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Kinematics of stars and brown dwarfs at birth

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Abstract. We use numerical N-body simulations in order to test whether the kinematics of stars and brown dwarfs at birth depend on mass. In particular we examine how initial variations in velocity dispersion can affect the spatial distribution of stellar and substellar objects in clusters. We use "toy" N-body models of a Pleiades-like cluster in which brown dwarfs have their own velocity dispersion $\sigma_{V_{\rm BD}}$ which is k times larger than the stellar one.
We find that in order to match the broad agreement between the brown dwarf fraction in the field and in the Pleiades, the velocity dispersion of brown dwarfs at birth has to be less than twice the stellar velocity dispersion, i.e. cannot exceed a few km s^{-1} in the Pleiades cluster. In order to discern more subtle differences between the kinematics of brown dwarfs and stars at birth, our simulations show that we need to look at clusters that are much less dynamically evolved than the Pleiades. One might especially seek evidence of high velocity brown dwarfs at birth by examining spatial distribution of stars and brown darfs in clusters that are about a crossing timescale old.

Key words. stellar dynamics – stars: low-mass, brown dwarfs – Galaxy: open clusters and associations: individual: Pleiades – stars: kinematics – methods: N-body simulations

1. Introduction

So far, most studies of the star formation process have dealt with the formation of stellar systems but with the recent discovery of brown dwarfs in 1995 (Nakajima et al. 1995; Rebolo et al. 1995) new perspectives have opened regarding the formation of condensed objects in molecular clouds. Today more than a hundred brown dwarfs (BDs) in various environments are known. However, their mode of formation is still controversial and the theoretical framework describing the stellar and substellar formation process(es) is not completely satisfactory. Regions of high density ($n(H_2) \sim 10^7$ cm^{-3}) in molecular clouds are needed to form proto-brown dwarfs but then for their mass to remain substellar their reservoir of gas has to be small or the accretion not very efficient.

Two main competing scenarios have been proposed so far to account for the formation of substellar objects. One assumes that brown dwarfs form like solar-mass stars by gravitational collapse of small, dense molecular cloud core and subsequent accretion. The supporting argument is that in the opacity limited regime the Jeans mass can be as low as a few Jupiter masses (Low & Lynden-Bell 1976). The alternative view assumes that brown dwarfs are ejected "stellar embryos" as proposed by Reipurth & Clarke (2001). In this scenario, molecular cloud cores fragment to form unstable protostellar multiple systems which decay dynamically. The lowest mass fragments are ejected from their birth place and deprived of surrounding gas to accrete remain substellar objects.

The brown dwarf properties predicted by these two different formation scenarios may in principle be quite different. In the former case, both stars and brown dwarfs form predominantly as single or binary ($N = 2$) systems; in this case there are no obvious reasons why properties such as the binary fraction or kinematics should depend on mass. In the latter scenario, by contrast, the dominant formation mechanism (again for both stars and brown dwarfs) is in small N (>2) clusters, and the gravitational interplay that precedes the break up of the system into stable entities implies a potentially strong mass dependence for resulting properties like the binary fraction and kinematics. In particular it has been suggested (Reipurth & Clarke 2001) that low mass objects (e.g. brown dwarfs) ejected from such clusters would have a higher velocity dispersion than higher mass objects.

Reipurth and Clarke's initial suggestion – that brown dwarfs in star forming regions may have a detectably higher velocity distribution from stars – has *not* been borne out by radial velocity studies (Joergens & Guenther 2001). Meanwhile, successive simulations have modified the predictions of small N clusters models. Delgado et al. (2003) and Sterzik & Durisen (2003) have emphasised that, in their simulations, the main difference in velocity dispersion is between single stars and binaries, and that brown dwarfs attain rather larger velocities – with respect to their parent cores – because they are more likely to be ejected as single objects. This dependence of ejection speed on binarity may readily be understood, since one binary is typically formed in each cluster in these simulations: this binary is able to eject the remaining stars from the cluster by slingshot gravitational encounters, whilst itself remaining close to the center of mass of the natal cluster. In the turbulent fragmentation calculations of Bate et al. (2003) and Delgado et al. (2004), by contrast, more than one binary is formed per cluster and so binaries are able to eject each other from the natal cluster. Consequently, in these simulations, the kinematics of the resulting objects do not depend strongly on either mass *or* binarity.

