Perseus in Sicily: From Black Hole to Cluster Outskirts
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Prodigious and Continuous Formation of Super Star Clusters from Cooled Intracluster Gas

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Abstract. Globular clusters (GCs) — compact and massive star clusters found ubiquitously around galaxies — are believed to be ancient relics (ages $\gtrsim$10 Gyr) from the early formative phase of galaxies, although their physical origin remains widely debated. The most numerous GC populations are hosted by giant elliptical galaxies, where they can exhibit a broad dispersion in colour interpreted as a wide spread in metallicity. Here, we show that many thousands of similarly compact and massive super star clusters have formed at an approximately steady rate over, at least, the past ∼1 Gyr around the nearby giant elliptical galaxy, NGC 1275, at the centre of the Perseus cluster. The number distribution of these young star clusters appears to exhibit a similar dependence in luminosity and mass as the even more numerous but older GCs around NGC 1275. In just a few Gyr, these super star clusters will evolve to become indistinguishable in broadband optical colours from the older GCs, and their spread in age add to the dispersion in colour of these GCs. The spatial distribution of the super star clusters resembles the filamentary network of multiphase gas in the cluster core, implying that they formed from molecular gas amassed from cooling of the hot intracluster gas. The sustained formation of super star clusters from cooled intracluster gas constitutes a previously unrecognised but prodigious source of GCs over cosmic timescales, and contributes to both their enormous numbers and broad colour dispersion in giant elliptical galaxies.

Keywords. Super Star Clusters, Globular Clusters, Intracluster Gas, Giant Elliptical Galaxy

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1. Introduction

Images taken with the Advanced Camera for Surveys (ACS) on the NASA/ESA Hubble Space Telescope (HST) are able to clearly separate, and even resolve, individual star clusters in NGC 1275. We have identified all the star clusters towards this galaxy from images taken in three filters: F435W in the blue (B), F550M in the middle of the visual band (V), and F625W in the red (R). Previous studies of NGC 1275 with the HST have been restricted to either small fields of view spanning the innermost region of this galaxy (Holtzman *et al.* 1992; Carlson *et al.* 1998), or those that employ the same images as we do but only identify star clusters at the outskirts of the galaxy (Canning *et al.* 2010; Canning *et al.* 2014). Although these studies revealed numerous compact and massive star clusters around NGC 1275, they did not establish the full properties of these star clusters (total number, overall spatial distribution, full age spread, luminosity or mass function, and formation rate over time), nor their relationship with other galaxies along the line

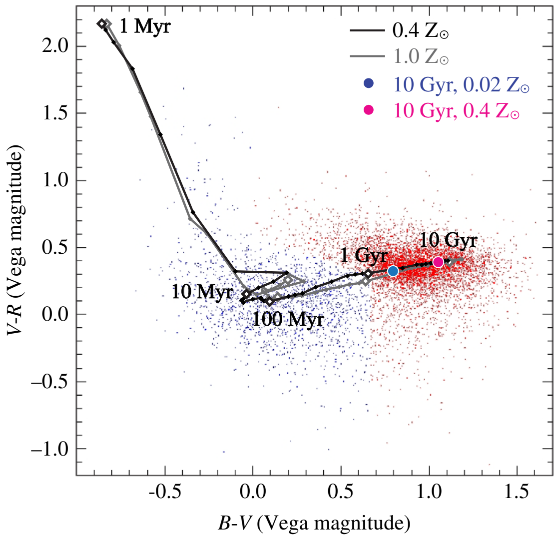

Figure 1. Colour-colour diagram of star clusters belonging to NGC 1275.

of sight. In our work, we identify star clusters throughout the $3'.4 \times 4'.0$ (73.4 kpc × 86.4 kpc) field of view common to all three filters, including the inner region of NGC 1275 where the light distribution is complex making a complete census of star clusters in this region challenging. As demonstrated below, in this way we are able to separate out star clusters associated with other galaxies along the line of sight, and determine in full the properties of those belonging to NGC 1275.

2. Results

Fig. 1 shows a colour-colour diagram of the star clusters detected in all three filters that do not include those bounded by two galaxies along the line of sight towards NGC 1275. Each point in this figure denotes an individual star cluster. Their ages can be inferred from theoretical evolutionary tracks for coeval stellar populations, provided their metallicity is known. The black line in Fig. 1 show evolutionary tracks for star clusters having a metallicity of $0.4Z_{\odot}$, corresponding to that of the intracluster gas (Werner *et al.* 2013), and the grey line to the Solar metallicity of $1.0Z_{\odot}$. These tracks are much more sensitive to age than metallicity over the parameter range plotted. The colour of a star cluster becomes redder with age as bluer, more massive, stars evolve away from the main sequence, resulting in generally increasing values in both $(B-V)$ and $(V-R)$ with age. The youngest star clusters having ages $\lesssim$6 Myr are bluest in $(B-V)$, but relatively red in $(V-R)$ owing to Hα+[NII] emission from leftover gas photoionized by massive stars that adds to the stellar continuum in the R filter. A striking feature of this colour-colour diagram is the very broad and continuous range in $(B-V)$ spanned by the star clusters, covering the full range of ages spanned by the stellar evolutionary tracks from the present epoch back in time to the early Universe.

