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The Pleiades mass function: Models versus observations

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Abstract. Two stellar-dynamical models of binary-rich embedded proto-Orion-Nebula-type clusters that evolve to Pleiades-like clusters are studied with an emphasis on comparing the stellar mass function with observational constraints. By the age of the Pleiades (about 100 Myr) both models show a similar degree of mass segregation which also agrees with observational constraints. This thus indicates that the Pleiades is well relaxed and that it is suffering from severe amnesia. It is found that the initial mass function (IMF) must have been indistinguishable from the standard or Galactic-field IMF for stars with mass $m \lesssim 2\,M_\odot$, provided the Pleiades precursor had a central density of about $10^{4.8}$ stars/pc^3. A denser model with $10^{5.8}$ stars/pc^3 also leads to reasonable agreement with observational constraints, but owing to the shorter relaxation time of the embedded cluster it evolves through energy equipartition to a mass-segregated condition just prior to residual-gas expulsion. This model consequently preferentially loses low-mass stars and brown dwarfs (BDs), but the effect is not very pronounced. The empirical data indicate that the Pleiades IMF may have been steeper than the Salpeter for stars with $m \gtrsim 2\,M_\odot$.

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

1. Introduction

Because of its richness and proximity (~120 pc, Robichon et al. 1999), the Pleiades cluster with an age of 120 Myr (Stauffer et al. 1998; Martín et al. 1998) is one of the best studied young open clusters. It has a mass of about 740 $M_\odot$, contains ~1000 stars and has a tidal radius of about 13.1 pc, a half mass radius of about 3.66 pc (Pinfield et al. 1998), and a binary-rich population with properties similar to that in the Galactic field (Bouvier et al. 1997). Recent stellar-dynamical computations suggest that the Pleiades-precursor may have been very similar to the about 1 Myr old Orion Nebula cluster (ONC) (Kroupa et al. 2001, hereinafter KAH), opening the possibility of seeing the same kind of object at two very different evolutionary stages.

Several surveys have been performed to date to measure its stellar mass function which is now well constrained from the stellar to the sub-stellar domain. Recent estimates extend as deep as 0.03 $M_\odot$ (Moraux et al. 2003). A pressing issue in star formation is to know whether this mass function (MF) observed at an age of ~100 Myr is representative of the initial mass function (IMF). In other words, is the observed Pleiades population representative of the cluster population at the time it formed and how did it evolve within 100 Myr?

KAH present calculations of the formation of Galactic clusters using Aarseth's Nbody6 variant GasEx (Aarseth 1999). They defined an initial model from a set of assumptions describing the outcome of the star formation process and studied how it could lead to the formation of the ONC and then to the Pleiades by dynamical and stellar evolution. They found encouraging consistency with observational constraints on the radial density profile, kinematics and binary properties for both the ONC and the Pleiades. With this contribution we compare the MF predicted by the models with currently available data to test if the Pleiades IMF may have been compatible with the "standard" IMF (Kroupa 2001) or with the log-normal IMF found to match the Galactic field population down to the substellar regime (Chabrier 2002).

In this paper, we describe briefly KAH's models in Sect. 2 before comparing them to current estimates of the Pleiades MF and presenting relevant results about the radial distribution and the evolution of the cluster population in Sect. 3. The conclusions are given in Sect. 4.

2. Model description and predictions

KAH develop stellar-dynamical models of cluster formation under realistic conditions. Their computations are performed with Aarseth's NBODY6-variant GASEX which allows accurate treatment of close encounters without softening and multiple stellar systems in clusters, incorporates stellar evolution and a Galactic tidal field in the solar neighbourhood. In the models the initial stellar and sub-stellar masses are distributed following the standard, or Galactic-average, three-part power-law IMF $\xi(m) \propto m^{-\alpha_i}$, where $dn = \xi(m)\,dm = \xi_L(m)\,d\log_{10}m$ is the number of objects in the mass interval $m, m + dm$ and $\log_{10}m$, $\log_{10}m + d\log_{10}m$, respectively. $\xi_L(m) = (m \ln 10)\,\xi(m)$ is the "logarithmic IMF". The standard IMF has (Kroupa 2001)

$$\begin{aligned} \alpha_0 &= +0.3, \quad 0.01 \le m < 0.08\ M_\odot; \\ \alpha_1 &= +1.3, \quad 0.08 \le m < 0.50\ M_\odot; \qquad (1) \\ \alpha_2 &= +2.3, \quad 0.50 \le m \le 50\ M_\odot. \end{aligned}$$

