GROUNDBASED AND SPACE OBSERVATIONS OF STAR CLUSTERS

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Star clusters are among the most beautiful astronomical objects in the sky. Though they have been observed from the dawning of optical astronomy, the research in this field still has great vitality and it is continuously triggered by the technological advances. Due to their primary importance as template stellar populations (SPs), any new discovery on star clusters yields exciting contributions to many astrophysical macro-areas ranging from stellar and galaxy evolution up to cosmology. The advent of 8-10m class telescopes, and the availability of new, high performance instruments (like optical and near-IR wide field imagers and multifiber spectroscopic facilities) is giving major impulses to this research field. Also, the high resolution of HST images, and the 10 years or more temporal baseline give the possibility to measure accurate proper motions of a large number of stars (Bedin et al. 2001, 2003), opening a new, very promising research branch. Unexpected results are coming out, revising old concepts and stimulating new ideas and projects: in one word opening new perspectives in the star cluster and SPs studies.

Our group has been very active in taking advantage of all these new facilities, developing a specific expertise which enabled us to carry out a number of high scientific impact projects for the study of star clusters.

a) We have invested a lot in terms of human and financial resources(in collaboration with Ivan King and Jay Anderson) in the development and application of a new software for accurate photometry and astrometry on WFPC2/HST and ACS/HST images. L. R. Bedin, first as PhD student and then as post doc in our group has been working on this full time, and the results we had in the last 3-4 years have shown the goodness of our choice. All the projects related to the reduction of HST images have been (initially) partially supported by ASI, and then by three specific PRIN projects (years 2000-01, 2002-03, 2003-05), and one "Progetto di Ateneo" (year 2002-2003).

b) We have also invested on the development of the pipeline for the reduction of groundbased wide field images (mainly from the WFI@2.2m). For this we had finantial support from a PRIN (years 1999-2000), a 4 year post doc grant (assegno di ricerca for Yazan Momany, who is the person of our group involved in wide field images data reduction), and a Progetto Giovani Ricercatori (2004, granted to Yazan Momany).

c) Despite our original specific expertise is on stellar photometry, we have invested resources to develop an expertise on multifiber high resolution spectroscopy. A PhD thesis (Alejandra Recio Blanco) has been devoted to this activity. We received partial support from the above mentioned PRINs and a from the University of Padova through a 4-year post doc grant (assegno di ricerca for Alejandra Recio Blanco)

In the last years, thanks also to the expertise gained with the above efforts, our team produced an unprecedented number of discoveries, significantly contributing to add new pieces to the puzzle of the formation and evolution of SPs in star clusters. Among these, the discovery of a helium rich population in Omega Centauri (Bedin et al. 2004, Piotto et al. 2005), and the discovery of a severe discrepancy between the age from the white dwarf cooling sequence and the main sequence turnoff age in the supermetal rich, old open cluster NGC6791

In particular, we concentrated on globular clusters (GCs). The new, emerging scenario which we contributed to depict is radically changing the naive picture of GCs harboring a simple SP. We are now facing the problem of understanding and modeling these ancient "living" systems, which have

a much more complex formation history than previously thought and experienced dynamical evolution with a continuos interaction with the Galaxy.

In order to help recomposing a coherent picture of GC formation and early evolution, here we present an ambitious program, which can be separated in the projects outlined here and detailed below.

1) ACCURATE GC DISTANCES AND ACCURATE ABSOLUTE AGE DETERMINATION
The aim of this project is the determination of accurate absolute ages of as many as possible GCs through the measurement of very accurate distances, metallicities, and reddenings.

2) STAR FORMATION IN GCs
We intend to investigate the presence of multiple star formations in GCs by:
a) Searching for double or broadened MS stars in massive GCs from archive and new ACS/HST images;
b) Investigating the properties of extended blue HB tails in a statistically significant sample of clusters with a large number of hot HB stars;
c) extending our investigation on the SPs of Omega Centauri.

