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STAR CLUSTERS
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HIGHLIGHTS OF COMMISSION 37 SCIENCE RESULTS

Abstract. It is widely accepted that stars do not form in isolation but result from the fragmentation of molecular clouds, which in turn leads to star cluster formation. Over time, clusters dissolve or are destroyed by interactions with molecular clouds or tidal stripping, and their members become part of the general field population. Star clusters are thus among the basic building blocks of galaxies. In turn, star cluster populations, from young associations and open clusters to old globulars, are powerful tracers of the formation, assembly, and evolutionary history of their parent galaxies. Although their importance (e.g., in mapping out the Milky Way) had been recognised for decades, major progress in this area has only become possible in recent years, both for Galactic and extragalactic cluster populations. Star clusters are the observational foundation for stellar astrophysics and evolution, provide essential tracers of galactic structure, and are unique stellar dynamical environments. Star formation, stellar structure, stellar evolution, and stellar nucleosynthesis continue to benefit and improve tremendously from the study of these systems. Additionally, fundamental quantities such as the initial mass function can be successfully derived from modelling either the Hertzsprung−Russell diagrams or the integrated velocity structures of, respectively, resolved and unresolved clusters and cluster populations. Star cluster studies thus span the fields of Galactic and extragalactic astrophysics, while heavily affecting our detailed understanding of the process of star formation in dense environments. This report highlights science results of the last decade in the major fields covered by IAU Commission 37: Star clusters and associations. Instead of focusing on the business meeting - the out-going president presentation can be found here: `http://www.sc.eso.org/ gcarraro/ splinter2015.pdf` - this legacy report contains highlights of the most important scientific achievements in the Commission science area, compiled by 5 well expert members.

1. Embedded and massive star clusters in the Milky Way

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The past decade has been an era of discovery in the Milky Way, ushered in by our increasing capability to see through dust. This text is a short summary of the observations

502

that have helped shape our understanding of massive star formation and young clusters in the Galaxy. I must apologise from the beginning for all the very relevant work that I have not been able to review. My reference list is just intended as a collection of examples to illustrate the broad range of excellent research carried out by our community. It is only natural that I concentrate on what I know best.

Deep infrared surveys of the Galactic Plane have revealed hundreds of new open clusters hidden by high obscuration. The publication of the 2MASS catalogue was followed by a number of dedicated searches, some by eye (e.g. Dutra *et al.* 2003), others using automated methods (e.g. Froebrich *et al.* 2007), that resulted in close to one thousand new cluster candidates. The *Spitzer*/GLIMPSE survey (Churchwell *et al.* 2009) presented us with a mid-IR view of the Galactic Plane at high spatial resolution, leading to a new collection of even more highly absorbed clusters (e.g. Mercer *et al.* 2005). The process has continued as new, deeper surveys, such as VVV, have come on line (e.g. Borissova *et al.* 2014; Barbá *et al.* 2015).

Many of these clusters are low-mass stellar groups still embedded in their parental clouds (e.g. Soares *et al.* 2008). Others are more massive young clusters with high-mass stars (e.g. Messineo *et al.* 2009; Chené *et al.* 2013). Finally, a significant number are simply old open clusters affected by interstellar extinction. Discriminating between these types is not always easy without more detailed investigation. Even though some semi-automated methods have been proposed to discern their nature (e.g. Beletsky *et al.* 2009), follow-up deep photometry (e.g. Ivanov *et al.* 2005) and, above all, (in most cases, near-IR) spectroscopy is necessary for a good characterisation (e.g. Zhu *et al.* 2009; Messineo *et al.* 2010). Because of this, a large number of these candidates still remain unexplored.

Infrared imaging has also resulted in a novel picture of the interstellar medium. Large numbers of bubble-like structures have been found (Churchwell *et al.* 2006; Simpson *et al.* 2012), likely marking sites of massive star formation (Deharveng *et al.* 2010). Highly reddened high-mass stars have been identified in the vicinity of many them (e.g. Marco & Negueruela 2011; Pinheiro *et al.* 2012). In less obscured environments, bright-rimmed clouds also seem to mark sites of ongoing star formation in the immediate neightbourhood of high-mass stars (e.g. Panwar *et al.* 2014). *Herschel* observations have shown the concentration of proto-stellar cores along filaments. This increasing body of data supports a view of massive star formation as a process extending over large spatial scales, and thus resulting in measurable age spreads in many young regions (e.g. Bik *et al.* 2012). Infrared imaging has also allowed the identification of bow-shocks produced by high-mass stars ejected from massive clusters (e.g. Peri *et al.* 2012), giving rise to a lively theoretical discussion on the origin of isolated high-mass stars.

Adopting a more global point of view, statistical studies of the distribution of mid-IR sources have provided strong constraints on massive star formation in the Milky Way, providing estimates of the current global star-formation rate (e.g. Robitaille & Whitney 2010), typical duration of different phases (e.g. Mottram *et al.* 2011; Morales *et al.* 2013) or incidence of triggered star formation (e.g. Thompson *et al.* 2012). More recently, and in contrast, *Herschel* has provided a very detailed view of gas and dust around a few massive star-formation sites (e.g. Russeil *et al.* 2013).

But the opportunities for discovery do not only come from infrared imaging. The combination of X-ray imaging of young clusters with IR catalogues has become the preferred method to investigate the formation of low-mass stars in environments dominated by high-mass stars (e.g. Prisinzano *et al.* 2011; Feigelson *et al.* 2013), providing valuable input for theories of high-mass star formation (e.g. Kuhn *et al.* 2014; Rivilla *et al.* 2014). Radio surveys have detected large numbers of new H II regions (e.g. Anderson *et al.* 2011), whose ionising stars or clusters remain in most cases still unknown. Radio

observations have also produced one of the most significant advances in the past few years: the generalised use of geometric parallaxes to masers for determination of distances to star-forming regions, an extremely powerful tool to probe the structure of the Milky Way (see references in Reid *et al.* 2014).

