New Surprises in Old Stellar Clusters

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Galactic globular clusters have a long and distinguished history as conspicuous providers of simple populations where models of low-mass stars can be tested. However their simplicity has been challenged several times and a few peculiar objects have been identified. Only recently has the case for extended star formation histories become really compelling, with the unprecedented quantity and quality of data from Hubble Space Telescope imagers and multiplexing spectrographs on large telescopes. With ages close to that of the Universe, globular clusters can also help us uncover the earliest phases in the formation of the Milky Way. In both areas, one of the major challenges is to have an abundance ranking of all clusters based on the same metallicity index, and for as many stars as possible inside each cluster; a homogeneous metallicity compilation is only available for about half of all globular clusters. A few years ago we began a project to help close this gap and we report on a few surprising results that are emerging.

In his book *Reflecting Telescope Optics* Ray Wilson (Wilson, 2004) writes that the 60-inch telescope on Mt. Wilson was, in its time, "arguably the greatest relative advance in astronomical observing potential ever achieved [together with W. Herschel's 20-foot focus telescope]", made possible by the technical genius of George Ritchey. The telescope had its first light on 8 December 1908, and eight years later it was used by Harlow Shapley to publish the first paper of his series "Studies Based On The Colors And Magnitudes In Stellar Clusters". In the introduction, he recalled that, "No serious attempts have been made to determine accurate magnitudes, chiefly because of the lack of dependable magnitude scales for the fainter stars." Such attempts could finally be made thanks to the availability of that superb telescope, which could collect photometric data of such distant objects as Galactic globular clusters (GCs).

Among the motivations to undertake his work, Shapley quoted the possibility of solving the problem of "the order of stellar evolution; that is, the probable character of the progression of spectral type (color) with age". Almost one hundred years later, this motivation still underlies a large fraction of stellar cluster studies. In particular globular clusters have been, and still are, crucial in testing theories of low-mass stellar evolution, because their stars were born in a single episode, thus representing the simplest conceivable population. Or at least this has been the common wisdom for many years. But as observations and data analysis techniques have improved, this view has started to change. This change has been helped in part by our work, as we illustrate here, after setting things in context.

A few historical notes

The practice of using GCs to test the resolving and light-collecting power of new telescopes and instrumentation continued until well after Shapley, and these beautiful objects are still often featured in press releases today when new facilities are inaugurated. So it is not surprising that just a handful of years after its first light in 1948, the 200-inch telescope at Palomar was used by Arp, Baum & Sandage (1953) to resolve the faint stars defining the turnoff feature in the colour–magnitude (CM) diagram of M92. It was a breakthrough that suggested the connection between the main sequence in the CM diagram of young clusters, and the later evolutionary phases seen in globular cluster diagrams.

The theoretical interpretation of such diagrams came almost immediately with the work of Hoyle and Schwarzschild, who, in 1955, were able to calculate a stellar age of 6.2 Gyr by comparing the track of a 1.1 $M_{\odot}$ star to the CM diagram of the clusters M92 and M3. To be able to perform the analytic calculations, some simplifications had to be introduced, so the

Figure 1. The fuzzy object above the ESO 3.6-metre telescope (and the NTT in the foregound) is Omega Centauri, the most massive globular cluster in the Milky Way. This object was perhaps the nucleus of a dwarf galaxy that was disrupted several Gyr ago.

track was only in qualitative agreement with the observations. However computers soon became powerful enough to allow numerical calculations, which were pioneered by Icko Iben and collaborators. Iben & Rood (1970) were able to follow the evolution of metal-poor stars for objects of different mass, metallicity, and helium abundance, thus yielding isochrones that could be compared quantitatively to observed CM diagrams. The comparison exercise was immediately performed by Sandage (1970) with four globular clusters, and his investigation set the foundations for the classic research lines that extend into our times.

Based on the colour and luminosity of the clusters' turnoffs, Sandage established an average age of 11.5 Gyr, and cluster-to-cluster age differences formally not greater than ~ 2% (although photometric errors allowed an age spread as large as one Gyr). The data were not in conflict with contemporary estimates of the Hubble time, and they were also consistent with the rapid-collapse (~ 10^8 yr) formation of the Milky Way halo, as proposed by Eggen, Lynden-Bell & Sandage (1962). Globular clusters had thus acquired a prominent role both for cosmology and for theories of galaxy formation. The new perspective also brought questions about cluster and star formation in the primordial Universe, and about survival mechanisms against internal and external disruption processes.

