Mem. S.A.It. Vol. 84, 911

Memorie della

Why brown dwarfs are special

Arguments from IMF theory vs. observations

I. Thies, J. Pflamm-Altenburg, and P. Kroupa

Argelander-Institut für Astronomie – Universität Bonn, Auf dem Hügel 71, D-53121 Bonn, Germany, e-mail: ithies@astro.uni-bonn.de

Abstract. The lower end of the stellar initial mass function (IMF) is the topic of an ongoing debate. Among the most popular myths is the assumption of a continuous fall off from stars to brown dwarfs in both the IMF itself and the binary statistics of stars and BDs. However, recent analytical star-formation models by Hennebelle & Chabrier (2008) or Padoan & Nordlund (2002) could model the stellar part quite well while failing to reproduce the substellar region satisfactorily. We show that the deviation of these model IMFs to the observed ones is essentially just the IMF of the separate substellar population introduced in Thies & Kroupa (2007) and later confirmed numerically in Thies et al. (2010). In addition, new estimates to the binarity and companion mass-ratio distribution resulting directly from the two-population model are presented.

Key words. (Stars:) brown dwarfs – Stars: formation – Stars: luminosity function, mass function – (Stars:) binaries: general

1. Introduction

The stellar initial mass function (IMF) is a key tool for star formation research since it reflects the physical processes of the formation and dynamics of stellar populations (Bastian et al., 2010; Kroupa et al., 2013). Consequently, the IMF is subject to extensive research and ongoing debates in observation and theory. While the majority of the star-formation research community currently favours a continuous star-like formation mechanism from brown dwarfs (BDs) to the most massive stars (Padoan & Nordlund, 2002, 2004; Hennebelle & Chabrier, 2008), careful analysis of available data reveals a disagreement between the predictions of this continuous model and the observational evidence. In particular, an observed dearth of BD companions to stars, the so-called 'brown dwarf desert' (Grether & Lineweaver, 2006), and the distribution of the binding energies of BD-BD binaries (Fig. 1) imply at least one important separate formation channel of BDs and probably some very-low-mass stars (VLMSs).

Semi-analytical star-formation models like those by Padoan & Nordlund (2002) and Hennebelle & Chabrier (2008) successfully reproduce the stellar IMF while systematically producing too few BDs if realistic physical conditions are assumed in the star-forming cloud. In this contribution we quantify this BD deficiency in the analytical approach by Padoan & Nordlund (2002) with respect to the

Send offprint requests to: I. Thies

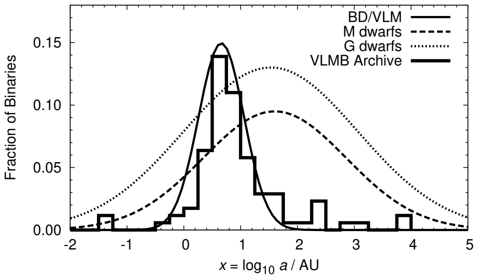

Fig. 1. The orbital separations distributions of M dwarfs (dashed line), G dwarfs (dotted line) and BDs (solid line; cf. Kroupa et al. 2013). The observational data from the Very-Low-Mass-Binary Archive (2009) are given by the solid histogram and include marginally bound or captured distant BD binaries. The distributions cannot be transformed into each other by mere mass scaling, thus implying different formation channels for the majority of BDs.

empirical IMFs in Chabrier (2003) and Thies & Kroupa (2007). The resulting residual mass function (RMF) is introduced and discussed in the context of the empirical composite IMF by Thies & Kroupa (2007) and the mass spectrum of substellar clumps from SPH computations in Thies et al. (2010).

2. Methods

2.1. The IMF

The empirical IMFs by Chabrier (2003) and Thies & Kroupa (2007) are based on the observational data from young star clusters. While the former assumes a common origin of BDs and stars, the latter accounts for observational evidence for a separate substellar population. Consequently, it is composed of two partial IMFs, star-like and brown-dwarf-like, with the full IMF being the sum of both. Analytical attempts to model the star-formation process itself have been performed by Padoan & Nordlund (2002, 2004) and Hennebelle & Chabrier (2008, 2009). We have calculated the residual mass function (RMF) as the difference between observed and analytical mass function for the example of Padoan & Nordlund (2002) after normalisation:

$$\xi_{\mathrm{res}}(m) = \xi_{\mathrm{obs}}(m) - \xi_{\mathrm{theo}}(m)\,, \tag{1}$$

where $\xi_{\mathrm{obs}}(m)$ refers to either the IMF by Chabrier (2003) or by Thies & Kroupa (2007), while $\xi_{\mathrm{theo}}(m)$ is the analytical model by Padoan & Nordlund (2002). In general, the mass function is defined as

$$\xi(m) = \frac{\mathrm{d}N}{\mathrm{d}m}\,, \tag{2}$$

and, in the logarithmic scale,

$$\xi_{\mathrm{L}}(m) = \frac{\mathrm{d}N}{\mathrm{d}\log_{10} m} = \ln(10)\, m\, \xi(m)\,. \tag{3}$$

