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STAR CLUSTERS WITH THE GTC

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RESUMEN

Los cúmulos estelares representan actualmente una herramienta muy útil en el estudio de diferentes campos de la astronomía moderna. Estos objetos están proporcionando una inestimable información acerca del origen, estructura y procesos de formación estelar que tienen lugar en sistemas extragalácticos. Por otro lado, una gran parte de nuestro conocimiento acerca de cómo se forman las estrellas individuales proviene del estudio de los cúmulos resueltos en estrellas. En esta contribución discutimos y analizamos los principales objetivos científicos en este campo a la luz de la primera generación de instrumentos para el **Gran Telescopio Canarias**.

ABSTRACT

Star clusters are becoming very useful probes in the studies of many topics in modern Astronomy. Actually, they are providing invaluable information about the origin, structure and star formation processes in extragalactic systems. Otherwise, most of our knowledge on how individual stars are formed is derived from the analysis of stellar clusters resolved into stars. In this contribution we review the main scientific objectives in this field, in the light of the first generation instruments for the **Gran Telescopio Canarias**.

Key Words: **GALAXIES: STAR CLUSTERS — GLOBULAR CLUSTERS**

1. INTRODUCTION

Along the XX Century the stars clusters have been used by the astronomers for a wide variety of scientific objectives and they became useful probes in a rich bunch of astronomical topics.

They were used by Shapley to estimate the size of the galactic system and to put the Sun far away of any central position in the Galaxy. Star clusters have been the natural lab for Stellar Evolution experiments. All what we know about how stars evolve from birth to dead have been learned testing our evolutionary models with observational color-magnitude (CM) diagrams of star clusters.Even considering that the open cluster system in our Galaxy can be only observed in a small portion of the Galactic disk, they have notably contributed to know: (1) The spiral structure of the Milky Way. (2) The radial metallicity gradient in our stellar system. (3) The correlation (or the lack of) between age and metallicity. (4) The vertical structure of the young galactic disk, etc.

Otherwise, globular clusters are our better known fossils. The study of the globular cluster system lead Bob Zinn, in the seventies, to challenge the paradigmatic scenario for the formation of the Milky Way proposed by Eggen, Lynden-Bell & Sandage in the beginning of the sixties and to prepare the venue (or, at least, the way to explain the visit) of the Sagittarius dwarf galaxy.

More recently, the discovery of new bound stellar systems with the mass of the old globular clusters and the age of the OB-associations bridges a link between open and globular clusters, establishing a continuum of age and mass in the distribution of the stellar systems and opening a promising future for the study of the star clusters in this and other galaxies.

Thus, if the GTC wants to appear in the *Who is who?* of the modern telescopes, it cannot forget the study of these stellar systems, and we must discuss about what kind of star cluster programs propose more interesting astronomical objectives and what of them are suitable to be observed with the first light instrumentation.

But, before to go to what we can do for the star clusters with the GTC, we must define what they are.

2. STAR CLUSTERS

Stars clusters are gravitationally bound stellar systems which were born from the same parental cloud and then, the star members are coeval and share the same chemical composition. Thus the CM diagrams of different clusters represent snapshots of the mass evolutionary stage at different ages, for different chemical compositions. As an example we show, in Figure 1, two CM diagrams corresponding to the, likely, oldest open cluster in the Milky Way disk, Berkeley 17, together with a 5 Myr old

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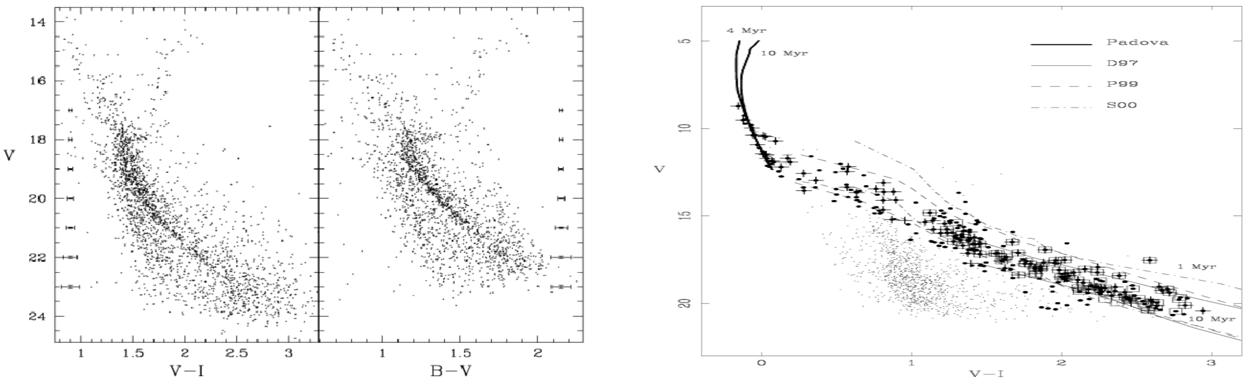

