NGC 2419: a large and extreme second generation in a currently undisturbed cluster

M. Di Criscienzo, F. D’Antona, A. P. Milone, P. Ventura, V. Caloi, R. Carini, A. D’Ercole, E. Vesperini and G. Piotto

1INAF, Osservatorio Astronomico di Roma, Via Frascati 33, I-00040 Monteporzio Catone (Roma), Italy
2Department of Astronomy, University of Padova, Vicolo dell’Osservatorio 3, I-35122 Padova, Italy
3IAC – Instituto de Astrofísica de Canarias, E-38200 La Laguna, Tenerife, Canary Islands, Spain
4INAF, IASF–Roma, via Fosso del Cavaliere 100, I-00133 Roma, Italy
5Department of Physics, University of Rome ‘La Sapienza’, P.le Aldo Moro 2, I-00185 Roma, Italy
6INAF – Osservatorio Astronomico di Bologna, via Ranzani 1, I-40127 Bologna, Italy
7Department of Physics, Drexel University, Philadelphia, PA 19104, USA

Accepted 2011 March 3. Received 2011 March 3; in original form 2010 December 22

ABSTRACT

We analyse complementary Hubble Space Telescope and Subaru data for the globular cluster NGC 2419. We make a detailed analysis of the horizontal branch (HB), which is composed of two main groups of stars: the luminous blue HB stars, which extend by evolution into the RR Lyrae and red HB region, and a fainter, extremely blue population. We examine the possible models for the latter group and conclude that a plausible explanation is that they correspond to a significant (∼30 per cent) extreme second generation with a strong helium enhancement (Y ∼ 0.4). We also show that the colour dispersion of the red giant branch is consistent with this hypothesis, while the main-sequence data are compatible with it, although the large observational error blurs the possible underlying splitting.

While it is common to find an even larger (50–80) percentage of second generation in a globular cluster, the presence of a substantial and extreme fraction of these stars in NGC 2419 might be surprising, as the cluster is at present well inside the radius beyond which the Galactic tidal field would be dominant. If a similar situation had been present in the first stages of the cluster life, then the cluster would have retained its initial mass and the percentage of second-generation stars would have been quite small (up to ∼10 per cent). Such a large fraction of extreme second-generation stars implies that the system must have been initially much more massive and in different dynamical conditions from what it is today. We discuss this issue in the light of existing models of the formation of multiple populations in globular clusters.

Key words: stars: abundances – stars: Hertzsprung–Russell and colour–magnitude diagrams – globular clusters: general – globular clusters: individual: NGC 2419.

1 INTRODUCTION

Most of the globular clusters (GC) spectroscopically examined so far have been shown to contain multiple stellar populations. Together with stars that have the typical composition of halo stars of the same metallicity, these GCs contain a population of stars whose gas has been subject to the full CNO cycle (decrease in the oxygen content) and to proton–capture reactions on light nuclei (e.g. formation of sodium from neon). Taking as a probe the Na–O anticorrelation, Carretta et al. (2009a) showed that all the 19 Galactic GCs they examined displayed it. As the chemical signatures of the anomalies are present also in turnoff (TO) stars and among the subgiants (e.g. Gratton et al. 2001; Briley, Cohen & Stetson 2002; Briley et al. 2004), they cannot be attributed to ‘in situ’ mixing in the stars but to some process of self-enrichment occurring during the first stages of the cluster life.

Photometric evidence for the presence of multiple populations is also numerous and sometimes suggestive of star formation occurring in successive bursts. The photometric signatures can be attributed in part to helium differences [morphologies of the horizontal branches (HB), multiple main sequences (MS)] or sometimes even to merging of different initial cluster-like structures (Carretta et al. 2010).

Different models have been discussed in the literature for the formation of multiple stellar populations. A general feature is...
that, apart from some exceptions, the iron content of normal and anomalous stars does not differ significantly [according to Carretta et al. (2009b), the iron spread in most GCs is contained within $\sim 0.05$ dex]. The gas that has the chemical signatures of second-generation (SG) stars must have been at least partially nuclearily processed in stars of the first stellar generation (FG) and thus does not include supernova ejecta.

A major problem is that both the interpretation of the HB morphologies in terms of helium enrichment and the spectroscopic information show that, in the clusters examined so far, the percentage of stars of the SG is generally $\sim 50$--$80$ per cent (D’Antona & Caloi 2008; Carretta et al. 2009a). Such a large fraction of SG stars cannot be the result of chemical evolution within a ‘closed box’, simply because the processed matter available from more massive stars is always a small percentage of the FG mass. Anomalous initial mass functions (IMFs) of the FG do not solve the problem; instead, it is required that the matter forming the SG stars is collected from a much larger stellar ensemble than what can be inferred by extrapolating to larger masses the present-day mass function of FG stars. Possible models imply that either the GC has formed in the environment of a dwarf galaxy now dispersed (e.g. Bekki & Norris 2006) or the SG has formed in the core of a much more massive FG cluster, filling its tidal volume and losing about 90 per cent of its initial mass (D’Ercole et al. 2008) in the first phases of its dynamical evolution. In all cases, a multiple-generation cluster is today believed to be a ‘small’ remnant of the evolution of a stellar system that is initially much more massive [see also Vesperini et al. (2010) for a study of the cluster properties required for the formation of a significant SG population and the implications for the contribution of GCs to the Galactic halo assembly].

Important clues to understand the GC formation might come from the analysis of the stellar content of GCs that evolved in isolation since their formation and did not undergo any significant loss of stars that altered the initial relative numbers of FG and SG stars. In this work, we examine NGC 2419, one of the most massive Galactic GCs. The cluster core relaxation time-scale is $\sim 10^9$ yr, while the half-mass relaxation time is much longer than the Hubble time (Harris 1996). It is very distant ($\sim 87.5$ kpc according to Di Criscienzo et al. 2011), its present truncation radius is 8.74 arcmin ($\sim 220$ pc) according to Trager, King & Djorgovski (1995) and its tidal (Jacobi) radius is $\sim 700$ pc (see Section 7). Had this cluster evolved in its current environment since its formation, it might have retained memory of the conditions imprinted by the formation processes. On the other hand, NGC 2419 has a very extended HB morphology, with the presence of a well-populated blue hook, generally regarded as a sign of the presence of an extreme, helium-rich population (e.g. Lee et al. 2005; D’Antona et al. 2002, hereafter D2002).

We take advantage of two rich Hubble Space Telescope (HST) and Subaru observational samples, discussed in Section 2, and of new models computed for the purpose for this work (Section 3) to make a detailed analysis of the HB population (Section 4), of the giant branch (Section 5) and of the MS (Section 6). We find several compelling reasons to suggest that this cluster contains two stellar generations, with a very helium-rich SG comprising $\sim 30$ per cent of the cluster present population. In Section 7, we discuss this result and what it implies for the formation and dynamical history of this cluster.

## 2 Observational Data Samples

The observations consist of three different data sets including the HST images described in Section 2.1.1 and ground-based images taken with the Subaru telescope and described in Section 2.2. The main properties of these images are listed in Table 1.

### 2.1 HST data set

To analyse the Advanced Camera for Surveys (ACS)/Wide-Field Camera (WFC) images, we followed the recipes described in Anderson et al. (2008). We used software that analyses all the exposures simultaneously and generates a single list of stars. Stars are measured independently in each image by using a spatially varying $9 \times 10$ array of empirical ‘library point-spread functions (PSFs)’ from Anderson & King (2006) and a spatially constant perturbation for each exposure that accounts for variations in the telescope focus.

