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New Horizons in Astrometry, Photometry, and Spectroscopy of Globular Clusters

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Abstract. In the last few years, new instruments, and new reduction techniques for both optical imaging and spectroscopy with groundbased and space facilities have disclosed new horizons in Galactic globular cluster research. We present some of the most interesting (and challenging) projects we have started to fully exploit the new instruments.

Key words. Techniques: Astrometry – Photometry – Spectroscopy – Globular Clusters

1. Introduction

In the last five years the advent of the 8-10m class optical telescopes, and the availability of new, high performance instruments have given to the astronomers the possibility of acquiring up to two order of magnitude more observational data with the same amount of observing time than in the recent past.

The larger collecting area of groundbased telescopes, and new generation cameras like the Advanced Camera for Surveys (ACS) on the Hubble Space Telescope (HST), has allowed deeper investigation of the sky. CCD mosaics have given the possibility to map and to get accurate photometry of large portions of the sky, covering, for each pointing, fields as large as 60 arcmin^2. Multifiber spectrographs allow to get many hundreds, up to more than one thousand spectra for each pointing. Also, the high resolution of HST images, and the ten years or more temporal baseline give the possibility to measure accurate proper motions of a large number of globular cluster (GC) stars.

On one hand, this quantum step in the observing possibilities and performances has implied radical changes in the way the astronomers reduce and analyze their data. On the other hand, it has given the possibility to imagine and execute new, interesting, and sometime rather challenging projects we could not even think about ten years ago. The first,

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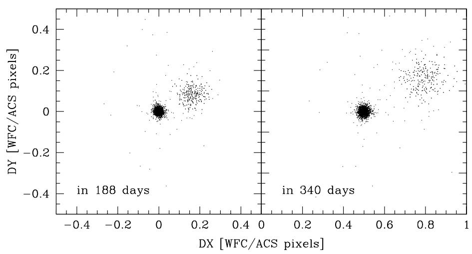

Fig. 1. Clear separation of the M4's members from the foreground/background field objects, in just 188 days. A comparison with the 340 day displacements shows how the internal pms of both members and non-members are appreciable.

sometime puzzling results are coming out, and more can be easily expected for the near future.

2. HST Photometry and Astrometry

In King et al. (1998) we pioneeristically showed that the Wide Field Planetary Camera 2 (WFPC2) on board of *HST* allows astrometric position measurements with a precision of the order of a few milliarcseconds (mas) on a single image. Since then, our reduction technique has furtherly improved (Anderson et al. 2000), making it possible to get astrometric accuracies of the order of $\sim$ 1mas/frame. This accuracy, allows to get in just few years proper motions with errors significantly smaller than what can be achieved by using groundbased plates and/or CCDs with a much larger time baseline (up to a factor ~50). As an example, Fig. 2 shows that in only 6 months we are able to separate the field stars from the M4 cluster members at least as clearly as in Cudworth et al. (1990, cf. their Fig. 1), who used groundbased plates with a time baseline of 90 yrs.

It is important to realize that accurate position measurements are an essential ingredient for accurate photometry. If properly reduced, the imaging camera of *HST* can provide unequaled high-precision (instrumental) photometry, also in crowded regions as often GC fields are, thanks to its high spatial resolution. The ACS camera has furtherly improved the photometric performances attainable with HST, moving the limiting magnitude to almost two magnitude fainter than the WFPC2, for the same exposure time.

Coupling the high photometric and astrometric accuracy, a number of investigations are possible. A few of them are listed in the following.

2.1. Hydrogen Burning Limit

There is a limiting mass below which a star cannot ignite the hydrogen in its core. This is the so called hydrogen burning limit (HBL). It is important to obtain color magnitude diagrams (CMD) and luminosity functions (LF) of GC stars down to the HBL, for at least two reasons. It allows: 1) to study the radius-luminosity relation, and the stellar structure in general, down to less than $0.1m_{\odot}$; 2) to get the stellar mass function down to the substellar regime, and therefore gather information on the contribution of the barionic matter to the dark matter.

