STELLAR EVOLUTION IN GLOBULAR CLUSTERS AND HST

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## 1. INTRODUCTION

Globular clusters (GC) have been regarded among the most obvious targets for the Hubble Space Telescope since the very first conception of this project, and some observational programs have been exemplified in publications concerning the future use of HST (e.g. Westphal 1982 and Macchetto 1982, in the "Patras Book", Bahcall 1985, see also the 1985 Report of the STScI working group on Stars and Star Clusters).

In this talk I will focus on a few issues concerning the evolution of stars in globular clusters, for which HST observations are expected to provide crucial insight. I will not touch upon problems in cluster dynamics, which certainly will also take advantage from HST observations, (although, to some degree, stellar evolution and cluster dynamics may not be completely decoupled subjects).

A discussion of this general subject can start by considering that there are six evolutionary phases to be investigated (MS, RGB, HB, AGB, POST-AGB, WD), six instruments on board of HST (FGS, HSP, FOS, HRS, FOC, WF/PC) and six GC families that HST can resolve (MW, FORNAX, LMC, SMC, M31, M33), for a total of $6^3 = 216$ possible combinations (!). While, by good fortune, most *matrix elements* are just nonsensical (e.g. HSP observations of WDs in M31 globulars), still there is a fairly large number of sensible combinations. I will then further restrict the discussion to studies of cluster color-magnitude diagrams (CMD) which will become feasible with HST, a choice largely dictated by my own personal taste. I will then exemplify the case with three hypothetical projects making use of HST imaging capabilities, each concerning respectively globulars in the Milky Way, in the Magellanic Clouds, and in M31.



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## 2. GALACTIC GLOBULARS: FOR COMPLETENESS SAKE

There are basically two ways of using HST imaging capabilities in connection with the subject of stellar evolution in galactic globulars: either one tries to go deep (faint) or to go *complete*. The only really faint evolved stars in MW globulars are white dwarfs, and much has already been said about them as targets for HST. The other evolved stars (i.e. stars in post-main sequence evolutionary stages) are so bright that have not attracted as much the attention of the potential HST astronomer. However, HST is basically a photon-starving telescope, as John Bahcall (this volume) will emphasize, and it is then particularly suited for the observation of relatively bright stars located in crowded fields. Therefore, what HST will easily make possible, thanks only to its superior angular resolution, is the photometry of ALL the evolved stars in a GC in a fairly short observing time. In other words, it allows the construction of really complete CMDs. Conversely, the observation of very faint GC stars (e.g. WDs) requires to push HST to its limits in a partly innatural way.

With few exceptions, the advantages of *going complete* in at least a well defined portion of a GC have not been fully appreciated. Quite often only the isolated stellar images are measured, with the result of obtaining CMDs where magnitudes and colors are (internally) very accurate, but where the luminosity function (LF) is virtually useless because of uncontrolled selection effects. However, as emphasized by Paczynski (1984), the LF provides a much harder information, compared to the shapes of cluster loci and isochrones, which are so much undermined by color/temperature uncertainties (e.g. Iben and Renzini 1984).

### 2.1 Luminosity function, ages, and model testing

The LF of a globular cluster, in a broad sense, is the (number) distribution of stars along the various branches of the CMD. For several reasons the LF can hardly be used to derive a cluster age (cf. Renzini 1986a,b), but can be used in a more subtle, fundamental way that I shall try to illustrate.

Indeed, dating GCs is a three step procedure: 1) a number of observable quantities are measured via astronomical observations of a Globular cluster (e.g. $\Delta M_{TO}^{RR}$, [Fe/H], etc.), 2) these observables are fed into a theoretical machinery that we call the clock (i.e. a theoretically established relation between some observables and age), and 3) one faithfully sorts an age. Certainly, it is important to improve the accuracy with which the observables are measured, as this will reduce the internal error in the age determination. But what about the accuracy of the clock itself? i.e. what about the reliability of theoretical evolutionary models?

In strict connection with these questions, it appears that accurate (i.e. complete) cluster LFs provide the best possible way of testing the evolutionary models, and then of assessing the reliability of the clock. When an extensive and complete

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photometric survey of cluster stars becomes available, a whole variety of meaningful checks becomes feasible. For example: i) checking the contribution of the various evolutionary stages to the total cluster light, in the mood of Figure 5 in Renzini and Buzzoni (1986), ii) checking the duration of the various evolutionary stages, according to Eq. (1) below, and iii) checking the composition stratification inside stars, using the LF of the RGB.

