Revealing the formation mechanism of the shell galaxy NGC474 with MUSE*

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ABSTRACT

Stellar shells around galaxies could provide precious insights into their assembly history. However, their formation mechanism remains poorly empirically constrained. We present MUSE@VLT data of the most prominent outer shell of NGC 474, to constrain its formation history. The stellar shell spectrum is clearly detected, with a signal-to-noise ratio of around 65 pix−1. We use a full spectral fitting method to determine the line-of-sight velocity and the age and metallicity of the shell and associated point-like sources within the MUSE field of view. We detect six globular cluster (GC) candidates and eight planetary nebula (PN) candidates which are all kinematically associated to the stellar shell. We show that the shell has an intermediate metallicity, [M/H] = -0.83±0.12 and a possible α-enrichment, [α/Fe] ~ 0.3. This metallicity and the number of PNe are consistent with a progenitor galaxy more massive than 10^9 M⊙. The photometry of the shell suggest that it is possibly composed of stars from the low metallicity outskirts of an intermediate mass (~1:10) companion. We show that at least two globular cluster candidates are quite young, with ages below 1.5 Gyr, which gives a lower-limit for the merger age. We note that spectroscopic data on the center of NGC 474 shows the presence of a young (~ 1 Gyr) stellar population. We conclude that the shell formation event is likely to be an intermediate-mass merger which happened around 1.5 Gyr ago and which has collaterally triggered the formation of massive, up to ~ 6 × 10^4 M⊙, star cluster, and a nuclear starburst in NGC 474.

Key words. galaxies: interactions; galaxies: peculiar; galaxies: star clusters: general; galaxies: halos

1. Introduction

According to the current cosmological paradigm, galaxies assemble through a continuous process of accretion of gas and successive merging with other galaxies (White & Rees 1978). This merging history can leave low-surface brightness (LSB) imprints in the halo of galaxies, in the shape of stellar streams, plumes, tidal tails or shells (see e.g. Mihos et al. 2005; Martínez-Delgado et al. 2010; van Dokkum et al. 2014; Duc et al. 2015; Mancillas et al. 2019b; Müller et al. 2019). Thus, the study of these features can help reconstructing the assembly history of galaxies (see e.g. Foster et al. 2014; Longobardi et al. 2015), as well as even serve as probes for gravity in the low acceleration regime (see e.g. Ebrová et al. 2012; Bílek et al. 2013).

Young prominent tidal tails are mostly gas-rich and can be analysed through their gas component (see e.g. Yun et al. 1994; Duc et al. 2000; Williams et al. 2002). However, plumes, streams and shells are relatively gas poor (but see Charmandaris et al. 2000) and only their faint stellar absorption lines are usually available for spectroscopy. An alternative to study the dynamics and chemical composition of gas-poor tidal features is to use bright point sources, such as globular clusters (GC) or planetary nebulae (PN) to study the dynamics and chemical composition of plumes or streams (see e.g. Durrell et al. 2003; Mullan et al. 2011; Forbes et al. 2012; Blom et al. 2014; Foster et al. 2014).

Stellar shells are relatively frequent around elliptical and lenticular galaxies (~ 20%, Tal et al. 2009; Duc et al. 2015; Pop et al. 2018, but see Krajnović et al. 2011) and have relatively high surface brightness for LSB structures (up to 25 mag arcsec−2, Johnston et al. 2008; Atkinson et al. 2013) compared to streams and plumes. They thus appear as conve-
nient tracers of past merging events. Shells systems have been classified within three types, corresponding to the distribution of the shells position angles: Type I for aligned shells, Type II for random orientation and Type III for ambiguous or undetermined orientations (Wilkinson et al. 1987).