The current view of large-scale star formation in the Milky Way, emerging from all these developments, is complex. A typical configuration may be illustrated by the G305 star-forming region. High-mass stars in two moderately massive young clusters, Danks 1 and 2, drive a huge wind-blown bubble, whose rim is teeming with star-formation sites, where embedded lower-mass proto-clusters are forming just now. A diffuse population of proto-stars is scattered over the whole region (Hindson *et al.* 2013 and references). The output of such a process is a classical OB association with massive central clusters, such as Per OB1 or Cas OB8. Many giant molecular clouds seem to harbour similar configurations, among them the Carina Nebula (e.g. Preibisch *et al.* 2011), where Trumpler 14 has a mass $M_{cl} \approx 10^4\, M_\odot$ (Ascenso *et al.* (2007)), or the W3 region (Román-Zúñiga *et al.* 2015) that seems to form a larger structure with W4 and W5, included within Cas OB6. Others, such as W33 (Messineo *et al.* 2015) or W51, lack the central massive clusters, and will very likely evolve into dispersed associations, similar to Cyg OB2 (Wright *et al.* 2014). This may also be the future of one of the most powerful star-forming regions known in the Milky Way, W49A (Homeier & Alves 2005).

As a result of spatially concentrated star formation, we find massive young clusters. For many years, it was believed that the Milky Way lacked clusters with masses $\geqslant 10^4\, M_\odot$. Then the obscured open cluster Westerlund 1 (Wd1) was found to host a population of > 70 supergiants of spectral types ranging from O to M (Clark *et al.* 2005; Negueruela *et al.* 2010). A direct extrapolation of the number of massive stars detected would suggests a mass $M_{cl} \approx 10^5\, M_\odot$ for a standard initial mass function(IMF). Direct star counts in the infrared give a lower limit of $5 \times 10^4\, M_\odot$ (Gennaro *et al.* 2011). The cluster seems to have formed monolithically in a single burst lasting less than 0.4 Ma (Kudryavtseva *et al.* 2012).

Many clusters have joined the list of massive clusters over the past decade. Some of them were already known, but their masses have been revised upwards. For example, Trumpler 14, mentioned above, or NGC 3603, for which Harayama *et al.* (2008) derive a mass in the range $M_{cl} = 1-1.6 \times 10^4\, M_\odot$ with indications of a top-heavy IMF. These mass estimates depend strongly on the distance adopted to the cluster and, hence, the extinction law. This problem becomes especially acute for the clusters close to the Galactic centre, affected by very heavy and variable reddening, with an extinction law that deviates strongly from the Galactic average (e.g. Nishiyama *et al.* 2009). For example, the mass of the Arches cluster is hotly debated. The extinction law adopted or even possible colour terms due to the very high reddening affect the luminosity function, which has to be later translated into a mass function. Masses ranging from $M_{cl} < 10^4\, M_\odot$ to several $10^4\, M_\odot$ have been found depending on assumptions (see references in Clarkson *et al.* 2012). But even much less reddened clusters are subject to such uncertainties. An extreme case is Westerlund 2, for which distances ranging from ~ 3 to ~ 8 kpc have been claimed (Carraro *et al.* 2013), because of very different estimates of the reddening law.

Besides W49A, the strongest candidate for the most massive star-forming region in the Milky Way is W43 (Bally *et al.* 2010; Nguyen Luong *et al.* 2011), located close to the point where the Galactic bar joins the Scutum-Crux arm. The vigour of star formation in this area is likely related to this location, as there are indications of inflows from the spiral arm towards the densest regions (Motte *et al.* (2014)). Not far from W43, and at about the same distance from the Sun, several clusters rich in red supergiants have been found (e.g. Figer *et al.* 2006; Davies *et al.* 2007). These clusters have ages in the

$10 - 20$ Ma range, and estimated masses between 2 and $> 5 \times 10^4 \, M_\odot$. At least two large associations with $> 10^5 \, M_\odot$ have been found around them (Negueruela *et al.* 2011, 2012). The presence of so many extreme examples of present or recent star formation within a small span of the Galactic Plane ($\sim 6°$) seems to hint at a very privileged location. Further support for this interpretation would come from the detection of a similarly hefty complex at the opposite end of the Bar. Even though at least one massive cluster has been found in that general direction (Davies *et al.* 2012), the exact position where we should expect this starburst region is not certain. The young massive cluster vdBH 222, though originally thought to mark this far end of the bar (Marco *et al.* 2014), seems to be closer to us (and the Galactic Centre), suggesting that very large associations do not necessarily form at special places, and so hinting at the possibility that star formation in the inner Milky Way may be rather more vigorous than in the outer spiral arms.

Finding massive young clusters is not an end in itself. They not only inform us about star formation in violent environments, but also play a significant role as laboratories for the study of high-mass star evolution. With its huge population of evolved high-mass stars spanning all stages of evolution, Wd1 is the prime example. The different evolutionary paths of isolated and binary high-mass stars can be directly observed and documented within its co-eval population (Clark *et al.* 2014 and references therein). Similarly, multi-epoch spectroscopic surveys of young open clusters have become fundamental tools to understand the physical properties of high-mass stars (Evans *et al.* 2005, 2011, and related references). As we move into the era of large spectroscopic surveys, this potential will be fullfilled. At the same time, ALMA is starting to look at the sites of massive star formation with unprecedented resolution. In the near future, more advanced instrumentation on the 10-m class telescopes, the launch of JWST and the advent of giant telescopes with adaptive-optics-assisted instrumentation offer the promise of not only an extended era of discovery, but also profound advances in our understanding of how star formation on large scales proceeds, and how high-mass stars are born, evolve and return to the interstellar medium the enriched material that will feed the future stellar generations.