Evidently, the relative kinematics of stars and brown dwarfs and of single stars and binaries can shed some light on the conditions in star forming cores and could ultimately answer the question of whether stars (and brown dwarfs) are formed as isolated single and binary systems, as small N aggregates containing typically one binary or as aggregates containing more than one binary. (Note that this question is not easy to answer by direct observations, since the timescale for the break up of putative small clusters implies that this process occurs in the deeply embedded phase. However, high resolution imaging of the driving sources of Herbig Haro objects by Reipurth (2000) suggests that the multiplicity of stars in deeply embedded regions is indeed high.)

Direct observations of the kinematics of young stars and brown dwarfs is unlikely to be fruitful however. The differences in velocity dispersion predicted by theoretical models are small (of the order of a km s^{-1}). When one bears in mind that these velocities are measured with respect to star forming cores, which are in themselves in relative motion at $\sim$1 km s^{-1}, it is unsurprising that the study of Joergens & Guenther (2001) – involving small numbers of objects, with velocity resolution of $\sim$0.2 km s^{-1} and rather small dynamic range in mass – did not detect any differences.

In this paper, we propose another approach that could potentially detect any mass dependence of the kinematics of stars (and brown dwarfs) at birth. Here we examine the statistical consequences of such an effect on the spatial distribution of stars and brown dwarfs in clusters. This approach has the advantage that one can work with large samples of stars and brown dwarfs, whose positions and masses are known with high accuracy. On the other hand, we cannot predict how initial variations in velocity dispersion affect the spatial distributions of stars and brown dwarfs in a cluster at a given age without further, N-body, modeling. This is partly because two body relaxation leads to mass segregation in older clusters, even in the absence of a mass dependent initial velocity dispersion. Our purpose in this paper, therefore, is to use "toy" N-body models (in which brown dwarfs are introduced with a velocity dispersion that is a variable multiple of the stellar velocity dispersion) in order to establish under what circumstances could one detect a higher velocity dispersion at birth for low mass objects. We stress that this toy models for the kinematics is not supposed to correspond to the outcome of any particular numerical star formation model but is designed to provide a ready parameterization of the problem. We also underline that in no models are any sudden discontinuities in kinematic properties expected at the hydrogen burning mass limit.

We use the Pleiades as the testbed for our calculations. This is because the brown dwarf population of the Pleiades has been the subject of intensive scrutiny in recent years (Moraux et al. 2003; Dobbie et al. 2002; Pinfield et al. 2000; Zapatero-Osorio et al. 1999; Bouvier et al. 1998) so that the present day mass function in this cluster is reasonably well constrained. We shall proceed by first placing an upper limit on the initial velocity dispersion of brown dwarfs in the Pleiades, based on the broad similarity between the normalization of stars to brown dwarfs in the Pleiades and in the field, which limits the number of brown dwarfs that can have left the cluster to date. We shall then explore whether the radial distribution of brown dwarfs in the cluster can place meaningful limits on their initial velocity distribution.

2. Numerical simulations

We performed numerical simulations of the dynamical evolution of a Pleiades-like cluster using the code NBODY2 (Aarseth 2001) on a Sun workstation. This code is an algorithm for direct integration of N-body problem based on the neighbour scheme of Ahmad & Cohen (1973) and employs a softened potential ϕ of the form

$$\phi = -\frac{m}{(r^2 + \epsilon^2)^{1/2}} \tag{1}$$

to reduce the effects of close encounters.

The model of cluster we used is defined as follows. At time $t = 0$ the stellar density $n(r, t)$ conforms to Plummer's model

$$n(r, 0) = \frac{3}{4\pi r_0^3} N \left[1 + \left(\frac{r}{r_0}\right)^2\right]^{-5/2} \tag{2}$$

where $N = 1900$ is the number of cluster members and $r_0 = 2.2$ pc is a scale factor determining the dimensions of the cluster. It is related to the half-mass radius r_h by $r_h \simeq 1.3\, r_0 = 2.86$ pc (Aarseth & Fall 1980). This leads to an overall initial central density $n(0, 0) = 42.6$ objects/pc^3. Initially, the stellar population is assumed to be in virial equilibrium with a velocity distribution everywhere isotropic (cf. Aarseth et al. 1974, for a practical scheme for the generation of the initial positions and velocities). Note that the true initial conditions of a cluster are not very well known and are likely to be very complex. Isothermal models are sometimes preferred to describe open cluster density initial states, however Plummer models are also used and have already been proved to reproduce reasonably well the Pleiades cluster (Kroupa et al. 2001). In Sect. 3.1 we compare our results to observational data and find a reasonable agreement.

