

Probing the circumnuclear stellar populations of starburst galaxies in the near-infrared

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ABSTRACT

We employ the NASA Infrared Telescope Facility’s near-infrared spectrograph SpeX at 0.8–2.4 μm to investigate the spatial distribution of the stellar populations (SPs) in the four well-known starburst galaxies: NGC 34, NGC 1614, NGC 3310 and NGC 7714. We use the STARLIGHT code updated with the synthetic simple SPs models computed by Maraston. Our main results are that the near-infrared light in the nuclear surroundings of the galaxies is dominated by young-/intermediate-age SPs ($t \leq 2 \times 10^9$ yr), summing from ~ 40 up to 100 per cent of the light contribution. In the nuclear aperture of two sources (NGC 1614 and NGC 3310), we detected a predominant old SP component ($t > 2 \times 10^9$ yr), while for NGC 34 and NGC 7714 the younger component prevails. Furthermore, we found evidence of a circumnuclear star formation ring-like structure and a secondary nucleus in NGC 1614, in agreement with previous studies. We also suggest that the merger/interaction experienced by three of the galaxies studied, NGC 1614, NGC 3310 and NGC 7714, can explain the lower metallicity values derived for the young SP component of these sources. In this scenario, the fresh unprocessed metal poorer gas from the destroyed/interacting companion galaxy is driven to the centre of the galaxies and mixed with the central region gas, before star formation takes place. In order to deepen our analysis, we performed the same procedure of SP synthesis using the Maraston & Strömbäck evolutionary population synthesis models. Our results show that the newer and higher resolution M11 models tend to enhance the old-/intermediate-age SP contribution over the younger ages.

Key words: galaxies: bulges – galaxies: ISM – galaxies: starburst – galaxies: stellar content – infrared: galaxies – infrared: stars.

1 INTRODUCTION

A galaxy that is undergoing an intense star formation, usually in the central region ($r \lesssim 1$ kpc) is called a starburst galaxy (SB). These objects present star formation rates (SFRs) of 5–50 $M_{\odot} \text{ yr}^{-1}$ within a region of 0.1–1 kpc extent, exceeding the values found within a similar region in the Galactic centre ($0.5 M_{\odot} \text{ yr}^{-1}$; Gusten 1989) or in normal galaxies (e.g. Heckman 2000). Also, its spectrum is char-

acterized by unusually bright emission lines, especially hydrogen and helium recombination lines.

It is widely known that what powers the starburst are massive stars that emit their primary radiation in the ultraviolet (UV) part of the spectrum (Heckman 2000), while the interstellar medium absorbs these radiation and re-radiates it at longer wavelengths. Massive stars evolve rapidly to red supergiants (RSGs) that emit most of their radiation in the near-infrared (NIR). These RSGs, therefore, are indicators of young stellar populations (SPs), providing means to identify recent starbursts in the NIR (Oliva et al. 1995). Thus, SBs are key sources to study the formation and evolution of massive stars in galaxies.

Moreover, the thermally pulsing asymptotic giant branch (TP-AGB) stellar phase has an important contribution in the NIR (Maraston 1998, 2005; Riffel et al. 2008), being enhanced in young-to intermediate-age SPs ($t < 2$ Gyr). With the new generation of the

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evolutionary population synthesis (EPS) models that include the empirical spectra of stars in the TP-AGB phase (Maraston 2005, hereafter M05), it became possible to study in more detail the SP of galaxies in the NIR. A further benefit with the inclusion of these empirical spectra of C- and O-rich stars to the models (Lançon & Wood 2000) was the detection of NIR characteristic absorption features from the CN band. Riffel et al. (2007) for instance, detected the 1.1 μm CN band in the spectra of SBs and Seyfert galaxies. In addition, Martins et al. (2013) detected the band at 1.1 μm and that at 1.4 μm of the same molecule.

Even though tracing star formation in the NIR is a difficult task, this spectral range is the most suitable one to unveil the SPs in highly obscured sources (Origlia & Oliva 2000). With the improvement of infrared (IR) arrays, it became possible to obtain spectra at moderate resolution on faint and extended sources (Riffel et al. 2008, hereafter R08) allowing a more detailed study of SPs in the NIR spectral region. Also, the simultaneous wavelength coverage provided by these instruments via cross-dispersed spectroscopy brings an improvement to the SP synthesis once it avoids the aperture and seeing effects that usually affects the study in the *J*, *H* and *K* spectroscopy done in long-slit and single-band modes. It is worth mentioning that the *James Webb Space Telescope* will be optimized for observations in the IR. Thus, it is important to test the SP synthesis method in this spectral region.

In spite of the large amount of results about SPs gathered by means of NIR in active galactic nuclei (AGNs) or individual objects, few studies have concentrated on the analysis of the SPs along the spatial directions at distances larger than a few hundred of parsecs. It is thus necessary to develop proxies for the analysis of SPs along the radial direction and compare these results with those found at other wavelengths. This allows us to find out complementary information that the SP synthesis in the NIR is able to provide. To this purpose, we selected a sample composed by the four well-known SBs in the local Universe (NGC 34, NGC 1614, NGC 3310, NGC 7714), which were widely studied in the optical and NIR (see Section 2.1) and whose spatial extension and proximity allow the study of SPs at distances as large as several hundreds of parsecs.

An important aspect regarding our sample is the fact that all four galaxies are merging systems. It is known that mergers can trigger star formation (Mihos & Hernquist 1999), as well as create peculiar structures as tidal tails, bridges (e.g. Toomre & Toomre 1972) and rings (e.g. Lynds & Toomre 1976). An evidence of that is the presence of luminous H II regions in collisional rings (e.g. Fosbury & Hawarden 1977; Marston & Appleton 1995) and in extended tidal tails (e.g. Duc & Renaud 2013). In fact, interacting galaxies usually have strong IR emission (luminous infrared galaxies - LIRGs and ultraluminous infrared galaxies - ULIRGs;¹ e.g. Rieke et al. 1980) and present different types of nuclear activity like nuclear starbursts, AGN as well as post-starburst activity. With this in mind, we also would like to emphasize the importance of the detailed study of star-forming interacting systems in the local universe using NIR spectral range. These results can provide further support to studies of high-*z* sources (e.g. Pope et al. 2013), once almost all systems displayed intense bursts of star formation and were strongly interacting at the early universe ($z \sim 1-5$; Carilli & Walter 2013).

