Mon. Not. R. Astron. Soc. **348,** 187–191 (2004)

Evidence for a fundamental stellar upper mass limit from clustered star formation

C. Weidner★ and P. Kroupa★†

Institut für Theoretische Physik und Astrophysik, Universität Kiel, 24098 Kiel, Germany

Accepted 2003 October 23. Received 2003 October 14; in original form 2003 July 11

ABSTRACT

The observed masses of the most massive stars do not surpass about 150 $M_\odot$. This may either be a fundamental upper mass limit which is defined by the physics of massive stars and/or their formation, or it may simply reflect the increasing sparsity of such very massive stars, so that the observation of even higher mass stars becomes unlikely in the Galaxy and the Magellanic Clouds. It is shown here that if the stellar initial mass function (IMF) is a power law with a Salpeter exponent ($\alpha = 2.35$) for massive stars then the richest very young cluster R136 seen in the Large Magellanic Cloud (LMC) should contain stars with masses larger than 750 $M_\odot$. If, however, the IMF is formulated by consistently incorporating a fundamental upper mass limit then the observed upper mass limit is arrived at readily even if the IMF is invariant. An explicit down-turn or cut-off of the IMF near 150 $M_\odot$ is not required: our formulation of the problem contains this implicitly. We are therefore led to conclude that a fundamental maximum stellar mass near 150 $M_\odot$ exists, unless the true IMF has $\alpha > 2.8$.

Key words: stars: early-type – stars: formation – stars: luminosity function, mass function – galaxies: star clusters – galaxies: stellar content.

1 INTRODUCTION

The existence of a finite stellar upper mass limit has long been debated in the literature (Elmegreen 2000; Massey 1998, references therein). Observational evidence for such a limit is scarce because stars more massive than 60–80 $M_\odot$ are very rare. While stellar formation models lead to a mass limit of approximately 100 $M_\odot$ imposed by feedback on a spherical accretion envelope (Kahn 1974; Wolfire & Cassinelli 1986, 1987), theoretical work on the formation of massive stars through disc-accretion with high accretion rates, which allows thermal radiation to escape pole-wards (e.g. Nakano 1989; Jijina & Adams 1996), calls the existence of such a limit into question. Some massive stars may also form by the coagulation of intermediate-mass proto-stars in very dense cores of emerging embedded clusters driven by core contraction due to the very rapid accretion of gas with low specific angular momentum, thus again avoiding the theoretical feedback-induced mass limit (Bonnell, Bate & Zinnecker 1998; Stahler, Palla & Ho 2000).

In his review, Massey (1998) points out that it is difficult to infer the masses of very massive stars because stars heavier than 100 $M_\odot$ do not have their maximum luminosity in the optical bands, and are therefore not easily distinguished on the basis of photometry from stars with somewhat lower masses. Using combined photometric and spectroscopic methods, Massey & Hunter (1998) find stars with masses ranging up to $m = 140$ $M_\odot$ (or even 155 $M_\odot$ depending on the stellar models used) in the rich (about 10^5 stars) and very young (1–3 Myr) R136 cluster in the Large Magellanic Cloud, and that the initial mass function (IMF) has a Salpeter exponent ($\alpha = 2.35$) for $3 \lesssim m/M_\odot \lesssim 100$. Given this IMF, Massey (1998) emphasizes that the observed most massive star mass of around 150 $M_\odot$ is simply a result of the extreme rarity of even more massive stars, rather than a reflection of a fundamental maximum stellar mass: the observed numbers of very massive stars are consistent with the numbers expected from sampling from the IMF and the number of stars in a cluster.

