FORMATION AND EVOLUTION OF STARS IN GALACTIC BULGES

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ABSTRACT. A fair fraction of stars in the Galactic Bulge (a possibly in bulges in general) appears to be more metal rich than the sun. Some of the current limitations in quantitatively modelling such super metal rich (SMR) stars are briefly recalled, including the question of the helium enrichment, of the metallicity dependence of mass loss, and of the metal opacity. Recent color-magnitude diagrams for stars in the Galactic Bulge are show that the bulk of Bulge stars must be very old, although current data do not allow to determine the age with sufficient accuracy to establish the relative age of the Halo and of the Bulge. The question of the nature of the most luminous (AGB) stars in bulges and in M32 is then addressed in some detail, discussing a series of methodological aspects which would need careful consideration before using bright AGB stars as age indicators. It is concluded that – for the time being – none of the claims for the presence of an intermediate age component in the Galactic Bulge, in M32, and in the bulge of M31 is completely exempt from ambiguities, and ways for elimitating such ambiguities are suggested. Finally, from the evidence that bulges are dominated by a very old stellar population it is concluded that star formation in bulges probably started and was essentially completed *before* the completion of star formation in the halo: bulges are likely to *on average* older than halos.

1. Introduction

There is still no general consensus on how the Galaxy formed, and how long it took to built up its various components. We all agree that the Halo is old, and the disk contains young stars. But what about the Bulge? In which genetic relation is it with the rest of the Galaxy? Is it younger or older than the Halo? We cannot really say we understand the Galaxy until we find the answers to these questions, since the Bulge is really the *core* of the Galaxy, and then its formation is the core of the Galaxy formation problem. Moreover, the Bulge of our own Galaxy together with that of our Local Group companion M31 are reasonable prototypical of bulges in general (Frogel 1990), and the bulges of spirals are generally regarded as stellar systems sharing a number of properties with early-type galaxies. It follows that answering the questions above will help a great deal in understanding galaxy formation in general. The study of stellar populations in resolved bulges can therefore help making progress in one of the central issues of modern astrophysics and cosmology. In this brief review I will address just three points: (1) the quest for the evolution of super metal rich (SMR) stars in the Bulge, (2) the color-magnitude diagrams of field and globular cluster stars in the Bulge, and (3) the interpretation of the bright end of the luminosity funcion of the Gralactic Bulge, of M32, and of the bulge of M31. From these considerations about the stellar content of bulges I will finally draw some speculative inferences about their formation.

H. Dejonghe and H. J. Habing (eds.), Galactic Bulges, 151–168.

2. Problems with the Evolution of SMR Stars

It is now well established that the Galactic Bulge contains stars exceeding the solar metallicity (Whitford & Rich 1983; Rich 1988). These are very rare objects in the solar neighborhood, and their evolution still presents several aspects which are not (quantitatively) fully dominated.

2.1 THE COMPOSITION OF SMR STARS

A first problem that we encounter when dealing with SMR stars concerns the actual chemical composition to adopt for them, i.e. the detailed proportions of the various elements for given overall metal abundance Z. For example, to construct models we need to specify the relative oxygen abundance [O/Fe], and the helium abundance Y. Here I concentrate on the helium problem.

There is little doubt that along with metals mass losing stars and supernovae contribute also some helium to the enrichment of the interstellar medium (Peimbert 1983; Pagel 1989). However, the actual size of this enrichment remains rather uncertain, i.e. value of the helium enrichment parameter $\Delta Y/\Delta Z$ is still poorly constrained by either theory or observations, with most popular values ranging from 1 to 3. The actual helium abundance for given metal abundance Z is given by the standard relation:

$$Y(Z) = Y_{\rm p} + \frac{\Delta Y}{\Delta Z} Z, \qquad (1)$$

where $Y_{\rm p}$ is the primordial helium abundance, for which I assume $Y_{\rm p} = 0.24$. For illustration purposes I will explore values of $\Delta Y/\Delta Z$ between 0 and 3, although larger values have been occasionally proposed. It is important to realize that SMR stars may be rather unusual objects indeed. For example, assuming $\Delta Y/\Delta Z = 2$ (a conservative value!) and solar proportions ([M/Fe]=0) hypothetical SMR stars with [Fe/H]=1 (such as the most extreme SMR stars in the Bulge, according to Rich 1988) would consist of

20% METALS
65% HELIUM
15% HYDROGEN

with hydrogen having been reduced to a minority constituent. Notice that the increase in metals and helium tend to have opposite, partially compensating effects on several evolutionary properties. More metals means more opacity, and fainter ZAMS stars. More helium means larger mean molecular weight, and therefore more compact and brighter ZAMS stars for given mass. It is easy to realize that the choice of $\Delta Y/\Delta Z$ will decide which of the two effects will dominate over the other, and therefore will determine for example whether the stellar lifetime (for given mass) is an increasing or a decreasing function of Z, or similarly for the mass of evolving stars (for given age) as a function of Z.

The case is illustrated in Fig. 1, which shows the (initial) mass of evolving stars (i.e., the mass $M_{\rm RG}$ of stars having just reached the base of the red giant branch, RGB) as a function of metallicity Z, for a 15 Gyr old stellar population (adapted from Renzini and Greggio 1990). We can easily notice that – not surprisingly – for $Z \lesssim Z_\odot$ the effect of the helium enrichment is virtually negligible, and the

