Stellar content, planetary nebulae, and globular clusters of [KKS2000]04 (NGC1052-DF2)

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ABSTRACT

[KKS2000]04 (NGC1052-DF2) has become a controversial and well-studied galaxy after the claims suggesting a lack of dark matter and the presence of an anomalously bright globular cluster (GC) system around it. A precise determination of its overall star formation history (SFH) as well as a better characterisation of its GC or planetary nebulae (PN) systems are crucial aspects to: i) understand its real nature, in particular placing it within the family of ultra diffuse galaxies; ii) shed light on its possible formation, evolution, and survival in the absence of dark matter. With this purpose we expand on the knowledge of [KKS2000]04 from the analysis of OSIRIS@GTC spectroscopic data. On the one hand, we claim the possible detection of two new PNe and confirm membership of 5 GCs. On the other hand, we find that the stars shaping [KKS2000]04 are intermediate-age to old (90% of its stellar mass older than 5 Gyr, average age of 8.7 ± 0.7 Gyr) and metal-poor ([M/H] ∼ −1.18 ± 0.05), in general agreement with previous results. We do not find any clear hints of significant changes in its stellar content with radius. In addition, the possibility of [KKS2000]04 being a tidal dwarf galaxy with no dark matter is highly disfavoured.

Key words: methods: observational – techniques: spectroscopic – galaxies: evolution – galaxies: formation – galaxies: stellar content – galaxies: kinematics and dynamics

1 INTRODUCTION

The agreement between numerical simulations and observations at large scales is astounding. However, discrepancies appear at smaller scales, where baryon physics has to be added to the simulations. On such scales, dwarf galaxies, the most abundant kind in the Universe, have proven crucial in our understanding of galaxy formation and evolution (see Silk & Mamon 2012, for a review). In recent years, one particular family towards the faint end of the galaxy population stands out, the currently named ultra diffuse galaxies (UDGs, van Dokkum et al. 2015). UDGs are a puzzling family of faint galaxies with stellar masses similar to those of dwarf galaxies but with larger effective radii ($R_e > 1.5$ kpc).

While the growing consensus seem to suggest that UDGs are simply extended dwarf galaxies (e.g. Amorisco & Loeb 2016; Beasley et al. 2016; Beasley & Trujillo 2016; Di Cintio et al. 2017; Trujillo et al. 2017; Sánchez Almeida et al. 2018), there are works claiming that there might be some embedded in huge dark matter haloes (like DF44 or DFX1, van Dokkum et al. 2016, 2017; Zaritsky 2017) or even lacking dark matter (like [KKS2000]04/NGC1052-DF2, van Dokkum et al. 2018c, see also van Dokkum et al. 2019). [KKS2000]04 is of particular interest because, in addition to the claim of lacking dark matter, it would also possess an unusual population of luminous globular clusters (van Dokkum et al. 2018a). However, a revision of the distance assumed to this galaxy has been proposed to solve both anomalies (Trujillo et al. 2019). A proper characterisation of its globular cluster (GC) system and stellar population properties is needed to place [KKS2000]04, a seemingly anomalous galaxy, within the realm of the regular UDGs.

UDGs are characterised by old, metal-poor stars (Kadonwaki, Zaritsky & Donnerstein 2017; Gu et al. 2018; Pandya et al. 2018; Ruiz-Lara et al. 2018a; Ferré-Mateu et al. 2018), with the exception of some gas-rich, blue UDG progenitors.

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found in lower density environments that might point towards an evolution scenario for UDGs (Trujillo et al. 2017; Román & Trujillo 2017). In this regard, recent photometric and spectroscopic studies suggest that [KKS2000]04 is indeed old and metal-poor (Fensch et al. 2018; Trujillo et al. 2019), placing [KKS2000]04 as a normal UDG in terms of its stellar content. However, assuming a distance of 20 Mpc to this system, it still seems to hold a remarkably bright GC population (van Dokkum et al. 2018a) unseen among UDGs until now.