The software was designed to work well both in the crowded central regions of the cluster and in the external uncrowded field, and it is also able to measure almost all the stars that would be detected by eye. The photometry was calibrated into the ACS Vega-mag system by adopting the zero-points given in Sirianni et al. (2002) and following the procedure by Bedin et al. (2005). To exclude stars that are poorly measured, we followed the selection procedures given in Milone et al. (2009) and included in the analysis only relatively isolated, unsaturated stars with good values of the PSF-fit quality index and small rms errors in photometry and astrometry.

Variation of temperature can change the focus of the telescope and introduce small spatial variations of the PSF, which is not compensated for in our PSF model and can result in small spatial variations of the photometric zero-point. To minimize the effect of any residual PSF variation on the photometry, we used the method adopted by Milone et al. (2010). Briefly, we first determined the fiducial MS for the cluster and computed for each star its colour residual from it. Then, we corrected the star’s colour by the difference between its colour residual and the mean of its best-measured neighbours.

## Table 1. Description of the archive data sets used in this paper.

| Date              | $N \times$ Exp time (s) | Filter | Instrument | Programme |
|-------------------|-------------------------|--------|------------|-----------|
| 2002 Sep 25       | 2 x 400                 | F435W  | ACS/WFC    | 9666      |
| 2002 Sep 25       | 2 x 340                 | F475W  | ACS/WFC    | 9666      |
| 2002 Sep 25       | 2 x 360                 | F555W  | ACS/WFC    | 9666      |
| 2002 Sep 25       | 2 x 338                 | F606W  | ACS/WFC    | 9666      |
| 2002 Sep 25       | 2 x 340                 | F775W  | ACS/WFC    | 9666      |
| 2002 Sep 25       | 2 x 338                 | F814W  | ACS/WFC    | 9666      |
| 2002 Sep 25       | 3 x 340                 | F50LP  | ACS/WFC    | 9666      |
| 2002 Dec (4 nights)| 165 x 30/180            | V      | Suprime Cam/Subaru | –        |
| 2002 Dec (4 nights)| 16 x 30/180             | I      | Suprime Cam/Subaru | –        |
The spatially dependent correction was lower by 0.005 mag and accounted for both differential reddening and inaccuracies in the PSF model, regardless of the cause. The above procedure works well also in the case of a spread-out MS as well as in the case of a double or multimodal MS as shown, for example, in Milone et al. (2010), where this same technique was applied to the double MS in NGC 6752.

2.1.1 Artificial stars

The artificial-star (AS) experiments which have been used in this paper are also fully described in Anderson et al. (2008). Briefly, for each cluster, we generated a list of $10^5$ stars located on the entire ACS field of view, with a density that is flat within the core and declines as $r^{-1}$ outside of the core. The programs described in Anderson et al. (2008) allow the test of ASs to be performed for one star at a time and entirely in the software: following this procedure, ASs never interfere with each other. ASs have a flat luminosity function in $F606W$, instrumental magnitudes from $-5$ to $-14$ and colours that place them along the HB.

The AS routine measures the images with the same procedure as used for real stars. We consider an AS as recovered when the input and the output fluxes differ by less than 0.75 mag and the positions by less than 0.5 pixel and apply to the AS catalogue the same criterion of selection adopted for real stars.

Since completeness depends on crowding as well as on stellar luminosity, we measured it by applying the procedure described in Milone et al. (2009) that accounts for both the stellar magnitude and the distance from the cluster centre. Briefly, we divided the ACS field into seven concentric annuli and, within each of them, examined AS results in 9-mag bins, in the interval $-14 < m_{F814W} < -5$. For each of these $9 \times 7$ grid points, we calculated the completeness as the ratio of recovered to added stars within that range of radius and magnitude. This grid allowed us to estimate the completeness associated with any star at any position within the cluster. This completeness analysis given in Section 4.2 is used to derive the relative percentage of stars on HB.

2.2 Ground-based data set

Ripepi et al. (2007), using three different data sets [Subaru, Telescopio Nazionale Galileo (TNG) and HST] published a colour–magnitude diagram (CMD) of NGC 2419 which, for the first time, is both deep and covers a very large field of view around the cluster. In particular, the large field of view of the Suprime Cam (34 $\times$ 27 arcmin$^2$), covered by a mosaic of 10 CCDs and by dithering of the telescope pointings, resulted in a survey of a total area of 50 $\times$ 43 arcmin$^2$ centred on NGC 2419 and included both the TNG and HST fields. In the Subaru data, the cluster is centred on chip 2 and is totally covered by the five adjacent chips; the data consist of 30- and 180-s exposures in both the $I$ and the $V$ bands. The techniques used to perform both the PSF photometry and the absolute calibration are described in detail in Di Criscienzo et al. (2011). The samples cover a total range of about 9 mag, from the tip of the cluster red giant branch (RGB) around $V \sim 17$ down to 25.7 mag, about 2.3 mag below the TO, and extend over an area encompassing more than 1 tidal radius in the north–south direction and about 2 tidal radii in east–west from the cluster centre. We have not included in the catalogue stars lying at $r < 50$ arcsec to avoid incompleteness effects in the most crowded central regions. The consequence of this conservative choice is that the typical internal errors of the $V$-band photometry at the level of the HB are from 0.01 to 0.02 mag. The CMD by Ripepi et al. (2007) shows that the HB of NGC2419 extends down to an extremely long blue tail ending with a ‘blue hook’ (Whitney et al. 1998; D’Cruz et al. 2000).

In addition to the same data set, Di Criscienzo et al. (2011) have detected 101 variable stars of which 60 are new variables. According to their study, NGC 2419 contains 75 RR Lyrae stars, 40 of which are located at $r > 50$ arcsec. These observations complete the data for the brighter part of the HB, allowing an analysis through population synthesis. We found that 42 of the total number of RR Lyrae stars found in NGC 2419 by Di Criscienzo et al. (2011) are in the ACS field described in the previous section. This allows us to complete with the variables the ACS catalogue described in Section 2.1 for the upper part of the HB.

3 MODELS

We compute several sets of isochrones and HB evolutions. Based on the paper by Shetrone, Côté & Sargent (2001), we choose as our base composition a mixture with [Fe/H] = $-2.4$ and [$\alpha$/Fe] = 0.2 (standard). We also provide a set of models for the same iron content and [$\alpha$/Fe] = 0.4 ($\alpha$04). More recent results by Cohen et al. (2010) shifted this value in the range [Fe/H] from $\sim -2$ to $\sim 2$.2. We will see that the global interpretation of the cluster data is not affected by the exact choice of metallicity, but a slightly larger iron content is probably more adequate to understand the whole HB data (Section 4.2).

For $T > 10000$ K we used the OPAL opacities, in the version 3381–3393, in the version documented by Iglesias & Rogers (1996), with all the recent updates; at lower temperatures, the opacities by Ferguson et al. (2005) were adopted. Conductive opacities were taken from Potekhin et al. (1999, see www.ioffe.rssi.ru/astro/conduct). We adopt the new cross-section for the reaction $^4$N+$p$ (Formicola et al. 2004), but also provide a set of models for the old cross-section (Angulo et al. 1999). Finally, some comparisons with the data are also made with the help of the previous models described in D2002 and D’Antona & Caloi (2008) computed for a metallicity $Z = 2 \times 10^{-4}$ and no $\alpha$ enhancement. The description of the main inputs and of the corresponding models is given in Table 2.

We followed the MS and red giant evolution of low-mass tracks to provide isochrones for the chosen chemistry and the helium core mass at flash for each set. The red giant evolution was followed by adopting the Reimers (1975) mass-loss law, with the Reimers parameter fixed to $\eta = 0.3$. These core masses are also given in Table 2 and are taken as input for the computation of the HB models. The small helium increase in the envelope during the red giant evolution is also taken into account in the HB models. Further HB models were computed, with reduced helium core mass, in order to simulate the effect of late flash mixing. Models of low total mass ($M < 0.5M_\odot$), for envelope helium $Y = 0.7$, 0.8 and 0.9, were added to the main HB mass sets.