2. Open clusters in the Milky Way

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Open star clusters (OCs) have always received special interest, because by studying these objects, it is possible to make suggestions on the structure and kinematics of the Galactic disk and its dynamical and chemical evolution. However, there are two major obstacles to achieve these goals: 1) the sampling of OCs is complete only up to distances of 800 – 1000 pc and 2) no unbiased, homogeneous collection of fundamental parameters are available in the literature. Concentration of interstellar gas and dust toward the Galactic plane makes the detection of new OCs difficult especially in the visible range. To build a homogeneous catalog of OC parameters, homogeneous observational data and reliable methods of determination of the distances, ages, and reddening of the clusters are required. Nonetheless, these obstacles are cleared step by step in numerous studies, each considering few, sometimes a dozen, clusters at once.

The situation dramatically changed in the beginning of the 2000s, when large sky surveys became available. They triggered a new wave of interest to discover new, and investigate already known, open clusters. The greatest attention was drawn by Two-Micron All Sky Survey (*2MASS*, Skrutskie *et al.* 2006), whose data were collected in three near-*IR* bands. Searches for clusters were conducted either visually, on images recorded in one of the bands, or from the Point Source Catalog using an automated

routine (Ivanov *et al.* 2002; Dutra *et al.* 2003; Bica *et al.* 2003; Kronberger *et al.* 2006; Froebrich *et al.* 2007; Koposov *et al.* 2008; Glushkova *et al.* 2010; Schmeja *et al.* 2014; Scholz *et al.* 2015). They found about 2000 candidates, visible in infrared only. One thousand cluster candidates more were mined in other surveys: *DENIS* (Reylé & Robin 2002), *USNO-A2.0* (**?**), *GLIMPSE* (Mercer *et al.* 2005; Zasowski *et al.* 2013), *UKIDSS GPS* (Solin *et al.* 2012), *VVV* (Borissova *et al.* 2011, 2012, 2014; Solin *et al.* 2014), *WISE* (Camargo *et al.* 2015). Rübke *et al.* (2015) started the program of searching for MAssive Stars in Galactic Obscured MAssive clusterS (*MASGOMAS*) and developed a new automatic tool, which allows the identification of a large number of massive (a few 1000 solar masses) cluster candidates from the *2MASS* and *VVV* catalogs.

As *2MASS* is a homogeneous and all-sky catalog, many attempts were made to derive a homogeneous list of accurate physical parameter for OCs out of JHK_S data: refer, for example, to the papers by Koposov *et al.* (2008), Tadross (2008, 2009, 2011), Glushkova *et al.* (2010), Bukowiecki *et al.* (2011), Kharchenko *et al.* (2013). However, the comparison of parameters obtained in these investigations with respect to the largest catalog by Kharchenko *et al.* (2013), gives mean standard deviations for the distance, age and reddening as 1.2 kpc, 0.5 dex, and 0.27 mag, respectively (Netopil *et al.* 2015, which are definitely insufficient for comprehensive studies of the structure of the Galactic disc. Involving data from large surveys, scientists undertook massive determinations of other OC characteristics: the radial velocities of 110 OCs and the metallicities of 89 OCs were derived using data from RAdial Velocity Experiment (*RAVE*, Conrad *et al.* 2014), the mean proper motions and stellar membership probabilities for 1805 open clusters were found using *UCAC4* (Dias *et al.* 2014).

Since open clusters provide information about the chemical pattern of Milky Way disk, the study of their chemical composition attracts special interest. Paunzen *et al.* (2010) compiled data from the available sources in the literature to make up the catalog of OC metallicities based on photometric data, which lists 188 clusters (Paunzen *et al.* 2010) and set of high-quality cluster metallicities based on high-resolution spectroscopic studies for 78 clusters (Heiter *et al.* 2014). Heiter *et al.* 2014 show that none of the current models are able to satisfactorily describe the OC's metallicity as function of galactocentric distance. The present high-resolution spectroscopic Galactic surveys include OCs among their targets: Apache Point Observatory Galactic Evolution Experiment (*APOGEE*, the Gaia-ESO Survey (*GES*, Gilmore *et al.* 2012), the GALactic Archaeology with *HERMES* (*GALAH*, Anguiano *et al.* 2014) supply accurate radial velocities and detailed chemical abundances. Using 100 OCs from the uniformly observed complete *SDSS-III/APOGEE-1* DR12 dataset (*OCCAM* survey), Frinchaboy *et al.* 2015 presented age and multi-element abundance gradients for the disk of Milky Way. The INfrared Survey of Young Nebulous Clusters (*IN-SYNC*, Covey *et al.* 2015) leverages the stability and multiplex capability of the *APOGEE* spectrograph to obtain high resolution spectra at near-infrared wavelengths and to study the dynamics and star formation history of young clusters. Four young stellar groups in Perseus and Orion molecular complexes were investigated (Covey *et al.* 2015) based on homogeneous stellar parameters derived from *APOGEE* spectra for thousands of pre-main sequence stars (Cottaar *et al.* 2014). OCs are also included in the list for the space missions *Gaia* and *Kepler*.

Some projects were delivered especially to investigate OCs and derive their physical parameters in a precise and homogeneous way: for example, within the framework of Bologna Open Clusters Chemical Evolution project (*BOCCE*, Bragaglia & Tosi 2006) about 50 clusters were studied. *BOCCE* uses both comparison between observed color-magnitude diagrams (CMDs) and stellar evolutionary models, and the analysis of high-resolution spectra to derive age, distance and chemical composition. The Open