As a consequence, a full characterisation of the GCs in [KKS2000]04 is of the utmost importance. On the one hand, completeness issues affecting the sample of GCs presented in van Dokkum et al. (2018c) and van Dokkum et al. (2018a) might be biasing the reported GC luminosity function. On the other hand, the number of GCs correlates with the halo mass, which is also true for UDGs (Prole et al. 2019). In addition, spectroscopic confirmation of as many of its GCs as possible would enable a more precise determination of the velocity dispersion of the system. As a consequence, a better knowledge on the GC population of [KKS2000]04 is needed to clarify all these aspects.

Trujillo et al. (2019) recently provided a new catalogue of GC candidates of [KKS2000]04. Emsellem et al. (2018), making use of MUSE@VLT spectroscopic data and this catalogue, revised the velocity dispersion of the system by confirming one of the candidate GCs as well as adding to the list of GC candidates of [KKS2000]04. Emsellem et al. (2018), revised the velocity dispersion of the system by confirming one of the candidate GCs as well as adding to the list of GC candidates of [KKS2000]04. As a consequence, a full characterisation of the GCs in [KKS2000]04 is of the utmost importance. On the one hand, completeness issues affecting the sample of GCs presented in van Dokkum et al. (2018c) and van Dokkum et al. (2018a) might be biasing the reported GC luminosity function. On the other hand, the number of GCs correlates with the halo mass, which is also true for UDGs (Prole et al. 2019). In addition, spectroscopic confirmation of as many of its GCs as possible would enable a more precise determination of the velocity dispersion of the system. As a consequence, a better knowledge on the GC population of [KKS2000]04 is needed to clarify all these aspects.

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In this work we make use of OSIRIS@GTC long-slit spectroscopic data from [KKS2000]04 to analyse its stellar content, obtaining for the first time its star formation history (SFH) and assessing the possible existence of radial variations of the stellar properties in this system. We also expand on our knowledge of its GC system as well as search for new PNe. We describe the observations and the data reduction in Sect. 2. The main results are described in Sect. 3, while their main implications are discussed in Sect. 4.

2 DATA REDUCTION AND ANALYSIS

Deep spectroscopy is needed to study objects as faint as [KKS2000]04, with a central surface brightness of only $\mu(V_{606},0) = 24.4$ mag arcsec$^{-2}$. With this challenge in mind, we use the OSIRIS imager and spectrograph$^1$ (Cepa et al. 2000) mounted at the Gran Telescopio CANARIAS (GTC), in the Observatorio del Roque de los Muchachos. This instrument has been proven successful at recovering SFHs of UDGs before (Ruiz-Lara et al. 2018a). The OSIRIS observations analysed in this paper are part of the program GTC148-18B (PI: I. Trujillo) and were carried out during dark, clear (seeing $\sim 1.2^\prime$) nights in November-December, 2018. Given the size and faintness of the target, we used OSIRIS in its long slit mode (effective length of 7.8$''$ with a slit width of 3.5$''$ (maximizing the light entering the slit) and the R200B grism. The combination of the selected grism and slit width results in a final spectral resolution of around 13.8 $\AA$, and a potential wavelength range coverage from 3950 to 5700 $\AA$. In total, 20 different exposures of 1400 seconds were taken in three different slit orientations as shown in Fig. 1: slit1 configuration, 6 exposures; slit2 configuration, 6 exposures; and, slit3 configuration, 8 exposures (totalling 10 hours on source). The slit orientations were chosen in order to maximize the number of already-analysed (van Dokkum et al. 2018c) and candidate GCs discussed in Trujillo et al. (2019). This strategy was especially chosen to fulfill two main objectives. On the one hand, we wanted to collect as much light as possible to study the stellar content of the system. On the other hand, we were interested in the confirmation of membership of 4 new GCs proposed in Trujillo et al. (2019)$^2$, aware of the limitations of this observational strategy to obtain precise radial velocities.