In order to re-address this last point, we take an approach similar to that taken by Elmegreen (2000), but we rely on a different mathematical formulation. The idea is to quantify the expected mass of the most massive star, m_{max}, as a function of the stellar mass, M_{ecl}, in an embedded cluster, and to show that very rich clusters predict an m_{max} that is significantly larger than the observed most massive star. Thus we adopt the observed IMF and demonstrate that the observed cut-off mass is significantly below the maximum stellar mass that would be expected in rich clusters if there were no fundamental upper mass limit. The implication is thus that there must exist a fundamental upper mass limit, m_{max*}, such that $m_{max} \leqslant m_{max*}$ for all M_{ecl}. Using simple equations concerning the IMF, and noting that most if not all stars are born in stellar clusters (Lada & Lada 2003) with a universal IMF, we show that the solutions of these equations predict a very different high mass spectrum for a finite or

★E-mail: weidner@astrophysik.uni-kiel.de (CW); pavel@astrophysik.uni-kiel.de(PK)
†Heisenberg Fellow.

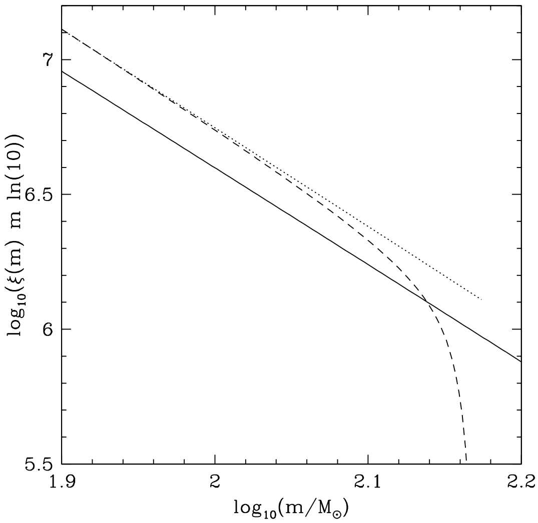

Figure 1. The 'logarithmic' IMF [$\xi_L(m) = \xi(m)\, m \ln\ 10$] over logarithmic stellar mass above 80 $M_\odot$ for three different cases. The solid line shows an unlimited Salpeter IMF, the dotted line a Salpeter IMF *truncated* at 150 $M_\odot$, and the dashed line a Salpeter IMF *limited* at 150 $M_\odot = m_{max*}$ in the way described in Section 2. All three cases are normalized to the same area over $0.01 \leqslant m/M_\odot < \infty$.

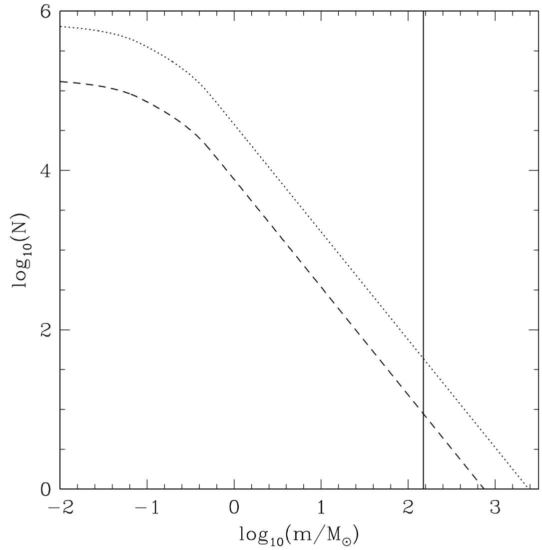

Figure 2. Number of stars (logarithmic) above mass m for R136 for different mass estimates (dotted line: $M_{R136} = 2.5 \times 10^5\ M_\odot$; dashed line: $M_{R136} = 5 \times 10^4\ M_\odot$, Selman et al. 1999). The vertical solid line marks $m = 150\ M_\odot$.

infinite fundamental upper stellar mass, m_{max*}, as demonstrated in Fig. 1.

Section 2 introduces the equations and the analytical and numerical methods used to solve them, while the results are given in Section 3. The implications are discussed in Section 4.