From numerical simulations, it could be inferred that the mechanisms responsible for shell formation are likely to be near-radial infalls of relatively massive galaxies (mass ratio above 1:10, see e.g. Quinn 1984; Hernquist & Weil 1992; Pop et al. 2018; Karademir et al. 2019), while mergers involving higher angular momentum tend to create stellar streams (Amorisco 2015; Hendel & Johnston 2015). It should be noted that high mass ratio are favored as higher mass progenitors should be able to create shells from a wider range of impact parameters (Pop et al. 2018). Shells are therefore thought to be made up of stars from the accreted and tidally disrupted satellite, at the apocenter of their orbit around the host galaxy. However, the spectrophotometric data needed to test these scenarios are scarce, mostly because they are extremely challenging to obtain (but see longslit spectra from Pence 1986). Moreover, this paucity makes that the extent to which point sources - namely GCs and PNe - could trace the kinematics of these stellar structures is still unknown.

In this study, we propose to empirically constrain the formation scenario of stellar shells by using the revolutionary capabilities of MUSE on one of the most spectacular shell-rich systems, NGC 474. This galaxy, classified as peculiar by Arp (1966) under the name Arp 227, is either a lenticular galaxy or a fast rotating elliptical (Hau et al. 1996; Emsellem et al. 2004), located at 30.9 Mpc (Cappellari et al. 2011). The deepest imaging data obtained to date on this system revealed a total of at least ten concentric shells and six radial streams up to 5.6′ from the galaxy (that is 50 kpc, Duc et al. 2015, MATLAS survey). The non-alignment of the position angles of the inner shells around the galaxy (within 100″, that is 15 kpc from the center) classified NGC 474 as a type II shell galaxy (Prieur 1990; Turnbull et al. 1999). These inner shell systems have already been studied via their photometry (Sikkema et al. 2006, 2007) which revealed the presence of a blue inner shell, a hint for a recent minor merger event. In this paper we present the data obtained on the brightest shell (24.8 mag.arcsec^{-2} in the g-band), located ∼30 kpc from the host, which has a few spatially associated GC candidates, selected by color on ultra-deep CFHT imaging (Lim et al. 2017, L17 in the following).

The paper is organized as follows. The data and methods are presented in Section 2 and the results in Section 3. The discussion and conclusion are presented in Section 4.
2. Data and methods

2.1. Observations and Reduction steps

VLT/MUSE observations were conducted in service mode during gray time from November 2017 to November 2018, with CLEAR conditions and observed seeing between 0.5" and 0.9". Observations were split into 16 observing blocks (OBs) of one hour each, amounting to a total 5.1h on-target integration time for each of the two pointings. Each OB was split into four individual on-target exposures with small dithers and 90 degree-rotations to avoid cosmic ray contamination and slicer patterns. All OBs had a "OSOOSO" sequence, where S stands for sky, with each 150 s exposure, and O stands for object, 583 s exposure. Fig. 1 shows the location of the field of view. We overlapped the two pointing footprints to increase the signal-to-noise on the shell.

The OBs were all reduced using the latest MUSE ESOREX pipeline recipes (version 2.4.2). The reduction follows the standard steps, including sky subtraction. To improve sky subtraction, we use the Zurich Atmosphere Purge software (ZAP, Soto et al. 2016), using the sky available on the left of the shell. We used 45 eigenvectors and 300 pixels for the window for the continuum subtraction.

On Fig. 1 is also shown the field of view of archival SAURON data centered on NGC 474 (de Zeeuw et al. 2002). This data is commented in Section 4.2.

2.2. Detection and spectral extraction

We detected GCs and PNe using SExtractor on collapsed cubes (Bertin & Arnouts 1996). GC detections were done on the fully collapsed cube. We selected well defined point-like detections that had a velocity consistent with being part of this system, that is ± 400 km s⁻¹ around the central velocity of NGC 474 and a S/N above 6 pix⁻¹, plus the candidates from L17. PNe were detected on stack of two collapsed cubes, each using only frames (slabs of 7.5 A) around the redshifted wavelengths of each of the [O III] doublet emission line. To remove the continuum, we subtracted from this image two similarly collapsed cubes from nearby, but featureless, spectral regions. Eight sources with unambiguous detection of the [O III] doublet (S/N > 2.5) were detected, their location is indicated on Fig. 1.