Thus, aimed at studying the nuclear and off-nuclear SP in SBs and building a scenario of the star formation history (SFH) of these sources, we will analyse the spacial distribution of the SPs, in

the NIR spectral range of NGC 34, NGC 1614, NGC 3310 and NGC 7714, by means of SP fitting.

This paper is structured as follows. In Section 2.1, we present a summary of previous SP studies of our sample and in Section 2.2 the observations and data reduction. In Section 3, we describe the method used to perform the SP synthesis. The results are presented and discussed in Section 4 and the conclusions are left to Section 5. We assume $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

2 THE DATA

2.1 Sample and previous SP studies

In this section, we summarize the properties of the galaxies as well as the results of the previous SP studies of our sample.

NGC 34: at a distance of 78.4 Mpc, this LIRG was classified as a merger system by Vorontsov-Velyaminov (1959). The nuclear activity classification of this galaxy is controversial. For example, Mazzarella, Bothun & Boroson (1991) and Riffel, Rodríguez-Ardila & Pastoriza (2006) classified this source as an SB. Yet, according to Gonçalves, Véron-Cetty & Véron (1999), its optical nuclear spectrum is not only starburst dominated, but also hosts a Seyfert 2 (Sy 2) nuclei. In fact, many studies have classified this source as an Sy 2 (e.g. Véron-Cetty & Véron 1986; Goldader et al. 1997a), while others have emphasized the apparent weakness of the [OIII] $\lambda 5007$ emission line relative to either H α or H β and classified NGC 34 as narrow-emission-line galaxy (e.g. Osterbrock & Dahari 1983; Goldader et al. 1997b).

Using optical images and spectroscopic observations, Schweizer & Seitzer (2007) proposed a scenario about the merging history of NGC 34. They suggested that two disc gas-rich galaxies of unequal mass (with an estimated mass ratio of $1/3 \leq m/M \leq 2/3$) merged, yielding a galaxy-wide starburst. This starburst occurred first ~ 600 Myr (showing a peak over 100 Myr ago) and, according to the authors, seems to have formed an extensive system of young globular clusters with ages in the range of 0.1–1.0 Gyr. This work also reveals a young, blue stellar exponential disc that formed ~ 400 Myr ago. At present, the two merging galaxies' nuclei appear to have coalesced, the starburst has shrunk to its current central (≤ 1 kpc) state and there is a strong gaseous outflow.

In addition, R08 analysed the inner 230 pc of this source in the NIR and detected a young-/intermediate-age SP with solar metallicity. Their results are in agreement with the fact that this galaxy has a strong 1.1 μm CN absorption band in its spectrum (Riffel et al. 2007) characteristic of SPs with that age (~ 1 Gyr; M05).

NGC 1614: at a distance of 63.7 Mpc, NGC 1614 is considered a suitable laboratory to study starbursts since it has a modest extinction and fairly face-on viewing geometry (Alonso-Herrero et al. 2001). This source is catalogued as LIRG and shows a spectacular outer structure with tidal tails or plumes, suggesting that this morphology and its extreme IR luminosity result from the interaction/merger with at least other two galaxies (e.g. Neff et al. 1990; Alonso-Herrero et al. 2001). Also, the highly asymmetric extended emission present around this source favours that this interaction scenario is still occurring (e.g. Kotilainen et al. 2001). *Hubble Space Telescope*/NIR camera and multi-object spectrometer (NICMOS) observations reported by Alonso-Herrero et al. (2001) show deep CO stellar absorption, interpreted by them as tracers of a starburst nucleus of ~ 45 pc in diameter surrounded by an ~ 600 pc diameter ring of supergiant H II regions revealed in Pa α line emission. This ring is coincident with a ring of radio continuum emission detected by Olsson et al. (2010), who conclude that the LINER-like activity

¹ LIRGs are defined as $10^{11} \leq L/L_{\odot} < 10^{12}$ and ULIRGs as $L/L_{\odot} \geq 10^{12}$.

Table 1. Log of observations.

| Galaxy | Type | RA (^h ^m ^s) | Dec. ([°] ['] ^{'''}) | <i>z</i> | Date of observation | <i>T</i> _{exp} (s) | Airmass | PA _{obs} (deg) | <i>E</i> (<i>B</i> − <i>V</i>) _G (mag) | Nuclear aperture (arcsec) | Scale (pc arcsec ^{−1}) |
|----------|--------|--|--|-----------|------------------------|--------------------------------|---------|----------------------------|--|------------------------------|-------------------------------------|
| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) | (11) | (12) |
| NGC 34 | SB/Sy2 | 00:11:06 | −12:06:26 | 0.019 774 | 24/10/03 | 1680 | 1.19 | 4 | 0.027 | 1.0 | 383 |
| NGC 1614 | SB | 04:33:59 | −08:34:46 | 0.016 070 | 24/10/03 | 1800 | 1.14 | 0 | 0.154 | 1.0 | 324 |
| NGC 3310 | SB | 10:38:45 | 00:33:06 | 0.003 641 | 21/04/02 | 840 | 1.21 | 158 | 0.022 | 1.4 | 71 |
| NGC 7714 | H II | 23:36:14 | 02:09:18 | 0.009 931 | 24/10/03 | 2400 | 1.05 | 348 | 0.052 | 1.0 | 192 |

Notes: (1) galaxy name; (2) galaxy classification; (3) right ascension; (4) declination; (5) average redshift, determined from the position of the emission lines of [S III] 0.9531 μm, He I 1.083 μm, Paβ and Brγ; (6) date of observation; (7) total exposure time for each galaxy; (8) airmass; (9) position angle of the slit; (10) galactic extinction from NED; (11) aperture diameter for the nuclear extraction; off-nuclear apertures were extracted with a diameter of 0.4 arcsec until the extended emission drop to 1 per cent of the peak value; (12) plate scale.

observed in NGC 1614 can be attributed to starburst activity, and not to an AGN. Alonso-Herrero et al. (2001) also states that the presence of a secondary nucleus can be interpreted as being a fragment of the companion galaxy, smaller than NGC 1614, which had long been destroyed. Thus, this source was classified as an advanced merger system by Doyon, Joseph & Wright (1989) and Neff et al. (1990). Moreover, R08 detected a dominant 1 Gyr old SP in the inner 154 pc in agreement to the fact that the integrated spectra of both NGC 34 and NGC 1614 are very similar.

