Stellar populations with MEGARA: The inner regions of NGC 7025

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Received 29 July 2021 / Accepted 11 October 2021

ABSTRACT

Context. This paper aims to determine the capabilities of the MEGARA spectrograph at the Gran Telescopio Canarias (GTC), which is an optical integral-field unit, for studying stellar populations. We also aim to exploit its combination of high spectral (R ∼ 6000, 12 000 and 20 000) and spatial (0.62″) resolution within its 12′′×11′′3 field of view. We do this by analysing the commissioning data of the nearby S0a galaxy NGC 7025.

Aims. We establish a systematic method through which we can determine the properties of the stellar populations in the observations made with MEGARA, more specifically, within the MEGADES legacy project. For this paper in particular, we determine the properties of the stellar populations of NGC 7025.

Methods. We used MEGARA observations of galaxy NGC 7025 that were taken during the commissioning phase of the instrument. We applied different approaches to estimate the properties of the stellar populations with the highest possible certainty. In addition to the specific study of NGC 7025 and in the context of the MEGADES survey, we have carried out a number of tests to determine the expected errors (including potential biases) in these star formation history (SFH) derivations as a function of these parameters, namely spectral setup, signal-to-noise ratio, σ, and the SFH itself.

Results. All the studies we conduct (both full spectral fitting and absorption line indices) of the stellar populations of NGC 7025 indicate that the stars that form its bulge have supersolar metallicity and considerably older ages (∼10 Gyr) in general. Using three different combinations of MEGARA spectral setups, we determined that the bulge of NGC 7025 has smild negative mass-weighted age gradient. For the more detailed SFH, our results indicate that in addition to a rather constant star formation at early epochs, a peak in the formation history of the stars in the bulge is also found 3.5–4.5 Gyr ago. This partly explains the mass-weighted age gradients we measured.

Conclusions. The scenario presented in NGC 7025 is that of an isolated galaxy under secular evolution that about 3.5–4.5 Gyr ago likely experienced a minor merger (mass ratio 1:10) that induced an increase in star formation and also perturbed the morphology of its outer disc. In addition to these specific results for NGC 7025, we report different lessons learned for the ongoing exploitation of the MEGADES survey with the GTC, such as the need to obtain combined observations in the LR-B + LR-V setups and a signal-to-noise ratio of at least 20 per Å.

Key words. galaxies: bulges – galaxies: evolution – galaxies: stellar content – techniques: imaging spectroscopy – instrumentation: spectrographs

1. Introduction

The study of stellar populations provides vital information about the processes that have shaped the galaxies from their formation to the present day. Availability of spatially resolved information about the age and metallicity of stars, both radially and in two dimensions, enables us to investigate the assembly of the different parts of galaxies. The different mechanisms that contribute to the formation and evolution of galaxies (monolithic collapse, major and minor galaxy mergers, secular processes, etc.) leave a distinct imprint on the 2D photometric and chemodynamical properties of galaxies, and through the latest developments in instrumentation, we are ready to further explore their roles.

One of these latest instrumental developments is the Multi-Espeñógrafo en GTC de Alta Resolución para Astronomía (MEGARA), a new optical integral-field unit (IFU) and multi-object spectrograph (MOS) of the 10.4 m Gran Telescopio Canarias (GTC; Gil de Paz et al. 2018; Carrasco et al. 2018). In this paper we use commissioning observations with the MEGARA IFU, which covers a region of 12.5 × 11.3 arcsec2, to explore the 2D stellar content of the bulge component of the nearby S0a galaxy NGC 7025. The 567 hexagonal fibres encompass the central 4.375 × 3.955 kpc2, assuming a sampling scale of 0.350 ± 0.001 kpc arcsec−1 (Rizzo et al. 2018).

In addition to providing clues about the SFH of the central regions of early-type spiral galaxies, the analysis of the stellar
populations in NGC 7025 constitutes a pilot study that will help us to determine what we can learn from the ongoing MEGARA guaranteed time observations that are being obtained as a part of the MEGARA Galaxy-Disks Evolution Survey (MEGADES; Chamorro-Cazorla et al., in prep.). The first stage of this project encompasses the analysis of the central regions of 50 nearby galaxies. Upon completion, the MEGADES legacy project fully exploits 400 hours of MEGARA observations. Currently, the inner regions of 41 galaxies have already been observed for ~130h, including both guaranteed time observations and three related open-time programs (GTC153-18B, GTC147-19A, and GTC117-19B). The initial goal with MEGADES is to provide a detailed study of the inner regions of nearby disk galaxies, both in terms of their spectrophotometric and chemical evolution and their dynamical characterisation, by disentangling the contribution of in situ and ex situ processes to the history of star formation and effective chemical enrichment of these regions. At a later stage, we will extend this study further out in galactocentric distance.

In addition to the study of their stellar populations and chemical enrichment, the dynamical characterisation of these inner regions will also allow us to identify and study potential galactic winds (GWs) that may be found in these regions. GWs constitute an important mechanism for redistributing dust and metals both in galaxies and towards the intergalactic medium (Veilleux et al. 2005). This mechanism has also been invoked to reproduce the scale relations observed in galaxies (Dutton & van den Bosch 2009), as well as to understand the apparent discrepancies between the theoretical and observed luminosity functions (Springel & Hernquist 2003) and to understand the evolution of galaxies (especially of high-redshift objects) through the green valley (Hopkins et al. 2008).

In order to carry out this pilot study for MEGADES, we used data taken during the commissioning of the MEGARA instrument of the galaxy NGC 7025. This galaxy is classified as an unbarred S0a galaxy, and it was among the first objects observed with the MEGARA IFU. We selected this galaxy from the MEGADES sample because of the presence of residual interstellar Na I that was previously detected with the CALIFA survey (Sánchez et al. 2012). The main incentive to study galaxies with this feature is our interest of studying galaxies that are possible candidates for hosting GWs. NGC 7025 shows bar-like non-circular flows, although photometrically at least, it is not considered to be a barred galaxy (Holmes et al. 2015). In addition, NGC 7025 is considered as a merger remnant with evident tidal features, but it is relatively isolated (Barrera-Ballesteros et al. 2015). In Fig. 1 we present a false-colour DECam Legacy Imaging Surveys of NGC 7025 (Dey et al. 2019) where we highlight two clearly visible dust-lanes/tidal features. While the innermost of these features clearly resembles a dust lane with the NE half of the disk being in the foreground, the outermost feature appears as a more diffuse tidal feature. Along with its isophotal twist, this caused Barrera-Ballesteros et al. (2015) to classify this object as a merger remnant. The photometric and kinematic analyses by Dullo et al. (2019) have shown that the bulge is a fast rotator with a low Sérsic index $n \sim 1.80$. However, a detailed stellar population analysis of the bulge is crucial if we are to properly understand this galaxy’s formation.

Throughout this paper, we assume a cosmological model with $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_{\Lambda} = 0.7$ and $\Omega_m = 0.3$. From the redshift of the galaxy ($z = 0.0172$; Rizzo et al. 2018), we obtain a luminosity distance of 74.7 Mpc for NGC 7025.