Models include non-instantaneous mixing of the chemical species within the convection zones. We follow the diffusive approach by Cloutman & Eoll (1976), solving for each chemical species the

---

1 The instrumental magnitude is calculated as $-2.5 \log(DN)$, where DN is the total digital counts above the local sky for the considered stars.

2 In contrast, the Subaru data for the ‘blue hook’ are largely incomplete and will not be used.
diffusive-like equation:

$$\frac{dX_i}{dt} = \left( \frac{\partial X_i}{\partial t} \right)_{\text{mix}} + \frac{\partial}{\partial m} \left[ (4 \pi r^2 \rho)^2 D \frac{\partial X_i}{\partial m} \right],$$

(1)

where $D$ is the diffusion coefficient, for which, given the convective velocity $v$ and the scale of mixing $l$, a local approximation ($D \sim \frac{1}{3}vl$) is adopted. The borders of the convective regions are fixed according to the Schwarzschild criterion. We include extra-mixing from all the formal convective boundaries up to the beginning of the asymptotic giant branch (AGB) phase: convective velocities are assumed to decay exponentially with an e-folding distance described by the free parameter $\xi$, which was set to $\xi = 0.02$, according to the calibration provided in Ventura et al. (1998), where the interested reader can also find a complete discussion regarding the variation of the convective velocities in the proximities of the convective borders. The treatment of overshooting is particularly relevant for the HB models, in which overshooting mimics semiconvection (e.g. Caloi & Mazzitelli 1990).

The models with $Z = 10^{-4}$ and $Y = 0.24$ give an evolving mass of $0.740 \pm 0.008 M_\odot$ to fit the location of the upper HB. Therefore, we compare in Fig. 1 the evolutionary tracks for this mass and different inputs. The biggest difference is that the old D2002 tracks, corresponding to $Z = 2 \times 10^{-4}$ and no $\alpha$ enhancement, are considerably cooler than the standard tracks. The best correspondence is found between the standard 0.74-M$\odot$ track and a track of 0.70 M$\odot$, also plotted in the figure. Doubling $[\alpha/\text{Fe}]$, but leaving the total metallicity unchanged, we find that the track of 0.74 M$\odot$ is only slightly cooler and more luminous. On the other hand, the $^{14}\text{N}+\text{p}$ cross-section does not look particularly relevant for this metallicity (but see also Ventura et al. 2009; Pietrinferni, Cassisi & Salaris 2010).

Synthetic models for the HB are computed according to the recipes described in D'Antona & Caloi (2008). We adopt the appropriate relation between the mass of the evolving giant $M_{\text{RG}}$ and the age, as function of helium content and metallicity. The mass on the HB is

$$M_{\text{HB}} = M_{\text{RG}}(Y, Z) - \Delta M,$$

(2)

where $\Delta M$ is the mass lost during the RG phase. We assume that $\Delta M$ has a Gaussian dispersion $\sigma$ around an average value $\Delta M_0$, and that both $\Delta M_0$ and $\sigma$ are parameters to be determined and in principle do not depend on $Y$. Once $Z$ and $Y$ are chosen, the $T_{\text{eff}}$ location of an HB mass is fixed. Consequently, different ages can be adopted, provided that the mass-loss is consistently adjusted.

The RR Lyrae are identified as those stars that, in the simulation, belong to the $T_{\text{eff}}$ interval $3.795 < T_{\text{eff}} < 3.86$. Their periods are computed according to the pulsation equation (1) by Di Criscienzo, Marconi & Caputo (2004).

### Table 2. HB models and isochrones.

| Name  | Z     | [Fe/H] | $^{14}\text{N}+\text{p}$ | $^{\alpha}/\text{Fe}$ | $Y$-HB  | $Y$-isochrones | $M_{\text{core}}/M_\odot$ |
|-------|-------|--------|-------------------|------------------|--------|----------------|---------------------|
| Standard | $10^{-4}$ | -2.4 | New | 0.2 | 0.24 | 0.24 | 0.505 |
|        | $10^{-4}$ | -2.55 | New | 0.4 | 0.25 |        |        |
| OLDN14 | $10^{-4}$ | -2.4 | Old | 0.2 | 0.24 | 0.24 | 0.508 |
| $\alpha$04 | $10^{-4}$ | -2.55 | New | 0.4 | 0.25 |        |        |
| D2002 | $2 \times 10^{-4}$ | -2.0 | Old | 0.0 | 0.24 | 0.24 | 0.508 |

Synthetic models for the RGB and for the TO region are computed according to the method described in Di Criscienzo, D’Antona & Ventura (2010).

We note that all the evolutionary sequences have been translated from the theoretical Hertzsprung–Russell (HR) diagram to the observational CMD by using the colour–$T_{\text{eff}}$ relation and bolometric corrections by Dotter et al. (2007). Obviously the synthetic spectra used for these computations do not represent accurately the peculiar atmospheres of hot flashers, because these stars are expected to have strongly enhanced He and C abundances at the surface. In more detail, for the atmospheres of hot flashers, Brown et al. (2001) have shown that an atmospheric composition of 96 per cent He and 4 per cent C (or N) produces lower fluxes in the F435W filter, compared to a standard metal mixture. Therefore, for the hot flasher model, one should use more appropriate – but not yet available – bolometric corrections, which, however, we do not expect to alter the basic conclusions of this analysis. As for the He-rich stellar population, Girardi et al. (2007) have shown that the effect of an enhanced He content of the order of $\Delta Y \sim 0.1–0.2$ on bolometric corrections and colours is negligible at the $T_{\text{eff}}$ values corresponding to hot HB stars.
Table 3. HB counts.

| Range                  | Subaru (obs) | ACS (obs) | ACS(corr) | SH2008 (corr) | D’A2008 (corr) |
|------------------------|--------------|-----------|-----------|---------------|---------------|
|                        | $r > 50$ arcsec, $\chi < 1.2$ | $r > 50$ arcsec, $\chi = 1$ | $r > 50$ arcsec, $\chi = 1$, $c > 0.5$ |               |               |
| UPPER ($M_1 < 21$)     | 334          | 351       | 95        | 461           | 446           |
| RR Lyrae               | 40           | 42        | 12        | 42            | 42            |
| MIDDLE                 | 70           | 80        | 30        | 130           | 53            |
| EHB                    | 61           | 160       | 74        | 363           | 257           |
| Total ($N_{tot}$)      | 504          | 633       | 211       | 996           | 798           |
| $N_{HB}/N_{tot}$       | 0.12         | 0.25      | 0.35      | 0.36          | 0.34          |
| BR(EHB)/BR(Total HB)   | 0.27–0.31    | 0.27–0.31 |           |               |               |

SH2008: Sandquist & Hess (2008); D’A2008; D’Antona & Caloi (2008).

4 HORIZONTAL BRANCH

The HB of NGC 2419 has been analysed in several recent studies (Ripepi et al. 2007; Dalessandro et al. 2008; Sandquist & Hess 2008). Including in the study of the HB the full RR Lyrae catalogue described by Di Criscienzo et al. (2011), we now have the possibility of further examining its characteristics. The HB is composed of two main parts: a luminous ($m_{F814W} < 21$ mag) blue section, with a tail extension in the RR Lyrae and in the red part (UPPER HB), and the extreme HB (EHB) subluminous hot stars, defined here as the group at $m_{F814W} > 23.5$ mag, that probably include both the B subdwarfs at $T_{eff} > 20,000$ K and the ‘blue hook’ stars in the standard definition related to their appearance in the UV (Whitney et al. 1998; D’Cruz et al. 2000; Moehler et al. 2002). In the middle, these two parts are connected by a tail of intermediate luminosity stars (MIDDLE HB). The relative numbers in these three sections are given in Table 3. We point out that the UPPER HB and the EHB are the dominant components. In the following, we use synthetic populations based on the models described above, in order to understand the main features of these two classes of objects.

