A&A 467, 117–121 (2007)
DOI: 10.1051/0004-6361:20066786
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Astronomy & Astrophysics

Testing the universal stellar IMF on the metallicity distribution in the bulges of the Milky Way and M 31

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Received 21 November 2006/ Accepted 22 December 2006

ABSTRACT

Aims. We test whether the universal initial mass function (UIMF) or the integrated galaxial IMF (IGIMF) can be employed to explain the metallicity distribution (MD) of giants in the Galactic bulge.

Methods. We make use of a single-zone chemical evolution model developed for the Milky Way bulge in the context of an inside-out model for the formation of the Galaxy. We checked whether it is possible to constrain the yields above 80 $M_\odot$ by forcing the UIMF and required that the resulting MD matches the observed ones. We also extended the analysis to the bulge of M 31 to investigate a possible variation of the IMF among galactic bulges. Several parameters that have an impact on stellar evolution (star-formation efficiency, gas infall timescale) are varied.

Results. We show that it is not possible to satisfactorily reproduce the observed metallicity distribution in the two galactic bulges unless assuming a flatter IMF ($x \leq 1.1$) than the universal one.

Conclusions. We conlude that it is necessary to assume a variation in the IMF among the various environments.

Key words. Galaxy: bulge – Galaxy: evolution – Galaxy: abundances

1. Introduction

The question of which is the most suitable initial mass distribution for bulges of galaxies is not addressed very often. In fact, bulge evolution models (e.g. Samland et al. 1997; Ferreras et al. 2003; Immeli et al. 2004; Costa et al. 2005) usually assume *a priori* that the zero age main sequence masses of stars are distributed following a power-law distribution:

$$\phi(m) \propto m^{-(1+x)} \tag{1}$$

with a Salpeter (1955) index ($x = 1.35$). Basic physical arguments support the idea of an initial mass function (IMF) varying among different environments (see e.g. Padoan et al. 1997; Larson 1998; or Nakamura & Umemura 2001; Schaerer 2002; Bromm & Larson 2004, for Population III stars).

On the other hand, so far there has not been a convincing observational evidence of such a variation in the stellar IMF based on direct stellar counts (see e.g. Chabrier 2003, for an extensive review). Massey (1998) find that the IMF is well represented by a Salpeter slope over an order of magnitude in metallicity, in the clusters and associations of the Milky Way and Magellanic Clouds, as well as in OB associations, while the slope appears to be much steeper in the field ($x \sim -3$). The invariance of the stellar IMF was confirmed by subsequent works. Kroupa (2001) summarized the available constraints by means of the multi-part power-law shape

$$\phi(M) \propto M^{-(1+x_i)} \tag{2}$$

where

$$\begin{aligned} x_1 &= 0.3 \text{ for } 0.08 \leq M/M_\odot \leq 0.50 \\ x_2 &= 1.3 \text{ for } 0.50 \leq M/M_\odot \end{aligned} \tag{3}$$

which we call the Universal IMF (UIMF)[1].

However, the IMF integrated over galaxies, which controls the distribution of stellar remnants, number of supernovae (SNe), and the chemical enrichment of a galaxy, is generally different from the stellar IMF and is given by the integral of the latter over the embedded star-cluster mass function, which varies from galaxy to galaxy. Weidner & Kroupa (2005) find such integrated galaxial IMF (IGIMF) to be steeper than the UIMF for a range of plausible scenarios, and they suggest a "maximum scenario", based on the Scalo (1986) star-count analysis of the local Galactic field, with an IGIMF which has the following indexes:

$$\begin{aligned} x_1 &= 0.3 \text{ for } 0.08 \leq M/M_\odot \leq 0.50 \\ x_2 &= 1.3 \text{ for } 0.50 \leq M/M_\odot \leq 1.00 \\ x_3 &= 1.7 \text{ for } 1.00 \leq M/M_\odot. \end{aligned} \tag{4}$$

In the following, we will refer to this IMF as to the IGIMF.

