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The Metallicity Distribution of the Bulge of M31

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Abstract. We present the first metallicity distribution (MDF) derived for the bulge of M31. We have used HST WFPC2 V and I images to construct the color-magnitude diagram of a field located at 1.55 kpc from the center of M31. We have translated the RGB star colors into abundances. We describe the M31 bulge MDF properties, compare them to those of the M31 halo. We discuss the analogy with our Galaxy and the implications for the formation of spiral galaxies.

Keywords. Galaxies: abundances, galaxies: bulges, galaxies: stellar content

1. Introduction

It seems far away the time when we could consider galaxy halos as smooth homogeneous spheroidal galactic components. The closer we look, the deeper we examine, the more stellar overdensities, patchy structures, tidal tails joining large galaxies and dwarf companions in the process of disruption are excavated. This is certainly the case for our Galaxy and M31 (Newberg *et al.*, 2002; Yanny *et al.*, 2003; Martin *et al.*, 2004; Ferguson *et al.*, 2002,2005; Brown *et al.*, 2003). All these observations, of recent past or contemporary interactions have been interpreted as direct evidences for a hierarchical formation of galaxies. Though, we could cautiously try to evaluate two questions: (i) in which proportion, the tidal streams, substructures, etc .. are indicative of the full processes involved in galaxy formation. (ii) How do the central regions of the galaxies reflect the properties of the halos?

The metallicity distributions (MDFs) derived from individual star analysis offer an excellent diagnostic of the star formation histories. Not only M31 and our Galaxy are excellent laboratories to evaluate the above (i) and (ii) points, they are also the only ones at the moment: we can resolve individual stars in any part of the two galaxies. The *halo* Milky Way (Ryan & Norris, 1991) and M31 (Durrell et al., 2001) MDFs differ by nearly all aspects: by their range of metallicities, the M31 halo MDF is narrower by at least 0.5 dex, by their peak metallicities, the M31 halo is more metal rich by 1 dex.

In order to derive the metalliciy distribution of the *bulge* of M31, we took advantage of a field at 1.55 kpc from the M31 nucleus, imaged with WFPC2 on board the Hubble Space telescope in V and I. This field is centered on the M31 bulge globular cluster, G170, which had caught our attention in its time (Jablonka *et al.*, 2000). Around it, we have access to the field stellar population. The planetary camera 36 × 36 arcsec^2 field of view encompasses ∼ 55 000 RGB stars. In this context, it is absolutely impossible to derive a metallicity distribution from spectroscopy of individual stars, it has to be done

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with the help of isochrones or cluster fiducials. For a proper comparison, combining the same type of observations and analysis, with the bulge of the Milky Way, we have used the recent work of the Zoccali *et al.* (2003).

2. The analysis

The analysis of the luminosity function of the G170 field reveals that the photometry is complete to below the red clump at V ~ 26 mag, I ~ 25 mag. This is corroborated by the artificial star experiments performed by Jablonka *et al.* (1999). They found a 91% completeness rate for RGB stars as faint as I = 25.

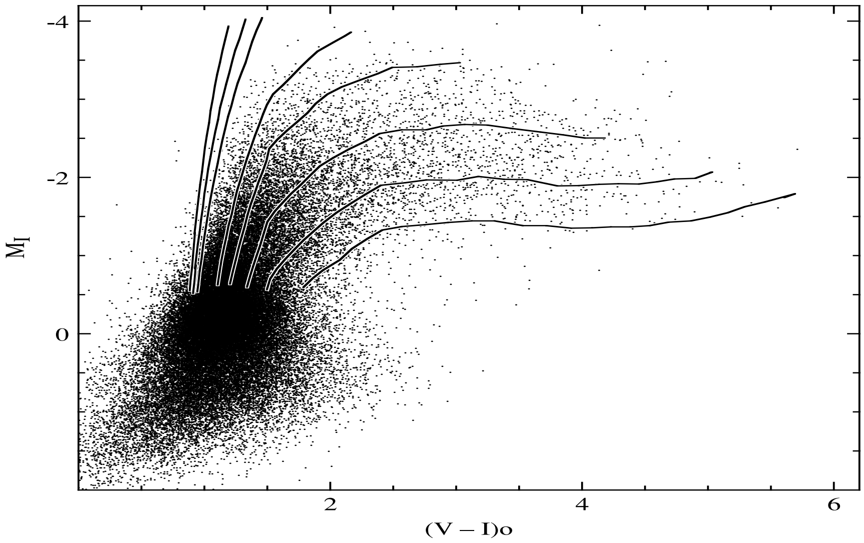

Figure 1.