Concerning points i) and ii), the first attempt in these directions is part of the archetipal study of M3 by Buonanno et al (BBCFS, this volume), based on the complete and accurate photometry of 10,000 cluster stars. Still, this study covers only $\sim 30,000\ L_{\odot}$ of cluster light, or $\sim 5\%$ of the total, and does not allow but a first, rough study of the advanced evolutionary stages. For example, when inserting this figure into the number/luminosity/time relation (Renzini and Buzzoni 1986):

$$N_j = B(t) L_T t_j \tag{1}$$

one infers the presence of $\sim 10$ early AGB stars in the sample ($B = 2\ 10^{-11} L_{\odot}^{-1} yr^{-1}$, $t_{AGB} = 1.5\ 10^7 yr$). While the theoretical prediction is in excellent agreement with the actual number of observed AGB stars (just 10 !), still the whole comparison is limited by the small number statistics.

The extension of the BBCFS study to the whole cluster ($\sim 6\ 10^5 L_{\odot}$) would in fact make available some 200 AGB stars, with an obvious improvement in the statistical accuracy, and even opening the possibility of studying the LF of the AGB in some detail. This is however impossible using ground based observations, as severe crowding prevents a complete and accurate photometric survey from being extended over a significantly larger fraction of the cluster (light). Conversely, HST will allow such a survey to be extended over the whole cluster, including the central regions!

Point iii) above is the one most intimately connected with the problem of cluster dating. Indeed, the clock itself is ultimately a relation between isochrone turnoff luminosity and age and then only main sequence, core hydrogen burning models are involved. These are therefore the models most worth testing, if one is primarily interested in GC ages. Moreover, in this like in many other cases, the accuracy of models of a certain evolutionary phase is best ascertained by looking at the immediate progeny of such models.

In this specific case, the main sequence lifetime is controlled by the rate of hydrogen burning, and therefore there is close connection with the actual composition stratification inside the star, as established in the course of the core hydrogen burning phase. In turn, such a composition profile controls the rate of evolution during the subsequent RGB phase. For example, a hypothetical mixing of the central regions would both prolong the MS lifetime (by providing fresh new fuel) and produce a shallower composition profile. Seemingly, a hypothetical diffusion of helium relative to hydrogen (cf. Stringfellow et al 1983) would both reduce the MS lifetime and produce a steeper composition profile.

While such, or other processes are hypothetically operating (during the MS stage) they may have little immediately observable consequences. But they would concur in establishing the final composition profile, through which the hydrogen burning shell will later eat its way during the subsequent RGB phase. Ultimately, there is therefore close connection between the composition profile at the end of the MS stage, and the actual LF of the RGB. Moreover, during the RGB phase there exists a relation between the mass of the stellar core (i.e. the mass coordinate of the hydrogen burning shell) and the stellar surface luminosity. Putting all this together, one can easily realize that the LF of the RGB allows to study the composition stratification inside the stars, and therefore to test the reliability of the models which provide the age calibration (clock).

However, this kind of "evolutionary stratigraphy" requires big, complete stellar samples (cf. Rood and Croker 1985, for illuminating simulations). From Eq. (1) we see that the larger the sample (larger sampled luminosity $L_T$), the larger the number of stars per unit duration, and then the larger the TIME resolution along an evolutionary sequence. In turn, thanks to the link between core mass and luminosity, the larger $L_T$, the larger the MASS resolution in the stratigraphic approach.

In principle, these considerations apply equally well to the AGB LF as a tool for probing the C-O-He stratification, as established during the core helium burning phase. The main difference is just that, compared to the RGB, the AGB is intrinsically less populated and the helium-burning shell is somewhat thicker, thus reducing the mass resolution of the evolutionary stratigraphy. Anyway, one can anticipate that good AGB luminosity functions will certainly provide the ultimate test concerning the nature and extension of the mixing processes active during the HB phase.

### 2.2 The luminosity function and HST planning

As emphasized by Bahcall (1985) , the knowledge of the cluster LF can be extremely useful for planning HST observations of globular clusters, in particular of white dwarf stars. For the bright part the LF used by Bahcall is the same as that obtained by Da Costa (1982) for the cluster 47 Tuc. I have recently realized that this LF is in severe conflict with what one would expect from theoretical evolutionary models (Renzini 1986b). In brief, from Da Costa LF one can infer a subgiant branch (SGB) to horizontal branch (HB) number ratio $N_{SGB}/N_{HB} \simeq 6$, the SGB being defined as the portion between turnoff and the base of the RGB. By adopting a HB lifetime of 0.1 Gyr, one then infers an SGB duration $t_{SGB} = 0.6$ Gyr.