Conversely, Piotto & Zoccali (1999) and Paresce & De Marchi (2000) measured the present-day mass function in Galactic globular clusters below ~0.7 $M_\odot$. They found evidence of variation in the MF slope among different environments, with a tendency toward flatter slopes in globular clusters compared to the Galactic field IMF; Paresce & De Marchi (2000) also state that, in the considered mass range, the observed mass function

[1] This IMF is the form corrected forunresolved binaries.

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represents the true stellar IMF for these environments. Zoccali et al. (2000) derived the IMF below 1 $M_\odot$ in the Galactic bulge and concluded that it is shallower than the Salpeter slope; it also shows similarity with the IMF of globular clusters. However, the somewhat smaller x_1 is probably the result of the evaporation of low-mass stars from the cluster (Baumgardt & Makino 2003), while the Bulge result is still consistent with the UIMF, within the uncertainties.

Concerning the range of masses over which star formation is possible, although stellar instabilities that potentially lead to disruption already occur above 60–120 $M_\odot$ (Schwarzschild & Härm 1959), stars of ∼140–155 $M_\odot$ were observed in the core of the R136 cluster (Massey & Hunter 1998) and in the Arches cluster (Figer 2005). Although Massey (2003) sustains that this upper limit may indeed be statistical rather than physical (i.e. there may not be regions that are rich enough to allow the detection of such stars), Oey & Clarke (2005) studied the content of massive stars in 9 clusters and OB associations in the Milky Way, LMC, and SMC and find that the expectation value for the maximum stellar mass lies, with high significance, in the range 120–200 $M_\odot$. This agrees with the conclusion of Weidner & Kroupa (2004) that a fundamental maximum limit for stellar masses can be constrained at about 150 $M_\odot$, unless the true stellar IMF has $x > 1.8$.

Attempts to constrain the IMF in the bulge of our galaxy based on observations of chemical abundances were carried out by Matteucci & Brocato (1990) and Matteucci et al. (1999), who fixed the index by the requirement of reproducing the observed metallicity distributions (MDs) of Rich (1988) and McWilliam & Rich (1994), respectively. They both concluded that the bulge IMF must be flatter than the Salpeter one, in general, and lie in the range $x = 1.1$–1.35, thus favoring the production of massive stars with respect to the solar vicinity. An even flatter IMF index was chosen by Ballero et al. (2007), who showed that it is necessary to assume $x_2 = 0.95$–1.1 (where x_2 is the one defined in Eq. (3)) to fit the MDs of Zoccali et al. (2003) and Fulbright et al. (2006) for the Galactic bulge and of Sarajedini & Jablonka (2005) for the bulge of M 31. Even shallower IMFs ($x = 0.33$) are compatible with these observed distributions, but give rise to a certain amount of oxygen overproduction.

Our present aim is to test the effect of adopting both the UIMF and the IGIMF on the predicted bulge MD and to compare the results with the MDs employed in Ballero et al. (2007). These IMFs will be extended to a much higher upper mass limit than in previous models, so we will try to find the combination of metal yields and evolutionary parameters that best fit the observations with these two IMFs.

In Sect. 2 we present the adopted chemical evolution models, in Sect. 3 we discuss the outcome of these models and the results of their comparisons with the observed MDs, and in Sect. 4 we draw some conclusions.

2. The chemical evolution models

We briefly summarize the chemical evolution model described in Ballero et al. (2007), which we use. The star formation rate (SFR) is parametrized as $\psi(r,t) = \nu G^k(r,t)$, where ν is the star-formation efficiency, i.e. the inverse of the timescale of star formation, $k = 1$ to recover the star formation law of spheroids (but it can be shown that remarkable differences do not arise with $k = 1.5$), and $G(r,t)$ is the gas surface mass density $\sigma_{\rm gas}$ normalized to the present time value. The bulge forms by accreting gas from the halo at a rate $\dot{G}(t) \propto e^{-t/\tau}$, where τ is the collapse timescale. The metallicity $Z_{\rm acc}$ of the accreted gas is very low,

