On the universal outcome of star formation: is there a link between stars and brown dwarfs?

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ABSTRACT

Given the current consensus that stars form from pre-stellar cloud cores that fragment into small-N groups which decay within a few \times 10^4 yr, and taking the observed properties of approximately 1-Myr-old stars in the Taurus–Auriga (TA) star-forming region as empirical constraints, we suggest a model that describes the multiplicity properties of the disintegrated groups. This model concisely describes the outcome of star formation in terms of dynamically unevolved binary properties. Two variants of the model are tested against data on very young stars in TA and the Orion Nebula cluster (ONC), as well as the older Pleiades and the Galactic field populations. The ‘standard model’ (SM) assumes that cloud-core fragmentation only produces stellar systems, while the ‘standard model with brown dwarfs’ (SMwBDs) assumes that cloud-core fragmentation proceeds down to substellar-mass cores. Brown dwarfs (BDs) enter the SM by being a separate, dynamically unimportant population. The models produce a very high initial binary proportion among stars (SM), and stars and BDs (SMwBDs), and both reproduce the measured initial mass function (IMF) in TA, the ONC and the Pleiades as well as the Galactic field. Concentrating on the SMwBDs, it is shown that the Briceno et al. result that TA appears to have produced significantly fewer BDs per star than the ONC is reproduced almost exactly without calling for a different IMF. The reason is that star–BD and BD–BD binaries are disrupted in the dense ONC. The model, however, fails to reproduce the observed star–star binary period distribution in TA, because it contains too many star–BD pairs. Also, the SMwBDs leads to too many wide star–BD and BD–BD systems. This is a problem if most stars form in clusters because Galactic field very low-mass star and BD binaries have a low binary fraction and do not contain wide systems. The SM, on the other hand, finds excellent agreement with the observed mass ratio and period distribution among TA and Galactic field stellar binaries, as well as the observed stellar period distribution in the ONC and the Pleiades. The conclusion of this work is therefore that the SM describes the initial, dynamically unevolved stellar population very well indeed for a large range of star-forming conditions, suggesting (1) a remarkable invariance of the star formation products, and (2) that BDs (and some very low-mass stars) need to be added as a separate population with its own kinematical and binary properties. This separate population may vary with star-forming conditions.

Key words: stellar dynamics – binaries: general – stars: formation – stars: low-mass, brown dwarfs – open clusters and associations: general – Galaxy: stellar content.

1 INTRODUCTION

The properties of multiple systems and the shape of the initial mass function (IMF) are the outcome of star formation. By studying these

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in different environments it may be possible to unearth variations that are important for constraining star formation theory. To achieve this it is necessary to apply exactly the same methodology to a variety of populations. The observational side of such a major endeavour is presented by the consistent work notably by Luhman and collaborators (e.g. Luhman et al. 2003a) on many very young populations. It is also necessary, however, to take into account changes in young stellar populations owing to stellar dynamical processes, in order to
verify if observed differences may not merely be due to the dynamical evolution, or even to uncover true differences in the absence of observed differences. For example, as has been stressed many times since a first thorough investigation of such issues by Kroupa, Tout & Gilmore (1991), a steep IMF can appear flatter if binary stars are abundant, thus appearing similar to a truly flat IMF if binary stars are sparse. It is worth keeping this bias in mind when investigating possible variations of primordial stellar populations. This we do here by concentrating on very recent observational evidence which allows us to probe star formation into the brown dwarf (BD) mass range.

Briceno et al. (2002) report nine new objects with masses in the range 0.015–0.1 \( M_\odot \) in the Taurus–Auriga (TA) star-forming region. The discovery is based on a deep optical survey combined with data from the Two-Micron All-Sky Survey and a follow-up spectroscopic survey of eight groups known to contain pre-main-sequence stellar members. Each of the survey areas comprises approximately 2.3 \( \times \) 2.3 pc\(^2\) (for a distance of 140 pc), and is complete down to masses \( m = 0.02 M_\odot \). They construct an IMF from the new sample and find a significant deficit of BDs in TA when compared with the Orion Nebula cluster (ONC). This may be the first direct evidence for a non-universality of the IMF at its low-mass end.

The assertion by Briceno et al. is very important for star formation theory, as it implies that the production of BDs through fragmentation of the cloud core may be dependent on the physical conditions of the molecular cloud, given that the cloud cores in which the ONC and the TA-aggregates formed were very different in density and mass. Thus in TA groups of a few dozen binaries are forming in a volume of about 1 pc\(^3\) (Gomez et al. 1993; Hartmann 2002) within which up to 10\(^3\) ONC stars may have formed (Kroupa, Aarseth & Hurley 2001, hereinafter KAH). As pointed out by Briceno et al., the sense of the discrepancy between TA and the ONC is expected if the distribution of stellar masses reflects that of Jeans-unstable fragments. TA should be producing fewer BDs by direct fragmentation than the ONC, because the Jeans mass \( M_\text{Jeans} \propto \rho^{-1/2} T^{3/2} \), so that \( M_{\text{TA}} > M_{\text{ONC}} \) since the gas density is about two orders of magnitude lower in TA than it was in the ONC, \( \rho_{\text{TA}} \approx 10^{-2} \rho_{\text{ONC}} \), while the temperatures, \( T \), are not likely to have differed by more than a factor of a few. That BDs may have a star-like formation history is also tentatively supported by the mass function (MF) of pre-stellar cores in \( \rho \) Oph which Motte, André & Néri (1998) and Bontemps et al. (2001) find to be indistinguishable from the very young (class II) stars and the Galactic field IMF in the mass range 0.06–2 \( M_\odot \). The conditions in \( \rho \) Oph appear to be such that the observed masses are consistent with Jeans fragmentation of the molecular cloud down into the substellar mass range without significant further evolution of the masses by interactions between protostars or competitive accretion.

Within the Briceno et al. survey regions, the authors find the spatial distribution of BDs and stars to be indistinguishable and both to show similar \( K\)-band excesses indicating similar accretion disc processes. Briceno et al. find no evidence for a different formation mechanism between BDs and stars. This is also supported by the high-resolution optical spectra of seven low-mass stellar and BD members of TA obtained by White & Basri (2003), who find that the kinematics of the BDs cannot be distinguished from the stellar motions. They conclude that the BDs form like stars albeit with smaller disc masses and smaller accretion rates. That is, stars and BDs should be formed with the same kinematical, spatial and binary properties. Given that they find no kinematical differences between their BDs and the stars, they exclude the embryo-ejection hypothesis. According to this hypothesis (Reipurth 2000; Boss 2001; Reipurth & Clarke 2001; Boss 2002; Bate et al. 2003), BDs may be unfinished stellar embryos that are expelled from forming multiple-star systems. The dynamical expulsion leads to relatively fast-moving (\( v \gtrsim 1 \) km s\(^{-1}\)) BDs with truncated discs (Sterzik & Durisen 1998, 2003, hereinafter SD98, SD03; Delgado-Donate, Clarke & Bate 2003, hereinafter DCB). The spatial distribution of the BDs so produced should therefore differ from the distribution of the stars. Briceno et al. do not observe a difference and they thus also discard the embryo-ejection hypothesis.

