing and random pairing. The IMFs have been fitted via the IMF$_{\text{pop}}$. It should be noted that $\alpha_{\text{BD}} \geq 1$ for $f_{\text{BD}} \gtrsim 0.4$ for random pairing in IC 348, i.e. the turnover of the (bi-logarithmic) IMF in the substellar region vanishes, although the discontinuity remains (see Section 4.2). Similarly, the lower panel shows the trends with $f_{\text{BD}}$ in the case of equal-mass pairing if the BD-like IMF$_{\text{sys}}$ is used for fitting.

The most remarkable feature is that $\alpha_{\text{BD}}$ remains almost constant for equal-mass pairing in BD-like binaries. For random pairing $\alpha_{\text{BD}}$ increases with $f_{\text{BD}}$ in a similar way for all three clusters. A similar growth is found even for equal-mass pairing if IMF$_{\text{sys}}$ is used for fitting. For comparison, the constant values assumed for the Pleiades are shown in the lower panel of Fig. 3 (straight dashed lines at $\alpha_{\text{BD}} = 0.3$ and 1.0).

The fitting of $m_{\text{max,BD}}$ yields values slightly below 0.07 $M_\odot$ for the ONC and the Pleiades. This is probably due to the Gaussian smearing of log $m$ that has been used for smoothing the fit. For TA and IC 348, however, $m_{\text{max,BD}}$ is found to be around 0.1 $M_\odot$ and between 0.15 and 0.23 $M_\odot$, respectively. Furthermore, our results for the best-fitting $R_{\text{pop}}$, the population ratio, and the magnitude of the discontinuity can be summarized as follows: for $f_{\text{BD}} = 0$ the best-fitting $R_{\text{pop}}$ is about 0.07 for the ONC and the Pleiades while it is about 0.15 for TA and IC 348. It increases for larger $f_{\text{BD}}$, reaching about twice these values for the extreme binarity of $f_{\text{BD}} = 0.6$. That is, if a realistic value of $f_{\text{BD}} \approx 0.2$ is assumed, we expect about one BD-like body per 10 star-like ones for the ONC and the Pleiades, and about one BD-like body per five star-like bodies for the others.

This result is remarkable given that e.g. Slesnick, Hillenbrand & Carpenter (2004) state a higher BD-to-star ratio for the ONC than for TA and IC 348. The result can be interpreted as a consequence of the large mass overlap of the BD-like and the star-like regime in IC 348 (and a moderate overlap in TA), i.e. that many BD-like bodies are in actually VLMSs and thus are counted as normal stars. Another issue is whether the substellar peak in the ONC MF (see the thin dashed histogram in Fig. 2) is an artefact (Lada & Lada 2003) or a real feature. In the latter case, $R_{\text{pop}}$ would be significantly higher (about 75 per cent, given the histogram data) for the ONC than suggested by our results.

One may criticise the way of assigning a mass to an observed system. In TK07 the model-observed IMF has been created by simply adding the masses of all components, i.e. IMF$_{\text{obs}} = \text{IMF}_{\text{sys}}$. Because the observed data are being derived from luminosity functions rather than from mass functions, the correct way would be to convert luminosities into masses via the mass–luminosity relation (MLR). This would require rather complicated calculations because full-scale modelling would involve age-spreads and age-dependent MLRs with very significant uncertainties (Wuchterl & Tscharnuter 2003).
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\[ \alpha \equiv \alpha_{BD} \equiv 0 \quad \text{BD} \quad \text{and} \quad \alpha = 0.3 \quad \text{(short-dashed horizontal line) and} \]

\[ +0.4 \quad +0.6 \quad \text{IC 348} \quad n \quad R \] and the BD-to-star ratio \( f_{BD} \) found in this study are plotted against \( \log \) from our \[ \alpha \] are about \[ R = 0.3 \quad (\text{thin} \quad \text{20000 stars pc} \quad 1200–1206 \quad R \] and \[ 0.1 \quad 1.0 \quad (\text{thin dotted curve}). \] For all clusters there is \[ \text{Upper panel: the best-fitting BD IMF power-law indices for the} \]

\[ \text{Figure 3. Upper panel: the best-fitting BD IMF power-law indices for the} \]

\[ \text{ONC (solid line), TA (dashed line) and IC 348 (dash–dotted line) with equal-mass pairing and random pairing of BD binaries (dotted, narrow-dotted and double-dotted curves, respectively), as a function of the assumed BD binary fraction,} \]

\[ f_{BD}, \text{fitted via the primary-object mass function for both BDs and stars (see text). The upper/lower uncertainty limits of } \alpha_{BD} \text{ are about} \]

\[ +0.3/–0.3 \text{ for the ONC, } +0.5/–2.8 \text{ for TA and } +2/–0.6 \text{ for IC 348. While } \alpha_{BD} \text{ remains approximately constant for equal-mass pairing, there is} \]