A uniform database of metallicities

The determination of absolute ages requires knowledge of cluster distances, which are difficult to obtain because of the paucity in the solar vicinity of population II standard candles that can be calibrated via parallax. Relative ages are comparatively easier to obtain, and therefore many studies after Sandage tried to uncover the age distribution of Galactic globular clusters, with mixed results. The situation was reviewed by Stetson, van den Bergh & Bolte (1996), who concluded that "as of the current date the state of the field is still somewhat muddled", but also hoped that "data now being collected by numerous groups in various sub-disciplines may resolve the remaining controversy within a few years". The controversy arose in considerations of whether there was an age spread, or a majority of coeval clusters plus a few younger ones with possible extragalactic origin. To settle the question, a large, homogeneous and high quality photometric database of CM diagrams was needed, a task that was becoming possible at that time thanks to the introduction of charge coupled devices (CCDs) as detectors into astronomical instrumentation.

With these detectors, errors better than 0.01 magnitudes could be achieved at the cluster turnoff, which opened the way to comparing the position of that feature — relative to the red giant branch or the horizontal branch — in many different clusters, with sufficient accuracy to detect age differences of the order of 0.5 Gyr. Because of the small format of those early CCD chips, the fast, post-turnoff phases of stellar evolution (the horizontal branch in particular) could not be well sampled, so the photometric colour of the turnoff relative to the giant branch became the easiest parameter to be measured. The combination of all these ideas was behind the Rosenberg et al. (1999) study, which was based on a homogeneous photometric database for 35 clusters, assembled with the 91-centimetre Dutch telescope at La Silla and the 1-metre Johannes Kapteyn Telescope (JKT) at La Palma. The conclusion was that most globular clusters were formed in a single epoch, but a few objects were clearly formed at later stages. Meanwhile Ortolani et al. (1995) had also found that the Bulge is coeval with the oldest Halo clusters. This is consistent with recent simulations of the formation of the Galaxy which find that up to 80% of the Milky Way could have been formed *in situ* (e.g., de Rossi et al., 2009).

Table 1. Major metallicity compilations. For each reference, NP and NC are the number of programme clusters, and the number of clusters with [Fe/H] homogenised on the same scale. The fifth column lists whether (r)esolved stars or (i)ntegrated light was studied.

Reference	Acronym	NP	NC	i/r	Method
Searle, L. & Zinn, R. 1978, ApJ, 225, 357	SZ78	19	–	r	Mean of reddening-free magnitudes for seven bands
Zinn, R. 1980, ApJS, 42, 19	Z80	79	84	i	Reddening-independent colour quotient Q_{39}
Zinn, R. & West, M. J. 1984, ApJS, 55, 45	ZW84	60	121	i	EW of Ca II K line, *G*-band, Mg I triplet
Armandroff, T. E. & Zinn, R. 1988, AJ, 96, 92	AZ88	27	–	i	EW of Ca II infrared (IR) lines
Rutledge, G. A. et al. 1997, PASP, 109, 907	RHS97	52	70	r	EW of Ca II IR lines
Carretta, E. et al. 2009, A&A, 508, 695	C09	19	133	r	EW of Fe lines in medium-resolution spectra
Harris, W. E. 2010, arXiv, 1012.3224	H10	157	–	–	Average of literature

Notwithstanding the success of relative age studies, they still suffer from one major problem: in addition to its age, the luminosity and colour of a star at the turnoff depend on its metallicity, so a key input to relative age studies is a metallicity compilation that is also homogeneous. Rosenberg et al. (1999) could take their [Fe/H] values from Rutledge et al. (1997), which was based on homogeneous measurements of the equivalent widths (EW) of the Ca II infrared triplet lines. The photometric data were collected in the *V*- and *I*-bands because it had been shown empirically that the *V–I* colour difference is much less sensitive to [Fe/H] than the *B–V* one (Saviane et al., 1997). However homogeneous [Fe/H] values are available for only a fraction of clusters, a fact that was one of the main motivations for our project.