Figure 1 shows the G170 field data adjusted for the distance and reddening of M31, $(m - M)_0 = 24.43$ (Freedman & Madore 1990) and $E(B - V) = 0.062$ (Schlegel, Finkbeiner, & Davis 1998), respectively. The solid lines are the RGB sequences from the theoretical isochrones of Girardi *et al.* (2002) for an age of 12.6 Gyr and metallicities of Z=0.0001, 0.0004, 0.001, 0.004, 0.008, 0.019, 0.04, and 0.07 for a scaled-solar abundance mixture. Since no theoretical isochrones are presently available with differential elemental abundances, we consider this prior as the safest. We have combined the models of Girardi *et al.* (2002) for metallicities up to Z=0.019 with those of Salasnich *et al.* (2000) for higher metallicities.

Quoting a number of previous results, Rich (2004) summarizes the evidences that, like the MW, the M31 bulge is likely to be old (i.e. $\geqslant$10 Gyr). Under this assumption, we adopted a mean age of 12.6 Gyr. The RGB colors being rather insensitive to age for old stellar populations, its precise value is not important. Tests we have performed show that an age change of ±0.1 in the logarithm from our nominal 10.1 value (10 Gyr $\leqslant$ Age $\leqslant$ 15.8 Gyr) results in a change of less than ±0.05 dex in the peak metal abundance of the population.

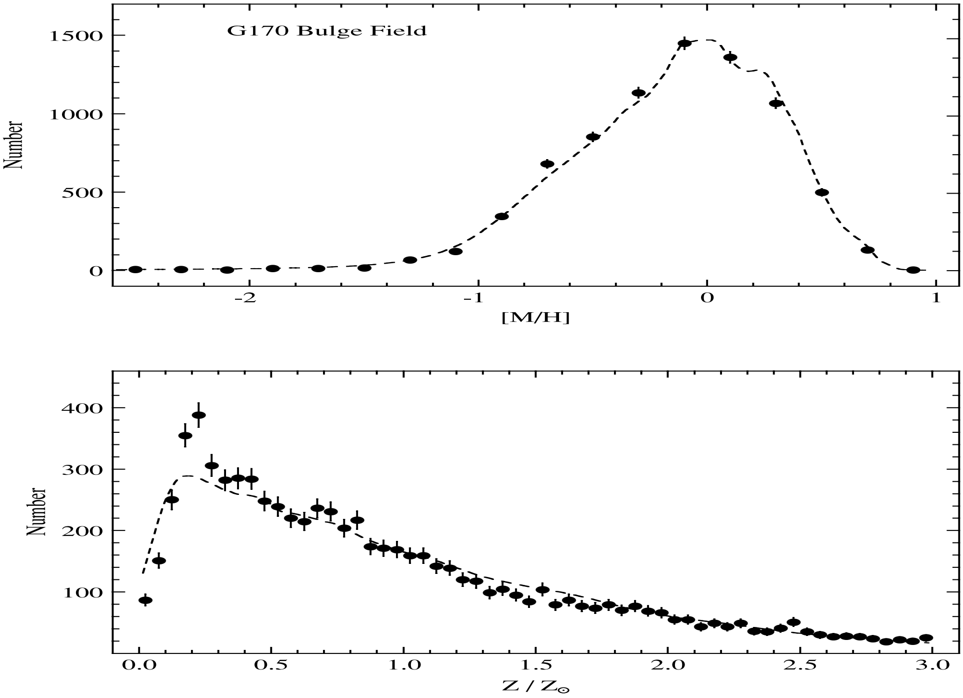

Figure 2.

Figure 2 displays the binned (filled circles) and generalized (dashed line) histograms representing the metallicity distribution functions (MDFs) of the M31 bulge region near the cluster G170. We use a logarithmic (top panel) and linear (bottom panel) scale. The logarithmic M31 bulge MDF peaks at $[M/H]{\sim}0.0$ with a steeper dropoff to the metal-rich end as compared with the metal-poor region. The interval of metallicity is $\sim$ 2 dex wide. The [M/H] range between -2.5 and -1.5, which is well populated in M31 halo, is absent in the bulge. The MDFs shown in Fig. 2 are largely insensitive to the age of the isochrones as long as an age older than ~10 Gyr is adopted. In addition, we explored the effects of errors in our reddening and distance modulus values on the shape of the resultant MDFs. Errors of ±0.02 in $E(V-I)$ and ±0.1 mag in $(m-M)_I$ produce MDFs that have the same peak abundance ($[M/H]{\sim}0$) and very similar metal-rich and metal-poor tails suggesting a negligible effect on our conclusions. Furthermore, MDFs were constructed using stars in two additional magnitude ranges ($-1.2 \geqslant M_I \geqslant -1.7$ and $-1.2 \geqslant M_I \geqslant -2.2$). Once again, no significant differences were seen in the properties of the distributions.