2 METHOD

For our calculations we use a four-component power-law IMF:

$$\xi(m) = k \begin{cases} \left(\dfrac{m}{m_H}\right)^{-\alpha_0}, & m_{low} \leqslant m \leqslant m_H, \\ \left(\dfrac{m}{m_H}\right)^{-\alpha_1}, & m_H \leqslant m \leqslant m_0, \\ \left(\dfrac{m_0}{m_H}\right)^{-\alpha_1} \left(\dfrac{m}{m_0}\right)^{-\alpha_2}, & m_0 \leqslant m \leqslant m_1, \\ \left(\dfrac{m_0}{m_H}\right)^{-\alpha_1} \left(\dfrac{m_1}{m_0}\right)^{-\alpha_2} \left(\dfrac{m}{m_1}\right)^{-\alpha_3}, & m_1 \leqslant m \leqslant m_{max}, \end{cases} \tag{1}$$

with exponents

$$\begin{aligned} \alpha_0 &= +0.30, & 0.01 &\leqslant m/M_\odot \leqslant 0.08, \\ \alpha_1 &= +1.30, & 0.08 &\leqslant m/M_\odot \leqslant 0.50, \\ \alpha_2 &= +2.30, & 0.50 &\leqslant m/M_\odot \leqslant 1.00, \\ \alpha_3 &= +2.35, & 1.00 &\leqslant m/M_\odot, \end{aligned} \tag{2}$$

where $\mathrm{d}N = \xi(m)\ \mathrm{d}m$ is the number of stars in the mass interval m to $m + \mathrm{d}m$. The exponents α_i represent the Galactic field (or standard) IMF (Kroupa 2001, 2002). The advantages of such a multi-part power-law description are the easy integrability and, more importantly, the fact that *any given part of the IMF can be changed readily without affecting the other parts*. For example, the stellar luminosity function for late-type stars poses significant constraints on the IMF below $m \lesssim 1\ M_\odot$ (Kroupa, Tout & Gilmore 1993; Reid, Gizis & Hawley 2002; Kroupa 2002) which therefore must remain unaffected when changing the IMF for massive stars. The observed IMF is today understood to be an invariant Salpeter power law above a few $M_\odot$, being independent of the cluster density and metallicity for metallicities $Z \gtrsim 0.002$ (Massey 1998).

The basic assumption underlying our approach is that stars in every cluster follow this same universal IMF.

2.1 Number of stars

The number of stars above a mass m is

$$N = \int_m^{m_{max*}} \xi(m)\, \mathrm{d}m, \tag{3}$$

where the normalization constant k (equation 1) is given by the stellar mass of the cluster,

$$M_{ecl} = \int_{m_{low}}^{m_{max}} m\xi(m)\, \mathrm{d}m. \tag{4}$$

Here we use the cluster mass in stars prior to gas blow-out and thus prior to any losses to the stellar population due to cluster expansion (Kroupa & Boily 2002).

In Fig. 2 it is shown that a significant number of stars with masses $m > 150\ M_\odot$ should be present in R136 (10 stars for $M_{R136} = 5 \times 10^4\ M_\odot$ and 40 stars for $M_{R136} = 2.5 \times 10^5\ M_\odot$) if no fundamental upper mass limit exists ($m_{max*} = \infty$) and if the IMF is a Salpeter power law above about 1 $M_\odot$. None, however, are observed. This sets the problem for which we seek a solution by considering a finite m_{max*}.

2.2 The limited case

First we examine the case for which a finite upper mass limit for stars exists. Here two upper mass limits have to be differentiated: the fundamental maximum mass a star can have under any circumstances, m_{max*}, and the 'local' upper mass limit $m_{max} \leqslant m_{max*}$ for stars in a cluster with a stellar mass M_{ecl}. The mass of the heaviest star in a cluster, m_{max}, follows from stating that there is exactly one such star in the cluster:

$$1 = \int_{m_{\rm max}}^{m_{\rm max*}} \xi(m)\,\mathrm{d}m. \tag{5}$$

Note that Elmegreen (2000) uses $m_{\rm max*} = \infty$ in his formulation of the problem. After inserting equation (2) the integral can be solved, giving ($\alpha_i \neq 1$)

$$1 = k\left[\left(\frac{m_{\rm H}}{m_0}\right)^{\alpha_1}\left(\frac{m_0}{m_1}\right)^{\alpha_2} m_1^{\alpha 3}\right]\left(\frac{m_{\rm max*}^{1-\alpha_3}}{1-\alpha_3} - \frac{m_{\rm max}^{1-\alpha_3}}{1-\alpha_3}\right), \tag{6}$$

