# Globular Clusters with the VLT

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## 1. Introduction

Globular clusters are the best example of a "simple" stellar population, i.e. a group of stars with the same age and chemical composition (with a few exceptions) where the only varying parameter is mass. Therefore, they are ideal laboratories to study stellar astrophysical problems such as the evolution of Population II stars and the phenomena related to the environmental conditions (e.g. internal cluster dynamics, binary formation and evolution, star interactions, captures, mergers, X-ray sources, pulsars, etc.). Moreover, considering their integrated properties, they can be used as test particles to study the formation, evolution and dynamics, and the stellar populations of the parent galaxies.

Given the extent of the subject and its possible connections to many astrophysical fields, we shall present and discuss briefly only some topics of major scientific interest involving globular clusters, with some evaluation on the most efficient telescope/instrument combination to reach the desired results. The telescopes we have considered are the 4-m-class (NTT-like), 8-m-class (VLT-like), HST and ISO. The specific cases where the VLT is the best choice with respect to the other telescopes will be treated in some more detail, and the most suitable instruments will be suggested.

## 2. Cosmological Tests

Cosmological models can be tested using two main aspects of globular cluster properties, namely absolute ages which are related to the age of the universe, and dark matter content which is related to the baryonic matter in the universe.

### *2.1 Absolute ages*

Globular clusters (GC) are nearly the first objects that formed at the time of the galaxy formation. The oldest metal-poor clusters set thus a lower limit to the age of the universe. The better the accuracy of globular cluster dating, the more stringent will be the cosmological implications. In the Colour-Magnitude Diagram (CMD), the optimal *clock* is the Main Sequence (MS) turn-off (TO). The absolute age of a globular cluster is obtained by linking the TO observable parameters (i.e. magnitude and colours) to the corresponding quantities (i.e. luminosity and temperature) in the theoretical isochrone with the same chemical composition. Since stellar clocks are intrinsically based on stellar models, the *verification* of the validity of these models is both *complementary* and *necessary* to any dating procedure.

A few rough estimates may be useful before proceeding. Assuming an absolute age of 15 Gyr, an uncertainty of ± 1 Gyr is given formally by an error of 0.07 mag in the TO luminosity, or 0.30 dex in the metallicity [m/H], or 0.03 dex in the helium content Y.

The errors currently obtained on TO absolute luminosity ($\sim$ 0.2 mag), metallicity ($\sim$ 0.2 dex), and helium abundance ($\sim$ 0.02) lead to an error on the absolute age not smaller than 3 Gyr.

Therefore the problem, from the observational point of view, is four-fold:

- Test the evolutionary models (assumptions, input physics, approximations, etc.) to ensure a proper *clock running*. See Section 4 which is devoted to the discussion of this item.
- Derive the TO apparent magnitude and colour as accurately as possible from the observations, to ensure a proper *clock reading*. The TO luminosity level is a quantity of intrinsically difficult sharp definition, as the TO region is almost vertical in the V-(B-V) plane. Alternative filter combinations should probably be devised. The required photometric accuracy ($\sim$ 0.01–0.02 mag for the individual stars at the TO) can be obtained if the observations reach at least 2–3 mag below the TO ($V \sim$ 20–27, depending on the cluster distance).

This can already be done with good CCD equipment and 4-m-class telescopes on sufficiently well-populated external zones of the clusters.

- Estimate accurate chemical abundances (not only overall metallicity, [m/H], and helium abundance, Y, but also the relative abundances of elements such as Fe,C,N,O, etc. which are very important for the determination of the correct theoretical model), with an accuracy of at least 0.1 dex. The bright red giant branch (RGB) stars can be used for this purpose, although some tests to verify that these abundances do not differ from those of the MS stars are recommended. The spectroscopic observations of the RGB stars can be obtained with 4-m-class telescopes, the MS stars are much fainter ($V > 17$) and require the use of an 8-m-class telescope and high-resolution spectrographs (MFAS, UVES).
- Estimate accurate distances to the clusters, as the *absolute* magnitude of the TO is needed to determine the age. This relies upon the use of various types of "standard candles", for example:

– The RR Lyrae variables. Absolute magnitudes can be obtained using the Baade-Wesselink method which requires accurate V(RI)K light and radial velocity curves. The accuracy presently attained on individual field stars is about 0.15 mag using 1.5-m telescopes with CORAVEL and 1-m telescopes for the photometry (Cacciari *et al.* 1992). A few stars in three among the nearest GCs have been analysed with considerable better accuracy. This programme is feasible with 4-m-class telescopes, and by averaging the results on several stars in a cluster, a sufficiently high *internal* accuracy can be obtained.

– The HB luminosity level, applied to globular clusters in M31. Given the large distance to M31, its globular clusters can be considered all at the same distance. Therefore, the apparent magnitude level of the HBs as a function of metallicity provides directly the slope of the HB luminosity-metallicity relation, whereas the zero-point of this relation has to be set by other methods (see above). This needs accurate photometry ($\sim$ 0.1 mag) of individual stars at $V = 25$–26 in crowded fields where the spatial resolution is essential. The HST is presently the only instrument capable of this performance.

– The RGB tip. This method needs accurate and complete luminosity functions of all bright stars ($M_V \sim -3$, $V \sim$ 10–17) in very populous clusters to reduce the impact of statistical fluctuations. It can be done with small/medium-size telescopes.

– The field subdwarfs with known accurate parallaxes (e.g. from Hipparcos) and metallicity determinations. These stars are used to match the MS stars in a globular cluster with the same metallicity, and thus derive their absolute magnitudes. All the necessary photometric and spectroscopic observations can be done with small/medium-size telescopes.