The system is assumed to be isolated. No external potential is included but any object which reaches the cluster tidal radius would in reality be stripped off by the galactic tide and lost by the cluster.

For simplicity and in order to focus on how the initial kinematics affects the the spatial distribution of the cluster population, our model does not include gas. We assume that the gas has already left the cluster when we start the simulations and thus the original cluster may have expanded and lost a large fraction of its primordial members because of the change of the gravitational potential (Adams 2000;

Boily & Kroupa 2003a,b). This explains in particular why our initial system is not as concentrated as e.g. the cluster models used by Kroupa et al. (2001) to reproduce the Pleiades. We shall discuss how the presence of gas would affect our results later on.

The smoothing length employed for the gravitational interactions on small scales is $\epsilon = 5 \times 10^{-4}\, r_0 \sim 200$ AU. To justify the choice of this value, one can estimate the rate of encounters per star closer than ϵ by

$$f = 4\sqrt{\pi} n \left(\sigma_V \epsilon^2 + \frac{Gm\epsilon}{\sigma_V} \right) \quad (3)$$

(e.g. Binney & Tremaine 1987) where n is the local stellar density, σ_V is the velocity dispersion and m is the stellar mass, assumed to be the same for all stars. Assuming n does not change with time, we find the probability for a star located at $r = 0$ to have encounters closer than ϵ is ∼9% in 120 Myr – wich is about the age of the Pleiades (Stauffer et al. 1998; Martín et al. 1998). Since the stellar density decreases with time, this value is an upper limit indicating $\epsilon \sim 200$ AU is appropriate for our simulations.

The mass of the $N = 1900$ objects are distributed over a three power-law mass function

$$\xi(m) = \frac{\mathrm{d}n}{\mathrm{d}m} \propto m^{-\alpha_p}, \quad p \in [1..3] \quad (4)$$

with

$$\begin{aligned} \alpha_1 &= 0.6 \text{ for } m_{1,\mathrm{inf}} = 0.01 \leq m \leq m_{1,\mathrm{sup}} = 0.3\ M_\odot, \\ \alpha_2 &= 1.3 \text{ for } m_{2,\mathrm{inf}} = 0.3 \leq m \leq m_{2,\mathrm{sup}} = 1.0\ M_\odot, \\ \alpha_3 &= 2.3 \text{ for } m_{3,\mathrm{inf}} = 1.0 \leq m \leq m_{3,\mathrm{sup}} = 10.0\ M_\odot, \end{aligned}$$

which corresponds to the Pleiades mass function determined by Moraux et al. (2003). This MF estimate has not been corrected for binarity which means that this mass function corresponds to the *system* mass function. Likewise, our simulations do not include any treatment of binarity. Using a softened potential inhibits binary formation and each object issued from this mass distribution is considered as a single object. This choice can be justified by results obtained by de la Fuente Marcos & de la Fuente Marcos (2000) who performed simulations to investigate the dynamical evolution of substellar population in cluster with Aarseth's NBODY5 code (Aarseth 1985). Some of their models include a population of hard binaries, which are the most important binary stars in term of dynamics, but the results are all very similar (see their Fig. 2). This suggests that close two body encounters are not too important and that a softened potential ϕ with an adequate ϵ can be used.

In practice, the mass of each member i is readily obtained by

$$m_i = m_{\mathrm{p,sup}}^{-(\alpha_\mathrm{p}-1)} - (i-1) g_{N_\mathrm{p}} \quad (5)$$

with

$$g_{N_\mathrm{p}} = (m_{\mathrm{p,sup}}^{-(\alpha_\mathrm{p}-1)} - m_{\mathrm{p,inf}}^{-(\alpha_\mathrm{p}-1)}))/(N_\mathrm{p} - 1)$$

where N_p is the number of objects having a mass between $m_{\mathrm{p,inf}}$ and $m_{\mathrm{p,sup}}$. A convenient representation for this distribution is the mass-generating function

$$m(X) = \begin{cases} \dfrac{0.3}{[1 - 1.35(X - 0.55)]^{-2.5}} & \text{if } 0 < X \leq 0.55, \\ \dfrac{1}{[1 - 1.45(X - 0.85)]^{3.33}} & \text{if } 0.55 < X \leq 0.85, \\ \dfrac{0.24}{[1 - 0.99X]^{0.77}} & \text{if } 0.85 < X \leq 1, \end{cases} \quad (6)$$

where X is distributed uniformly in [0, 1]. The intervals here are the same as the mass intervals in Eq. (4). This function has been computed in the way described in Kroupa et al. (1991).