NGC 3310: it is a well-known nearby SB ($d = 13.2$ Mpc) which presents a disturbed morphology (Elmegreen et al. 2002), suggesting that it recently underwent at least one significant merger. Balick & Heckman (1981) were the first to propose this merging scenario, suggesting that star formation occurring in the past 10^8 yr has been triggered by a collision with a dwarf galaxy. These authors also state that the well-known ‘arrow’ morphology (Walker & Chincarini 1967) on the western side comprises the remnant of this dwarf galaxy. NGC 3310 harbours a circumnuclear ring of about 8 to 12 arcsec in diameter (720–1080 pc; Elmegreen et al. 2002) that has been studied over a wide range of wavelengths, such as X-rays (e.g. Zezas, Georgantopoulos & Ward 1998), far-UV (e.g. Smith et al. 1996), UV (e.g. Meurer et al. 1995), optical (e.g. Balick & Heckman 1981; Grothues & Schmidt-Kaler 1991; Pastoriza et al. 1993), NIR (e.g. Telesco & Gatley 1984; Pastoriza et al. 1993; Elmegreen et al. 2002), IR (e.g. Telesco & Gatley 1984) and radio (e.g. Balick & Heckman 1981). This ring is filled with giant H II regions (Pastoriza et al. 1993). Studying the inner 56 pc of this source in the NIR spectral range, R08 detected an intense starburst activity, with four starbursts, one dominant at 1 Gyr, which contributes with up to ~30 per cent of the light in this spectral range.

NGC 7714: an SB galaxy at 37.3 Mpc classified as a prototypical SB by Weedman et al. (1981). This galaxy is in interaction/merger with its companion NGC 7715, and such interaction could be responsible for the star formation bursts (Kinney, Bohlin & Calzetti 1993). In fact, Lançon et al. (2001) show the bridge between NGC 7714 and its companion NGC 7715 (see their fig. 2). This source is very well studied with large amount of data in the optical and NIR part of the spectrum (e.g. González-Delgado et al. 1995, 1999; Lançon et al. 2001; Brandl et al. 2004). For example, analysing narrow-band Hα imaging, González-Delgado et al. (1995) conclude that the star formation burst in the inner 5 arcsec (945 pc) of the galaxy is a collection of smaller H II regions with ages between 4 and 5 Myr. With very little silicate absorption and temperature of the hottest dust component of 340 K, NGC 7714 is defined by Brandl et al. (2004) as the perfect template for young, unobscured starburst. Moreover, analysing the optical continuum and far-infrared (FIR) colours, Bernlöhr (1993) found that the star formation in this source is consistent with a continuous SFR dur-

ing the past 20 Myr. R08 detected three star formation bursts, one dominant at 1 Gyr which contributes with up to ~34 per cent of the light and two minor bursts with ages 30 (~10 per cent) and 50 Myr (~13 per cent).

2.2 Observations and data reduction

Spectra of NGC 1614, NGC 34, NGC 3310, NGC 7714 were obtained at the NASA 3 m Infrared Telescope Facility (IRTF) in two observing runs. The first one in 2002 April 21, and the second one on the night of 2003 October 24. Table 1 shows the log of observations for all galaxies. The SpeX spectrograph² (Rayner et al. 2003) was used in the short cross-dispersed mode (0.8–2.4 μm). The detector consists of a 1024 × 1024 ALADDIN 3 InSb array with a spatial scale of 0.15 arcsec pixel^{−1}. A 0.8 arcsec × 15 arcsec slit oriented along the parallactic angle (see column 9 of Table 1) was used, providing a spectral resolution, on average, of 320 km s^{−1}. This value was determined both from the arc lamp and the sky line spectra and was found to vary very little with wavelength along the observed spectra. The seeing, on average, was 0.8 arcsec. As SpeX does not provide the position of the slit centre, we derived them by matching the slit and the image profile using χ² statistics. The results are shown in Fig. 1 where we present the slit position overlapping the NICMOS images of the galaxies. For NGC 7714, we present the Wide Field and Planetary Camera 2 (WFPC2) *F814W* filter ($\lambda = 7940$ Å) image, as there is no NICMOS image available for this galaxy.

Observations were done nodding in an object–sky–sky–object pattern, with the sky position usually several arcminutes from the galaxy nucleus, free of extended emission or background stars. Immediately after each galaxy, an A0V telluric star, close in airmass to the former, was observed to remove telluric features and to perform the flux calibration, see Riffel et al. (2006) where a complete description of the reduction procedure is provided. In summary, the spectral reduction, extraction and wavelength calibration procedures were performed using SPEXTOOL,³ the in-house software developed and provided by the SpeX team for the IRTF community (Cushing, Rayner & Vacca 2004). In addition to the nuclear spectrum, a different number of off-nuclear apertures were extracted for each galaxy, depending on the size of the extended emission across the slit. Table 1 (column 11) lists the diameter of the nuclear apertures. Off-nuclear spectra were extracted with a diameter of 0.4 arcsec along the spatial direction at both sides of the nuclear