– The White Dwarfs (WDs). According to theoretical predictions (Fusi Pecci and Renzini 1979, Renzini 1985) the WD cooling sequence is well defined in the logL–logT$_e$ plane (to within ± 0.03 mag) and could be used in Galactic GC distance determination. Since very accurate photometry and medium-low resolution spectroscopy (to confirm the WD nature and to distinguish between DA and DB types) of very faint stars is needed, the use of an 8-m-class telescope is required. However, the very high space resolution and the possibility to observe in the UV wavelength range make HST a better suited instrument for this purpose. Nonetheless, the VLT can be used profitably on certain aspects of this programme (e.g. spectroscopy), and also to search for WD candidates in the more external regions.

As an example, for a WD star at approximately 25,000° K ($M_V \sim 10 \Rightarrow m_V \sim 23$–30) an error in the temperature of 1000°K (corresponding to $\Delta$(1800-V) = 0.078, $\Delta$(U-B) = 0.025 and $\Delta$(B-V) = 0.005) produces an error in the absolute bolometric magnitude of 0.234 mag. Accurate UV photometry of many very faint stars is therefore very important in order to define a reliable distance modulus. To avoid using UV data, not accessible from the ground, one can try to detect and measure cooler WDs, which are however fainter (a temperature difference of 10,000°K corresponds to a magnitude difference of about 1.5 mag). At magnitudes $m_V \sim 25$–32 the same error in temperature and luminosity as above corresponds to photometric errors $\Delta$(U-B) = 0.06 and $\Delta$(B-V) = 0.02, and by observing 10–20 WDs significant results can be obtained. The major problems will be crowding and field decontamination, and a sufficiently wide population sampling.

- *GC Peak Luminosity Function*

Some further impact of the GCs on the distance-scale determination is offered by the study of globular clusters in external galaxies (after proper calibration on Local Group clusters). This method does not intend to find the distance and age of globular clusters, but uses the brightest globular clusters as standard candles to derive the distance to external galaxies. The zero-level assumption is that the Luminosity Functions (LFs) of GCs are described by the same law everywhere or, at least, that it is possibile to know in detail how the LFs vary with varying galaxy morphological types and masses.

This method needs very deep imaging over quite large fields for magnitudes and colours (and possibly photometric metallicity indices), and medium-low resolution spectroscopy for testing the GC nature and membership and for abundance determinations. Depending on how far one wants to reach (M81, NGC 5128, Virgo, etc.), a transition from 4-m-class telescopes to HST is necessary for imaging. Similarly, 8-m-class telescopes with MOS capability are necessary for an effective spectroscopic investigation (MFAS, FORS).

### *2.2 Very Low Mass (VLM) stars, Brown Dwarfs (BD) and dark matter*

Many candidates exist for baryonic dark matter, with masses ranging from black holes down to comets. Among the most popular candidates are the stars at the low-mass end of the Initial Mass Function (IMF). These degenerate dwarfs are commonly roughly divided into two sub-groups, i.e. the very low mass stars (VLM) above the hydrogen-burning limit ($\sim 0.08\ M_\odot$), and the brown dwarfs (BD) with $M < 0.08\ M_\odot$.

The latest results on microlensing of LMC stars presented by Alcock *et al.* (1993) and Aubourg *et al.* (1993) add support to the existence and importance of these very low luminosity degenerate objects. However, to provide a significant quantity of baryonic dark matter to the Galactic halo, a steepening of the IMF slope at very faint limits, well into the VLM and BD regions, is absolutely necessary.

The main challenging problems are (a) constructing a statistically complete and uncontaminated sample of these very faint stars, (b) transforming the observed MS Luminosity Function into a Present-Day Mass Function (PDMF) via a theoretical mass-luminosity relation and known bolometric corrections, and (c) understanding the relationship between the PDMF and the IMF.

Globular clusters offer the environment where a sufficiently homogeneous group of VLM and BD objects could still live unless dynamical evolution and stripping have totally depleted the clusters. Though the clusters' low metallicity makes the VLM and BD brighter than expected in the solar neighbourhood and in the Galactic disk, these objects in the typical Galactic globulars (even in the closest ones) are very faint, V > 25–27, and securing statistically complete and uncontaminated LFs is extremely difficult with the available tools.

By measuring deep I-band LFs in six GCs, Fahlman *et al.* (1989) and Richer *et al.* (1991) have claimed that most GCs probably have very steep IMFs (slope $x > 2.5$, with Salpeter IMF $x = 2.35$), implying a large number of low-mass Pop II stars in the halo. On the other hand, Piotto and collaborators (see Piotto 1993) have found that the PDMFs measured in the mass range $0.5 < M/M_\odot < 0.8$ in about 20 GGCs correlate with position in the Galaxy.

Recently, Paresce *et al.* (1994) using deep HST-WFPC2 images have obtained the LF for the MS of NGC 6397 down to $m_I \sim 25$. Their corresponding PDMF rises to a plateau between $\sim 0.25$ and $\sim 0.15\ M_\odot$, but drops towards the expected mass limit of the hydrogen-burning MS at about $0.1\ M_\odot$. As they note, this result is in clear contrast to that obtained from the ground for the same cluster by Fahlman *et al.* (1989) and may alter strongly the possible implications on dark matter problems.

According to the Wide Field Direct Visual Camera specifications (Wampler 1994), this imager at the VLT would be capable of providing a space resolution of 0.1 arcsec FWHM (almost comparable with HST), a larger field of view and 10 times the HST collecting area. Assuming the limiting magnitude $I \sim 28.5$ (for S/N $\sim 2$ in 10 hours) one could for instance extend the LF obtained in NGC 6397 by Paresce *et al.* (1994) by at least two magnitudes.