3) GLOBULAR AND OPEN CLUSTER MASS FUNCTIONS
There are two sunprojects going on:

a) determination of the present day mass function down to the limiting mass for the ignition of the hydrogen burning in core for a number of globular and open clusters;
b) determination of the stellar initial mass function from the observed present day local mass function

4) A CATALOG OF GALACTIC GLOBULAR CLUSTER COLOR MAGNITUDE DIAGRAMS (AND PROPER MOTIONS!)
We are extending the HST snapshot catalog (Piotto et al. 2002) with groundbased wide field images both for photometry and astrometry.

5) BLUE STRAGGLERS IN GLOBULAR AND OPEN CLUSTERS
From the HST snapshot catalog and the under preparation groundbased WFI catalog (see point 4), we intend to continue our research on BS, extending the sample, and studying their distribution inside the cluster in order to share some light on their nature and their origin.

6) WHITE DWARF COOLING SEQUENCE IN GLOBULAR AND OPEN CLUSTERS
After the surprising results on the white dwarf cooling sequence of NGC6791, we started a project (HST time already allocated) for the study of the cooling sequence in other open and globular clusters.

7) MODEST COLLABORATION
One of us (GP) is responsible of the working group 8 "Observations" within the international collaboration called MODEST (Modelling of Dense Stellar System).

8) GCS IN THE GALACTIC BULGE

We will dedicate a special effort to the study of the galactic bulge GCs in the attempt to better contrain the epoch of their formation and early evolution.

9) OPEN CLUSTERS AS TRACERS OF THE MILKY WAY DISK FORMATION

This observational project aims at better understanding the spiral pattern inside the disk, the history of star formation from the disk early assembly to now, and its detailed chemical evolution.

10) EXTRASOLAR PLANETS

Taking advantage of our expertise in accurate stellar photometry, we have recently started four programs for the search of extrasolar planets with the transit method:

a) the first one is an investigation aimed at the identification of extrasolar planets in open clusters.
b) The second one is a more generic survey for the search of extrasolar planets in a few Galactic star rich fields with the Asiago Schmidt telescope (RATS project)
c) We are also investigating on the possibility to detect debris of planet formation around solar type stars from the polarization of the unresolved signal coming from the system.
d) We recently started an observational program aimed to study the pre-main sequence properties of stars in young infrared clusters searching for protoplanetary hot disk signatures.

These programs on extrasolar planet search have been recently financed with a specific PRIN (bando 2004).

A final note. Our group has invested a lot in the formation of young researchers. More than a dozen of undergraduated students have been followed and had the undergraduate degree in Astronomy presenting an original thesis work working within the above mentioned projects. At the present time, all of them have a post doc position (ESO, Nice Observatory, and Cambridge). Since year 2000, three Phd students got their degree working within our group, and at the present time we are the supervisors of other three PhD students.

Project 1 - ACCURATE GC DISTANCES AND ACCURATE ABSOLUTE AGE DETERMINATION

Globular clusters have traditionally been considered as good tracers of the process that led to the formation of their host galaxy. Absolute ages set a constraint on the epoch of the galaxy formation, with important cosmological consequences. Relative ages provide detailed information on the formation process of the host galaxy. We have recently extended (De Angeli et al. 2005) our original work on GC relative ages (Rosenberg et al. 1999) based on a set of photometrically homogeneous color-magnitude diagrams by adding the HST snapshot catalog. In the next years, we plan to put these relative ages on a absolute age scale by measuring accurate absolute ages for a subset of the De Angeli et al. (2005) clusters.

For the absolute age determination, accurate distances, metallicity, and reddening are mandatory.

As for the distance, our group has started a project which will provide distances with uncertainties smaller than 2-3% for a selected number of GCs. The method that we are using to measure distances is very simple (Piotto et al. 2004a): we compare the dispersion of internal proper motions, an angular quantity, with that of radial velocities, a linear quantity; the result is a distance. Radial velocities for thousands of stars in GCs, with an accuracy of a few hundred km/s are now easily attainable with FLAMES/GIRAFFE@VLT. As for the proper motions, already in King et al. (1998) we pioneeristically showed that the 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 and King 2003, Bedin et al. 2003)

making it possible to get astrometric accuracies of the order of about 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 of 50).