² <http://irtfweb.ifa.hawaii.edu/~spex/>

³ <http://irtfweb.ifa.hawaii.edu/~cushing/Spextool.html>

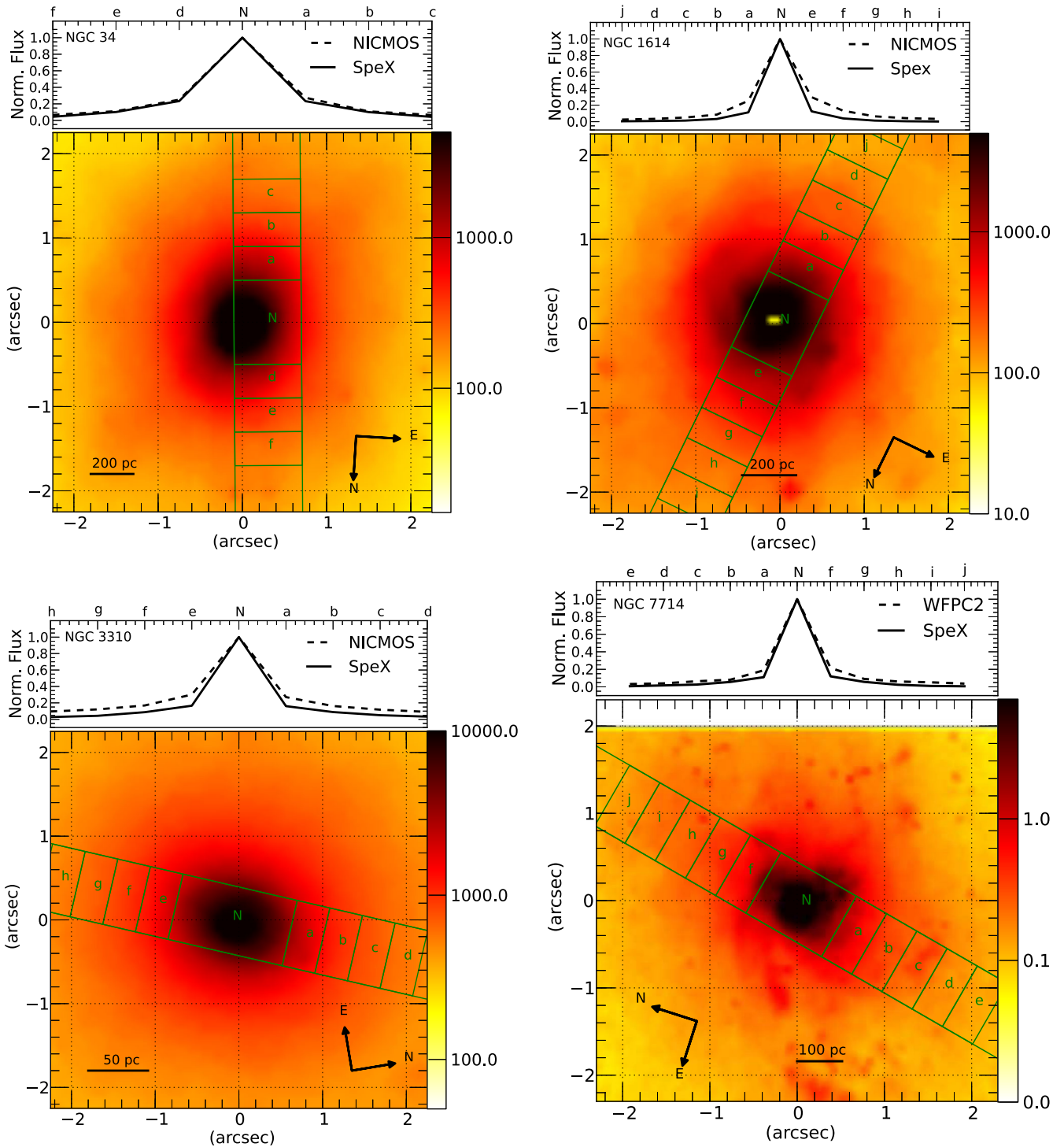


Figure 1. Top: NICMOS and SpeX profile (continuum profile at $\lambda_{\text{cent}} = 12\,230\text{\AA}$). Bottom: slit position overlapping the NICMOS image of the galaxies. For NGC 7714, we present WFPC2/F814W image.

aperture until the signal drops to 1 per cent of the peak nuclear value.

Telluric features removal and flux calibration were done using XTELLCOR (Vacca, Cushing & Rayner 2003), another software available by the SpeX team, which was designed specifically to perform telluric corrections on spectra obtained with SpeX. Thereafter, the different orders were merged into a single 1D spectrum from 0.8 to 2.4 μm using the *xmergeorders* routine. The agreement between the

overlapping region of two consecutive orders was excellent and usually with errors of less than 1 per cent. Finally, the merged spectra were corrected for Galactic extinction using the Cardelli, Clayton & Mathis (1989) law and the extinction maps of Schlegel, Finkbeiner & Davis (1998).

Figs 2–5 show the nuclear and off-nuclear spectra for each source, already corrected by redshift. The most prominent absorption and emission lines are marked, as well as the telluric absorption

