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Memorie della

The Cosmic-Lab project

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Abstract. Cosmic-Lab was a five-year project aimed at probing the complex interplay between dynamics and stellar evolution by using Galactic Globular Clusters (the most populous stellar aggregates in the Milky Way) as Cosmic Laboratories, and blue straggler stars, millisecond pulsars and intermediate-mass black holes (the most exotic by-products of this interplay) as test-particles. Cosmic-Lab represents the largest and most comprehensive approach ever attempted at using star clusters as dynamical laboratories. In the following I present a short summary of the most relevant results obtained within the project.

Key words. Stars: Population II – globular clusters: general – blue stragglers – pulsars: general

1. Introduction

Galactic Globular Clusters (GCs) are the most populous and dense stellar aggregates in the Milky Way. They are dynamically active systems, where phenomena like stellar collisions, mass exchanges within binary systems, in/outward migration of different classes of stars are very effective. Such a vigorous dynamical activity (Meylan & Heggie 1997) can substantially modify the (otherwise normal) evolution of stars, thus creating a variety of exotic objects, like Blue Stragglers stars (BSSs), millisecond pulsars (MSPs), etc. (see, e.g, Bailyn 1995; Ferraro et al. 2015a) that cannot be interpreted in the context of the passive evolution of single stars.

Cosmic-Lab was a five-year project with the aim of clarifying the complex interplay between dynamics and stellar evolution, by using Galactic GCs as cosmic laboratories, and three classes of exotica (BSSs, MSPs and intermediate-mass black holes - IMBHs) as probe particles. The wide variety of results obtained within the project (discussed in the contributions by Dalessandro, Alessandrini, Beccari, Cadelano, Pallanca, Lanzoni, Sollima, Mucciarelli, Lapenna, Massari, Saracino, in this Volume) provided new knowledge about the internal evolution of GCs, and new methodologies to properly investigate these systems and their stellar populations. A schematic summary is reported in the following.

2. Blue Stragglers Stars

By using the large photometric dataset collected by our group in the last few years, we pursued the investigation of BSSs in a sample of 25 GCs (Ferraro et al. 1997, 2003, 2006; Lanzoni et al. 2007a,b), finding that the shape of BSS radial distribution differs from cluster to cluster (see, e.g., Beccari et al. 2011, 2012; Contreras Ramos et al. 2012; Dalessandro et al. 2013a,b, 2015; Sanna et al. 2012, 2014). These results contributed to solidly demonstrate that in most of the cases the BSS radial distribution is bimodal, in a few GCs it shows only a central peak, and in the remaining cases it is completely flat. Motivated by such a solid observational panorama, we proposed the first physical interpretation of these findings, thus defining of the "dynamical clock" of stellar systems. In Ferraro et al. (2012a) we demonstrated that the shape of the BSS radial distribution is a powerful indicator of the level of dynamical evolution suffered by the host cluster since its formation. This is because BSSs are significantly heavier than the majority of cluster stars and therefore progressively sink towards the centre under a process similar to sedimentation. Hence by measuring the level of sedimentation (indicated by the position of the radial distribution minimum) we have been able to rank stellar systems in terms of their dynamical age. Interestingly enough, whenever studied in comparable details, the radial distribution of binary systems and that of BSSs have been found to be very similar (see Dalessandro et al. 2011; Beccari et al. 2013, 2015), in agreement with what expected if they are both shaped by dynamical friction, as assumed in the dynamical clock framework.

The phenomenon of the two distinct sequences of BSSs first discovered in the core-collapse cluster M30 by Ferraro et al. 2009a was further investigated during the Project: (1) mass-transfer models (Xin et al. 2015) have been found to nicely reproduce the red sequence in M30, which cannot be reproduced by any collisional model (Sills et al. 2009); (2) this feature was detected in other dynamically-evolved GCs, namely NGC 362 (Dalessandro et al. 2013b) and M15 (Ferraro et al. 2016a; see also the case of NGC 1261 discussed in Simunovic et al. 2014). These results strongly suggest that BSS properties are powerful observational tools able to trace the entire dynamical evolution of stellar systems, from the very beginning of their history (when dynamical friction was still ineffective), up to the occurrence of core collapse.