With the high accuracy proper motion and radial velocity measurement, the distance uncertainty mainly depends on the sampling error, which goes with the sqrt{2n}, where n is the number of measured stars (typically a few thousands). In order to take into proper account the presence of rotation and of anisotropyc velocity distribution we are developing for each cluster a dynamical model (this was the main argument of the thesis of one of our PhD students, Francesca De Angeli, now post doc at Cambridge, but she is still collaborating with us on this project).

Finally, in collaboration with the group of Raffaele Grattion (INAF-Osservatorio Astronomico di Padova), we are measuring (Gratton et al. 2005) very accurate metallicity (error of the order of 0.05 dex) and reddening (uncertainties smaller than 0.01 magnitudes) for the same GCs for which we will measure accurate distances can be obtained following the method described in Gratton et al. (2003). Gratton et al. (2003) have also shown that with these accurate reddening and metallicities, distances with uncertainties of the order of 4% can be obtained by comparing the cluster main sequence (MS) with the local subdwarfs, thus extending the sample of cluster with accurate distance determination. The method can be furtherly improved by using as reference the MS of the clusters with geometric distance determination.

With the new distance, metallicity, and reddening measurements we can obtain absolute ages with errors smaller than 1 Gyr, where the main uncertainty is now on the stellar evolution models, and not on the distance and metal content.

For a selected number of nearby clusters, an important and independent cross check on the age from the TO can be obtained by using the white dwarf (WD) cooling sequence
(see Progetto 6)

Project 2 - STAR FORMATION IN GCs

a) Omega Centauri
The ability to obtain accurate astrometry implies also accurate photometry. And this is at the basis of one of the most puzzling discoveries on GC research of the recent years: the double MS in Omega Centauri (Bedin et al. 2004). By reducing deep ACS/HST images of Omega Centauri, we showed that the MS of this clusters is splitted into two, distinct branches. The MS split is present all over the cluster. Follow-up spectroscopic observations with FLAMES@VLT have made the scenario even more complicated. Based on spectra which add up to more than 200 hours of exposure time each, Piotto et al. (2005) have shown that the bluer MS is more metal rich than the redder one, contrary to what is expected from any canonical evolution model of stars with canonical abundances. Apparently, the only way to explain these - at the moment unique - results is to assume that the blue main sequence stars are anomalously rich in helium (Y=0.38, Piotto et al. 2005). Piotto et al. (2005) suggest that these helium rich stars could be second generation stars formed from material polluted by 10-12 solar masses SNe, and possibly intermediate mass AGB ejecta. The presence of a subsample (20-25%) of helium rich stars could also explain the anomalously extended horizontal branch of Omega Centauri.

In the next two years, we intend to continue the study of the stellar population in Omega Centauri, both photometrically and spectroscopically, with data we have recently collected at FLAMES@VLT and new ACS/HST data from observations already scheduled for the next months.

2) Star formation in other GCs
The new results on Omega Centauri call for further investigation. The main question that we would like to answer is: is the double MS in Omega Centauri unique among GCs, or is it an extreme case representing a process which has been at work also in other clusters. A more general problem we want to address is related to the early evolution of GC stellar population: are there any signatures of a multiple star formation in other GCs? Is there any evidence of a population of He rich stars in other GCs.

This is not a new problem. Multiple star formation has been proposed to explain the O-Na anticorrelation (Gratton et al. 2001) in GC stars: the fact that the anticorrelation is observed both in red giant and main sequence stars seems to exclude an origin from deep mixing (Gratton, Sneden, and Carretta 2004 and references therein), favoring the formation of a second generation of stars from material polluted by ejecta of intermediate mass asimptotic giant branch (IM-AGB) stars. This material should also be enriched in He. An enhanced He content has been invoked by Sweigart (2000) and D'Antona et al. (2002) in order to explain the presence of anomalously hot horizontal branch stars in a number of GCs.