We extracted each point source with a Gaussian weight function to provide a S/N-optimised extraction. The full-width at half-maximum is chosen to be ~ 0.8" to approximately match the resulting point spread function. The background is measured locally in eight nearby locations, using the same Gaussian weight. In each channel, we subtracted the median value of background regions to the source flux. The variance between those eight sky apertures is added to the source flux variance channel per channel. The flux from the shell is obtained by a sum of the flux on the full shell, after masking point sources, weighted by the white-light image to optimize the S/N.

The best single stellar population (SSP) fit for the shell and the brightest GC, GC 2, are shown in Fig. 2. The gray regions are affected by residual sky lines and are not used for the fit. The other fits are presented in the Appendix and the methods are described in the next subsection. We note strong Balmer and calcium triplet (CaT) absorption lines but no emission lines. The S/N around the Hα line is 65 pix⁻¹ for the shell, 26.9 pix⁻¹ for GC 2 and 6.6 pix⁻¹ for GC 3, respectively. The PNe candidate spectra are shown in Fig. 3. The S/N goes from 9.1 for PN 6 to 4.5 for PN 4.

2.3. Fitting procedure

The method is the same as the one described in Fensch et al. (2019). It is mainly based on pPXF (Cappellari 2017) and the eMILES SSP stellar library Vazdekis et al. (2016). We linearly interpolate for sixteen more metallicity values, between [Fe/H]= -2.32 and -0.71, as done in Kuntschner et al. (2010). In the following we summarize the main points of the procedure.

For the shell and the GC candidates, we use pPXF with Legendre polynomials to account for uncertainty in the different flux calibration between our data and the eMILES library. For the kinematic fits, we use 12-degree multiplicative and 14-degree additive Legendre polynomials, and the full eMILES library, similar to Emsellem et al. (2019). For the stellar population fits, we use 12-degree multiplicative and no additive Legendre polynomials, and we individually fit with each SSP, as in Fensch et al. (2019). The ages we derive are then that of the best fitting single burst of star formation. Uncertainty is calculated by redistributing randomly the residuals of the best fit onto the best fit for 100 times and measuring the dispersion in the new best fit value for the 100 fits. For the PNe, we use a double Gaussian line emission template, with same width, to fit the [OIII] doublet. The uncertainty is obtained in the same way as for the shell and GCs.

3. Results

3.1. Full spectra analysis

The result of the kinematic fits is shown in Fig. 4. The GC and PN candidates have measured velocities within 50 km s⁻¹ from the shell’s velocity, as determined from the integrated MUSE spectrum. This kinematical association thus confirms a plausible association between them and the shell. One should have in mind that the velocity profile of a stellar shell is expected to present a four-horn profile with a wide separation between the extreme values (up to 150 km s⁻¹, see e.g. Ebrová et al. 2012). A spread of velocities of the PNs and GCs around the velocity of the integrated shell spectra is thus expected for such systems. We further note that the shell velocity, 2307.6 ± 2.7 km s⁻¹ is similar to that of the central regions of NGC 474 (2315 ± 5 km s⁻¹ Cappellari et al. 2011). This fits within the interpretation that the shell is made of stars originating from the disrupted satellite that just reach the apocenter of their orbits in the potential well of the host galaxy: the sharp contrast of the shell emerges from a favorable projection, for which the apocenter, its motion, and the center of NGC 474 are on a plane aligned with the observer’s sky plane (see e.g. Bilek et al. 2016; Mancillas et al. 2019 b).