Initially all objects, stars and brown dwarfs, are assumed to be in binary systems with component masses chosen randomly from the IMF. The total binary proportion

$$f_{tot} = \frac{N_{bin}}{N_{bin} + N_{sing}},$$

where N_{bin} and N_{sing} are the number of binary and single-star systems respectively, is then equal to unity. The models initially consist of 10^4 stars and brown dwarfs in 5000 binaries.

Two models are constructed, both with a spherical Plummer density profile for the stars and the gas initially. The half-mass radius is $R_{0.5} = 0.45$ pc for model A with an initial central number density $\rho_C = 10^{4.8}$ stars/pc^3, and $R_{0.5} = 0.21$ pc for model B with $\rho_C = 10^{5.8}$ stars/pc^3. Both models are embedded in a gas potential with twice the mass in stars and with the same density profile as the stellar component. The gas is removed due to the action of the O stars after 0.6 Myr and the dynamical evolution is integrated for 150 Myr. By assuming a star-formation efficiency of 33 per cent and removing the residual gas within a thermal time-scale, the initially embedded cluster (the proto-ONC) expands rapidly, matches the ONC by about 1 Myr, and by 100 Myr it forms a bound star cluster which resembles the observed Pleiades and which forms the nucleus of an expanding association.

The MF measured in the Pleiades today may bear witness to these events, because if the embedded cluster was significantly mass segregated prior to gas removal, then mostly the low-mass stars will have been lost, and the Pleiades would then be deficient in very-low-mass stars.

The evolution of the two cluster models is discussed in KAH and compared to observational constraints on the structure, kinematics and binary-star properties for both the ONC and the Pleiades cluster. The core radii as well as the number of stars within these radii predicted at 0.9 Myr and 100 Myr by both models are in reasonable agreement with observed values for the ONC and the Pleiades respectively. Available velocity dispersion measurements are also consistent with the models. The observed ONC radial density profile is well reproduced by model B but not model A, whereas for the Pleiades the best fit is given by model A. Concerning the period distribution for late-type binaries, both models are consistent with the Pleiades data, although an intermediate model in term of central density would be better. For the ONC, only model B leads to agreement with the measured proportion of binaries with periods $P \ge 10^5$ days, model A retaining too many binaries. Overall though, both models fit the ONC and the Pleiades data quite well, suggesting that the Pleiades cluster most probably formed from an ONC-like object. Therefore the initial state of the Pleiades will have been much more concentrated than presently observed with a half-mass radius between 0.2 and 0.5 pc.

In this paper we extend this study by a comparison to the Pleiades MF which is now constrained down to the sub-stellar regime. The system MF which is constructed by counting only the system masses is compared with the observed MF, because the observational surveys cannot resolve binary stars. It is interesting to investigate the Pleiades MF to see if it may have changed and whether it differed from the standard IMF, given that the search for IMF variations constitutes one of the most important issues of star formation work.

3. The observed Pleiades mass function

Moraux et al. (2003) performed a deep and extended survey of the Pleiades cluster using the CFH-12K camera. The survey covered 6.4 sq.deg. reaching up to 3 degrees from the cluster's centre and the covered mass range extends from 0.03 to 0.45 $M_\odot$. The authors used the NextGen (Baraffe et al. 1998) and Dusty (Chabrier et al. 2000) models to convert their luminosity function into a mass function and they used the Stauffer & Prosser open cluster database[1] to complete their data for $m \ge 0.4\ M_\odot$. They thus computed the mass function from 0.030 $M_\odot$ to 10 $M_\odot$ and found that it is reasonably well-fitted by a log-normal function in logarithmic units (Moraux et al. 2003, Fig. 9)

$$\xi_L(m) = \frac{dn}{d\log m} \propto \exp\left[-\frac{(\log m - \log m_0)^2}{2\sigma^2}\right] \qquad (2)$$

with $m_0 \simeq 0.25\ M_\odot$ and $\sigma = 0.52$. It is shown in Fig. 1.