### 2. Observations

#### 2.1. MEGARA spectroscopy

MEGARA provides good enough spatial resolution at the distance of our object for the purpose of the objectives of the MEGADES survey. Each fibre captures the light of an hexagonal spaxel circumscribed in a circle of 0.62 arcsec in diameter (217 pc at the distance of NGC 7025). Additionally, apart from the 567 fibres covering the inner regions of our target, the disk being in the foreground, the outermost feature appears as a more diffuse tidal feature. Along with its isophotal twist, this caused Barrera-Ballesteros et al. (2015) to classify this object as a merger remnant. The photometric and kinematic analyses by Dullo et al. (2019) have shown that the bulge is a fast rotator with a low Sérsic index $n \sim 1.80$. However, a detailed stellar population analysis of the bulge is crucial if we are to properly understand this galaxy’s formation.

### Table 1. Global properties of NGC 7025.

| Property   | NGC 7025 | References |
|------------|----------|------------|
| Morphology | S0a      | (1)        |
| Redshift   | 0.0172 ± 0.0001 | (2)        |
| RA (J2000) | 21°07′47.34″ | (3)        |
| Dec (J2000)| +16°20′09″1″ | (3)        |
| $\log(M_{\star}/M_\odot)$ | 11.26 | (4) |
| $\log(M_{\text{bul}}/M_\odot)$ | 10.65 | (5) |
| $r_e (")$ | 23.0 | (6) |
| $r_e (")$ | 4.68 | (5) |
| $m_b$ | 12.85 | (1)/(7) |
| $M_{\text{bul}}$ | ~22.59 | (5) |
| $D_L$ (Mpc) | 74.7 ± 0.9 | (2) |
| PA (deg) | 44.78 | (2) |
| $L_{\text{IR}}$ (erg s$^{-1}$) | $36.1 \times 10^{39}$ | (8) |

### References

(1) García-Benito et al. (2015). (2) Rizzo et al. (2018). (3) NASA/IPAC Extragalactic Database. (4) Barrera-Ballesteros et al. (2015). (5) Dullo et al. (2019). (6) Sánchez-Blázquez et al. (2014). (7) Sánchez-Blázquez et al. (2014). (8) Gomes et al. (2016).
the MEGARA IFU pseudo-slit includes 56 additional fibres that are distributed in 8 different bundles placed between 1.75–2 arcmin around the IFU and that are devoted to measuring the sky background simultaneously to the observations. The spectral range that the MEGARA instrument covers ranges from 3653 to 9700 Å with low (LR), medium (MR), and high spectral (HR) resolutions of $R \sim 6000$, 12,000, and 20,000, respectively, through the use of 18 different volume phase holographic (VPH) gratings that are available to both the IFU and MOS modes.

In preparation for the optimisation of the MEGADES survey, we carried out commissioning observations of NGC 7025 that were taken with all 18 MEGARA VPHs. After the initial analysis conducted by Dullo et al. (2019), we decided for both this work and for the observations of the inner regions of the MEGADES sample to focus on the low spectral resolution (LR; $R \sim 6000$) VPHs because they allow us to cover a wider spectral range with still good enough spectral resolution. In addition, the high central velocity dispersion of this galaxy, $\sigma \sim 250 \text{ km s}^{-1}$ (Dullo et al. 2019) limits the advantage (in terms of information content) of using MR and HR VPHs. For the study of the disks of the MEGADES sample, especially for low-inclination galaxies, we might have to also rely on medium (MR; $R \sim 12000$) and high-resolution (HR; $R \sim 20\,000$) data.

We used the LR VPH observations obtained with the four bluest LR VPH gratings of all those available in MEGARA. These VPHs are VPH405-LR (henceforth LR-U), VPH480-LR (LR-B), VPH570-LR (LR-V), and VPH675-LR (LR-R) (see Fig. 2 for the different NGC 7025 spectra taken with these instrument setups and the concatenation of all of them). The data for each of these VPHs are shown in Table 2. The selection of these VPHs was motivated by the fact that redwards of LR-R, telluric absorptions and the residuals from bright sky emission lines prevent us from improving the results of our stellar population analysis at the signal-to-noise ratios reached by our data. Although all four LR VPHs were analysed (see Appendix A), we mainly focused on the LR-B and LR-V VPHs for the detailed study of the stellar populations in NGC 7025 because these setups yield better signal-to-noise ratios for a given exposure time (compared to LR-U) and include multiple spectral features that are sensitive to the star formation and chemical histories (compared to the more limited information content in this regard of the LR-R spectral range). Nevertheless, the addition of LR-R data will be key for the study of GWs in emission, which is one of the main objectives of MEGADES as a survey (Chamorro–Cazorla et al., in prep.).

The spectra were obtained on the night of 2017 August 1. For LR-U, LR-B, and LR-V, we took three exposures of $3 \times 900 \text{ s}$, and for LR-R, we took three exposures of $3 \times 600 \text{ s}$. The observing log for these observations is given in Table 3. We used different standard stars for the flux calibration. In particular, we employed spectra from the standard star BD+33 26 42 for the flux calibration of LR-B ($3 \times 60 \text{ s}$ exposures), LR-V ($3 \times 30 \text{ s}$ exposures), and LR-R ($3 \times 15 \text{ s}$ exposures). For the flux calibration of LR-U, we used data from the standard star BD+174708 ($3 \times 15 \text{ s}$ exposures). These spectra were obtained on the night of 2017 July 30. We also made use of the corresponding calibration data, including Th-Ne and Th-Ar arc-lamps, halogen lamps, and twilight spectra.

2.2. Data reduction

Data reduction was performed using the MEGARA data reduction pipeline version 0.6.1 (Pascual et al. 2018, DRP hereafter). This is described in Castillo-Morales et al. (2020) for the MEGARA 2D spectroscopic observations.

The first step, before executing any of the MEGARA DRP reduction recipes, is to cleanse the images of cosmic rays. Although three different raw images were initially obtained for each setup with the idea of removing cosmic rays through the median combination of these images, some affected pixels still survived to this procedure. In a second step, we used the CLEANEST software (Cardiel 2020) to interactively interpolate the remaining bad pixels. After this step, we continued with the data reduction using the DRP. Firstly, the bad pixels are masked and the bias subtraction is performed. This bias subtraction is done by using a master bias obtained with the MegaraBiasImage task. After this step is completed, the path of the light coming from each fibre is traced through the CCD using the DRP tasks MegaraTraceMap and MegaraModelMap on a series of consecutive flat halogen lamp frames. After we trace the spectra, the wavelength calibration is carried out with the routine MegaraArcCalibration, using ThAr or ThNe arc-lamp frames depending on the wavelength range, to an accuracy of 0.03 Å and 0.01 Å (rms), respectively. We then correct for variations in sensitivity, from blue to red and global (i.e., from fibre to fibre), with the MegaraFiberFlatImage task, and we implement an illumination correction with the MegaraTwilightFlatImage task, using halogen and twilight flat frames. The absolute flux calibration is performed using the standard star frames mentioned before, whose reference data were extracted from the CALSPEC calibration database (Bohlin et al. 2020). To determine in which area of the detector the standard star is located, we use the MegaraLcbAcquisition routine. After this position is determined, we use the task MegaraLcbStdStar along with the La Palma extinction curve published by King (1985) to produce the sensitivity curve. Then we run the MegaraLcbImage recipe, whose final result is a set of two row-stacked spectra (henceforth RSS) FITS frames. The two RSS FITS files produced by MegaraLcbImage have 623 spectra with a common flux calibration and wavelength solution, plus a constant reciprocal dispersion for all fibres. One of these two frames includes the sky background spectrum, while the other is obtained after subtracting the median spectrum of all 56 sky fibres that are located at the edges of the MEGARA IFU+MOS field of view.