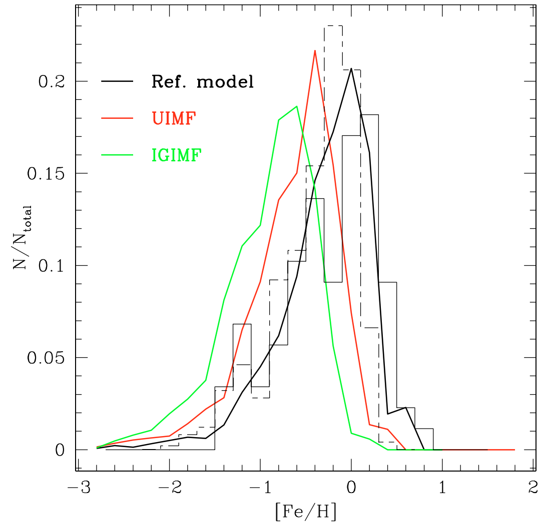

Fig. 1. [Fe/H] distributions calculated with the adoption of different IMFs. The solid line represents the fiducial model of Ballero et al. (2007). The data are compared with the observed distributions of Zoccali et al. (2003, dashed histogram) and Fulbright et al. (2006, solid histogram). This figure excludes the IGIMF as a plausible one for the Galactic bulge.

and it can be shown that the results do not change significantly if we consider $Z_{\rm acc} \simeq 0$.

The type Ia SN rate is computed according to Matteucci & Recchi (2001) following the single degenerate scenario of Nomoto et al. (1984). Stellar lifetimes (Kodama 1997) are taken into account in detail; nucleosynthesis prescriptions are taken from François et al. (2004), who constrained the stellar yields in order to reproduce the chemical properties of the solar neighbourhood via the two-infall model of Chiappini et al. (2003). The gas is supposed to be well-mixed and homogeneous at any time. The binding energy of the Galactic bulge (contributed by the bulge itself and the dark matter halo), as well as the thermal energy injected by SNe, is calculated as in Matteucci (1994); when the thermal energy equals the binding energy, the star formation is highly suppressed, even though the gas remains bound to the bulge itself after this occurs. This event does not have a great impact on the predicted MD, since in any case it occurs when most of the gas has already been processed into stars. However, it helps avoid overestimating the high-metallicity tail of the MD. Finally, the adopted IMF has the general shape of a multi-part power law:

$$\phi(M) \propto M^{-(1+x_i)} \tag{5}$$

where the subscript refers to different mass ranges.

The reference model of Ballero et al. (2007), which best fits the MD and the [α/Fe] vs. [Fe/H] ratios in the Bulge, has $\nu = 20$ Gyr^{-1}, $\tau = 0.1$ Gyr, and a two-slope IMF, namely $x_1 = 0.33$ for $0.08 \le M/M_\odot \le 1$ (in agreement with the photometric measurements of Zoccali et al. 2000) and $x_2 = 0.95$ for $1 \le M/M_\odot \le 80$.

3. Model results

In Ballero et al. (2007) we showed that an IMF with the Salpeter (1955) index ($x = 1.35$) for $1 \le M/M_\odot \le 80$ or with the Scalo (1986) index ($x = 1.7$) for $2 \le M/M_\odot \le 80$ could not fit the observed MDs in any way, causing the resulting distribution to be

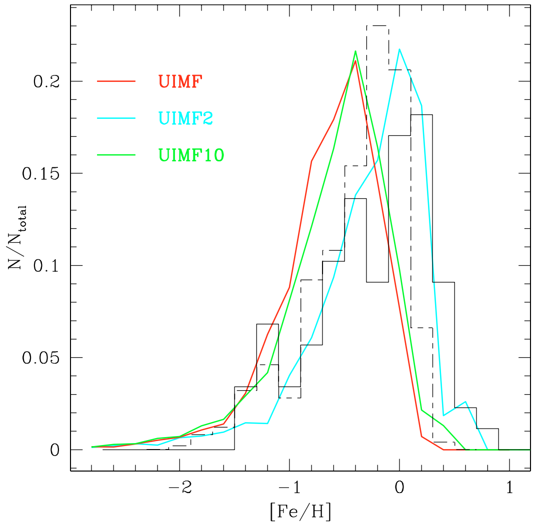

Fig. 2. [Fe/H] distributions obtained with the UIMF and the adoption of different yields for massive stars (see text for details), compared to the same observed distributions of the previous figure. A huge variation in the Fe yields above 80 $M_{\odot}$ leads to a negligible shift in the MD.