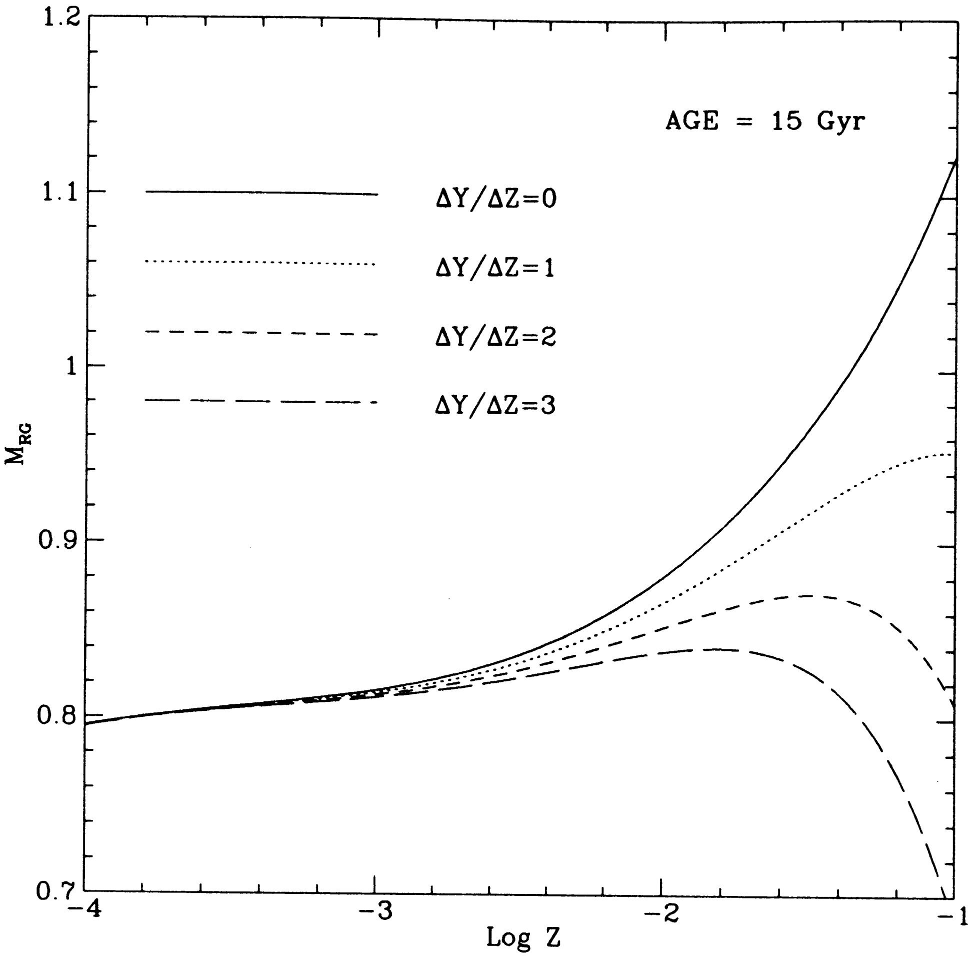

Fig. 1.– The mass of 15 Gyr old stars that evolve off the main sequence (or the mass at the base of the RGB) as a function of the metal abundance Z, and for various values of the helium enrichment parameter $\Delta Y/\Delta Z$.

various options run close to each other. But as Z grows beyond solar $M_{\rm RG}$ becomes increasingly sensitive to the actual value of the $\Delta Y/\Delta Z$ parameter, and for $Z = 5Z_\odot$ the various relations dramatically diverge.

In turn, the smaller $M_{\rm RG}(Z)$ the bluer (hotter) the subsequent horizontal branch (HB) phase, while the larger $M_{\rm RG}(Z)$, the more fuel will be available during the asymptotic giant branch (AGB) phase, and thus the brighter the AGB temination. We very clearly see how the choice of the parameter $\Delta Y/\Delta Z$ is going to dramatically affect at once the UV output and the luminosity of the brightest and coolest stars in old stellar populations. The direct determination of $\Delta Y/\Delta Z$ in a SMR environment would then be of great value for our understanding of SM-R populations, such as those dominating in giant elliptical galaxies. Perhaps the observation of planetary nebulae in Baade's Window may offer a viable opportunity.

2.2. MASS LOSS vs METALLICITY

Unfortunately $\Delta Y/\Delta Z$ is not the only ill known parameter able to affect the evolution of SMR stars. Red giants lose mass via a low velocity stellar wind, and again how much mass is lost during the RGB phase determines first the effective temperature at which stars later spend their HB phase, and then the maximum luminosity that they reach on the AGB. Empirical mass loss rates for RGB stars are rather uncertain, and we don't have any empirical indication whatsoever as to whether the mass loss rate has a direct dependence on metallicity. I will now illustrate how sensitive is the post-RGB evolution to small variations in the adopted mass loss rates, especially in the case of SMR stars. Following Greggio and Renzini (1990), to describe mass loss along the RGB I adopt a slightly modified version of the standard parameterization (Fusi Pecci and Renzini 1976) of the empirical rate (Reimers 1975):

$$\dot{M} = -4 \times 10^{-13} \eta \left(1 + \frac{Z}{Z_{\rm crit}}\right) \frac{L}{gR} \qquad (M_\odot\,{\rm yr}^{-1}), \tag{2}$$

where the factor $(1 + Z/Z_{\rm crit})$ is introduced so as to mimic a direct metallicity dependence, with $|\dot{M}|$ increasing with Z by an amount which – by construction – reaches a factor of 2 at $Z = Z_{\rm crit}$. I do not pretend to have a specific physical or astrophysical justification for this choice*, but just notice that for $Z \ll Z_{\rm crit}$ the standard rate is recovered, and as we are interested in the SMR range fairly high values of $Z_{\rm crit}$ will be explored. With such assumption ($Z_{\rm crit} \gtrsim Z_\odot$) there is no influence whatsoever on the HB morphology at the metallicities spanned by galactic globulars. Even for $Z \gtrsim Z_\odot$ the implied increase of $\dot{M}$ over standard values is very modest, i.e., less than a factor of 2, well within the present observational uncertainties. Yet, such a small increase can dramatically affect the HB and post-HB evolution of low mass stars, as we are going to see. The case is conveniently illustrated in Fig. 2, where – for an age of 15 Gyr – the mass of stars on the HB ($M_{\rm HB} = M_{\rm RG}$ minus the mass lost along the RGB) is displayed for several combinations of $\Delta Y/\Delta Z$ and $Z_{\rm crit}$. The parameter η has been fixed to 0.35 by demanding to $Z = 0.001$ HB models to lie within the RR Lyrae strip, so as to mimic the even HB morphology of intermediate metallicity globular clusters.

From Fig. 2 we can fully appreciate how a modest increase of mass loss with metallicity – such as that described by Eq. (2) – can lead to diverging predictions for the post-RGB evolutionary phases of SMR stars. Suffice to mention that at high metallicity a mass difference of $\lesssim 0.03 M_\odot$ is sufficient to move a star from the red to the far blue side of the HB. As for Fig. 1, we see again that assumptions that have no effect at low to intermediate metallicities, can have dramatic consequences in the SMR regime, with variations as small as 10-20% in the adopted mass loss rate being able to turn a red HB into a very blue one. Seemingly, a difference of a few

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* A trend of this kind could in principle be produced by e.g. a mass loss enhancement due to dust grain formation.