The reduction of all the individual exposures was performed independently using a pipeline specifically designed for dealing with OSIRIS-long slit data based on a set of PYTHON–IDL routines. The pipeline follows all standard reduction steps such as bias subtraction, flat fielding, C-distortion correction, wavelength calibration, and cosmic rays removal (L.A. Cosmic, van Dokkum 2001). Given the faintness of the object under analysis, special attention was paid to the sky subtraction. We use the Kelson’s sky subtraction algorithm (Kelson 2003) for such purpose. This technique relies on the knowledge of the CCD distortions and the curvature of the spectral features (previous reduction steps) to obtain a characteristic sky spectrum from carefully selected pixels with sky information. These sky pixels were carefully selected at the sides of [KKS2000]04 avoiding contamination from the galaxy as well as from other background or foreground sources. At this stage of the reduction, some artefacts such as ghosts (in occasions as bright as the galaxy itself given its low surface brightness) and CCD imperfections were notable, especially in the spectral range around 4710–4760 $\AA$ that is avoided in the subsequent analysis. The outcome of this reduction scheme (i.e. 20 exposures fully-reduced 2D spectra) is treated differently for the different goals of this work.

2.1 Point-like sources

The study of the GC membership (Sect. 3.1) and the search for new PNe (Sect. 3.2) were done after all exposures corresponding to each slit configuration were combined using IRAF task imcombine (median combination with an avsigclip rejection operation). The analysis of these three combined 2D spectra facilitates the location and extraction of the individual sources. Spectra of the GCs and GC candidates were extracted using APALL in IRAF. Background regions were defined by eye and fit with a 2nd-order polynomial in order (following the GC curvature in the CCD).

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1 For more information on the OSIRIS instrument we refer the reader to the instrument’s webpage: http://www.gtc.iac.es/instruments/osiris/

2 By the time the observations were performed none of the new GC candidates had any spectroscopic velocity measured.
to decontaminate the GC spectra from the galaxy light that might be included because of the width of the slit. The spectra were extracted using optimal extraction based on the noise characteristics of the OSIRIS CCD. The GCs under analysis in this work are indicated in Fig. 1 as green circles. Following Emsellem et al. (2018) we have decided to identify the candidate GCs as “T” followed by a number given by the Table 2 in Trujillo et al. (2019). For the already confirmed GCs we follow the notation introduced in van Dokkum et al. (2018c).

The detection of new PN candidates (line emitters in general) was made by visually inspecting the spectral region where the Hβ and [OIII] emission is expected (4850–5100 Å), scanning the whole spatial extent covered by the three slits. For an easier and more robust detection, we clean those spectra from stellar emission by subtracting the mean spectrum of the adjacent pixels. The regions where the PN candidates found in this work are expected are highlighted in Fig. 1 as cyan rectangles (see Sect. 3.2).

2.2 [KKS2000]04 main body

The brightest regions within [KKS2000]04 are combined together to obtain two integrated spectra from which the stellar content of the galaxy can be recovered. Because of the lower surface brightness of these regions, this time we prefer to work on the individual exposures rather than on the already combined exposures in each slit position. This approach allowed us to improve the statistics and perform a robust mean to obtain cleaner spectra, characterised by a higher S/N and less affected by the different artefacts of the OSIRIS CCD (Ruiz-Lara et al. 2018b). The two integrated spectra are representative of the inner 1/4 Re of the galaxy and an intermediate region up to ~ 1/2 Re, avoiding contamination from point sources (Re = 22.6”). During the analysis of this dataset we found the presence of ghosts and CCD artefacts in the Hβ and Mgb region for the slit3 configuration exposures (spatially displaced with respect to the exposures corresponding to the other 2 configurations). For this reason, we decided to avoid those exposures in the
3 RESULTS

In this section we summarise the main results that we obtained regarding GC membership, search for new PNe, and the stellar content of [KKS2000]04.