\[ \text{a strong increase with increasing } f_{BD} \text{ for the random pairing case. Lower panel: the BD IMF power-law indices for the case of equal-mass pairing, but} \]

\[ \text{this time fitted via the BD system MF (and the stellar primary MF). The upper/lower limits of } \alpha_{BD} \text{ are about} \]

\[ +0.3/–0.3 \text{ for the ONC, } +0.7/–3.5 \text{ for TA and } +2.5/–0.6 \text{ for IC 348. In contrast to the equal-mass case in the} \]

\[ \text{upper panel, } \alpha_{BD} \text{ is now increasing with } f_{BD}. \text{ For comparison, the fixed } \alpha_{BD} \text{ is 0.3 (short-dashed horizontal line) and } \alpha_{BD} = 1.0 \text{(long-dashed horizontal line for the Pleiades have been added).} \]

\[ \text{Instead, a simpler way to at least embrace the real relation is to} \]

\[ \text{repeat the analysis (or parts of it) by using the primary mass instead} \]

\[ \text{of the system mass. This corresponds to the extreme case that the} \]

\[ \text{contribution of less massive companions is negligible. This method} \]

\[ \text{has been used in the present contribution with similar results as} \]

\[ \text{in TK07. In addition, similar calculations have been made for a} \]

\[ \text{substellar system IMF and for a stellar primary IMF, for equal-mass} \]

\[ \text{pairing of BDs, and for random pairing of stars.} \]

\[ \text{4.2 The discontinuity in the low-mass IMF} \]

\[ \text{A measure for the discontinuity at the HBL, } \mathcal{R}_{HBL}, \text{ is given by} \]

\[ \text{equation (6). For a continuous IMF } \mathcal{R}_{HBL} = 1, \text{ while values sig-} \]

\[ \text{nificantly different from 1 indicate a discontinuity. Fig. 4 displays} \]

\[ \mathcal{R}_{HBL} \text{ as a function of } f_{BD}. \text{ For all clusters } \mathcal{R}_{HBL} \text{ shows a similar} \]

\[ \text{steady increase. The uncertainties (not shown in the graph) can be} \]

\[ \text{estimated from those of } \alpha_{BD} \text{ and are about } \pm40 \text{ per cent for each} \]

\[ \text{value. Thus the discontinuity between the BD-like and the star-like} \]

\[ \text{IMF persists for both the system and the primary-body IMF for the} \]

\[ \text{BD-like population. It is largest (i.e. } \mathcal{R}_{HBL} \text{ is smallest) for } f_{BD} = 0. \text{ The results from TK07 show that this even holds true if the system} \]

\[ \text{IMF fit is applied to the stellar population.} \]

\[ \text{4.3 IMF slope and BD-to-star ratio in relation to the stellar density} \]

\[ \text{Certain theories of BD formation (e.g. Bonnell et al. 2008) sug-} \]

\[ \text{gest a dependency of the rate of BD formation on the star–cluster} \]

\[ \text{density. Correlating the BD IMF index, } \alpha_{BD}, \text{ and the BD-to-star} \]

\[ \text{ratio, } \mathcal{R}, \text{ against the stellar density, } n, \text{ may uncover such expected} \]

\[ \text{dependencies. For TA, } n = 1–10 \text{ stars pc}^{-3} \text{ (Martín et al. 2001), } n \approx \]

\[ 500 \text{ stars pc}^{-3} \text{ for IC 348 (Duchêne, Bouvier & Simon 1999), and } n \approx \]

\[ 20000 \text{ stars pc}^{-3} \text{ for the ONC (Hillenbrand & Hartmann 1998). The values of } \alpha_{BD} \text{ found in this study are plotted against } \log_{10} n \text{ in} \]

\[ \text{Fig. 5 (upper panel). In addition, the BD-to-star ratio, } \mathcal{R}, \text{ is shown} \]

\[ \text{Figure 4. The ratio of BD-like to star-like bodies at the HBL as a function of} \]

\[ \text{the BD-like binarity, } f_{BD}, \text{ for the ONC (solid curve), TA (dashed curve),} \]

\[ \text{IC 348 (dash–dotted curve), as well as for the Pleiades for } \alpha_{BD} = 0.3 \text{ (thin} \]

\[ \text{dashed curve) and } \alpha_{BD} = 1.0 \text{ (thin dotted curve). For all clusters there is} \]

\[ \text{a similar trend towards a higher } \mathcal{R}_{HBL}, \text{ with increasing binary fraction. But} \]

\[ \text{even for the highest plausible binary fraction } \mathcal{R}_{HBL} < 0.5. \text{ A continuous} \]

\[ \text{IMF would require } \mathcal{R}_{HBL} \equiv 1. \]