Clusters Chemical Abundances from Spanish Observatories survey (*OCCASO*, Casamiquela *et al.* 2014) plans to derive abundances for more than 20 chemical species in at least 6 Red Clump stars in 30 northern OCs. Nine clusters have been studied by *OCCASO*. Sejong Open Cluster Survey (SOS, Sung *et al.* 2013) – a project dedicated to providing homogeneous photometry of a large number of OCs in the SAAO Johnson Cousins' *UBVI* system, has many relatively small sparse unstudied clusters among its targets. The *OPD* survey (Caetano *et al.* 2015) is *UBVRI* photometric survey of southern open OCs, which is complementary to *OAN-SPM UBVRI* survey of 406 northern clusters (Michel *et al.* (2016)). Lasting 17 years, *WIYN* Open Cluster Study (*WOCS*, Mathieu & WOCS Collaboration 2013) is dedicated to comprehensive photometric, astrometric, and spectroscopic studies of select OCs. In their recent investigation (Thompson *et al.* 2014) new deep wide-field optical and near-infrared photometry ($UBVRJHK_S$) of the cluster M35 is presented, against which several isochrone systems are compared: Padova, PARSEC, Dartmouth, and Y^2. Two different atmosphere models are applied to each isochrone: ATLAS9 and BT-Setti. For any isochrone set and atmosphere model, observed data are accurately reproduced for all stars more massive than 0.7 $M_\odot$. For less massive stars, Padova and PARSEC isochrones consistently produce higher temperature than observed. Dartmouth and Y^2 isochrones with BT-Setti atmospheres reproduce optical data accurately; however, they appear too blue in IR colors. *WIYN's* extension – the Southern Open Cluster Study (*SOCS*, Kinemuchi *et al.* 2010) includes 24 clusters, wide-field photometry results are already available for three of them. Faria *et al.* (2014) determined the radial velocity of stars belonging to a group of open clusters using spectra with spectral resolution of 4000 and plan to calculate the mean radial velocities of a number of OCs. To investigate star formation processes, Lim *et al.* (2015a) initiated a photometric survey of young open clusters in the Galaxy and already studied 13 famous OCs having a wide range of surface densities ($\log(\sigma)$=-1 – 3 $stars/pc^2$) and total masses ($500 - 50000$ $M_\odot$) and also distributed in five different spiral arms in the Galaxy. Lim *et al.* (2015a) found that the slope of the IMFs in the high-mass regime appears to be shallow for massive compact clusters, and the mass of the most massive star in a given cluster also has a tendency to be large in massive clusters. Costa *et al.* (2015) started a program that determines the properties of Local (Orion) spiral arm. They plan to carry on a comprehensive study of 29 young OCs which includes a $UBVRI$ photometric analysis and determination of their kinematics. The first cluster NGC 2302 has already been investigated.

When large catalogs and data sets became available in the literature, and massive determination of parameters of clusters became possible, numerous automated and semi-automated techniques were developed to retrieve these parameters primarily by using color-magnitude diagrams. One of the most powerful tools is the Automated Stellar Cluster Analysis package (*ASteCA*, Perren *et al.* 2015, which makes use of positional and photometric data to provide accurate estimates of the cluster's metallicity, age, extinction and distance values, and robust stellar cluster image and photometry simulation package *MASSCLEAN* (Popescu & Hanson 2010), which creates synthetic clusters and generate CMD templates for a variety of cluster masses and ages, and which mimic the observational photometric errors when using isochrone fitting (Popescu *et al.* 2014).

Thanks to All Sky Automated Survey (*ASAS*, Pojmanski *et al.* 2005), a large number of new Galactic Cepheids have been discovered during the last dozen years. That is why new attempts were undertaken to find Cepheids attributed to open star clusters. Taking into account all possible characteristics of these variable stars and OCs, Anderson *et al.* (2013) found five new genetic relations between Cepheids and clusters, and Chen *et al.* (2015) reported 8 new Chepheid-cluster pairs. Some papers were devoted to photometric and

spectroscopic observations of known clusters hosting the Cepheids, in order to confirm membership of Cepheids in OCs and refine cluster's physical parameters (Majaess *et al.* 2013a,b, 2012, Turner *et al.* 2012).

One of the most interesting results of the studies of individual clusters was published by Davies *et al.* (2011) on GLIMPSE-C01 referred to in the literature as an old globular cluster traversing the Galactic disk. The authors obtained high-resolution near-infrared spectroscopy of over 50 stars in the cluster and found the average radial velocity is consistent with being part of the disk, and determined the cluster's dynamical mass to be $8 \times 10^4\, M_\odot$. From analysis of the cluster's M/L ratio and location of the red clump, Davies *et al.* (2011) suggested the cluster's age to be 400–800 Myr and concluded that GLIMPSE-C01 is the most massive Galactic intermediate-age cluster discovered to date.

This way, the number of known Milky Way open clusters increased from about 1500 to almost 4000 during the last $10 - 15$ years. The main physical parameters were derived for most of them but quality of these determinations is insufficient to study the Galactic disk comprehensively. That is why a lot of new different surveys were started to measure a large range of open cluster's properties.

3. Globular clusters in the Milky Way

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The last ten years have seen a renewed interest in Galactic globular clusters (GC), mainly because they have been demonstrated to be much more complex and intriguing than believed in the past. The main reason is that spectroscopic and, later on, photometric observations have driven a dramatic shift from considering GCs as the best approximation of simple stellar populations (see e.g. the review by Renzini & Fusi Pecci 1988) to the simplest example of *multiple* stellar populations (e.g. the review by Gratton *et al.* 2004). We use here the words "populations" and "generations" as synonym, implying that in the same GC stars of (slightly) different age coexist. This is the generally accepted scenario, although there are still many problems in explaining the mechanism of GC formation and internal self-enrichment (in light elements for all GCs, in heavier elements only for a fraction). For recent reviews see for instance Gratton *et al.* (2012) for spectroscopic results, Piotto (2009) for photometry, and Charbonnel (2015) for theoretical challenges.

We present here selected highlights in Galactic GC work of the last decade, with a strong bias towards multiple populations and observations.