Fig. 1. **Left Panel:** CM diagrams for the cluster Berkeley 17, likely the oldest open cluster in the galactic disk (Bragaglia et al. 2006). **Right Panel:** CM diagram of the young open cluster NGC 2362 showing an extended sequence of stars with x-ray emission (Delgado et al. 2006).

star cluster, showing X-ray activity along the whole range of masses (NGC 2362).

But also the stars clusters appear, on the sky, in an ample variety of shapes and views depending on their age, size, distance, location and environment where they were born and where they are still living and, sometimes, need to be observed in wavelengths other than optical to unveil the gas cradle where the stars were formed.

Pleiades is a classical young cluster not very far from us where we can see the material left over after the formation of the cluster surrounding the brightest stars. Globular cluster, on the contrary, are three order of magnitudes more massive and a few thousand times older than Pleiades. When we move to our close satellites other examples appear where young clusters have masses similar to the globular clusters in the Milky Way.Extreme examples of this category of objects are the clusters in the Antenna galaxy which appear to drawn an outer blue way, delimiting the external edge of the galaxy.

The study of the star clusters suffered an internal revolution with the launching of the Hubble Space Telescope, and with the installation of the new 8-10 m class ground based telescopes. With these new tools, in the last decades, we have learned very much about the physical properties of the star cluster population in the Universe, which can be summarized in:

- Mass ranges between a few hundreds and 10^8 solar masses (e.g. W3 in NGC 7552).
- Metallicities ([Fe/H]) between 0.5 and -3.0 have been observed within our own Galaxy and super star clusters(SSCs) were detected in many low metallicity environments as the blue compact dwarf galaxies are.
- Ages appear to be between 1 Myr and 14 Gyr.
- Velocity dispersions are mostly bracketed between 5 and 20 km s^{-1}. Only for a few of very massive clusters we can find values higher than twenty.

Otherwise star clusters appear in a wide variety of physical environments. They have been observed in the disk of normal spirals, in nuclear regions of active galaxies, in the halo of spiral and elliptic galaxies, in Antenna type galaxies, interacting galaxies, and in starburst and dwarf galaxies. Thus, everywhere.

But what are the main questions to be answered in the study of the star clusters?

2.1. *Main Scientific Objectives*

The main scientific objective in the study of the star cluster is to understand, how do they form? In particular, how the more massive clusters are being formed and how do they survive after the violent mass loss happening in the first millions years after their birth.

The balance between gravity and internal kinetic energy is suddenly broken against the forces of cohesion. However we are observing massive clusters as old as one hundred million years and older.

We also observe that some galaxies have a numerous population of star clusters; on the other hand many other galaxies show only a few of these objects. What physical variables, if any, control the switch between isolated and clustered star formation in galaxies? Elmegreen & Efremov (1997) proposed the existence of an extra pressure as the main additional ingredient for the star formation giving rise to clusters rather than to isolated stars. However we wonder if this is the only variable controlling the star formation mode and what role are playing other variables as, for example, the metallicity of the gas or the magnetic field in that region.

When the cluster can be resolved into stars, we dispose of an excellent lab for studying the evolution of stars with time, the initial mass distribution and the early phases in the formation of the low mass stars and, overall, the evasive frontier between star and planet.