3. Analysis

Traditionally, the approach taken to study stellar populations in nearby galaxies has been to analyse different spectral features along their semi-major axis, using long-slit spectroscopy. Bearing this in mind, but taking advantage of the 2D spectroscopic information afforded by the MEGARA IFU, we drew elliptical rings around the central point of NGC 7025 and extracted their spectra to derive radial spectral information of the galaxy. The centre of these rings is the brightest fibre for each observation. We considered a constant ellipticity of 0.21 for all of them and ordered by the MEGARA IFU, we drew elliptical rings around the central point of NGC 7025 and extracted their spectra to derive radial spectral information of the galaxy. The centre of these rings is the brightest fibre for each observation. We considered a constant ellipticity of 0.21 for all of them and a position angle of 46.78° (Dullo et al. 2019). Each of the rings has a width of 1 arcsec. The analysis of the spectra of NGC 7025 using elliptical annuli not only preserves most of the information content on the spatial variation of the stellar population properties, but also provides improvement in signal-to-noise ratios over both the long-slit and pixel-by-pixel 2D studies. It therefore reduces uncertainties.

1 DOI: 10.5281/zenodo.1974953
2 https://www.stsci.edu/hst
In Fig. 2 we plot the spectra for every elliptical ring extracted from our observations with the MEGARA IFU for the different low spectral resolution VPHs we analysed. The flux of the spectra is shifted vertically so that all spectra can be properly displayed. The signal-to-noise ratios of the spectra was estimated using the residuals of the regions that best fit in these spectra by the Penalized Pixel-Fitting software (pPXF) by Cappellari & Emsellem (2004) (see also Cappellari 2017), and they vary across VPHs. For LR-U, we reach a signal-to-noise ratio per angstrom of ∼36, which is the lowest of all. This is because MEGARA is least sensitive in this spectral range. For the remaining VPHs, the signal-to-noise ratio values we derived are significantly higher, averaging 180 for LR-B, 250 for LR-V, and 140 for LR-R. Within each VPH setting, the spectra do not reveal any obvious difference, possibly because the region covered by the MEGARA IFU does not reach beyond the NGC 7025 bulge, so that the stellar populations are rather homogeneous.
Table 2. MEGARA VPH characteristics.

| VPH | Spectral coverage [Å] | Rec. disp. [Å pix\(^{-1}\)] | \(\Delta \lambda_{\text{FWHM},c}\) [Å] |
|-----|------------------------|-----------------------------|--------------------------|
| LR-U | 3728–4342              | 0.186                       | 0.67                     |
| LR-B | 4351–5251              | 0.230                       | 0.79                     |
| LR-V | 5166–6176              | 0.270                       | 0.94                     |
| LR-R | 6158–7288              | 0.310                       | 1.11                     |

Notes. (1) VPH name; (2) wavelength coverage common to all fibres (in Å); (3) reciprocal dispersion (in Å pix\(^{-1}\)); (4) spectral resolution at the corresponding central wavelength of each setup.

Table 3. NGC 7025 MEGARA observing log.

| VPH | Date            | Exp. time [s] | Seeing (") |
|-----|-----------------|---------------|-------------|
| LR-U | 01 Aug. 2017   | 3 × 900 s     | 0.6 ± 0.2   |
| LR-B | 01 Aug. 2017   | 3 × 900 s     | 0.6 ± 0.2   |
| LR-V | 01 Aug. 2017   | 3 × 900 s     | 0.6 ± 0.2   |
| LR-R | 01 Aug. 2017   | 3 × 600 s     | 0.6 ± 0.2   |

Notes. (1) VPH name; (2) observing date; (3) total number of exposures and time per exposure (in seconds); (4) seeing, as provided in the GTC log files (in arcsec).

Fig. 3. LR-V continuum intensity distribution in the bulge of NGC 7025 after averaging the spectral range between 5600 and 5870 Å. The elliptical rings from which the galaxy spectra are extracted (see the text for further detail) are overplotted. Flux units are Jy.

In Fig. 3 we show a continuum image of NGC 7025 taken with the MEGARA IFU. This image was obtained by collapsing the LR-V spectra within the range between 5600 and 5870 Å (see Table 2 for the spectral coverage of each VPH). We also show the elliptical rings from which we extracted the spectra that we used to perform the radial study of the stellar populations in NGC 7025.

3.1. Stellar population synthesis models

The stellar population synthesis models we used for this study are those that are included in the MILES simple stellar population (SSP) grid (Vazdekis et al. 2010), which are based on the Padova+00 stellar libraries (Sánchez-Blázquez et al. 2006 and Falcón-Barroso et al. 2011). These models cover the range 3525–7500 Å at 2.5 Å spectral resolution (full width at half maximum; FWHM). Although the spectral resolution of MEGARA is better than the spectral resolution of these models, the mismatch in the case of NGC 7025 does not have much of an impact because the relatively high velocity dispersion of inner regions of this galaxy broadens the lines to values greater than the spectral resolution of the models anywhere within the MEGARA IFU field of view. These MILES SSPs cover a range in age from 0.063 Gyr to 17.78 Gyr and in metallicity from −2.32 to +0.22 (M/H). The ages of the SSP models extend beyond the age of the universe in order to mitigate possible edge effects at very old ages (Gil de Paz & Madore 2002). We used a unimodal initial mass function (IMF hereafter) with a logarithmic slope of 1.3 (Salpeter 1955), as suggested by Dutton et al. (2013) for massive spiral galaxies. These SSP models will be broadened to match the velocity distribution of the stars in the observed spectra. For the spectral indices (Sect. 3.2), this is achieved by making use of a Gaussian kernel, whereas for the spectral analysis to be performed with pPXF (Cappellari 2017), a Gauss-Hermite method is employed (see more details in Sect. 3.3).

3.2. Spectral line indices

As an initial approach to the problem of stellar population modelling, we carried out an analysis based on spectral indices, as this is the simplest (and also the most classic) and serves as a reference for what we can expect in later more complex analyses. We examined different indices covering a wide spectral range in order to evaluate the impact of different wavelengths and specific features on the age and metallicity derived for the stellar populations of the galaxy.