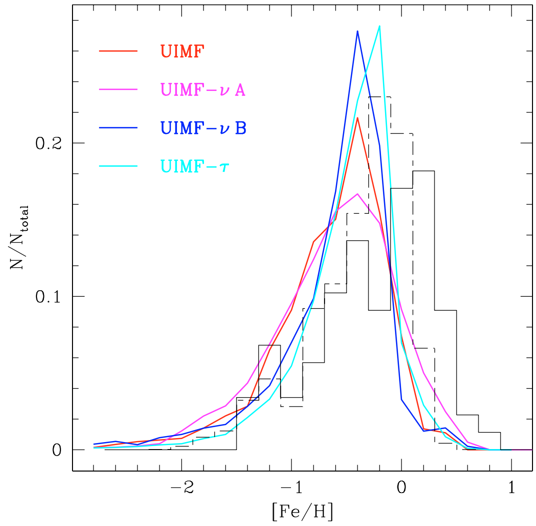

Fig. 3. Comparison of the observed MDs with those calculated with the UIMF and with models that adopt different values for the star-formation efficiency (UIMF-νA and B) and the gas infall timescale (UIMF-τ). Namely, higher values were chosen for τ and both higher and lower values for ν.

shifted towards low metallicities. Now we test whether an extension of these IMFs to a wider range of masses can provide an Fe enrichment sufficient to shift the calculated MD to the suitable position.

Figure 1 compares the MD obtained with the reference model and with the adoption of the UIMF and IGIMF, as described by Eqs. (3) and (4), and with all the other parameters kept constant with respect to the reference model. The yields of François et al. (2004) have been extrapolated above 80 $M_{\odot}$ by freezing the yields. It is quite evident that the UIMF reproduces neither of the observed MDs, being shifted to metallicities that are too low. Even worse results are obtained with the IGIMF, which has $\langle$[Fe/H]$\rangle \simeq -0.9$, i.e. $\simeq$0.5–0.7 dex lower than the observed ones.

We then tried to force the UIMF by changing the yields above 80 $M_{\odot}$, which have not been constrained so far. We found out (see Fig. 2) that, even if we adopt stellar yields as large as ten times the extrapolated ones (Model UIMF10), which is rather unrealistic, the predicted MD is only negligibly affected. Only if we double all the Fe yields from massive stars ($M > 10\ M_{\odot}$, Model UIMF2) does the calculated MD become consistent with the observations, but this would require also doubling the yields of other elements in order to preserve the agreement with e.g. the [α/Fe] vs. [Fe/H] plots (see Ballero et al. 2007), and this is theoretically implausible. Also, the adoption of these Fe yields for the solar neighbourhood would destroy the agreement of the two-infall model with the observed solar vicinity MD (e.g. Chiappini et al. 2003; Hou et al. 2000).

The main contributors to the Fe enrichment in the bulge are type II SNe, which have massive progenitors, since the timescales of enrichment are so short. As a consequence of that, Ballero et al. (2007) predict overabundance of α-elements relative to Fe for a wide range of [Fe/H]. It should be possible to obtain a larger enrichment from type Ia SNe, which originate from low- and intermediate-mass stars, by adjusting other parameters that have an effect on chemical evolution, such as the star-formation efficiency ν or the infall timescale τ. Therefore, we also investigated two more models: model UIMF-νA, where we set $\nu = 5$ Gyr^{-1}, and model UIMF-τ, where $\tau = 0.25$ Gyr. The star formation and gas consumption in this case should be slower, giving type Ia SNe more time to enrich the interstellar medium with Fe. However, it should be possible to enhance the Fe production by increasing the contribution of type II SNe with a faster enrichment, i.e. increasing the star-formation efficiency; therefore, we also considered model UIMF-νB, where $\nu = 50$ Gyr^{-1}.