In such a model, brown dwarfs ($0.01 \leq m \leq 0.08\ M_\odot$) constitute 25% by number but only less than 3% by mass. Initially these proportions are the same everywhere in the cluster, i.e. there is no mass segregation, so that stellar and substellar objects have the same radial distributions. The initial density of stars and brown dwarfs in the center are $n_\star(0,0) = 32$ and $n_{\mathrm{BD}} = 10.6$ objects/pc^3 respectively.

In our toy model we assume that substellar objects represent a peculiar population having its own velocity dispersion $\sigma_{V_{\mathrm{BD}}}$. We arbitrarily choose

$$\sigma_{V_{\mathrm{BD}}} = k \times \sigma_{V_\star} \quad (7)$$

initially where $k \in [1.0 - 3.0]$ and $\sigma_{V_\star}$ is the stellar velocity dispersion.

Then we let the cluster evolve dynamically under the effect of gravitational interactions between members over 12 crossing times. Since $t_{\mathrm{cr}} \simeq 10$ Myr for the Pleiades (Pinfield et al. 1998), this corresponds to about the age of the cluster, i.e. 120 Myr. Thus, we can follow the evolution of the star and brown dwarf population within the cluster from their birth to the age of the Pleiades depending on their initial kinematics.

Note that we only present the results for one set of initial conditions but we also performed other simulations using different numbers of objects N, which means in particular using various seed numbers to initialize the cluster model. The results are similar to those described in the following sections.

3. Results and discussion

3.1. Characteristic radii

Over the timescale of the simulations the half mass radius does not change much through the simulations. It goes up to ∼3.2–3.4 pc after 12 crossing times which is consistent with observational results obtained for the Pleiades ($r_\mathrm{h} = 3.6$ pc, Pinfield et al. 1998). This result does not depend on the initial substellar velocity dispersion which is indeed expected considering the fact that brown dwarf represent only 3% of the cluster mass.

A nominal core radius r_c is calculated in NBODY2 using the definition of the density radius given by Casertano & Hut (1985) slightly modified in order to obtain a convergent result using a smaller sample ($n \simeq N/2$). It is determined by the rms expression (Aarseth 2001)

$$r_\mathrm{c} = \left(\frac{\sum_{i=1}^{n} |\boldsymbol{r}_i - \boldsymbol{r}_\mathrm{d}|^2 \rho_i^2}{\sum \rho_i^2} \right)^{1/2}, \quad (8)$$

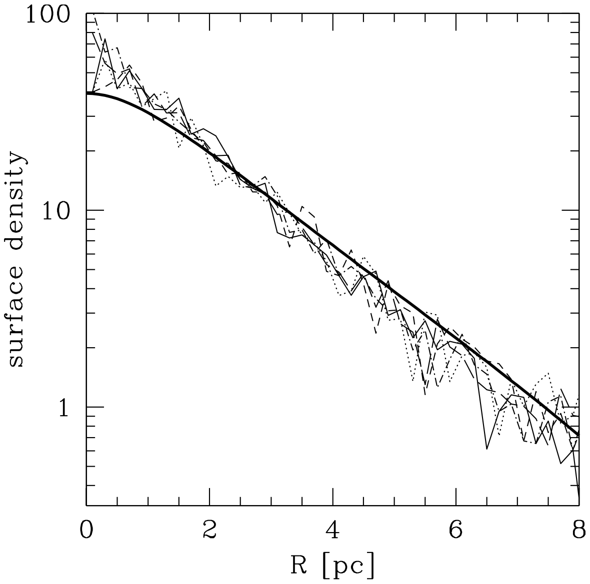

Fig. 1. The projected radial density profiles for $0.1 \leq m \leq 3\ M_\odot$. The different thin curves correspond to different values of $\sigma_{V_{\rm BD}} = k \times \sigma_{V_\star}$ with $k \in [1.0\text{–}3.0]$, the symbols are the same than in Fig. 2. The thick curve correspond to the best-fitting King profile of observational data for the Pleiades from Pinfield et al. (1998, their Fig. 2).