3.1 Revisiting the globular cluster membership

The spectra corresponding to the [KKS2000]04 GCs (see Sect. 2.1) have been analysed using FXCOR in IRAF to determine their velocities and assess their real link with [KKS2000]04. The spectra were logarithmically rebinned, continuum-normalised with a low-order polynomial, and Fourier filtered to remove high-frequency noise and low-frequency continuum variations. We used three MILES model templates (using the base models of Vazdekis et al. 2010) for the cross-correlation, with ages of 12 Gyr and metallicities of $[M/H] = −2.27$, $−1.79$ and $−1.49$ (with similar spectral characteristics as the ones we expect for the [KKS2000]04 GCs). We obtain velocities compatible with being associated to [KKS2000]04 for GC39, GC71, GC77 and GC85 (van Dokkum et al. 2018c), as well as T3 (Emsellem et al. 2018). In addition, we are able to rule out membership for T7 (foreground star, see also Emsellem et al. 2018). Unfortunately, we could neither confirm nor deny membership for T1 or T2 due to the low quality of its spectrum as a result of their extreme faintness ($V_{000}$ magnitude of 23.46 and 23.81, respectively). A quick comparison with the velocities obtained for the same objects in other works shows large offsets. However, given the observing strategy, not being specifically designed to obtain precise velocities for the GCs (wide slit and low spectral resolution), we expected large error bars and offsets with respect to previous works. Nevertheless, this observing strategy does allow us to confirm or rule out membership. Table 1 summarises our results for the 8 GC analysed.

3.2 On the search for new PNe

Encouraged by the work by Fensch et al. (2018) and Emsellem et al. (2018), where the authors claim the detection of three PNe in [KKS2000]04, we examined the spectroscopic data presented in this work to search for new possible candidates. We confirm the presence of PN1 and PN3, the two PNe covered by this new dataset. In addition, we find the possible detection of another two line emitters at $\sim 5036$ Å, wavelength corresponding to the $[O\text{iii}]\lambda 5007$ line according to the redshift of the galaxy (see van Dokkum et al. 2018c; Fensch et al. 2018; Emsellem et al. 2018; Danieli et al. 2019, and this work). The detection of this line is around 2-3 $\sigma$ above the noise level in both cases (see Fig. 2). This detection, added to the theoretical intensity ratio between the two lines comprising the $[O\text{iii}]$ doublet of 2.98 (Storey & Zeippen 2000), hampers the detection of the weakest line of the doublet ($[O\text{iii}]\lambda 4959$) with this set of data (within the noise level). We must bear in mind that the significance of our detections are highly minimised because of the fact that we are mixing together the information coming from a 3.5’-width area (slit width).

PNe are not the only point-like line emitters that can be found in galaxies. Supernova remnants or H II regions are other astrophysical objects that are compatible with being point-like sources in galaxies at distances of 13 Mpc or beyond (as is the case of this system, see van Dokkum et al. 2018c; Trujillo et al. 2019). In the blue, $F([O\text{iii}]\lambda 5007) > F(H\beta)$ is usually regarded as a telltale for PNe. In particular, $log\left(\frac{F([O\text{iii}]\lambda 5007)}{F(H\beta)}\right)$ above 0.7 would ensure the PN nature of our detections (see, e.g. Frew & Parker 2010). The detection of the $[O\text{iii}]\lambda 5007$ line in our PN candidates (2-3 $\sigma$), together with the lack of detection of $H\beta$ (meaning signal around $\sigma$, see Fig. 2) allow us to set a lower limit for $log\left(\frac{F([O\text{iii}]\lambda 5007)}{F(H\beta)}\right)$ of $0.5^{+0.1}_{−0.3}$. Thus, although our detections seem to suggest that these point sources are PNe, we cannot discard them as possible H II regions. From herein, we will denote these point-like line emitters as PN candidates and not categorically as PN.