This compares to $t_{SGB} \simeq 3.5$ Gyr, as predicted theoretically by evolutionary models (Mengel et al 1979) with the appropriate composition, [Fe/H]$= -0.7$. There is therefore a discrepancy by at least a factor of 5, even when allowance is made for the error in reading the LF directly from Bahcall's Figure 1. On the contrary, the LF obtained by BBCFS for M3 does not disagree with theoretical expectations, and I conclude that Da Costa LF is probably incomplete by about a factor of 5 at the level of the SGB. This conclusion is not based on a faithful belief in the theory, but rather on the appreciation that star counts down to a plate limit is the most dangerous way of deriving a LF. Note also that an indication of severe incompleteness in the old LF is already evident when looking at the more recent 47 Tuc LF obtained by King, Da Costa and Demarque (1985, their Figure 3). In particular, when normalizing to the integral of the bright part (rather than at one arbitrary bin) already at V=17 the new LF is roughly a factor of 3 above the old one.

Concerning the anticipated number of white dwarfs in globular clusters, these findings will change slightly some of the numbers given in Renzini (1985) . Having in general:

$$N_{WD} = a\, 10^{-11} L_V t_{cooling}, \tag{2}$$

I obtained $a \simeq 4.7$ using Bahcall/Da Costa LF, and one now finds $a = 3.0 \pm 0.2$ using the LF of BBCFS. Moreover, the BBCFS visual to bolometric conversion factor for M3 is 1.43 (i.e. $L_{bol} = 1.43 L_V$, rather than $2L_V$ as adopted in Renzini, 1985). Therefore, also the fully theoretical approach gives $a \simeq 3$, in very good agreement with the semiempirical approach. The conclusion seems to be that in Bahcall (1985) both the number of WDs, and the number of lower main sequence contaminants have been underestimated by about a factor of 5 (this latter statement rests on the assumption that Bahcall's adopted lower main sequence LF is correct). Correspondingly, the number of pixels available per stellar image has probably been overestimated in Renzini (1985).

Finally, one important aspect of cluster LFs needs to be strongly emphasized. Obviously enough, most of the cluster light comes from few stars, while most stars provide very little light. So, the LF for the bright part of the M3 CMD obtained by BBCFS covers most of the stars contributing to the integrated light of the studied portion of the cluster, but does not extend faint enough to include the bulk of the cluster stars, which are still fainter than the completeness limit. Conversely, other deep LFs obtained with CCDs over small cluster portions (small sampled $L_V$) involve mainly low mass stars which contribute little or negligible light to the cluster luminosity. On the contrary, the luminosity to number conversion function (cf. Bahcall 1985) requires a LF (correctly) encompassing all stars, i.e. extending from the top to the bottom of the CMD. Such a LF is not yet available, and then it appears appropriate to give very high priority to attempts at properly, carefully matching the bright and faint portions of the LF in at least a few clusters. This is really important for the most efficient planning of deep HST observations of MW globular clusters.

### 2.3 Unanticipated applications (a curious example)

I would like to exemplify now how the knowledge of the LF for whole, popolous globular clusters might have useful applications far beyond those one can currently anticipate, some of which have been mentioned in the previous sections. I will illustrate the case by mentioning a recent, unexpected application of stellar counts on GC color-magnitude diagrams (Renzini 1987).

It has been recently suggested that perhaps "the solutions to the neutrino problem in the Sun and the missing mass problem in the Galaxy are one and the same" (Press and Spergel 1985, see also Gilliland et al 1986 and references therein). In brief, in this scenario weakly interacting massive particles (WIMPs, also called cosmions), while providing the missing mass, are continuously collected by the Sun, where they isothermalize the inner, neutrino producing core, thus reducing the solar neutrino flux below the observed $\sim 2$ SNUs.

However, if the solar core is isothermalized by WIMPs, so it would happen also to the inner core of HB stars, and core convection would then be suppressed during the core helium burning stage. This would have major, dramatic consequences on HB and AGB stars; in particular the HB lifetime would be drastically reduced by the suppression of the continuous fuel replenishment otherwise ensured by convection. On the contrary, the AGB lifetime would be considerably lengthened, because shell helium burning would now start from a point much closer in mass to the stellar center. Correspondingly, the lifetime ratio $t_{AGB}/t_{HB}$ would be increased by almost one order of magnitude over the canonical value, $\sim 0.14$. Since star counts over complete samples for 15 globulars give $N_{AGB}/N_{HB} \simeq 300/2000 = 0.15 \pm 0.01$ (Buzzoni et al 1983), one can safely infer that the core of HB stars cannot be kept isothermal by pervasive WIMPs.