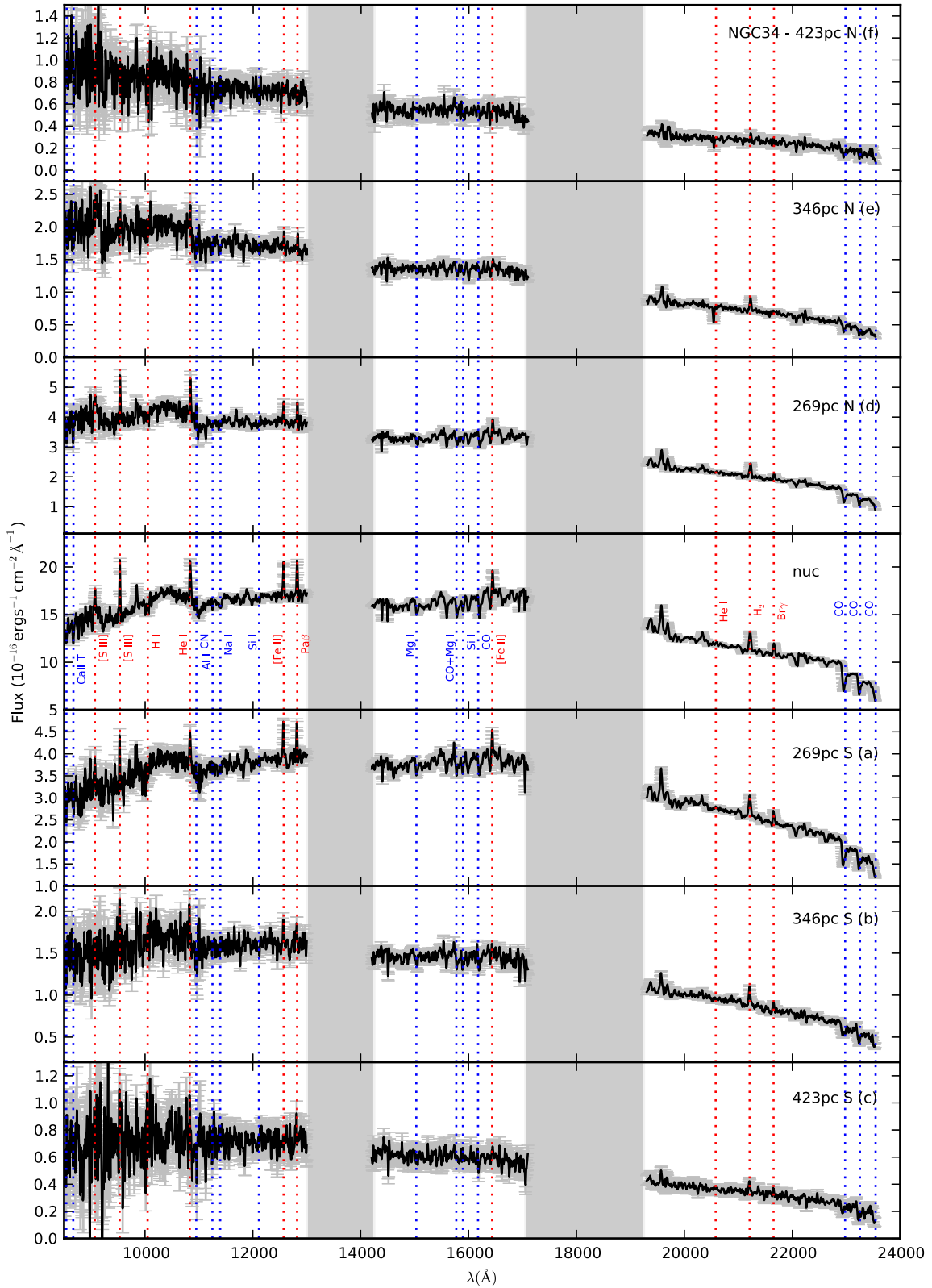


Figure 2. NGC 34 nuclear and extended region spectra. North (N) and south (S) are on the labels. The letters representing the apertures are used along the other figures (see Fig. 1). Error bars are in grey. Absorption (blue) and emission (red) lines are marked. Telluric absorption regions are displayed in the shaded area (grey).

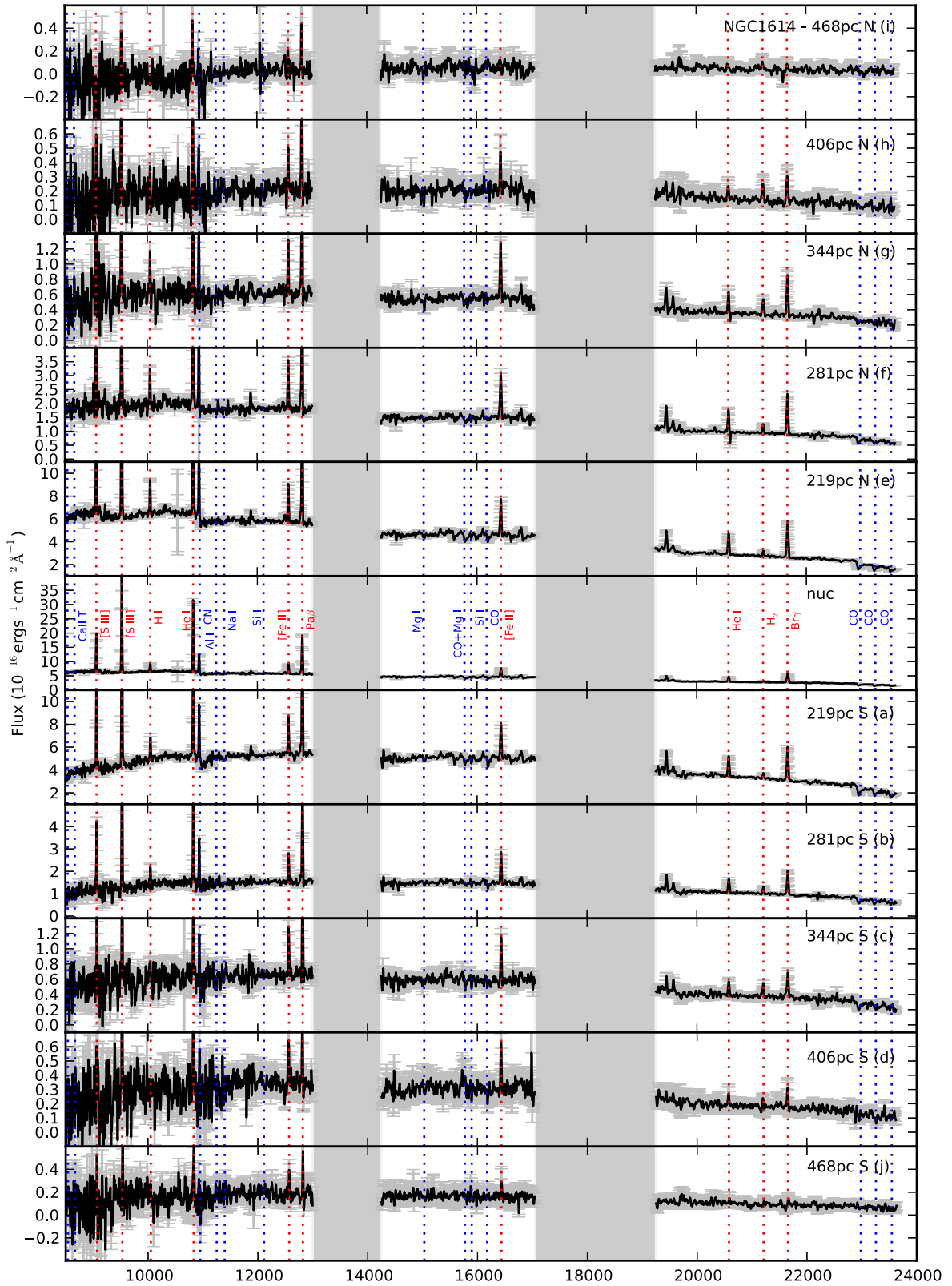


Figure 3. Same as Fig. 2, but for NGC 1614.

regions. The redshift, listed in Table 1 (column 5), was determined from the position of the emission lines of [S III] 0.9531 μm , He I 1.083 μm , Pa β and Br γ measured in the nuclear spectrum of each galaxy.