4.1 Luminous part of the HB: a unique population with a small spread in mass

The histogram of the number of stars as a function of $m_{F814W}$ in Fig. 2 shows that the upper HB is extremely peaked in colour and magnitude. This feature has also been found in M53 (Rey et al. 1998), but not in other low-metallicity clusters, such as M15 (Bingham et al. 1984) and M68 (Walker 1994), and strongly suggests that this portion of the HB is populated by stars spanning a narrow mass range. Fig. 3 shows the mass distribution obtained in our simulations as follows. For any choice of the evolutionary track set, a very small mass spread is sufficient to describe the peaked distribution in colour (or $T_{eff}$). In fact, the RR Lyrae and red HB region, scarcely populated, are accounted for by the late evolution of the masses starting their HB life near the peak in the star number distribution. Also note that the evolution at these low metallicities remains close to the zero-age horizontal branch (ZAHB) for all the interested masses, even in the $Z = 2 \times 10^{-4}$ models of D2002. The simulations for this UPPER HB are done in both the Subaru and the ACS magnitudes, whose data are described in Section 2. Fig. 4 shows some results for the standard tracks and for both sets of data. We fixed the cluster age at 12 Gyr, at which the mass evolving in the RGB is 0.813 $M_\odot$. An average mass-loss of 0.073 $M_\odot$ along the red giant phase then leads to an average mass of 0.74 $M_\odot$ in HB. A small spread in mass ($\sigma = 0.008 M_\odot$) is enough to provide a good fit of the UPPER HB, considering small observational errors in each magnitude of 0.01 mag. Both the Subaru (left-hand panel) and ACS (right-hand panel) data are reasonably fitted. The simulation of the Subaru data shows a larger number of RR Lyrae stars than what is found in the observations, possibly because the variable star catalogue is not yet complete. We did not investigate further this problem. In any case, we find that the period distribution of our RR Lyrae sample can be satisfactorily interpreted in terms of a ‘tail distribution’, in the same way as the colour distribution discussed above.

One interesting feature of these simulations is that we cannot reproduce the extension of the HB towards fainter magnitudes, without adding hypotheses: any symmetric increase in the mass-loss spread not only does not account for the long tail of stars at $m_1 > 21$, but also no longer allows a good fit of the peak. The tail, which, however, concerns only a relatively small fraction of stars, may be ascribed to some asymmetry in the mass-loss or to...
a relatively small enhancement in the helium content of these few stars (see later). By changing the set of tracks (see Table 2) in the simulations of the UPPER HB, the qualitative behaviour does not change. This part of the HB can still be interpreted as being populated by the evolution of a small interval of masses, around the one which provides the fits of the peak in magnitude and colour.

Note that a change in the cluster age does not necessarily require a change in the mass evolving on the HB, since a smaller (larger) mass-loss along the RGB can be assumed for older (younger) ages.

The adopted metallicity (or exact elemental distribution) does change the evolving mass; for example, the D2002 set (\(Z = 2 \times 10^{-4}\)) needs an average mass-loss of 0.113 \(M_\odot\), 0.04 \(M_\odot\) larger than the mass lost from the standard tracks (see Fig. 3).\(^4\)

### 4.2 Percentage of stars and the helium content in the EHB

In this work, we will not attempt to make precise fits of the EHB population, as the blue and near-infrared bands that we are analysing are not the best on which to accomplish such a comparison; they are best performed in the ultraviolet bands (e.g. Brown et al. 2001, 2010; Lee et al. 2005). The aim of our simulations will be to understand, from the percentage of stars in this group, the relative birthrates of the UPPER HB and the EHB. According to our completeness analysis on ACS data\(^5\) described in Section 2.1.1, the EHB contains about 35 per cent of the total HB stars. This is consistent with the value of 36 per cent obtained by Sandquist & Hess (2008) in their careful analysis, whose counts are reported in the fifth column of Table 3. The large fraction of stars rules out binary evolution for several reasons: (1) the binary fraction in luminous GCs, as NGC 2419 typically does not exceed ~4 per cent (Milone et al. 2008); (2) observationally, no binaries have yet been found among the EHB stars (Moni Bidin et al. 2006, 2008); (3) in any case, the formation of B and O subdwarfs is a very peculiar and rare event in the binary evolution (e.g. Han et al. 2003) and (4) the merging formation channel, which could be perhaps invoked in the dense core regions, is ruled out, as the EHB stars are distributed everywhere in the cluster within the tidal radius.

If the EHB is populated by stars having the same composition and age that we used for the UPPER HB, then these stars would have masses of \(~0.51-0.52\) \(M_\odot\), whose location in the ZAHB extends to the EHB region (see Fig. 2). Consequently, the mass-loss of 0.073 \(M_\odot\), which could account for the UPPER HB, must be increased to \(~0.3\) \(M_\odot\). Note that the standard HB lowest mass stars (\(M_m \sim 0.506\) \(M_\odot\)), being the core mass at flash 0.505 \(M_\odot\) do not cover the lowest luminosities of the EHB. As we will see later, we can push these masses a bit further down, by including the location of models that have suffered a late-flash mixing (Brown et al. 2001; Cassisi et al. 2003; Brown et al. 2010), but the problem is not fully solved with ‘standard’ models, and we prefer to attempt a different solution.

A dichotomy in the mass-loss remains unexplained, so we decided to test the case of similar mass-loss for the EHB stars, but including a very helium-rich composition for the progenitors, so that the total mass remnant after the helium flash is very small and lies at large \(T_{\text{eff}}\) (D2002). We assumed for the helium abundance in the EHB stars a value \(Y = 0.42\). As we will see, the mass-loss in the RG cannot be kept exactly the same as for the UPPER HB, but must be increased by \(~0.035-0.05\) \(M_\odot\) in order to reach the masses (and luminosities) of the EHB. We did not try to refine this result: a better correspondence between the mass-loss in the UPPER HB and in the EHB can be obtained very easily by increasing the metallicity of the models (as discussed in Section 4.1). We see that the lowest mass model of the \(Y = 0.42\) standard set (\(M = 0.468\) \(M_\odot\)) is much closer to the bottom magnitudes of the EHB, thanks to its smaller core mass.

Obviously, the choice \(Y = 0.42\) is a bold attempt to model the higher helium content of the EHB and must not be regarded as a ‘precise’ value. Note, for example, that this value is higher than the maximum helium content of super-AGB stars’ ejecta (Siess 2010; Ventura & D’Antona 2011), the possible progenitors of a very helium-rich SG in GCs.

### 4.3 From the number ratio to the relative birthrates of EHB and UPPER HB stars

We will perform detailed simulations of the EHB stars in NGC 2419 with the aim to derive a reliable ratio of birthrates of the EHB to UPPER HB, from their number ratio. The simulations allow us to take into account both the different evolutionary times of the EHB stars, with respect to the UPPER HB, and the non-inclusion in the EHB of a possible percentage of helium-rich stars that evolve directly to the white dwarf stage.