However, the lowest mass point of the MF looks a bit different and is located much above the log-normal fit. Similar features are observed for other clusters around the same spectral type (M7-M8) and Dobbie et al. (2002) argued this reflects a sharp local drop in the luminosity–mass (L–M) relationship, due to the onset of dust formation in the atmosphere around $T_{eff} = 2500$ K. A change in the slope of the L–M relationship implies that the masses of objects with spectral types later than M7 may be significantly underestimated by the current NextGen and Dusty models and that the number of objects in this lowest mass bin may be overestimated. By applying the empirical magnitude–mass relation given by Dobbie et al. (2002; their Fig. 3) for the Pleiades low mass stars and brown dwarfs, we find that the lowest mass point of the Pleiades MF goes down whereas higher mass points go up (see Fig. 1). The log-normal fit does not change however and becomes even better.

Even if this dust effect has still to be investigated, it suggests that the lowest mass point of the Pleiades MF may come

[1] Available at `http://cfa-www.harvard.edu/stauffer/opencl/`

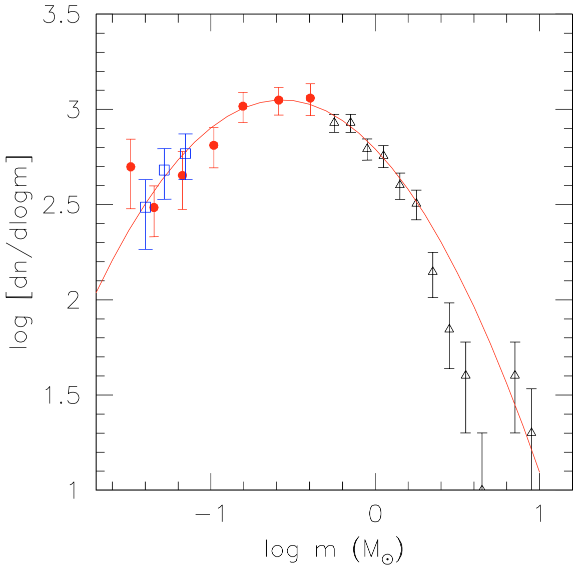

Fig. 1. The Pleiades mass function. The open triangles are from the Prosser and Stauffer Open Cluster Database and the filled circles are the data points from Moraux et al. (2003). The open squares have been obtained by applying the empirical magnitude-mass relation given by Dobbie et al. (2002). The log-normal fit (Eq. (2)) found by Moraux et al. (2003) is shown as a solid line.

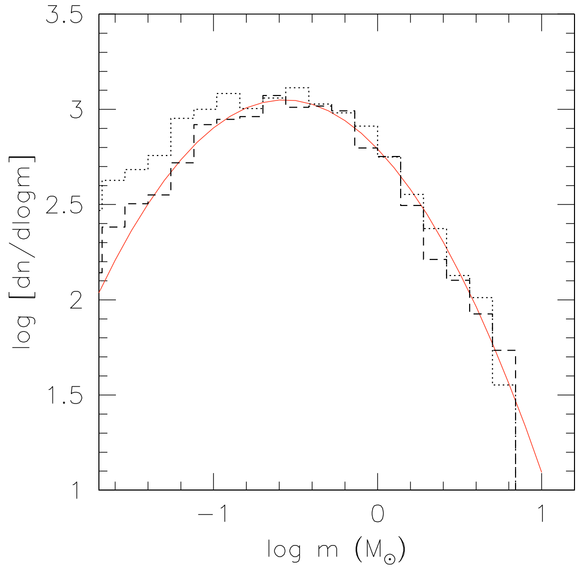

Fig. 2. Comparison of the log-normal fit of the observed Pleiades MF (shown as a solid line) to the model MFs. The dashed (dotted) histogram represents the system mass function at an age of 100 Myr from model A (B) of KAH for all systems within $R \leq 15$ pc of the model cluster center. They have been scaled to match the Pleiades data around $m \simeq 1\ M_\odot$.

down in the future and we consider the log-normal distribution as a good approximation of the observed MF in this mass domain.

For $m \gtrsim 2\ M_\odot$ however, this fit does not seem to be steep enough. The 2–4 $M_\odot$ MF points are more than 2-sigma below the log-normal fit.