We intend to investigate this problem in two different ways:

1) Search for double or broadened MS stars in massive GCs from archive and new ACS/HST images;
2) Investigate the properties of extended blue HB tails in a statistically significant sample of clusters with a large number of hot HB stars;

Project 3 - GLOBULAR AND OPEN CLUSTER MASS FUNCTIONS

We are carrying out two separate but complementary projects:

a) since King et al. (1998) we have started an ambitious project to to measure
star cluster mass functions down to the hydrogen burning limit (HBL).
Close to the HBL, because of the steepening of the mass luminosity relation, the cluster sequence vanishes and becomes confused within the field stars. Within this project, we extract cluster stars using multiepoch observations and selecting by proper motion
(as we already did in NGC6397, King et al. 1998, and M4, Bedin et al. 2003, NGC6791, King et al. 2005). We have a number of first epoch and observed or scheduled second epoch HST observations to obtain present day mass function down to the HBL, covering the entire GC metallicity range, and extending our investigation to the supra solar metallicity of the old, star rich, open cluster NGC6791. The purpose of the project is to investigate the metallicity effects on the mass function.

b) for a few clusters, selected among those with the least impact with the Galactic gravitational potential, we are working (within the MODEST collaboration, see below) to a project for the derivation of the global initial mass function from the observed present day local mass function. The purpose of the project is to investigate the effect of cluster parameters on the stellar mass function, continuing a long term project started more than 15 years ago (Capaccioli, Ortolani, Piotto 1991, Piotto, Cool, King 1997, Piotto and Zoccali 1999).

Project 4 - A CATALOG OF GALACTIC GLOBULAR CLUSTER COLOR MAGNITUDE DIAGRAMS (AND PROPER MOTIONS!)

We have recently completed a survey based on WFPC2@HST snapshot observations of of the core of 74 Galactic GCs which resulted in the publication of a catalog of accurate color magnitude diagrams (Piotto et al. 2002). This catalog has demonstrated to be a mine of information on the GC SP. Our group has already published 16 refereed papers based on this catalog, but many papers from other authors, based on the same catalog (that we made accessible to the entire community via web: http://dipastro.pd.astro.it/globulars) came and are coming out. We are presently working to the extension of the HST snapshot database using the ESO-WFI@2.2 imager in order to cover, for the same clusters clusters observed with HST in order to investigate the cluster population out to the cluster tidal radii. We have multiband observations for 80 clusters, presently under reduction, and expect that the groundbased catalog will have a similar impact of the HST snapshot one (see an example in Momany et al. 2004).
A further extension of this project is very recently started. Jay Anderson is at the present time hosted in our Department for two months. He is extending his astrometric and photometric software to the WFI@2.2m images. We plan to measure accurate position of the stars in the WFI@2.2m images. These measurement will become first epoch position for proper motion measurements by comparing the stellar epoch position (after 5 to 10 years, starting from year 2000, depending on the cluster distance) from second epoch images to be collected with Omegacam@VST.

Project 5 - BLUE STRAGGLERS IN GLOBULAR AND OPEN CLUSTERS

Based on the HST snapshot catalog, we have extracted the largest catalog of GC blue stragglers. This catalog has allowed us to demonstrate that the frequency of blue stragglers in GCs anticorrelates with the total cluster mass (Piotto et al. 2004b). Within the MODEST collaboration, we have also constructed a model (Davies, Piotto, De Angeli 2004) which explains the empirical correlations as a consequence of the evolution of the GC binary population. We intend to extend this catalog by using the groundbased catalog which will also allow to investigate the radial distribution of BS.
We are presently working at the preparation of a catalog of BS in open cluster to further investigate the properties and the origin of these objects.

Project 6 - WHITE DWARF COOLING SEQUENCE IN GLOBULAR AND OPEN CLUSTERS

We have recently started a project (base on HST obserbations) for the study of the cooling sequence of the white dwarfs (WD) in globular and open clusters. The WD cooling sequence is an important cluster age indicator, completely independent from the classical age indicator, i.e. the TO of the main sequence. By using the HST observations from the project on the HBL (see above), we could observe the WD cooling sequence in the supra solar metallicity open cluster NGC6791. With our big surprise, the age from the peak of the WD cooling sequence and the TO age for this cluster are badly in disagreement (Bedin et al. 2005). This important result opened a number of questions on the level of knowledge we have of the physics of the final evolution stage of the stars. In view of our puzzling results, we planned to extend this investigation, and we have recently been granted with HST time for the study of the bottom of the WD cooling sequence in the open cluster NGC2257 and in the GC NGC6121 (M4).