The results of the SSP analysis is shown in Fig. 5 and are summarized in Table 1. The low S/N of GC 3 and GC 6, below 10 pix⁻¹, do not allow the fit from pPXF to converge in terms of stellar populations of these GCs and are not shown in that Figure. Our estimation gives the shell an intermediate age and metallicity, that is 3.55±0.06 Gyr and [M/H] = −0.83±0.12. We note that these age and metallicity are significantly lower than that of the host galaxy as determined from the SAURON observations: 7.65 ± 1.39 Gyr and [M/H] = −0.12 ± 0.05 within 1 R_e (McDermid et al. 2015).

GC 4 and GC 5 are estimated to have a low metallicity and old age, above 9 Gyr, consistent with being old globular clusters. Their masses are estimated to be around 10⁵ M☉ from the fit. Their metallicity is similar to the so-called blue GCs (Brodie...
& Strader 2006). GC 1 and GC 2 are estimated to have a higher metallicity and much younger ages, around 1 Gyr. The estimated mass for these clusters are respectively $2.50 \times 10^4 \ M_\odot$ and $5.91 \times 10^4 \ M_\odot$.

3.2. Spectral indices

As a complementary method, we estimate age, metallicities and $\alpha$ element enrichment from the standardized Lick/IDS system\(^1\) (Worthey et al. 1994). We show two diagnostic plots in Fig. 6, making use of the theoretical Lick indices for the MILES spectral library from Thomas et al. (2010). The error bars are the dispersion of the results of the Lick indices measurement on the re-noised spectra used for the measurement of the uncertainties in the previous section. We only show the result for the stellar shell, GC1 and GC2. The other objects have a too low SNR and thus have a significant fraction of their re-noised spectra with a negative equivalent width for at least one of the absorption lines of interest (more than 25% against maximum one for the shell, GC1 and GC2).

The first diagnostic uses the Mg\(b\) index as a probe of the $\alpha$ elements, and $<\text{Fe}>$, defined as the average between Fe5270 and

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\(^1\) We used the pyphot package available at this address: https://mfouesneau.github.io/docs/pyphot/index.html
Table 1. Results of the full spectra fitting procedure. For the GCs, the S/N is measured in the neighborhood of the Hα line and given in units of pix$^{-1}$. For the PNe, the S/N is integrated over the [OIII]5007 line.

| Name  | RA (J2000) | DEC (J2000) | S/N | Velocity | Age [Gyr] | M/H | GC: Mass [M$_\odot$] | PNe: M$_{5007}$ [mag] |
|-------|------------|-------------|-----|----------|-----------|-----|---------------------|------------------------|
| Shell |            |             | 65.0| 2307.6 ± 2.7 | 3.55$^{+0.04}_{-0.03}$ | -   | -                   | -                      |
| GC1   | 01:20:19.1987 | 03:25:49.4674 | 13.9| 2294.7 ± 5.4 | 1.41$^{+0.02}_{-0.02}$ | -1.07$^{+0.02}_{-0.02}$ | 2.50 $\times 10^{4}$ ± 5.89 $\times 10^{3}$ | -                      |
| GC2   | 01:20:19.2836 | 03:25:40.4404 | 26.9| 2298.0 ± 4.8 | 0.56$^{+0.04}_{-0.06}$ | -0.22$^{+0.02}_{-0.02}$ | 5.91 $\times 10^{4}$ ± 2.24 $\times 10^{3}$ | -                      |
| GC3   | 01:20:18.8817 | 03:25:34.9047 | 6.6 | 2307.6 ± 17.4 | -         | -   | -                   | -                      |
| GC4   | 01:20:19.2141 | 03:25:20.0695 | 17.5| 2304.0 ± 8.7 | 12.59$^{+2.17}_{-3.49}$ | -1.69$^{+0.10}_{-0.01}$ | 1.21 $\times 10^{5}$ ± 2.21 $\times 10^{4}$ | -                      |
| GC5   | 01:20:18.6095 | 03:24:40.3496 | 19.4| 2267.5 ±28.4 | 8.91$^{-3.84}_{+3.63}$ | -1.73$^{+0.10}_{-0.16}$ | 1.35 $\times 10^{5}$ ± 3.51 $\times 10^{4}$ | -                      |
| GC6   | 01:20:19.1119 | 03:24:30.7437 | 9.4 | 2320.0 ±49.5 | -         | -   | -                   | -                      |
| PN1   | 01:20:17.7024 | 03:25:57.4425 | 4.1 | 2287.5 ± 6.6 | -         | -   | -3.87 ± 0.09        | -                      |
| PN2   | 01:20:17.6471 | 03:25:28.4427 | 4.1 | 2275.6 ± 6.5 | -         | -   | -4.10 ± 0.08        | -                      |
| PN3   | 01:20:19.7309 | 03:25:21.2427 | 4.8 | 2317.2 ± 6.3 | -         | -   | -3.42 ± 0.10        | -                      |
| PN4   | 01:20:18.0078 | 03:25:13.2424 | 3.7 | 2294.5 ± 7.8 | -         | -   | -3.32 ± 0.11        | -                      |
| PN5   | 01:20:18.3818 | 03:24:54.6427 | 4.2 | 2302.5 ± 6.8 | -         | -   | -3.99 ± 0.11        | -                      |
| PN6   | 01:20:17.4201 | 03:24:48.0424 | 6.9 | 2286.0 ± 4.6 | -         | -   | -4.46 ± 0.07        | -                      |
| PN7   | 01:20:18.8894 | 03:24:48.0424 | 2.8 | 2350.7 ± 8.3 | -         | -   | -3.98 ± 0.12        | -                      |
| PN8   | 01:20:17.9410 | 03:24:47.6425 | 6.8 | 2316.8 ± 4.0 | -         | -   | -4.51 ± 0.08        | -                      |