A few years ago, we have started a project to obtain CMDs and LFs down to the HBL, with the WFPC2 at the beginning, and the ACS, at the present time. As shown by King et al. (1998), there are evidences of failures of the theoretical mass-luminosity relations around $0.1m_{\odot}$. Moreover, Bedin et al. (2001) found that the models are able to reproduce the observed CMDs in the metal poor regime, but they deviates more and more for metal rich clusters, like M4. For this reason, we started a number of investigations in order to observe the faintest part of the CMDs covering the entire metallicity range of Galactic GCs.

It is important to note that in this project the high accuracy proper motions are a fundamental ingredient. Toward the faintest magnitudes, the mass-luminosity relation tends to stretch, and therefore there are less and less stars per magnitude bin. Consequently, the field stars dominate more and more, and the proper motion criterion becomes a very efficient way to get rid of them. Presently, we are working on NGC 6121 (M4) and NGC 6397, and waiting for the second epoch data for NGC 104 (47Tuc), ωCen, and the super metal rich, old open cluster NGC 6791. Figure 2.1, which

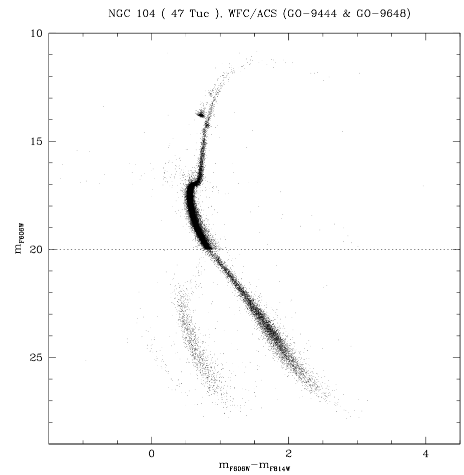

Fig. 2. Color Magnitude Diagram of 47Tuc. The magnitudes are in the ACS Vega-mag system defined by Bedin et al. (2004a). The CMD extends by more than 16 magnitudes. Note the cluster WD sequence and the SMC sequence.

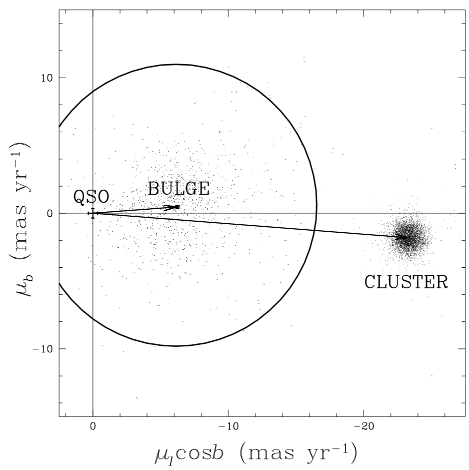

Fig. 3. The possibility to refer the motion of the stars to an extragalactic source has allowed to obtain the absolute proper motion of M4 $((\mu_\alpha \cos\delta,\ \mu_\delta)_{J2000} = (-13.21 \pm 0.35, -19.28 \pm 0.35)$ mas yr^{-1}), and an estimate of the Galactic constant with an unprecedented accuracy: $A-B = V_0/R_0 = 27.6 \pm 1.7$ km s^{-1} kpc^{-1}.

shows a CMD of 47Tuc spanning more than 16 magnitudes, gives a clear example of the kind of data we can obtain and work on.

It is worth mentioning that the first epoch images of ωCen collected for this project allowed the serendipitous discovery of the puzzling double main sequence described by Bedin et al. (2004a, see also Bedin et al. in this book). Again, only the extremely accurate photometric precision reached, thanks to the ACS@HST performances and our reduction software allowed to identify this tiny, but extremely important (for our understanding of the ω Cen stellar population) feature.

2.2. Absolute motion of the clusters

In the background of the GC fields, there may be many extragalactic sources; sometimes even point sources as QSOs. Taking advantage of the high accuracy with which point source positions can be measured, we can refer the motion of the field and cluster stars to an extragalactic reference frame. This is what has been done by Bedin et al. (2003): a QSO in the background of one of the M4 fields covered with the WFPC2@HST has allowed to measure the absolute motion of both cluster and of field stars. Because of the M4 position, the latter are mainly Galactic bulge stars, and the measurement of their absolute proper motion has given an estimate of the Galactic constant with an unprecedented accuracy (Fig. 2.2).