The abundance of light elements in GC stars shows large star-to-star scatter, at variance with what happens for the bulk of field halo stars; these variations are anti-correlated (C and N, O and Na, and Mg and Al are depleted and enhanced, respectively). These so called "anomalies" in light elements had already been detected in many GCs, but generally only in giant stars. However, the presence of products of hot H-burning also in main sequence stars called for more massive stars as original polluters (see subsection on models) and we now speak of first-generation (FG) and second-generation (SG) stars in GCs. After the first pioneering works, light element (anti-)correlations were routinely found also among main sequence and unevolved stars, using also high-resolution spectra, see e.g. Carretta *et al.* (2005); Cohen *et al.* (2005); Kayser *et al.* (2006, 2008); Pancino *et al.* (2010); Smolinski *et al.* (2011); Lardo *et al.* (2012) for C, N, and Pasquini *et al.* (2005); Lind *et al.* (2009); Bragaglia *et al.* (2010); D'Orazi *et al.* (2010); Monaco *et al.* (2012); Dobrovolskas *et al.* (2014) for Na, O, Mg, Al, and Li. This decade saw a wealth of observations on large samples of stars and of clusters, also thanks to multi-object

high-resolution spectrographs, like Hydra or FLAMES, so that a quantitative analysis of the light elements anti-correlation became possible. Large scale studies were conducted, see the long list of GCs and papers in Gratton *et al.* 2012, among which we have for instance the closest GCs, i.e., M 4, NGC 6752, NGC 6397, and M 22 (e.g. Marino *et al.* 2008; Carretta *et al.* 2009b,a; Yong *et al.* 2008; Korn *et al.* 2007; Marino *et al.* 2011b), very massive clusters like ω Cen (Marino *et al.* 2011a) and M 54 Carretta *et al.* (2010a), and low mass GCs like NGC6838 (Cordero *et al.* 2015). Recently, also high-resolution surveys produced results in this field (Mészáros *et al.* 2015; San Roman *et al.* 2015). All evolutionary phases were targeted. The red giant branch (RGB) was the favourite, but also the horizontal branch (HB) was observed and in some GCs also He was measured (see e.g. Villanova *et al.* 2009; Marino *et al.* 2014; Gratton *et al.* 2015), an important diagnostics of the multipopulation scenario. Helium has also been measured in RGB stars, but only in NGC 2808 (Pasquini *et al.* 2011) and ω Cen (Dupree & Avrett 2013). More recently, the Asymptotic Giant Branch (AGB) observations showed that at least in some GCs the AGB stars do not show the same level of modification in light element abundances (Campbell *et al.* 2013; Charbonnel *et al.* 2013, but see also Johnson *et al.* 2015). Briefly, in all the examined MW GCs (and interestingly, also in GCs of the LMC (Johnson *et al.* 2006; Mucciarelli *et al.* 2009 and Fornax Letarte *et al.* 2006), a prominent Na-O anti-correlation has been found. Possible, rare, exceptions are very low-mass GCs, like the two Sgr clusters Ter 7 and Pal 12 (e.g. Sbordone *et al.* 2005), and Rup106 (Villanova *et al.* 2013). The Na-O anti-correlation appears almost a defining properties of (massive) GCs and is not present among field stars or open clusters (Bragaglia *et al.* 2012, 2014; Cunha *et al.* 2015; MacLean *et al.* 2015, but see Geisler *et al.* 2012 for a different opinion on NGC6791). An even more extreme departure from the simple stellar population paradigma comes from the finding of GCs with dispersion in iron and heavy elements. After ω Cen, also M 22 was found to display an intrinsic metallicity spread by Da Costa *et al.* (2009); Marino *et al.* (2009) (recently challenged by Mucciarelli *et al.* 2015), correlated with a spread in neutron-capture elements. Among GCs displaying iron and n-capture element spreads are for instance M 54, NGC 1851, and M 22.

The impact of different abundances of light element ions the photometric properties of stars in GCs (especially in the filters containing molecular features of CNO elements, see Sbordone *et al.* e.g. 2011) is exploited to better understand the origin of GCs. Different abundances between FG and SG stars translate into spread and even split sequences along the whole CMD of GCs. These multiple sequences are observed with several photometric systems, including broad band (e.g. Marino *et al.* 2008; Milone *et al.* 2008; Han *et al.* 2009; Lardo *et al.* 2011), intermediate band (Yong *et al.* 2008; Carretta *et al.* 2011), and narrow band (Lee *et al.* 2009; Lim *et al.* 2015b). The recent exploitation of the UV Hubble Space telescope (HST) filters allows to reach also features of OH hydride (see the UV GC survey described in Piotto *et al.* 2015). HST observations reveal split sequences all the way from the main sequence (MS) up to the red giant branch (RGB) and horizontal brand (HB, see for instance the spectacular main sequence (MS) of NGC 2808, Piotto *et al.* 2007). The large photometric samples allow to study the radial distribution of stellar populations across the cluster area (e.g. Lardo *et al.* 2011; Milone *et al.* 2013; Kravtsov *et al.* 2011). Usually SG stars are found more centrally concentrated, as predicted by most scenarios of GC formation. Photometry permits to detect even discrete populations in a single GC, like NGC 2808 (Milone *et al.* 2015), confirmed by abundance analysis of individual stars (Carretta 2015). The coupling between precise spectroscopy and photometry unravels a variegated landscape for Galactic GCs, that come in different flavours. Most GCs are monometallic (concerning iron and heavier elements). A growing number of objects shows a spread in Fe (see above). They also share a few other common properties: a correlation

between Ca and Fe (suggesting enrichment by type II SNe), and an enhancement of elements from slow neutron-capture process observed among stars of the more metal-rich cluster component. This suggests that, like ωCen and M 54, the remnant nuclei of former dwarf galaxy (e.g. Bekki & Freeman 2003; Bellazzini *et al.* 2008), these GCs may be the final products of cluster formation in a dwarf galaxy environment (e.g. Bekki & Yong 2012). Maybe related to the multiple populations in GCs, in the LMC and SMC many intermediate-age clusters with extended or even split main sequence turn-off's and red clumps have been found (e.g. Milone *et al.* 2009; Girardi *et al.* 2009; Correnti *et al.* 2015). This may be due to extended star formation (e.g. Goudfrooij *et al.* 2011) or to stellar rotation (e.g. Bastian & de Mink 2009) or binarity (e.g. Yang *et al.* 2011). No light elements anti-correlation has yet been found in these clusters (Mucciarelli *et al.* 2014).