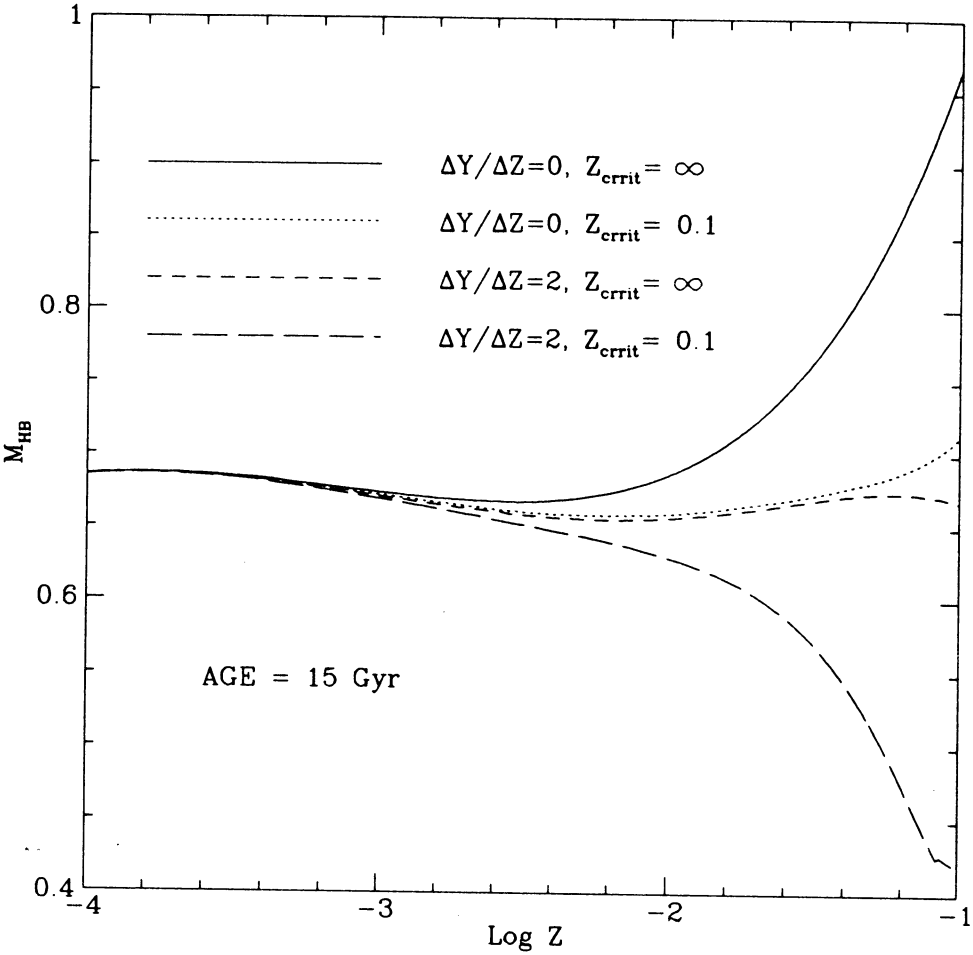

Fig. 2.– The mass of HB stars as a function of metallicity, for a population 15 Gyr old and for four different combinations of the $\Delta Y/\Delta Z$ *and* $Z_{\rm crit}$ *parameters. Clearly,* $Z_{\rm crit} = \infty$ *corresponds to a mass loss rate with no direct dependence on metallicity. The mass loss rate parameter* $\eta = 0.35$ *has been adopted.*

$0.01 M_\odot$ in the core mass at the end of the AGB would correspond to a difference up to one magnitude in the maximum AGB luminosity.

We don't know what particular combination of the $\Delta Y/\Delta Z$ and $Z_{\rm crit}$ parameters nature has chosen for SMR stars. Thus we are stuck when we try to predict the color of the HB and the maximum AGB luminosity of such stars, but the theory of stellar evolution cannot be blamed for this unconfortable situation. The two parameters in question are in fact *external* to the theory, and should be independently determined. Once the parameters are specified, the stellar evolution theory has no difficulty in accurately predicting the evolution of SMR stars during the RGB phase and beyond, with just one reservation that I discuss in the next section.

2.3. THE METAL OPACITY

At very low metallicities (say $Z \simeq 10^{-4}$) the contribution of metals to the opacity is small compared to that of electron scattering over most of stellar interior, including the important temperature range between ~few 10^5 to ~few 10^6 K, where metal opacity comes from the last ionization stages of abundant elements such as O, Ne, Mg, Si, and Fe. However, as metallicity increases so does the metal contribution to opacity while the electron scattering contribution clearly stays the same. In the SMR regime one then encounters the opposite situation, with the electron scattering opacity becoming a (small) fraction of the metal opacity. It has been recognized for years (cf. Iben & Renzini 1984) that the metal opacity in this particular temperature range represents perhaps the most uncertain ingredient in the construction of stellar models (apart from convection), an obvious consequence of the huge number of ionization stages, energy levels and electronic transitions which must be taken into account, and of the complexities introduced by the perturbation of these levels due to the high particle density. It is now well known that the so called *Livermore* opacities recently computed by Iglesias & Rogers (1991) can be a few times larger than the old *Los Alamos* opacities. Of course, the difference comes from the contribution of the metal in the critical temperature range. Fig.s 1 and 2 have been constructed using stellar models buit up with the old opacities, and no doubt the new opacities will have a strong impact on the run of quantities such as $M_{\rm RG}$ and $M_{\rm HB}$ with metallicity. For the reasons above, such an impact will be small at low metallicity, and may be very large in the SMR regime. Again, opacity adds further uncertainty especially where helium enrichment and mass loss already make very difficult to risk detailed predictions. To my knowledge Livermore opacities are not yet available for SMR compositions, and we should be aware that existing SMR isochrones may give the wrong age, as they all are based on the old opacities.

For the three reasons detailed in this section it appears that we are in serious trouble in trying to predict the HB morphology and AGB termination of SMR stars in galactic bulges. Given this situation an empirical approach appears to be wise, and I will recall some of the main results in the next section.

3. Color-Magnitude Diagrams of the Galactic Bulge

Terndrup (1988) was first in obtaining fairly deep and extensive CCD photometry of stars in Baade's Window (BW). From the main sequence turnoff – and isochrones based on the old opacities – Terndrup concluded that the mean stellar age is 11-14 Gyr, while the fraction of stars younger than 5 Gyr must be negligible, as anticipated by Rich (1985). Yet, photometric errors do not allow to delineate the turnoff region very accurately, and Terndrup result can be taken as evidence that the dominant population in the Bulge is very old, while open the question of the precise age is left open. Terndrup's CMD also shows that the bulk of HB stars are red, which would exclude those combination of the $\Delta Y/\Delta Z$ and $Z_{\rm crit}$ parameters which give a blue HB (supposing we know the age) for the metallicity of the surveyed stars (1 to 2 times solar, according to Terndrup).

One limitation of studying field stars in BW is that there exist a range of metallicities, and it is difficult to establish whether the scatter in the CMD is entirely accounted by the scatter in metallicity, or if also a distribution of ages is

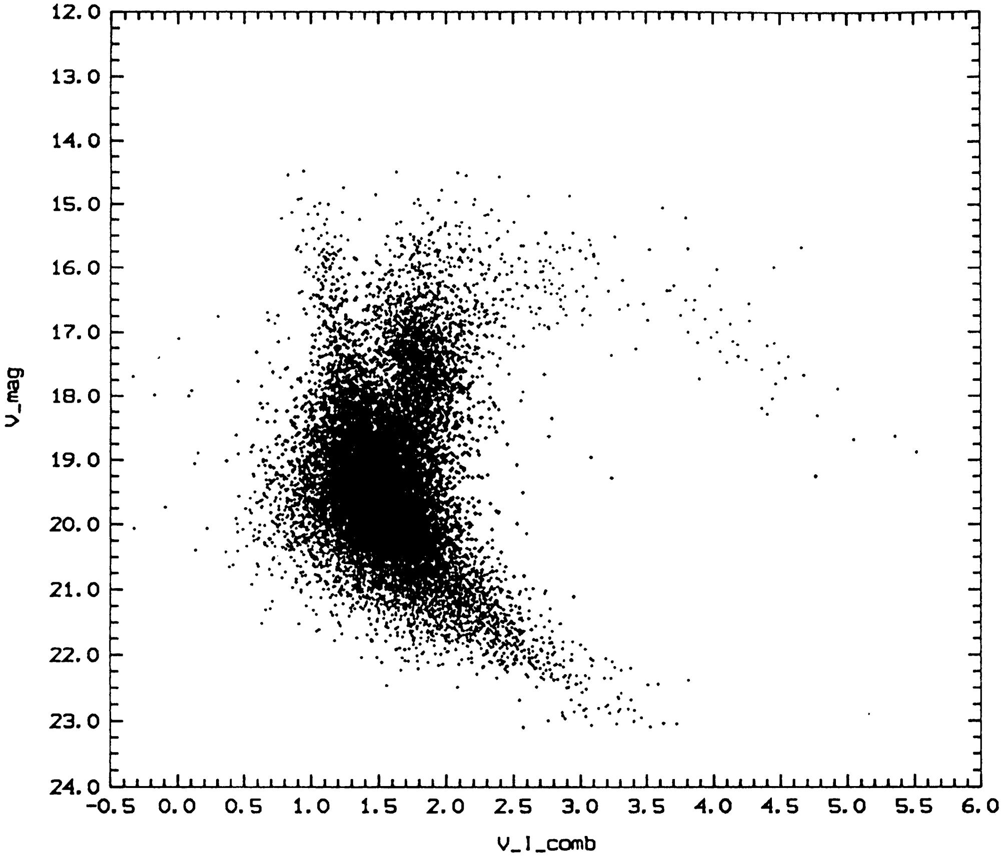

Fig. 3.- The $V-(V-I)$ CMD for stars in Baade's Window. Courtesy of Ortolani & Rich (1992).