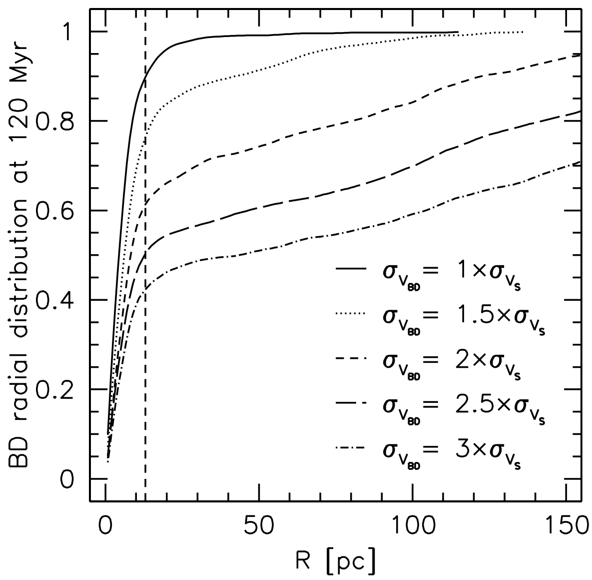

Fig. 2. Cumulative radial distribution of brown dwarfs after ∼120 Myr calculated by our NBODY2 numerical simulations of the dynamical evolution of a Pleiades-like cluster. The different curves correspond to the different values of the substellar initial velocity dispersion, $\sigma_{V_{\rm BD}} = k \times \sigma_{V_\star}$ with $k \in [1.0\text{–}3.0]$ (k increases from top to bottom). The vertical dashed line represents the extend of the Pleiades cluster.

where $\boldsymbol{r}_i$ is the three-dimensional position vector of the ith star and $\boldsymbol{r}_{\rm d}$ denotes the coordinates of the density centre. The density estimator $\rho_i = 3\,M_5/(4\pi r_6^3)$ is defined with respect to the sixth nearest particle r_6 and takes into account the total mass (M_5) of the five nearest neighbours. (See Casertano & Hut 1985, for definitions of density centre and density estimator.) In our simulations, $r_{\rm c} = 1.3$ pc at $t = 0$ and $r_{\rm c} \sim 0.8$ pc at $t = 12\,t_{\rm cr} \simeq 120$ Myr. However, to be compared to the observational core radius $R_{\rm c}$ these values have to be divided by ∼0.8 (Heggie & Aarseth 1992) and we obtain $R_{\rm c}$ between 1.6 and 1 pc. For the Pleiades et al. (1998) found $R_{\rm c} = 0.6° = 1.3$ pc for a cluster distance of 125 pc which is reasonably consistent with our model.

We also compare the projected radial density profiles obtained at $t \simeq 120$ Myr to the observed Pleiades profiles for $0.1 \leq m \leq 0.3\ M_\odot$ (see Fig. 1) and we find a reasonable agreement.

3.2. Dynamical evolution of the substellar population

Figure 2 illustrates the effect of the initial velocity dispersion of brown dwarfs on their spatial distribution at the age of the Pleiades cluster (∼120 Myr). The vertical dashed line corresponds to the tidal radius $r_{\rm t}$ of the Pleiades (∼13 pc, Pinfield et al. 1998). All the objects located at larger radii are in reality lost by the cluster.

If the stellar and substellar initial velocity dispersion are similar ($k = 1.0$), then as many brown dwarfs as low mass stars have been lost after 120 Myr (about 10%). This result is perfectly consistent with the simulations performed by de la Fuente Marcos & de la Fuente Marcos (2000), which indicates in particular that our choice of the softening parameter ϵ is adequate. Like the stars, these brown dwarfs have diffused as a result of successive two body interactions to beyond the notional tidal radius. However, as soon as $k \geq 2.0$ then 40% or more of the initial brown dwarf population have left the cluster.

If it does happen, this loss of brown dwarfs occurs quite quickly, in a couple of crossing times, i.e. a few tens of Myr. We note from Fig. 3 that the depletion rates obtained after only 20 Myr are already important and of the same order as those obtained after 120 Myr. This means in particular that our results do not depend much on the age of the cluster and are not affected by the errors in open cluster age determinations, typically in the range of 30 to 50%. This can be explained by the fact that if an object has a velocity larger than the cluster escape velocity $\upsilon_{\rm esc}$ it will be lost after a few crossing times $t_{\rm cr}$. The depletion rates found at 20 Myr correspond indeed to about the fraction of brown dwarfs initially unbound in our Plummer distribution. For our Pleiades-like model, we have $t_{\rm cr} \simeq 10$ Myr and $\upsilon_{\rm esc} = \sqrt{2}\upsilon_{\rm vir} = 1.6\ {\rm km\,s^{-1}}$, with the virialised velocity $\upsilon_{\rm vir} = 1.15\ {\rm km\,s^{-1}}$. Thus, if brown dwarfs form following the ejection scenario proposed by Reipurth & Clarke (2001) with a resulting average velocity larger than the cluster escape velocity or with a velocity dispersion larger than a few ${\rm km\,s^{-1}}$, then a large number of substellar objects will be lost relatively quickly.