Fitting a Gaussian kernel to our data, we measured 11 different spectral indices. Seven of them were taken from Worthey et al. (2014), namely Hβ, Hα, Fe4383, C4668, CN1, Mgb, and Ti4296. The \(\langle \text{Fe} \rangle = (\text{Fe}5270+\text{Fe}5335)/2\) index was taken from González (1993), while the Ca3934, Fe4045, and Mg4480 indices were given by Rodríguez-Merino et al. (2020). Spectral index errors were computed using the line flux uncertainty obtained as in Tresse et al. (1999). In Fig. 4 we show the 2D maps for the \(\langle \text{Fe} \rangle\) index (left panel) and its error (right panel). Only measurements whose error is smaller than 0.5 Å are shown in the left panel. The comparison between the indices measured and those predicted by the SSP models (at the same level of broadening) are presented in Sect. 4.1.

3.3. Stellar population and kinematical fitting

We performed a full spectral fitting analysis of our spectra using pPXF by Cappellari (2017). This software enables the extraction of the stellar kinematics and stellar population properties by means of analysing the absorption spectrum of galaxies or specific regions within galaxies, including individual spaxels. In order to ensure that the emission lines do not affect the fitting of the absorption features, we masked all the emission lines in the spectra as well as absorption lines of interstellar origin, such as NaD (see Fig. 5). We also masked regions affected by telluric absorptions or residuals from bright sky lines (e.g., [O I]\(\lambda\)5577 Å).

For our fittings, we followed Kacharov et al. (2018) and set pPXF to use tenth-order both additive and multiplicative polynomials and first-order regularisation with a low regularisation factor \(R = 5\). The use of these polynomials ensures that our analysis is free of any low-frequency effects that may be present in the spectra (e.g., reddening and residual blue-to-red variations not...
corrected by the data reduction). We also followed the method proposed by these authors for estimating the uncertainties in the derived stellar population properties, which is based on the wild bootstrapping method (Wu 1986). This uncertainty estimation only allows us to calculate the statistical error coming from the variance of the spectra. The effect of possible errors coming from the models themselves and the spectral libraries cannot be included as we have no prior knowledge of them. To this must be added the unknown capability of reproducing a complex star formation and chemical history of any stellar population composed from these models. Briefly, the method was applied as follows. First, we fit the spectrum with pPXF and obtained the best fit and the residuals from this initial fitting. When this initial fitting was completed, we resampled the residuals obtained previously with the wild bootstrapping method. The resampled residuals were added to the best fit to obtain a new spectrum with the errors distributed in a different way. We repeated this resampling procedure 100 times for each spectrum we analysed and fit these new spectra with the resampled errors. The set of 100 best-fitting solutions yields the probability distributions of the derived properties. For the derived kinematical parameters, pPXF already provides direct robust error estimates.

In an attempt to understand the limitations of our analysis, we made extensive tests with pPXF using mock spectra. We show the results of all these tests in Appendix A. Following the results from our rigorous test, and together with the assessment of the amount of information that can be extracted from each VPH in terms of absorption features as well as the relative sensitivity of the VPHs, we decided to focus on the results of the analysis conducted on the combination of LR-B+LR-V data. When the spectra of both observations are concatenated, it has first to be verified whether they have the same pointing. In the case of LR-B and LR-V, the centre of the galaxy is shifted one spaxel away from the other. Because we do not have the same pointing, we can only concatenate the spectra extracted from the elliptical regions explained above in Sect. 3. When we have the spectra...
separately, we identify a region of the spectrum that has no features in the region in which the two VPHs overlap in wavelength. Then we match the two spectra using the flux ratio at that point. This has no impact on our analysis because pPXF subtracts the stellar continuum from the spectra with polynomials. The last step is to resample the whole new spectrum, considering that the original observations have different resolutions, to the resolution of the spectrum with the lowest resolution. We also show the results we obtained for each setup individually to highlight the impact of the spectral range under study on the stellar population properties we derived.

4. Results

4.1. Spectral line indices

All the indices, including the predictions from reference grid of SSP models (see Fig. 6), were computed based on the definitions of these indices by Worthey et al. (2014), Tang et al. (2014), and Rodríguez-Merino et al. (2020). To create a reference grid that was as close as possible to the NGC 7025 data, we broadened the MILES SSP models with a Gaussian kernel to match the velocity dispersion of 250 km s\(^{-1}\) measured by Dullo et al. (2019) on NGC 7025.

In the 2D (Fe) index map (Fig. 4), we find a deeper index (larger in absolute value) within the innermost 2 arcsec. This is true for other spectral indices as well because absorption lines are found to be deepest, in general, in the innermost regions of NGC 7025. At greater distance to these central regions, the values we obtain become somewhat higher (shallower), but noisier. This is to be expected because as the right panel of Fig. 4 shows, the errors become larger when the S/N of the galaxy declines farther away from the centre of the MEGARA IFU and the signal of the galaxy becomes fainter.

The 2D distribution shown in Fig. 4 needs to be placed into context with the help of Fig. 6, where we show the relation between the values of all indices we measured and the age and metallicity of the SSP MILES models. This figure represents the most classical approach to quantifying the variation in strength of spectral features with the properties of the stellar populations. The indices measured for each of the spectra of the elliptical rings are shown with a star. The order of the elliptical annuli follows the same colour pattern as in Fig. 2. From the innermost to the outermost, their colours are blue, orange, green, red, purple, and brown, with an increment of 1 arcsec in semi-major axis radius in between every consecutive annulus. For the central measurement (red star), this corresponds to an elliptical aperture, not an annulus, of 1 arcsec in semi-major axis radius.

Figure 6 reveals several interesting insights. First, for most indices we favour old ages and high metallicities and an overall tendency for having deeper indices in the central regions (especially for indices reaching high EW values, such as Fe, C, CN, or Mg b\(^{3}\)). However, we also find that the closest SSP model to each data point differs significantly depending on the index used. For example, we obtain SSP ages in the range 1–2 Gyr for Ca3934-Mg4480 or Fe4045-Mg4480, but ages close to 10 Gyr for (Fe)-H\(_{\alpha}\), (Fe)-Mg b, or (Fe)-Fe4383. In this regard, it seems that the bluer the index, the more sensitive it is to the presence of a young stellar population, which leads to a younger SSP age. This suggests that NGC 7025 has experienced an extended SFH, which explains the differences in the observed spectra compared to the predictions of single (in terms of age and metallicity) stellar population models. In any case, all pairs of indices we obtained are consistent with supersolar metallicities.

Another issue that we find is that in some cases, the measurements for NGC 7025 fall outside the predictions of our SSP grid for any age or metallicity considered. The reason might be that we did not include models with different \(\alpha\)-enhancement values when we created the reference grid because our default MILES SSP models (based on the Padova+100 isochrones; Girardi et al. 2000) do not incorporate multiple \(\alpha\)-enhancements. For this reason, we repeated the whole analysis procedure using models with different \(\alpha\)-enhancement values based on the BaSTI isochrones (Pietrinferni et al. 2004, 2006). Although these results are not shown in this paper, they do not solve the problem, but make it worse instead. The \(\alpha\)-enhancement models, which might reduce these offsets, effectively decrease the contribution of iron instead of increasing the abundances of the \(\alpha\)-elements.