These general questions are translated to more specific objectives which can be grouped into the following items:

Resolved Clusters:

- Determination of the initial mass function
- Low mass tail
- Individual stars
- Metallicity spread
- Age spread

Compact Clusters:

- Cluster properties in different environments
- Interaction with the gas

In fact, at shorter scales, these specific objectives resume in a short list of physical variables we can measure with different uncertainties depending on the available observational tools. They are:

Individual stars in clusters:

- Chemical composition
- Masses
- Effective temperature
- Age
- Extinction
- Radial velocities
- Proper motions

Star Clusters:

1. *Resolved clusters*
   - Extinction
   - Distance
   - Age
   - Metallicity
   - Integrated mass
   - Luminosity function
   - Members selection
2. *Compact clusters*
   - Mass (Luminous & Dynamical)
   - Age
   - Velocity dispersion
   - Chemical composition
   - Metallicity

As example of observational projects dealing with the measurement of these variables in star clusters we could mention the followings: A direct imaging study of the well known star forming region NGC 346 which clearly shows the presence of a deep branch of pre-main sequence (PMS) stars. The PMS stars appear to show a larger spread in age than the MS stars (Nota et al. 2006). The Adaptive Optics in infrared is able to provide a very accurate astrometry for binary and triple systems located not very far from us. The results derived from the study of the Trapezium system, where motions of amplitudes around 15 km s^{-1} are measured at 450 pc from the Sun, can be seen in Close et al. (2003). High resolution infrared spectroscopy of compact clusters, as this SSC in NGC 6946, provides interesting information about the physical properties of the cluster (Larsen et al. 2006). In this case, variables such as, velocity of the cluster, velocity dispersion, chemical composition, age, dynamical mass and mass to light ratio have been estimated.In addition to the Balmer and He I absorption lines, the spectra of young clusters in the post-nebular phase (10-20 Myr old) also show the Ca II triplet at 855 nm. A good example of the use of this triplet to get information about clusters in the nuclear region of several galaxies can be seen in Walcher et al. (2005). Imaging and low resolution spectroscopy of the globular cluster system in the galaxy NGC 1399 provided information about the luminosity distribution of the clusters, a rough radial velocity for membership proposal, a crude estimation of the effective radius (using the task ISHAPE designed by Soren Larsen) and some analysis of the morphology of extended objects. (Richtler et al. 2004). There is a very interesting study showing different images in visible and IR bands of the star forming region NGC 1333 (Hodapp et al. 2005). We can see there how the appearance of the region is completely different for different wavelengths, and the presence of some knots (apparently connected to embedded clusters) are only seen at larger wavelengths. This paper also presents an analysis of the polarization vector in K band which provides nice information about the interaction between the cluster emission and the surrounding gas. So, here we have pointed out some examples of the observational research on star cluster we can do with good telescopes and adequate instrumentation. However most of these works rest on the comparison between observational properties and model expectations. I would not like to finish this part of my talk without mentioning the important task performed by several groups for providing us with accurate and precise models of stellar evolution and simple population synthesis. Here we present an incomplete but representative list of the most popular models.

PMS stars
D'Antona & Mazzitelli 1994, 1997
Baraffe et al. 1998
Palla & Sthaler 1999
Siess et al. 2000

Evolutionary Tracks
Geneva models (A. Maeder)
`http://obswww.unige.c/mowlavi/evol/stev_database.html`
Padova models (C. Chiosi & L. Girardi)
`http://pleiadi.pd.astro.it/`
Yale models (P. Demarque)
`http://www.astro.yale.edu/demarque/yyiso.html`

Synthetic Colors
Infrared 2MASS (Bonatto et al. 2004)
UBV + SLOAN (Girardi et al. 1993, 1995,1998, 2000)
Lick indices TMK04 (Thomas et al. 2004)

Synthetic Colors & Spectra
STARBURST99 (Leitherer et al. 1999)
`http://www.stsci.edu/science/starburst99/`
GALEV (Anders & Fritze-v. Alvensleben 2003)
`http://www.unisw.gwdg.de/~galev/panders/`
BC03 (Bruzual & Charlot 2003)
`http://www.cida.ve/~bruzual/bcXXI.html`
High Resolution Spectra (González-Delgado et al. 2006)
`http://www.iaa.csic.es/~rosa/research/synthesis/HRES/ESPS-HRES.html`

TABLE 1

NUMBER OF PAPERS ON STAR CLUSTERS PER YEAR AND TELESCOPE(S) IN THE PERIOD 2003-05.

year	GEMINI	SUBARU	KECK	VLT
2003	6	7	24	13
2004	5	3	23	27
2005	10	2	19	24

3. PHYSICAL VARIABLES AND INSTRUMENTATION

In order to answer the question, *What can we do for the star clusters with the GTC?* we must know what kind of observational works are currently done with the 8-10 m class telescopes and what attached instrumentation is the most popular for the study of star clusters. Looking into the database and archives of the main telescope consortia, and by simple counting in the period 2003-2005, we find the number of published papers on star clusters based on observations taken at the different telescopes (see Table 1). These figures do not pretend to be an exhaustive analysis of the productivity of the different consortia, but just to provide an indicative idea of the number of papers, on star clusters, per year generated by the *biggest* telescopes.

