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Births and infancy of brown dwarfs: an introduction

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Abstract. Brown dwarfs cover the interesting mass range between stars and planets. As such, they share part of the properties of either groups of objects, particularly those related to their origins. At the high mass end of the distribution, it is quite likely that the majority of brown dwarfs form in the same way as normal stars from the gravitational collapse of dense molecular cores of substellar mass. The border between brown dwarfs and planets does not present major discontinuities, indicating that the former can be born both from direct collapse of individual cores and from gravitational instabilities in circumstellar disks. After an overview of some of the most significant events that have marked the first eighteen years of studies of brown dwarfs, I will concentrate on current issues related to both their formation and early evolution, highlighting some of the current problems faced by the theory of the formation of BDs as normal stars.

Key words. Stars: Brown Dwarfs – Stars: Formation – Stars: Early evolution

1. Introduction

If something has come of age, it has reached full and successful adulthood. This is certainly the case for Brown Dwarfs (BDs), whose transition from childhood to adulthood is celebrated at this Conference. Both theoretically and observationally, the study of BDs has witnessed a tremendous progress which is poised for even further development. It is a remarkable achievement that these faint objects have been studied in a variety of environments, from star forming regions, to young and more evolved clusters, to the field thus allowing to trace their evolutionary history in time. In the last decade, several theories have been put forward to address their origins, from direct gravitational collapse of pre-stellar cores to dynamical interactions in cluster forming molecular cores and disk fragmentation around already formed stars. This diversity naturally reflects the variety of physical processes that take place in the early phases of star formation and that affect stars of all masses, not just those at the bottom of the IMF. However, it also reveals a deficit of some critical observations that can provide stringent constraints on the preferred mode(s) of BD formation.

In this review, I will first present a timeline of some critical events that have marked the development of the research on BDs since conception. The choice of these particular times is in some case subjective, and other important events may have been overlooked. However, in the spirit of this celebration, one can look at it as a sort of family album. I will then look into the issue of the birth of BDs and the var-

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ious models that have been proposed over the years. Rather than describing each of them, I will consider the most viable, in my opinion, mechanism that posits that BDs originate in the same manner as normal stars from the collapse and fragmentation of dense molecular cores. However, I will also highlight how the current understanding of low-mass star formation is still plagued by the poor knowledge of the initial conditions of dense cores and their subsequent evolution. Finally, the infancy of BDs will be addressed mostly from the viewpoint of deuterium burning. This is the major event of an otherwise quiet history of contraction and cooling that can be used as a means to constrain the formation mechanisms at the critical border between BDs and massive planets.

2. A family album

Year 1963; Age −32: Conception In 1963, theory demonstrates that objects of substellar mass can be maintained in thermo-mechanical equilibrium. The observational confirmation of this prediction represents one of the longest gestations recorded in modern astronomy. Two independent papers appear at short distance, reaching similar conclusions about the limiting mass, $M^{\rm H}_{\rm min}$, at the bottom of the Main Sequence (Hayashi & Nakano 1963; Kumar 1963). Both groups determined a value of $M^{\rm H}_{\rm min} \sim 0.08$–$0.07\,M_\odot$ for a Population I gas composition, with some (Kumar) or very weak (Hayashi & Nakano) dependence on the metal abundance. The current limit restricts the interval to $M^{\rm H}_{\rm min} = 0.075$–$0.070\,M_\odot$, in agreement with the early predictions. The paternity on the BDs has been the subject of an interesting debate that was settled with the publication of the proceedings of the IAU Symposium 211 dedicated to *Brown Dwarfs* (Martín 2003); see also Nakano (2013) for a recent account.