There are thus two possibilities for the origin of BDs that emerge from the preceding discussion. These can be framed as hypotheses (Section 2.2) that may then be tested against observational data. To test which hypothesis is consistent with the Briceno et al. data as well as data that are available for other populations, it is necessary to construct initial populations and allow these to evolve dynamically to the required ages. The theoretical stellar populations are constructed using a set of minimal assumptions by matching the IMF, binary star period, mass ratio and eccentricity distributions of T Tauri stars and late-type main-sequence Galactic field populations. The simultaneous fit to the pre-main-sequence and main-sequence data implies most Galactic field stars to be born in modest clusters (Kroupa 1995), which is also arrived at from direct observational surveys (Carpenter 2000; Lada & Lada 2003), and an analysis of the distribution and lifetimes of local Galactic clusters (Adams & Myers 2001). The ‘dominant-mode cluster’ contains initially 200 binaries and has a half-mass radius \( R_{0.5} \approx 0.8 \) pc. The ‘standard model’ (SM) of star formation thus obtained (Section 2.3 below) leads to a very good description of stellar populations in star clusters and the Galactic field.

The purpose of this contribution is to test the SM by extending it to include BDs. We apply the ‘standard model with BDs’ (SMwBDs) to the TA star-forming region and to the ONC and the Pleiades, and systematically study the implications of the SMwBDs for the observed number of BDs and for the orbital parameter distributions in a variety of environments such as TA, the ONC and the Pleiades. This may shed light on the origin of BDs. The underlying goal is to seek the simplest physically motivated description of the initial population that is consistent with all available data for different environments. This will yield useful constraints on the star formation process and will also provide a realistic input population for extensive star cluster modelling.

The pre-main-sequence populations in TA and in the ONC are especially suited for such a comparison because they offer examples of very different environments, TA giving birth to groups of a few dozens of late-type binaries, while the ONC is a post-gas-expulsion cluster containing a few thousand systems (= single stars plus binaries). The TA population is composed predominantly of binaries (and some higher order multiples), while the ONC has a binary proportion similar to that in the Galactic field. Stars more massive than about 1.5 \( M_\odot \) do not form in TA because of the limited molecular cloud masses, while the much more massive ONC precursor gave birth to a few O stars. Both have a similar age (about 1 Myr).

A discussion of state-of-the-art theoretical work on star formation and the line of arguments leading to the standard star formation model is given in Section 2. The stellar-dynamical models of the TA aggregates, the ONC and the Pleiades are introduced in Section 3. Section 4 models the Briceno et al. data. Section 5 presents the implications of the SMwBDs on the period and semi-major axis distributions of stellar and BD binaries, for standard and non-standard IMFs. The conclusions are given in Section 6.
counting all stars individually, while the ‘initial MF of systems’ or the ‘initial system MF’ refers to the distribution of system masses in the initial population. Likewise, ‘stellar MF’ and ‘system MF’ refer to possibly evolved mass distributions, and an ‘observed MF’ is taken to mean the empirical MF of unresolved systems. A ‘system’ can be a single star or be composed of physically bound multiple stars.

2 THE OUTCOME OF STAR FORMATION

This section addresses the current consensus on star formation. A comparison of state-of-the-art theoretical work with available empirical constraints allows us to distill the properties of the systems that actually form through fragmentation of cloud cores. Thus we can also infer a useful algorithmic description of the outcome of this process. This is important because the full problem of cloud collapse leading to stars cannot be computed fully self-consistently, but a description of initial populations is nevertheless needed for a wide variety of astrophysical problems. The description of this outcome, referred to as the ‘standard model’, details the characteristics of a dynamically unevolved stellar population. Such characteristics are the IMF, the initial binary proportion and the initial distribution function of angular momenta (periods, eccentricities and mass ratios), and can be referred to as being the dynamical properties of a population. The question being addressed here and in past and future contributions is how the characteristics of this initial population vary with star-forming conditions. Once these characteristics and their possible variation with the physical conditions in molecular clouds are known, these can be used to set up initial populations for $N$-body computations of star cluster formation and evolution, as well as to construct entire Galactic field populations using the method of ‘dynamical population synthesis’ [the construction of Galactic field populations from dispersing star clusters (Kroupa 1995)]. Knowing how and if at all the dynamical properties vary would also place important constraints on the cloud collapse work.

2.1 Cloud-core fragmentation

In the following we differentiate between a ‘cloud core’ that may form a cluster and a pre-stellar cloud core or ‘kernel’ which only forms a stellar system (cores of stellar mass with extent about 0.03 pc: Myers 1998). It has been realized for some time now that a collapsing slowly rotating kernel fragments into multiple accreting hydrostatic cores that initially form a bound system (e.g. Burkert & Bodenheimer 1996; Boss 2002). The latest high-resolution hydrodynamical collapse computations (Bate et al. 2003) deal with the collapse of a section of a molecular cloud and show that it develops a distribution of kernels each of which rapidly fragments into small-$N$ systems that disrupt and merge with the rest of the system. These results are very encouraging, and the latest such experiment by Bonnell, Bate & Vine (2003) finds a stellar IMF which is virtually identical to the Galactic field IMF that has been found to be rather surprisingly invariant (Kroupa 2002).

A problem faced by all these computations (Kroupa & Bouvier 2003a, hereinafter KB1) is that stellar feedback cannot be included, so that it is unknown at this stage how much gas is accreted and how much is removed again through outflows and photoionization in the event of OB stars forming in the vicinity. The fragmentation of magnetized kernels is reported by Boss (2002) with the result that binaries or multiples form readily, but the magnetic effects need to be treated in approximate ways. In addition, at present the collapse of each kernel proceeds unhindered and achieves very high densities that lead to rather violent dynamical evolution of the emerging stellar system. Such groups decay within about $N$ crossing times (e.g. DCB) by expelling members stochastically, unless their initial configuration is hierarchical. In the presence of feedback the additional energy input is likely to limit the collapse because of the higher thermal energy of the gas, thus probably leading to more extended, less violent small-$N$ stellar groups.

Based on the results of available cloud collapse calculations, SD03 elaborate a very useful model which assumes that cloud cores fragment into $1 \lesssim N \lesssim 10$ stars and BDs within a region with half-mass radius $R_{50} \approx 125$ au (from SD98). The nominal crossing time is $t_{\text{cross}} = (2R_{50})^{3/2}/(GM_{50})^{1/2}$, where $M_50$ is the mass of the group and $G$ is the gravitational constant. The crossing time is typically 300 yr. SD03 study the multiple-star properties of the disintegrated groups by evaluating their data after 300 $t_{\text{cross}} \approx 10^5$ yr. They find good agreement of their model BDs and stellar systems with those observed in the Galactic field (their fig. 2, compare with Fig. 5 below).

The model appears to be challenged, though, by the high binary proportion observed in the TA stellar population. The decay time of the multiple systems is too short, being typically very much shorter than 100 $t_{\text{cross}}$, to explain the observed high multiplicity fraction in TA, which is composed mostly of $N \approx 1$ old binary systems. This point is shown graphically by fig. 1 in Reipurth & Clarke (2001). Since about 50 per cent of the ejected single stars have three-dimensional velocities less than 1 pc Myr$^{-1}$ (fig. 5 in SD03), a large fraction of single stars would therefore remain within the observed areas for 1 Myr or longer, thus significantly reducing the binary fraction there, in contradiction to the observations. Also, the stars ejected with $v \gtrsim 1$ km s$^{-1}$ would form a halo population of single stars around the stellar aggregates that is not observed. The BDs expelled from the SD03 groups have a median velocity of 2 pc Myr$^{-1}$, implying that the BDs and stars ought to have well separated in TA, contrary to the conclusions drawn by Briceno et al. and others, as discussed in Section 1.