Fig. 3. Spectra of the eight PNe candidates. The location of the [OIII] doublet at the redshift of NGC 474 is shown with gray dashed lines.

Fe5335 (Evstigneeva et al. 2007), for the iron abundance. For the ages considered (younger than 5 Gyr), we see that the spectral indices of these objects are consistent with a $\alpha$-enrichment $[\alpha/Fe] = 0.3$, but with rather large error bars due to the low SNR. We note that globular clusters are typically enriched in $[\alpha/Fe]$ = 0.3-0.5 (see review by Brodie & Strader 2006).

The second diagnostic uses the age-sensitive index Hβ and the total metallicity-sensitive index [MgFe]$^+$ = $\sqrt{Mg b × (0.72 Fe 5270 + 0.28 Fe 5335)}$ (Evstigneeva et al. 2007). For GC 2, the two methods give very similar results. However, the Lick indices suggest a younger age and higher metallicities for the shell and GC 1 than our full fitting method. For the shell, Lick Indices suggest $[M/H] \approx -0.33$ and an age between 1 and 3 Gyr. For GC 1, they suggest $[M/H] \approx -0.15$ and an age around 0.8 Gyr but with large uncertainties. We note that Lick Indices do not show a metallicity difference between the two GCs, unlike the full spectral analysis. This second method confirms the trend that GC 1 and GC 2 are younger than the light-averaged stellar population in the stellar shell. We discuss the age difference between the two GCs in Section 4.2.

Fig. 4. Line-of-sight velocity of the GCs, PNe and NGC 474. The black dashed line shows the line-of-sight velocity of the shell, and the gray shadow its uncertainty.

Last, the color-color diagram of detected GCs from L17’s catalog is shown in Fig. 7. The estimated young ages of GC 1 and GC 2 is confirmed by their blue color (g-i < 0.5 mag), which excluded them from the L17 analysis. We note that GC 3 has similar (u-g, g-i) colors as GC 1 and GC 2, and was also rejected as GC candidates from the L17 analysis. However, its low S/N spectrum does not allow an estimate of its age and metallicity. These 3 GC candidates have bluer colors than the shell (g-i = 0.6 mag, L17). The origin of these GCs will be discussed in the following section.