The current state of [Fe/H] data is summarised in Figure 2 and in Table 1. The largest homogeneous spectroscopic sample of individual stars is still that of Rutledge et al. (1997) and if we add the clusters of Saviane et al. (2012) then we find that ~ 55% of objects have a metallicity measurement based on the same index (the "reduced" equivalent width of the Ca II infrared triplet). We then have to move to integrated-light spectroscopy, to the samples of ZW84 and AZ88 (see Table 1). They are based on the equivalent widths of various metallic lines (Ca II K line, *G*-band and Mg I triplet), and of the Ca II infrared triplet, respectively. After excluding objects in common with the

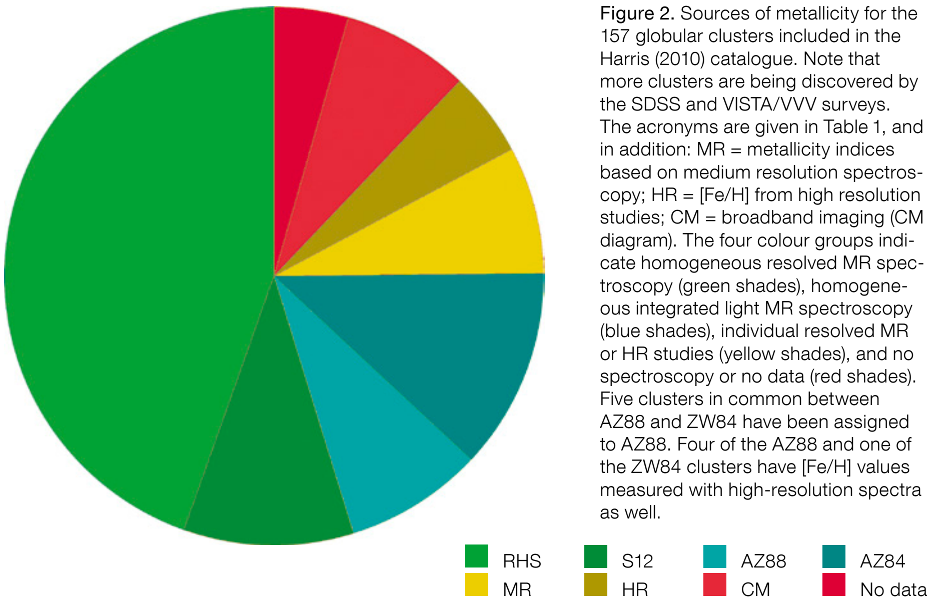

Figure 2. Sources of metallicity for the 157 globular clusters included in the Harris (2010) catalogue. Note that more clusters are being discovered by the SDSS and VISTA/VVV surveys. The acronyms are given in Table 1, and in addition: MR = metallicity indices based on medium resolution spectroscopy; HR = [Fe/H] from high resolution studies; CM = broadband imaging (CM diagram). The four colour groups indicate homogeneous resolved MR spectroscopy (green shades), homogeneous integrated light MR spectroscopy (blue shades), individual resolved MR or HR studies (yellow shades), and no spectroscopy or no data (red shades). Five clusters in common between AZ88 and ZW84 have been assigned to AZ88. Four of the AZ88 and one of the ZW84 clusters have [Fe/H] values measured with high-resolution spectra as well.

cited studies, these two datasets comprise 8 % and 12 % of clusters, respectively. No other homogeneous datasets exist: 12 % of clusters have medium or high-resolution spectroscopic data of resolved stars from a variety of sources, and for another ~ 8 % the metallicity estimate comes from their CM diagram. Finally there are a handful of objects for which no [Fe/H] data exist.

Rutledge et al. (1997) obtained their spectra with the modest 2.5-metre Dupont telescope at Las Campanas, so homogeneous [Fe/H] data are missing mostly for outer halo or heavily extincted clusters. As relative age studies include more and more outer halo objects, we are forced to take metallicities from a variety of sources. For example Marín-Franch et al. (2009) based their study on the largest homogeneous photometric sample of Galactic globular clusters (64 objects), but for as many as 25 % of them they had to estimate [Fe/H] from the Zinn & West (1984) compilation of the reddening-independent Q_{39} photometric index. To summarise, for almost half of GCs, the metallicity values are based on data that are either not spectroscopic, not homogeneous or not of individual stars. Furthermore, even when all these conditions are satisfied, the number of stars measured might be too small to look for metallicity dispersions, precisely the area where globular clusters started to show the first surprises.