\[ \text{Figure 5. The power-law index } \alpha_{BD} \text{ and the BD-to-star ratio } \mathcal{R} \text{ from our} \]

\[ \text{model (assuming equal-mass pairing for BDs) and from the literature are} \]

\[ \text{plotted in dependence of the logarithmic central stellar density of TA, IC 348 and the ONC. The references for } \mathcal{R} \text{ are Luhman (2006) for TA, Preibisch} \]

\[ \text{et al. (2003) for IC 348 and Slesnick et al. (2004) for the ONC.} \]
in the lower panel, where

\[ R = \frac{N(0.02 \leq m \leq 0.075 \, M_\odot)}{N(0.15 \leq m \leq 1M_\odot)}. \] (7)

The mass limits are chosen in accordance with Kroupa et al. (2003) and TK07. The crosses connected with solid lines show the results of our modelling while the open circles with dashed lines are values taken from Luhman (2006) (TA), Preibisch, Stanke & Zinnecker (2003) (IC 348) and Slesnick et al. (2004) (ONC).

For \( \alpha_{\text{BD}} \) a regression line has been calculated. However, only three clusters have been analysed in this study, and there are large uncertainties. Especially for TA and IC 348 the confidence range is rather large here. Thus, the linear fit is only poorly constrained and well in agreement with a constant \( \alpha_{\text{BD}} \). Furthermore, \( R \) also does not show a significant trend with increasing stellar density. From our analysis (Fig. 5) it follows that \( \alpha_{\text{BD}} \approx 0.3 \) and \( R \approx 0.2 \) for equal-mass pairing of BDs.

5 SUMMARY

A discontinuity in the IMF near the HBL appears if the binary properties of BDs and VLMSs on the one hand, and of stars on the other, are taken into account carefully when inferring the true underlying single-object IMF. This implies that BDs and some VLMSs need to be viewed as arising from a somewhat different formation channel than the stellar formation channel, but this result has been obtained by TK07 under the assumption that BDs have a binary fraction of only 15 per cent. A higher binary fraction may close the gap between the stellar and the BD IMF. We refer to BDs and those VLMSs formed according to the putative BD channel as ‘BD-like’ bodies, whereas stars and those BDs formed according to the stellar channel as star like. The BD-like channel remains unknown in detail, but theoretical ideas have emerged (Sections 1, 2.2 and 4.3).

Here we have extended the analysis of TK07 for BD-like binary fractions up to 60 per cent for the ONC, the TA association, IC 348 and the Pleiades by using slight modifications of the techniques introduced in TK07.

As a main result, we found that the discontinuity that comes about by treating BDs/VLMSs and stars consistently in terms of their observed multiplicity properties remains even for the highest BD binary fraction. These results suggest that the BD binary fraction, \( f_{\text{BD}} \), is not the dominant origin of the discontinuity in the IMF, and that, consequently, two separate IMFs need to be introduced.

It is re-emphasized that by seeking to mathematically describe the BD and stellar population in terms of the relevant mass- and binary-distribution functions, it is unavoidable to mathematically separate BDs and VLMSs from stars. The two resulting mass distributions do not join at the transition mass near 0.08 \( M_\odot \). The physical interpretation of this logically stringent result is that BDs and VLMSs follow a different formation history or channel than stars. This result is obtained independently by theoretical consideration of star formation processes (Reipurth & Clarke 2001; Goodwin & Whitworth 2007; Stamatellos et al. 2007; Bonnell et al. 2008).

With this contribution we have quantified how the power-law index of the BD-like IMF and the BD-to-star ratio changes with varying binary fraction of BD-like bodies. The BD-like power-law index, \( \alpha_{\text{BD}} \approx 0.3 \), remains almost constant if equal-mass pairing of BD-like binaries is assumed, while \( \alpha_{\text{BD}} \) increases somewhat with increasing \( f_{\text{BD}} \) in the case of random pairing over the BD-like mass range. All values of \( \alpha_{\text{BD}} \) are between \(-0.1\) and \(+1.3\). We also find that although the stellar density differs from a few stars pc\(^{-3}\) (TA) to about 20 000 stars pc\(^{-3}\), the resulting \( \alpha_{\text{BD}} \) is constant within the uncertainties. Similarly, the BD-to-star ratio does not show a trend with increasing stellar density. This suggests the star formation and BD formation outcome to be rather universal at least within the range of densities probed here.