The results of SD03 are strictly valid only for stellar groups that do not contain gas, and are as such very important benchmark models in a regime where the physics is well understood. The early dynamical evolution of such groups is likely to be dominated by the gas in the kernel, however, and DCB develop such a small-$N$ model. DCB place $N = 5$ seeds into a non-rotating gaseous core initially in hydrostatic equilibrium and which comprises 90 per cent of the mass of the embedded system. The subsequent evolution is governed by competitive accretion and mutual ejections until either a binary or a long-lived hierarchical system remains. DCB continue the computations until all the gas is accreted on the seeds, which is, as they state, not realistic but which defines another extreme set of models that, together with the SD03 models, may bracket reality.

The overall result is similar to what SD03 find, namely that the groups decay rapidly leaving a multiple system. There are notable differences, though, as a result of including gas dynamics. The ejection velocities are typically larger, despite the additional retarding potential given by the mass in gas, as a result of the group of accreting seeds contracting because of the accretion of low angular momentum gas. The shrinking of the groups leads to more energetic dynamics. Seeds are expelled rapidly, within a few $t_{\text{cross}}$, so that the models predict that mostly BDs are expelled with a median speed of about 2 pc Myr$^{-1}$ (their fig. 8). The remaining seeds that form hierarchical multiple systems or binaries accrete the rest of the gas and thus acquire stellar masses.

The prediction of DCB is thus that BDs have a negligible binary fraction while the stars have a high multiplicity fraction, close to
2.2 Two hypotheses

Taking into account the theoretical results and the empirical constraints discussed above, we set up a model which describes the outcome of the fragmentation of kernels. The model is guided more by the empirical evidence from TA on the size, density, number of stars and binary star properties than by the theoretical results discussed above, since the physics and thus the detailed outcome of fragmentation of a kernel are not well understood yet. Thus, while we assume that pre-stellar cloud cores fragment into multiple systems, the properties of the systems must also be consistent with the observational data. A kernel can thus fragment into a binary or long-lived hierarchical multiple system. The multiple can be either a hierarchical triple or a hierarchical quadruple. The latter can be approximated by two weakly bound binaries. A physical reason why fragmentation would not produce chaotic, dynamically violent small-N groups with short lifetimes could be the energy input through stellar feedback which may oppose collapse to high densities and thus limit N per kernel.

From the discussion in Section 1 it follows that there are two principle possibilities for the origin of BDs. These can be framed as hypotheses that may then be tested against observational data.

(i) Hypothesis A: only stellar systems form from pre-stellar cores, and BDs and some very low-mass stars are unfinished embryos expelled from the kernels. Motivation of this comes from the work of SD03 and DCB (e.g. their fig. 14) and is consistent with the embryo-ejection hypothesis. Hypothesis A leads to the ‘standard model’ (SM), according to which BDs are a separate population of mostly single objects. This additional population is dynamically insignificant because it contributes less than 5 per cent in mass for usual IMFs (Kroupa 2002). The formation histories of BDs and stars differ fundamentally.

(ii) Hypothesis B: the fragmentation can also occur in pre-stellar cores with substellar masses, leading to the formation of many BD binary systems (DCB). This hypothesis essentially states that BDs and stars form in exactly the same manner, and is consistent with the above-mentioned rejection of the embryo-ejection hypothesis by Briceno et al. and White & Basri. Hypothesis B leads to the ‘standard model with BDs’ (SMwBDs). It implies that BDs and stars are born with the same binary and kinematical properties. The hypothesis assumes that substellar-mass kernels fragment, the parent kernel distribution thus being assumed to extend well into the substellar regime, as is, in fact, indicated to be the case in ρ Oph (Motte et al. 1998; Bontemps et al. 2001). As a result, BDs have a high binary fraction, as is also emphasized by DCB in their section 7, and there are many star–BD systems.

2.3 The standard model of star formation

We try here to produce a realistic model of a stellar population and make it evolve dynamically before comparing it with the observed properties of TA, the ONC and the Pleiades. The original version of the standard model did not include BDs (Kroupa 1995). This is referred to as the SM. A further discussion of this model is available in KB1, and Kroupa (1998) discusses the implied properties of runaway stars. Some of its success is reiterated here by showing previously unpublished results, followed by its extension through the inclusion of BDs, which we refer as the SMwBDs. Whenever we spell out ‘standard model’ we refer to the general properties of both variations of this model (SM and SMwBDs).

2.3.1 The SM (hypothesis A)

A ‘standard model’ describing the outcome of low-mass star formation in terms of an invariant field-like IMF, random pairing of mass from the IMF to form binaries, a birth period distribution function and no mass dependence of binary properties can be formulated which reproduces the available data.

Fig. 1 compares the observed MF in TA with the SM (upper panel) and with the SMwBDs (lower panel). Both models assume the standard IMF which can be written as a three-component power law (equation 2 in KB1), $\xi(m) \propto m^{-\alpha}$, where $\xi(m)$ is the number of stars and BDs in the mass interval $m$ to $m + dm$, and $\alpha = 0.3$ for 0.01–0.08 $M_\odot$, $\alpha = 1.3$ for 0.08–0.5 $M_\odot$ and $\alpha = 2.3$ for $m > 0.5 M_\odot$. The figure plots the ‘logarithmic MF’, $\xi_{\log_{10} m}$, $\xi_{\log_{10} m} = m \log(10) \xi(m)$, where $\xi_{\log_{10} m}$ is the number of stars/BDs or systems in the interval $\log_{10} m$ to $\log_{10} m + d \log_{10} m$, $\xi_{\log_{10} m} \propto m^\Gamma$ and $\Gamma = 1 - \alpha$. The figure shows that the measured system MF in TA is indistinguishable from the standard initial system MF and thus perfectly normal.

For the ONC, Muench et al. (2002) measure $\alpha = 2.2$ for $m > 0.6 M_\odot$, $\alpha = 1.2$ for 0.12 < $m/M_\odot$ < 0.6 and $\alpha = 0.3$ for 0.025 < $m/M_\odot$ < 0.12. This system MF is virtually identical to the standard IMF. Since it is the measured MF of unresolved binary systems, the underlying IMF may be somewhat steeper (larger $\alpha$) than the standard IMF (i.e. containing relatively more low-mass stars, e.g. Fig. 1 for models extending to 50 $M_\odot$). In addition, the MF has been measured within the inner regions of the ONC which may differ from the global MF since mass segregation is well pronounced in the cluster (Hillenbrand & Carpenter 2000). The global ONC IMF may thus be steeper still than the standard IMF. Apart from this caveat due to mass segregation, the uncertainties in mass estimates for stars and young stellar-mass objects that are $\lesssim 1$ Myr old unfortunately preclude firm conclusions on differences or similarities in the measured MFs. The usual approach taken to estimate masses of such young stars is to compare their locations in the
Figure 1. The thick histogram shows the observed MF of stars and BDs in TA arrived at by Luhman et al. (2003b). These data are compared with the standard IMF (equation 2 in KB1) without (upper panel) and with (lower panel) BDs, assuming that all stars and BDs can be observed (dashed curves), or that only unresolved binary system masses can be measured (solid curves). Binary systems are constructed by random pairing from the IMF in all cases, and the results are shown after pre-main-sequence eigenevolution (see Section 2.3.3) has been allowed to act. The models have been generated with 4000 stars and have been scaled to the data using the same scale-factor in all cases. Upper panel: the thick curves are for stellar masses in the mass range 0.07 \( \leq m/M_\odot \leq 1.5 \), which is applicable to TA, while the thin curves show the models if 0.07 \( \leq m/M_\odot \leq 50 \), which is applicable to rich clusters. Note that inclusion of stars more massive than 1.5 \( M_\odot \) has a negligible effect on the binary star MF at low masses. In the SM BDs need to be thought of as an additional (dynamically unimportant: Kroupa 2002) population such that the overall theoretical MF agrees with the empirical one. In this case the BDs do not participate in the pairing to binary systems with stellar primaries initially, although some star–BD binaries will result through dynamical capture and partner exchanges in the groups and clusters in which most stars form. Lower panel: the same as the upper panel, apart from the lower mass limit being 0.01 \( M_\odot \). The discrepancy of the SMwBDs between the initial system MF (solid curve) and the empirical data for \( \log_{10}(m/M_\odot) < -1.4 \) could be easily alleviated by slightly increasing the MF power-law index \( \alpha_0 \) in the BD mass regime. The results shown in Fig. 7 suggest this not to be necessary, however.