The reliable determination of the exact position of these PN candidates is also hindered by the observing configuration, namely the slit width. However, we can claim that they should be located within the rectangles given by these coordinates: PN4, $[40.4457, −8.4025]$, $[40.4458, −8.4021]$, $[40.4449, −8.4018]$, $[40.4448, −8.4022]$; PN5, $[40.4491, −8.4025]$, $[40.4495, −8.4023]$, $[40.4491, −8.4014]$, $[40.4487, −8.4016]$). Visual inspection of HST images of this galaxy reveals the presence of point-like sources within both rectangles. However, further confirmation and full exploitation of the possible implications of these two new potential detections need proper follow-up.

3.3 [KKS2000]04 stellar populations

We analyse the stellar content of the main body of [KKS2000]04 (see Sect. 2.2) following an extensively tested and widely used methodology based on a series of full-spectral fitting codes (e.g. Sánchez-Blázquez et al. 2011, 2014; Seidel et al. 2015). Although this technique is thoroughly explained in those works, here we summarise its main steps. First, we study the stellar kinematics shaping the observed spectrum and analyse the possible presence of gaseous emission using pPXF (penalized pixel fitting code; Cappellari & Emsellem 2004; Cappellari et al. 2011) and GANDALF (Gas AND Absorption Line Fitting; Sarzi et al. 2006; Falcón-Barroso et al. 2006), respectively. Once the stellar kinematics is recovered and the emission removed from the observed spectrum, we apply STECKMAP (STEllar Content and Kinematics via Maximum A Posteriori likelihood; Ocvirk et al. 2006b,a) to characterise its stellar populations.

3 Coordinates given by the location where emission is found and the width of the slit (3.5”). The format of the coordinates for each rectangle is as follows: [vertex1, vertex2, vertex3, vertex4] with vertexi = [RAi, DECi] in degrees.
The models are publicly available at http://miles.iac.es and are based on the MILES empirical library (Sánchez-Blázquez et al. 2006; Falcón-Barroso et al. 2011).

Because of the reported degeneracy between stellar metallicity and velocity dispersion when fitted simultaneously using full-spectral fitting techniques (Sánchez-Blázquez et al. 2011), we fix the stellar kinematics of the STECKMAP run to the pPXF values. Throughout all these steps we make use of the MILES\textsuperscript{4} models (base models, following the MILES stars chemical pattern) generated using the BaSTI (Pietrinferni et al. 2004) isochrones (Vazdekis et al. 2015). The recovered SFH and corresponding errors are computed following Ruiz-Lara et al. (2018b), i.e. by combination of 12 different solutions scanning the whole STECKMAP parameter space (errors from a set of 25 Monte Carlo simulations in each of the 12 individual solutions). Thus we minimise the impact of the STECKMAP input parameters that might, somehow arbitrarily, affect the final solution. We should highlight that this technique has been proven successful at replicating the SFH recovered from the analysis of deep colour-magnitude diagrams from the Hubble Space Telescope (Ruiz-Lara et al. 2015), in particular using OSIRIS long slit data of similar quality as the one studied here (Ruiz-Lara et al. 2018b).

This analysis allows us to obtain its stellar kinematics and characterise its stellar content. We obtain a systemic velocity of \(1845 \pm 46\) km/s and \(1784 \pm 55\) for the inner and intermediate regions of [KKS2000]\textsuperscript{04}, in general agreement with the two previous determinations: Danieli et al. (2019) found a value of \(1805 \pm 1.1\) km/s, whereas Emsellem et al. (2018) state \(1792_{-1.8}^{+1.4} \pm 0.2\) km/s. Unfortunately, the low spectral resolution of our observational setup hampered the reliable determination of the stellar velocity dispersion of the system (see Emsellem et al. 2018; Danieli et al. 2019) as well as a more precise measurement of the velocities. Regarding the possible presence of ionised gas in the spectrum, GANDALF was not able to detect any gaseous contribution to the observed spectrum with the required signal, suggesting that there is no ongoing star formation in [KKS2000]\textsuperscript{04}. This technique has been proven successful at replicating the SFH recovered from the analysis of deep colour-magnitude diagrams from the Hubble Space Telescope (Ruiz-Lara et al. 2015), in particular using OSIRIS long slit data of similar quality as the one studied here (Ruiz-Lara et al. 2018b).
$2 \times 10^{5-6} M_\odot$, which is compatible with the mass expected from stellar evolution ejecta (around 1% of the stellar mass, i.e. $6 \times 10^4 M_\odot$).