necessary (even supposing to have taken photometric errors out). Being chemically homogeneous, the metal rich globular clusters of the Bulge offer an attractive perspective for an accurate dating of bulge stars, but unfortunately the clusters are projected against a very densely populated field, and to avoid field contamination one is forced to push the survey towards the cluster center, where crowding degrades the photometric accuracy. Ortolani *et al.* (1990, 1992a,b) have obtained CMD's of the metal rich clusters NGC6553, NGC6528, and Terzan 1. Undoubtely these are old clusters, but how old it is still difficult to say given the mentioned theoretical and observational uncertainties. All the three clusters have very red HB's, but what is most stryking in their CMD is the morphology of the red giant branches. For example, in the V vs $V-I$ plot the upper RGB and the AGB become fainter in V for increasing $V-I$, to the extent that the tip of the RGB becomes fainter (in V) than the HB itself. This behavior is due to the strong blanketing of the TiO molecules, and demonstrates that the upper RGB and AGB are both

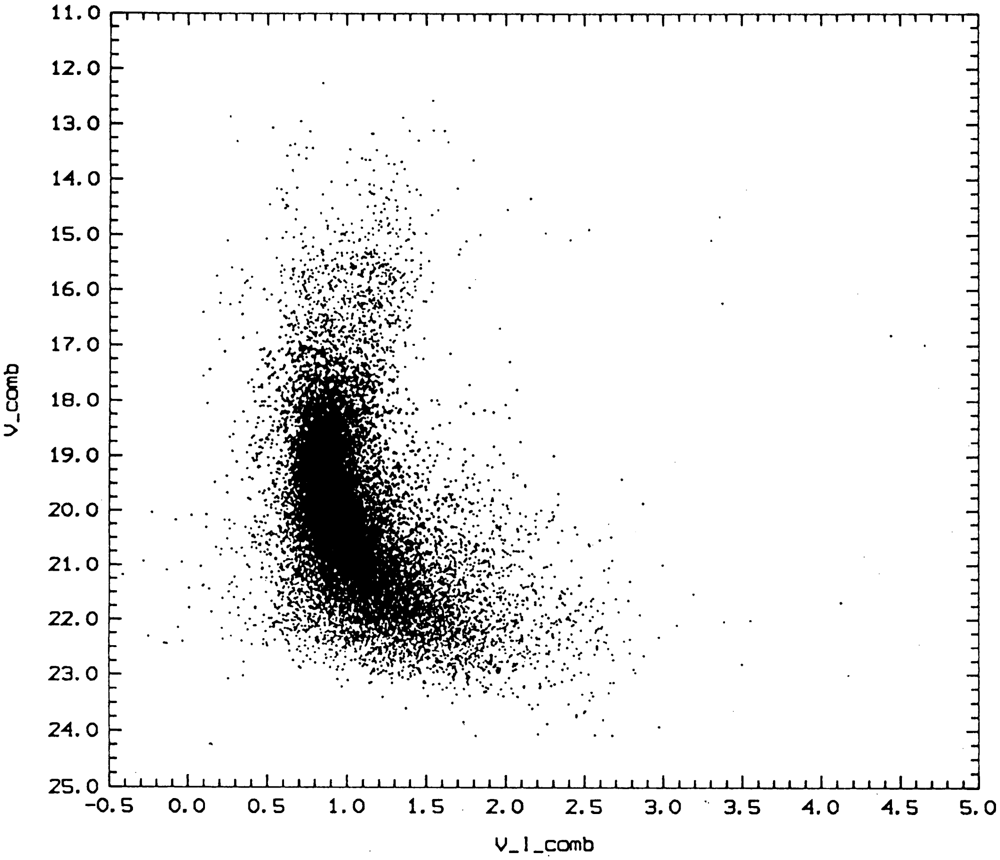

Fig. 4.- The $V - (V - I)$ CMD for stars in a Bulge field ~ 8° from the Galactic center. Courtesy of Ortolani & Rich (1992).

composed of M-type stars, contrary to the case of more metal poor clusters where both branches are made up of K-type giants. This is a crucial aspect, especially for population synthesis studies, as all evolutionary population synthesis models have so far assumed the RGB stars to be K giants.

Ortolani & Rich (1992) have recently obtained high resolution, deep NTT images of several Bulge fields at various galactocentric distances. Fig. 3 shows their $V - (V - I)$ CMD for a field in BW, $-4°$ from the Galactic center. The main sequence turnoff at $V - I \simeq 1.5$ is fainter than $V \simeq 20$, unfortunately too close to the frame limit to put stringent constraints on age. Very evident is the foreground contamination by disk main sequence stars, while very prominent are the red HB clump around $V \simeq 17$, and the peculiar RGB+AGB which extend to $V - I \simeq 5.5$ and $V \simeq 19$. Clearly, contrary to the case of galactic globular clusters (see Renzini & Fusi Pecci 1988), the upper RGB must contribute very little light to the integrated V-band luminosity of the Bulge. Fig. 4 shows a somewhat deeper

CMD that Ortolani and Rich have obtained for a less crowded field ~ 8° from the Galactic center. Crowding, reddening and absorption are significantly lower than in the BW field ($A_V \simeq 0.7$ mag against ~ 1.8 mag). The red HB clump can be recognized at $V \simeq 16$, while the turnoff is somewhat fainter than $V \simeq 19$. The HB to turnoff luminosity difference is therefore 3.0–3.5 magnitudes, consistent with the typical value of halo globular clusters, and therefore there is no *appreciable* difference in age (cf. Renzini 1991). I should caution, however, that a difference of a few 0.1 mag (corresponding to a few Gyr age difference) could hardly be noticed on the basis of these data. I conclude that judging from the existing CMD's the Bulge is definitely old, but "how old is old" cannot yet be said with sufficient accuracy to tell whether there is an appreciable age difference with respect to halo globulars. Unaberrated HST observations will certainly help.

4. The AGB Termination and the Age of Youngest Stars in Bulges

Given the difficulties encountered in accurately dating Bulge stars using the turnoff clock, the attempt to use other clocks is certainly a commendable effort. The luminosity of the AGB termination has been widely used for dating purposes in a variety of astrophysical objects, including Magellanic Cloud globular clusters, M32, the bulge of M31, and our own Galactic Bulge. In this latter case *bona fide* bright AGB stars are represented by long period variables (LPV) and OH/IR sources, objects discussed in greater detail by Whitelock and Habing at this meeting. In this section I will address a few questions concerning their use as age indicators.