as long as $m_{\rm max} > m_1$. For $m_0 \leqslant m_{\rm max} < m_1$ we would have

$$1 = k\left\{\left[\left(\frac{m_{\rm H}}{m_0}\right)^{\alpha_1} m_0^{\alpha 2}\right]\left(\frac{m_1^{1-\alpha_2}}{1-\alpha_2} - \frac{m_{\rm max}^{1-\alpha_2}}{1-\alpha_2}\right) + \left[\left(\frac{m_{\rm H}}{m_0}\right)^{\alpha_1}\left(\frac{m_0}{m_1}\right)^{\alpha_2} m_1^{\alpha 3}\right]\left(\frac{m_{\rm max*}^{1-\alpha_3}}{1-\alpha_3} - \frac{m_1^{1-\alpha_3}}{1-\alpha_3}\right)\right\}, \tag{7}$$

and so on. For the numerical results obtained in this work $m_{\rm max*} = 150\ \mathrm{M}_\odot$ is assumed.

In order to solve this equation with two unknowns, k and $m_{\rm max}$, we need an additional equation. This is provided by the mass in embedded-cluster stars (equation 4). With the use of $\xi(m)$ (equation 1), equation (4) leads to ($\alpha_i \neq 2$)

$$M_{\rm ecl} = k\left[\frac{m_{\rm H}^{\alpha_0}}{2-\alpha_0}(m_{\rm H}^{2-\alpha_0} - m_{\rm low}^{2-\alpha_0}) + \frac{m_{\rm H}^{\alpha_1}}{2-\alpha_1}(m_0^{2-\alpha_1} - m_{\rm H}^{2-\alpha_1}) + \frac{\left(\frac{m_{\rm H}}{m_0}\right)^{\alpha_1} m_0^{\alpha 2}}{2-\alpha_2}(m_1^{2-\alpha_2} - m_0^{2-\alpha_2}) + \frac{\left(\frac{m_{\rm H}}{m_0}\right)^{\alpha_1}\left(\frac{m_0}{m_1}\right)^{\alpha_2} m_1^{\alpha 3}}{2-\alpha_3}(m_{\rm max}^{2-\alpha_3} - m_1^{2-\alpha_3})\right] \tag{8}$$

for $m_{\rm max} > m_1$ and with $m_{\rm low}$ set to 0.01 $\mathrm{M}_\odot$ throughout this paper. For $m_0 \leqslant m_{\rm max} < m_1$ equation (8) would be truncated at an earlier term, and so on.

Finally, inserting equation (6), after a short transformation, into (8) gives $M_{\rm ecl}$ as a function of $m_{\rm max}$. This must now be solved for $m_{\rm max}$ in dependence of $M_{\rm ecl}$. This is done by finding the roots of this result after subtracting $M_{\rm ecl}$. Fig. 3 shows the solution for a power law with $\alpha_3 = 2.35$ and $m_{\rm max*} = 150\ \mathrm{M}_\odot$ as a dashed line.

2.3 The unlimited case

In the case of $m_{\rm max*} = \infty$, equations (4) and (8) remain as they are while (5) and (6) change to

$$1 = \int_{m_{\rm max}}^{\infty} \xi(m)\mathrm{d}m \tag{9}$$

and (as long as $m_{\rm max} > m_1$ and $\alpha_3 > 1$)

$$1 = -k\left[\left(\frac{m_{\rm H}}{m_0}\right)^{\alpha_1}\left(\frac{m_0}{m_1}\right)^{\alpha_2} m_1^{\alpha 3}\right]\left(\frac{m_{\rm max}^{1-\alpha_3}}{1-\alpha_3}\right), \tag{10}$$

respectively. As only the normalization factor k deduced from (10) changes, equation (8) stays the same, and inserting (10) into (8) gives $M_{\rm ecl}$ in dependence of $m_{\rm max}$ for the unlimited case.