3. A simple model

In order to do the spadework on the interpretation of the MDF in terms of star formation history for the bulge of M31, we considered a few easy to handle analytical formulations.

First, we analyzed the M31 bulge MDF in the context of the simple model. This scenario assumes no infall nor outflow of gas and the instantaneous recycling approximation.

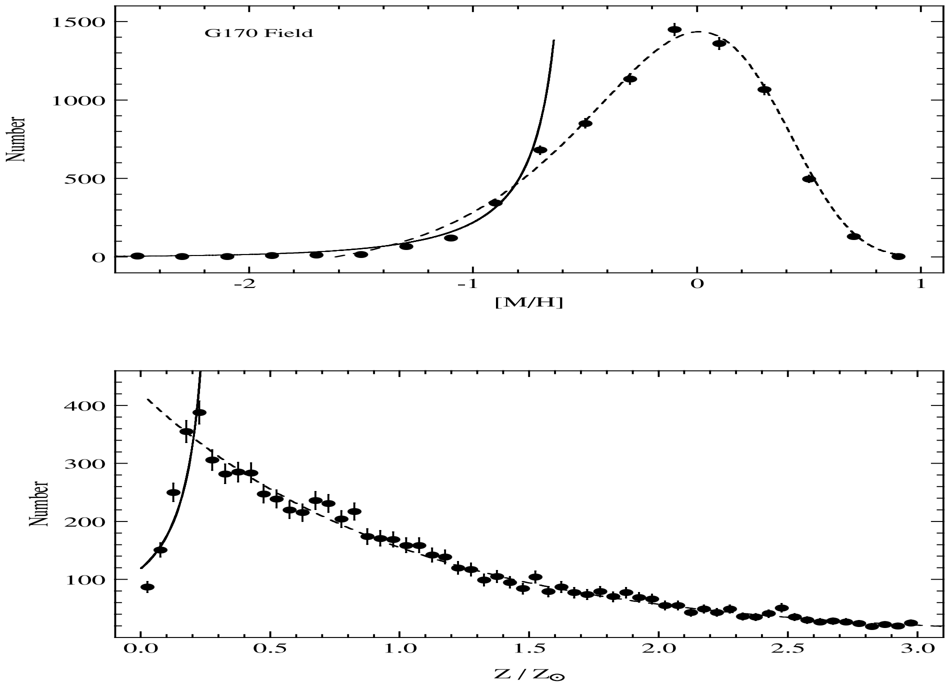

Figure 3.

We could indeed find a value of the yield for which this simple model would provide an excellent fit to the region around the peak of the MDF. However, below $[M/H]\sim -0.8$, the model consistently predicts more stars than are present in the observations. This feature is indicative of the classic G-dwarf problem for which a number of solutions have been proposed.

One immediate solution is that stars are formed from pre-enriched gas. In Figure 3, the dotted line represents the predicted MDF if an initial $[M/H]\sim -1.6$ is assumed. It does fit the logarithmic MDF in the upper panel, it does however a poor job at the low metallicity tail of the linear MDF in the lower panel.

Another solution to the G-dwarf problem is that gas could have flowed into the system while star formation was occurring. The simplest of these ‘infall’ or ‘accreting-box’ models assumes that the gas accretion rate is approximately the same as the star formation rate yielding a roughly constant gas mass. In this case, the metal abundance distribution takes on a hyperbolic form, and is represented by the solid line in Figure 3. It provides an excellent fit to the low-Z tail of the distribution, which ever representation is chosen. Figure 3 suggest that some sort of gas infall occurred early in the history of the M31 bulge, leading to an abundance of $[M/H]\sim -1.6$ from which subsequent generations of stars formed. We note that the “gas infall” scenario to explain the MDF of M31’s bulge fits nicely with the results of Durrell, Harris, & Pritchet (2001). They constructed an MDF for an M31 halo field at 20 kpc from the center. Based on this and the results of previous investigators, Durrell *et al.* (2001) suggested that gas may have ‘leaked’ out of the M31 halo and been ‘accreted’ into the bulge. This is precisely the solution we suggest in order to explain the G-dwarf problem in the M31 bulge MDF.