The fact that basically all the initially unbound objects are lost by the cluster is quite straightforward and constitutes a robust result that does not depend much on the initial conditions, like the IMF or the initial spatial distribution. Evidently the actual fractions of stars and brown dwarfs that would be bound at the start of our simulations would partly depend on the prior dynamical history of the cluster when it contained significant quantities of gas, an issue that is beyond the scope of the present paper. We note however that changes in the cluster

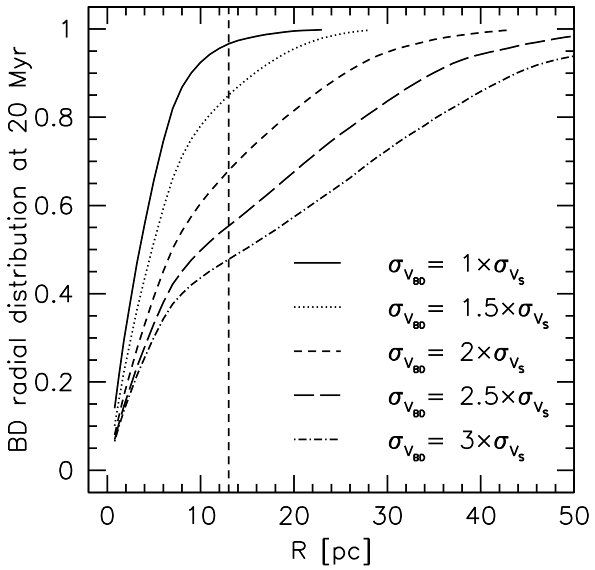

Fig. 3. Cumulative radial distribution of brown dwarfs after ~20 Myr for different values of initial substellar velocity dispersions $\sigma_{V_{BD}} = k \times \sigma_{V_\star}, k \in [1.0\text{–}3.0]$.

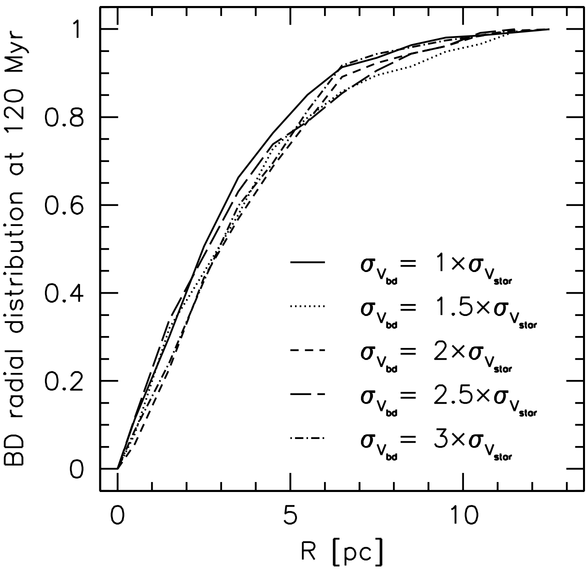

Fig. 4. Cumulative radial distribution of brown dwarfs inside the cluster after $12t_{cr} \sim 120$ Myr for several initial substellar velocity dispersions $\sigma_{V_{BD}} = k \times \sigma_{V_\star}, k \in [1.0\text{–}3.0]$.

potential due to gas loss would not affect the kinematic properties of the stars and brown dwarfs *differentially* and in this study we focus on the possible observable consequences of stars and brown dwarfs having different kinematical properties at birth.

However, an important observational constraint is that the Pleiades mass function is found to be similar to those of several star forming regions (where the gas is still present), such as the Trapezium (Muench et al. 2002) or IC 348 (e.g. Luhman et al. 2003), and of the field (cf. Moraux et al. 2003). This indicates that it is still representative of its initial mass function and that the dynamical effects did not affect the shape of the IMF in 120 Myr. This means in particular that there was *no* significant preferential escape of brown dwarfs in the Pleiades. Therefore, the substellar initial velocity dispersion must be less than twice the stellar velocity dispersion and cannot exceed a few km s^{-1}.