The conclusion is that, most likely, the WIMPs idea is not a viable solution for the solar neutrino problem, unless the WIMP annihilation cross section is tuned to within a permitted range of $\pm 1.5$ dex, in such a way as to ensure WIMPs survival in the Sun, but their digestion and destruction prior to the HB phase. The WIMP supporter could then maintain that star counts in GCs provide a measure of the WIMP annihilation cross section....

## 3. THE GLOBULAR CLUSTERS IN THE MAGELLANIC CLOUDS

Globular clusters in the Magellanic Clouds span an age from $\sim 0.01$ to $\sim 10$ $Gyr$. The construction of complete CMDs for whole clusters will correspondingly allow the test of stellar models in a mass range from $\sim 1M_{\odot}$ up to $\sim 10M_{\odot}$. Moreover, the combined study of CMDs, integrated colors and spectra of MC clusters represents a fundamental step for population synthesis investigations, as it provides the "template stellar populations" for the test and calibration of synthesis codes and their ingredients (cf. Renzini and Buzzoni 1986, Renzini 1986c). In this regard, of particular interest are clusters $\sim 0.5$ to a few Gyr old, as most of their light is provided by stars around $2M_{\odot}$, just as in the case of the high redshift galaxies which are either within reach now, or will become so with the next generation of Very Large Telescopes.

For some time I had the impression that the greatest advantage of using HST on MC clusters would have been in reducing the field contamination, the argument being that the field-to-clusters ratio is obviously minimum in the crowded central regions of the clusters. However, it turns out that in excellent seeing conditions many clusters can be thoroughly resolved from the ground, and CCD photometry is possible for virtually all the stars around turnoff or beyond. The photometric accuracy is however seriously degraded, and it appears that accurate and complete CMDs for whole GCs can best be obtained with HST, which will also allow near-UV photometry (note that in clusters 1 Gyr old the turnoff temperature is $\sim 10,000K$). The emphasis has then shifted from field contamination (which may remain a problem) to accuracy and completeness. In this regard, an application of Eq. (1) to MC clusters indicates the necessity of using virtually all the clusters in crucial age bins, if one wants to ensure a statistically significant coverage of all the relevant evolutionary stages.

In conclusion, also the HST study of stellar evolution in MC globulars does not require to go really deep (at least in young and intermediate age clusters), but rather "to go complete". Again, the specific characteristic of HST which will be exploited is its angular resolution, which will allow accurate photometry even in very dense fields.

## 4. THE M31 CLUSTER FAMILY

It is widely recognized that GCs play a very important role in our attempts at understanding the origin and early evolution of the MW galaxy. Having said this, it becomes immediately clear that it is of the highest possible interest for the general problem of galaxy formation and evolution to extend such studies to another giant spiral galaxy, such as M31.

Indeed, HST will make possible the construction of M31 cluster CMDs extending 1 to 2 magnitudes below the HB level (which in Andromeda is at $<B> \simeq 25.5$, cf. Pritchet 1986), and simulations of FOC observations show that fairly accurate photometry can be obtained (Bragaglia et al 1986). Among the many possible uses of such CMDs two are particularly worth noting: 1) a plot of $V_{HB}$ vs the metallicity indicator $(B-V)_{o,g}$, and 2) a plot of any HB morphology indicator vs $(B-V)_{o,g}$. We can correspondingly refer to a "vertical" and a "horizontal" study of the HB in M31 globulars.

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The "vertical" plot is of crucial importance for both the distance scale problem, and for the age of GCs, as it allows a direct assessment of the metallicity dependence of the HB luminosity (cf. Sandage 1982; Renzini 1986a; Buonanno 1986; Sweigart, Renzini and Tornambe' 1987).

The "horizontal" plot will allow the study of the "second parameter" problem in another GC family, with all its meaningful aspects (e.g. comparison with the MW family, trends with M31 galactocentric distance, and so forth, cf. Fusi Pecci's and Zinn's reviews in this volume). This application of the CMDs of M31 globulars is also of great interest for the study of the integrated light of stellar populations, as clearly demonstrated by the still uncertain interpretation of the integrated spectra of these clusters (Burstein et al 1984; Rose 1985; Renzini 1986c; Fusi Pecci, this volume). Indeed, it will be possible to directly assess as to whether the famous $Mg_2 - H\beta$ anomaly is produced by a systematically different metallicity dependence of the HB morphology (e.g. Cacciari et al 1982), or if other causes need to be envisaged.