Observational evidence of multiple stellar populations calls for some FG stars to have polluted material from which the SG stars formed. The most commonly discussed FG polluters are intermediate mass asymptotic giant branch (AGB) stars (Ventura & D'Antona 2008, e.g.) and fast rotating massive stars (FRMS Decressin *et al.* 2007, e.g.), but also interactive massive binaries have been proposed (de Mink *et al.* 2009), very massive stars (Denissenkov & Hartwick 2014), or early disk accretion (Bastian *et al.* 2013). However, multiple populations also pose tight constraints that challenge (m)any model(s) of GC formation. The currently observed ratio of FG to SG stars (about 1/3 and 2/3, Carretta *et al.* 2010b; Bastian & Lardo 2015) is not easily reconciled with the amount of yields provided by any candidate FG polluter (see for instance Bastian *et al.* 2015). This "mass budget" problem was often circumvented by scenarios assuming that GCs were initially from 10 up to 100 times more massive than present-day GCs (Bekki *et al.* 2007; Decressin *et al.* 2007; D'Ercole *et al.* 2008, 2010; Carretta *et al.* 2010b; Schaerer & Charbonnel 2011). However, evidence is growing that in external dwarf galaxies harbouring old GCs (showing multiple populations) these objects cannot have been more than 3-4 times more massive at their formation epoch, since they already account for about 25% of the galaxy mass in metal-poor stars (Larsen *et al.* 2012, 2014; Tudorica *et al.* 2015). Another severe challenge is posed by the very same existence of the observed anti-correlations, which require a certain amount of pristine gas to be mixed with ejecta of polluters to reproduce the observations. In some scenario (e.g. with AGBs, D'Ercole *et al.* 2010) dilution is mandatory since AGBs produce a correlation between Na and O abundance. From where this gas with primordial composition came after the GCs were swept by the first type II Supernovae is an issue still open, widely discussed but with no completely satisfactory answer up to now. A recent scenario proposed by Trenti *et al.* 2015 shows a possible way out, with blobs of pristine gas nearby the outcome of a major mini-halo mini-halo merger at high redshift, which could be later accreted refurbishing the evolving proto-GC with fresh reservoir of diluting matter. This mechanism could also be an attractive way to explain the discreteness observed both in CMDs and in the anti-correlations (see e.g. Milone *et al.* 2013, 2015 and Carretta *et al.* 2012; Carretta 2015, for NGC 6752 and NGC 2808).

Clusters lose mass and stars during their evolution (see, e.g., Baumgardt *et al.* 2008). Stars probably lost by GCs have been searched for in halo samples using the peculiar SG chemistry. CN band strength was used by Martell & Grebel (2010); Martell *et al.* (2011) on Segue SDSS spectra, while enhanced Na and/or depleted O abundances were considered by Carretta *et al.* (2010b); Ramírez *et al.* (2012). These papers provided a fraction of SG-like halo stars of about 1.5 to 3%. Recently, using data from the public spectroscopic survey Gaia-ESO Lind *et al.* (2015) found a probable GC escapee. For a discussion on the contribution of GC stars to the halo, see for instance Gratton *et al.* (2012). With the advent of large photometric surveys such as SDSS, Pan-STARRS, DES, VST ATLAS,

VVV, etc new GCs have been found, see e.g., Laevens *et al.* (2014); Belokurov *et al.* (2014), even if the objects found are sometimes classified as GCs or ultrafaint dwarfs depending on the study. The Galactic GC populations has increased in number, but the newly discovered clusters are all low-mass systems. Wide field imaging has been used systematically to look for extended and extra-tidal structures (e.g. Jordi & Grebel 2010; Carballo-Bello *et al.* 2012) In a few cases, tidal tails or streams still connected to the originating GC have been found (e.g., NGC 288, Grillmair *et al.* 2013 or Pal 14, Sollima *et al.* 2011), but there are many more without a clearly associated progenitor cluster. Furthermore, streams, moving groups, common proper motions groups have been sometimes associated to now dissolved clusters, in some cases using chemical tagging. Examples of a positive and negative identification, respectively, are the Aquarius stream (consistent with being GC debris, Wylie-de Boer *et al.* 2012) and the Kapteyn group (not associated with ω Cen, Navarrete *et al.* 2015).

"Exotic" objects in GCs comprise for instance blue stragglers stars (BSS), low-mass X-rays binaries, and millisecond pulsars (MSP), all very good tracers of the evolution of close binary systems in dense environments and of the dynamical history of the parent cluster. The study of BSS proceeded with the collection of large samples covering the entire extension of the GCs (e.g. Dalessandro *et al.* 2008; Leigh *et al.* 2011; Salinas *et al.* 2012), in the determination of their dynamical status (e.g. Ferraro *et al.* 2009a; Simunovic & Puzia 2014; Ferraro *et al.* 2012) and chemical composition (e.g. Lovisi *et al.* 2012). For more detailed and recent highlights on BSS, see for instance the contributions in 'Ecology of Blue Straggler Stars', held in 2012. Ransom *et al.* (2014) found 21 new MSP in tbe massive GC Terzan 5, which shows the largest number of X-ray sources among GCs. This cluster is particularly interesting also because Ferraro *et al.* (2009b) found it hosts two stellar populations with different iron contents and ages and proposed it to be the remnant of one of the primordial building blocks that formed the bulge (and not a true GC). The different metallicity was later confirmed by Origlia *et al.* (2013); Massari *et al.* (2014).