4.2. Results from full spectral fitting

We now present the results from the stellar population analysis of NGC 7025 from the full spectral fitting method as detailed in Sect. 3.3. We recall that MEGARA FoV allows us to explore only the inner region (the central 4 × 4.0 kpc\(^2\)) of NGC 7025, so that we only probe the bulge of this galaxy (\(r_{e, bul} = 4.363; r_{e, bul} = 1.48\) kpc).

In Fig. 7 we show the age extracted from the different elliptical rings that were applied to the LR-V, LR-B, and LR-B+LR-V IFU data of NGC 7025. We employed the ChainConsumer Markov chain Monte Carlo (MCMC) Bayesian method to estimate the age gradients using the Python code from Hinton (2016). We fitted our data linearly, but with a small modification. Instead of fitting a linear relation described as \(y = mx + c\), we fitted a model such as \(y = \tan(\phi) + c\) following the recommendation by the code developer. By doing so, the prior has a more uniform distribution. The median output values for the slope [\(\tan(\phi)\)] and the y-intercepts along with their corresponding marginalised 1\(\sigma\) errors are given in Table 4.

Figure 7 shows the radial age profile for NGC 7025 from the LR-V setup. Overall, it is evident that the bulge of the galaxy has an old age (~10.5 Gyr) and a negative age gradient of ~0.93 ± 0.21 Gyr kpc\(^{-1}\). In the right panel, we show the corresponding probability distribution of the arc tangent of the slopes (see above) and y-intercepts that we obtained with the
Fig. 6. Spectral indices measured in the bulge of NGC 7025. The reference grid has been created using three different metallicities \([\text{M/H}] = -0.71, 0.00, \text{and } 0.22\) (solid blue, green, and red lines, respectively). Ages range from 1 to 17 Gyr, and the ages (in Gyr) of some of the models are marked in the plot. Stars, including their uncertainties, represent the indices measured in the spectra of the elliptical rings we extracted from NGC 7025. The rings from the innermost to the outermost radii are colour-coded blue, orange, green, red, purple, and brown.

The ChainConsumer MCMC Bayesian fitting method. This plot excludes a flat age gradient \((\phi = 0)\) with high confidence.

In the results from the analysis of the LR-B setup (middle panels of Fig. 7), two clear differences are noticeable. First, the absolute values for the mass-weighted ages of NGC 7025 are slightly different in this case \((\sim 9 \text{ Gyr})\) from those derived for LR-V, as expected from the spectral line index analysis. In addition to this, we find that the age gradient we derived, \(-0.36^{+0.24}_{-0.22}\) Gyr kpc\(^{-1}\), is shallower than that obtained for LR-V. This difference is large enough to exclude the flat age gradient solution only at a \(\sim 1-2\sigma\) level. The comparison between these results shows how delicate the spectral range of use is when the properties of composite stellar populations in galaxies are derived.

Finally, to try to shed some light on this issue, we examined what happens if we combine the LR-B and LR-V observations. Bottom panels of Fig. 7 show the results obtained with this configuration. These results (see also Table 4) are much closer to those obtained by analysing only LR-B observations than by analysing LR-V observations. Here the trend with galactocentric distance seems to flatten out farther from the centre of NGC 7025. We do not see this in the LR-B data. This could be due to the increasing effect of the spectral features present in the spectral range covered by LR-V, perhaps due to the higher signal-to-noise ratio of LR-V (compared to LR-B) at these outer radii.

These results strongly suggest that the absolute value of the age (even if it is a mass-weighted value) of a composite stellar population is markedly sensitive to the spectral range covered by the observations. However, we can rely more robustly on relative changes, such as age gradients (in our case, a flat age gradient is
The evolution of the chemical abundances of elements constitutes one of the three components of galaxy evolution, along with the spectrophotometric and dynamical evolution (Tinsley 1972). Therefore the derivation of the overall metallicity of stellar populations, together with that of the gas in its different phases, is key for the study of stellar populations and galaxy evolution in general. In addition, given the well-known degeneracy between age and metallicity in stellar populations, especially when only photometry is available (Worthey 1994), we now

Table 4. Age gradients [tan(φ)] and y-intercepts derived from different spectral setups following the ChainConsumer MCMC Bayesian method.

| MEGARA VPH | Slope [Gyr kpc\(^{-1}\)] | Intercept [Gyr] |
|------------|--------------------------|----------------|
| LR-V       | −0.93 ±0.21              | 11.41 ±0.25    |
| LR-B       | −0.36 ±0.24              | 9.33 ±0.29     |
| LR-B + LR-V| −0.31 ±0.26              | 9.27 ±0.27     |

excluded at ≥1σ confidence level in all cases). Figure 8 simultaneously displays the age gradients of the galaxy from the three VPH configurations. To remove the global offset in age between the different setups, we subtracted the value of the age measured in the central ring from all measurements. For the sake of a better visualisation, we slightly shifted the data points along the x-axis. This figure shows that within the errors, all the results we obtained agree with a mild negative age gradient. However, the need for a careful analysis in order to draw firm conclusions should be emphasised, especially when dealing with composite stellar population.

The evolution of the chemical abundances of elements constitutes one of the three components of galaxy evolution, along with the spectrophotometric and dynamical evolution (Tinsley 1972). Therefore the derivation of the overall metallicity of stellar populations, together with that of the gas in its different phases, is key for the study of stellar populations and galaxy evolution in general. In addition, given the well-known degeneracy between age and metallicity in stellar populations, especially when only photometry is available (Worthey 1994), we now
address the analysis of the (mass-weighted) stellar metallicities derived from our pPXF analysis of NGC 7025. Thus, we show in Fig. 9 the results obtained when measuring the age and metallicity in rings at different galactocentric radii from the realisations explained in Sect. 3.3. This figure shows that as anticipated from the analysis of the spectral indices (Sect. 4.1), the galaxy exhibits a supersolar metallicity distribution for the most part. When we compare these results with those we obtained for the absorption line indices, they agree best with those inferred from the iron indices (see Fig. 6). However, we should mention here that in the metallicity range between 0 (solar) and 0.22 dex, no SSP model is available, which means that all intermediate points between these two values are the result of the different weights obtained in the fitting of only a few models with discrete metallicity values. This means that we have a rather poor sampling of this area of the space of parameters. This is a relevant issue because the impact of metallicity on the spectrophotometric output of the stellar populations is not linear. Nevertheless, this factor should not have a major impact on the age related results, at least for the derivation of relative properties, because we consistently derive supersolar metallicities. Furthermore, as expected, we note a degeneracy associated with our results: a younger age can be partly compensated for by a higher stellar metallicity.

Our results for both age and metallicity are similar to those obtained by de Amorim et al. (2017) using data from the CAL-IFA survey (Sánchez et al. 2012). They were analysed with the spectral synthesis code STARLIGHT (Cid Fernandes et al. 2005).