The relative birthrate of the EHB population, \(B_{\text{REL}}\), can be written as

\[
B_{\text{REL}} = \frac{(1 + f)N_E/t_E + N_U/t_U + N_M/t_M}{(1 + f)N_E/t_E + N_M/t_M + N_U/t_U},
\]

where E, U and M indicate the extreme, upper and middle HBs, respectively, and \(f\) is the fraction of stars that, due to mass-loss, cannot ignite the helium flash and evolves directly to helium white dwarfs. The \(t\)s represent the typical evolutionary times in each of the...
A large and extreme SG in NGC 2419

Figure 4. Simulation of the UPPER HB of NGC 2419 in the Subaru magnitudes (left-hand panel) and in the ACS magnitudes (right-hand panel). In each figure, the histograms of star counts as a function of the absolute magnitudes $M_{F814W}$ or $M_I$ and of the reddening-corrected colour $m_{F814W} - m_{F435W}$ or $V - I$ are compared to the histograms of the simulations. A small mass spread of 0.008 $M_\odot$ has been assumed. Note that the morphology of the tracks does not allow us to account for the ‘blue tails’, unless we postulate an asymmetric mass-loss. The assumed colour excess ($\delta_{\text{col}}$) and the apparent distance modulus are also reported.

HB groups. The relation can be rewritten stressing the time-scales’ ratios:

$$
\frac{BR_E}{BR_{\text{tot}}} = \frac{(1 + f)N_E \times t_U/t_E}{(1 + f)N_E \times t_U/t_E + N_M t_U/t_M + N_U}.
$$

Fig. 5 shows the luminosity versus time evolutions of typical masses populating the HB: the 0.72-, 0.74- and 0.76-$M_\odot$ standard tracks are taken as a reference. Comparison with one track computed with the old $^{14}N$+$p$ cross-sections shows that the time-scales do not change significantly. In the middle, the 0.509-$M_\odot$ evolution, for $Y = 0.24$, shows that the evolutionary times increases by $\sim$10 per cent, while the evolution of 0.468 and 0.480 $M_\odot$ for $Y = 0.42$, evolving at the lowest luminosity, shows an increase by $\sim$50 per cent, and a bit more if we consider models representing the result of late helium flashers (see later in this section). Note that the evolutionary times in HB depend very much on how semiconvection and/or overshooting are treated. In our case, models are computed by fixing our parameter to $\zeta = 0.02$ for diffusive extra-mixing (see Section 3), and we are implicitly assuming that the overshooting affects in a similar way both the UPPER HB and the blue hook models.

In order to have a reasonable idea about the factor $f$, we must make simulations and discuss the hypotheses hidden in these simulations. Although the photometry is not as good as in other clusters, we can make the approximation that the EHB group is a mixture of HB stars’ progeny of giants that suffered an ‘early’ late flash after leaving the RGB plus stars that suffered a ‘late’ late flash and have been subject to deep mixing during this event (Brown et al. 2001). Which fraction of stars followed which path can be extracted from comparison between the simulations and the data. If we wish to simulate the late flash product, the limiting total remnant mass, following the late flash, is not the helium core mass reached at the flash occurring on the RGB (plus a few thousands of $M_\odot$ in the hydrogen-rich envelope), but is smaller, as the late flash can ignite at a smaller core mass. Following the few results in the literature (D’Cruz et al. 1996; Miller Bertolami et al. 2008) and our own preliminary computations (Ventura et al., in preparation), we put a limit at the minimum core mass for ignition of the late flash at 0.015 $M_\odot$ below the core masses listed in Table 2. In order to
simulate the late flash products, we compute models at these very low total masses by imposing the fact that helium at the surface is increased to $Y = 0.9$. In D’Antona, Caloi & Ventura (2010), we proposed to fit the blue hook sequence in the cluster ω Cen by models with helium increased to $Y = 0.8$ and showed that a very interesting reproduction of the ‘vertical’ shape of the blue hook was possible. Nevertheless, the presence of carbon enhancement in the atmospheres of blue hook stars (Moehler et al. 2002, 2007) links them more closely to the result of flash mixing, so this is the approach we follow in this work.

### 4.4 Simulations of the EHB

Among the different possible hypotheses, we limit the discussion to the following cases.

(i) The EHB is populated by stars having the same standard chemistry ($Y$ and [Fe/H]) of the UPPER HB, but subject to larger mass-loss on the RGB. The limiting mass is a bit smaller than the helium core mass at flash, $M_{\text{min}} = (0.505–0.015 \, M_\odot)$, when this occurs on the RGB.

(ii) The EHB is populated by stars with $Y = 0.42$, and the minimum mass is fixed as in case (i), that is to $M_{\text{min}} = (0.466–0.2) \, M_\odot$.

(iii) Stars in the EHB follow the same path as in (ii), but the fraction of masses smaller than 0.468 $M_\odot$ is considered ‘late flashers’ and their surface composition is considered to have been altered by deep mixing providing $Y = 0.9$. Probable carbon enrichment to 1–3 per cent is not taken into account in the models.

The last case corresponds to the typical evolution in other clusters containing blue hook stars. Although our ACS sample is incomplete, we compare the simulations to the sample without any correction, as we are interested particularly in obtaining a reliable description of the EHB sample luminosities and in evaluating the possible number of ‘lost’ helium white dwarfs than in the completeness problems. We will use the corrected fraction of EHB stars (Table 3) when we will try to understand the relative birthrates. Therefore, a total number of 160–170 stars are assumed in the simulations. We fix the average mass lost on the RGB ($\delta M$) and its dispersion $\sigma$. We fix the limiting minimum mass, as discussed above, and any extraction ending with a smaller mass is rejected and accounted for as a helium white dwarf. From the simulation, we see that we need to lose a bit more than 0.073 $M_\odot$ taken to reproduce the UPPER HB, by 0.035–0.05 $M_\odot$. We do not think that this is relevant, as we have seen that a slightly different choice of the input metallicity may allow us to require a larger mass-loss for the UPPER HB, consequently reducing the discrepancy between the mass-loss needed between the UPPER HB and the EHB.

Fig. 6 shows one of the simulations corresponding to case (i). The (red) triangles and the dot–dashed histogram represent a simulation obtained for assuming a sample of stars with $Y = 0.24$, mass-loss $\delta M = 0.309 \, M_\odot$ on the RGB and $\sigma = 0.01 \, M_\odot$. The limiting mass is assumed to be 0.509 $M_\odot$ for the normal HB, and the mass extraction is further extended to 0.49 $M_\odot$, assuming this to be the limiting mass for the late helium flash. No mixing is included, so the hypothesis is quite conservative, but including models with mixing does not much improve the fit, as these models have too high a luminosity in any case. 102 helium white dwarfs are predicted by this simulation, a number that we cannot consider to be realistic. If we attempt to reduce the number of helium white dwarfs by decreasing the average mass lost on the RGB, the simulated stars become too luminous with respect to the observed EHB sample.

Note that we cannot change the distance modulus, which is obtained by fitting the UPPER HB. In Fig. 6, the MIDDLE HB is also simulated, by a separate simulation of standard composition stars with a mass-loss of 0.22 $M_\odot$ and mass dispersion $\sigma = 0.05 \, M_\odot$. It is not possible to reproduce these stars either by a simulation centred on the EHB, with a larger mass spread, or as an extension of the UPPER HB, as discussed above.

Fig. 7 shows an example of simulations for case (ii). The mass spread around the average value is taken to be $\sigma = 0.006 \, M_\odot$. The total number of helium white dwarfs of the simulation is only nine, namely ~5 per cent. Case (iii) is explored in Fig. 8. The fit of the EHB sample is very adequate here, thanks to the inclusion of the dimmer (in the F814W band) points corresponding to the supposed flash-mixed stars. Note that also in this case, the number of helium white dwarfs is predicted to be zero.

Other simulations predict a larger number of helium white dwarfs, depending on the assumed mass-loss dispersion. Independent of the observational incompleteness, we stress that the blue hook progenitors are probably within ~20 per cent more than the EHB sample.