4. Comparison models/observations

4.1. The mass function

The system MFs at $t = 100$ Myr resulting from the dynamical and stellar evolution of KAH's models, assuming random pairing and a binary fraction $f_{\rm tot} = 1$ at $t = 0$ are compared to the log-normal fit of the observed Pleiades MF in Fig. 2 over the entire mass range. The system MF from model A (resp. model B) is shown as a dashed (resp. dotted) histogram.

Both models reproduce well the log-normal distribution for $m \gtrsim 0.1\ M_\odot$ which indicates that the observed MF (data points in Fig. 1) is also steeper than the model MF for $m \gtrsim 2\ M_\odot$. This discrepancy cannot be the effect of the stellar evolution since the models include its treatment but may indicate that the true stellar IMF in the Pleiades may have been steeper than Salpeter ($\alpha = 2.35$) above 2 $M_\odot$.

It is useful to note that *the KAH models* do not constitute a fit but *are a prediction of the Pleiades MF* in the stellar and the sub-stellar regime under the assumption that the Pleiades IMF was identical to the standard IMF (Eq. (1); Kroupa 2001). Our result here suggests that this may indeed have been the case except for the possibly steeper IMF for $m \gtrsim 2\ M_\odot$.

For $m \lesssim 0.1\ M_\odot$ down to the sub-stellar regime, model A yields a better fit than model B which suggests that the Pleiades may not have formed from an embedded cluster as concentrated as model B. The larger number of isolated BD systems predicted by model B compared to model A in Fig. 2 results from the early release of brown dwarf companions from their primary in the initially denser environment of model B. The observed period-distribution of late-type Pleiades binaries seems also to be better reproduced with model A for $P \leq 10^6$ days (see KAH, their Fig. 11), although an intermediate model in terms of central density would lead to improved agreement for longer periods. Therefore, our results tend to favour model A but model B cannot be excluded since it is still consistent with the observational result within the uncertainties (especially for the lower mass bins where the effect of dust formation still needs to be investigated).

By 100 Myr the binary fraction is not equal to one any longer and depends on mass. During the early stage of the cluster's life, many binaries are disrupted because of gravitational interactions. The binding energy being weak for low mass binaries, many brown dwarfs (BDs) have been freed and the BD-BD binary fraction predicted by the models is ~20% (see KAH, their Fig. 9) which is consistent with current observational results ranging from 15–50%. Martín et al. (2003) find $\sim 15\% \pm^{15}_{5}$ for resolved Pleiades systems with separations from 7–12 AU but Pinfield et al. (2003) suggest that the Pleiades total (i.e. unresolved in general) binary fraction is from 30–50%. Overall, the observational constraints on late-type binaries are in reasonable agreement with the models, as shown by KAH. The binary proportion of the massive stars decreases first through disruption and then increases as new companions are captured.

The mass function of all the objects counted individually is represented by a histogram in Fig. 3 for both models. It corresponds to the Pleiades MF we would observe if we were able

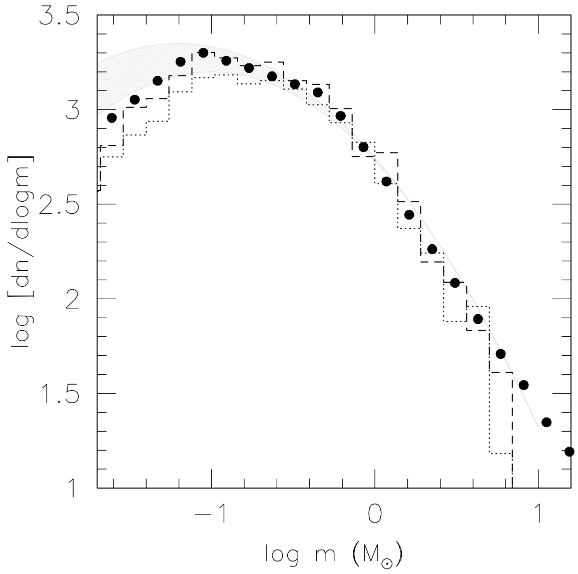

Fig. 3. The single object mass function for model A (dashed histogram) and model B (dotted histogram) at t = 100 Myr and $R \leq$ 15 pc. The shaded region represents the field mass function from Chabrier (2003) with uncertainties. The dots correspond to the shape of the standard three-part power-law IMF. All models are scaled to agree between 0.5 $M_{\odot}$ and 1 $M_{\odot}$.