3.3. Radial distribution

As discussed above, the vast majority of objects has a typical velocity of a few km s^{-1} and remains bound to Pleiades-like clusters after ~100 Myr. However, if brown dwarfs still have a larger dispersion velocity than that of stars, even if only slighty larger, we may hope to find a signature of their ejection by looking at their radial distribution.

Figure 4 shows the effect of the initial velocity dispersion on the brown dwarf radial distribution for a Pleiades-like cluster after $12t_{cr} \sim 120$ Myr. The number of objects inside a sphere having a radius $R = 13$ pc has been normalised to one. The radius has been chosen to correspond to the Pleiades tidal radius so that the shown radial distributions represent what an observer would obtain if he studied the substellar population in the cluster.

Strikingly, we find that at the age of the Pleiades, the spatial distribution of brown dwarfs in the cluster provides *no* information about the velocity dispersion of brown dwarfs at birth. This is because those brown dwarfs whose velocity exceeds the escape velocity of the cluster will have already left the cluster (on a crossing timescale ~10 Myr) and those that remain have a velocity distribution (and hence spatial distribution) that is very similar to that of the low mass stars.

In order to find possible evidence of a population of brown dwarfs with high velocities at birth, it is instead necessary to examine clusters that are only about a crossing time old. This expectation is borne out by Figs. 5 and 6 which compare the normalised distributions of stars and brown dwarfs within a Pleiades-like cluster at an age of 10 Myr for various ratios of $\sigma_{V_{BD}}$ to $\sigma_{V_\star}$. Evidently, at this age, two-body relaxation is ineffective in producing a more diffuse brown dwarf distribution (as evidenced by the fact that the brown dwarf and stellar distributions are very similar at this age if $\sigma_{V_{BD}} = \sigma_{V_\star}$). Thus any differences in the spatial distribution of stars and brown dwarfs at such a young age would be indicative of different velocity distributions at birth.

Figure 5 shows the effect of the initial velocity dispersion on the brown dwarf radial distribution for a Pleiades-like cluster after $1t_{cr} \sim 10$ Myr. We note that as soon as the brown dwarf velocity dispersion is larger than that of stars the substellar radial distributions are different from the one obtained for $\sigma_{V_{BD}} = \sigma_{V_\star}$.

Figure 6 compares the spatial distribution of low mass stars to that of brown dwarfs for two different values of $\sigma_{V_{BD}}$ after 10 Myr. When the stellar and substellar velocity dispersions are similar then the radial distributions are also the same, whereas this is not the case for $\sigma_{V_{BD}} = 2\times\sigma_{V_\star}$. In that case about 90% of the low mass stars ($0.08 \le m \le 0.5\ M_\odot$) are located at less than 5 pc from the cluster center compared with only 65% of the brown dwarfs at the same location. We have to reach a radius of ~9 pc to include 90% of the substellar population.

In the presence of gas, the results would be similar. One would expect gas expulsion due to e.g. photoionisation or

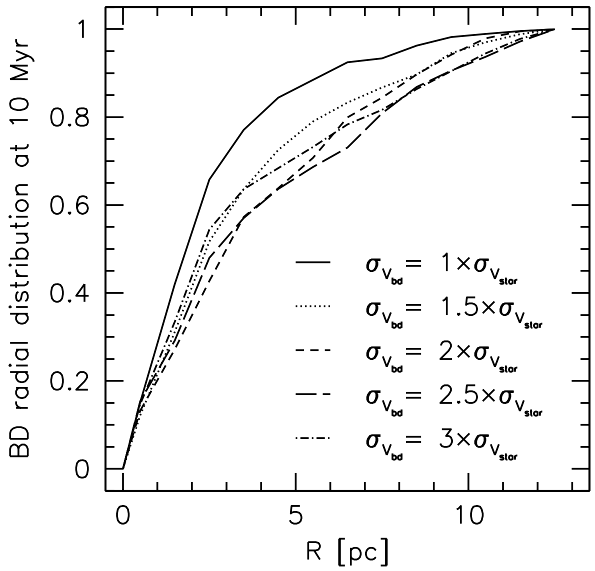

Fig. 5. Cumulative radial distribution of brown dwarfs inside the cluster at $t = 1t_{\rm cr} \sim 10$ Myr for several initial velocity dispersions $\sigma_{V_{\rm BD}} = k \times \sigma_{V_\star}, k \in [1.0\text{–}3.0]$.