Year 1995; Age 0: Birth The quasi-simultaneous discovery of the first BDs spurred a great deal of excitement (Rebolo et al. 1995; Nakajima et al. 1995; Basri et al. 1995). The echo of the discovery was vividly felt during the meeting *Cool Stars, Stellar Systems and the Sun, 9th Cambridge Workshop* held in October 1995 in Firenze, Italy (Pallavicini & Dupree 1996). In a dedicated Session on "Low Mass Stars and Brown Dwarfs", the main players in the field entertained a lively discussion on the recent discoveries and their implications. Unfortunately, no written record of the debate exists, although the presentations of the main papers are included in the Proceedings. Remarkably, in the same session M. Mayor and D. Queloz announced the detection of a Jovian mass-companion to the solar-type star 51 Peg. A *very cool* meeting, indeed!

It is interesting to recall some remarks that are present in the first papers of 1995 and that are still of interest 18 years later. For example, it is stated that one of the main reasons to study BDs is their mass range between stars and planets and the fact that their atmospheres are related to planetary atmospheres, thus providing critical information for the study of other planetary systems. In spite of their similarities, however, BDs and planets were thought to form differently: planets as condensations within protoplanetary disks, while BDs by direct condensation from interstellar gas, like normal stars. It was also remarked that, although plenty of BDs were expected to be found in the Pleiades, their total mass would amount to a few $M_\odot$, too small to significantly contribute to the cosmological dark matter budget. Finally, there was an indication of an increase of the Pleiades cluster mass function beyond the substellar limit.

Year 1998; Age 3: Infancy The first three years of exciting research on BDs were summarized by G. Basri (1998). Among the main issues it is worth pointing out: the definition of a BD based on the mode of formation; the minimum mass for D-burning; the lack of direct mass determination from BD binary systems; the Li-test introduced by Magazzù et al. (1993) and splendidly applied to PPL 15 and Teide 1 in the Pleiades. Of particular importance was the realization that the search for young BDs in star forming regions would be facilitated by their higher effective temperatures and luminosities. At age 3, most of the substellar objects discovered in Star Forming Regions (SFRs) were still classified as "candidates", lacking a confirmation from spectroscopy or from the Li-test. In order to appreciate the expectations delivered by the first studies, let us mention the final remark in which Basri wishes that *"...with any luck, this review will become obsolete in a very few years"*. The next years were not disappointing in this respect!

Year 2001; Age 6: School Activity is a distinctive property of school age, but sometimes too much action leads to unexpected consequences. For BDs this implies a radical departure from the normal assumption about their origin as scaled-down versions of normal stars. In 2001, Reipurth & Clarke suggest that BDs could inherit their tiny masses as a result of dynamical interactions and ejections in small (3-5 objects) groups of fragments or protostars. The similarity of the timescales for interactions and ejections and for accretion ensures the efficiency of the mechanism. Even the formation of sub-dwarfs objects could result from the ejection of dynamically unstable collapsing fragments that prematurely stop further accretion (Boss 2001).

Year 2005; Age 10: Twins The discovery of the first young brown dwarf eclipsing binary system in the Orion Nebula Cluster (Stassun et al. 2005) finally allowed a direct measurement of the mass and radii of BDs. With a mass of M_1=0.055 $M_\odot$ and M_2=0.035 $M_\odot$ (at 10% accuracy), both objects indeed fall in the substellar domain. The very short period (~9.8 days) and the surprising reversal in effective temperature (the secondary being the hotter member) provided important constraints on the formation mechanism of binary BDs and on their surface properties, including the effects of tidal heating and the presence of spots and magnetic fields.

Year 2008; Age 13: Teen Ager Not unexpectedly, the evidence for the presence of bipolar molecular outflows launched by a young BD arrives at the age of maximum activity (Phan-Bao et al. 2008), even though the emission from high-velocity optical jets had been detected a few years earlier (Whelan et al. 2005). The derived properties of the outflow (mass, mass-loss rate) are typical of young low-mass stars, albeit two to three orders of magnitudes smaller. Along with the evidence for the presence of circumstellar disks (e.g., Natta et al. 2002), all these indicators point toward a continuation of the paradigm for activity of young stars into the BD mass regime without a clear discontinuity.