On the other hand, VLMs and BDs have high density and cool atmospheres ($T_{eff} < 3000$°K) dominated by $H_2$ molecules, hence they emit predominantly in the red and IR bands. Both ISAAC and NIRMOS would thus be most suitable for both detection and low-resolution spectroscopy of very faint candidates. For example, NIRMOS can provide unique LFs as faint as J = 25 and H = 24 with S/N = 10 in 1 hour with pixel scale 0.3 arcsec, and also low-resolution spectroscopy (R = 200) for candidates as faint as J = 22 and H = 21 with S/N = 10 in 4 hours (Le Fèvre 1994).

## 3. Tests of Galactic Formation and Evolution

The various models of galactic formation and chemical evolution (see Majewski 1993 for references) can be tested by investigating three main aspects of the globular cluster system, namely: (i) the age spread, (ii) the relation between location within the Milky Way, kinematics, dynamics, metallicity and age, which provides also the galaxy total mass and its distribution out to distances of ~100 Kpc, and (iii) the abundance ratios, which are a signature of the initial chemical composition of the protocluster stars and hence of their origin. This can be done by studying an adequate sample of individual stars in each cluster to derive the average properties of the cluster itself, or by investigating the integrated properties directly.

Globular clusters in our own Galaxy (GGCs) and in the other galaxies of the Local Group (including the dwarf spheroidals) represent the best template stellar populations for this purpose, as they cover the requested wide range in ages and metallicities, provided they can be assumed as reliable representatives of the halo and bulge stellar population. A similar complementary approach has to be pursued with field stars, but we shall not discuss them here.

### 3.1 Age spread and the HB "second parameter" problem

In order to distinguish between different models of galaxy formation, an accuracy not worse than ± 0.5 Gyr is necessary in the *relative* ages (coupled with complementary data on abundances and kinematics). Relative ages with respect to a given reference cluster can be derived more easily and accurately than absolute ages, after proper calibration of suitable photometric and spectroscopic features.

In a resolved cluster, the two basic methods presently used are the so-called *vertical method*, which measures the magnitude difference $\Delta V_{HB}^{TO}$ between the Turnoff (TO) and the Horizontal Branch (HB) (see Buonanno *et al.* 1989, Sandage and Cacciari 1990), and the *horizontal method*, based on the colour difference between the TO and the RGB (VandenBerg *et al.* 1990, Sarajedini and Demarque 1990). To achieve the error in age of ± 0.5 Gyr, the errors in magnitudes and colours must be smaller than 0.03–0.04 mag and 0.01 mag, respectively. The chemical abundances must be known at the level of accuracy requested for the absolute age determination. These requirements can be met using (V,B-V) or (V,V-I) photometry and spectroscopy, both currently feasible with 4-m-class telescopes for most of the galactic halo and Magellanic Cloud GCs. Globular clusters in the bulge, however, need IR (K,V-K or K,J-K) observations because of the very large extinction in that region of the Galaxy, and 8-m-class telescopes are necessary to obtain accurate magnitudes at least 2–3 mag fainter than the TO (K(TO) $\geq$ 16) and properly define the unevolved MS. Moreover, since the required space resolution is very high, Adaptive Optics techniques are crucial. The scheduled VLT instruments ISAAC and CONICA, equipped with large-format arrays and AO facility, can satisfy these requirements, allowing deep and both high (for the central regions) and medium (for the external zones) space resolution imaging in various near-IR filters.

In non-resolved clusters, ages could be estimated by means of integrated colours and spectroscopic indices, after proper calibration on the local template clusters, for which age and metallicity are known. For the clusters in M31, where the TO region for direct age estimate is not accessible even to HST, a multiobject spectrograph on a 4-m-class telescope is sufficient for the purpose. For more distant clusters, FORS and MFAS on the VLT are the ideal instruments thanks to the size of the field of view, the number of slits or fibers, and the spectral resolution.

The use of the VLT opens a new window to this type of studies as deep imaging and spectroscopy can be extended into the IR. In fact, in the near-IR region there are many interesting stellar absorption features due to atomic (neutral metals such as Si, Mg, Al, etc.) and molecular (CO, OH, $H_2O$, CN, etc.) species which are very sensitive to the variation of the fundamental stellar parameters of cool stars. In fact, young stellar systems are characterized by the presence of cool and red M supergiants, while in older stellar populations the integrated luminosity is dominated by less massive and hotter giants.

For this purpose an 8-m-class telescope is necessary to take IR spectroscopy at different resolving powers (depending on the intrinsic broadening of the selected atomic and molecular lines) of a complete sample of globular clusters in our Galaxy and in the Local Group. Only the $\sim$ 20 brightest clusters both in our Galaxy and in the Magellanic Clouds are presently observable in the IR at medium-low resolution with a 4-m telescope, having K $<$ 16 mag per square arcsec. An instrument like ISAAC can provide these fundamental data. A multifiber imager-spectrometer (like NIRMOS) is crucial, especially to observe globular cluster systems in the Local Group galaxies, which are spatially separated by a few tens of arcsec, depending on the galaxy distance.

Another possible approach to deal with relative characteristics between GGCs is to study their HB morphologies, in particular the so-called "HB second parameter effect", i.e. the occurrence of extremely blue or red HBs in clusters having the same (intermediate) metallicity.

In the Galaxy the "second parameter" morphology seems to be related with the Galactocentric distance (Zinn 1986). Differences in age up to 3–5 Gyr have been detected among globular clusters (see Buonanno *et al.* 1994, for references), and age is presently the most favoured second parameter candidate. However, the dynamical and structural conditions of the clusters (stellar density, concentration, kinematics, etc. see Section 4) could play a rôle (Fusi Pecci *et al.* 1993).

HBs in GGCs are sufficiently bright (including the faintest part of the extended BHB) to allow very accurate photometry with medium-size telescopes (apart from the highly crowded central regions which require the use of HST). As mentioned below, spectroscopic measurements necessary to disentangle basic evolutionary problems related to HB stars require very high resolution, hence the use of the VLT.