3 THE SP SYNTHESIS METHOD

There are two key ingredients when performing SP synthesis in galaxies: the base set (a set of simple SPs templates – SSPs) and

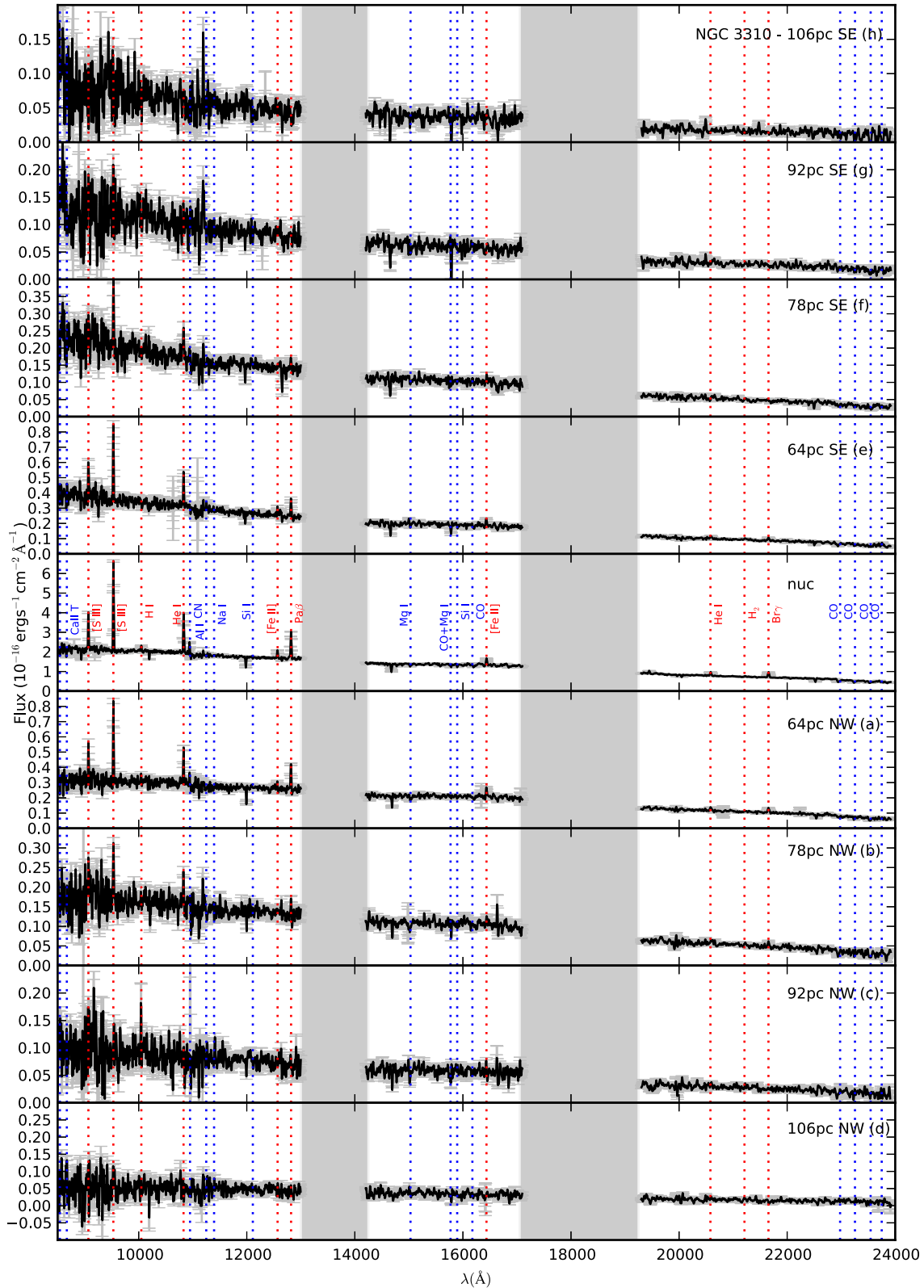


Figure 4. Same as Fig. 2, but for NGC 3310. North-west (NW) and south-east (SE) are on the labels.

the code. The purpose is to disentangle the SP components from the spectral energy distribution of a galaxy into the different SPs contributions. For that, the code will mix the SSPs until it fits the galaxy's absorption spectra. Thus, an ideal base set should cover

the range of spectral properties observed in the galaxy sample (Cid Fernandes et al. 2005) and should provide enough resolution in age and metallicity, in order to best fit the observed spectrum. In other words, a reliable base set would be a library of integrated spectra