4.1. THE LUMINOSITY OF SMR AGB STAR

In a previous review (Renzini & Greggio 1990) it was pointed out that the core mass-luminosity relation for TP-AGB stars still remains to be explored for SMR compositions, to the extent that the question " *Are bright AGB luminosities in bulges a result of young ages or of large Z + Y ?*" is still unsettled (Renzini 1992). According to Boothroyd & Sackmann (1988) the luminosity of AGB stars would scale as the cube of the mean molecular wieght, i.e.:

$$L(M_{\rm H}) = \mu^3 f(M_{\rm H}), \qquad (3)$$

where $M_{\rm H}$ is the core mass. On the basis of this relation we can estimate how brighter a SMR AGB star would be compared to stars of the same core mass and the composition of e.g. the cluster 47 Tuc. For the latter I adopt $(Y, Z) = (0.24, 0.004)$ and correspondingly $\mu = 0.59$. For illustration purposes I further adopt $\Delta Y/\Delta Z = 3$, which for $Z = 5Z_\odot = 0.1$ implies $Y = 0.54$ and $\mu = 0.85$. Therefore, for given core mass, such SMR thermally pulsing AGB stars would be $(0.85/0.54)^3 = 3$ times brighter than TP-AGB stars in 47 Tuc, which corresponds to 1.2 mag. Since the AGB in 47 Tuc and similar clusters extends to $M_{\rm bol} \simeq -4.5$ (Frogel & Elias 1988), Eq. (3) would easily predict an AGB extension up to $M_{\rm bol} \simeq -5.5$ for a SMR composition.

I should caution, however, that relation (3) comes from fitting a rather restricted number of models, and that the SMR regime was not explored by Boothroyd & Sackmann. My suspicion is also that the effect of metals and helium cannot be simply cumulated through the mean molecular weight. Indeed, the effect of the CNO abundance on the strength of hydrogen burning shell is not described by μ, and therefore the actual relation must be more complicated than Eq. (3). Such a relation can be established only after a more extensive esploration of the composition parameter space.

4.2. THE LUMINOSITY-TIME-NUMBER RELATION

Occasionally bright stars are found in old stellar populations, and we would like to know their significance for the age distribution of the constituent stars, and therefore for the formation process of galaxies. Crucial for understanding the nature of such bright stars is considering their frequency with respect to the bulk population in which they appear. In a coeval population the number of stars in a generic post-MS evolutionary stage is given by:

$$N_{\rm j} = B(t)L_{\rm T}t_{\rm j}, \tag{4}$$

where $L_{\rm T}$ is the total bolometric luminosity of the population and $t_{\rm j}$ is the duration of the generic phase "j" (Renzini & Buzzoni 1986). The ***specific evolutionary flux*** $B(t)$ is a slow function of age, and for ages in excess of $\sim$ 1 Gyr we have $B(t) \simeq 2 \times 10^{-11}$ stars per year per $L_\odot$ of the parent population. To my understanding Eq. (4) is one of the most robust predictions of stellar evolutionary theory, almost completely exempt from the unceratinties plaguing other specific aspects of the theory, such as e.g. those mentioned in §2. Thus, from number counts Eq. (4) allows to estimate the duration of a given evolutionary phase, provided all evolving stars experience such a phase. If a specific category of stars is produced by only a fraction of the population, but we know the duration of the phase, then Eq. (4) allows to estimate the fraction of the population which possess the ability to generate such stars. I will now exemplify with a few specific – albeit miscellaneous – applications how this relation can be used to study the stellar populations in bulges.

4.2.1. Estimating Lifetimes (e.g. of LPV and OH/IR Stars). Knowing the total luminosity of a population, than star counts allow to derive the duration of specific evolutionary phases. For example, the galactic globular 47 Tuc contains 4 LPV stars and its total luminosity is $8 \times 10^5 L_\odot$. From Eq. (4) one immediately derives that in this cluster the average duration of the LPV phase is $(2.5 \pm 1.2) \times 10^5$ yr.

Let me make another example. At this meeting Habing has reported that there are (at least) 250 OH/IR stars in the Bulge field with $|\ell| < 3^\circ$ and $|b| < 5^\circ$. What is the average lifetime of Bulge OH/IR stars? If all evolving stars in the Bulge go through the OH/IR phase, then:

$$t_{\rm OH/IR} = \frac{250 \times 10^{11}}{2\,L_{\rm T}(6^\circ \times 10^\circ)},$$

where $L_{\rm T}(6^\circ \times 10^\circ)$ is the total luminosity sampled by the $6^\circ \times 10^\circ$ field of coverage. Alternatively, suppose that from other means we know the average duration of the OH/IR stage, then the ratio of actual number of OH/IR stars to that predicted by Eq. (4) gives the fraction of the Bulge population which actually produces OH/IR stars. Crucial to both estimates is the preliminary determination of the intrinsic sampled luminosity L_T, a quantity that it should not be difficult to obtain, e.g. from a model of the light distribution in the Bulge*.

4.2.2. Normalizing Luminosity Functions. Luminosity functions (LF) of globular clusters, bulges, and other resolved galaxies are often compared to each other in order to derive astrophysical inferences from their similarities and differences. A comparison of this kind needs the various LF's to be normalized in some way. A way which has been frequently adopted consists in matching the faint end of two or more LF's, so as to emphasize differences in the bright portion. This procedure should be avoided, because it can lead to erroneous conclusions. The faint end of an empirical LF is in fact seriously affected by incompleteness, and in a way which differs from one studied stellar system to another (e.g. the faint end of the LF of M giants in the Galactic Bulge is certainly affected by a different degree of incompleteness compared to IR bright giants in the bulge of M31). There is instead only one correct way of normalizing the LF's of different stellar populations, and this is to refer star numbers to sampled luminosities: the number to luminosity ratio (N_j/L_T) is in fact proportional to durations, i.e. it is equal to $B(t)t_j$, an intrinsic property of the stars in the population.

As an example, I will consider the case of the bright end in the LF of M32, which extends to $M_{bol} \simeq -5.5$ (Freedman 1992). This is one mag brighter than in galactic globular clusters of comparable metallicity, and Freedman discusses various possibilities for extending by this amount the AGB LF. Eventually she inclines in favor of an intermediate age component, thus adding new fuel to a still burning debate (cf. Greggio & Renzini 1990, and references therein). Freedman's LF of M32 refers to a $40'' \times 100''$ field of view, with an alleged typical surface brightness of $V = 21$ mag/$\square''$, or $B = 21.9$, given the color of M32 $(B - V = 0.9)$. With a true modulus 24.4 to M32, the absolute B magnitude of the sampled area is $M_B = 21.9 - 24.4 - 2.5\mathrm{Log}(4000) = -11.5$, or $L_B = 5.3 \times 10^6 L_\odot$. This corresponds to a total bolometric luminosity ~ 3 times larger, or $L_T \simeq 1.6 \times 10^7 L_\odot$. Freedman lists 10 stars with $-5.5 < M_{bol} < -4.5$, and their lifetime from Eq. (4) is $\simeq 3 \times 10^4$ yr if all the stars in M32 were to climb the AGB up to $M_{bol} = -5.5$. This is an exceedingly short time for a one magnitude interval on the AGB, which instead is covered in $\sim 1.5 \times 10^6$ yr by an individual AGB star (e.g. Renzini & Voli 1981). This means that in M32 only one evolving star every ~ 50 actually succeds in climing above $M_{bol} = -4.5$, and therefore the bright end of the LF is produced by just a trace component in the M32 population. This trace component can either be an intemediate age contaminant to the dominant, old population, or the progeny of blue stragglers – coeval to the old population – resulting from the merging of binary components as suggested by Renzini & Greggio (1990), or some combination thereof (also a contamination from the disk of M31 cannot be excluded in the outer parts, Davidge & Jones 1992). Actually, Renzini & Greggio estimated the number of bright AGB stars progeny of blue stragglers to be $\sim 6 \times 10^{-13} L_T t_{AGB}$, that for the estimated sampled luminosity $(1.6 \times 10^7 L_\odot)$ and $t_{AGB} = 1.5 \times 10^6$ gives a total