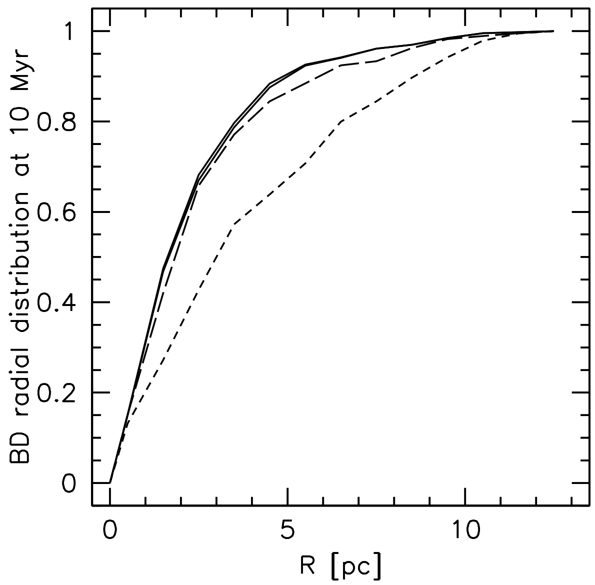

Fig. 6. Radial distribution of low mass stars (0.08−0.5 $M_\odot$; solid line) and brown dwarfs (dashed lines) inside the cluster after $1t_{\rm cr} \sim 10$ Myr. The long-dashed line corresponds to $\sigma_{V_{\rm BD}} = \sigma_{V_\star}$ and the short-dashed line to $\sigma_{V_{\rm BD}} = 2 \times \sigma_{V_\star}$.

stellar winds to occur within a few Myr, i.e. on a timescale less than the crossing timescale of the cluster, and for the stars and brown dwarfs to respond to such gas loss on about a crossing timescale. If brown dwarfs have a larger velocity dispersion than stars, we therefore expect to find a signature of this initial kinematics in studying the spatial distribution of stars and brown dwarfs in clusters that are about a crossing timescale old.

4. Conclusion

We have shown that the observed similarity between the brown dwarf to star ratio in the Pleiades, in star forming regions and in the field implies that the velocity dispersion of brown dwarfs at birth cannot exceed 2× the stellar velocity dispersion in the Pleiades. This imposes an upper limit on the brown dwarf velocity dispersion at birth of a few km s^{-1}. Thus either brown dwarfs are not dynamically ejected from their natal cores or else the ejection velocities with respect to their natal cores is low. Such a velocity dispersion limit would rule out the common incidence of very hard encounters (i.e. at <4 AU, Delgado et al. 2004) in the natal cores, but would be consistent with the results of current hydrodynamical simulations (Delgado et al. 2003; Bate et al. 2003). We stress that the velocities quoted here are limits on the 3D velocity dispersion for a Maxwellian distribution and so do not necessarily rule out a tail of objects with significantly higher velocities such, for example, as the (not substellar) object PV Ceph, for which a velocity of 20 km s^{-1} has recently been claimed (Goodman & Arce 2003).

We have shown that the radial density profile of brown dwarfs and stars in the Pleiades provides *no* information about the velocity dispersion of brown dwarfs at birth. This is because any brown dwarfs with velocities greater than the escape velocity of the cluster would have long ago escaped the cluster and thus the residual brown dwarf population has a velocity distribution – and hence spatial distribution – that is very similar to the stars.

We therefore conclude that if we seek *positive* evidence for a modestly higher velocity distribution of brown dwarfs at birth, we need to look at clusters that are significantly different from the Pleiades. There are two possibilities here. Firstly, the upper limits we have derived could still imply a significant preferential loss of brown dwarfs from loosely bound regions. For example, Preibisch et al. (2003) suggested that this could be the cause of the small fraction of brown dwarfs observed in IC 348 for which the escape velocity is only ~0.8 km s^{-1} (Herbig 1998). Kroupa & Bouvier (2003) found also that the ejection mechanism could explain a part of the deficit of substellar objects in the Taurus association. Secondly, one might seek evidence of high velocity brown dwarfs at birth by instead examining clusters that are about a crossing timescale old. In this case, the brown dwarfs would be expected to have a more extended distribution than the stars, which could *not*, at such a young age, be confused with the signature of two body relaxation. Even if the brown dwarf velocity dispersion exceeds that of stars by only 50%, the spatial distributions of the two populations are quite different at this age (contrast dashed lines in Fig. 5 with solid line in Fig. 6) Thus brown dwarf surveys in clusters of various ages and degrees of richness will afford further opportunities to constrain the velocities of brown dwarfs at birth.

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