The simulations show that the EHB is better simulated including the presence of a large population with enhanced helium. We can now go back to equation (4), including the number ratios of table 3 by Sandquist & Hess (2008), $f$ between 0 and 0.2, assuming also $t_0/t_U = 1.56$, $t_0/t_U = 1.13$ from the models. If we consider the cluster ‘SG’ to be limited to the EHB sample, the birthrate of this population will be between 27 ($f = 0$) and 31 ($f = 0.2$) per cent of the total cluster population. If we include the MIDDLE HB in the SG, the figures increase to 40–44 per cent of the total. The MIDDLE HB, however, does not reach the very high helium contents required for the EHB sample.

We now examine the other HR diagram features to understand whether this conclusion is consistent with the information derived from the RGB and MS.
A large and extreme SG in NGC 2419

Figure 7. As in Fig. 6, the ACS data are compared to a simulation that assumes $Y = 0.42$ for the EHB stars. In addition to the $Y = 0.24$ tracks shown also in Fig 6, three tracks are for $Y = 0.42$ and $M = 0.468$, $0.480$ and $0.5 M_\odot$. The lowest track is for $M = 0.452 M_\odot$ (core mass of $0.45 M_\odot$). The dot–dashed histogram represents the simulation described in the text, which assumes an average mass-loss $\delta M = 0.123 M_\odot$ on the RGB, and $\sigma = 0.006 M_\odot$. Nine helium white dwarfs are predicted by the simulation.

5 INTRINSIC BROADENING OF THE BASE OF THE RGB

In order to confirm the suggestion that the blue hook stars are enhanced in helium, we analyse the stars along the RGB, where a large He enhancement manifests itself as an RGB split or as a spread in a well-populated CMD. Theoretical predictions (e.g. Catelan et al. 2010) show that the base of the RGB of He-enhanced models is hotter than their lower helium counterparts, by about $\Delta (B - I) / \Delta Y = -0.7$. For the case explored here ($\Delta Y \sim 0.18$), this spread is larger than the observational errors for both our data sets (Subaru and HST). The size of the predicted split/spread decreases progressively towards the RGB tip, where the presence of AGB stars may also complicate any empirical test. Consequently, we restrict our analysis to the interval in apparent magnitude in between the base of RGB and $m_F814W \sim 19$ mag.

The main challenge in identifying intrinsic spreads in the colours of the RGB comes from the fact that photometric errors can generate similar signatures. Anderson et al. (2009) have introduced an efficient approach to distinguish intrinsic colour broadening from mere photometric errors that consists in analysing different data sets and see if all of them share the same features. The large number of ACS/WFC archive images of NGC 2419 (see Table 1) gives us the precious opportunity to follow a similar procedure for this cluster. Specifically, we made three independent CMDs by using images in six passbands: (i) $m_{F435W}$ and $m_{F814W}$, (ii) $m_{F475W}$ and $m_{F850LP}$ and (iii) $m_{F555W}$ and $m_{F775W}$.

The $m_{F435W}$ versus $m_{F475W} - m_{F814W}$ CMD is shown in Fig. 9(a). The wide colour baseline of this CMD provides an optimal resolution of any doubling or a spread of the observed sequences due to helium variations. A visual inspection of this CMD immediately suggests that NGC 2419 has a broad RGB with the tail of stars being blueshifted with respect to the main RGB population.

To further investigate this suggestion in panel (b), we show a zoom of the CMD around the RGB region where the colour spread is more evident. The red continuous line is the RGB fiducial obtained by following the recipes given in Milone et al. (2008). Briefly, we have divided the RGB into intervals of 0.2 mag in the $F435W$ band, calculated the average colour and magnitude for each of them, and interpolated these points by means of a spline. In panel (c), we have subtracted from the colour of each star the colour of the...
fiducial at the corresponding magnitude and plotted $m_{F435W}$ as a function of the obtained colour difference ($\Delta m_{F435W} - m_{F814W}$). The histogram colour distribution plotted in panel (d) is clearly skewed towards blue colours, and we have arbitrarily isolated RGB stars with $\Delta m_{F435W} - m_{F814W} < -0.06$. These stars are represented as blue crosses in (a) and (c).

We note that if the RGB broadening is due to photometric errors alone, then a star that is bluer than the RGB fiducial in the $m_{F435W}$ versus $m_{F435W} - m_{F814W}$ CMD has the same probability of being bluer or redder in other CMDs obtained with independent data. But if the colour spread is real, the selected blue stars will have bluer colours in all the CMDs. In Fig. 10, we compare the CMD of Fig. 9 with CMDs from two other data sets. The upper panels are the CMDs zoomed in around the RGB. Each (red) line is the RGB fiducial obtained with the method described above and we have kept for each star the same colour as in Fig. 9. The lower panels show the colour distributions. The fact that the histogram distributions of the selected blue stars systematically have bluer colours demonstrates that the RGB broadening is intrinsic. We can now consider this evidence as the consequence of a population in the cluster with an enhanced primordial helium. A quantitative comparison is done by performing simulations able to reproduce the colour distribution. Population synthesis follows the outline described in Ventura et al. (2009). A good match is obtained by assuming a sample of 70 per cent of stars with primordial helium abundance and 30 per cent of stars with $Y = 0.42$, if $\sigma_{\text{obs}} = 0.018$ mag (see Fig. 11). These assumptions are compatible with the observational errors of the ACS/HST data, and the simulations can reproduce both the width and the shape of the distribution.

![Figure 10](https://example.com/image10.png)

**Figure 10.** In order to show that the RGB broadening is intrinsic, we compare the CMD of Fig. 9 with CMDs from two other data sets (see Table 1). Upper panels are the CMDs zoomed in around the RGB and the (blue) cross identifies stars selected as ‘blue’ in Fig. 9. Lower panels show the colour distributions in these new colours. The fact that the histogram distributions of the selected blue stars systematically have bluer colours demonstrates that the RGB broadening is intrinsic.

![Figure 11](https://example.com/image11.png)

**Figure 11.** Left-hand panel: zoom of the CMD region at the base of RGB from ACS data together with our best simulation (see the text). Right-hand panels: distribution of the difference between the colour of each star and the averaged ridge line calculated for this part of RGB in three different intervals of magnitude (solid histogram), which highlight the intrinsic broadening of the data well reproduced by our simulation (dashed, shaded histogram) made up of 30 per cent of stars with $Y = 0.42$ and the rest with primordial helium abundance.

![Figure 12](https://example.com/image12.png)

**Figure 12.** Same as Fig. 11, but in this case the simulation includes only stars with primordial helium content ($Y = 0.24$).

In contrast, Fig. 12 shows that a single population with fixed $Y = 0.24$ is not able to reproduce the observed population, especially in the faintest magnitude interval. To quantify this statement in Fig. 13, we show the cumulative distributions of the colour differences ($\Delta m_{F435W} - m_{F814W}$); the results of the comparison between the distributions using a Kolmogorov–Smirnov (K-S) test are also

© 2011 The Authors, MNRAS 414, 3381–3393

*Monthly Notices of the Royal Astronomical Society © 2011 RAS*
listed which show that the agreement between observations and simulations is better if we assume a double population.

If we could reduce the observational errors, the split of the two RGBs would be observable for $\sigma_{\text{obs}} = 0.01$ mag in the same colours at least at the base of RGB; at the distance of NGC 2419, this will be possible when the next-generation telescopes (e.g. E-ELT or JWST) are available.

We note that in the case of NGC 2419, the population that we recognize as the SG is bluer on RGB than the primordial one, contrary to what happens for other clusters which show evidence of multiple populations, in particular M4 (Marino et al. 2008) and NGC 6752 (Milone et al. 2010) where Na-rich stars are cooler than Na-poor ones. We interpret this evidence as the consequence of the strong He enhancement found for the SG stars which, at the low metallicities of NGC 2419, prevails on the effects of light element abundances (such as Na enhancement or O depletion).