3. Analyses

Before assigning ages to individual star clusters, we first have to separate out GCs, which individually can have a very different metallicity than the values adopted in the two evolutionary tracks plotted in Fig. 1. GCs generally exhibit a bimodal colour distribution,

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indicating distinct metal-poor (bluer) and metal-rich (redder) populations that differ by about a factor of ten in metallicity (Brodie *et al.* 2006; Harris 2010). In giant elliptical galaxies, however, the colour distribution of GCs can be continuous rather than bimodal (Harris *et al.* 2017); if GCs constitute a single ancient population ($\gtrsim$10 Gyr old), their metallicities would then span the enormous range $\sim 0.005 Z_{\odot}$–$1.0 Z_{\odot}$ (Harris *et al.* 2017). Even then, GCs are commonly divided into two populations having average metallicities that differ by an order of magnitude. In Fig. 1, the colour of 10-Gyr star clusters having a metallicity of $0.02 Z_{\odot}$ representative of the metal-poor GC population is indicated by a blue filled circle, and those having a metallicity $0.4 Z_{\odot}$ representative of the metal-rich GC population is indicated by a red filled circle. There is a clear concentration of star clusters in these regions of the colour-colour diagram, as would be expected for GCs belonging to NGC 1275.

The star clusters plotted in Fig. 1 can be separated into two groups based on whether they have an isotropic or anisotropic spatial distribution. Those coded blue in this figure, hereafter referred to as blue star clusters (BSCs), have a highly anisotropic spatial distribution. In stark contrast, those coded red in Fig. 1 have an isotropic distribution that decreases radially outwards in surface density, as is characteristic of GCs. There is an appreciable concentration of star clusters along the dusty spiral arms of a foreground infalling galaxy known as the High Velocity System (HVS), indicating that some of the star clusters towards the HVS belong to this galaxy. Those in the central innermost region also has been omitted from Fig. 1, as they likely belong to yet another spiral galaxy lying along the line of sight towards NGC 1275. The BSCs in this region are unusually bright (Holtzman *et al.* 1992), and furthermore have a different luminosity and mass function compared with the remaining BSCs. Away from the HVS and central spiral, the vast majority if not all of the BSCs must belong to NGC 1275, as is evident by their spatial concentrations in patterns largely related to the morphology of the gaseous nebula in NGC 1275.

We find the BSCs and GCs to exhibit a similar dependence in their luminosity or mass functions. Furthermore, in a previous study of over two-hundred BSCs in NGC 1275, their radial light profiles have been found to resemble GCs (Carlson *et al.* 2001). At a given luminosity or mass interval, the BSCs over the age range $\sim$100-900 Myr are approximately one-tenth or one-hundredth (strict lower limits, given those bounded by the HVS have been excluded), respectively, as numerous as the GCs over the sky area searched. The GCs in NGC 1275 have maximal masses of $\sim 10^7$ $M_{\odot}$, similar to the most massive GCs found in other giant elliptical galaxies (Harris *et al.* 2014). The BSCs have maximal masses of $\sim 10^6$ $M_{\odot}$, about an order of magnitude higher than the typical GC mass at the peak in their number distribution (Brodie *et al.* 2006; Harris 2010), and two orders of magnitude higher than the maximal masses of open star clusters in our Galaxy. Across the three age intervals plotted for the BSCs, their mass function is approximately constant, indicating an approximately steady formation rate over the past $\sim$1 Gyr. Over the mass range $\sim 5 \times 10^4 - 1 \times 10^6$ $M_{\odot}$ for the BSCs spanning ages $\sim$100-900 Myr, their formation rate is 1.2 Myr^{-1} at a total mass rate of 1×10^5 $M_{\odot}$ Myr^{-1}; i.e., at a typical rate of one star cluster every 1 million years having a mass close to that of GCs at the peak in their number distribution. These values are lower limits as some bounded by the HVS likely belong to NGC 1275, and furthermore we do not include the even more numerous BSCs detected in only one or two filters and likely having lower individual masses. Note that we cannot rule out the possibility of significant temporal modulations in the formation rate of BSCs on relatively short timescales; indeed, the mass formation rate of the youngest BSCs (ages $\lesssim$50 Myr) has been estimated to be about an order of magnitude larger (Canning *et al.* 2014).

4. Interpretation

The close spatial relationship between the BSCs and the gaseous nebula in NGC 1275 indicates that these star clusters formed from the nebular gas (Canning *et al.* 2010; Canning *et al.* 2014). Indeed, the atomic gas nebula in this galaxy is accompanied by an exact counterpart in molecular gas (Lim *et al.* 2012; Salome *et al.* 2006), the reservoir for star formation. NGC 1275 is the nearest, but by no means atypical, example of a cluster central giant elliptical galaxy possessing multiphase gas and exhibiting recent star formation. Such features are found preferentially if not exclusively among the central giant elliptical galaxies of relaxed clusters (Cavagnolo *et al.* 2008; Werner *et al.* 2014), where the intracluster gas (at temperatures $\sim 10^{7-8}$ K) at the cluster core is especially dense and therefore experiences vigorous radiative cooling.

About 25 years ago, the discovery of relatively large populations of compact and massive but young star clusters in nearby galaxies experiencing a brief period of highly elevated star formation (starbursts) due to interactions or mergers suggested that some ancient GCs may have formed through such events (e.g., Whitmore *et al.* 1993; Whitemore & Schweizer 1995) In such episodes, the available reservoir of cool gas is rapidly consumed by star formation and dispersed by stellar winds, supernovae, or AGN activity. In cluster central galaxies, however, cooled intracluster gas can be continuously or intermittently replenished, depending on AGN activity in the cluster central galaxy as well as global disturbances due to cluster-cluster mergers. The sustained formation of progenitor GCs from cooled intracluster gas can help explain not just the unusually large populations of GCs in cluster central galaxies, but their resulting wide distribution in ages (and perhaps also metallicities owing the enrichment of the intracluster gas) and therefore colours can contribute to the broad dispersion in colours of presumed ancient GCs in these galaxies.

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