Fig. 3 shows that the solution for unlimited stellar masses (dotted line) has a much faster rise than for the limited case. If there were no fundamental upper mass limit for stars then a Salpeter IMF would predict stars with much larger masses ($m_{\rm max} > 200\ \mathrm{M}_\odot$) for clusters with $M_{\rm ecl} > 10^{4.5}\ \mathrm{M}_\odot$ than are observed to be present. This is also found to be the case by Elmegreen (2000).

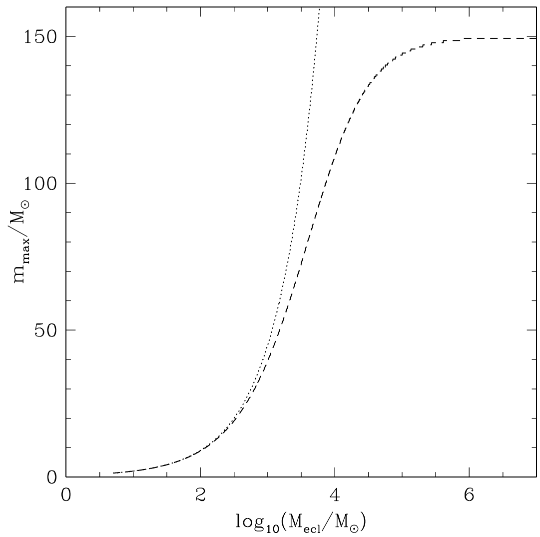

Figure 3. Dependence of the stellar upper mass limit, $m_{\rm max}$, on the cluster mass for a limited ($m_{\rm max*} = 150\ \mathrm{M}_\odot$: dashed line) and an unlimited ($m_{\rm max*} = \infty$: dotted line) fundamental upper stellar mass and $\alpha_3 = 2.35$.

3 RESULTS

The results of solving $m_{\rm max}(M_{\rm ecl})$ for a grid of cluster masses ranging from $M_{\rm ecl} = 5\ \mathrm{M}_\odot$ (Taurus–Auriga-like stellar groups) to $10^7\ \mathrm{M}_\odot$ (very massive stellar super clusters) are plotted in Figs 4 and 5.

Fig. 4 shows the variation of the maximum possible mass for a star, $m_{\rm max}$, as a function of the cluster mass, $M_{\rm ecl}$. In the unlimited case (long-dashed line), a linear relation (in double logarithmic units) is seen. Two vertical lines indicate the observational mass interval for R136 in the Large Magellanic Cloud (Selman et al. 1999). Without a fundamental upper mass limit, R136, for which Massey & Hunter (1998) measure a Salpeter power-law IMF for $m>$ few $\mathrm{M}_\odot$, should have stars with $m > 750\ \mathrm{M}_\odot$, whereas no stars with $m > 150\ \mathrm{M}_\odot$ are seen. Similar values are found from statistical sampling of the IMF

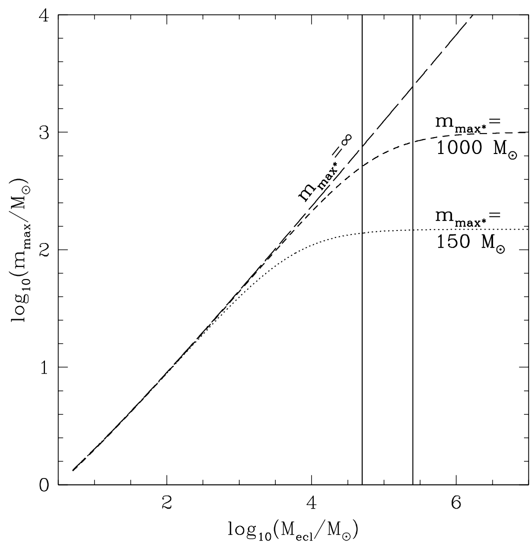

Figure 4. Double logarithmic plot of the maximal stellar mass versus cluster mass. Shown are three cases: finite total upper mass limit of $m_{\rm max*} = 150\ \mathrm{M}_\odot$ (dotted line); $m_{\rm max*} = 1000\ \mathrm{M}_\odot$ (short-dashed line); and no limit, $m_{\rm max*} = \infty$ (long-dashed line). The vertical lines mark the empirical mass interval for R136 in the LMC.