2.3. Internal Motions and Distances

Surely, one of the most interesting projects made feasible by the combination of the capability of high astrometric accuracy and of the multifiber high resolution facilities is the measurement of accurate distances. The basic idea is very simple, and not new. Almost geometric distances can be obtained by comparing the velocity dispersion (a linear quantity) and the proper motion dispersion (an angular quantity) of cluster stars. Radial velocities with a 100m/s errors are relatively easy to obtain, and our proper motion errors are sensibly smaller (and in any case well under control) than the proper motion dispersion (e.g. Fig.

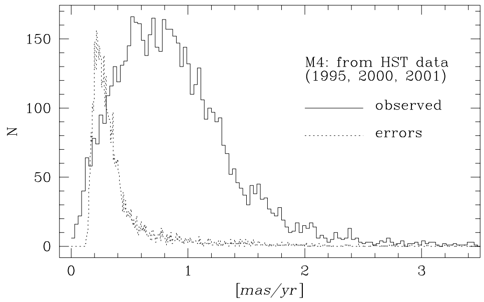

Fig. 4. Comparison between the internal proper motion dispersion and the proper motion measurement errors for M4.

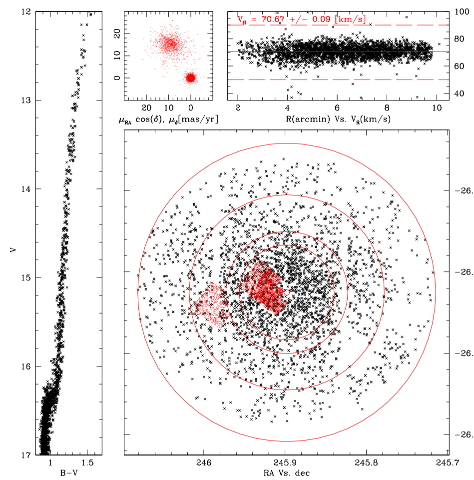

Fig. 5. Internal proper motion and radial velocity dispersion for M4: preliminary results.

2.3). The main source of error is the sampling error, which goes with the $\sqrt{2n}$, where n is the number of measured stars. With a few thousand stars measured, we can aim at distances with errors smaller than 2% (Fig. 2.3). Mass segregation, anisotropy, and rotation complicate the job, and a model is needed to properly compare the radial velocity and the proper motion distribution to get accurate distances. We are presently working at the model, and at the measurement of proper motions (from multi-epoch HST images) and of radial velocities (from FLAMES@VLT) for 5 clusters: 47Tuc, NGC 2808, NGC 6121, NGC 6397, NGC 6752. For other 8 clusters multi-epoch HST data suitable for proper motion dispersion measurements are available.

The final aim of the project is the measurement of accurate absolute ages, with uncertainties of the order of a few hundred million years. For this, we also need accurate reddening, and accurate metallicities, which can be measured on FLAMES data (that we plan to acquire, possibly during 2004, within an approved ESO project, PI: Gratton).

2.4. White Dwarf Cooling Sequence

The end of the white dwarf (WD) cooling sequence (WDCS) in GCs is very difficult to observe (Hansen et al. 2002), and there is a lively debate in the literature (De Marchi et al. 2004; Richer et al. 2004) on whether it has been reached on M4, where it has been searched with WFPC2 deep images (123 HST orbits). The end of the WDCS is of great importance, as it provides an age estimate of old stellar systems, independent from the standard method based on the location of the main sequence turn-off. The best targets are the closest GCs, and the ACS camera offers a unique opportunity to efficiently identify it. During Cycle 13 we have been granted with 10 orbits (GO-10146 PI: Bedin), which we estimate to be enough to reach the termination of the WDCS of M4 at a magnitude $V \sim 30$, with S/N=5.

3. WFI Photometry and Astrometry

The number of wide field imagers (WFI) at the focus of some groundbased telescope (INT, 2.2m, AAT, LBT, VST) is continuously increasing, and the field of view becomes larger and larger. The WFIs have allowed to completely map a number of open and globular clusters. This implies large number of stars, with the possibility of studing also fast evolving phases. The WFIs also allow large radial coverage, and therefore the study of the radial distribution of stars in different CMD sequences, including peculiar objects. Also the study of tidal tails of open and globular clusters is easily feasible.