4. Discussion
4.1. What is the progenitor of the shell?
Numerical simulations have shown that shell formation could emerge from relatively major mergers (> 1:10 in stellar mass ratio, Pop et al. 2018; Karademir et al. 2019). The estimated stellar population properties for the shell (see Section 3), with
a metallicity of \([\text{M}/\text{H}] = -0.83^{+0.12}_{-0.12}\) are typical of galaxies with stellar masses of \(\approx 10^8 \, M_\odot\) (see review by Maiolino & Mannucci 2019). In Section 3.2, we have noted that the stars in the shell are consistent with being enriched in \(\alpha\)-elements, \([\alpha/\text{Fe}] \sim 0.3\). Satellites of the Milky Way and Andromeda galaxy also have \([\alpha/\text{Fe}]\) between 0 and 0.4, with no clear correlation with mass or metallicity (Vargas et al. 2014). The possible \(\alpha\)-enrichment of the stars in the stellar shell does not exclude the possibility of the progenitor being a dwarf galaxy.

The stellar mass of a galaxy can also be roughly assessed independently via the number of PNe it hosts. The total number of PNe per bolometric luminosity in the brightest 1 mag of the luminosity distribution is typically \(\alpha_1 = 3 \times 10^{-7}/40 \, \text{PNe}/L_\odot\) (Buzzoni et al. 2006, the factor 1/40 being derived for the canonical PN luminosity function). We have detected six PNe with \(M_{\text{bol}}\) between \(-4,51\) and \(-3,51\) mag. Assuming that these six PNe are associated to the stellar population of the shell progenitor and not to the halo of NGC 474, which is reasonable given their similar line-of-sight, we can estimate a bolometric luminosity of \(L_{\text{bol}} \approx 8 \times 10^8 \, L_\odot\). We note that this rough mass estimation falls in the same ballpark as the one derived from the PNe number. Given that NGC 474 is surrounded by many shells and that the shells are expected to host only a fraction of the stellar light from the progenitor (around 30% from simulations, see Ebrová et al. 2020), the progenitor is very likely to be more massive than a typical dwarf galaxy. We note that a progenitor galaxy with a mass above \(10^{10} \, M_\odot\) should have a stellar metallicity of \([\text{M}/\text{H}] > -0.5\) (Panter et al. 2008; Maiolino & Mannucci 2019), higher than the one derived from the spectral analysis. One should note that we have so far assumed that the progenitor has a constant metallicity, which is a disputable hypothesis for galaxies with a mass around \(10^{10} \, M_\odot\). It might thus be that the shell is formed by stars from the low metallicity outskirts of an intermediate mass companion. We also note that this hypothesis would imply \(~ 60\) PNe in the brightest 1 mag of the luminosity distribution, associated with stars from the progenitor and scattered around NGC 474.

One may wonder if all the shells around NGC 474 were formed by the same event. In this case, the total mass of the progenitor could in principle be obtained via deep integrated photometry, once the origin of each shell has been inferred.
A chemodynamical observational and numerical study of the whole shell system is therefore needed to distinguish between the hypothesis of several shell forming minor mergers or a more massive merger forming many shells.

The stellar metallicity and the number of PNe associated with the shell point towards a progenitor with stellar mass securely above $10^7 \, M_\odot$. The integrated light of the shell by L17 hints to a more massive progenitor, typically more massive than the LMC. The mass of NGC 474 is estimated to $10^{10.9} \, M_\odot$ (Cappellari et al. 2013). We therefore estimate that the event that created this shell was probably a $\sim 1:10$ mass ratio merger.

4.2. **Could the shell forming event trigger massive star cluster formation?**

From cosmological zoom simulations, Mancillas et al. (2019b) have estimated that stellar shells can remain visible for 3 to 4 Gyr. In Section 3, we estimated that GC 1 and GC 2 have ages younger than 1.5 Gyr. One may thus wonder if they were formed during the event that formed the shell.