### 4.3. Star formation history of NGC 7025

The output from our pPXF fits also allows us to reconstruct the SFH of NGC 7025 as a function of galactocentric distance using the elliptical rings as employed above. This provides us with complementary information to the one presented in Sect. 4.2, where, in order to estimate the age gradients, we used the (mass-weighted) age of all the stellar populations present in each of the regions under study. In contrast, here we can analyse the contribution of each of them to the light we observe within the FoV of the MEGARA IFU. These data can help us to determine whether we detect stellar populations in our data that were born at different epochs throughout the history of the galaxy.

We did not limit ourselves to the best-fitting weights obtained for each spectrum (from which best-fitting SFHs are derived), but also included the realisations described in Sect. 3.3 to ensure that our results reflect the impact of observational uncertainties and (age-metallicity) degeneracies. In Fig. 10 we show the average SFHs for all of these realisations, together with their uncertainties, for the observations carried out with the three different VPH setups explored in this paper. We show six different SFHs, which correspond to the six elliptical rings. Within each panel, we show in different colours the SFHs for the different MEGARA configurations: LR-B, LR-V, and LR-B+LR-V.

As for the SFH obtained from the LR-V data (green curves in Fig. 10), we find that the fractional star formation rate (SFR) progressively increases from ~4 Gyr to ~10 Gyr (in look-back time), before it plateaus at older ages and then increases again at the very old age end. As we move outwards, this rise in SFR at old ages becomes progressively less pronounced, while simultaneously, a mound of SFR at ages ~9 Gyr develops. We also find a peak in the SFR at very young ages that weakens farther from the centre of the galaxy. In addition to the little residual star formation that could be present within our MEGARA IFU pointing (see the emission-line map in Barrera-Ballesteros et al. 2015), this effect could also be due to the lack of sensitivity of the LR-V setup to intermediate ages. Thus, the LR-V spectrum of an intermediate-aged population might also be reproduced by the combination of a relatively young burst and an older population.

The age gradient reported in Sect. 4.2 can be clearly deduced from these plots as a consequence of this behaviour. In the case of the LR-B setup (blue curves in Fig. 10), the SFH is quite extended. It is rather flat between ages 3 to 13 Gyr and decreases in the last ~3 Gyr. This behaviour also causes the radial changes in the SFH to become more subtle. The only noticeable difference in between the SFH of the different rings that might cause the mild radial variation in mass-weighted age previously reported is the change in relative strength and age between the rise in SFR at ~4 Gyr and the bump at ~9 Gyr.

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**Fig. 8.** Age gradients for LR-V, LR-B, and LR-B+LR-V spectral setups. In this plot, the age of the central ring is subtracted from the remaining age measurements. The scatter points are shifted slightly on the x-axis for better visualisation. Shaded red and blue areas show confidence levels for LR-V and LR-B setups. Dashed dark and light lines also represent 1σ and 2σ confidence levels, respectively, for the LR-B+LR-V spectral setup.

**Fig. 9.** 1σ ellipses of the age and metallicity probability distributions obtained for the 100 realisations for each VPH. The order of the rings follows the same colour pattern as in Fig. 2. The blue ellipse is the innermost, and the brown ellipse is the outermost.
Fig. 10. Mass fraction (equivalent to the fractional SFR) as a function of time for the different elliptical rings analysed in NGC 7025 (ring 1 is the central region, and ring 6 is the outermost region). Each panel shows the mass fraction from the LR-B, LR-V, and LR-B+LR-V data together with the corresponding 1σ uncertainties.

The combination of the LR-B and LR-V data provides a more complete view of the SFH of the inner regions of NGC 7025 (purple curves in Fig. 10). In this case, we find that from the second elliptical region outwards, an epoch of high SFR develops at ages around 3.5–4.5 Gyr on top of a low-SFR plateau (that comes with relatively low uncertainties in fractional SFR), which starts to rise again beyond ~11 Gyr and ends with a peak at ages older than the age of the Universe. This result highlights the importance of obtaining SFHs derived from deep spectroscopic data when analysing composite stellar populations. Thus, had we considered the age gradient estimates alone, which use the mass-weighted average of the SSP ages of all the models considered, the two periods of star formation in NGC 7025 would have remained unnoticed. In this regard, the age gradients derived for each setup (and the differences reported between them in Table 4) can now be interpreted as the results of a complex history of star formation with multiple episodes of star formation and a relatively quiescent epoch in between them.

We might think that the differences between the results of the three different setups are large and that they do not behave as expected a priori. However, Fig. 10 shows that if we consider the uncertainties in each curve, the discrepancy between the different setups is not great and the results are compatible over most of the SFH of the galaxy.

5. Discussion

Once we have all the results of the study of the stellar populations in the central region of NGC 7025 we now aim to reconstruct its evolutionary history. Dullo et al. (2019) showed that the bulk of the stellar population in the bulge was formed through secular processes instead of by a major merger (this includes evidence for its fast rotation, low Sérsic index, and large-scale negative colour gradient). Our results now suggest that in addition to this early secular formation, about 3.5–4.5 Gyr ago, something occurred that caused the stellar populations in the bulge to rejuvenate, either through in situ star formation or through the accretion of stars (from the inner disk or from a companion).

NGC 7025 has traditionally been classified as an isolated galaxy (Karachentseva 1973). However, Barrera-Ballesteros et al. (2015) classified this galaxy as a merger remnant with evident tidal features. This post-merger scenario for NGC 7025 nicely fits the results we obtained here, with NGC 7025 forming stars through secular processes until 3.5–4.5 Gyr ago when a merger took place that led to a temporary increase in the star formation rate.

Regarding the morphological evidence for a past merger in the case of NGC 7025, we show in Fig. 1 a set of ellipses tracing some non-axisymmetric features. Some of them follow what appears to be obscuring dust lanes, while others resemble extended stellar tidal features, each with a different axial ratio and position angle that can be interpreted as consequence of a warp in its outer disk. Warping can occur for several reasons. One reason is a merger. The well-formed disktogether with the estimated time of the merger causes us to think that if the warp were due to a merger, it should be a minor one with a mass ratio between galaxies of 1 to 10 (Lotz et al. 2010). Interestingly, such
a minor merger could trigger an initial starburst that would cause the further heating of the gas, causing the galaxy to stop forming new stars. This is compatible with the sharp drop in SFH seen 2.5 Gyr ago in the bulge of NGC 7025. Another argument supporting this scenario is the fact that this galaxy has boxy outer isophotes (Naab et al. 2006), which can be seen in the high-contrast DECam false-colour image shown in Fig. 12. By running the IRAF task ELLIPSE on the DECam r-band image of NGC 7025, we derive $a_4/a$ and $b_4$ radial profiles (see Fig. 11). In the region in which the outer isophotes can be measured with low uncertainties (between 60–70 arcsec; see Fig. 12), we find values of $-1 \times 10^{-4}$ and $-0.2$ for $a_4/a$ and $b_4$, respectively, which is indicative of the presence of boxy isophotes.