Figure 3 shows the STECKMAP fits (red) and the observed spectra (black) for the inner ($R < 1/4 R_e$) and intermediate ($1/4 R_e < R < 1/2 R_e$) parts of the galaxy. The fit is good given the quality of the spectrum and the systematic errors affecting the data reduction of such faint object (residuals always below 7% and within the spectral noise given the S/N of the spectra, shaded green areas in the figure). The initial mass fractions as a function of age for the inner (blue) and intermediate regions (red) are displayed in Fig. 4. The bulk of the [KKS2000]04 population ($\sim 90\%$ in mass) is older than 5 Gyr, consistent with having little or no stars younger than 4-5 Gyr. Given the predominance of old ages (where present to initial mass transformations are almost constant according to the MILES models mass evolution), the difference between initial and present mass fractions is accounted for by the errors. The average age is $8.7 \pm 0.7$ Gyr ($8.6 \pm 1.0$ Gyr for the intermediate radius). The metallicity is basically constant with an average value of [M/H] $\sim -1.18 \pm 0.05$ dex for the inner parts and $-1.1 \pm 0.1$ dex for the intermediate region. So, we can conclude that the SFH does not change over the analysed radial range, and thus, no radial change in age or metallicity is found. Table 2 summarises the main findings from the analysis of the two integrated spectra coming from the two regions under study.

Figure 3. Inner (top panel) and intermediate-radius (bottom panel) observed, integrated spectra (black) for [KKS2000]04. The model spectra from STECKMAP is shown in red together with the residuals in green. The shaded grey area depicts a spectral region not considered in the fit as it is an artefact in the OSIRIS CCD found in all slit configurations (see text for details). The shaded green area represents the expected residuals (noise) taking into account the S/N of the analysed spectra.

Figure 4. Recovered initial mass fraction as a function of age for the inner (blue, $R < 1/4 R_e$) and intermediate (red, $1/4 R_e < R < 1/2 R_e$) parts of [KKS2000]04. Error bars are computed taking into account different tests using STECKMAP scanning the whole input parameter space.

4 DISCUSSION

[KKS2000]04 has received a lot of attention after the claims by van Dokkum et al. (2018c) that it lacks dark matter. Currently, most of the efforts focused on this galaxy concentrate on estimating its dynamical mass (using the GC system or the main body stellar velocity dispersion; e.g. van Dokkum et al. 2018c; Fensch et al. 2018; Emsellem et al. 2018; Martin et al. 2018; van Dokkum et al. 2018b; Emsellem et al. 2018; Danieli et al. 2019) and a better determination of its distance (e.g. Trujillo et al. 2019; van Dokkum et al. 2018d; Blakeslee & Cantíllo 2018; Fensch et al. 2018). Within this context, in this work we expand on the current knowledge on this galaxy with new spectroscopic data gathered with the GTC telescope.

A more robust characterisation of the GC system around this galaxy is one of the likely solutions to assess its apparently anomalous nature, improve the determination of the dynamical mass of the system as well as delimit the distance measurement. Trujillo et al. (2019), after a careful inspection of HST images of [KKS2000]04, propose 8 new GC candidates of which one (T3) has already been confirmed and another one ruled out (T7, Emsellem et al. 2018). The addition of this new GC to the list of confirmed GCs [KKS2000]04 as well as three PN candidates also obtained the stellar velocity dispersion of the [KKS2000]04 main body. In both cases the velocity dispersion that they obtain ($\sigma_{GC,PN} = 10.5^{+4.0}_{-2.2}$ km/s; $\sigma_\star = 16.3^{+5}_{-2}$ km/s) is above those found by van Dokkum et al. 2018c (using the GC system, $\sigma_{GC} = 7.8^{+5.2}_{-2}$ km/s) and Danieli et al. 2019 (via the integrated spectrum of the main body, $\sigma_\star = 8.4^{+2.1}_{-0.9}$ km/s). In this work, we confirm the membership of 5 GCs (previously analysed in the literature) as part of this system. In addition, two new PN candidates are proposed, increasing the number of point sources in this system by 2. Unfortunately, the low spectral resolution of the data and the ob-