Observations and simulations of interactions of galaxies have shown that such events could trigger the formation of star clusters, similar in mass to GC 1 and GC 2 (see e.g. Whitmore et al. 2010; Renaud et al. 2015; Lahén et al. 2019). Sikkema et al. (2006) have found hints for newly formed GCs in the nucleus of two shell galaxies (type II NGC 2865 and type III NGC 7626), but not for NGC 474. We have noted in Section 3 that GC 1 and GC 2 have different ages and metallicity. To explain that, one may estimate the free-fall time at the radius of the shell, that is 30 kpc. Via abundance matching (Behroozi et al. 2013; Diemer & Kravtsov 2015) one may estimate that the most likely halo to host NGC 474 would have a total mass of $9 \times 10^{11} \, M_\odot$ and a virial radius of 1200 kpc, which gives a free-fall time of about 100 Myr. This means that the GCs have already passed close to the nucleus of NGC 474 several time since their formation, and makes it possible that their formation happened at different passages of the associated material close to that nucleus.

One way to test the hypothesis of triggered star cluster formation is to check whether we see traces of star formation from the same epoch in the nucleus of NGC 474, where we may expect the build-up of a gas reservoir leading to a potential starburst.

We note that Jeong et al. (2012) and Zaritsky et al. (2014) classified NGC 474 as a blue outlier among early-type and lenticular galaxies because of its relatively blue color and elevated near-UV emission. Moreover, Sikkema et al. (2007) noticed pronounced dust lanes (estimated mass of $\sim 10^4 \, M_\odot$ in the central 15′ of NGC 474, which align with the location of ionized gas. No molecular gas was found in the central region of NGC 474 (upper limit: $M(H_2) < 10^{7.5} \, M_\odot$, see Combes et al. 2007; Mancillas et al. 2019a). Schiminovich et al. (1997) and Rampazzo et al. (2006) found an HI tail due to the interaction with NGC 470 (spiral galaxy westward of NGC 474 in Fig. 1), but it is not superimposed with the shell.

To investigate the presence of a young stellar population in the host galaxy, we use the central kpc of the SAURON data cube centered on NGC 474 from de Zeeuw et al. (2002) and used the pPXF regularization procedure from Cappellari (2017), with 3-degree multiplicative Legendre polynomials and the previous eMILES library. To avoid degeneracies due to the presence of emission lines, namely H$_\beta$ and the [OIII] doublet, we perform a first fit by masking the location of these lines and fix the obtained velocity and velocity dispersion for a second fit enabling emission lines.

The regularized fit to the data and the weights of the different templates are shown respectively in the upper and lower panel of Fig. 8. We note the use of very metal-poor templates by the regularization. They might be due to imperfection of the used SSP, in particular in terms of [$\alpha$/Fe] (we only use ‘base models’, see Vazdekis et al. 2016). We discard them in the following. On top of old and metal-rich templates, typical of elliptical galaxies, we note that the regularization makes use of templates of age and metallicity similar to GC 1 and GC 2 (see Fig 5). The SAURON spectrum of NGC 474 therefore supports the hypothesis of a nuclear starburst around 1 Gyr ago. We note that this timescale is similar to the estimated ages of the massive stellar clusters, and suggests that both the starburst and cluster formation could have been caused by a single galaxy merger. However, we warn that the structure of NGC 474 is complex (see e.g. Sikkema et al. 2007) and that this young stellar component cannot yet be unambiguously connected to the shell. The fit infers a total mass for the young component of $3.22 \pm 1.37 \times 10^7 \, M_\odot$, to be compared with $4.00 \pm 0.83 \times 10^6 \, M_\odot$ for the old and metal-rich component.

One may thus wonder what is the origin of the gas that fuelled this starburst and the formation of the GCs. Indeed, the nucleus of NGC 474 does not host any detectable H$_2$ and we note that no HI has been detected at the vicinity of the shell (Schiminovich et al. 1997; Rampazzo et al. 2006; Mancillas et al. 2019a). This suggests that these episodes of star formation were very efficient at consuming or ejecting the gas and calls for a dedicated numerical study of star cluster formation in shell-forming galaxy interactions.