6 MAIN SEQUENCE

Sandquist & Hess (2008) have ruled out the hypothesis of a very high initial helium abundance ($Y \sim 0.4$) for blue hook stars, mainly by noting that the distribution in the colour of the MS stars from their data resembles a Gaussian distribution and does not show any asymmetry which would arise from the presence of 30 per cent of He-rich stars. The symmetry of the MS is confirmed by both our data sets where no bimodal MS or any noticeable asymmetry of the distribution emerges; however, our simulations show that the observational errors of our data, which increase with magnitude, may be able to cancel any colour shift. To explain this point in Fig. 14, we also show that the data are perfectly matched with a synthetic population formed by 30 per cent of stars with $\Delta Y = 0.18$ with respect the main population.

In conclusion, we note that although Sandquist & Hess (2008) limit a maximum $\Delta Y$ among the cluster stars to <0.05, this value is derived from the ratio $R = N_{\text{HB}}/N_{\text{RG}}$ where $N_{\text{RG}}$ are the giants above the HB level and not from the broadness of the MS. As is well known, this ratio is not a sensitive helium indicator, if the horizontal part of the HB corresponds to the luminosity level of standard helium stars (see also Caloi & D’Antona 2007). This is in fact the case for NGC 2419, where helium-rich stars are only those in the EHB.

7 CONCLUSIONS AND DISCUSSION: WHY TWO POPULATIONS?

The fundamental result of this work is as follows: in contrast to previous results, we have built a well-founded case for the presence of two different stellar populations in NGC 2419, a distant massive GC, now well isolated from the tidal influence of the Galaxy. The first stellar population is identified with the UPPER HB including the luminous blue stars, the RR Lyrae stars and the few red HB stars.

These have a normal He abundance and are easily interpreted as the result of the evolution of a small range of initial stellar masses in ZAHB. The second stellar population represents 30 per cent of the total cluster stellar population and is identified with the EHB being subdivided into a B-subdwarf part plus a blue hook, which we fit with models having initial helium content $Y = 0.42$ and subject to a mass-loss very similar to the mass-loss required for the UPPER HB.

The value $Y = 0.42$ is not mandatory, as a different, larger choice of the initial $\text{[Fe/H]}$ may allow a fit with a smaller (but in any case very high) helium. The MIDDLE HB may be part of the helium-enriched population – but with a much smaller helium enhancement – or may be attributed to a tail of larger mass-loss along the RGB, in standard helium stars. In the most conservative case (only the EHB is helium rich), we conclude that 27–30 per cent of the cluster stars are born from an ‘SG’ very helium-rich gas.

It is now interesting to discuss the implications of the results presented in this paper for the initial properties of NGC 2419 and its subsequent dynamical history.

© 2011 The Authors, MNRAS 414, 3381–3393

Monthly Notices of the Royal Astronomical Society © 2011 RAS
According to the models presented in D’Ercole et al. (2008, 2010), the extreme population must have formed early in the SG formation process directly out of the pure ejecta of massive AGB stars without any dilution with pristine gas. For example, in D’Ercole et al.’s (2010) model for NGC 2808 (a massive cluster with a significant fraction of E stars), the extreme population observed in this cluster would have formed in the time interval of 31.7–44 Myr from the AGB ejecta of stars with masses in the range of 7.5–9 M⊙. If we assume that the extreme population of NGC 2419 was also formed from the ejecta of stars in this same range of masses and adopt a Kroupa-1993 IMF (Kroupa, Tout & Gilmore 1993), the total amount of gas lost by these massive AGB stars is M⊙ = 0.01MFG, where MFG is the initial GC mass, composed exclusively of FG stars. From the observational results presented in this paper, we can write MSG,F,E ≃ 30 M⊙, where MFG is the mass of the extreme population and MFG is the present GC mass. Assuming that all the AGB ejecta is exhausted by star formation and that no substantial loss of SG stars is suffered by the cluster during its successive dynamical evolution, we obtain MFG = 0.01MFG and, in the end, MFG = 30 M⊙. If a Kroupa-2001 IMF (Kroupa 2001) is adopted, the larger fraction of the total cluster mass contained in stars within the range of 7.5–9 M⊙ leads to MFG ≃ 15 M⊙. These computations show that for any choice of the IMF, NGC 2419 lost a large amount of its original mass than ‘normal’ Galactic GCs, even up to 97 per cent.

The above conclusions are not surprising as a few more massive clusters found to host E stars also have a spread of heavy elements and must have been initially more massive by a similar large factor (see e.g. Renzini 2008). However, the unusual relative number of extreme and intermediate stars in NGC 2419 is likely to be the result of a peculiar SG formation history. Specifically, the lack of a significant fraction of an intermediate SG population suggests that the SG formation episode was interrupted earlier before the ejecta of AGB stars with M < 7 M⊙ could be formed into SG stars. This is at odds with the ubiquitous presence of a large fraction of intermediate SG stars found in all the other clusters that have been studied with spectroscopic observations (see e.g. Carretta et al. 2009a).

The peculiar star formation history suggested by the results presented in this paper might be connected to the cluster’s early dynamical evolution. Unfortunately, without any information on the orbit of NGC 2419 and the properties of the tidal environment in which this cluster was embedded during the very early stages of its evolution, it is difficult to build a model of the early dynamical processes behind the interruption of the SG formation event and the mass-loss this cluster must have suffered.

At its current Galactocentric distance (Rg ≃ 90 kpc; Harris 1996), the Jacobi radius of NGC 2419 determined by the strength of the Galactic tidal field at Rg is rJ ≃ 700 pc. Considering that its estimated King truncation radius is rF ≃ 220 pc and its half-mass radius is rh ≃ 30 pc, one could infer that NGC 2419 must be the prototype of a cluster evolving in isolation and therefore have not been able to lose any AGB ejecta or stellar mass. However, one can easily envisage a number of conditions leading to a significantly different early dynamical history affecting both the gas and the stellar content. Assuming, for example, that the cluster was on an eccentric orbit with the pericentre at 11 kpc, as suggested by Casetti-Dinescu et al. (2009) (see also the discussion in Cohen et al. 2010), it is possible that an early tidal shock event and/or a cluster early expansion (triggered by primordial gas and SN ejecta expulsion as discussed in D’Ercole et al. 2008) in a stronger tidal field might have affected the SG formation process and caused the loss of a significant fraction of the initial FG mass.

Another possibility is that NGC 2419 was located, during the early stages of its evolution, in the inner regions of a dwarf galaxy and therefore subject to a stronger tidal field than it is now; also in this case, the early expansion phase as modelled in D’Ercole et al. (2008) might have led to a strong FG loss. Indeed, Newberg et al. (2003) suggested that NGC 2419 might have once been part of the Sagittarius galaxy [see, however, Law & Majewski (2010) for a recent discussion of this possibility].

Although only additional studies on the stellar population and on the orbital properties of NGC 2419 will allow us to better constrain its dynamical and star formation history, our results give further support to previous suggestions (van den Bergh & Mackey 2004; Mackey & van den Bergh 2005; Cohen et al. 2010, and very recently Bruns & Kroupa 2011) that NGC 2419 must be the remnant of a much more massive system.

ACKNOWLEDGMENTS

We thanks the referee for his useful suggestions that improved the final version of the paper. Financial support for this study was provided by PRIN MIUR 2007 ‘Multiple stellar populations in GCs: census, characterization and origin’. EV was supported in part by NASA grant NNX10AD86G.