Year 2013; Age 18: Come-of-Age Fifty years after the theoretical prediction of their existence and eighteen years after discovery, BDs have eventually reached the threshold for independence, as highlighted at this meeting. The field has grown to full maturity and promises new and unexpected developments, including the fact that BDs are among the closest neighbors to the Sun (Luhman 2013; Bihain et al. 2013).

3. Origin(s) of BDs

There is no shortage of physical mechanisms to explain the formation of BDs. Extensive reviews can be found in the recent literature, e.g. Joergens (2013), so that there is no need for another summary. The diversity of the possible origins is shown in Fig. 1. The two branches account for the main alternatives: BDs resulting from the collapse of self-gravitating pre-stellar cores, as in the case of low- and very low-mass stars, or as a by-product of already formed, hydrogen-burning stars. The latter path offers several options, including dynamical interactions/ejections during the formation of stellar clusters and/or the fragmentation of circumstellar disks, and also the early truncation of accretion owing to the exposure to photoionizing radiation from nearby OB stars that effectively removes the gas from the envelope and disk of a collapsing protostar. In particular, models of the formation of BDs from disc fragmentation and in clusters are discussed elsewhere in this volume (see Vorobyov, Thies).

In the following, I will take the point of view that BDs mainly form as normal stars, with the other channels playing some contribution. One can refer to the review by Luhman (2012) for an account of the main observational evidence in support of this scenario, but the main conclusion is that the "Taurus mode" of formation, i.e. from isolated, low-mass dense cores, produces a sufficient number of BDs. The critical question, not only limited to BDs,

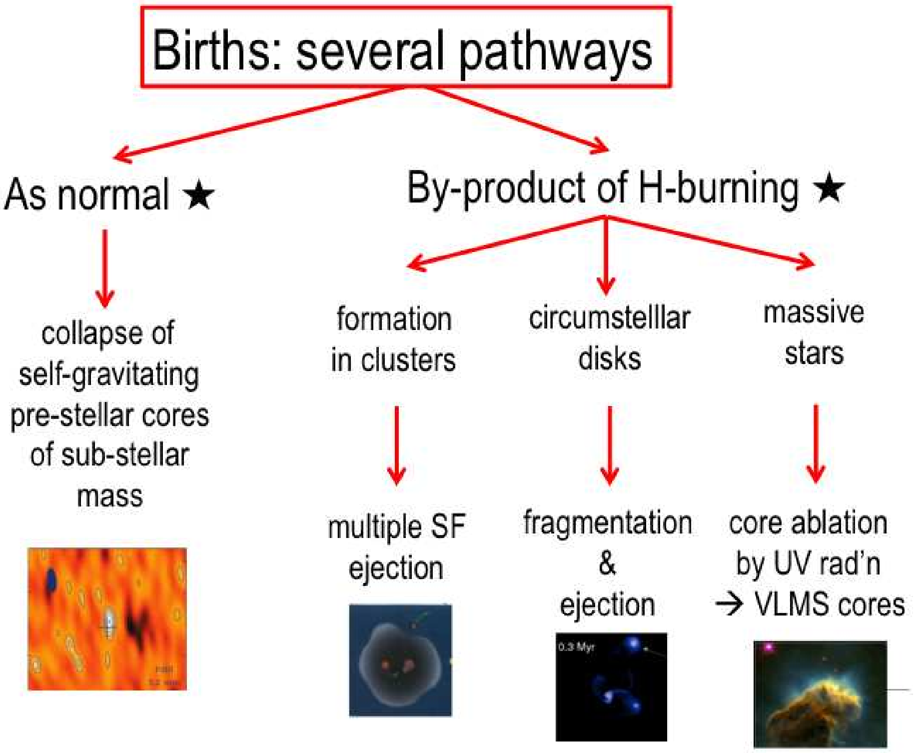

Fig. 1. Main formation channels for Brown Dwarfs.

that I would like now to address is the following "*Do we actually understand how this mode of formation works?*".