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* For the bolometric luminosity of an old population one can use $L_T \simeq 3\, L_B$, where L_B is the blue luminosity (see Fig. 1.4 in Renzini 1993). This should be accurate within 10-20%.

of 14 AGB stars in the $-5.5 < M_{\rm bol} < -4.5$ range. This beutifully compares to 10 stars in this range observed by Freedman (1992)*, and I would be tempted to conclude that there is no need invoking an intermediate age component to explain the LF of M32. Crucial for this conclusion is the estimated luminosity $L_{\rm T}$ sampled by the covered area in Freedman's study. If the actual average surface brightness of the covered area is much fainter than $V = 21$ mag/$\square''$, then there would be room for an intermediate age component. Accurate surface photometry for M32 has been recently obtained by Peletier (1992), who gives $R = 23.2$ (corresponding to $V = 23.7$) mag/$\square''$ at $r = 109''.4$ from the center. Since Freedman's field of view was centered $120''$ from the center, it is indeed quite possible that the actual sampled luminosity is significantly lower than $1.6 \times 10^7 L_\odot$ as estimated above. On the other hand, it is worth noting that – scaling from 47 Tuc – with $t_{\rm PLV} = 2.5 \times 10^5$ yr and $L_{\rm T} = 1.6 \times 10^7 L_\odot$ Eq. (4) gives $N_{\rm LPV} \simeq 80$ LPV stars. Freedman's counts give about 100 stars in the magnitude range $-4.5 < M_{\rm bol} < -3.6$, and again there appears to be consistency†.

An intermediate age component is also favored by Elston & Silva (1992). Theirs is a $4' \times 4'$ field of view centered $3'$ from the center of M32. They count 135 stars in the luminosity range $-5.5 < M_{\rm bol} < -4.5$, and argue that 25% of main sequence stars should be blue stragglers in order to explain them in terms of blue straggler progeny. I do not understand which kind of calculation is behind this figure, but I would agree with their conclusion if the total luminosity sampled by their field of view is significantly lower than $135/(6 \times 10^{-13} \times 1.5 \times 10^6) = 1.5 \times 10^8 L_\odot$. Life would be much simpler if observers would preliminarily estimate the *sampled luminosity* $L_{\rm T}$ ($\simeq 3\,L_{\rm B}$) of the covered area of their targets. Additional motivations for this wishful expectation are presented next.

4.2.3. Estimating the Stellar Population of a Pixel. CCD and IR-array stellar photometry in nearby galaxies such as M32 and the M31 bulge are becoming common practice. Like in the photometry of galactic globular clusters, crowding is certainly a problem when measuring stellar magnitudes in such distant objects. However, the observational conditions are much different compared to those prevailing for galactic globulars, the targets for which existing photometric packages have been first conceived and then optimized. Table 1 illustrates the case.

Column 1 gives the distance from the center of the galaxy and column 2 gives the corresponding blue surface brightness. The third column gives the absolute blue magnitude that is sampled by one $\square''$ having assumed a distance modulus 24.4 mag, while columns 4 and 5 give the corresponding blue and bolometric luminosity (i.e. again sampled by one $\square''$). For this latter conversion I have adopted $L_{\rm T} = 3\,L_{\rm B}$.

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* This number comes from Freedman's Table 2, which may not list all stars brighter than $M_{\rm bol} = -4.5$. Her Table 1 lists 25 stars which in K are brighter than the faintest star in Table 2, and therefore the actual number of stars in the quoted magnitude range must be between 10 and 25: still consistent with my estimate for blue straggler progeny AGB stars.

† Freedman has successively applied incompleteness corrections to her actual counts, but such corrections are not explicitly given. Were they such to significantly increase over ~ 100 the number of stars, then this conclusion would be invalid.

TABLE 1
STELLAR POPULATION SAMPLING IN M32 AND THE BULGE OF M31

<table>
<tr><th colspan="7">M32</th></tr>
<tr><th>r</th><th>$SB_{\rm B}$ mag/□″</th><th>$M_{\rm B}$ mag/□″</th><th>$L_{\rm B}$ $L_\odot$/□″</th><th>$L_{\rm T}$ $L_\odot$/□″</th><th>$N_{\rm LPV}$ stars/□″</th><th>$N_{\rm RGT}$ stars/□″</th></tr>
<tr><td>5″</td><td>17</td><td>−7.4</td><td>1.2×10^5</td><td>3.6×10^5</td><td>2</td><td>7</td></tr>
<tr><td>27″</td><td>18</td><td>−6.4</td><td>4.8×10^4</td><td>1.4×10^5</td><td>0.7</td><td>3</td></tr>
<tr><td>2′</td><td>21.9</td><td>−2.5</td><td>1.3×10^3</td><td>4.0×10^3</td><td>0.02</td><td>0.08</td></tr>
<tr><th colspan="7">M31 Bulge</th></tr>
<tr><td>2′</td><td>19.8</td><td>−4.6</td><td>9×10^3</td><td>2.7×10^4</td><td>0.14</td><td>0.5</td></tr>
<tr><td>4′</td><td>21</td><td>−3.4</td><td>3×10^3</td><td>9×10^3</td><td>0.05</td><td>0.18</td></tr>
</table>

LPV's and of RGB stars in the last quarter of magnitude below the RGB tip. To get these numbers I have used Eq. (4), with $t_{\rm LPV} = 2.5 \times 10^5$ yr (see §4.2.1), and $t_{\rm RGT} = 10^6$ yr, the time RGB models spend in the corresponding luminosity interval (Sweigart & Gross 1978; see also Fig. 1 in Renzini 1992), thus implicitly assuming that the stellar population of M32 is similar to that of 47 Tuc. I recall that LPV's such as those in 47 Tuc reach a peak $M_{\rm bol} \simeq -4.5$, or $\sim 5000 L_\odot$, while the RGB tip is at $M_{\rm bol} \simeq -3.8$, or $\sim 2600 L_\odot$. For the M32 surface brightness at $r = 2'$ Table 1 gives the value taken by Freedman (1992) to be representative of a $100'' \times 40''$ field, but see the discussion in §4.2.2.