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5 We have used Eq. (12) in Olmo-García et al. (2017) with the galaxy at 13 Mpc, the electron density in the range 10-100 cm$^{-3}$, and an electron temperature of $10^4$ K.
observational setup prevent us to measure velocities with the needed accuracy as to further constrain the dynamical mass of [KKS2000]/04, but serve as starting point for follow-up observations.

The discovery of new PNe goes beyond the simple fact of adding new independent measurements to the velocity dispersion computation. Fensch et al. (2018) use the luminosity-specific PN number ($\alpha = N_{PN}/L_{bol}$) to claim that the PN formation rate of [KKS2000]/04 is similar to other galaxies. Following similar reasoning\(^6\), and given the number of assumptions made, the addition of two more PNe (still to be confirmed) would place the $\alpha$ parameter in the range between $4 \times 10^{-7}$ to $8 \times 10^{-6}$, still compatible with a typical metal-poor, old stellar system (Buzzoni, Arnaboldi & Corradi 2006). If these two new PNe are confirmed as such\(^7\), the measurement of their luminosity would allow to improve the sampling of the PNLF, which could potentially result in another independent constraint to the distance to the galaxy. Unfortunately, the lack of spatial resolution in the OSIRIS dataset makes such detailed measurements impossible due to the inability to pinpoint the exact location of the sources. However, a simple comparison of the light that we detect for PN3 and the new PN4 (observed in the same slit configuration), allowed us to infer that the flux ratio between PN4 and PN3 is $0.83^{+0.02}_{-0.12} (F_{PN4}/F_{PN3})$. Thus, although PN4 could potentially help to better constrain the PNLF, its faintness hinders its use to further delimit the distance to [KKS2000]/04 using the bright abrupt cut-off of the PNLF (Ciardullo 2012).

Fensch et al. (2018) also provided the first spectroscopic determination of the age and metallicity of [KKS2000]/04 ($8.9 \pm 1.5$ Gyr and $\langle M/H \rangle \sim -1.07 \pm 0.12$). These values are in perfect agreement with the ones that we derive for its inner ($8.7 \pm 0.7$ Gyr and $\langle M/H \rangle \sim -1.18 \pm 0.05$ dex) and intermediate-radius ($8.6 \pm 1.0$ Gyr and $\langle M/H \rangle \sim -1.1 \pm 0.1$ dex) parts. These age and metallicity determinations, together with Figure 14 in Trujillo et al. (2019), question the validity of using the surface brightness fluctuations (SBF) method to estimate the distance to this galaxy. The predicted SBF ($\langle M_{s14} \rangle$) for both, Padova00 (Girardi et al. 2000) and BaSTI (Pietrinferni et al. 2004), stellar tracks in this range of age and metallicity deviate significantly from the Blakeslee et al. (2010) relation between $\langle M_{s14} \rangle$ and colour. Several other SBF calibrations can be found in the literature credible only within certain colour ranges (Cantiello et al. 2018; Carlsten et al. 2019) that should be used accordingly with the observed datasets.