Project 7 - MODEST COLLABORATION

One of us (GP) is responsible of the working group 8 "Observations" within the international collaboration called MODEST (Modelling of Dense Stellar System, http://www.manybody.org/modest). This collaboration intend to develop the status of the art dynamical models of real star clusters. The comparison with the observations of the model results is considered a fundamental aspect of this project, and our group is expected to coordinate the collection of available observational data and stimulate new observations to this purpost. The radial velocity and proper motion data, the mass functions, the stellar distribution from the inner core to the outskirts that we are collecting for the above mentioned projects are also important

Project 8 - GCS IN THE GALACTIC BULGE

The galactic spheroids i.e. elliptical galaxies and the bulges of spirals, include a major fraction of the stellar mass in the nearby universe. In the case of the galactic bulge we have the unique opportunity to resolve it in single stars well below the main sequence turnoff. It has been generally assumed that the spheroids formed very early in the history of the galaxies, but the current models of hierarchical galaxy formation predict a much later stellar formation. We demonstrated that the globular clusters in the bulge are relatively old, with an age comparable with the clusters of the halo (Ortolani et al., 1995, Ortolani et al., 2001). Our spectroscopic results indicate a nearly solar iron abundance and the overabundance of some alfa elements (in particular Si and Mg) indicating an early fast enrichment by massive supernovae (Barbuy et al., 2004, Melendez et al., 2003), but still there are some indicators, such as the bright OH/IR stars, often interpreted as tracers of a younger population.
The aim of this research is the study of the nature and evolution of the galactic bulge population and of its substructures (bar, inner disk...), including the age and the relation age-metallicity, the chemical composition, the mass function.

The specific goal of this project is the study of the relation between the bulge and the halo and the bulge vs. the disk. In particular, we intend to:

a) Study the distribution of detailed elemental ratios in the bulge population.
We plan to establish the relative abundances for individual elements in order to clarify the history of the chemical enrichment in the Bulge. In particular the contribution of the enrichment by SNI relatively to SNII will be checked, as well as the close box model. Specific abundance ratios, for example alpha elements and oxygen vs. iron are very sensitive to the star formation history.

b) Improve of the actual parameters (in particular the distance) for all the GCs in the direction of the galactic bulge within about ± 20 degrees around the galactic center. For the highly reddened GCs we will use IR photometric observations (in sinergy with the BO RU).

c) Determine the age of the GCs and field stars in the bulge and compare with the age of the halo stellar population.
The ages will be mainly derived by comparing the CMDs of the bulge GCs with the CMDs of the halo GCs. Our expected main improvement (particularly for the field stars) comes from the use of the radial velocities in order to clean the samples from the disk star contamination. We already have data in some bulge fields from VLT/VIMOS.

d) Extend the study of the relative proper motions and to prepare a database for future studies of absolute motions.
The proper motions in GCs are used mainly to clean the CMDs from the field stars, but they will be used as well for the calculation of motions in the Galaxy of the clusters themself. The relative proper motions will be derived both from old, ground based, CCD images or from archive HST data. It is our goal to combine proper motions with radial velocities.

e) Discovery and study new star clusters in the bulge fields.
Bica and collaborators recently published lists of star cluster candidates in the direction of the inner bulge (Dutra and Bica, 2001, AA) from near-IR surveys already available (e.g., the 2MASS). We studied some of them at higher resolution in order to get their basic parameters (Dutra et al., 2003). A statistical comparison with other infrared, low latitude star clusters, is also planned.

Project 9 - OPEN CLUSTERS AS TRACERS OF THE MILKY WAY DISK FORMATION

Open Star Clusters are natural tracers of the Galactic disk structure and past evolution. This observational project aims at better understanding the spiral pattern inside the disk, the history of star formation from the disk early assembly to now, and its detailed chemical evolution.
Quite surprisingly, the spiral structure, star formation history and chemical evolution of the Galactic disk remain poorly known despite the ernormous progress in observational techniques occured in the last few decades. In particular, the Third Galactic Quadrant is becoming an unexpectedly interesting direction where to look for answers to key questions like the origin and assembly of the Galactic disk, its detailed structure
and star formation history. The discovery of a possibly dwarf galaxy -Canis Major- engulfing right now in the Milky Way and the presence of the galactic warp are two simple illustrations of the interest in this direction. Another intriguing aspect which
adds more spice to the investigation of this region, is its very complicated spiral pattern. We do not know yet whether there is or not a spiral arm developing inside this quadrant, and if so, whether this spiral arm is the extensions of the Local or the Perseus arm. Since a few years we started an observation campaign to probe this region with open star clusters, for which we are obtaining robust determinations of age, distance and metallicity.