Hertzsprung–Russell diagram with pre-main-sequence contraction tracks. These are calculated by assuming that the stars begin fully convective and in hydrostatic equilibrium, whereas the collapse and accretion invalidate this assumption for objects younger than about 1 Myr (Wuchterl & Tschamuter 2003). Systematic errors that may vary depending on the hydrodynamical history and thus entropy deposition history of the hydrostatic core in a kernel may therefore affect mass estimates for such young stars and BDs. Given these two caveats, we conclude that, pending further analysis, the MFs of TA and the ONC may be considered as very similar if not identical.

Concerning the approximately 100 Myr old Pleiades cluster, Moraux, Kroupa & Bouvier (2004) find excellent agreement with the observed MF and the model system MF obtained from the cluster formation computations of KAH that assume the standard IMF.

Observations of low-mass, approximately 1 Myr old pre-main-sequence stars in low-density star-forming regions have established that most are in binary systems (Duchêne 1999) with a flat mass ratio distribution for mass ratios \( q = m_2/m_1 \geq 0.2 \) (Woitas, Leinert & Kühler 2001), where \( m_1 \) and \( m_2 \) are the primary and secondary mass, respectively. Random pairing from the standard stellar IMF also gives such an approximately flat distribution (Fig. 2). Most stars appear to be born in modest clusters similar to the ‘dominant mode cluster’ (Section 1). Disruption of binary systems in such modest star clusters leads to fine agreement with the overall mass ratio distribution for Galactic field binaries (Fig. 2), as well as with the mass ratio distribution of Galactic field G dwarfs (Fig. 3).

The orbital properties of late-type Galactic field binaries do not appear to vary with the mass of the primary. Thus M, K and G dwarfs have indistinguishable period distribution functions (Fig. 4).
The Galactic field G dwarf mass ratio distribution, $q_1 = m_f / m_p$, $0.9 \leq m_p / M_\odot \leq 1.1$, $m_s \leq 1.1 M_\odot$. Top panel: short-period distribution of secondary star masses. The dashed histogram represents the initial distribution ($t = 0$) after pre-main-sequence eigenevolution (Section 2.3.3), and the solid histogram is the final distribution. It barely changes because the stellar-dynamical interaction cross-section is too small for the typical star-forming cluster. The solid circles are G-dwarf main-sequence short-period binary star data (Mazeh et al. 1992). Bottom panel: the same as the top panel but for long-period systems for which eigenevolution is insignificant. The solid dots are G-dwarf main-sequence long-period binary star data (Duquennoy & Mayor 1991). Note that the primordial or birth distribution (before eigenevolution sets in) in the upper panel is the same as in the lower panel. Eigenevolution evolves the short-period mass ratio distribution to the form shown in the upper panel.

The distribution of periods is given by

$$f_P = \frac{N_{\text{bin},P}}{N_{\text{sys}}},$$

where $N_{\text{sys}} = N_{\text{bin}} + N_{\text{ang}}$ is the number of systems with primaries in the corresponding mass range, while $N_{\text{bin},P}$ is the number of binaries in the bin $\log_{10} P$ (the period $P$ is in days throughout this text) with primaries in the same mass range. The SM, which assumes that all primaries have a birth period distribution function (equation 3 in KB1) and is independent of primary mass, is plotted in Fig. 5. There is a significant difference between the Galactic field binary population and the pre-main-sequence population, but the difference is accounted for very well by the SM assuming that most stars form in modest star clusters. Particularly noteworthy is the probably significant empirical change in $f_p$ near the hydrogen-burning mass limit. This change is complemented by the observation that M dwarfs have a similar period distribution to G dwarfs (Fig. 4), while very low-mass stars and massive BDs have a period distribution confined to $\log_{10} P < 4.9$ (Section 5, semimajor axis $a < 20$ au and assuming a system mass of $0.16 M_\odot$). Note that we do not include the Reid & Gizis (1997) M-dwarf datum in Fig. 5 because that survey is incomplete (Henry et al. 1997). Incompleteness has the effect that not all low-mass companions are seen, leading to an underestimate of the binary fraction. The detected binary systems can be used to construct a mass ratio distribution, but will be biased to $q \approx 1$ systems because these are brightest and thus more easily seen. This may be one reason for the peak in the empirical data evident in Fig. 2. The SM reproduces this peak, but in this case it is a result of pre-main-sequence eigenevolution. Larger samples will be needed to constrain the overall mass ratio distribution better. We mention for completeness that SD03 include the Reid & Gizis mass ratio, rather than binding energy, angular momentum and mass ratio. This is done because the period distribution functions can be more readily derived observationally.

The dependence of the binary fraction on the mass of the primary star $f_n$, is plotted in Fig. 5. There is a significant difference between the Galactic field binary population and the pre-main-sequence population, but the difference is accounted for very well by the SM assuming that most stars form in modest star clusters. Particularly noteworthy is the probably significant empirical change in $f_n$ near the hydrogen-burning mass limit. This change is complemented by the observation that M dwarfs have a similar period distribution to G dwarfs (Fig. 4), while very low-mass stars and massive BDs have a period distribution confined to $\log_{10} P < 4.9$ (Section 5, semimajor axis $a < 20$ au and assuming a system mass of $0.16 M_\odot$). Note that we do not include the Reid & Gizis (1997) M-dwarf datum in Fig. 5 because that survey is incomplete (Henry et al. 1997). Incompleteness has the effect that not all low-mass companions are seen, leading to an underestimate of the binary fraction. The detected binary systems can be used to construct a mass ratio distribution, but will be biased to $q \approx 1$ systems because these are brightest and thus more easily seen. This may be one reason for the peak in the empirical data evident in Fig. 2. The SM reproduces this peak, but in this case it is a result of pre-main-sequence eigenevolution. Larger samples will be needed to constrain the overall mass ratio distribution better. We mention for completeness that SD03 include the Reid & Gizis
The recent detection of substellar objects in a variety of environments, however, prompts for the inclusion of BDs in the model. The simplest scenario in concordance with the assertion that BDs form like stars is simply to extend the standard model to include BDs. That is, the SMwBDs assumes that binaries are born by fragmentation of a cloud kernel and that the two fragments have masses sampled randomly from the IMF which extends into the BD mass range, and that the primordial star–star, star–BD and BD–BD binaries have the same period distribution function. Note that this changes the orbital distribution functions of star–star binaries, since in the SMwBDs some stellar primaries have BD rather than stellar companions. The star–star binary fraction is thus lower in the SMwBDs than in the SM.