Apart from the average stellar age and metallicity of [KKS2000]/04, which is also in excellent agreement with previous determinations for UDGs (Kadowaki, Zaritsky & Donnerstein 2017; Gu et al. 2018; Pandya et al. 2018; Ruiz-Lara et al. 2018a; Ferré-Mateu et al. 2018), the SFH recovered for this galaxy here (see Fig. 4) resembles those of the UDGs with known SFHs in the Coma cluster (Ruiz-Lara et al. 2018b; Ferré-Mateu et al. 2018). In the case of the Coma UDGs, their structural and stellar population properties were interpreted as the outcome of the combination of internal processes and environmental effects within the cluster (Yozin & Bekki 2015; Amorisco & Loeb 2016; Di Cintio et al. 2017). The similarity between the [KKS2000]/04 SFH and those of Coma UDGs might suggest that similar processes were also important in [KKS2000]/04, with the lack of younger stars pointing towards a halt of the star formation of this system long ago. In particular, ram pressure stripping and starvation might produce such an effect by: i) removing gas from this system or accelerating the use of the gas reservoir; ii) inhibiting the subsequent formation of stars; and iii) permitting the system to evolve passively until it acquires the current properties (Román & Trujillo 2017; Trujillo et al. 2017).

In fact, the claimed lack of dark matter in [KKS2000]/04 and its large peculiar radial velocity (regardless of the distance) have supported the hypothesis of this system being a tidal dwarf galaxy (TDG, Duc & Mirabel 1998; Duc et al. 2014; Lane, Salinas & Richtler 2015; van Dokkum et al. 2018c; Fensch et al. 2018). However, Trujillo et al. (2019) already analysed and discarded this possibility based on the absence of gas in this system, its average stellar age and metallicity, dynamical mass, environment, and numerical simulations predictions. The recovered SFH for this system reinforces those claims. [KKS2000]/04 completely stopped forming stars $\sim 2$ Gyr ago, although uncertainties are consistent with being a quiescent galaxy since $\sim 4$ to 6 Gyr ago (when $\sim 90\%$ of its mass was already in place). The large initial mass that [KKS2000]/04 should have had in order to survive tidal stripping for that long (Klessen & Kroupa 1998) plays against a tidal origin for [KKS2000]/04 if it was not embedded in a massive dark matter halo: a TDG with the [KKS2000]/04 properties and no dark matter should have been disrupted long ago (Ploeckinger et al. 2018). Apart from that, the location of [KKS2000]/04 in the stellar mass-metallicity plane is fully compatible with it being a dwarf galaxy (Fensch et al. 2018), not falling in the TDG region.

\footnotesize

\begin{center}
\begin{tabular}{cccccc}
\hline
Region & $S/N$ (pixel$^{-1}$) & V (km/s) & LW Age (MW) (Gyr) & LW $\langle M/H \rangle$ (MW) (dex) \\
\hline
R $< 1/4R_e$ & 43 & 1845 $\pm$ 46 & 8.7 $\pm$ 0.7 (9.8 $\pm$ 0.5) & $-1.18 \pm 0.05$ (1.20 $\pm$ 0.07) \\
1/4R_e $< R < 1/2R_e$ & 21 & 1784 $\pm$ 55 & 8.6 $\pm$ 1.0 (9.8 $\pm$ 0.9) & $-1.1 \pm 0.1$ (1.2 $\pm$ 0.1) \\
\hline
\end{tabular}

\textbf{Table 2.} Parameters derived for the two analysed regions. (3) Heliocentric-corrected velocity computed using pPXF; (4) and (5) average age and metallicity estimations (both, light and mass-weighted) from the SFH recovered combining all STECKMAP tests.
\end{center}

\footnotesize

\(^6\) Assuming that the detected PNe belong to the brightest 2.5 mag of the PNe luminosity function (PNLF), Fensch et al. (2018) proposed that $\alpha = 10 \times N_{PN, 2.5}/L_{bol}$, with $L_{bol}$ ranging between $6 \times 10^{48}$ and $10^{49}$ L$_{\odot}$.

\(^7\) Quick inspection of the MUSE datacube analysed in Emsellem et al. (2018) and Fensch et al. (2018) does not show clear evidence of the presence of these two candidate PNe (E. Emsellem and J. Fensch, private communication).
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