Last, we locate the GC candidates all around NGC 474 (see field of view in Fig. 9) with similar colors as confirmed young GC 1 and 2. We chose GC candidates with $0.3 < g-i < 0.5$ and $0.9 < u-g < 1.1$, depicted as *young candidates* in Fig. 7. There are nine young candidates in total, including GC 1, 2 and 3. There

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**Fig. 7.** Color-color diagram of the point source detections in L17, corrected for foreground dust extinction. The thick points are the GC candidates selected by L17, while the light points were rejected. The 6 GCs within our field of view are shown as black squares, with their names on the right-hand side. The blue square and points show the selection of the GC candidates considered as young candidates in Section 4.
is one more young candidate in the MUSE field-of-view. After verification, this source was discarded from the present analysis because of its very low S/N = 2.8 pix$^{-1}$, which did not permit any reliable analysis. Apart from GC 1 and GC 2 (with resp. $m_g = 23.04 \pm 0.02$ mag and $22.19 \pm 0.01$ mag), these candidates have $m_g$ between 24 and 25 mag. We note that their relative faintness would not allow age and metallicity measurement using MUSE with less than 10.2 h of on-source integration. These six young candidates are shown with cyan circles in Fig. 9. We note that they are located in the vicinity of the studied shell, inner stellar shells or tidal features, suggesting a possible link with the events that created these structures.

5. Conclusion

We use MUSE@VLT to study the origin of an external stellar shell around the host galaxy NGC 474.

We find eight PNe and six GC candidates (including three candidates from Lim et al. 2017) which are kinematically associated with the stellar shell. From the inferred metallicity and the number of PNe associated with the shell we derive a lower limit of the mass of the progenitor of $10^9$ M$_\odot$. The photometry of the shell indicates a progenitor with a mass above $10^{10}$ M$_\odot$. This favours the hypothesis that the shell is made of the low metallicity stars from an intermediate mass progenitor, with an around 1:10 mass ratio merger.

Full spectral fitting of the four GC candidates with high enough S/N shows that two of them are consistent with being old globular clusters while the other two show signs of young ages (<1.5 Gyr) and relatively high metallicity ([M/H] > -1.1). The study of the Lick Indices confirms the trend that GC 1 and GC 2 are younger than the stars in the shell. Their different age and metallicity hint to a formation at different passage of the associated material close to the nucleus. This is consistent with their blue color, which excluded them from previous analysis of GCs in this system. Regularization of full spectral fitting on SAURON data of the central kpc of NGC 474 hints for the presence of a relatively young stellar population, with age and metallicity similar to that of these young GC candidates. This suggests that these young GC candidates might have formed during the merging event that causes the formation of the stellar shell. We note the presence of nine GC candidates with similar colour around NGC 474, all fainter that GC 2, the brightest young cluster candidate, which is estimated to have a mass of $\sim 6 \times 10^4$ M$_\odot$.

This analysis thus shows that this stellar shells is likely to have formed through intermediate mass ratio merger that triggered a central starburst in the host and the formation of massive star clusters.

Acknowledgements. JF would like to thank the ESO User Support Department for their great help on performing these observations. The authors thank Richard McDermid and Harald Kuntschner for interesting discussions respectively about NGC 474 and Lick Indices. C.L. acknowledges support from the National Natural Science Foundation of China (NSFC, Grant No. 11673017, 11833005, 11933003, 11621303, 11973033 and 11203017).
Appendix A: GC spectra and fits
Fig. A.1. Same as Fig. 2

Fig. A.2. Same as Fig. 2
Fig. A.3. Same as Fig. 2

Fig. A.4. Same as Fig. 2
Fig. A.5. Same as Fig. 2