Project 10 - EXTRASOLAR PLANETS

Taking advantage of our expertise in accurate stellar photometry, we have recently started an investigation aimed at the identification of extrasolar planets with the photometric transit method. This is a new project; two PhD students of ours are full time working on this.
There are four independent investigations going on:

a) Extrasolar planets in open clusters
We collected multisite observations for 10 consecutive nights for 2 suprasolar metallicity, old, and star rich open clusters (NGC6791 and NGC6257). We are presently working at the development of the data reduction pipeline and of the light curve analysis routines with the purpose of identifying photometric signatures of the transit. We want to understand whether the moderately crowded environment of an open cluster allows the formation and the survival of planetary systems. One PhD student of ours (Marco Montalto) is full time involved in this project.

b) RATS (Radial velocity And Transit Survey)
Parallel to this projects, we have started, in collaboration with the researchers at the INAF-Osservatorio Astronomico di Padova, a survey for the search of extrasolar planets in a few selected, star rich Galactic field. The survey implies the identification of extrasolar planet candidates from

the photometric signature of a transit in the light curves of the target stars from a sequence of images obtained at the Asiago Schmidt telescope, and the high resolution spectroscopic follow up for the confirmation of the nature of the transiting object with the echelle spectrograph at the 1.82m Copernico telescope in Asiago. A PhD student (Fabrizio De Marchi) is full time working on it.

c) We investigated on the possibility to detect debris of planet formation around solar type stars from the polarization of the unresolved signal coming from the star and its planetary system. This study requires very high accuracy polarization measurements.
We already published a statistical paper on this topic (Tamburini et al., 2002) and we are working on a theoretical model.

d) We recently started an observational program aimed to study the pre-main sequence properties of stars in young infrared clusters. The results show that numerous K infrared excess stars are present in clusters younger than about 2-3 Myr, rapidly increasing at younger ages. These stars are likely hosting a protoplanetary "hot" disk. The data will allow to study the evolutionary time scale of such disks and the radiation field effects

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Research Products:
2000:papers with referee: 27
papers without referee: 14
2001:papers with referee: 23
papers without referee: 10
2002:papers with referee: 25
papers without referee:30
2003:papers with referee: 17
papers without referee:32
2004:papers with referee: 21
papers without referee: 20
TOTAL: papers with referee:113
papers without referee:106

In total, the 219 papers published by this group in the last five years have received 1328 citations (by May 18, 2005, ADS source).

List of 5 representative publications:
Piotto, G., King, I., Djorgovski, G., Sosin, C., Zoccali, M., Saviane, I., De Angeli, F., Riello, M., Recio Blanco, A., Rich, R.M., Meylan, G., Renzini, A., 2002, *"HST Color-magnitude diagrams of 74 Galactic Globular Clusters in the HST F438W and F555W bands"*, Astron. & Astrophys., 391, 945

Piotto, G., De Angeli, F., King, I., Djorgovski, S.G., Bono, G., Cassisi, S., Meylan, Recio-Blanco, A., G., Rich, M., Davies M. 2001, *"Relative Frequencies of Blue Stragglers in Galactic Globular Clusters: Constraints for the Formation Mechanisms"*, Astrophys. J. Lett., 604, L109.

Bedin, L., Piotto, G., Anderson, J., Cassisi, S., King, I., Momany, Y., Carraro, G. 2004, „*Omega Centauri: The Population Puzzle Goes Deeper"*, Astrophys. J. Lett., 605, L125.

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Carraro, G., Bresolin, F., Villanova, S., Matteucci, F., Patat, F., Romaniello, M. 2004, *"Metal Abundances in Extremely Distant Galactic Old Open Clusters. I. Berkeley 29 and Saurer 1"*, Astron. J.,128, 1676