Let us consider the exciting case of the pre-BD core, Oph B-11, discovered in Ophiucus through mm-interferometry (André et al. 2012). The physical interpretation is in the framework of the gravo-turbulent fragmentation scenario in which dense gas is formed by shocks resulting from supersonic interstellar turbulence (Padoan & Nordlund 2002; Hennebelle & Chabrier 2008). Then, pre-BD cores such as Oph B-11 are just the tail of a much broader distribution of core masses. As such, they should also be rarer than those spawning low-mass stars. Unfortunately, it is still too early to argue in one way or the other, but surveys are undergoing that will be able to establish their relative frequency. In any case, the main problem is the origin of dense cores and the evidence for the presence of shocks associated with them, as postulated in the turbulent fragmentation scenarios and colliding large-scale flows. To gain further insight, let us now look at some recent developments.

3.1. Filaments, filaments everywhere

The results of the *Herschel* observations have fully revealed the ubiquitous presence of filamentary structures within molecular clouds (André et al. 2010; Molinari et al. 2010). Inside filaments, dense cores form by fragmentation and evolve toward gravitational instability and collapse to give birth to stars and BDs. It appears that these prestellar cores are preferentially located within the densest filaments. The theory of the equilibrium of isothermal filaments identifies a critical value of the mass per unit length $M_{\rm L,crit} = 2c_{\rm s}^2/G \approx 20\,M_\odot\ {\rm pc}^{-1}$, where $c_{\rm s}$ is the isothermal sound speed (Inutsuka & Miyama 1997). If the line mass of the filament exceeds the critical value, the isothermal filaments can collapse indefinitely. In addition, the predicted density profile is given by

$$\rho_{\rm eq}(r) = \rho_{\rm c}\left[1+\left(\frac{r}{H_0}\right)^2\right]^{-2}, \qquad (1)$$

where $\rho_{\rm c}$ is the central density and H_0 is the scale height of the filament (Ostriker 1964). For filaments in near equilibrium the fragments should be separated by a few times the initial filament diameter. In real clouds, the inner width of the filaments appears to be remarkably uniform at ~0.1 pc (Arzoumanian et al. 2011). Note that an Ostriker-type profile as in Eq. 1 is also frequently used to describe the density distribution for the kernel inside the filamentary structures that characterize the large-scale simulations of BD formation within turbulent cloud cores (Stamatellos et al. 2011).

A recent analysis of the high resolution *Herschel* observations of one of the major filaments of the Taurus molecular cloud, B211/B213, has allowed a detailed comparison of the columns density and dust temperature maps with the theoretical expectations (Palmeirim et al. 2013). While the temperature profile shows a deviation from the assumed isothermality in the innermost part of the filament (the polytropic index from the fit is γ=0.97), the density distribution departs from the Ostriker-profile quite significantly at large radii. According to Palmeirim et al., the power-law fit has $\rho \propto r^{-2}$, much shallower than the r^{-4}- dependence expected for isothermal filaments. However, such flatter distributions may result in the presence of a magnetic field (Fiege & Pudritz 2000), or in the case of collapsing cylinders with a polytropic equation of state. Indeed, the B211/213 filament is elongated in a direction perpendicular to the orientation of the large-scale magnetic field (Chapman et al. 2011).

3.2. Filaments and dense core formation

These interesting results must be confronted with those of another set of observations of the same region of Taurus obtained by Hacar et al. (2013). The complex B211/B213 is known to be an active site of star formation, containing a population of pre-stellar cores, Class 0 and I sources, as well as classical and weak-line T Tauri stars. Although its geometrical structure appears as a long (∼10 pc) single filament, the internal structure presents clear evidence of enhanced fragmentation in several main regions which also contain the majority of the YSO population.