2.3.3 Eigenevolution

The standard model, originally formulated without BDs, takes into account that close (orbital periods $P \lesssim 10^3$ d) pre-main-sequence binaries evolve through system internal processes (termed ‘eigenevolution’). This is necessary to account for the observed correlations between eccentricity, orbital period and mass ratio (upper versus lower panel in Fig. 3). The birth period distribution function [equation (3) in KB1 and the thin solid curve in Fig. 4] evolves instantly in the model, but within a few orbital times in reality, to the initial distribution, shown as the dotted histograms in Fig. 6 below. While the resulting changes to the IMF are negligible (Kroupa 2001), eigenevolution does lead to some BDs in short-period systems acquiring stellar masses. This leads to an overproduction of short-period star–star binaries over the original formulation of the model, with the consequence that the star–star period distribution function flattens in the SMwBDs. This is evident in Fig. 10 below. This problem can, in principle, be removed by not allowing short-period BD companions to grow in mass during the formation phase. Such a change to the model, however, would only be attempted once its failures in other respects have become more apparent.

3 STELLAR-DYNAMICAL MODELS

This section briefly describes the stellar-dynamical models of the TA groups and of the ONC. We note that we only set up $N$-body models of the SMwBDs, because the SM follows trivially in the sense that the period distribution functions remain very similar for star–star systems in the SM to those for the combined star–star and star–BD distributions in the SMwBDs. This is the case because a star–BD and a star–star binary of the same mass and binding energy behave very similarly. BDs play an unimportant role for the dynamical evolution of clusters with normal IMFs comprising less than 5 per cent in mass (Kroupa 2002), which is why BDs can be neglected altogether in the SM where only the multiplicity properties of the stars are of interest. BDs can be added, in the first instance, in the form of gedanken experiments, essentially by adding the required number of test-particles with the required kinematical properties.

Six TA-like model aggregates (T0–T5) are constructed with 140 numerical renditions of each (table 1 in KB1). The initial conditions

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Figure 5. Multiplicity fraction, $f_m$, versus primary mass, $m_p$, for the SM compared with observational data (from Kroupa 1995). The upper solid curve is the initial TA-like model, while the lower solid curve shows the Galactic field model population. It evolves from the initial population through stellar-dynamical processes in modest star clusters. Approximately 1 Myr old pre-main-sequence data are indicated by the dashed rectangle (e.g. Duchêne 1999). These data are based on an interpolation of the observed restricted period ranges (Fig. 6). The approximately 5 Gyr old Galactic field population is shown as three solid circles: from right to left, G dwarfs (Duquennoy & Mayor 1991), K dwarfs (following Leinert et al. 1993) and M dwarfs (Fischer & Marcy 1992). The estimate of the M-dwarf binary fraction by Kroupa, Tout & Gilmore (1993) is indicated by the open square. The recent data for Galactic field very low-mass stars and massive BDs is the solid circle from Close et al. (2003) and Gizis et al. (2003). It appears to violate the near-constant $f_m$ versus $m_p$ relation, and is confirmed by the independent survey of Bouy et al. (2003).
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The evolution is integrated for 40 Myr for the TA-like aggregates and for 150 Myr for the ONC/Pleiades models with the high-precision Nbody6-variant GasEx (KAH), which allows accurate treatment of close encounters and multiple stellar systems in clusters through special mathematical transformation techniques of the equations of motion (regularization), so that a force-softening parameter is not needed (Aarseth 1999). Subsequently to the N-body integration, a data reduction software package is used to distill the data presented in this contribution.

The evolution of the aggregates is described by KB1. Briefly, the aggregates largely dissolve within 10 Myr; thereafter only a long-lived group containing a few systems (= binaries plus single stars) remains within the central 1-pc region. Binary destruction is inefficient, and in all cases the binary proportion remains significantly higher than is observed in the Galactic field. This means that TA-like star formation events did not contribute significantly to the Galactic field population.

The initial period distribution function that enters all models considered here is shown as the dotted histogram in Fig. 6. The pre-main-sequence data appear to show a different trend (\( f_p \) decreasing with increasing \( \log_{10} P \) for \( \log_{10} P > 3 \)), but close inspection shows that only two data points deviate from the initial model and that this deviation is at a level of less than 2\( \sigma \). The figure also shows that the distribution does not evolve significantly in TA-like aggregates.

The distribution does evolve significantly in the ONC-like models A and B. By 1 Myr the evolution has created period distribution functions of late-type stellar primaries that agree with the observed distributions in the ONC and the Pleiades (figs 10 and 11 in KAH). The BD velocity distribution function resulting from the TA models has a tail of high-velocity (\( 1 \lesssim v \lesssim 10 \) km s\(^{-1} \)) BDs, which are nearly exclusively single and comprise about 15 per cent of all BD systems. The high-velocity tail results from ejections of BDs from short-lived three- and four-body systems that form through binary encounters in the TA-like groups. In this respect, the SMwBDs cannot be distinguished from the embryo-ejection model. The embryo-ejection model, however, implies the majority of BDs to be single and to have velocities \( v \gtrsim 1 \) km s\(^{-1} \). In sharp contrast, for TA the SMwBDs implies that the slow-moving BD systems with a velocity \( v \lesssim 0.5 \) km s\(^{-1} \), which amount to about 60 per cent of all BD systems, retain a high binary proportion of 60 per cent or larger.

4 THE NUMBER OF BROWN DWARFS PER STAR

The first question that we address here within the framework of hypothesis B is if stellar-dynamical evolution of TA-like aggregates can explain the Briceno et al. (2002) result without calling for a different IMF. The expectation is that this may be the case, because binary–binary encounters in the ONC will have been much more destructive as a result of the significantly higher stellar density and shorter crossing time than in the TA aggregates. Indeed, the ONC is known to have a significantly smaller binary proportion than the TA population (Prosser et al. 1994, see also KAH). An observer would thus see more BDs per star in the ONC than in the TA aggregates simply because the BD companions have been freed from their stellar primaries and because star–BD and BD–BD binaries have been disrupted preferentially owing to their weaker binding energy. This issue of apparent (but not true) IMF variations in clusters has been much stressed elsewhere (Kroupa 2001), but it is important to return to this notion in a case-by-case study.
To investigate the issue of an apparent depletion of BDs in TA relative to the ONC population, the ratio

$$R_{\text{obs}} = \frac{N_{\text{sys}(0.02-0.08 \, M_{\odot})}}{N_{\text{sys}(0.15-1.0 \, M_{\odot})}}$$  

(2)

is computed for each of the models; $N_{\text{sys}}$ is the number of systems with primaries in the respective mass range. The lower mass limit, $m = 0.02 \, M_{\odot}$, is given by the observational limits of the Briceno et al. (2002) survey. This ratio is similar to the two ratios considered by Briceno et al., and has the advantage of not being sensitive to detailed structure in the IMF, as stressed by Briceno et al. The ratio $R_{\text{obs}}$ used here does not include stars more massive than 1 $M_{\odot}$, because star formation in TA is biased against the production of such stars given the limited supply of gas. The data provided by