Photometry of HBs in the Magellanic Clouds and in the Fornax dSph galaxy is also feasible with 4-m-class telescopes, and would possibly need HST only in order to achieve sufficient space resolution in the central regions. Useful spectroscopy of individual HB stars in the MCs and beyond, however, cannot be done without 8-m-class telescopes and instruments like FORS, MFAS, NIRMOS, etc. to yield abundances and velocities as accurate as those presently obtained in the Galactic GCs.

For the globular clusters in M31 and beyond, the use of HST or of the VLT with highly sophisticated Adaptive Optics devices is indispensable to detect individual HB stars because of the faintness of the stars and the spatial resolution necessary to resolve them.

In unresolved clusters the best (possibly only?) way to detect "second parameter" HB morphologies is probably in the UV (with HST), after proper calibration with local clusters, but there are problems with the possible dominant impact of just a few UV-bright stars. Useful information on the HB morphologies can be obtained also using visual and near IR photometry (UVK) once the metallicity effects have been estimated with low resolution spectroscopy in the red,
where the major contribution is due to cool stars.

### 3.2 Dynamics of the GC system and the parent-galaxy total mass

The necessary data for a comprehensive study of the dynamics and kinematics of the GC system are radial velocities, spatial motions and knowledge of orbit type and possible interactions with the parent galaxy. In turn, globular clusters themselves can be used as test particles to study the radial mass distribution and the total mass of the parent galaxy.

For the Galactic GCs, radial velocities can be obtained with the highest accuracy from the analysis of a large number of individual cluster stars, and the use of 4-m-class telescopes is adequate to this purpose. Obtaining space motions and orbital shapes is however the crucial item. According to the latest estimates (Tinney, 1994) important progress can be made using CCD devices and 8-m-class telescopes, as accurate proper motions could be obtained using a relatively short baseline (5–10 years).

Spectroscopic observations of extragalactic cluster candidates in very distant galaxies require typical integration times of several hours per cluster. In addition, since clusters beyond $\sim$ 2 Mpc can hardly be distinguished from foreground stars and background galaxies, the observing efficiency will be considerably lowered by the contamination from spurious objects. The use of Multi Object Spectroscopy on the VLT is therefore essential to make these programmes feasible and efficient.

### *3.3 Chemical abundances and abundance ratios*

The surface composition of unevolved stars reflects that of the ISM at the epoch of their formation. Therefore, in a simple, closed-box model of the galactic chemical evolution, the element-to-element abundance ratios are determined by the interplay between the timescales of star formation and evolution, because the yields of production of different elements are a function of stellar mass. Since the star formation rate is usually related to the density of the ISM from which the stars form, it is important to study stars at various locations corresponding to different densities of the ISM, in particular in the galactic halo and bulge. Since globular clusters as such do not play a specific rôle in this issue, we refer the interested reader for instance to Larson (1974), Gratton and Sneden (1989) and McWilliam and Rich (1994) for the latest results.

## 4. Stellar Evolution Tests

Globular clusters in the Galaxy or in the MCs where different age-metallicity combinations can be found, are excellent laboratories to test the assumptions and results of the stellar evolution theory. Many basic quantities (e.g. age, primordial helium abundance, etc.) can be determined once the model validity is verified and guaranteed (see for discussion and references Renzini and Fusi Pecci 1988, Chiosi *et al.* 1992). Some of these tests use photometric techniques on relatively bright stars (e.g. luminosity functions of post-MS stars) and can be carried out satisfactorily with 4-m-class telescopes (or HST if high space resolution is required). Other tests, which are based on high-resolution spectroscopy of bright and faint stars, are more relevant for the present discussion.

### *4.1 Spectroscopic tests of stellar evolution*

The original surface composition of stars is altered during their evolution by various mechanisms. Therefore, the study of abundances of stars in different stages of their evolution, but likely with the same original composition, provide basic and sensitive tests of stellar evolution. We will now consider separately different phenomena which have been observed, or are likely to be important, for old (small-mass) stars and which can be excellent programmes for an 8-m-class telescope.

- *Diffusion and Lithium abundances in main-sequence and turn-off stars*

Diffusion on the Main-Sequence may affect the abundance of Li for stars in the Turn-Off region of globular clusters. Li abundance in metal-poor stars provides a basic constraint on cosmological models. A significant fraction of the present Li may have been formed during the Big Bang; once this fraction is determined, it should severely constrain the baryonic density in the universe.

In this respect, a very important result was achieved by Spite *et al.* (1984), who found a constant Li content (LogN(Li) = 2.05 ± 0.2) among a large group of unevolved, metal-poor, old stars, that is likely to be the Big Bang signature. However, Li is manufactured also by other processes: the most important contribution is spallation by cosmic rays on interstellar grains, but a significant fraction may come from intermediate-mass stars during their AGB phase. On the other hand, Li is easily destroyed in stars and a careful discussion of these mechanisms (which depend on details in the internal structure of MS and TO stars) requires a comparison with stars having an appropriate range in mass, ages, metallicity, and luminosity. Stars in globular clusters are thus very important, since these parameters are known with much better accuracy than for field stars.

A determination of the Li abundance for a star at the turn-off of NGC 6397 (the closest cluster, V(TO) $\sim$ 16) has been obtained recently by Pasquini and Molaro (1994) using EMMI at the ESO NTT. However, these observations ( $R = 28{,}000$, $4 \times 90$ min) are clearly at the limit of a 4-m-class telescope's possibilities, and a systematic study of stars of different luminosity in various clusters can only be done using an 8-m-class telescope. UVES at the VLT is very well suited for these studies.