4. Extragalactic star clusters

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The following pages try to extract the results from 10 years of world wide intensive research using the extremely short style of a conference summary and applying a strong bias to observational work. Brodie & Strader (2006) review "Globular clusters and Galaxy Formation", Harris (2010) "massive star clusters in galaxies", Portegies Zwart *et al.* (2010) "young massive clusters", Kruijssen (2014) concepts of GC formation.

New M31 GCs have been detected, many within the "Pan-Andromeda Archaeological Survey" (McConnachie *et al.* 2009) and the data base for M31 GCs has been significantly increased both in quantity and quality (Puzia *et al.* 2005; Kim *et al.* 2007; Lee *et al.* 2008; Fan *et al.* 2010; Huxor *et al.* 2014; di Tullio Zinn & Zinn 2013, 2015). A updated analysis of the properties of the M31 GCS is given by Huxor *et al.* (2011). A flattening of the surface density profile at a radius of about 30 kpc corresponds to a flattening in the stellar surface brightness profile, which might indicate an accretion of the outer halo. More direct evidence for accreted clusters is found in Mackey *et al.* (2010, 2013). Structural parameters are presented by Barmby *et al.* (2007); Peacock *et al.* (2010). 300 metallicities of old GCs have been derived by (Caldwell *et al.* 2011). The metallicity distribution is unimodal in contrast to that of the Milky Way and giant ellipticals. Detailed element abundances for GCs from integrated light have been derived by Colucci *et al.* (2009).

Strader *et al.* (2011) combine kinematic data and structure parameters to derive M/L-ratios for 200 GCs and confirmed previous findings that the M/L_V-values decline with increasing metallicity, contrary to what naively is expected from stellar models. Shallower mass functions of metal-rich clusters can explain this. M/L_V-values also increase with cluster mass, possibly as a consequence of mass segregation. This is disputed by Shanahan & Gieles (2015). The kinematics of the outer halo GCs in M31 is studied by Veljanoski *et al.* (2014). Groups of GCs are related to the debris of stellar streams. The Fornax dwarf spheroidal shows an extremely large ratio of stars in GC to field stars of a similar low metallicity. This constrains the loss of first generation stars in GCs Larsen *et al.* (2012).

Nearby spirals with high star formation rates have been surveyed for clusters by Bastian *et al.* (2012) (M83), Larsen *et al.* (2011) used HST data to measure colour magnitude diagrams for resolved young massive clusters in nearby spiral galaxies. There is no gap visible between the H-burning main sequence stars and the He-burning supergiants like in canonical isochrones. Age spreads of a few Myrs are able to fill this gap, may be also interacting binaries.

The Initial Cluster Mass Function (ICMF) of young clusters in spiral galaxies has been investigated by Larsen (2009). A original Schechter function with a cut-off mass of $\approx 2 \times 10^5 M_\odot$ describes the GC luminosity functions well, if the luminosity evolution is only secular. (Elmegreen 2006) provides insight into the similarity of cluster and stellar IMFs. Based on a sample of 37 nearby dwarf galaxies, Cook *et al.* (2012) study the relation between SFR and cluster formation. Galaxy mergers can host a plethora of massive clusters. The Antennae galaxies are prominent targets with age distribution of GCs studied by Fall *et al.* 2005, new spectroscopic data (Whitmore *et al.* 2005; Bastian *et al.* 2009), general demographic model and application to the antennae (Whitmore *et al.* 2007). The latter work demonstrates that the enhanced number of massive clusters in mergers is a sample size effect due to the high star formation rate. The Antennae are also a test ground for the evolution of clusters, in particular the processes of disruption (Fall *et al.* 2009; Renaud *et al.* 2008; Karl *et al.* 2011; Renaud & Gieles 2013). Some young clusters in the Antennae have been observed with ALMA, but large reservoirs of molecular gas in the clusters have not been found (Cabrera-Ziri *et al.* 2015). Cluster formation and disruption in mergers through simulations have been investigated by Kruijssen *et al.* (2012). (Bastian *et al.* 2013) give structural parameters for 36 clusters in NGC 7572. Among them is W3, the most massive cluster known, whose profile extends out to 500 pc.

The nearest merger remnant (and giant elliptical) is NGC 5128 (CenA). Ages, metallicities are known for about 400 objects (Gómez *et al.* 2006; Rejkuba *et al.* 2007; Woodley *et al.* 2010a,b). One third of this sample show ages less than 8 Gyr. Taylor *et al.* (2010) find an increase of the M/L-values with the dynamical mass. The GCS has been searched over an area of 1.5deg^2 (Harris *et al.* 2012). More than 1000 GCs are now known. NGC1316 (Fornax A) is after CenA the closest merger remnant. Its GCS host clusters of a wide age-range down to 0.5 Gyr (Richtler *et al.* 2014). Among them are objects as massive as $1.6 \times 10^7 M_\odot$ (Bastian *et al.* 2006). There is an isolated young star cluster complex which demonstrates GC formation outside periods of high star formation rate (Richtler *et al.* 2012).

The nearby galaxy clusters Virgo and Fornax have been intensively surveyed with HST/ACS which produced a bulk of papers. From the Virgo survey: Peng *et al.* (2008) study formation efficiencies of GCs. The GC mass fraction is lowest at intermediate host luminosity, the specific frequency is dominated by blue clusters. Dwarf galaxies near to M87 seem to be tidally stripped of their GCs. Villegas *et al.* (2010) on the GC luminosity

function and distance determination: the dispersion of the GCLF correlated tightly with the host's absolute magnitude. Mieske *et al.* (2006) on colour-magnitude relations in GCSs, Liu *et al.* (2011) on colour gradients within GCSs. Georgiev *et al.* (2010) find that the total mass in GCs scales with the halo mass of the host galaxy.

A new catalogue by Harris *et al.* (2013) updates our current knowledge of GCS properties and relations with host galaxy properties. The number of GCs obeys a fundamental plane-like relation $N_{GC} \sim (R_e \sigma_e)^{1.3}$ for galaxies of all luminosities. On the other hand the ratio mass in GCs/halo mass is essentially constant (Hudson *et al.* 2014), the GC number also scales with halo dark mass and Harris *et al.* (2015) even find a strict proportionality between the number of blue clusters and the halo mass. Harris *et al.* (2014b) compare the GC luminosity functions of seven brightest cluster galaxies and find identical shapes.