The composite IMF by Thies & Kroupa (2007) is also referred to as the canonical IMF. Rather than simply connecting the BD-like and star-like components at the hydrogen-burning mass limit at 0.08 $M_{\odot}$ there is an overlap between 0.07 and 0.15 $M_{\odot}$ indicating that bodies in this mass range may either belong to the star-like or to the BD-like population (see Eq. 55 in Kroupa et al. 2013). At the high-mass end of the BD-like population and at the low-mass end of the star-like population, the simple truncation used in the original definition has been replaced in this study by steep power-law functions to reduce numerical artifacts in the sum IMF. We chose power-law coefficients of +10 and -10 to keep the effect on the BD-like to star-like ratio negligibly small.

2.2. Monte-Carlo model of the binarity of stars and brown dwarfs

Besides the mass function itself also the binarity, f, is an important characteristic of stellar populations. It is defined as the ratio of the number of binary or higher-order systems, N_{bin}, to the total number of systems, N_{sys}. Here, the term *system* includes multiple systems and singles (their number being noted as N_{sng}) as well. Then

$$f = \frac{N_{\mathrm{bin}}}{N_{\mathrm{sys}}} = \frac{N_{\mathrm{bin}}}{N_{\mathrm{sng}} + N_{\mathrm{bin}}}\,. \tag{4}$$

For the star-like population we choose a binary fraction of 40 % (i.e. $f = 0.4$), and for the BD-like population it is 15 % (i.e. $f = 0.15$), in accordance with Thies & Kroupa (2007). The choice of 40 % binarity reflects the assumption

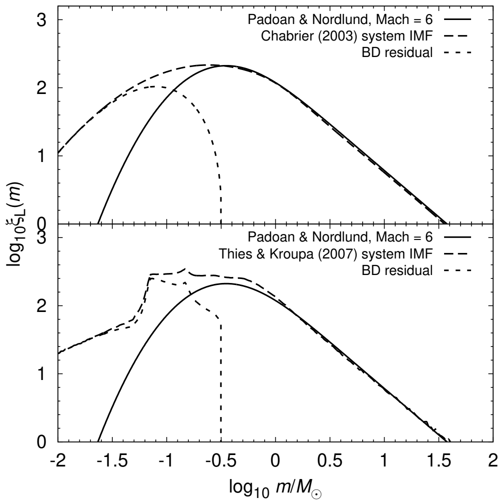

Fig. 2. **Upper panel:** The analytical IMF model $\mathcal{M} = 6$ by Padoan & Nordlund (2002, solid line) compared to the empirical IMF by Chabrier (2003, dashed line). These functions, originally defined as system mass functions, have been re-normalised by a constant shift in $\log_{10} m$ and $\log_{10} \xi_L$ direction to account for an average binary fraction of 50 % and an average binary system mass of 1.5 times the primary mass. The dotted line represents the residual mass function (RMF), i.e. the difference between both mass functions. **Lower panel:** Same as in the upper panel but with the composite (sum) IMF according to Thies & Kroupa (2007, dashed line) .

that about 40 % of the prestellar cores form a binary while the remaining cores form individual stars that combine to binaries to yield the overall birth binarity of 100 % (Kroupa et al., 2013). The number of systems must not be confused with the number of individual bodies, $N_{\rm bod}$. Since higher-order multiples are rare (Goodwin & Kroupa, 2005) only singles and binaries are considered in this work, so the total number of bodies is

$$N_{\rm bod} = 2N_{\rm bin} + N_{\rm sng} \,. \qquad (5)$$

3. Results

3.1. Residual mass function for semi-analytical models

Figure 2 shows the results of our calculations for the analytical model from Padoan & Nordlund (2002) with respect to the system IMF by Chabrier (2003) and Thies & Kroupa (2007), shown in the upper and lower panel, respectively. In both cases, the most striking feature of the corresponding RMF is an increase between 0.01 and about 0.1 $M_\odot$, i.e. slightly above the hydrogen-burning mass limit, and a sharp drop between that point and about 0.3 $M_\odot$.

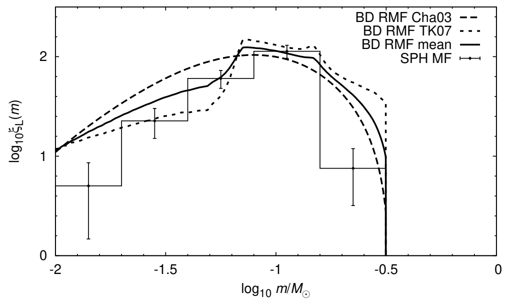

Fig. 3. The RMFs of Padoan & Nordlund (2002) vs. Chabrier (2003, dashed line) and Thies & Kroupa (2007, dotted line), with the the mean of both shown by the solid curve. The mass function from the SPH calculations (rescaled to the peak of the RMF) is superimposed as the histogram.