As suggested above, an alternative interpretation of the Briceno et al. result is thus that the birth population in the ONC was in fact

$$R_{\text{obs}} = \frac{10}{50} = 0.17 \pm 0.06,$$

while, for the central part of the ONC,

$$R_{\text{obs,ONC}} = \frac{47}{125} = 0.38 \pm 0.06.$$  

(4)

Fig. 7 plots the evolution of $R_{\text{obs}}$ for each of the KB1 models, as well as the two models calculated by KAH that reproduce the ONC and the older Pleiades. The figure demonstrates that the disruption of binary systems may lead to the observed apparent variation of the relative number of BD systems: identical initial stellar and BD populations lead to very different values of $R_{\text{obs}}$, depending on the degree of dynamical evolution. Thus models A and B reproduce $R_{\text{obs,ONC}}$. The initial rapid increase of $R_{\text{obs}}$ is due to the disruption of binary systems on a crossing time-scale (fig. 9 of KAH). It is interesting that model A yields a somewhat better fit, as this model also reproduces the radial density profile and the binary period distribution function observed in both the ONC and the Pleiades better than model B. The two models T0 and T1 of TA-like aggregates reproduce the Briceno et al. (2002) TA datum very well. The much smaller $R_{\text{obs}}$ is a result of the smaller fraction of disrupted BD systems in these models. The figure additionally plots the results from the other TA-like models (T2–T5) that assume non-standard IMFs in the BD regime (fewer BDs), and we note that model T5 ($\alpha_0 = -0.5$) is also consistent with the data. IMFs in the BD regime with too ‘flat’ a slope ($\alpha_0 < -1.5$) can be rejected with high confidence.

As suggested above, an alternative interpretation of the Briceno et al. result is thus that the birth population in the ONC was in fact
identical to that in TA, but that stellar-dynamical encounters destroyed a large number of primordial binaries in the ONC leading to the freeing of BDs. An observer would see different numbers of BDs per star in both environments. The discovery of a significantly lower frequency of BDs in TA does therefore not, by itself, constitute evidence for a variable IMF. Additional diagnostics are needed to infer a difference between the BD population in TA and in the ONC.

5 BINARY PROPERTIES

Although the observed relative number of BDs and stars does not imply a non-universal IMF, we now investigate the binary properties (especially the presence of BDs in wide systems) predicted by our models and compare them with observed properties. We here focus on the distribution function of orbital periods and semi-major axes for late-type stars and BDs.

5.1 A brief summary of available observational constraints

The observational pre-main-sequence data plotted as open squares in Fig. 6 only include star–star binaries.

Star–BD binaries are extremely rare in TA at separations of about 150 to 1000 au (White & Ghez 2001), and only one has been found (GG Tau Bb: White et al. 1999). Using HST spectroscopy, Hartigan & Kenyon (2003) find no BD companions to stars with separations $s = 15$ to 150 au among 20 systems in TA. However, this study relies on relatively bright (i.e. massive) companions to obtain spectra, which could impose a bias such that their sample is probably not complete and may therefore not indicate a true absence of BD companions.

While BDs are very rarely companions to stellar primaries with separations less than a few au (the so-called ‘brown dwarf desert’: Marcy & Butler 2000; Halbwachs et al. 2000), the frequency of wide star–BD systems for field and open cluster stars is not as clear: Reid & Gizis (1997) found no BD companion in the separation range 5–200 au to stars in the Hyades, while Gizis et al. (2001) suggested that BDs are quite commonly found as wide (>1000 au) companions to nearby field stars. Both studies, however, are limited by large statistical uncertainties.

The highly sensitive adaptive optics study of 39 very low-mass M8.0–L0.5 solar-vicinity dwarfs by Close et al. (2003) reveals nine companions and a sensitivity-corrected binary fraction of $15 \pm 7$ per cent with mass ratios $q > 0.7$, although $q = 0.5$ systems should have been detected. The semi-major axis ($a$) distribution is narrow with a peak near 4 au; orbits with $a > 20$ au are not present. These findings are in excellent agreement with the similar surveys made by Gizis et al. (2003) and Bouy et al. (2003), and with the survey of the Pleiades cluster by Martín et al. (2000, 2003). These results stand in contrast to the binary fraction of slightly more massive M0–M4 dwarfs, 32 ± 9 per cent (Fischer & Marcy 1992), which also show a broad semi-major axis range with a maximum near 30 au, very similar to G dwarfs (Fig. 4). HST imaging of 10 BDs selected from a magnitude-limited search of the 2MASS data base led Burgasser et al. (2003) to detect two BD–BD binaries with $s = 3.2$ and 1 au, but no companions with $s > 10$ au. Most binary surveys have been quite sensitive to wide separations, making any deficit of such wide systems a real effect and not a mere observational bias. This applies especially to our knowledge of TA for systems with separations larger than approximately 100 au, as well as to the surveys of Burgasser et al. (2003), Close et al. (2003), Gizis et al. (2003), Bouy et al. (2003) and Martín et al. (2000, 2003).

These data thus suggest a marked change of the binary properties near the hydrogen-burning mass limit, as is also stressed by Close et al. (2003), and is evident from Fig. 5. The origin of this behaviour may be primordial or dynamically induced, which we address in the following.

5.2 Models of the ONC and Pleiades with the standard IMF

The SMwBDs with the standard IMF is in good agreement with observational data available for the ONC and the Pleiades: there is very good agreement with the number of BDs per star seen in the central region of the ONC (Fig. 7), and the observed MFs in TA and the ONC (Section 2.3.1), the Pleiades (Moraux et al., in preparation) and the Galactic field are all well consistent with the SMwBDs. The period distribution for star–star binaries is also in good agreement with the data (Fig. 8) for both clusters and both models (although the initially less concentrated model A appears to fit somewhat better). The finding is thus that the SMwBDs with the standard IMF is consistent with the available data for the ONC and the Pleiades.

However, the SM for the ONC and Pleiades also leads to agreement with the period distribution constraints. In the SM the initial
period distributions would lie above the initial models shown in Fig. 8, as is evident in figs 10 and 11 in KAH. These figs 10 and 11 are for the SMwBDs but would look like and evolve as models that contain no BDs apart from a slightly reduced disruption efficiency (i.e. slightly less evolution) due to the higher binding energy of the stellar binaries. This is evident by comparing fig. 10 of KAH (with BDs) with the upper panel of fig. 4 in KPM (without BDs). Additional N-body computations are thus not needed to construct SMs explicitly. The evolution of the star–star binaries in the SM leads to period distributions that match the observational data, as shown in figs 10 and 11 of KAH.

Thus a distinction between the SM and the SMwBDs cannot be made yet on the basis of the available observational star–star binary data in the ONC and the Pleiades. We would need BD data to achieve this.

It may be possible to discard the SMwBDs if it can be shown that the star–BD and the BD–BD semi-major axis distributions differ from observational constraints in clusters. The model predictions for future observational tests are shown in Fig. 9. For instance, 7–15 per cent of all low-mass stars in clusters should have a BD companion with semi-major axis $a \geq 30$ au. The overall binary fraction of BDs in Pleiades-like clusters is approximately 20 per cent according to the SMwBDs. Using the location of data points in the colour–magnitude diagram to identify binary candidates, Pinfield et al. (2003) estimate the BD binary fraction in the Pleiades to be $50 \pm 11$ per cent, which is somewhat higher than but still consistent with the SMwBDs. Martín et al. (2000, 2003) find a BD binary fraction of about 15 per cent and a lack of BD binaries with $a > 27$ au in the Pleiades. It will be necessary to verify cluster membership and the nature of the suggested Pleiades BD binaries and to measure the component separations as well as mass ratios to allow firmer tests of the SMwBDs.