REFERENCES

Anderson J., King I., 2006, ACS Instrument Science Report, 2006-01, STScI, Baltimore, MD
Anderson J. et al., 2008, AJ, 135, 2055
Anderson J., Piotto G., King I. R., Bedin L. R., Gahathakurta P., 2009, ApJ, 697, L58
Angulo C. et al., 1999, Nuclear Phys. A, 656, 3
Bedin L. R., Cassisi S., Castelli F., Piotto G., Anderson J., Salaris M., Momany Y., Pietrinferni A., 2005, MNRAS, 357, 1038
Bekki K., Norris J. E., 2006, ApJ, 637, L109
Bingham E. A., Cacciari C., Dickens R. J., Pecci F. F., 1984, MNRAS, 209, 765
Briley M., Cohen J. G., Stetson P. B., 2002, ApJ, 579, L17
Briley M. M., Harbeck D., Smith G. H., Grebel E. K., 2004, AJ, 127, 1588
Brown T. M., Sweigart A. V., Lanz T., Landsman W. B., Hubeny I., 2001, ApJ, 562, 368
Brown T. M., Sweigart A. V., Lanz T., Smith E., Landsman W. B., Hubeny I., 2010, ApJ, 718, 1332
Brüns R. C., Kroupa P., 2011, ApJ, 729, 69
Caloi V., D’Antona F., 2007, A&A, 463, 949
Caloi V., Mazzitelli I., 1990, A&A, 240, 305
Carretta E. et al., 2009a, A&A, 505, 117
Carretta E., Grataglia A., Gratton R., D’Orazi V., Catelan S. 2009b, A&A, 508, 695
Carretta E. et al., 2010, ApJ, 722, L1
Casetti-Dinescu D. I., Girardi T. M., Majewski S. R., Vivas A. K., Wilhelm R., Carlin J. L., Beers T. C., van Altena W. F., 2009, ApJ, 701, 29
Cassisi S., Schlattl H., Salaris M., Weiss A., 2003, ApJ, 582, L43
Catelan M., Valcarce A. R., Sweigart A. V., 2010, in de Grijs R., Lepine J. R. D., eds. Proc. IAU Symp. 266, Star Clusters, Basic Galactic Building Blocks Throughout Time and Space. Kluwer, Dordrecht, p. 281
Cloutman L. D., Eilol J. G., 1976, ApJ, 206, 548
Cohen J. G., Kirby E. N., Simon J. D., Geha M., 2010, preprint (arXiv:1010.0031)
Dalessandro E., Lanzoni B., Ferraro F. R., Vespe F., Bellazzini M., Rood R. T., 2008, ApJ, 681, 311

© 2011 The Authors, MNRAS 414, 3381–3393

Monthly Notices of the Royal Astronomical Society © 2011 RAS

Downloaded from https://academic.oup.com/mnras/article-abstract/414/4/3381/997839 on 28 July 2018
D’Antona F., Caloi V., 2008, MNRAS, 390, 693
D’Antona F., Caloi V., Montalbán J., Ventura P., Gratton R., 2002, A&A, 395, 69 (D2002)
D’Antona F., Caloi V., Ventura P., 2010, MNRAS, 405, 2295
D’Cruz N. L., Dorman B., Rood R. T., O’Connell R. W., 1996, ApJ, 466, 359
D’Cruz N. L. et al., 2000, ApJ, 530, 352
D’Ercole A., Vesperini E., D’Antona F., McMillan S. L. W., Recchi S., 2008, MNRAS, 391, 825
D’Ercole A., D’Antona F., Ventura P., Vesperini E., McMillan S. L. W., 2010, MNRAS, 407, 854
Di Criscienzo M., Marconi M., Caputo F., 2004, ApJ, 612, 1092
Di Criscienzo M., D’Antona F., Ventura P., 2010, A&A, 511, A70
Di Criscienzo M. et al., 2011, AJ, 141, 81
Dotter A., Chaboyer B., Jevremovic D., Baron E., Ferguson J., Sarajedini A., Anderson Y., 2007, AJ, 134, 376
Ferguson J. W. et al., 2005, ApJ, 623, 585
Formica L. et al., 2004, Phys. Lett. B, 591, 61
Girardi L., Castelli F., Bertelli G., Nasi E., 2007, A&A, 468, 657
Gratton R. G. et al., 2001, A&A, 369, 87
Han Z., Podsidiłowski P., Maxted P. F. L., Marsh T. R., 2003, MNRAS, 341, 669
Harris W. E., 1996, AJ, 112, 1487 (updated in 2010, available at http://physwww.physics.mcmaster.ca/~harris/mwgc.dat)
Iglesias C. A., Rogers F. J., 1996, ApJ, 464, 943
Kroupa P., 2001, MNRAS, 322, 231
Kroupa P., Tout C. A., Gilmore G., 1993, MNRAS, 262, 545
Law D. R., Majewski S. R., 2010, ApJ, 718, 1128
Lee Y.-W. et al., 2005, ApJ, 621, L57
Mackey A. D., van den Bergh S., 2005, MNRAS, 360, 631
Marino A. F., Villanova S., Piotto G., Milone A. P., Momany Y., Bedin L. R., Medling A. M., 2008, A&A, 490, 625
Miller Bertolami M. M., Althaus L. G., Unlaguba K., Weiss A., 2008, A&A, 491, 251
Milone A. P. et al., 2008, ApJ, 673, 241
Milone A. P., Bedin L. R., Piotto G., Anderson J., 2009, A&A, 497, 755
Milone A. P. et al., 2010, ApJ, 709, 1183
Moehler S., Sweigart A. V., Landsman W. B., Dreizler S., 2002, A&A, 395, 37
Moehler S., Dreizler S., Lanz T., Bono G., Sweigart A. V., Calamida A., Monelli M., Nonino M., 2007, A&A, 475, L5
Moni Bidin C., Moehler S., Piotto G., Recio-Blanco A., Momany Y., Méndez R. A., 2006, A&A, 451, 499
Moni Bidin C., Catelan M., Villanova S., Piotto G., Altmann M., Momany Y., Moehler S., 2008, in Heber U., Jeffery C. S., Napiwotzki R., eds, ASP Conf. Ser. Vol. 392, Hot Subdwarf Stars and Related Objects. Astron. Soc. Pac., San Francisco, p. 27
Newberg H. J., Yanny B., Grebel E. K., Hennessy G., Ivezi Z., Martinez-Delgado D., 2003, ApJ, 596, 191
Pietrinferni A., Cassisi S., Solaris M., 2010, A&A, 522, A76
Potekhin A. Y., Baiko D. A., Haensel P., Yakovlev D. G., 1999, A&A, 346, 345
Reimers D., 1975, Mem. Soc. R. Sci. Liège, 8, 369
Renzini A., 2008, MNRAS, 391, 354
Rey S.-C., Lee Y.-W., Byun Y. I., Chun M.-S., 1998, AJ, 116, 1775
Ripepi V. et al., 2007, ApJ, 667, L61
Sandquist E. L., Hess J. M., 2008, AJ, 136, 2259
Shetrone M. D., Cóted P., Sargent W. L. W., 2001, ApJ, 548, 592
Siess L., 2010, A&A, 512, A10
Sirianni M., et al., 2002, Am. Astron. Soc., 201, 4101S (BAAS, 34, 1164)
Trager S. C., King I. R., Djorgovski S., 1995, AJ, 109, 218
van den Bergh S., Mackey A. D., 2004, MNRAS, 354, 713
Ventura P., D’Antona F., 2011, MNRAS, 410, 2760
Ventura P., Zeppieri A., Mazzitelli I., D’Antona F., 1998, A&A, 334, 953
Ventura P., Caloi V., D’Antona F., Ferguson J., Milone A., Piotto G. P., 2009, MNRAS, 399, 934
Vesperini E., McMillan S. L. W., D’Antona F., D’Ercole A., 2010, ApJ, 718, L112
Walker A. R., 1994, AJ, 108, 555
Whitney J. H. et al., 1998, ApJ, 495, 284

This paper has been typeset from a TeX/LaTeX file prepared by the author.