In both cases, the RMF fits the clump mass function obtained from the results of SPH computations by Thies et al. (2010), including subsequent computations. In total, 80 clumps from disc fragmentation have been found in 29 computations. Both RMFs, together with their mean, and the SPH clump mass function are directly compared in Fig. 3. The functional shape of the both RMFs is the same as the SPH mass function, and is also in agreement with the BD-like component of the composite IMF by Thies & Kroupa (2007), which is truncated near 0.2 $M_\odot$.

3.2. Binarity function

The canonical IMF used in the Monte-Carlo study is shown in the upper panel Fig. 4 in comparison to the system mass function, (dash-dotted curve), the primary-body mass function (dashed curve) and the individual-body mass function (solid curve). The lower panel depicts the BD-like and star-like components separately, with the sum of the individual-body MF is shown here as the thin dotted curve (identical to the solid curve in the upper panel).

Fig. 5 depicts the binarity as a function of the primary-body mass (solid curve). The stellar binary fraction adopted for this study is $f = 0.4$. Similar results have been obtained by Kroupa et al. (1993). For comparison, observational results by Kroupa et al. (2003) and Lada (2006) are indicated by the open squares and filled circles, respectively. The continuous increase of the binary fraction with primary mass is in good agreement with the observational data. It is a consequence of random pairing among the star-like population: an star near the lower mass limit has fewer possibilities to get an even less massive companion than a higher-mass star. Therefore, there is a lower binary fraction for M dwarfs than for G dwarfs. Above $\approx 1\ M_\odot$ the binarity is nearly constant at about 50 per cent.

4. Conclusions

The failure of theoretical star-formation models to describe both stars and BDs by a single mechanism, namely from cloud fragmentation, motivates the introduction of the residual mass function. It reflects the necessity to treat BDs separately which implies a separate albeit related formation channel for the majority of BDs. The theoretical evidence by Bonnell et al. (2008), Stamatellos & Whitworth (2009), Thies et al. (2010), and Basu & Vorobyov (2012) supports a separate population by fragmentation of dynamically processed material like gaseous dense filaments in star-forming clouds or extended young circumstellar discs. In addition, the embryo-ejection model by Reipurth & Clarke (2001) gives an example of BD formation by ejection of unfinished stellar embryos out of multiple protostar systems. Since both mechanisms are not covered by the analytical cloud fragmentation models by Padoan & Nordlund (2002) and Hennebelle & Chabrier (2008) they do not contribute to the resulting theoretical clump mass function. Therefore, an analytical model also covering BDs and VLMSs must include such a separate channel via dynamically processed material. The development of such a analytical or semi-analytical model will be covered by future work.

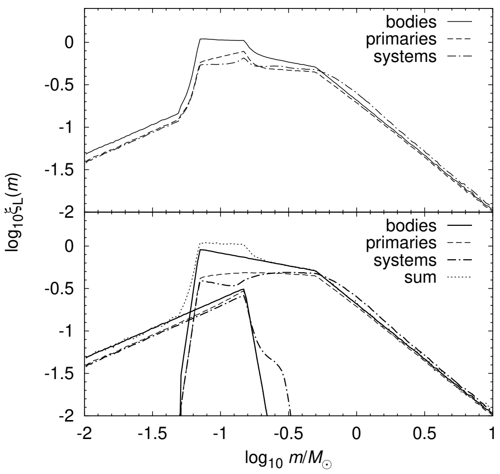

Fig. 4. Upper panel: The combined IMF of BD-like and star-like objects from our Monte-Carlo calculations for individual-body masses (solid curve), primary-body masses (dashed curve), and system masses (dash-dotted curve). The BD-like binarity is 15 % here and the star-like one is 40 % (see text). **Lower panel:** The IMFs for the BD-like and star-like population plotted separately. The line patterns are the same as in the upper panel for each separate IMF. For comparison, the individual-body sum IMF is superimposed (thin dotted curve, the same as the solid curve in the top panel).

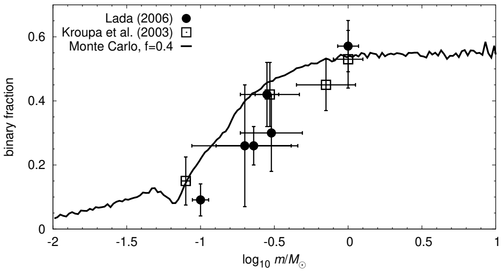

Fig. 5. Binary fraction for BDs and stars as a function of the primary-object mass (solid curve). Observational data by Lada (2006) and Kroupa et al. (2003) are depicted by solid circles and open squares, respectively.

In a related Monte-Carlo-study performed here we also found a good agreement of the two-populations composite model with observational data on field very-low-mass stellar and BD binaries. The binarity as a function of the primary mass is apparently continuous and monotonically rising from the stellar-substellar border to about Solar-type stars, and thus in agreement with observational findings. The smooth transition of binarity with primary mass is therefore not due to a smooth change of the nature of the binaries but, instead, a consequence of random pairing among stellar binaries.

Acknowledgements. This project is funded by DFG grant KR1635/27-1.

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