The possible success of the SMwBDs in the ONC and the Pleiades would definitely be mired if a significant fraction of Galactic field stars derive from ONC- and Pleiades-like clusters. The frequency of wide BD companions to field stars (Section 5.1) does not match the predictions of our SMwBD models if stars are predominantly formed in ONC-like clusters or in more modest clusters as is currently believed (Section 1). In this case the problem would be even worse, since the less dense modest clusters would lead to an even higher surviving fraction of BD and very low-mass stellar binaries extending to even larger separations than shown in Fig. 9. Only if most field stars formed in much denser clusters or have suffered additional dynamical evolution can the SMwBD be reconciled with our current knowledge.

As an aside, we note that Figs 8 and 9 also demonstrates that most of the evolution of the period distribution function occurs during the embedded cluster phase prior to 1 Myr, being consistent with observational data for a number of young populations. For example, the 2–3 Myr old cluster IC 348 already shows similar binary properties to those found for Galactic field main-sequence dwarf stars (Duchêne, Bouvier & Simon 1999). The observed MF in IC 348 should reflect this and be steeper by having a larger $\alpha$ than the observed MF in TA (Section 1, cf. Luhman et al. 2003a). Indeed, Muench et al. (2003) find a nearly exact match of the IC 348 MF with that measured in the ONC, again suggesting a remarkable degree of uniformity of the stellar populations.

In conclusion, we emphasize that the SM is consistent with the data in the ONC and the Pleiades cluster, while wide star–BD and BD–BD binaries appear to lead to inconsistencies of the SMwBDs with observational data. Since we already know that the SM also reproduces the properties of stellar systems in the Galactic field, we may be encouraged to conclude that the standard model without BDs (SM), rather than the SMwBDs, may be the preferred description of initial populations. This possible conclusion depends in part on the performance of the SMwBDs in TA, which is studied in the next section.

### 5.3 Models of TA with the standard IMF

Fig. 10 plots the initial and evolved period distributions for star–star binaries in the TA-like aggregates. The initial and the later distributions do not fit the pre-main-sequence data. This results from the problem already alluded to in Section 2.3.2, namely that many stellar primaries now have BD companions as a result of extending the standard model into the BD mass range. This reduces the proportion of star–star binaries to the level evident in the figure, because the period distribution function (equation 1) is normalized to the total number of systems, $N_{\text{sys}}$, with primaries in the corresponding mass range ($0.08 < m_p/M_\odot < 1.5$), while the $N_{\text{bin}, a}$ is the number of star–star binaries in the bin $\log_{10} P$ (star–BD systems are counted here as single stars).

Furthermore, in the SMwBDs the shape of the initial star–star period distribution function, plotted in Fig. 10 (dotted histogram), differs from the initial distribution plotted in Fig. 6, by being flatter. This is a result of some BDs in short-period binaries acquiring stellar masses as a result of the eigenevolution model (Section 2.3.3).
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Figure 10. As Fig. 6 but showing the distribution of periods for star–star binaries in TA-like aggregate T0 (T1 shows negligible evolution). The pre-main-sequence model does not agree with the pre-main-sequence data.

Figure 11. The distribution of semi-major axes of BD companions to stellar primaries according to the SMwBDs for TA-like aggregate T0 (T1 shows negligible evolution). The thin dotted histogram is the initial distribution, while the thick solid histogram shows the distributions at 1 Myr and the dashed histogram depicts the final (∼15 Myr old) distribution. All histograms are averages of 140 model renditions, and the error bars are standard deviations of the mean values.

The SMwBDs faces the more severe problem of leading to too many BD companions to stellar primaries as a result of random pairing from the IMF. The distribution of star–BD semi-major axes, plotted in Fig. 11, implies that about 23 per cent of all late-type stars in TA ought to have BD companions with separations in the range $10^2$–$10^4$ au. This means that about 13 of the 60 stars in the Briceno et al. (2002) survey ought to have such companions, whereas only GG Tau Bb is known (Section 5.1).

5.4 A different IMF for BDs in TA?

The simplest change to the model is to assume that the SMwBDs holds in TA (i.e. stars and BDs are paired at random from the IMF and there is no dependence of the orbital parameters on primary mass), and thus remain in line with the conclusions of Briceno et al. (2002) and White & Basri (2003) that the BDs in TA appear to have formed as the stars did, but that the IMF in TA differs from the standard IMF. The standard IMF has $\alpha_0 = 0.3$–0.08 $M_\odot$.

From Fig. 7 it is seen that model T5, which has $\alpha_0 = -0.5$, is still in agreement with the Briceno et al. (2002) datum for the number of BDs per star in TA. It also fits the ONC datum (by analogy with models A and B). Values $\alpha_0 \lesssim -1.5$ lead to too few BDs per star and are thus excluded.

It is therefore worthwhile to investigate if random pairing from the IMF with $\alpha_0 = -0.5$ can be brought into agreement with the available data for TA. Such an IMF implies fewer BD companions to stars, so that the star–star period distribution function will not be as suppressed. The initial period distribution of all binaries is identical to that shown in Fig. 6, and the evolution is also indistinguishable. That is, the disruption of binaries is very inefficient in model T5, just as it is in models T0 and T1, despite the longer embedded phase.

However, the distribution of periods of star–star binaries is still inconsistent with the pre-main-sequence data for TA (the open squares in Fig. 13), although the discrepancy is reduced relative to models T0 and T1 as expected. The number of BD companions to stellar primaries with separations in the range $10^2$–$10^4$ au in the Briceno et al. (2002) survey is expected to be about $0.13 \times 60 \approx 8$ systems (Fig. 14), whereas one has been detected. The model cannot be
Figure 13. The period distribution function of all star--star binaries in model T5 which assumes the SMwBDs but has a non-standard IMF in the BD mass range ($\alpha_0 = -0.5$). The thin dotted histogram is the initial distribution, while the dashed histogram is the final distribution at an age of about 15 Myr. The histograms are averages of 140 renditions of model T5, and the error bars are standard deviations of the mean values. The open squares are pre-main-sequence data and the open circles are main-sequence data as in Fig. 6.

Figure 14. Upper panel: the distribution of semi-major axes of BD companions to all stellar primaries according to model T5 which has a non-standard IMF in the BD mass range. Lower panel: the distribution of semi-major axes of all BD--BD binaries in model T5. In both panels the thin dotted histograms are the initial distributions, while the dashed histograms depict the final ($\approx 15$ Myr old) distributions. All histograms are averages of 140 model renditions, and the error bars are standard deviations of the mean values.

6 CONCLUDING REMARKS

Non-hierarchical multiple systems decay too rapidly, leading to too many single stars and too few binary systems when compared with the approximately 1 Myr old pre-main-sequence stellar population in TA. Pre-stellar cloud-core fragmentation therefore appears mostly to form binary and long-lived hierarchical multiple stellar systems. Available fragmentation models suggest that unfinished embryos can be expelled from such forming multiple stellar systems.