If we now separate the papers by instrument (see two examples in Tables 2 and 3) we observe that most papers are based on spectroscopic data, and particularly on high resolution spectra.

3.1. *First Light Instruments for the GTC*

For the Fist Light of the GTC, the consortium expects to have in operation, at least three of the four instrument listed below. Here we briefly describe the main technical performances and address the reader, for a more detailed description, to the pages in these proceedings devoted to the different instruments.

- **CanariCam:** Imaging, spectroscopy, polarimetry, and coronography; λ between 8-25 microns (mid-infrared)
  `http://www.iac.es/proyect/CCam/`
- **OSIRIS:** Imaging, spectroscopy, MOS, tunable filters, optical range (370-1000 nm)
  `http://www.iac.es/proyect/OSIRIS/`
- **ELMER:** Imaging, spectroscopy, MOS, optical range (instrument of contingency)
  `http://www.gtc.iac.es/instrumentation/elmer_es.asp`

TABLE 2

NUMBER OF PAPERS ON STAR CLUSTERS PER INSTRUMENT, BASED ON KECK OBSERVATIONS, FOR THE YEAR 2005

HIRES	LRIS	NIRSPEC	AO LGSA0-NIRC2	TOTAL 2005
7	7	4	1	19

[a]**HIRES:** High Resolution Echelle Spectrometer; R$\sim$ 25000-85000; MOS (40 objects).

[b]**LRIS:** Low Resolution Spectrometer; R$\sim$ 300-5000.

[c]**NIR-SPEC:** Imaging & Spectroscopy in IR; R$\sim$2000-25000 between λ= 1-5 microns.

[d]**AO LGSA0-NIRC2:** Adaptive Optics in IR.

TABLE 3

NUMBER OF PAPERS ON STAR CLUSTERS PER INSTRUMENT, BASED ON VLT OBSERVATIONS, FOR THE PERIOD 2003-2005

FORS1	FORS2	UVES	ISAAC	FLAMES
10	7	23	10	4

[a]**FORS1 & FORS2:** Imaging & Spectroscopy, R$\sim$ 1700 & R$\sim$ 2600, respectively.

[b]**UVES:** Two armed spectrograph; R$\sim$ 45000, long-slit.

[c]**ISAAC:** Two armed IR spectrograph ; R$\leq$ 3000.

[d]**FLAMES:** Multi-fiber in 25$'$ diameter; attached to **UVES** or **GIRAFFE**; R$\approx$ 2500-10000.

- **EMIR:** Wide-field, near-infrared, multi-object spectrograph in the nIR bands Z, J, H, K. λ between 1-2.5 microns. `http://www.iac.es/proyect/emir/emir.html`

Thus, with this battery of instruments we have at disposal the following observational techniques:
Imaging in Visible + nIR + mIR (CanariCam + OSIRIS + ELMER + EMIR)
Low Resolution Spectroscopy in Visible + nIR + mIR (CanariCam + OSIRIS + ELMER)
Medium Resolution Spectroscopy in nIR (EMIR)
where some instruments provide unique or very rare performances for the 8-10 m class telescopes, as for example:
mIR Polarimetry + Coronography (CanariCam)
Tunable Filters (OSIRIS)

With the available instrumentation we are ready to measure most of the physical variables, listed above, to achieve the main scientific objectives in the study of the star clusters; but perhaps not at the precision needed for some particular goals. Let us see this point in more detail.

3.2. *Analysis of some physical variables*

At 10 Mpc, in the border of the Local Group, 1 pc is seen under 0.02$''$. A typical cluster with an effective radius of 5 pc shows an angular diameter of about 0.2$''$. However the expected spatial resolution of any of the First Light instruments have a worse spatial resolution with theoretical values above 0.3$''$.