The most striking results come from the analysis of the velocity structure of the dense cores mapped by Hacar et al. in several molecular transitions. First, rather than a single component, the filaments consists of a complex network of several components at different velocities that, however, show an organized structure. In addition, the estimate of the mass per unit length of these components is $\sim 15\,M_\odot$ pc^{-1}, substantially lower than that ($\sim 54\,M_\odot$ pc^{-1}) obtained by Palmeirim et al. (2013), but very close to the theoretical limit discussed above. Finally, the components have internal velocity dispersions of the order of the sound speed and *coherent* velocity fields. Remarkably, these thermal subsonic motions are observed both in and out of the dense cores. The scenario proposed by Hacar et al. is one in which the main complex is organized in several *bundles*, each containing a number of *filaments* of similar kinematics. Some of these filaments are *fertile*, having spawned dense cores and new stars/BDs, while the majority is *inert*.

Overall, it appears that the process of core formation has proceeded in a hierarchical way, as a result of the quasi-static contraction of the large-scale molecular cloud, traced by ^{12}CO and ^{13}CO emission. Thus, the picture that emerges from these and similar observations (Hacar & Tafalla 2011) differs significantly from that supported by turbulent fragmentation models and colliding gas flows. The fact that BDs are also found in these environments (Luhman et al. 2009; Palau et al. 2012; Monin et al. 2013) clearly indicates that they do not represent a different population that requires special conditions for their formation. However, the real meaning of the statement "*BDs form like normal stars*" remains to be fully understood, given the uncertain origin of normal stars.

3.3. Origins: BD companions

BDs span the mass range between ~0.075 and ~0.013 $M_\odot$, corresponding to the minimum mass for the ignition of hydrogen and deuterium burning, respectively. Although the latter value depends somewhat on the initial helium and deuterium abundance, for most of the BD conditions the variation is limited to 0.012–0.014 $M_\odot$ (12-14 $M_{\rm Jup}$), corresponding to objects that can burn up to 50% of the initial deuterium content (Spiegel et al. 2011). The previous discussion on the extension of the formation mechanism of low-mass stars to BDs is most applicable to the upper end of the BD mass range. At the other extreme, the mass of BDs overlaps with that of the most massive planets that can form in protoplanetary disks. Of the two main routes for planet formation - by gravitational instability or direct collapse in protostellar disks (Boss 2003) or by accretion up to solid core by planetesimals, followed by gas accretion from protostellar disks (Alibert et al. 2005) - current estimates indicate that the latter is the most likely origin of the whole planet population (Borucki et al. 2011; Janson et al. 2012). Thus, an interesting question arises as to whether there is a *mass boundary* between BDs and planets possibly related to the formation mechanism(s). In this respect, the study of the properties of BD companions to stars can provide direct insights. However, a major problem is the well known paucity of BDs relative to planets orbiting close to solar-like stars, the so-called brown dwarf desert first found in radial velocity searches. Current estimates limit the frequency of close BD companions within 3 AU around FGKM stars to less than 1% (Sahlmann et al. 2011), while the occurrence at larger distances (>20 AU) increases to a few percent (Metchev & Hillenbrand 2009). It now appear that the lack of close BDs is not due to an observational bias since the expected signal of at least several hundreds meters per second would have been easily detected by the numerous surveys performed over the last decade.

Recently, the known sample of BD companions to solar-type stars has been analyzed with the aim of placing indirect constraints on the formation mechanisms (Ma & Ge 2013). Among the relations found in this analysis, two results stand out as particularly intriguing. First, the period-mass distribution displays a statistically significant lack of BDs with periods <100 days and mass in the interval 35-55 $M_{\rm Jup}$, possibly suggesting a dividing mass of the distribution at about 42 $M_{\rm Jup}$. Also, the distribution of the orbital eccentricity differs for BDs with mass higher or lower than the critical value of 42 $M_{\rm Jup}$: in the former case, the BD period is similar to that of stellar binaries with a circularization limit of ~12 days, while in the latter case the distribution resembles that of massive planets. Ma & Ge tentatively conclude that the existence of the two groups can be the result of a different birth process: BD companions with masses greater than 42 $M_{\rm Jup}$ share the same origin of stellar binary systems, while lower mass objects form in protoplanetary disks as massive planets. Interestingly, Vorobyov also finds an upper value of ~42 $M_{\rm Jup}$ for the formation of massive giant planets and brown dwarfs on wide orbits in unstable and fragmenting protostellar disks (see this volume).