This may be used to frame hypothesis A (Section 2.2) which leads to the standard model (SM) of star formation by assuming that star formation always produces a stellar population rich in binaries and a BD population that is added with separate kinematical and binary properties. This is the basis of our standard model without BDs (Section 2.3.1), which has been shown in the past to lead to excellent agreement with the stellar data in TA and the Galactic field as well as young clusters, and thus indicates a remarkable degree of invariance of the star formation products.

In this contribution we test in detail the alternative hypothesis B which assumes that pre-stellar cloud-core fragmentation leads to stellar and substellar binary systems with universal properties that
are taken from the successful SM. Hypothesis B is based in part on the observational evidence by Briceno et al. (2002) and White & Basri (2003) who suggest that BD formation cannot be distinguished from stellar formation on the basis of their accretion properties and their kinematics and spatial distribution. The resulting standard model with BDs (SMwBDs, Section 2.3.2) is tested here against observational data that include the number of BDs per star detected in TA and the ONC as well as the form of the IMFs and of the period distribution functions of binary systems. With this goal in mind, stellar-dynamical models are evolved to yield theoretical data that can be compared with the empirical data.

Based on their data, Briceno et al. (2002) conclude that the IMF of BDs in TA differs from the observed IMF in the central part of the ONC by having significantly fewer BDs per star. In contradiction to the claim by Briceno et al., the SMwBDs with the standard IMF yields excellent agreement with the observed number of BDs per star in TA and the ONC (Fig. 7). The reason for this is that dynamical evolution of the TA groups is very mild, leading to BDs staying locked up in binary systems, while in the ONC a large fraction of the primordial binary population is disrupted, freeing BDs. The observed number of BDs per star is therefore not a reliable measure of IMF differences if used alone. The properties of binary systems need to be consulted as well to allow more robust conclusions. This is true for any population.

Furthermore, the SMwBDs is in good agreement with the observed period distribution function of star–star binaries in the ONC and the Pleiades. The observed IMFs are also consistent with the standard IMF in both clusters and in TA (Section 2.3). Thus, in both the ONC and the Pleiades, the data are consistent with the BDs having formed with the same properties like the stars and therefore with the scenario that the fragmentation of pre-stellar cloud cores extends to substellar core masses and produces uncorrelated components, and that the orbital elements of the resulting binary do not depend on the mass of the primary. The prediction of the number of star–BD and BD–BD binaries as a function of semi-major axis is given in Fig. 9 for future tests of the SMwBDs in the Pleiades and the ONC.

However, available Galactic field data on the binary proportion near and below the substellar mass limit already pose a problem for the SMwBDs, because this model predicts the binary fraction to be much higher than is observed. There is also a marked disagreement between the SMwBDs and the data in TA. The model produces too few star–star and too many star–BD binaries. The attempt to save the SMwBDs for TA by changing the BD IMF fails. Random pairing produces too many star–BD binaries for all BD IMFs that are consistent with the observed number of BDs per star by Briceno et al. (2002).

Hypothesis B thus leads to a contradiction with the observational data in TA, and with the properties of Galactic field binaries near and below the substellar mass limit. Hypothesis B should therefore be discarded with the implication that BDs form a distinct population with pairing properties different from those for stars, as is the case in the SM (hypothesis A).

Returning to the standard model without BDs, it is useful to reiterate here that this SM leads to excellent agreement with the binary star data in TA, the ONC and the Pleiades as well as the Galactic field, and with the IMF in all four populations. Hypothesis A cannot be rejected, and actually accounts very well for a large range of stellar populations.

If we were to insist that this is the more appropriate description, then we would have to infer that the BDs do not have the same formation history as stars and that they therefore form an additional population. The ONC may be sporting a higher BD production efficiency per star than TA, according to the data of Briceno et al. The IMF of BDs therefore may depend on environment (as suggested by Briceno et al.), but this IMF would not be a trivial extension of the stellar IMF to BDs, as is assumed to be the case in the SMwBDs. However, before the conclusion can be reached with confidence that the BD IMF is variable, it is necessary to study whether loss of BDs from the shallow potential well of the TA aggregates (Bouvier et al. 2001) may not account for the observed differences.

The conclusion that BDs may be treated as an additional population with its own formation history appears to be in conflict with the hypothesis that the turbulence spectrum of molecular clouds is responsible for the mass distribution of pre-stellar cores which is expected to be continuous across the stellar/substellar mass boundary (Padoan & Nordlund 2002). The observation of Motte et al. (1998) that the pre-stellar cloud-core mass spectrum already looks like the standard IMF supports this notion. Also, the fragmentation of collapsing cores is probably a process that cannot depend on the mass of the final outcome (star or BD) to the degree suggested here. It is difficult to see how BDs can come as an entirely separate population, since the hydrogen-burning process occurs much later than the fragmentation process. On the other hand, the physics of cloud-core collapse and its fragmentation is far from being understood, so it can be argued that the present finding that BDs seem to behave differently from stars may be allowing the type of insights we have been hoping for all along. It may be that cloud cores only fragment when they have sufficient mass, $m_\ast$, and that the gas reservoir is always much larger than the mass in the initial fragments. This has been assumed to be the case by DCB who adopt $m_\ast \geq 0.25 M_\odot$ because they require their five initial seeds per kernel to have masses larger than the opacity limit for fragmentation.

Whatever the physical mechanisms may be that ultimately produce the BD population, the conclusion that BDs may form a population which does not have binary properties that are a natural extension of stellar binaries has also been found to be the case for very low-mass solar neighbourhood stars (Section 5.1) and is evident in Fig. 5. Close et al. (2003) find it ‘very hard to explain the total lack of systems with separations larger than 16 AU by scaling the observed semi-major axis distribution of T Tauri stars’. Such a scaling would overproduce the number of wide systems very significantly compared with observations. The SMwBDs is, essentially, such a scaling. An ‘extra BD population’ could be the result of any one of the following processes: BDs may be ejected unfinished embryos from accreting systems; or they may be hydrostatic cores that lose their accretion envelopes because of encounters with other protostars in rich clusters; or by photo-evaporation of their accretion envelopes through nearby O stars. These processes will be active for stars so that an (unknown) fraction of very low-mass and low-mass stars will probably also belong to such an extra population. The above-mentioned scenarios for the origin of BDs possibly imply that a larger fraction of hydrostatic cores may be able to accrete the available mass reservoir and thus become stars in quiescent star-forming regions such as TA, thus perhaps naturally leading to the deduced smaller number of BDs per star there. We note that the putative extra population would need to have accretion and kinematical properties that are consistent with the observations of Briceno et al. (2002) and White & Basri (2003): we recall from Section 1 that these authors had rejected the embryo-ejection hypothesis, to which we have now returned, given the results of the present study. The possibilities for the origin of BDs are studied in more detail by Kroupa & Bouvier (2003b).
In summary and to answer the question posed in the title of this paper: the results presented here and in other research based on the SM appear to suggest that the outcome of star formation is rather surprisingly invariant. Specifically, TA, the ONC, the Pleiades and the Galactic field appear to have had the same initial stellar population which can be described very well by the SM plus an additional, primarily single, BD population. Evident differences can be attributed to stellar-dynamical evolution, and to the limited molecular cloud masses which naturally lead to a smaller stellar upper mass limit in TA than in the ONC. Only in the substellar mass regime may the observations indicate different MFs in TA and the ONC, as is in fact suggested by Briceno et al. (2002).

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