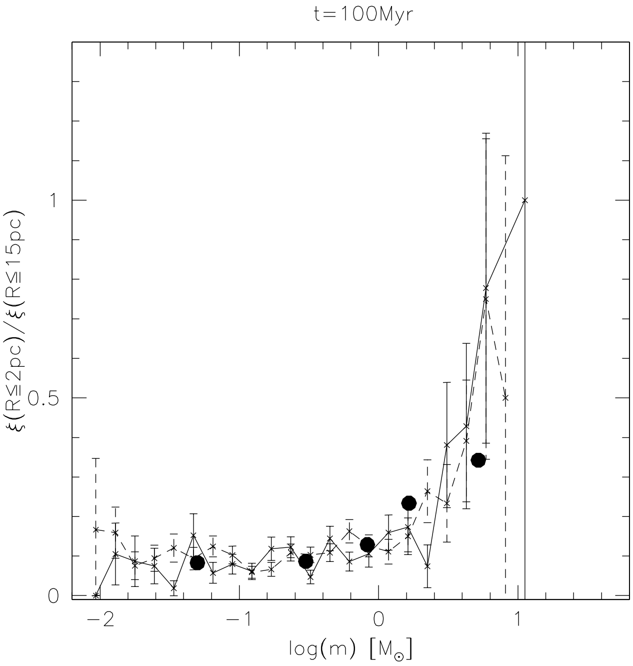

Fig. 4. Ratio of the number of systems within $R \leq 2$ pc to the total number of cluster systems ($R \leq 15$ pc) per mass bin at t = 100 Myr. The solid line corresponds to model A and the dashed line to model B. The stellar data points are from the observational survey of Pinfield et al. (1998) and the sub-stellar one is from Moraux et al. (2003) (filled circles).

to resolve all the binaries. If we compare this single star MF with the standard IMF indicated by the dots, we find that the overall shapes are similar, although model B shows a marginal deficit of BDs compared to model A. This indicates that the main difference between the Pleiades MF observed at an age of ~100 Myr and the Pleiades IMF is mainly due to the binarity effect and that the cluster dynamical evolution had little effect on its mass distribution.

The Galactic disk log-normal MF obtained by Chabrier (2003, Eq. (17)) by fitting L and T dwarf samples (Chabrier 2002) is found to be slighty above the histograms in the sub-stellar domain. This suggests that either the Pleiades IMF is different from the Chabrier's field IMF in this mass range or that the number of brown dwarfs in the field has been overestimated. The ratio

$$R = \frac{N_{\rm obj}(0.02\text{–}0.08\ M_{\odot})}{N_{\rm obj}(0.15\text{–}1\ M_{\odot})}$$

where $N_{\rm obj}$ is the number of objects in the respective mass range is found to be equal to 1.07 ± 0.17 for Chabrier's Galactic disk log-normal MF, whereas it is equal to 0.81 ± 0.05 for the three-part power-law standard Pleiades IMF.

4.2. Mass segregation

In Fig. 4, the fraction of systems per mass bin contained in the cluster centre ($R \leq 2$ pc) and predicted by the models at t = 100 Myr is compared with observational constraints. The solid line corresponds to model A and the dashed line to the initially more concentrated model B. The observational results for the Pleiades are indicated by the filled circles. The data points come from Pinfield et al. (1998) for the stellar domain and from Moraux et al. (2003) for the sub-stellar regime. The King density profile found by these authors for each mass bin has been de-projected, thus providing the spatial density which has then been integrated between 0 and 2 pc to obtain the number of systems in the inner part of the cluster.

Model predictions are consistent with observations. The more massive stars are concentrated around the cluster centre whereas the low mass objects are much more spread out throughout the cluster.

That the mass segregation at t = 100 Myr is similar for the two models indicates the cluster to be completely relaxed at this age, and that the memory of the initial concentration has been lost. However, if we compare the models after 1 Myr, mass segregation has not occurred yet for model A whereas it is already present for model B (see KAH, Fig. 15). This model evolved more rapidly than model A by virtue of its larger initial density and thus shorter relaxation time.