Dwarf galaxies show a tendency of increasing specific frequency with decreasing luminosity (Miller & Lotz 2007). How the GCSs of dwarf galaxies are affected by galaxy harassment in clusters, is studied by Smith *et al.* (2013). The critical parameter is the dark matter fraction that remains after interaction processes. Brüns *et al.* (2011) explain both compact and extended clusters by dynamical evolution in star cluster complexes. Massive young GCs are also seen in star forming dwarf galaxies (Adamo *et al.* 2011) which in the context of hierarchical clustering may have been important for the assembly of GCSs.

The richest GCs of nearby galaxies are found in the central galaxies of the Virgo (Harris 2009) and Fornax galaxy clusters. As population and dynamical tracers GCs have a high significance for investigating the dark matter content and distribution as well as the population structure and formation history of M87 and NGC 1399. Regarding NGC 1399, Schuberth *et al.* (2010) presented about 700 GC radial velocities within 80 kpc of galactocentric radius. Blue and red clusters show distinct kinematical properties with a sharp transition. The red clusters resemble the galaxy light, while blue clusters behave more erratic and are probably accreted. The best fitting dark halo agrees reasonably well with that from X-ray studies, but a substructure within the dark halo that has been suspected in earlier X-ray studies, has not been confirmed.

M87 also received particular attention. Strader *et al.* (2011) provide a wealth of kinematical data for over 700 GCs that Agnello *et al.* (2014) use for a dynamical analysis. They found a dark matter fraction of 0.95 within a radius of 135 kpc and an inner dark matter profile that is steeper than predicted by cosmological simulations. Such a big sample also permits to analyse the orbital properties of GCs. Remarkably, the anisotropy seems to be mainly tangential which supports the idea that many objects on radial orbits have been dissolved. Near M87 has been found the object with the highest negative radial velocity detected so far, a GC with -1025 km/s (Caldwell *et al.* 2014). Its dynamical history is mysterious.

A significant increase of the database regarding metallicities (Usher *et al.* 2012) and kinematics of GCs in early-type galaxies (Pota *et al.* 2013a) was achieved by the still ongoing "The SAGES Legacy Unifying Globulars and GalaxieS Survey (SLUGGS)" (Brodie *et al.* 2014). Until now, almost 1000 metallicities and 2500 velocities of GCs in a dozen early-type galaxies have been published. Highlighting a few galaxies: The disputed metallicity bimodality of GCs in NGC 3115 has been confirmed by Brodie *et al.* (2012) through CaII triplet strengths. Breaking the degeneracy in dynamical models between potential and orbital anisotropy, (Napolitano *et al.* 2014) find the dark halo of NGC 5846 to be consistent with cosmological simulations, that its stellar IMF is Salpeter-like, and that the GC orbits are isotropic in the central parts and slightly radial at larger distances (Napolitano *et al.* 2014). More than 400 GCs with photometry and velocities build the database for M60 (Pota *et al.* 2015).

The correlation between central supermassive black hole masses and properties of GCSs have been discussed in several papers (Burkert & Tremaine 2010; Sadoun & Colin 2012; Pota *et al.* 2013b; Harris *et al.* 2014a). The latter two contributions could investigate larger galaxy samples and find the correlations weaker than described before. Massive nuclear GCs host supermassive black holes. Graham & Spitler (2009) provides a relation between the masses of a nuclear star cluster, the bulge and the black hole. Antonini *et al.* (2015) show how erosion by binary BHs may change the mass of a nuclear star cluster. Georgiev & Böker (2014) provides a catalogue of 228 nuclear star clusters in nearby spirals.

The discussion regarding the characteristic parameters and the nature of UCDs is continuing. Brodie *et al.* (2011) find, on the basis of a survey in M87, that the colour-magnitude relation of UCDs is offset from that of GCs. They conclude that the majority of UCDs are stripped nuclei of former dwarf galaxies. Norris & Kannappan (2011) point to the dual nature of UCDs characterised by mass. Above $7 \times 10^7 M_\odot$, UCDs are predominantly stripped nuclei, while at lower masses, many "normal" GCs may be mixed in. An interesting finding were the enhanced M/L-values of some UCDs in the Virgo cluster which could not be explained by stellar population models , perhaps indicative of dark matter (Haşegan *et al.* 2005). Later work on UCDs in the Fornax cluster did not confirm this (Hilker *et al.* 2007). In particular, the brightest and resolved UCD in the Fornax cluster shows population properties consistent with existing models Frank *et al.* (2011), but the discussion is going on Mieske *et al.* (2013). The study of a large number of UCDs around M87 suggests that UCDs are distinct from GCs by their sizes rather than by their masses. The UCDs in M87 show both radial distributions and orbital properties different from those of GCs (Zhang *et al.* 2015). Brüns *et al.* (2011) explain both compact and extended clusters by dynamical evolution in star cluster complexes. Convincing evidence that some UCDs evolve from bigger parent galaxies, is the detection of a supermassive black hole in a UCD in M60 that has 15% of the mass of its host system Seth *et al.* (2014).

Cosmological formation of GCs has not yet been identified, but GCs populating a galaxy cluster rather than an individual galaxy, have been found by Peng *et al.* (2011) in the Coma cluster, West *et al.* (2011) in Abell 1189, and by Alamo-Martínez *et al.* (2013) in Abell 1689. For the latter cluster, the authors quote a number of 160 000 GC within 400 kpc. The other extreme appears as "the most isolated globular clusters in the Local Universe" in the vicinities of M81 and M82 Jang *et al.* (2012). The Local Group does not seem to host very isolated GCs (di Tullio Zinn & Zinn 2013).

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