- *Mixing and environment*

Dredge up of CNO-processed material is expected to occur in GC stars at the base of the RGB (first dredge up) and perhaps during the latest stages of AGB evolution (third dredge up). Classical theory predicts a moderate mixing (with depletion of $^{12}$C, and enhancement of the surface abundances of $^{13}$C and $^{14}$N) during the first dredge up (VandenBerg and Smith 1988). No alteration is predicted for other observed elements, including O, Na and Al.

These predictions are generally rather well satisfied for most metal-poor field stars, which show a well-defined trend of C and N abundances and isotopic ratios with luminosity, and no clear indication of O depletion. The low $^{12}$C/$^{13}$C ratios observed in the brightest field halo giants could be explained by a slightly more severe mixing, which could be due to meridional circulation activated by core rotation (Sweigart and Mengel 1979). The only rare exceptions (Ba stars, CH stars, N-rich dwarfs) can probably be explained by pollution from an evolved companion, presently a white dwarf; Ba stars and CH stars are in fact known to be members of spectroscopic binary systems.

Observations of stars in GGCs show a far more complex picture (Smith 1987). Only in a few clusters (like M92 and NGC 6397) there is a quite good correlation of C and N abundances with star luminosity; in most clusters stars with weak and strong CN bands (both sharing a similar fraction of the overall population and sometimes exhibiting bimodal distributions in CN band strengths) stand side-by-side in all regions of the CMD, even at the TO level. These anomalies are correlated with variations of strength of the O, Na and Al lines: there is a clear anticorrelation between O and Na overabundances (Kraft *et al.* 1992), while the sum of CNO abundances is probably constant. Finally, several authors found very low $^{12}$C/$^{13}$C ratios.

There are strong indications that a dense environment plays an important rôle in causing these anomalies: however, the responsible mechanism has not been identified yet, candidates being enhanced core rotation (perhaps due to close encounters between protostars), pollution by (possibly temporary) companions or even by other cluster members, and/or some still unknown mechanism (mixing?) at work during evolution.

The dependence of these mechanisms on evolutionary phases and cluster dynamical parameters is different, and a systematic study of large samples of stars at different luminosities and positions in several clusters is decisive.

While specific observations for a few bright giants may be carried out with a 4-m-class telescope, a fiber instrument like MFAS (both in the Medusa and Argus mode) at an 8-m-class telescope is required for a systematic and complete study of fainter stars.

- *Mass loss and intracluster matter*

Stellar evolution models predict a mass loss of $\sim 0.2\ M_\odot$ prior to the HB phase and $\sim 0.1\ M_\odot$ on the asymptotic giant branch (AGB) (e.g. Fusi Pecci and Renzini 1976, Renzini 1977). This mass loss is required to explain the morphology of the HB observed in the GC colour-magnitude diagrams and the lack of any significant population of AGB stars brighter than the RGB tip.

Quantitative direct information on mass-loss rates can hardly be obtained so far for any star, and especially for globular cluster stars no reliable data are available. The basic features related to stellar mass loss are the lines in the UV domain, OH masers (1612 MHz), CO lines (in the microwave range), dust-induced features in the IR, and Ca H+K or $H_\alpha$ lines (but these can be contaminated by other contributions). As an example, with the VLT + UVES one could extend to GC stars the type of studies carried out by Reimers (1975) on field stars, based on the detailed analysis of high-resolution Ca H+K line profiles.

Assuming a constant gas-to-dust ratio and typical expansion velocities (Skinner and Whitmore 1988) useful data could be obtained using VLT + MIIS by observing the brightest GC stars for instance at 9.7, 11.5 and 18.0 $\mu$m, typical features already observed in bright nearby objects with high mass-loss rates.

As a result of stellar mass loss, some amount of interstellar matter should also be present in GCs. A typical GGC population of $\sim 10^3$ post-TO stars is expected to release about $10^2$–$10^3\ M_\odot$ of intracluster matter during the $\sim 10^8$-yr periods between each cluster passage through the galactic plane. This matter should be present if no "cleaning" mechanism is at work. A significant amount of gas and dust could then be accumulated in the central regions of the most massive and concentrated clusters (i.e. those with large central escape velocity).

The intracluster gas could be in the form of atomic (neutral or ionized) hydrogen and/or molecular $H_2$ and CO. Searches for HI and $H_\alpha$ emission (Smith *et al.* 1990, Roberts 1988, for a general review) in the central region of a few GGCs resulted only in marginal detections which would be incompatible with a total mass loss per star of $\sim 0.3\ M_\odot$, if the cluster is "closed". A few explanations for this apparent lack of gas have been suggested, and invoke for instance high gas velocities (e.g. winds driven by novae or flare stars) but the details are not well understood yet.

Searches for CO performed so far in the central regions of GGCs (Schneps *et al.* 1978) have been unsuccessful, but no firm conclusions can be derived from these observations because of the low sensitivity and the small beam of the employed receivers.

On the contrary, some evidence of cold dust was found in the intracluster medium of GGCs (Forte and Mendez 1989). Its origin is probably related to the processes of mass ejection during the RGB and AGB phases, which would imply the presence of dusty envelopes around red variables, as also suggested by the IR excess that has been measured around luminous giants and long-period variables in 47 Tuc (Frogel and Elias, 1988; Gillet *et al.* 1988). Multicolour polarization and CCD photometry of some clusters with $P \leq 2\,\%$ and scattered polarized light detected at a few core radii suggest that the dust distribution may be considerably extended within the central region of the observed GGCs.

In many clusters IRAS point sources have also been detected within their tidal field (integrated fluxes in a 30" aperture between 0.2 and 1 Jy, Lynch and Rossano 1990). For some of them this far-IR emission might indeed be due to dusty structures in the intracluster medium, because the IRAS sources are located in the cluster core. A few of them are extended at 12 $\mu$m, with typical sizes of 2–4 arcmin, and this could be a significant indication of the presence of cold dust in the intracluster medium. A mid-IR Imager/Spectrometer would allow to investigate the presence and the chemical composition of these dusty features in the circumstellar envelopes of the coolest giant stars and/or in the intracluster medium.