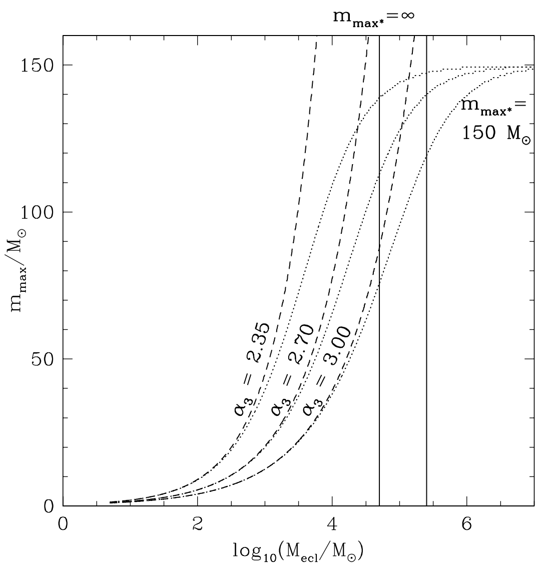

Figure 5. Maximal stellar mass versus cluster mass (logarithmic). Results are shown for different exponents (α_3) above 1 $M_\odot$ and for the limited ($m_{max*} = 150\ M_\odot$) and unlimited cases. The vertical lines mark the empirical mass interval for R136 in the LMC.

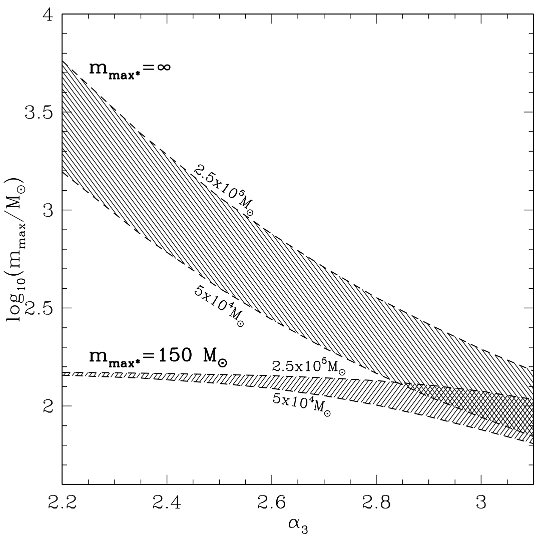

Figure 6. The mass limits (m_{max}) as a function of the IMF exponent α_3 (above 1 $M_\odot$) in the limited case ($m_{max*} = 150\ M_\odot$) and the unlimited case ($m_{max*} = \infty$) for the two mass limits of R136 shown in Figs 4 and 5.

(Elmegreen 2000). For $m_{max*} = 150\ M_\odot$ (dotted line), on the other hand, the cluster has an upper limit of 140–150 $M_\odot$, in agreement with the observational limit.

The influence of the high-mass exponent α_3 on the $m_{max}(M_{ecl})$ relation is shown in Fig. 5. Plotted are graphs for limited (150 $M_\odot$) and unlimited cases, each for $\alpha_3 = 2.35$ (Salpeter), 2.70 and 3.00. *Exponents* $\alpha_3 > 2.8$ *lead to a* $m_{max}(M_{ecl})$ *relation that allows upper masses in R136 of around* 150 $M_\odot$, *even for the unlimited case* ($m_{max*} = \infty$). Fig. 6 shows that in the case of R136 and for $\alpha_3 > 2.8$ no distinction can be made between $m_{max*} = 150\ M_\odot$ and ∞, given the uncertainty in M_{ecl}.