In Ferraro et al. (2016b) we defined an innovative "stellar scale" able to measure the stellar mass. This tool has been used to identify, among several photometrically indistinguishable stars, an object that is significantly heavier than its low-mass sisters (an evolved BSS). The stellar scale is based on the comparison between the chemical abundance obtained from the ionized lines of a given element and that derived from neutral lines of the same element. In fact, the former sensitively depends on stellar mass, while such a dependence is negligible for neutral spectral features of the same element. Since the abundances obtained from the two measurements must agree, the difference between the two values can be used to derive the stellar mass, as the pointer of a cosmic scale: when the correct stellar mass is assumed, the pointer marks zero. The stellar scale, "patented" within Cosmic-Lab, not only provided the first spectroscopic identification of an evolved BSS in a GC, but also opened a new route of investigation in the BSS science, allowing to access still unexplored stages of the evolution of these exotica, thus promising to bring new crucial constraints to the formation and evolutionary models of BSSs.

We also pursued the systematic characterization of the kinematical and chemical properties of BSSs in GCs (see Lovisi et al. 2012, 2013a,b; Mucciarelli et al. 2014a). The database collected so far counts almost 200 BSSs and is the largest acquired so far. These observations are opening a new perspective in our understanding of the BSS properties, especially in terms of their rotational velocities, and provide new crucial constraints to the theoretical modelling of these objects. The BSS pulsational properties were also investigated (Fiorentino et al. 2014, 2015) and both semi-analytical models and N-body simulations were developed to reproduce the BSS radial distributions (see Alessandrini et al. 2014, 2016; Miocchi et al. 2015).

3. Millisecond pulsars

Low mass X-ray binaries (LMXBs) and radio MSPs are thought to be, respectively, the starting and the ending stages of a common evolutionary path, where a neutron star accretes matter and angular momentum from a companion. Each stage of this evolution is characterized by different X-ray, radio and optical emission properties, the latter being imprinted on the surface of the companion star.

The identification and the characterization of MSP companion is of paramount importance in the contest of studying the complete evolutionary path which led to the formation of the accelerated neutron star. Within Cosmic-Lab, the search and the characterization of MSP companions have been successfully conducted both in the Galactic field (Pallanca et al. 2012, 2013a; Mignani et al. 2013, 2014; Ferraro et al. 2012b; Testa et al. 2015) and in GCs (Pallanca et al. 2013b, 2014; Cadelano et al. 2015a,b). In particular, the identification of 8 new companions to MSPs in GCs doubled the number of such objects known before the project, thus allowing to sketch a coherent evolutionary scenario (from the pre-natal stage, up to death) of these exotica. Indeed a global coherent picture seems to emerge, with the so-called "Redbacks" tracing the early phases of evolution, while systems with white dwarf companions and "Black widows" representing two alternative advanced stages. Particularly intriguing are the case of IGR J1824-2452H in the GC M28 (Pallanca et al. 2013b), which is the first empirical confirmation of the predicted transition between the accretion-powered and the rotation-powered stages of MSP evolution (Papitto et al. 2013), and the case of the neutron star burster EXO 1745-248 in Terzan 5 (Ferraro et al. 2015b), which is a system catch during the pre-natal stage of a MSP, an evolutionary phase during which heavy mass accretion on the compact object occurs, thus producing X-ray outbursts and the re-acceleration of the neutron star. Another particularly interesting result is the spectroscopic confirmation that the companion stars to binary MSPs experienced heavy mass-transfer. The chemical analysis (Mucciarelli et al. 2013a) of the companion to PSR J1740-5340 discovered by Ferraro et al. 2001 in NGC 6397 confirmed that this is a deeply peeled star, descending from a $\sim 0.8 M_{\odot}$ progenitor which lost ∼ 80% of its original material because of mass transfer.

4. Intermediate mass black holes

In Lanzoni et al. (2013) we used adaptive optics assisted spectroscopy to measure the radial velocity of more than 50 stars within the innermost 2″ from the centre of NGC 6388, a GC suspected to harbour a IMBH of about 6000 $M_{\odot}$ (Lanzoni et al. 2007c). By combining these data with 300 additional spectra of individual stars in the cluster outskirts (see Lanzoni et al. 2013 and Lapenna et al. 2014), we derived the entire velocity dispersion profile of NGC 6388, finding a centrally flat behaviour with a value of $\sim$ 13 km s^{-1}, fully compatible with no IMBH. These results are totally inconsistent with the steep cusp and the central value ($\sim$ 23 km s^{-1}) previously claimed from integrated-light spectra (Lützgendorf et al. 2011), and demonstrate that the determination of the velocity dispersion from this latter method can be severely biased in the case of Galactic GCs. This work defined a novel approach to the search for IMBHs in GCs and it has been now adopted in two dedicated Large Programmes currently running at the ESO-VLT.