ISO observations can provide a deep survey (0.1–1 mJ) of the cluster central regions with low spatial resolution and small field of view, due to the small-format arrays. The use of an 8-m-class telescope and large-format arrays would allow to make almost as deep surveys (down to $\sim$1 mJy per square arcsec) on a much larger field of view (a few arcminutes) and with high spatial resolution (0.1"/pixel and an Airy disk of 0.6" at 10 $\mu$m). A complete mapping of the emission regions would thus be possible, even for quite extended and low surface brightness areas. Note that the high spatial resolution available only with the VLT will allow to distinguish between diffuse emission (dust) and point sources (very cool stars, e.g. brown dwarfs or carbon stars). An instrument like MIIS could satisfy these requirements.

- *Gravitational settling, diffusion and rotation for HB stars*

As mentioned above, the distribution of stars on and their evolution off the ZAHB of GCs is not yet completely understood. However, it is known that the combined action of gravitational settling and outward diffusion by radiation pressure observed in Pop-I B8-F2 stars may change significantly the surface abundances of He and metals in the outer radiative envelope of hot HB stars, since the typical timescale of these phenomena ($10^8$ yr) is close to the HB lifetime. On the other hand, diffusion might be inhibited by rotation.

Observations of lines of He and heavier elements might then provide the age of stars on the HB, and then be used to distinguish between ZAHB and evolved stars once additional information on rotational velocities is available (see below). With proper modeling, one could get information on the direction of evolution off and along the HB. Earlier explorative observations of He lines have been done by Crocker and Rood (1988); however, an 8-m-class instrument is required for extensive observations of different elements as quite high spectral resolutions (UVES with $R > 40{,}000$) are necessary and the stars are faint ($V \sim 14 \Rightarrow 20$).

Spectroscopic observations of HB stars are also important to better understand the mass-loss mechanisms, since the colour distribution of these stars is controlled, for fixed core mass and composition, by the residual mass of the H-rich envelope. For instance, Renzini (1977) predicts that stars with fast core rotation evolve into blue HB stars, since the helium flash would occur at a higher luminosity and, in turn, the total amount of mass lost while experiencing the RGB phase would be larger.

Peterson (1983) found a high frequency of larger-than-normal rotational velocities in BHB stars of M13. While the relation between surface and core rotation is not clear yet, these relatively high rotational velocities could help explain the very blue horizontal branch of M13, a typical example of the second-parameter phenomenon. A confirmation of Peterson's result would thus be of paramount importance as one could eventually get direct hints on both rotation and mass loss. However, these observations are very difficult and uncertain as the blue HB stars are faint and reliable rotational velocities require high-resolution spectra with high S/N ratios. The use of an 8-m-telescope with a MOS capability is thus highly desirable.

### *4.2. Binaries: Blue Stragglers, CVs, X-ray sources, MSP, etc.*

It is common belief that any object which does not fit into the "standard evolution theory" of normal stars could somehow be related to a binary system. Though it seems unlikely that binarity is responsible for so many different types of stars, it may be interesting at least to mention several categories of "unusual" cluster members: objects include for instance:

- blue stragglers
- subdwarfs O and B
- cataclysmic variables
- dwarf Cepheids
- extremely blue HB stars
- novae
- Ba, CH stars, etc.
- UV-bright objects
- "naked" or "nude" very blue stars
- X-ray source
- millisecond pulsars (MSP)

Since until recently there was even some doubt whether binaries might exist at all in globular clusters, the questions to answer are: how many binaries are present in GGCs? and how do they form, survive, evolve, interact with the environment?

To study these variegated classes of objects different techniques have been successfully used in the optical, X-ray, and radio bands. Several interesting programmes could easily be carried on with the VLT, for the sake of example we list here a few of them:

1. Detection of radial velocity variables. Systematic surveys with MFAS aimed at checking velocities of individual cluster stars ($\sigma \sim 1$ km s$^{-1}$) may reveal a number of candidate binaries starting from the bright giants down to the faint MS.

2. Detection of photometric variables. A survey using both MFAS and FRISPI could lead to detect eclipsing binaries and to study their periods. In particular, the study of variability could be focused on blue stragglers as about 25% of them have been found to vary (Stryker 1993). Moreover, one could also use the properties of spectrophotometric binaries to yield distances.

3. Detection and study of cataclysmic variables and novae. Though the total number of such objects detected so far in GGCs is low and, moreover, their membership is frequently uncertain, one could use high-resolution spectra in the UV region taken with UVES to study in detail their properties. Since these stars are faint ($V > 18$ even in the closest clusters), the VLT is absolutely necessary.

4. Detection of a "second" MS. If binaries are still present in the MS of a cluster and if they are formed by approximately equal mass components, one expects to detect some spread in the intrinsic MS colour or even the existence of a second "binary MS" parallel to that of single stars. Preliminary detections of such an effect have been presented for instance by Bolte (1992), but more accurate data and a spectroscopic follow-up is necessary to confirm the evidence. The use of spectra obtained with MFAS may allow the detection of radial velocity variations in the candidates found via very deep imaging.

5. Study of X-ray sources and Millisecond Pulsars. This topic is so wide and the possible observations so many that we simply mention it. In this respect, especially spectrophotometry with MFAS and FRISPI are crucial to both identify and study the optical counterparts.