4. The comparison with our Galaxy

The most extended and complete luminosity function of the bulge of our Galaxy has been produced so far by Zoccali *et al.* (2003, herafter Z2003) who combined optical and near-infrared photometry for stars toward the Galactic bulge. Relying on a technique similar to our's, Z2003 converted their photometric colors to metallicities using fiducial globular cluster V–K RGBs covering the range $-1.9 \leqslant [M/H] \leqslant -0.1$. In order to be consistent with our M31 bulge MDF, we have rederived the Milky Way MDF using the Z2003 V–K photometry coupled with the scaled-solar Girardi *et al.* (2002) and Salasnich *et al.* (2000) model RGBs for the same metallicities as those shown in Fig. 1.

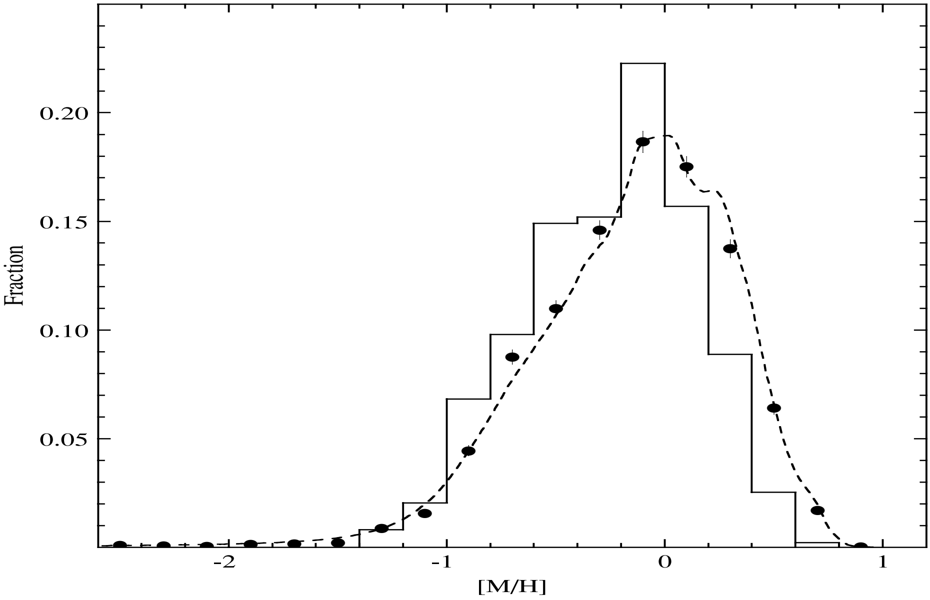

Figure 4.

Figure 4 compares the M31 (dashed line) and the MW (solid line) MDFs. Both bulge populations have a peak abundance close to the solar value, with the M31 peak being at most 0.1 dex more metal-rich. This small shift in metallicity between the two distributions could easely be attributed to the different Hubble types of the galaxies, M31 having an earlier one than our Galaxy, as bulges do show a metallicity-luminosity relation (Jablonka, Martin & Arimoto, 1996). Apart from that, the two MDFs are strickingly similar, if one considers the clear differences of their halos. The bulge of M31 obviously ignores the fact that the M31 halo is relatively "metal-rich", this is not translated at all in its MDF. Besides, the amount of the necessary pre-enrichement is small, compatible with a low primordial yield. We have checked that the "gas infall" scenario would match the low metallicity tail of the MW MDF, and that the pre enriched closed box model would satisfactorily fit the rest of the distribution. The statistics is poorer for the bulge our Galaxy (less than 500 stars) than for M31 (nearly 8000 stars), but all the rest being equal, it seems indeed that a common framework of formation for the two bulges can be invoked, differing only by a scaling factor.

5. Conclusions

The differences between the M31 and MW halo stellar populations are quite evident. The peak metallicity of the Galactic halo is located at [M/H] ~ -1.5 (Ryan & Norris 1991) while it is at [M/H] ~ -0.6 for the 20 kpc M31 field of Durrell *et al.* (2001). This suggests a fundamental difference in the values of the yields that shaped the halo MDFs, different star formation histories. The overall shapes of the two halo MDFs are also different. These observational facts are expected if the bulk of the halos is built up through the accretion of disrupted satellite galaxies, since variety should indeed be a product of this random process. The peak metallicity of the Galactic and M31 bulges are similar within 0.1 dex, the shape of the MDFs are alike. In light of these points, we suggest that the formation of the bulges of the MW and M31 is partly disconnected from the formation of the halos. While the early stages of formation of halos and bulges are linked, as pre-enrichement is required for the bulges and seem naturally provided by the initial star formation in the halos, the subsequent developpements of the latter (possibly mergers) does not seem to influence the bulge evolution. Otherwise, it is difficult to understand how the M31 and MW bulges could resemble each other so much, while embedded in very different halos.

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