Numbers in Table 1 are self-explanatory. In the sequel I will call for short "pixel" the area of one resolution element, and therefore sampled luminosities and numbers of stars per pixel are obtained by multiplying values in Table 1 by the actual area of the pixel in □″ units. Of course, the area of the so-defined pixel depends on the specific observation, and should not be confused with the physical pixel of the detector (when observations are seeing-limited the pixel area is roughly the seeing squared). Table 1 shows that 5″ from the center of M32 each □″ pixel samples a luminosity of $\sim 3.6 \times 10^5 L_\odot$, like that of a fairly populous globular cluster. Eq. (4) correspondingly predicts that in each pixel one finds on average 2 LPV's and 7 RGB tip stars, a very crowded pixel indeed. Running a photometric package on such a frame may produce a list of magnitudes, but I doubt that they will actually refer to individual stars. Rather, the package may call stars what actually are the 2, 3, or 4σ fluctuations in the number of bright stars per pixel, thus producing a bright extension of the LF which in fact is just an artifact of the observational conditions. The situation is only marginally better at $r = 27''$, with ~ 3 RGB tip stars per pixel and a 70% chance to find an LPV in a pixel. At $r = 2'$ the situation is now far better, with only a 2% chance to find an LPV in a given 1□″ pixel. Contrary to the previous two cases, the corresponding stellar photometry should be reasonably accurate, and along with it the resulting LF.

Field locations in Table 1 are not randomly chosen. In fact, Davidge & Nieto

(1992) have obtained near-IR CCD images with their frame extending from $r = 5''$ to $r = 27''$. They find an extended LF that they attribute to an intermediate age component. The FWHM size of their stellar images was only $0''.4$, and in today's terminology with such an outstanding resolution the area of their "pixel" is $\sim 0.16\,\square''$. Thus, luminosities and numbers in Table 1 should be devided by ~ 6. Even so, in the less crowded part of their $65'' \times 110''$ field each $\sim 0.16\,\square''$ "pixel" has a $\sim 10\%$ chance to contain one LPV, and thus $\sim 1\%$ of the "pixels" should contain 2 LPV's. Since their field encompasses $\sim 44,700$ pixels, this means that ~ 447 of them contain 2 LPV's, ~ 45 of them 3 LPV's, etc., which I suspect may account for a fair fraction of the bright portion of the resulting LF without necessarily appealing to an intermediate age component.

I have already discussed the $2'$ field studies by Freedman (1992). She also had very good seeing, with FWHM resolution of $0''.6$, roughly corresponding to pixels of $\sim 0.3\,\square''$. Numbers in Table 1 should then be divided by ~ 3, and no doubt observing conditions were much better in this field. Crowding could have been a little worse for the study of Elston & Silva (1992), whose field of view extends from $1'$ to $5'$ from the center. They had worse resolution, with $\sim 2\,\square''$ "pixels", but their bright star photometry should still be reasonably accurate, a conclusion which should also apply to the observations of Davidge & Jones (1992), pointing $100''$ from the center and with $\sim 1\,\square''$ pixels.

Table 1 also gives data for two locations in the bulge of M31. The outer one, at $4'$ from the center, was covered with near-IR imaging by Rich & Mould (1991), who found a significant extension of the AGB luminosity function up to $M_{\rm bol} \simeq -5.5$. They conclude that an intermediate age component is most likely necessary to explain the LF, although Davies *et al.* (1992) argue for a contamination from the disk of M31 being responsible for most if not all the effect, a possibility not completely excluded by Rich & Mould. With $1\,\square''$ pixels – such as in the R & M study – the $4'$ field looks very crowded, and I wonder if overlapping LPV's and RGB tip stars may have concurred in arificially extending the bright portion of the LF. For example, from Table 1 data we see that $\sim 0.05 \times 0.18 = 1\%$ of the pixels should contain a LPV+RGB tip star blend, and seemingly $\sim 3\%$ of them should contain 2 RGB tip stars, etc. Since there is a total of ~ 3000 pixels in the field of view, we see that a non trivial fraction of very bright stars may actually result from blends. The situation looks three times worse in a field $2'$ from the center, and I suspect that only with really outstanding seeing one can cope with stellar photometry in such very crowded field.

I am not in the position to definitely state that the bright part of the M31 bulge LF obtained by Rich and Mould is entirely due to blended images, but I would be very reassured if the LF were to remain the same even using data obtained from observations with far better resolution, e.g. such as those of Davidge & Nieto (1992) of M32. I would also be very interested in the results of simulated observations, for example cloning from the $4'$ field frame a mock $2'$ field doubling or so the surface brightness of the $4'$ field, something not too difficult to do starting from existing data.

Given the great variety of observational conditions that are encountered in stellar population studies (surface brightness of the target galaxy, distance, resolution of the telescope + camera + atmosphere), it would be certainly very useful for the producers of CMD's and LF's – as well as for their consumers – if we could dispose of a simple *rule of thumb* saying which photometry we should safely believe, and which we should look at with some more concern of how crowding may have affected the results. Without demonstration, I propose the following algorithm, with the proviso that it should be tested and calibrated by means of adequate simulations. Safe photometry of stars with luminosity L_* requires that

$$L_* \gg \Sigma_{L<L_*} \cdot \text{pixel area}, \tag{5}$$

where $\Sigma_{L<L_*}$ is the average surface brightness of the target in $L_\odot/\square''$ having subtracted the stars brighter than L_*, and the pixel area in $\square''$ has been defined above. Inequality (5) should apply to distant galaxies in which we aim at resolving the *brightest* stars in the population, as well as to nearby globular clusters where on the contrary the point is to get accurate magnitudes for the *faintest* stars in the population.

If criterion (5) is correct, then from Table 1 we see that there should be no problem with the mentioned M32 observations at $z \simeq 2'$, but I suspect that those at $5''$ and $27''$ may be in trouble, while those in the $4'$ field in M31 appear to be on the borderline. Certainly, at $5''$ from the center of M32 to reach the photometric quality reached by Freedman in her $120''$ field the pixel area should be ~ 100 times smaller, or the resolution $\sim 0''.06$, something that even an unaberrated HST can barely reach.

I wish these considerations have shown that one of the first questions to ask about a stellar field is *"what is the total luminosity sampled by the whole frame and by each resolution element?"*

5. Did Bulges Form First?

From a CMD of the Galactic Bulge such as that shown in Fig. 4 one can reasonably conclude that the bulk of stars are very old, quite possibly as old as galactic globulars, or thereabout. Unfortunately, existing CMD's can hardly set a tighter limit. From the LF of the brightest stars in the Galactic Bulge (Frogel & Withford 1987) and in the bulge of M31 one can also reach a similar conclusion, with still the reservation that a trace population of intermediate mass (age) stars cannot be entirely excluded. What can we conclude from this about the formation of bulges, i.e. about the star formation history in bulges?

I do not understand scenarios in which stars first start froming in a halo, and then successively the leftover, chemically enriched gas flows quietly in and goes to form the bulge. Seemingly, I do not understand scenarios in which disks form first, and then some dynamical instability depletes and heats up the inner disk to form the bulge. I do not understand why star formation should have started first in the low density halo, rather than in the central, high density regions of a protogalaxy. Seemingly, I do not understand why stars should have formed first in a disk, and then brought in some way to the center about which the disk itself rotates. It makes more sense to me if star formation was much more violent at the bottom of the galactic potential well, where high gas and cold cloud densities were certainly first achieved. What else was the *center* otherwise? Here chemical enrichment by supernovae, and heating of the residual gas – eventually discontinuing further stars formation – were probably much more rapid than in the outer parts of a galaxy like our own, and very high metallicities were soon achieved. The duration of the star formation epoch in a bulge was probably of the order of the local free fall time ($\sim$few 10^8 yr), since cold, star forming gas can hardly survive longer in a pressure supported system in which the *dynamical* temperature is of the order of several million degrees. Thus, stars in the metal poor halo came later, as the local free fall time is significantly longer, up to a few billion years in the outer parts. Thus, in this scenario the *spheroid* component of a spiral was buit up starting from the center, in such a way that the super metal rich bulge is – on average – older than the metal poor halo (Renzini & Greggio 1990), just the contrary of what one may naively expect. Rather than a latecomer, in this view a bulge is seen instead as the first seed about which the rest of a galaxy has then grown.