When the first CM diagrams of main sequence stars based on CCD imaging appeared, they showed a virtually zero-width locus, confirming the visual impression of a smooth, single-age stellar population. However as more and more data accumulated, things started to look less simple. In particular, abundance variations have been found for light elements in all clusters that have been searched so far (see the very recent review of Gratton et al. [2012]). In addition, a spread in one or more of iron-peak, n-capture, and α elements has also been found for ω Cen, M54, M22, NGC 1851, NGC 2419, Terzan 5 and NGC 5824. This is particularly interesting because it is direct evidence for extended star formation in these clusters. In three of these seven objects the spread was discovered or confirmed from our FORS2 project.

Improving the situation

In May 2006 we had two observing nights assigned to us at the VLT, to collect medium-resolution FORS2 spectra for globular clusters whose distance modulus is too large for high-resolution studies, either because of distance or high extinction. The weather did not help us very much, so of the 49 planned targets we could observe only twenty, plus eight calibrators. To increase observing efficiency we used the multi-object capability of FORS2: the maximum slit density can be reached with the mask exchange unit, however the lengthy operations of mask manufacture and insertion meant that only a few objects per night could have been observed. Therefore we opted for the configurable slits solution, and left the masks for the most compact objects.

All data were reduced with the FORS2 pipeline (Izzo et al., 2010) which delivers wavelength-calibrated, sky-subtracted spectra in an extremely efficient manner; organising the data took more time than reducing them. On the other hand because of the high crowding typical of globular clusters, often more than one star per slit was extracted, so a major part of the work was to cross-check the identification of the ~ 600 spectra. Cluster members were identified as objects with both radial velocity and reduced equivalent widths not deviating significantly from the average, taking into account that uncertainties in our mean velocities are of order 5–6 km/s. The fraction of stars that were eventually confirmed as members varies significantly from cluster to cluster, with a median value of 53 % and being always better than 20 %. Especially for bulge clusters where field contamination is high, the catalogues of member stars for follow-up high-resolution studies is another useful byproduct of our work.

The equivalent widths of calcium lines in red giant stars depend on the Ca abundance and also on their luminosity, so this dependency was removed by adding a linear term in $V–V_{HB}$ and obtaining the "reduced" equivalent width. A calibration relation from such reduced equivalent widths to the scale (Carretta et al., 2009) was then obtained, with 14 clusters having well-determined [Fe/H] values by high-resolution studies. It was then applied to convert the reduced equivalent widths of programme clusters into metallicity values. These new [Fe/H] values are significantly different from literature values for about half of our programme clusters, as graphically illustrated by Figure 3, which shows a type of diagram first introduced by Zinn (1993). Our new average abundances are lower than literature values for six clusters (Pyxis, Terzan 3, HP1, NGC 7006, NGC 6569 and

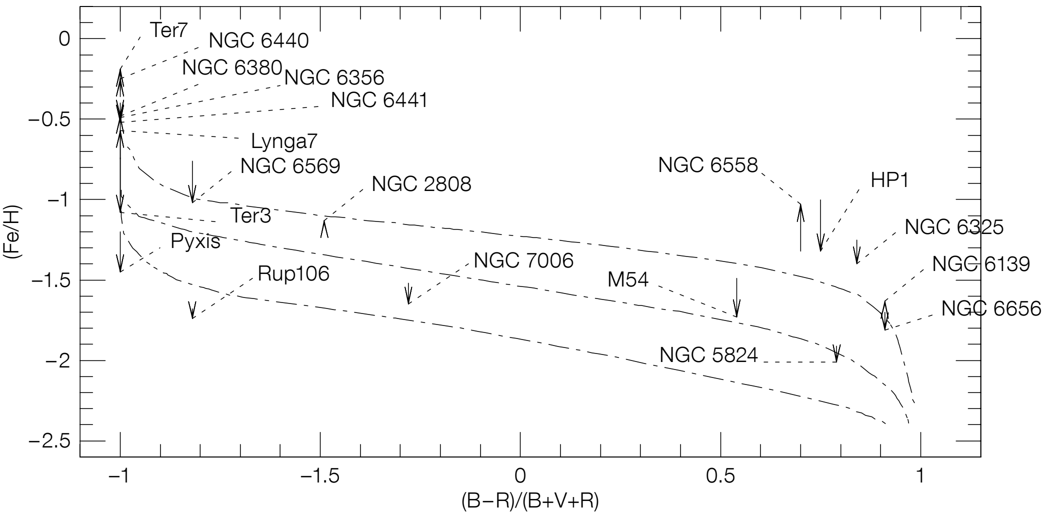

Figure 3. The metallicity of our programme clusters on the Carretta et al. (2009) scale is plotted here against horizontal branch (HB) type. Isochrones are from Rey et al. (2001), and are separated by 1.1 Gyr, with age decreasing from top to bottom. The oldest isochrone gives the age of clusters at $R < 8$ kpc (Rey et al., 2001). The arrows connect the position of the cluster, if [Fe/H] from Harris (2010) is used, to the position given by our metallicity value.