5. Cluster structure and properties

The structural and dynamical parameters of Galactic GCs have been traditionally estimated from surface brightness profiles, which, however, can suffer from shot noise biases. In Miocchi et al. (2013) we proposed the alternative approach of using resolved star counts for the determination of both the cluster centre of gravity, and the projected star density profile. This approach requires a proper combination of high-resolution photometry for the cluster centres, and wide-field imaging of the external regions, but it is much safer and solid. The 26 GCs discussed in Miocchi et al. (2013) represent the largest sample analysed so far with this approach. The exploration of the central region of Liller1 (Saracino et al. 2015) by using a new generation instrument equipped with a multi-conjugate adaptive optics facility at the GEMINI South Telescope (Chile) has shown that this system has the second largest collision rate (after Terzan 5) among all the Galactic star clusters, thus confirming that it is an ideal environment for the formation of collisional objects (such as MSPs). Detailed photometric, spectroscopic and astrometric properties of stellar populations in specific clusters can

Table 1. Cosmic-Lab in a Table

Year	Funded PhD positions	Post-Doc (months)	Assigned Obs. time (hours)	Presentations at conferences	N. of published refereed papers
2011	1	18	111	0	2
2012	1	44	132	10	10
2013	1	79	253	15	17
2014	1	77	254	20	14
2015	2	65	131	16	17
2016	0	18	41	9	4
TOT	6	301	885	70	64

be found in Dalessandro et al. (2012, 2013c, 2014a,b); Bellini et al. (2014); Lagioia et al. (2015); Massari et al. (2013); Mucciarelli et al. (2012, 2013b, 2014a,b,c); Origlia et al. (2014); Piotto et al. (2015); Schiavon et al. (2012).

6. Interdisciplinary discoveries

Although the project was essentially focussed on a specific astrophysical problem (the impact of dynamics on stellar evolution and vice versa), the results obtained have had a strong impact in other areas of the astrophysical research. In particular:

1) after the discovery of the double red clump in the GC-like stellar system Terzan 5 (Ferraro et al. 2009b; Lanzoni et al. 2010), we performed a massive photometric and spectroscopic study (Origlia et al. 2011, 2013; Massari et al. 2012, 2014a,b, 2015; Ferraro et al. 2016c) of this system which is known to harbour the largest population of MSPs in the Galaxy. Our study definitely demonstrated that Terzan 5 is not a GC, but, instead, it is the remnant of a much more massive structure that was able to retain the metal-enriched gas ejected at high-velocities from supernova explosions. In fact, in Terzan 5 we found three sub-populations with iron content varying by more than one order of magnitude (from 0.2 up to 2 times the solar value). Moreover, the chemical abundance patterns of these sub-populations appear to be strikingly similar to those observed in bulge field stars, thus suggesting that Terzan5 and the Galactic bulge shared a common origin and evolution. Finally in Ferraro et al. (2016c) we measured the age of the two main stellar populations: 12 Gyr for the (dominant) sub-solar component and 4.5 Gyr for the component at super-solar metallicity. This discovery classifies Terzan 5 as a site in the Galactic bulge where multiple bursts of star formation occurred, thus suggesting a quite massive progenitor possibly resembling the giant clumps observed in star forming galaxies at high redshifts. This connection opens a new route of investigation into the formation and evolution processes of spheroids and their stellar content.
2) we have found evidence of a previously unknown mechanism acting in the atmosphere of most AGB stars and affecting the neutral species of some chemical element (Lapenna et al. 2014, 2015b; Mucciarelli et al. 2015a,b): because of it, the abundances derived from neutral lines are systematically underestimated, while those measured from ionized lines remain unaffected. Such a behaviour well corresponds to what is expected in the case of non-local thermodynamic equilibrium (NLTE) conditions in the star atmosphere. For this reason, we refer to it as "NLTE effect", with the caveat that this could be not the case. In fact, the current NLTE models are unable to account for the observed effect, thus demonstrating that either our comprehension of NLTE is not adequate enough, or that some

more complex physical phenomena are occurring in AGB atmospheres. This effect has been found in all the investigated GCs. It affects most (but not all) AGB stars and, in some cases, also some red giant branch (RGB) stars. Moreover, it is particularly evident for iron and titanium lines (i.e., the elements providing the largest number of both neutral and ionized lines). The deep understanding of the detected phenomenon is of paramount importance since it has a huge impact on the proper determination of GC chemistry (and enrichment history). In fact our work has shown that the iron spreads claimed in a few GCs (namely NGC 3201 and M22) is spurious, and due to (neglected) NLTE effects that lower the iron abundance derived from neutral lines, leaving unaltered those derived from ionized lines. In fact, no iron spread is observed if the iron abundance obtained only from (the unaffected) ionized lines is considered.

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