An alternative scenario to this merger would be a fly-by encounter with another galaxy. An event of this kind could also lead to a gravitational perturbation strong enough to (1) cause a warp that might survive up to several billion years, depending mainly on the angle of incidence of the interaction (Kim et al. 2014), and (2) trigger star formation at the time of the fly-by passage. The main problem with this scenario is the fact that we do not find any certain candidate galaxy for such an encounter. The only object that could have had a close encounter with NGC 7025 about 3.5–4.5 Gyr ago is UGC 11677 (at a projected distance of 667 kpc). UGC 11677, with $m_B = 16$ mag, is two magnitudes fainter than NGC 7025, with $m_B = 14.1$ mag (Wenger et al. 2000). If it ever had a noticeable gravitational interaction with NGC 7025, it should show stronger signs of perturbation than NGC 7025 itself. However, Fig. 13 shows that UGC 11677 presents a rather regular morphology that is characteristic of a Sa-type galaxy with a prominent bulge and a relatively unperturbed edge-on disc.

6. Conclusions
We have performed a comprehensive analysis of the spectroscopic data taken with MEGARA of the inner regions of the early-type spiral galaxy NGC 7025. We measured absorption line indices and performed a full spectral fitting of these data. From these measurements we derived the SFH and mass-weighted ages at different galactocentric distances and the corresponding age gradients. Our results allow us to develop a scenario under which NGC 7025 is a galaxy that evolved secularly until about 3.5–4.5 Gyr ago, when it experienced a relatively minor merger (mass ratio 1/10) that induced an increase in star formation and perturbed the geometry of its disk and possibly finally quenched the star formation for the last 2.5 Gyr. In addition, this intermediate-age population seems to become more prominent in the outer regions of the bulge, which leads to a development of a peak in the SFH at these ages and to the mild negative age gradient we derived.
In addition to these specific results for NGC 7025, we reported different lessons learned for the ongoing exploitation of the MEGADES survey with GTC. First, our analysis showed that determining the stellar population properties in galaxies by measuring the absorption line indices leads to an incomplete picture, especially if the data do not cover a sufficiently wide spectral range. Nevertheless, the measurement of these absorption line indices does allow verifying the results obtained with more complex tools. Thus, if we aim to unravel the nature of stellar populations more precisely, we must consider full spectral fitting tools. Although this method may be more effective, we must also be aware that the spectral range we study can affect the results of our analysis: A bluer wavelength coverage is more sensitive to the presence of younger populations. Not only the wavelength range under study, but also the signal-to-noise ratio and even the velocity dispersion and resolution of the spectroscopic data that are used affect the uncertainties in the derivation of the SFH of composite stellar populations. In the context of the MEGADES survey, we carried out a number of tests to determine the expected errors (including potential biases) in these SFH derivations as a function of these parameters, namely spectral setup, S/N, \(\sigma\), and the SFH itself. In Appendix A we show the results of these tests for the combination of parameters for the MEGARA observations of NGC 7025 (LR-B, LR-V, and LR-B+LR-V setups and a galaxy velocity dispersion of \(\sigma \sim 250 \text{ km s}^{-1}\)).

Acknowledgements. Based on observations made with the Gran Telescopio Canarias (GTC), installed in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofísica de Canarias, in the island of La Palma. IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy (AURA) under a cooperative agreement with the National Science Foundation. This project used data obtained with the Dark Energy Camera (DECam), which was constructed by the Dark Energy Survey (DES) collaboration. The Legacy Surveys imaging of the DESI footprint is supported by the Director, Office of Science, Office of High Energy Physics of the US Department of Energy under Contract No. DE-AC02-05CH1123, by the National Energy Research Scientific Computing Center, a DOE Office of Science User Facility under the same contract; and by the US National Science Foundation, Division of Astronomical Sciences under Contract No. AST-0950945 to NOAO. This research has made use of the NASA/IPAC Extragalactic Database, which is funded by the National Aeronautics and Space Administration and operated by the California Institute of Technology. This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France. This research has made use of data from the NASA/IPAC Extragalactic Database, which is funded by the National Aeronautics and Space Administration and operated by the California Institute of Technology. This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France. This work has been supported by MINECO-FEDER grants AYA2016-75808-R and RTI2018-096188-B-I00. J.J.P. acknowledges financial support from the State Agency for Research of the Spanish MCIU through the Center of Excellence Severo Ochoa award to the Instituto de Astrofísica de Andalucía (SEV-2017-0709). J.J.P. acknowledges financial support from projects Estallidos6 AY A2016-79724-C4 (Spanish Ministry of Economy and Competitiveness), Estallidos7 PID2019-107408GB-C44 (Spanish Ministerio de Ciencia e Innovacion), grant P18-FR-2664 (Junta de Andalucía), and grant SEV-2017-0709 “Centro de Excelencia Severo Ochoa Program” (Spanish Science Ministry).

References
Barrera-Ballesteros, J. K., García-Lorenzo, B., Falcón-Barroso, J., et al. 2015, A&A, 582, A21

Bohlman, R. C., Hubeny, I., & Rauch, T. 2020, AJ, 160, 21

Cappellari, M. 2017, MNARS, 466, 798

Cappellari, M., & Emsellem, E. 2004, PASP, 116, 138

Cardiel, N. 2020, in Astronomical Data Analysis Software and Systems XXVII, eds. P. Ballester, J. Ibson, M. Solar, & K. Shortridge, ASP Conf. Ser., 522, 723

Carrasco, E., Gil de Paz, A., Gallego, J., et al. 2018, in Ground-based and Airborne Instrumentation for Astronomy VII, eds. C. J. Evans, L. Simard, & H. Takami, SPIE Conf. Ser., 10702, 1070217

Castillo-Morales, A., Pascual, S., & Gil de Paz, A. 2020, MEGARA Data Reduction Cookbook

Cid Fernandes, R., Mateus, A., Sodré, L., Stasińska, G., & Gomes, J. M. 2005, MNARS, 358, 363

del Águila, A. L., García-Benito, R., Cid Fernandes, R., et al. 2017, MNARS, 471, 3727

Dey, A., Schlegel, D. J., Lang, D., et al. 2019, AJ, 157, 168

Dullo, B. T., Chamarro-Cazorla, M., Gil de Paz, A., et al. 2019, ApJ, 871, 9

Dutton, A. A., & van den Bosch, F. C. 2009, in Galaxy Evolution: Emerging Insights and Future Challenges, eds. S. Jogee, I. Marinova, L. Hao, & G. A. Blanc, ASP Conf. Ser., 419, 355

Dutton, A. A., Treu, T., Brewer, B. J., et al. 2013, MNARS, 428, 3183

Falcón-Barroso, J., Sánchez-Blázquez, P., Vazdekis, A., et al. 2011, A&A, 532, A95

García-Benito, R., Zibetti, S., Sánchez, S. F., et al. 2015, A&A, 576, A135

Gil de Paz, A., & Madore, B. F. 2002, AJ, 123, 1864

Gil de Paz, A., Carrasco, E., Gallego, J., et al. 2018, in Ground-based and Airborne Instrumentation for Astronomy VII, eds. C. J. Evans, L. Simard, & H. Takami, SPIE Conf. Ser., 10702, 1070217

Girardi, L., Bressan, A., Bertelli, G., & Chiosi, C. 2000, A&AS, 141, 371

Gomes, J. M., Papaderos, P., Kehring, C., et al. 2016, A&A, 588, A68

González, J. J. 1993, PhD Thesis, Line strength gradients and kinematic profiles in elliptical galaxies.