4.3. Evolution of the mass function

In the previous sections it has been shown that the Pleiades cluster is dynamically evolved and that mass segregation has occurred, as is also found to be the case by Portegies Zwart et al. (2001). Here we consider the detailed structure of the MF to infer if the preferential loss of stars of a certain mass may be evident in the models. The ratio of the present-day MF at t = 100 Myr to the IMF is plotted for models A and B in Fig. 5. The comparison between the cluster population at 100 Myr and the initial cluster population shows that the evolved population

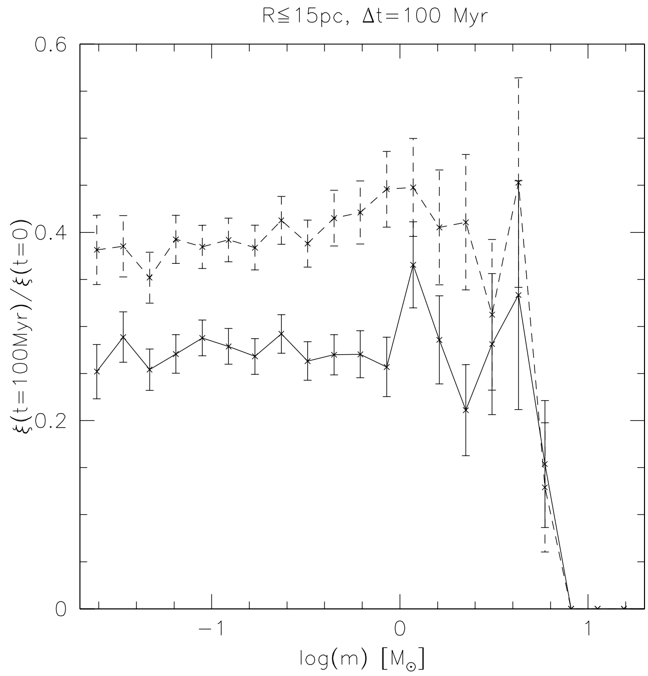

Fig. 5. Fraction of individual objects remaining inside the cluster ($R \leq$ 15 pc) at t = 100 Myr compared to the initial number of objects at t = 0. The solid line corresponds to model A and the dashed line to model B. The ratio of the individual object MFs is shown, not of the system MFs.

is depleted above about 4 $M_{\odot}$ due to stellar evolution. However there are no significant evolutionary effects that deplete the population of stars having a mass from 2–4 $M_{\odot}$. Therefore the difference between the observed Pleiades mass function and the models in this mass range is more likely due to binarity or a different IMF.

For model A the ratio is quite constant for less massive stars (and BDs) thus demonstrating that the same fraction of objects has been lost from the cluster independently of mass and thus *that energy equipartition did not play a major role in de-populating the embedded clusters but rather the violent process given by rapid gas expulsion* during which the model clusters lose about 2/3 of their population.

The larger ratio for model B comes about because this model is initially more concentrated thus ultimately leading to a more massive bound cluster because a larger fraction of the population evolves to a more bound state due to energy equipartition before gas expulsion, as already noted by KAH and considered in detail by Boily & Kroupa (2003a,b). For model B the ratio decreases from 0.45 at 1 $M_{\odot}$ to 0.38 below 0.08 $M_{\odot}$. This comes about in this model, which has a short equipartition time-scale, because less-massive objects end up with a lower cluster binding energy due to energy equipartition during the embedded phase. Gas expulsion then leads to the low-mass objects being preferentially lost. The effect is not very significant though, amounting to about 16 per cent.

5. Conclusions

The Pleiades is a young (≈120 Myr) close-by (≈120 pc) Galactic cluster and therefore allows very detailed observational scrutiny. The available data together with theoretical work suggest that the Pleiades may have been born similar to the ONC, and that its subsequent evolution passed a violent phase as a result of rapid gas expulsion once the massive cluster stars provided sufficient feedback to the young nebula. The theoretical models suggest that initially highly concentrated states (model B), with $\rho_{\rm C} \approx 10^{5.8}$ stars/pc^3, evolve to significant mass segregation prior to gas expulsion, while less-concentrated models with $\rho_{\rm C} \approx 10^{4.8}$ stars/pc^3 (model A) do not. As a result, the former loses slightly more of its low-mass members relative to higher-mass ones than the latter (Fig. 5).