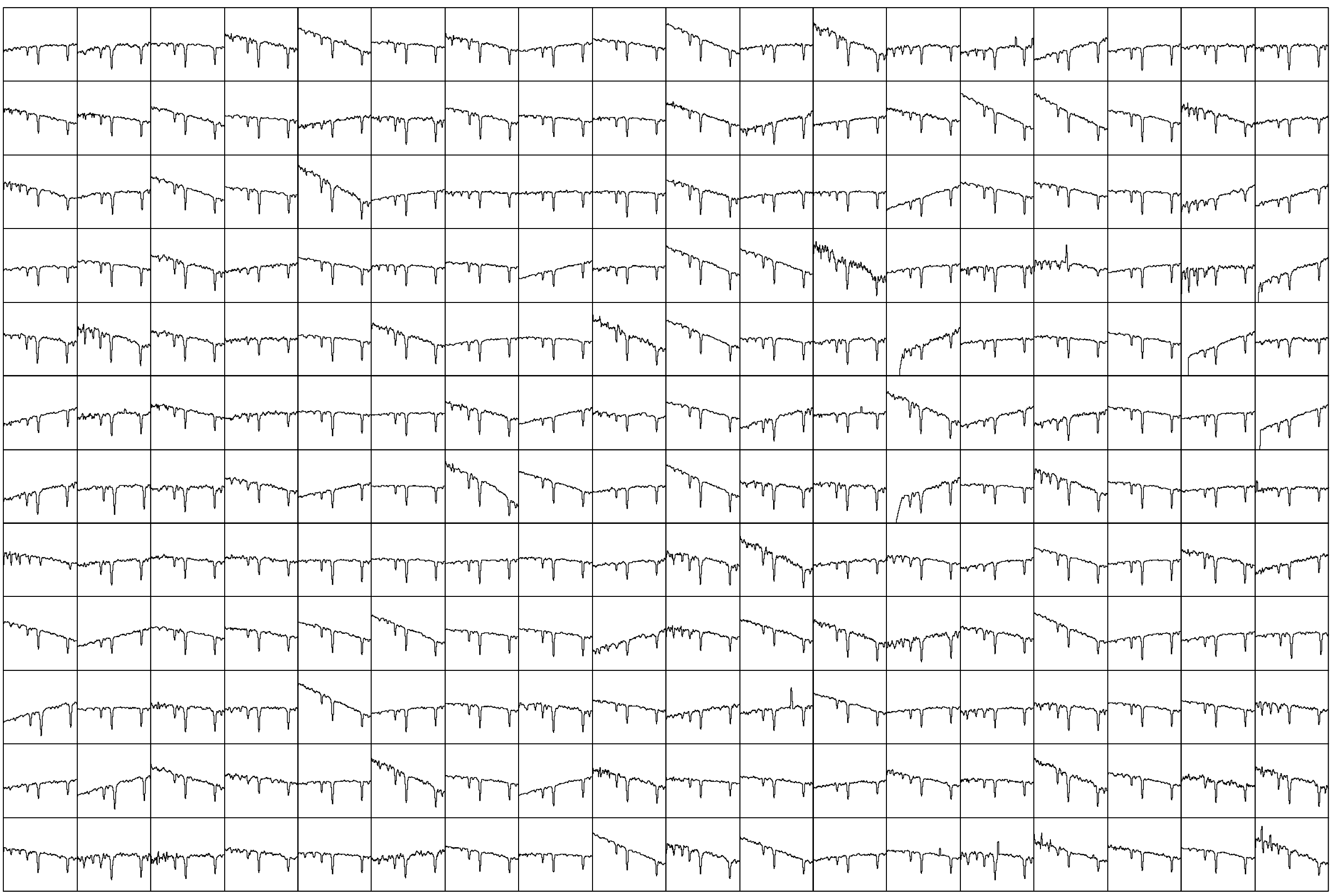

Figure 4. The 216 useful spectra of NGC 5824 and foreground stars taken with FORS2 in the calcium triplet region (840–870 nm). The three most prominent lines belong to the Ca II ion, with wavelengths of 849.8, 854.2 and 866.2 nm.