We wish to discuss here in some more detail the study of the blue straggler stars (BSS) and of their possible descendants. BSS can be formed via several mechanisms mostly involving the interaction and merging of stars in binary systems (both primordial and formed through subsequent encounters in dense cluster cores). These BSS have similar photometric characteristics but different physical properties, and are expected to have a mass in the range 0.8–1.6 $M_\odot$ (Nemec 1991; Fusi Pecci *et al.* 1992; Bailyn 1992). When they evolve off the MS and into the He-core burning phase, they are expected to be located on the red extreme of the HB due to their large mass (Seidl *et al.* 1987). Therefore, although their location on the HB looks *normal*, their mass distribution is very different from typical (single) red HB and RGB stars.

Metal-poor clusters with blue HBs are the ideal place where these candidate BSS descendants could be better detected, as they would be the only stars located at the red HB extreme. On the other hand, these stars might display some different characteristics if they had not been able to lose a substantial fraction of the large angular momentum acquired with the merging.

In this case, a large rotational velocity should be expected, the presence of a large convective envelope would probably cause a strong dynamo effect, and hence a rather strong activity (analogous to that observed in FK Com objects). These effects should be detectable with appropriate spectroscopic observations. Finally, He, CNO (mainly O isotopic ratios) and Li abundance anomalies might be present, even though the theoretical background is not well defined at present (Bailyn 1992; Pritchet and Glaspey, 1991).

While adequate observations of a few very bright BSS descendants in some clusters are feasible with a 4-m-class telescope, an 8-m telescope is absolutely required for most BSS progeny, as well as for the direct observation of BSS themselves. The need of a quite high spectral resolution ($R = 30{,}000$) and a statistically significant sample of stars requires the use of a fiber-fed, optical and IR medium/high-resolution spectrograph (the determination of the O isotopic ratio can best be done with high-resolution observations of the CO bands in the K wavelength region).

## 5. Cluster Internal Dynamics

Globular clusters are ideal sites to test dynamical models of stellar systems, since they are relatively simple structures where large samples of individual objects can be observed.

Early dynamical models of globular clusters as a population of spherically distributed point-like single-mass objects were constructed by King (1966). These models predict a rather simple dynamical evolution of a cluster, with the formation of a dense core which finally collapses (gravothermal instability: Antonov 1962), while the outer parts of the cluster are dispersed (evaporation: Ambartsumian 1938, Spitzer 1940).

With later (multi-mass) modifications, King's models describe rather well the properties of the majority of GGCs, allowing to derive important global parameters like the mass-to-light ratios, total mass, etc. However, there is a substantial fraction of clusters whose light profiles clearly deviate from King's model predictions, since they do not exhibit the expected central plateau; these clusters have been identified (Djorgowsky and King 1986) as post-core collapse clusters, since it has been recognized long ago that formation of close binary systems and stellar evolution in very dense cluster cores may provide an energy source able to prevent the final collapse of the cluster core (Henon, 1961). However, numerical simulations of the dynamical behaviour of post-core collapse clusters are rather uncertain, due to the presence of large instabilities (gravo-thermal oscillations: Bettwieser and Sugimoto 1984, Goodman 1987).

Furthermore, since there are now strong arguments supporting significant modifications of stellar surface abundances and even stellar evolution itself in very dense environments, a systematic study of the dynamical properties of a very large cluster sample would be highly welcome.

These programmes require high precision measures of radial velocities (error $< 1$ km s$^{-1}$) for a large sample of stars in various cluster regions.

On a 4-m-class telescope, these observations are limited to a few bright giants, whereas MFAS is very well suited for these programmes, the Argus mode being useful for the cluster core and the Medusa mode for the outer regions.

Finally, it is natural to conclude by mentioning one of the most obvious dreams of anyone working on globular clusters, i.e. to observe the very central regions (a few fractions of a parsec) with the maximum possible spatial resolution. To this aim, the VLT in its interferometric configuration is the *only* instrument capable of achieving the necessary resolution. If one could reach the nominal resolution of about 0.004 arcsec, one could really make an incredible step forward even compared to the best results one could possibly obtain from HST in its best configuration ($\sim$ 0.02 arcsec).

## 6. Conclusions

In conclusion, it is quite evident even from our schematic and incomplete review of globular cluster studies that the VLT will be an extremely important tool for yielding a better insight into most of the current hot problems. A fruitful complementarity exists between the results uniquely achievable from space (with HST, ISO, etc.) and those one can better obtain from the ground with the VLT and its many detectors. In this respect, it is important to note that (i) there are crucial observing programmes which require not only the use of the already planned VLT instruments (i.e. FORS, ISAAC, CONICA, UVES, and MFAS) but also of some instruments presently under study or just proposed like MIIS, NIRMOS, FRISPI, and WFDVC; and (ii) several extremely important issues in the study of globular cluster problems can best be addressed in the IR wavelength range, and since neither HST nor ISO for various different reasons are able to carry out the necessary observations, IR instruments for the VLT (especially in the near and intermediate IR) should have a very high priority in the selection, construction and commissioning.