If we turn to the available spectroscopic capabilities, we can see that variables such as: radial velocity, velocity dispersion, and chemical composition can not be measured with the required accuracy for star clusters at the frontier of the Local Group and even nearer. Some figures can give a better idea of the accuracy we can estimate some physical variables with the actual instrumentation:[2]

CanariCam: R$\sim$ 1500
Main capabilities: ΔV$\sim$200 km s^{-1}; rms of the error$\sim$63 km s^{-1}; error$\sim$32 km s^{-1}; Metallicity.
ELMER: R$\sim$ 2500
Main capabilities: ΔV$\sim$120 km s^{-1}; rms of the error$\sim$40 km s^{-1}; error$\sim$20 km s^{-1}; Metallicity.
EMIR: R$\sim$ 4000
Main capabilities: ΔV$\sim$75 km s^{-1}; rms of the

[2]Metallicity means a first order approach to the knowledge of the chemical abundances of some astronomical objects.

error~30 km s^{-1}; error~15 km s^{-1}; Metallicity + Rough chemical composition.

OSIRIS: R~ 5000

Main capabilities: ΔV~65 km s^{-1}; rms of the error~20 km s^{-1}; error~10 km s^{-1}; Metallicity + Rough chemical composition.

It is obvious that we can do a lot of work with these facilities, but there are some specific questions which require of new instrumentation. If we want to estimate the dynamical mass of compact clusters or to study in detail the physical properties of member stars in clusters we should need a larger field of view, multi object spectroscopy (MOS) and better spectral resolution. In these proceedings we can see how many teams are working in new instruments which will provide new capabilities, as for example: **FRIDA**, **NAHUAL** and the update of **UES@WHT**, but if we want to be competitive with the other large telescopes in the field of the star clusters (see Tables 2 and 3) a spectrograph with intermediate–high spectral resolution (R$\geq$10000) and multi object observational mode is needed.

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REFERENCES

Anders, P., & Fritze-v. Alvensleben, U. 2003, A&A, 401, 1063
Baraffe, I., Chabrier, G., Allard, F., & Hauschildt, P. H. 1998, A&A, 337, 403
Bonatto, C., Bica, E., & Girardi, L. 2004, A&A, 415, 571
Bragaglia, A., Tosi, M., Andreuzzi, G., & Marconi, G. 2006, MNRAS, 368, 1971
Bruzual, G., & Charlot, S. 2003, MNRAS, 344, 1000
Close, L. M., et al. 2003, ApJ, 599, 537
D'Antona, F., & Mazzitelli, I. 1994, ApJS, 90, 467
D'Antona, F., & Mazzitelli, I. 1998, ASP Conf. Ser. 134: Brown Dwarfs and Extrasolar Planets, ed. R. Rebolo, E. L. Martin, & M. R. Zapatero Osorio (San Francisco: ASP), 134, 442
Delgado, A. J., González-Martín, O., Alfaro, E. J., & Yun, J. 2006, ApJ, 646, 269
Elmegreen, B. G., & Efremov, Y. N. 1997, ApJ, 480, 235
Girardi, L., & Bertelli, G. 1998, MNRAS, 300, 533
Girardi, L., Chiosi, C., Bertelli, G., & Bressan, A. 1995, A&A, 298, 87
Girardi, L., Bressan, A., Chiosi, C., Bertelli, G., & Nasi, E. 1996, A&AS, 117, 113
Girardi, L., Bressan, A., Bertelli, G., & Chiosi, C. 2000, A&AS, 141, 371
González-Delgado, R. et al. 2007, MNRAS, in press
Hodapp, K. W., Bally, J., Eislöffel, J., & Davis, C. J. 2005, AJ, 129, 1580
Larsen, S. S., Origlia, L., Brodie, J. P., & Gallagher, J. S. 2006, MNRAS, 368, L10
Leitherer, C., et al. 1999, ApJS, 123, 3
Nota, A., et al. 2006, ApJ, 640, L29
Palla, F., & Stahler, S. W. 1999, ApJ, 525, 772
Richtler, T., et al. 2004, AJ, 127, 2094
Siess, L., Dufour, E., & Forestini, M. 2000, A&A, 358, 593
Walcher, C. J., et al. 2005, ApJ, 618, 237