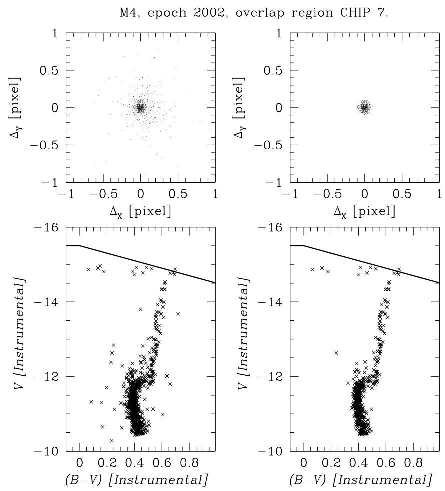

Fig. 6. Proper motion measurements in a field of M4 from two epoch WFI@2.2m images separated by only 2.8 years.

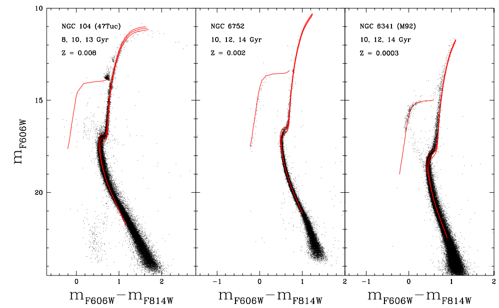

Fig. 7. The CMDs of 47Tuc, NGC6752, and M92, calibrated to the ACS Vega-mag system defined by Bedin (2004b) are compared with the models by Pietrinferni et al. (2004) transformed to the same system.

The most interesting and still largely unexplored possibilities are again on the astrometric performances of these devices. First of all, astrometry with an accuracy of 0.2 arcsec or better is needed to point the fibers of multifiber spectroscopic facilities. We have also applied our astrometric technique to a number of WFIs, including the WFI at the ESO 2.2m telescope, with encouraging results: presently we are able to reach an astrometric precision of 12mas/frames, enough to get proper motions to clean the cluster sequences from the background contamination (cf. Fig. 3).

4. Transforming the Models into the ACS@HST Bands

Most of the astronomical photometric investigations are based on some "standard" photometric system. Here, by "standard", we mean a photometric system that has been widely used for a long time in different observatories (e.g., the Johnson-Kron-Cousins, Strömgren, Thuan-Gunn, etc. systems), and possibly defined by a number of standard stars well distributed in the sky, and whose fluxes have been carefully measured. The calibration to a "standard" system is sometimes the only way to properly use the collected data, e.g. when we need to compare our photometric sequences with others collected with different instruments or at different epochs. However, when the transmission curves of the equipment used to collect the observations are rather different from those of any existing "standard" system, the transformation of the data to a "standard" system is difficult, and can be unreliable, particularly for extreme stars (i.e., extreme colors, unusual spectral type, high reddening, etc.).

In the case of ACS@HST, the many filters often differ substantially from the "standard" ones, and the high photometric precision makes the resulting systematic differences more evident. Therefore, it is advisable to avoid to transform the ACS/WFC instrumental magnitude into some "standard" photometric system.

After more than two years of operation, no reliable calibration to some physical units of the ACS data are available. Therefore, we decided to calibrate our ACS data in the simplest way (Bedin 2004b): we used as a reference the spectrum of Vega (from ftp:// ftp.stsci.edu/ cdbs/ cdbs2/ grid/ k93models/ standards/ vega_reference.fits) and multiplied it by the system transmission curves in order to obtain the flux within the given pass bands, which can be easily transformed into magnitudes. Similarly, the same procedure has been used to transform the theoretical models by Pietrinferni et al. (2004) into the observational plane. While it is foreseeable that the calibration of the ACS photometry will be improved when the light-diffusion and CTE effects will be better characterized, the models in the ACS bands based on the most updated in–flight transmission efficiency curves are solid and a good reference points, and can be used for a more quantitative interpretation of the observed data.

The interested reader can find the models transformed to the ACS in flight Vega-mag photometric system at the following web address: http://www.te.astro.it/BASTI/index.php.

Figure 3 shows an example of comparison of the CMDs from ACS data and the models using the calibration procedure defined by Bedin (2004b).

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