Both models are in good agreement with the observed MF in the Pleiades (Fig. 2), although model A yields a better fit which may suggest that the Pleiades precursor had a concentration near $\rho_{\rm C} \approx 10^{4.8}$ stars/pc^3 rather than being more concentrated. The cluster's stellar IMF could thus have been very similar to the Galactic-field average IMF for stars with $m \lesssim 2\,M_{\odot}$. No significant stellar IMF variation can thus be detected, in comparison to the Galactic-field. The sub-stellar part of the Pleiades mass function also seems correctly reproduced by the dynamical evolution of dense clusters. This suggests only marginal evaporation of the lowest cluster members relative to higher mass stars on a timescale of 100 Myr.

The Pleiades do appear to have a deficit of stars with $m \gtrsim 2\,M_{\odot}$ (Fig. 2) compared to the number expected from the average IMF indicating that the Pleiades IMF may have been steeper, $\alpha_3 > 2.3$ for $m \geq 2\,M_{\odot}$. This is interesting, because there exists evidence that the stellar IMF corrected for binarity for massive stars is probably steeper than a Salpeter IMF (Sagar & Richtler 1991; Kroupa & Weidner 2003). These authors found $\alpha_3 \approx 2.7$ whereas an *apparent* Salpeter IMF indicates $\alpha_{\rm app} = 2.35$. However, it will be necessary to compute additional models with different values for the star-formation efficiency and mass to map-out feasible Pleiades precursors and the range of physical conditions within the solution space. For example, a lower initial density and thus a presumably larger loss of massive stars during gas expulsion may reduce the discrepancy found here of the measured MF and the standard IMF.

The Pleiades show very pronounced mass segregation (Fig. 4) which is well reproduced by both models. This indicates that the mass segregation that develops in model B prior to gas expulsion is forgotten by 100 Myr. The Pleiades is therefore in a completely relaxed state, having almost completely lost memory of its initial condition. These, however, are reflected in the properties of its binary population, because the initial concentration limits the binary-star periods that survive to old cluster age (KAH).

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References

Aarseth, S. J. 1999, PASP, 111, 1333
Baraffe, I., Chabrier, G., Allard, F., & Hauschildt, P. H. 1998, A&A, 337, 403
Boily, C. M., & Kroupa, P. 2003a, MNRAS, 338, 665
Boily, C. M., & Kroupa, P. 2003b, MNRAS, 338, 673
Bouvier, J., Rigaut, F., & Nadeau, D. 1997, A&A, 323, 139
Chabrier, G. 2003, PASP, 115, 763
Chabrier, G. 2002, ApJ, 567, 304
Chabrier, G., Baraffe, I., Allard, F., & Hauschildt, P. H. 2000, ApJ, 542, 464
Dobbie, P. D., Pinfield, D. J., Jameson, R. F., & Hodgkin, S. T. 2002, MNRAS, 335, L79
Kroupa, P. 2001, MNRAS, 322, 231
Kroupa, P., & Weidner, C. 2003, ApJ, 598, 1076
Kroupa, P., Aarseth, S., & Hurley, J. 2001, MNRAS, 321, 699 (KAH)
Kroupa, P., Bouvier, J., Duchêne, G., & Moraux, E. 2003, MNRAS, 346, 368
Martín, E. L., Barrado y Navascués, D., Baraffe, I., Bouy, H., & Dahm, S. 2003, ApJ, 594, 525
Martín, E. L., Basri, G., Gallegos, J. E., et al. 1998, ApJ, 499, L61
Moraux, E., Bouvier, J., Stauffer, J. R., & Cuillandre, J.-C. 2003, A&A, 400, 891
Pinfield, D. J., Jameson, R. F., & Hodgkin, S. T. 1998, MNRAS, 299, 955
Portegies Zwart, S. F., McMillan, S. L. W., Hut, P., & Makino, J. 2001, MNRAS, 321, 199
Robichon, N., Arenou, F., Mermilliod, J.-C., & Turon, C. 1999, A&A, 345, 471
Sagar, R., & Richtler, T. 1991, A&A, 250, 324
Stauffer, J. R., Schultz, G., & Kirkpatrick, J. D. 1998, ApJ, 499, L199