Because massive stars are very rare, the IMF exponent is often based on limited statistics and usually valid only for stars with $m \lesssim 40\ M_\odot$. We therefore also consider the possibility that the IMF slope is Salpeter to a certain limit (e.g. 40 $M_\odot$) but then turns down sharply. For this purpose we set $m_1 = m_{border}$ in equation (1) with $\alpha_2 = 2.35$ (0.5 $M_\odot$ $-m_{border}$), and find that $\alpha_{m>m_{border}} = \alpha_3$ such that equation (9) is fulfilled for $m_{max} = 150\ M_\odot$. The result is plotted in Fig. 7.

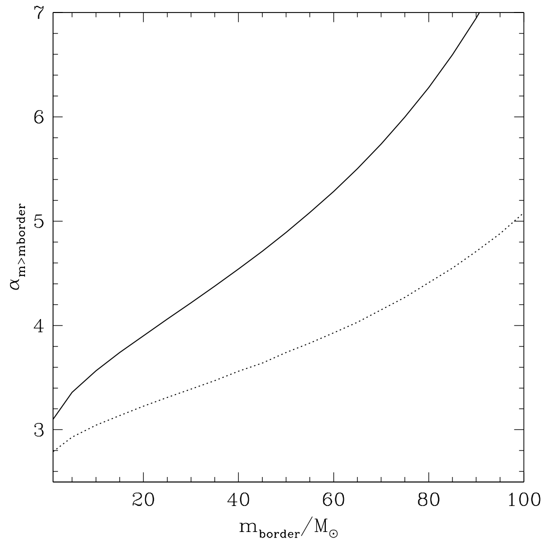

Figure 7. The power-law exponent α needed to produce a high-mass limit of 150 $M_\odot$ for R 136 (solid line: $M_{R136} = 2.5 \times 10^5\ M_\odot$ and dotted line: $M_{R136} = 5 \times 10^4\ M_\odot$) when the IMF is Salpeter up to a certain mass limit m_{border}.

From Fig. 7 it is evident that, in order to reproduce the observed limit of about 150 $M_\odot$ for R136 from a formally unlimited mass-scale and a down-turn mass (m_{border}) of, say, 40 $M_\odot$, the exponent has to change to $\alpha_{m>m_{border}} = 3.6$ (for $M_{R136} = 5 \times 10^4\ M_\odot$) or 4.5 ($M_{R136} = 2.5 \times 10^5\ M_\odot$). Such a down-turn near 40 $M_\odot$ is not seen in those populations that do contain more massive stars (e.g. R136 contains about 40 O3 stars, Massey & Hunter 1998), and we therefore consider $m_{max*} \approx 150\ M_\odot$ as being the more realistic possibility. Note though that the existence of m_{max*} leads to a sharp decline of the IMF near 120 $M_\odot$, which leads to a similar effect to an increase of $\alpha_{m>m_{border}}$ near this mass (Fig. 1). However, our formulation needs one additional parameter (m_{max*}) to account for this down-turn of the IMF implicitly, while modelling an explicit down-turn would need two additional parameters (m_{border} and $\alpha_{m>m_{border}}$).

For massive stars the multiplicity proportion is typically very high, with most O stars having more than one companion (e.g. Zinnecker 2003; Kroupa 2003), possibly implying that the true underlying binary-corrected IMF has $\alpha_3 \gtrsim 2.7$ (Weidner & Kroupa, in preparation; Sagar & Richtler 1991). If this is the case then m_{max*} cannot be constrained given the available stellar samples because the Local Group does not contain sufficiently massive, young clusters.

4 DISCUSSION AND CONCLUSIONS

Using a fairly simple formalism based on current knowledge of the IMF we have shown that the mere existence of a fundamental upper mass limit implies that the highest mass a star can have in a massive cluster is different from the case without such a limit. For low-mass clusters ($M_{ecl} < 10^3\ M_\odot$) the differences of the solutions are negligible (Fig. 4), but in the regime of the so-called ‘stellar super-clusters’ ($M_{ecl} > 10^4\ M_\odot$) they become very large. Without such a limit, clusters such as R136 in the LMC would have stars with $m > 750\ M_{\odot}$.