### *References*

Alcock C., *et al.* 1993, *Nature*, **365**, 621.
Ambartsumian V.A. 1938, Ann. Leningr. State Univ. No. 22.
Antonov V.A., 1962, Vestn. Leningr. Gros. Univ. **7**, 135.
Auburg E., *et al.* 1993, *Nature*, **365**, 623.
Bailyn C.D. 1992, *ApJ*, **392**, 519.
Bettwieser E., Sugimoto D. 1984, *MNRAS*, **208**, 439.
Bolte M. 1992, *ApJ*, **376**, 514.
Buonanno R., Corsi C.E., Fusi Pecci F. 1989, *A&A*, **216**, 80.
Buonanno R., Corsi C.E., Fusi Pecci F., Richer H.B., Fahlman G.G. 1994, *AJ*, in press.
Cacciari C, Clementini G., Fernley J.A. 1992, *ApJ*, **396**, 219.
Chiosi C., Bertelli G., Bressan A. 1992, *ARA&A*, **30**, 235.
Crocker D.A., Rood R.T. 1988, in *Globular Cluster Systems in Galaxies*, IAU Symp. No. 126, eds. J.E. Grindlay and A.G.D. Philip, Kluwer, Dordrecht, p. 509.
Djorgowsky S.G., King I.R. 1986, *ApJL*, **305**, L61.
Fahlman G.G., Richer H.B., Searle, L., Thompson I.B. 1989, *ApJ*, **343**, L49.
Forte J.C., Mendez M., 1989, *ApJ*, **354**, 222.
Frogel J.A., Elias J.H. 1988, ApJ, **324**, 823.
Fusi Pecci F., Renzini A. 1976, *A&A*, **46**, 447.
Fusi Pecci F., Renzini A. 1979 in *Astronomical Uses of the Space Telescope*, eds. F. Macchetto, F. Pacini, M. Tarenghi (ESO), p. 181.
Fusi Pecci F., Ferraro F.R., Corsi C.E., Cacciari C., Buonanno R. 1992, *AJ*, **104**, 1831.
Fusi Pecci F., Ferraro F.R., Bellazzini M., Djorgovski S.G., Piotto G., Buonanno R. 1993, *AJ*, **105**, 1145.
Gillet F.C., deJong T., Neugebauer G., Rice W.L., Emerson J.P. 1988, *AJ*, **96**, 116.
Goodman J. 1987, *ApJ*, **313**, 576.
Gratton R.G., Sneden, C. 1989, *A&A*, **234**, 366
Helou, G. and Walker, D.W., 1986, *IRAS Small Scale Structure Catalog*, U.S. GPO, Washington D.C.
Henon M. 1961, *Ann. d'Ap.*, **24**, 369.
Hodge, P.W., 1983, *ApJ* **264**, 470.
Käufl, H.U., Jouan, R., Lagage, P.O., Masse, P., Mestreau, P. and Tarrius, A., 1992, *The Messenger* **70**, 67.
King I.R. 1966, *ApJ*, **71**, 64.
Kraft R.P., *et al.* 1992, *AJ*, **104**, 645.
Larson R.B., 1974, *MNRAS* **166**, 585.
Le Fèvre O. 1994, in *Instruments for the ESO-VLT booklet.*
Lynch D.K., Rossano G.S. 1990, *AJ*, **100**, 719.
Majevski S.R. 1993, *ARA&A*, **31**, 575.
McWilliam A., Rich R.M., 1994, preprint.
Nemec J. 1991, *Nature*, **352**, 286.
Molaro P., Pasquini L., 1994, *A&A*, **281**, L77.
Paresce F., De Marchi G., Romaniello M., 1994, preprint.
Peterson R.C. 1983, *ApJ*, 275, 737.
Piotto G. 1993, in *Structure and Dynamics of Globular Clusters*, ASP Conf. Ser. 50, eds. S. Djorgovski & G. Meylan, p. 233.
Pritchet C.J., Glaspey J.W. 1991, *ApJ*, **373**, 105.
Reimers D., 1975, *Mem. Soc. R. Sci. Liège*, **6**(8), 369.
Renzini A. 1977, in *Advanced Stages of Stellar Evolution*, eds. P. Bouvier and A. Maeder, Geneva Obs., Geneva, p. 151.
Renzini, A., 1977, in *Advanced Stellar Evolution*, P. Buovier and A. Maeder eds., Saas-Fee, Geneva Obs., p. 149.
Renzini A. 1985, *Astronomy Express*, **1**, 127.
Renzini A., Fusi Pecci F. 1988, *ARA&A*, **26**, 199.
Richer H.B., Fahlman G.G., Buonanno, R., Fusi Pecci F., Searle, L., Thompson I.B. 1991, *ApJ*, **381**, 147.
Roberts M.S. 1988, in *Globular Cluster Systems in Galaxies*, IAU Symp. 126, J.E. Grindlay and A.G.D. Philip eds., Kluwer, Dordrecht, p.411.
Sandage A.R., Cacciari, C. 1990, *ApJ*, **350**, 645.
Sarajedini A., Demarque P. 1990, *ApJ*, **365**, 219.
Schneps M.H., Ho P.T.P., Barrett A.H., Buxton R.B., Myers P.C. 1978, *ApJ*, **225**, 808.
Seidl E., Demarque P., Weinberg D. 1987, *ApJS*, **63**, 917.
Skinner C.J., Whitmore B. 1988, *MNRAS*, **231**, 169.
Smith G.H. 1987, *PASP*, **99**, 67.
Smith G.H., Wood, P.R., Faulkner, D.J., Wright, A.E. 1990, *ApJ*, **353**, 168.
Spite M., Maillard J.P., Spite F. 1984, *A&A*, **141**, 56.
Spitzer L. 1940, *MNRAS*, **100**, 396.
Stryker L.L. 1993, *PASP*, **105**, 1081.
Sweigart A.V., Mengel, J.G. 1979, *ApJ*, **229**, 624.
Tinney C.G. 1994, in *Science with the VLT*, ESO-Garching.
VandenBerg D.A., Bolte M., Stetson P.B. 1990, *AJ*, **100**, 445.
VandenBerg D.A., Smith G.H. 1988, *PASP*, **100**, 314.
Wampler E.J. 1994, in *Instruments for the ESO-VLT booklet*
Zinn R.J. 1986, in *Stellar Populations*, Norman C.A., Renzini A. and Tosi M., eds., Cambridge University Press, Cambridge, p. 73.

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# Scientific Capabilities of the VLT Adaptive Optics System

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## 1. Introduction

The theoretical angular resolution power of a telescope of diameter D is limited by diffraction and is proportional to $\lambda$/D. However, atmospheric turbulence severely restricts the capabilities of astronomical telescopes. Whatever the aperture diameter, the resolving power of the telescope is limited by the seeing angle and so the image of a point source is spread most often