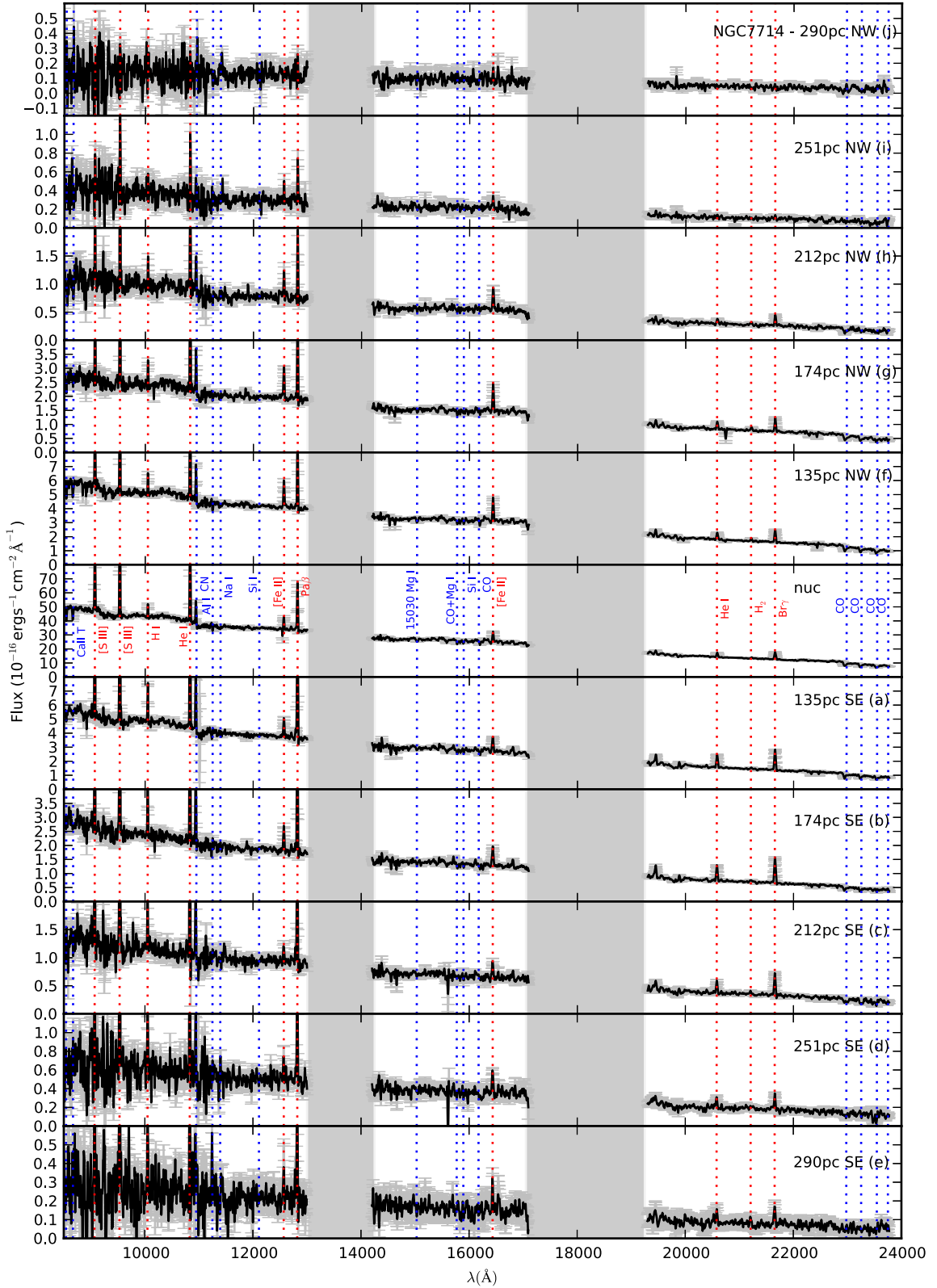


Figure 5. Same as Fig. 2, but for NGC 7714. North-west (NW) and south-east (SE) are on the labels.

of star clusters (i.e. they only depend on ages and metallicities of the stars and are free from any assumptions on stellar evolution and the initial mass function; Bica & Alloin 1986; Riffel et al. 2011a). However, up to now there is no such library available in the

literature for the NIR spectral region. In this way, the use of a base set composed of theoretical SSPs, covering this spectral region, is becoming a common approach (e.g. Riffel et al. 2009; Martins et al. 2010, 2013; Storch-Bergmann et al. 2012).

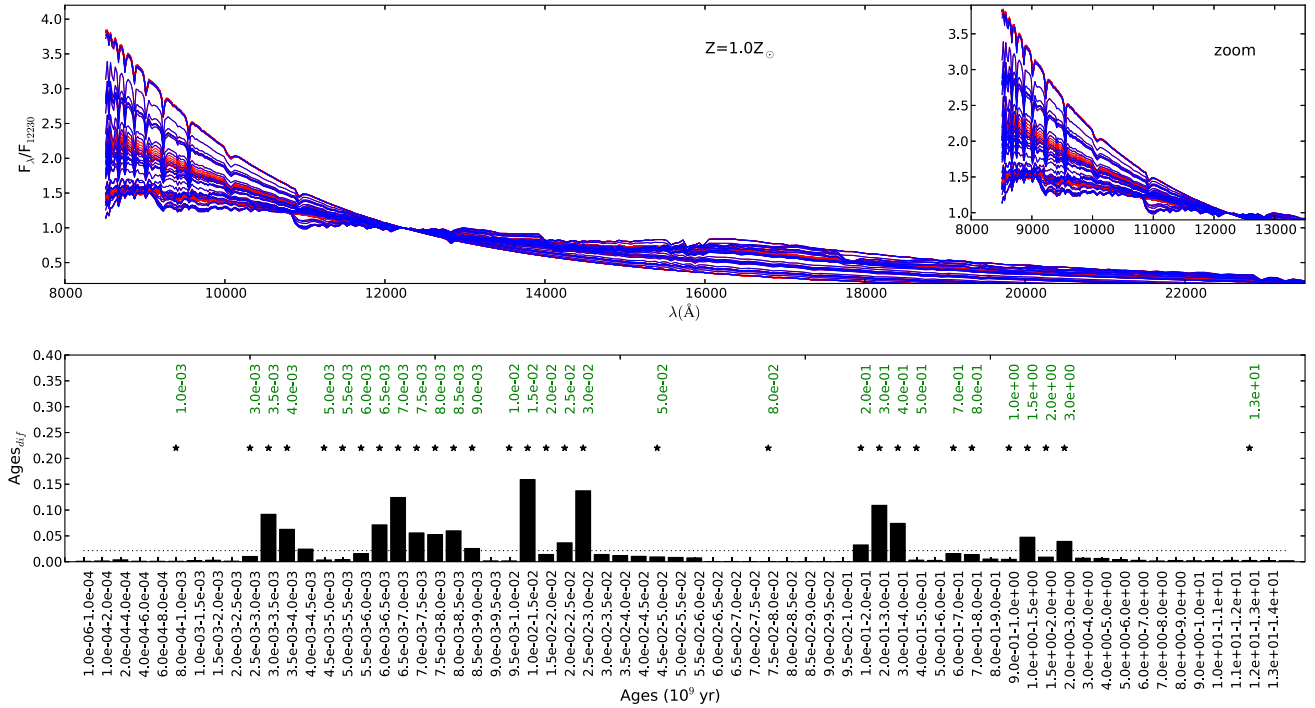


Figure 6. All the 67 M05 SSPs for $Z = Z_{\odot}$ are plotted (red) in the upper panel together with the 31 SSPs selected (blue) to compose the base set for this metallicity. In the bottom panel, the quadratic difference between two consecutive SSPs with consecutive ages is shown. The representative templates chosen to compose the base of elements are marked with a star and the correspondent ages are plotted in red in the top panel. A zoom of the blue end (where the main differences are observed) is also shown.