Elmegreen (2000) presents a random sampling model for star formation from the IMF which is similar to our model. However, Elmegreen assumes a Salpeter power-law IMF above 0.5 $M_{\odot}$ and no specific stellar mass limit. In order to reduce the number of high-mass stars above $\sim$130 $M_{\odot}$ he assumes an exponential decline for the probability to form a star after a turbulent crossing time. The results of the Elmegreen (2000) model are summarized by him as follows: 'There is a problem getting both the Salpeter function out to $\sim$130 $M_{\odot}$ in dense clusters and at the same time not getting any $\sim$300 $M_{\odot}$ stars at all in a whole galaxy.'

He discusses the following six explanations for this problem.

(i) Stars more massive than $\sim$150 $M_{\odot}$ exist but have not been found yet.

(ii) A self-limitation in the star formation process prohibits stars above a certain limit.

(iii) Super-massive stars exist but evolve so quickly that they do not leave their primordial clouds – making them observable only as ultra-luminous infrared sources.

(iv) A limit for the cloud size for coherent star formation is assumed.

(v) The star-forming clouds are destroyed after a star of a certain (maximum) mass forms.

(vi) The IMF is not universal, but different for various star-forming regions.

Case (i) can be excluded here because of the number of super-massive stars expected, for example in R136. Concerning case (iii), no such sources have been found to our knowledge. Cases (ii), (iv) and (v) lead to a physical upper limit consistent with this work. From the point of view of this work it is not possible to differentiate between them. Finally, as several observations of various clusters show a universal Salpeter IMF up to $\sim$120 $M_{\odot}$ (e.g. Massey & Hunter 1998; Selman et al. 1999; Smith & Gallagher 2001) case (vi) appears unlikely. Elmegreen thus sees the finite upper mass limit as a cut-off to the unlimited solution.

In contrast, we introduce the fundamental upper mass limit consistently into the formulation of the problem, and by combining this with the use of a realistic IMF we are able to show strong deviations of the solutions beyond a simple cut-off. The formulation presented here has the advantage of explaining the observations with the simple assumption that all stars form with the same universal IMF.

ACKNOWLEDGMENTS

This work has been funded by DFG grants KR1635/3 and KR1635/4.

REFERENCES

Bonnell I. A., Bate M. R., Zinnecker H., 1998, MNRAS, 298, 93
Elmegreen B. G., 2000, ApJ, 539, 342
Jijina J., Adams F. C., 1996, ApJ, 462, 874
Kahn F. D., 1974, A&A, 37, 149
Kroupa P., 2001, MNRAS, 322, 231
Kroupa P., 2002, Sci, 295, 82
Kroupa P., 2003, NewA Rev., in press (astro-ph/0309598)
Kroupa P., Boily C. M., 2002, MNRAS, 336, 1188
Kroupa P., Tout C. A., Gilmore G., 1993, MNRAS, 262, 545
Lada C. J., Lada E. A., 2003, ARA&A, 41, 57
Massey P., 1998, in Gilmore G., Howell D., eds, ASP Conf. Ser. Vol. 142, The Stellar Initial Mass Function. Astron. Soc. Pac., San Francisco, p. 17
Massey P., Hunter D. A., 1998, ApJ, 493, 180
Nakano T., 1989, ApJ, 345, 464
Reid I. N., Gizis J. E., Hawley S. L., 2002, AJ, 124, 2721
Sagar R., Richtler T., 1991, A&A, 250, 324
Selman F., Melnick J., Bosch G., Terlevich R., 1999, A&A, 347, 532
Smith L. J., Gallagher J. S. III, 2001, MNRAS, 326, 1027
Stahler S. W., Palla F., Ho P. T. P., 2000, Protostars and Planets IV. Univ. Tucson Press, Arizona, p. 327
Wolfire M. G., Cassinelli J. P., 1986, ApJ, 310, 207
Wolfire M. G., Cassinelli J. P., 1987, ApJ, 319, 850
Zinnecker H., 2003, IAU Symp. 212, in press (astro-ph/0301078)

This paper has been typeset from a TEX/LATEX file prepared by the author.