We see in Fig. 3, however, that the attemp to shift the position of the MD by means of a change in these parameters is not successful, as already shown in Ballero et al. (2007) since they mainly act on the broadness of the distribution.

In the case of a very high star-formation efficiency, the effect can be explained if we consider that gas consumption occurs very rapidly and that stars are no longer formed after a very short time. On the other hand, since the enrichment is very fast, there is a lack of metal-poor stars. The opposite occurs in the case of a lower star-formation efficiency. In the case of different timescales of infall, the peak is actually shifted, as can be seen from the figure, but this shift it is not useful since the correct shape of the MD is not preserved. This is because, if the gas accretes more slowly, the number of stars produced at low metallicities is lower, so the calculated MD gets sharper.

Finally, Fig. 4 shows the MDs resulting from our reference model and the model with the UIMF compared to the MD of M 31 as measured by Sarajedini & Jablonka (2005) translating the observed color-magnitude diagram at ~1.6 kpc (G170 bulge field) from the center into a MD function by means of red giant branches with various metallicities. This MD, though still consistent with the ones of the Galactic bulge and therefore indicating a similar enrichment history of the two bulges, is slightly more metal-poor on average and is compatible with both the reference model and the model with the UIMF; however, we also plotted the MD calculated with $x_2 = 1.1$, like in Matteucci & Brocato (1990, model MB90), which gives the best fit. In any case, we can safely conclude that an IMF with $x \sim 1$ is more suitable for galactic bulges than the UIMF.

Other possibilities that could affect the chemical evolution have not been investigated. The lower mass cutoff of the IMF

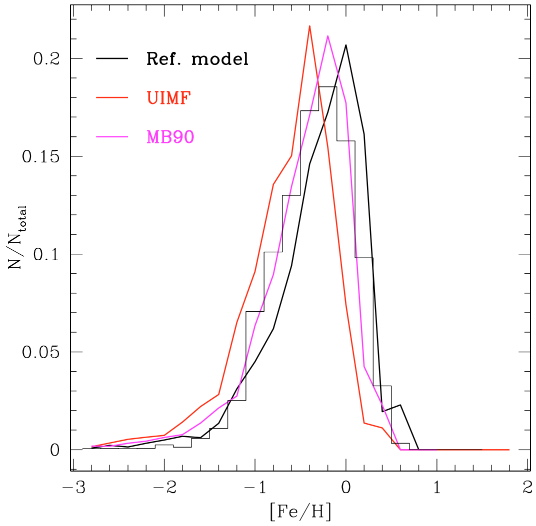

Fig. 4. [Fe/H] distribution function for the G170 field of the M 31 bulge field G170 (histogram) measured by Sarajedini & Jablonka (2005) compared with the results of our reference model and of the UIMF model. We also show the results of model MB90, which is intermediate between the two and provides the best fit to the observed MD.

is constrained by measurements in the bulge field and cluster giant stars (Kuijken & Rich 2002; Zoccali et al. 2003; Rich & Origlia 2005) that indicate that the bulk of them is roughly 10 Gyr old; therefore, the value of the lowest mass cutoff cannot be higher than $\sim 1\ M_\odot$. No difference is expected to arise if we increase $M_{\rm inf}$ to that value, since stars below $1\ M_\odot$ have not yet contributed to the bulge enrichment. Furthermore, it has already been shown by Ballero et al. (2006) that the adoption of a mass cutoff of $10\ M_\odot$ for the so-called Population III stars up to a metallicity suitable for the formation of these stars (i.e. $Z \simeq 10^{-8}$–10^{-4}; Bromm & Larson 2004) has almost no effect on the predicted MD, and even less of one in the bulge since such metallicities are reached in a very short time.

Lowering the SFR with the UIMF/IGIMF models in the bulge and accreting supersolar-metallicity populations, such as are evident in the ancient super-metal-rich open cluster NGC6791 (Salaris et al. 2004), or accreting supersolar gas may be able to match the observed MD in the bulges of the Milky Way and M 31. This scenario would avoid changing the IMF, but would also imply substantial accretion events in the build-up of bulges. Such accretion episodes are likely to modify the [α/Fe] vs. [Fe/H] plots at variance with observations. Due to the stochastic nature of mergers, each of them introduces a wide spread in the plots, which is not observed. Continuous outflows have the effect of lowering the effective yields (see Tosi et al. 1998) and thus cannot be invoked to reproduce the observed MD with the adoption of the UIMF.