4. Infancy of BDs

While the origin of BDs is still uncertain, their subsequent evolution as fully formed, contracting objects is much better understood. Once the main accretion phase is finished and a BD has reached its final mass, the evolution is governed by contraction and cooling. If the BD mass is greater than approximately (63 $M_{\rm Jup}$; Burrows et al. 2001), lithium burning can be ignited, but, owing to its tiny abundance, it leaves no consequence on the dynamical evolution. Most of the interesting action takes place around the minimum mass for D-burning, ~12 $M_{\rm Jup}$, where the impact of the initial conditions imprinted during the formation process is most significant. As in the case with normal stars, also for BDs the initial conditions determine how young object undergo the onset of D-burning.

Traditionally, the initial contraction of BDs has been followed assuming some arbitrary initial distribution on the internal entropy that determines both the central and surface properties. Since the memory of the initial conditions is rapidly erased in the course of evolution, this approach is valid for mature objects, but not for young ones. Two classes of models have been developed: a "hot start model" characterized by a high level of entropy and luminosity ($\sim 10^{-3}\,L_{\odot}$) and a "cold start model" where all the energy of the accreting gas is radiated away at the accretion shock on the core surface, yielding a small radius and low luminosity ($\sim 10^{-6}$-$10^{-5}\,L_{\odot}$; Burrows et al. 1997; Baraffe et al. 2002, 2003; Marley et al. 2007). Which one of these conditions is appropriate clearly depends on the specific accretion history of each object, but in principle both the core accretion and the gravitational disk instability scenarios should be capable of delivering a proto-planet/BD in a high or low entropy state. In the past, more attention has been given to the exploration of the disk instability models, mainly because it was believed that objects forming via core accretion could not reach masses beyond $\sim 10\,M_{\rm Jup}$ owing to the formation of a gap in the disk that effectively shuts off further accretion. However, it has been shown that for objects above a certain mass value, the onset of eccentricity instabilities in the disk actually allows the continuation of accretion at relatively high rates (Kley & Dirksen 2006). Thus, proto-BDs can form even in the core accretion scenario, although the maximum mass limit is still uncertain.

Several studies have tried to overcome the problem of the arbitrary initial conditions, consistently coupling the accretion phase and core formation to gravitational contraction to gauge the effects on D-burning (Mordasini et al. 2012; Mollière & Mordasini 2012; Bodenheimer et al. 2013). The sensitivity on the resulting evolution is mainly displayed by objects forming via core accretion with low levels of internal entropy. The main effect is that the onset of D-burning occurs abruptly, causing a rapid expansion of the core radius (by about 50%) and a concurrent rise in luminosity. This behavior is not seen in the hot start case since BDs begin their evolution with large radii and then gradually contract and cool at high temperature until they reach the critical value for D-burning. Since the increase in luminosity experienced in the cold start scenario is quite substantial (up to two orders of magnitude), the evolution of luminosity versus time can provide a valuable diagnostic of objects at the transition between BDs and planets, possibly constraining their formation history.

5. Conclusions

The observational evidence now suggests that BDs mainly originate from the collapse of bound dense cores of substellar mass and the accretion of gas from a circumstellar disk. The high incidence of circumstellar disks and outflows, along with a rather normal binary frequency and the ability to form individual/multiple systems in isolation offer stringent constraints in support of this view. However, how the initial conditions for the actual formation of normal stars and BDs are established within the filamentary structures of molecular clouds is still partially obscure. The high resolution sub-mm observations obtained with *Herschel*, along with the complementary information on the chemical and dynamical state of the gas in filaments and cores are providing key insights into this exciting puzzle. Paraphrasing the final remark in one of the first reviews on BDs, it is hoped that the concepts expressed here and in the other contributions of this volume will *not* become obsolete in a few years.

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