NGC 6715), so to retain their horizontal branch (HB) morphology they must be younger. The higher abundances of Lynga 7, NGC 6558 and NGC 6380 suggest instead older ages. Zinn had introduced the diagram of Figure 3 to see whether the age distribution of Galactic clusters would support the extended halo formation proposed by Searle & Zinn (1978). In this scenario, our [Fe/H] revision would bring more clusters into the "young halo" class, however the HB morphology depends also on the mass loss along the red giant branch (RGB) and the helium abundance, so the conclusion will have to be confirmed with precise turnoff photometry.

The second finding of our project is that, for three clusters, the dispersion of reduced equivalent widths is larger than the measurement error. We thus confirmed the [Fe/H] dispersion of M54 and discovered a metallicity dispersion in M22 (in parallel with Marino et al. [2009]) and probably in NGC 5824. The metallicity distribution of M22 (NGC 6656) has been discussed in Da Costa et al. (2009), where it was found to range from –2.2 to –1.2 dex, and to share many properties with those of ω Cen, including a fast rise to a peak and a broad tail to higher abundances. M22 could be well characterised because three FORS2 masks were dedicated to this cluster (41 member stars), while the small number of stars did not allow us to perform a similar detailed analysis for NGC 5824; we could only estimate a value ≈ 0.11–0.14 dex for its dispersion. However with observations carried out both at Gemini and at the VLT in period 87, we were able to collect spectra for a couple of hundred stars, of which more than a hundred were confirmed as cluster members. The data analysis is in progress, but the new data seem to confirm the presence of a metallicity spread. Figure 4 shows a montage of all useful spectra extracted with the FORS2 pipeline.

Outlook

The discovery of metallicity dispersions was greatly advanced by the advent of multiplexing spectrographs at 8–10-metre class telescopes, but the other important breakthrough in globular cluster research could only have been achieved with the Hubble Space Telescope (HST). By measuring stellar magnitudes on archival Wide Field Planetary Camera 2 (WFPC2) images with his specialised software, Anderson (2002) discovered that the main sequence of ω Cen is split in two. Multiple stellar populations were subsequently discovered in many other clusters, including those having metallicity dispersions. The latter are also among the most massive in the Galaxy, and some of them appear to be associated with stellar streams: M54 (M_V = –10.0) is clearly the nuclear star cluster of the Sagittarius dwarf galaxy, which is currently being tidally disrupted by the Milky Way, and NGC 1851 (M_V = –8.3) is surrounded by an extensive stellar halo that may have resulted from the destruction of the dwarf galaxy in which the cluster was once embedded (Olszewski et al., 2009).

Theoreticians have been able to simulate ω Cen as the nuclear remnant of a disrupted dwarf galaxy (Bekki & Freeman, 2003) and Newberg et al. (2009) have suggested that NGC 5824 (M_V = –8.8) may be associated with the newly discovered Cetus Polar Stream (CPS). The nuclear cluster scenario is quite appealing because it would offer an explanation for the peculiarities illustrated above. If a cluster is located in a deep potential well inside a dwarf galaxy, it might be able to retain or to accrete gas, thus forming multiple generations of stars or developing chemical anomalies. It is also interesting to note that both M54 and NGC 5824 lie on the same young isochrone in Figure 3, and that stars in the nuclei of early-type dwarf galaxies tend to be younger than the underlying population (e.g., Monaco et al. 2009; Paudel et al., 2011). It should be added that metallicity spreads might be explained by other mechanisms (e.g., merging clusters with different [Fe/H]), and for these we refer to Gratton et al. (2012).

In a bigger picture, finding evidence of disrupting satellites in the Galactic Halo has great significance for the current Lambda Cold Dark Matter galaxy formation paradigm. In this scheme, the Galaxy is built up through the merger and accretion of lower mass systems, predominantly at early epochs. Indeed, while the spatial and kinematic signatures of this process have been erased in the inner parts of the Galaxy, in its halo where dynamical times are long, several stellar streams have been identified in the past. There is however still an order of magnitude discrepancy between the large number of predicted satellites in the Milky Way and the observed ones. Any addition of a new remnant is therefore important to confirm the paradigm.

Under the working hypothesis that clusters with metallicity spreads signpost halo substructures, we have been assigned more than 13 hours of additional FORS2 time in period 89 to extend our sample, and potentially to find still more unknown examples of these peculiar stellar systems.

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