4. Conclusions

We have tested the possibility of the UIMF of Kroupa (2001) or the "maximal" IGIMF of Weidner & Kroupa (2005) holding in the bulge of our galaxy and of M 31. To this purpose, we included those IMFs in the chemical evolution model of Ballero et al. (2007), which reproduces the properties of the Galactic bulge well. The upper mass limit was extended to $150\ M_\odot$ in agreement with late findings (Weidner & Kroupa 2004; Oey & Clarke 2005; Figer 2005; Koen 2006), and the stellar yields of François et al. (2004) were extrapolated up to that mass. An attempt to constrain the yields above $80\ M_\odot$ by assuming a priori the validity of the UIMF was also made, and other parameters such as the star-formation efficiency or infall timescale were varied in order to achieve a better fit.

Table 1. Statistical properties of the measured (upper part) and calculated (lower part) metallicity distributions of galactic bulges.

Observed distribution	M	μ	σ
Zoccali et al. (2003, MW)	−0.2	−0.397	0.444
Fulbright et al. (2006, MW)	+0.2	−0.248	0.523
Sarajedini & Jablonka (2005, M 31)	−0.2	−0.369	0.438
Models			
Ref. Model	+0.0	−0.297	0.502
UIMF	−0.4	−0.632	0.501
IGIMF	−0.6	−0.896	0.494
UIMF2	−0.4	−0.580	0.493
UIMF10	+0.0	−0.272	0.514
MB90	−0.2	−0.447	0.493
UIMF-νA	−0.4	−0.481	0.587
UIMF-νB	−0.4	−0.599	0.503
UIMF-τ	−0.2	−0.550	0.417

Table 1 summarizes the statistical properties of the observed and calculated distributions. The first column shows the reference or the model name; the second column reports the position of the peak on the [Fe/H] axis, i.e. the mode M; and in the third and fourth columns the average μ and the standard deviation σ of the considered distribution are shown, respectively. Together with the reference, it is indicated whether it applies to the Milky Way (MW) or M 31 bulge. It was found that it is not possible to satisfactorily reproduce the observed MDs of the Galactic bulge and of M 31 with the UIMF, which has a Salpeter (1955) index above $0.5\ M_\odot$, because the predicted MD is too metal-poor. The adoption of the IGIMF, which has a Scalo (1986) index above $1\ M_\odot$, worsens the agreement further. This highlights the fact that the main Fe contributors in galactic bulges are type II SNe, since the timescales of enrichment are so short. Changing the nucleosynthesis prescriptions does not have remarkable effects, unless very unrealistic assumptions about the stellar yields of all massive stars are made. Even dramatic changes of yields above $80\ M_\odot$ do not practically affect the calculated distribution. We thus do not exclude the possibility of a higher mass-cutoff, but show that it is impossible to put constraints on it based on chemical abundances, since the weight in the IMF of stars in the mass range $80 < M/M_\odot < 150$ is negligible.

Changes in ν and τ do not lead to any improvement because they mainly have an effect on the breadth of the distribution and not on the position, which is governed by the adopted IMF. This clearly indicates that, if the bulges of the Galaxy and M 31 formed inside-out through the accretion of very metal-poor gas, a variation in the stellar IMF is necessary among different environments and that an IMF index around $x \sim 1$, flatter than that of the UIMF, is preferable for galactic bulges. Theoretically speaking, it can be explained if we note that the star formation in bulges proceeds like in a burst (see Elmegreen 1999); there are suggestions in the literature (e.g. Baugh et al. 2005; Nagashima et al. 2005; Okamoto et al. 2005) about a top-heavy IMF in starbursts. Figer (2005) also finds a flat IMF in the Arches cluster near the Galactic center (however, see also Kim et al. 2006).

Acknowledgements. S.K.B. wishes to thank Ata Sarajedini for providing material in a very timely manner.

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