Hinton, S. R. 2016, J. Open Source Softw., 1, 00045

Holmes, L., Spekkens, K., Sánchez, S. F., et al. 2015, MNARS, 451, 4397

Hopkins, P. F., Cox, T. J., Kereš, D., & Hernquist, L. 2008, ApJS, 175, 390

Kacharov, N., Neumayer, N., Seth, A. C., et al. 2018, MNARS, 480, 1973

Karakchentsova, V. E. 1973, Astroiz. Izv. Spots. Astroiz. Obser., 8, 3

Kim, J. H., Peirani, S., Kim, S., et al. 2014, ApJ, 789, 90

King, D. 1985, ING Technical Note, No. 31

Lott, J. M., Jonsson, P., Cox, T. J., & Primack, J. R. 2010, MNARS, 404, 575

Naab, T., Jusseit, R., & Burkert, A. 2006, MNARS, 372, 839

Pascual, S., Picaizo-Sánchez, P., Cardiel, N., Africa, C.-M., & de Paz, A. G. 2018, Guaxu-ucm/megaradrp: v0.6.1

Petrińfer, A., Cassisi, S., Salaris, M., & Castelli, F. 2004, ApJ, 612, 168

Petrińfer, A., Cassisi, S., Salaris, M., & Castelli, F. 2006, ApJ, 642, 797

Rizzo, F., Fraternali, F., & Iorio, G. 2018, MNRAS, 476, 2137

Rodríguez-Merino, L. H., Mayya, Y. D., Coelho, P. R. T., et al. 2020, ApJ, 889, L131

Salpeter, E. 1955, ApJ, 121, 161

Sánchez, S. F., Kennicutt, R. C., Gil de Paz, A., et al. 2012, A&A, 538, A8

Sánchez-Blázquez, P., Peletier, R. F., Jiménez-Vicente, J., et al. 2006, MNARS, 371, 703

Sánchez-Blázquez, P., Rosales-Ortega, F. F., Méndez-Abreu, J., et al. 2014, A&A, 570, A6

Springel, V., & Hernquist, L. 2003, MNARS, 339, 289

Tang, B., Worthey, G., & Davis, A. B. 2014, MNARS, 445, 1538

Tinsley, B. M. 1972, A&A, 19, 283

Tresse, L., Maddox, S., Loveday, J., & Singleton, C. 1999, MNARS, 310, 262

Vazdekis, A., Sánchez-Blázquez, P., Falcón-Barroso, J., et al. 2010, MNARS, 404, 1639

Véilleux, S., Cecil, G., & Bland-Hawthorn, J. 2005, ARAA, 43, 769

Wenger, M., Ochsenbein, F., Egeret, D., et al. 2000, A&AS, 143, 9

Worthey, G. 1994, ApJS, 95, 107

Worthey, G., Danile, A. B., & Faber, S. M. 2014, A&A, 561, A36

Wu, C. F. J. 1986, Ann. Stat., 14, 1261
Appendix A: Mock data tests

In order to analyse the results to be obtained as part of the MEGADES survey using pPXF, we first wished to verify the performance of the software with the different SSPs to be used to fit these spectra. Thus, we created different mock spectra from templates of different ages, 1.00, 3.16, 5.01, 6.31, 7.94, 10.00, and 12.59 Gyr, and with solar metallicity. To do this, we took the original templates (Vazdekis et al. 2010) and broadened them to different velocity dispersion values, 50, 100, and 250 km s\(^{-1}\), and added different (Gaussian) noise levels until we obtained a signal-to-noise ratio of 10, 20, 50, 100, and 150 at the central wavelength of each spectral setup.

These mock spectra were divided into different spectral ranges that covered the same regions of the optical spectrum of each individual MEGARA VPH or some combination of these. Thus, we created mock spectra in the spectral ranges of LR-U, LR-B, LR-V, LR-R, LR-U+LR-B+LR-V, LR-B+LR-V+LR-R, and LR-U+LR-B+LR-V+LR-R. Here we specifically show the results for LR-B, LR-V, and LR-B+LR-V because we focused on these configurations for NGC 7025. These mock spectra were analysed using the same wild bootstrapping method we followed for the observations of NGC 7025, as explained in section 3.3.

In Figure A.1 we report the results obtained by measuring with pPXF the age and metallicity of the mock spectra realisations made for an SSP model with an age of 10 Gyr and solar metallicity in the LR-V spectral range with a signal-to-noise ratio of 100 and a line-of-sight velocity dispersion of 250 km s\(^{-1}\). Although the scatter of the results is quite large, we recover the input age and metallicity of the original model to 1\(\sigma\).

Fig. A.1. Age and metallicity for MILES model realisations for an age of 10 Gyr and solar metallicity in the LR-V spectral range with a signal-to-noise ratio of 100 and \(\sigma\) of 250 km s\(^{-1}\). The red star shows the input values, while the black ellipse encompasses the region with all the solutions within 1\(\sigma\).

Fig. A.2. Age of the original SSP models vs. the results obtained by analysing with pPXF the spectra of different realisations, all broadened to \(\sigma\) = 250 km s\(^{-1}\). We show the results from different spectral ranges, from left to right: LR-V, LR-B, and LR-B+LR-V and several signal-to-noise ratios in different colours.
This is simply one of the examples of the results that could be obtained from all the possible combinations outlined above, which we now analyse in more detail. Thus, Figure A.2 shows the difference between the age of the original templates and the age predicted by pPXF for different spectral ranges and velocity dispersion values.

In general, our fitting method (based on pPXF; Cappellari & Emsellem 2004) tends to overestimate the age of the templates, especially in intermediate-age SSPs. As expected, as the signal-to-noise ratio increases, the results improve both in terms of variance and offset. An increase in these differences is also seen as the spectral lines become broader, but this effect (not shown here) is not as significant, at least for the range in line widths considered here. These performance tests naturally lead to relative results (such as age gradients) being more robust than those based on absolute age determinations.

This information is relevant for understanding the limitations of our method, and especially, for its application to actual observations of the ongoing MEGADES survey with MEGARA at the GTC. In Figure A.3 we show how the age results behave when MEGARA data are used for the innermost elliptical aperture measured in NGC 7025 and different VPHs combinations (black scatter points). On the other hand, the solid blue line and corresponding shaded areas represent the average and 1σ results obtained from the analysis of the SSP mock spectra, as described above. All ages are referenced to the age obtained by combining all the VPHs discussed in this paper, which are also those considered for their use as part of MEGADES (LR-U, LR-B, LR-V, and LR-R). Interestingly, we find that LR-B, LR-V, and LR-B+LR-V are the best combinations given the exposure times and signal-to-noise ratios targeted with our MEGADES observations.