There is still no conclusive evidence for a significant fraction of stars in the Galactic Bulge and in the bulge of M31 to belong to an intermediate age population. A *contamination* of this kind cannot be excluded either, and one can imagine a number of ways in which it might have been produced. But in any event one should attempt to distinguish between the main episode of stars formation and any possible subsequent addition. Considerations such as those developed in the previous sections may help quantifying these arguments, and set more precise limits on the age distribution of stars in bulges.

Before concluding this review, I would like to mention a few problems by which I am still intrigued, but which may soon be satisfactorily solved by means of dedicated observations:

- Is the difference in the upper LF between the Galactic Bulge (Frogel & Withford 1987), the bulge of M31 (Rich & Mould 1991), and M32 (Freedman 1992) real?
- The Bulge CMD's such as that displayed in Fig. 3 show a well populated, fairly bright MS which is due to foreground contamination by disk stars. How many bright red giants, Miras, and OH/IR stars in the same fields do not belong to the Bulge, but are the RGB/AGB progeny of the foreground population?
- If the extension of the LF in M32 is due to a blue straggler progeny, why such an extension is not seen in the Galactic Bulge LF?
- Why the Bulge LF of Frogel & Whitford does not show the expected drop at $M_{\rm bol} \simeq -3.8$ associated to the RGB tip (see Renzini 1992)?
- Are all Miras really AGB stars? After all, pulsation is an evelope phenomenon, and the deep structure does not matter. When metallicity increases the RGB moves to lower temperatures and larger radii, thus favoring pulsational instability. In the SMR regime could this suffice to cause the brightest RGB stars to become Miras?
- Are the two previous problems related to each other? i.e. is the drop in the Bulge LF washed out by the SMR stars near the RGB tip being variable?

I wish to thank Sergio Ortolani and Mike Rich for their permission to reproduce their CMD's of the Bulge, and for our frank, entertaining debates on this subject.

REFERENCES

Boothroyd, A.I., Sackmann, I.-J. 1988, ApJ, 328, 641

Davidge, T.J., Jones, J.H. 1992, AJ, 104, 1365

Davidge, T.J., Nieto, J.-L. 1992, ApJ, 391, L13

Davies, R.L., Frogel, J.A., Terndrup, D.M. 1992, AJ, 102, 1729

Elston, R., Silva, D.R. 1992, AJ, 104, 1360

Freedman, W.L. 1992, AJ, 104, 1349

Frogel, J.A. 1990, in Bulges of Galaxies, ed. B.J. Jarvis & D.M. Terndrup (Garching: ESO), p. 177

Frogel, J.A., Elias, J.H. 1988, ApJ, 324, 823

Frogel, J.A., Whitford, A.E. 1987, ApJ, 320, 199

Fusi Pecci, F., Renzini, A. 1976, A&A, 46, 447

Greggio, L., Renzini, A. 1990, ApJ, 364, 35

Iben, I.Jr., Renzini, A. 1984, Phys. Rep. 105, 329

Iglesias, C.A., Rogers, F.J. 1991, ApJ, 371, 408

Ortolani, S., Barbuy, B., Bica, E. 1990, A&A, 236, 362

Ortolani, S., Bica, E., Barbuy, B. 1992a, A&AS, 92, 441

Ortolani, S., Bica, E., Barbuy, B. 1992b, A&A, in press

Ortolani, S., Rich, R.M. 1992, in preparation

Pagel, B.E.J. 1989, in Evolutionary Phenomena in Galaxies, ed. J.E. Beckman & B.E.J. Pagel (Cambridge Univ.), p. 368

Peimbert, M. 1983, in Primordial Helium, ed. Shaver, P.A., Kunth, D., Kjär, K. (Garching: ESO), p. 267

Peletier, R.F. 1992, ESO Preprint No. 851

Reimers, D. 1975, Mem.Soc.Roy. Liège, 6^{th} Ser., 8, 369

Renzini, A., 1991, in Observational Tests of Cosmological Inflation, ed. T. Shanks *et al.* (Dordrecht: Kluwer), p. 131

Renzini, A., 1992, in The Stellar Populations of Galaxies, ed. B Barbuy & A. Renzini (Dordrecht: Kluwer), p. 325

Renzini, A., 1993, in Galaxy Formation, ed. J. Silk & N. Vittorio (Amsterdam: North Holland), in press

Renzini, A., Buzzoni, A. 1986, in Spectral Evolution of Galaxies, ed. C. Chiosi & A. Renzini (Dordrecht: Reidel), p. 135

Renzini, A., Greggio, L. 1990, in Bulges of Galaxies, ed. B.J. Jarvis & D.M. Terndrup (Garching: ESO), p. 47

Renzini, A., Voli, M. 1981, A&A, 94, 175

Rich, R.M. 1985, Mem. S.A.It. 56, 23

Rich, R.M. 1988, AJ, 95, 828

Rich, M.R., Mould, J.R. 1991, AJ, 101, 1286

Sweigart, A.V., Gross, P.G. 1978, ApJS, 36, 405

Terndrup, D.M. 1988, AJ, 96, 884

Whitford, A.E., Rich, R.M. 1983, ApJ, 274, 723

DISCUSSION

Baum: Let's assume that star formation got underway very very early in the centre and I think your arguments for that are good. That it should proceed very rapidly where the material is dense, is also very logical. But, by what reasoning can we conclude that it was over and done with very rapidly?

Renzini: My reasoning is that the Bulge is a hot type system that is not rotationally supported and has velocity dispersion of order 100 km/s. What I find difficult is to understand how you can keep molecular clouds at the density of the stars we see today (spatially averaged) with such high random velocities without forming stars on a short time scale. The remaining gas will go up to several million degrees and flow out due to supernovae explosions.

Baum: Would you consider that that conclusion might be kept open until we finish the observations?

Renzini: Of course! I was making a bet, indeed.

Rich: A comment on the G-dwarf problem: in fact the number of 47-Tuc like stars, from my abundance distribution, should be around 10 to 15%. So you have to fold in lifetimes on the giant branch and so on. The jury is still out, but I would say from the surveys, that when you normalize them and remember that the mean abundance is twice solar (so the normalization pushes it to higher abundances), I still think there is a bit of G-dwarf problem at this time. There are no luminous carbon stars seen anywhere in the Bulge, so if it's the progeny of the bright main sequence that does superpose that field which is there, it isn't making luminous carbon such as we see in reasonable volumes in the solar neighborhood.

Rich On the issue of Todry M31: in fields taken two years apart, we see individual stars vary by more than more than a magnitude in K, in a field that is more than 400 parsec from the nucleus.

Norman: How sure are you that the Bulge is extremely old?

Renzini: I would just reverse the question, show me the young stars.