## 5. CONCLUSIONS

Obviously enough, one cannot offer any conclusion concerning HST observations of globular clusters, but there are two points worth making, which both concern the impact on this field of the two-year delay in the planned launch of HST. First, there are now far more cluster CCD data still on tape, than have been elaborated and presented at this meeting. The exciting results we have seen here represent just the tip of the CCD iceberg, while by 1988 an impressive body of first quality cluster CMDs and LFs will likely be available. It is hard to say whether this situation will make advisable to update some of the GTO projects. But certainly it would be important to dispose of complete and deep cluster LFs before GO projects are completely finalized (cf. Section 2.2).

The second point concerns the HST photometric systems (cf. Koornneef et al 1986), which are significantly different from those used so far in ground based observations of GCs. I will then conclude by just asking the following question to the audience: would it be useful to soon start adopting the HST photometric systems also for ground based observations?

I would like to express my gratitude to the Space Telescope Science Institute for its hospitality, and to STScI staff members Ralph Bohlin, Carla Cacciari, Holland Ford, Jan Koornneef, Duccio Macchetto, and Francesco Paresce, for useful conversations about the HST operations and capabilities. I would also like to thank the BBCFS group members for their patience in day by day satisfying my curiosity for their work on M3, and to Franceso Ferraro for computing at my request several LF integrals.

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DISCUSSION

**GNEDIN:** There is an interesting idea, by Prof. Okun' from the Moscow Inst. of Theo. Phys., concerning the solar neutrino problem. The interaction between the spin of a neutrino and the solar magnetic field may reverse the spin and convert antineutrinos into neutrinos. Therefore one could expect that the antineutrino flux would decrease. As the strength of the magnetic field depends on the solar cycle, one could expect the antineutrino flux to vary with the solar cycle. There is some evidence of this effect.

**REES:** A comment about WIMPS, in case anyone here takes them seriously. If the Dark matter is in the form of WIMPS, and if globular clusters formed by a "primary" (pregalactic) mechanism, each cluster would be embedded in a "mini-hole" of WIMPS gravitationally bound to it. The stars in globular clusters would then have capture ~ 100 times as many WIMPS as the Sun -- primarily because the capture cross section (taking gravitational focusing into account) goes inversely with the WIMPS random velocities, which would be < 10 km/s for those trapped in clusters, rather than > 200 km/s for those filling the halo.

**RENZINI:** Yes, so the $N_{AGB}/N_{HB}$ argument may tell something about dark matter very hypothetically associated to globular clusters.

**TRIMBLE:** Have you given any thought to the effect on estimated ages of globular clusters. Faulkner thought it might be important.

**RENZINI:** I heard that John has made this suggestion, but I've not seen the preprint.

**TRIMBLE:** I think the effect will be small, but no exact calculations have been done and, as Martin Rees says, it depends on the number of WIMPS.

**RENZINI:** It must certainly depend on how many WIMPS one is willing to dump.

**ALCAINO:** Due to the fact that with the HST we will reach one magnitude below the horizontal branch level of globular clusters in M 31, the HB position will be a useful check to the current distance determination of Andromeda via the Cepheids.

**RENZINI:** Yes, I agree.

**KING:** Your suggestion of using HST photometric systems from the ground is a good one. Using synthetic magnitudes (from spectrophotometric curves and sensitivities), I have tried to convert one UBV system to another, and so far I have failed.

**DA COSTA:** The 47 Tuc luminosity function data of Da Costa (1982) agrees well with the original work of Hesser and Hartwick in the subgiant region, and with the newer data of Hesser and Harris at fainter magnitudes (V < 21,5). I do not think that it is possible that a factor of 5 would have been missed.

**RENZINI:** I think the contrary, and your more recent luminosity function of 47 Tuc (King, Da Costa and Demarque 1985) already indicates that the 1982 luminosity function was severely incomplete at the level of the subgiant branch.

**HESSER:** The luminosity functions, of which I'm aware, for the 47 Tuc subgiant branch are heavily weighted towards photographic data. Our recent CCD study in two small fields at large radii do not sample well the subgiant region, a shortcoming we hope to overcome.

**RENZINI:** So the point is that there is a factor of 5 disagreement between theory and stellar counts for the subgiant branch of 47 Tuc. I bet for the theory.

**BOND:** In regard to using the M 31 globular clusters to get the dependence of horizontal-branch luminosity upon metallicity, won't the depth of the M 31 system along the line of sight smear out any relationship?

**RENZINI:** No, the dispersion in distance modulus is of the order of five hundredths of magnitude, considerably smaller than the effect one is seeking to see.

**OZERNOY:** After all, what is the best estimate for the age of the oldest globular clusters and what is the uncertainty of the estimate.

**RENZINI:** As Don VandenBerg mentioned some days ago, the best estimates give 16 billion years with an uncertainty of ~ 25%