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REFERENCES

Adams F. C., Fatuzzo M., 1996, ApJ, 464, 256
Basri G., Reiners A., 2006, AJ, 132, 663
Bonell I. A., Clark P. C., Bate M. R., 2008, MNRAS, in press
Bouvier J., Stauffer J. R., Martin E. L., Barado y Navascues D., Wallace B., Bejar V. J. S., 1998, A&A, 336, 490
Bouy H., Brandner W., Martin E. L., Delfosse X., Allard F., Basri G., 2003, AJ, 126, 1526
Burgasser A. J., Kirkpatrick J. D., Reid I. N., Brown M. E., Miski C. L., Gizis J. E., 2003, ApJ, 586, 512
Burgasser A. J., Reid I. N., Siegler N., Close L., Allen, P., Lowrance P., Gizis J., 2007, in Reipurth B., Jewitt D., Keil K., eds, Protostars and Planets. Univ. Arizona Press, Tucson, p. 427
Close L. M., Siegler N., Freed M., Biller B., 2003, ApJ, 587, 407
Dobbie P. D., Pinfield D. J., Jameson R. F., Hodgkin S. T., 2002, MNRAS, 335, L79
Duchêne G., Bouvier J., Simon T., 1999, A&A, 343, 831
Goodwin S. P., Whitworth A., 2007, A&A, 466, 943
Goodwin S. P., Kroupa P., Goodman A., Burkert A., 2007, in Reipurth B., Jewitt D., Keil K., eds, Protostars and Planets. Univ. Arizona Press, Tucson, p. 133
Grether D., Lineaweaver C. H., 2006, ApJ, 640, 1051
Guenther E. W., Wachterl G., 2003, A&A, 401, 677
Hillenbrand L. A., Hartmann L. W., 1998, ApJ, 492, 540
Jeffries R. D., Maxted P. F. L., 2005, Astron. Nachr., 326, 944
Joergens V., 2006, A&A, 446, 1165
Kenyon M. J., Jeffries R. D., Naylor T., Oliveira J. M., Maxted P. F. L., 2005, MNRAS, 356, 89
Kroupa P., 1995a, MNRAS, 277, 1491
Kroupa P., 1995b, MNRAS, 277, 1507
Kroupa P., 1995c, MNRAS, 277, 1522
Kroupa P., 2001, MNRAS, 322, 231
Kroupa P., Bouvier J., 2003a, MNRAS, 346, 434
Kroupa P., Bouvier J., 2003b, MNRAS, 346, 369
Kroupa P., Gilmore G., Tout C. A., 1991, MNRAS, 251, 293
Kroupa P., Tout C. A., Gilmore G., 1993, MNRAS, 262, 545
Kroupa P., Petr M. G., McCaughrean M. J., 1999, New Astron., 4, 495
Kroupa P., Aarseth S., Harley J., 2001, MNRAS, 321, 699
Kroupa P., Bouvier J., Duchêne G., Moraux E., 2003, MNRAS, 346, 354
Lada C. J., Lada E. A., 2003, ARA&A, 41, 57
Lafreniere D., Jayawardhana R., Brandeker A., Ahmic M., van Kerkwijk M. H., 2008, ApJ, 683, 844
Lodieu N. et al., 2007, MNRAS, 379, 1423
Luhman K. L., 2004, ApJ, 617, 1216
Luhman K. L., 2006, ApJ, 645, 676
Luhman K. L., Briceño C., Stauffer J. R., Hartmann L., Barrado y Navascués D., Caldwell N., 2003a, ApJ, 590, 348
Luhman K. L., Stauffer J. R., Muench A. A., Rieke G. H., Lada E. A., Bouvier J., Lada C. J., 2003b, ApJ, 593, 1093
McCarthy C., Zuckerman B., Becklin E. E., 2003, in Martin E., ed., IAU Symp. 211, Brown Dwarf, Astron. Soc. Pac., San Francisco, p. 279
Martin E. L., Dougados C., Magnier E., Ménard F., Magazzù A., Cuillandre J.-C., Delfosse X., 2001, ApJ, 561, L195
Martin E. L., Barrado y Navascués D., Baraffe I., Bouy H., Dahm S., 2003, ApJ, 594, 525
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Moraux E., Bouvier J., Stauffer J. R., Cuillandre J.-C., 2003, A&A, 400, 891
Muench A. A., Lada E. A., Lada C. J., Alves J., 2002, ApJ, 573, 366
Padoan P., Nordlund Å., 2004, ApJ, 617, 559
Preibisch T., Stanke T., Zinnecker H., 2003, A&A, 409, 147
Reipurth B., Clarke C., 2001, AJ, 122, 432
Reipurth B., Guimarães M. M., Connelley M. S., Bally J., 2007, AJ, 134, 2272
Salpeter E. E., 1955, ApJ, 121, 161
Slesnick C. L., Hillenbrand L. A., Carpenter J. M., 2004, ApJ, 610, 1045
Stamatellos D., Hubber D. A., Whitworth A., 2007, MNRAS, 382, L30
Thies I., Kroupa P., 2007, ApJ, 671, 767
Wuchterl G., Tscharnuter W. M., 2003, A&A, 398, 1081

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