Since the NIR carries fingerprints from evolved stars (e.g. Riffel et al. 2007; Ramos Almeida, Pérez García & Acosta-Pulido 2009; Martins et al. 2013) and these are crucial to model the absorption line spectra of the galaxies, we used the M05 EPS models. They include empirical spectra of C- and O-rich stars (Lançon & Wood 2000) and thus, are able to predict these features. These models (grey lines in Fig. 6) span over an age range from 1 to 15 Gyr according to a grid of 67 models with four different metallicities.⁴ Since, small differences in the SP are washed away in real data (i.e. they are diluted by the noise in real data; Cid Fernandes et al. 2004), we decided only to include in the base the representative SSPs (i.e. where significant differences between them are observed) to avoid redundant information and degeneracies in the base set. In order to choose the elements to compose the base, we compute the square root of the quadratic difference between two consecutive SSPs with consecutive ages (t) normalized to the unit at 12 230 Å and divided by the number of pixels (N), i.e. solving the equation

$$\text{Ages}_{\text{dif}} = \frac{1}{N} \sum_{\lambda} |F_{\lambda}(t_i) - F_{\lambda}(t_{i+1})|. \quad (1)$$

An example of the results of this procedure, for the solar metallicity, is shown in Fig. 6. The representative SSPs (which constitute the base set) are marked with a star and are overplotted in red on Fig. 6, top panel. Note that this procedure was done only in the wavelength interval between 8000 and 24 500 Å and for the four metallicities with all ages available. The final base set results in 31 ages, $t =$

0.0010, 0.0030, 0.0035, 0.0040, 0.0050, 0.0055, 0.0060, 0.0065, 0.0070, 0.0075, 0.0080, 0.0085, 0.0090, 0.010, 0.015, 0.020, 0.025, 0.030, 0.050, 0.080, 0.2, 0.3, 0.4, 0.5, 0.7, 0.8, 1.15, 2, 3, and 13 Gyr, and 4 metallicities, $Z = 0.02, 0.5, 1$ and $2 Z_{\odot}$. Thus, the final base set is composed of 124 SSPs.

It is important to call the attention to the fact that the spectral resolution of the M05 models in the NIR is significantly lower ($R \leq 250$) than that of the observed data ($R \sim 750$; Rayner et al. 2003) and varies with wavelength. For this reason, the observations were degraded to the model's resolution, by convolving them with a Gaussian. One example of a final smoothed spectrum is shown in Fig. 7.

Once the base set is defined, the other fundamental ingredient in SP fitting is the code, which will mix the individual components of the base set to get the best fit to the observed spectrum. Here, we used the STARLIGHT code (Cid Fernandes et al. 2004, 2005, 2009, 2010, 2011; Mateus et al. 2006; Asari et al. 2007, 2009) which mixes computational techniques originally developed for empirical population synthesis with ingredients from EPS models. Briefly, the code fits the observed spectrum O_{λ} with a combination in different proportions of N_s SSPs in the base set, $b_{j,\lambda}$ taken from the EPS models. Another important aspect is that the code fits the entire spectrum, from 0.8 to 2.4 μm, excluding emission lines and spurious features (e.g. cosmic rays, noise and telluric regions), which are masked out or clipped (see below for details).

The extinction law used in this work was the Calzetti law (Calzetti et al. 2000) implemented by HYPERZ (Bolzonella, Miralles & Pelló 2000), a public photometric redshift code which computed the Calzetti law for $\lambda > 2.2 \mu\text{m}$.

Velocity dispersion is a free parameter for STARLIGHT, which broadens the SSPs in order to better fit the absorption lines in

⁴ It is worth calling attention to the reader that Maraston do provide models with $Z = 0.005$ and $3.5 Z_{\odot}$, but only for ages older than 1 Gyr; therefore, we left them out of the base set.

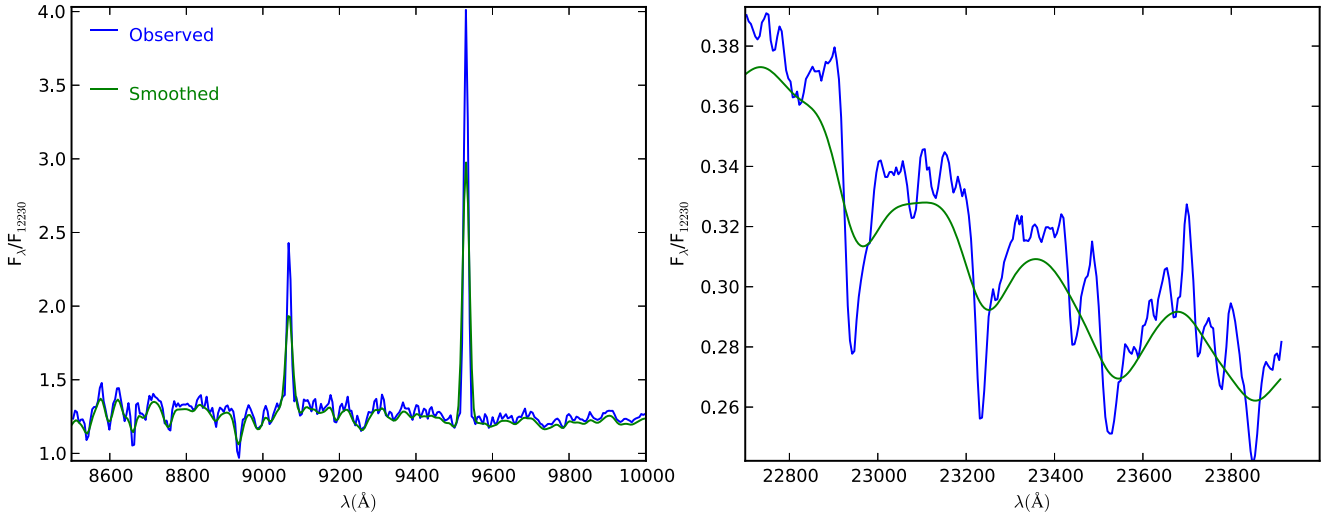


Figure 7. Comparison between the observed nuclear spectrum of NGC 3310 (blue) and the result of the Gaussian smoothing (green). We split the spectrum in two parts, the left-hand panel presents the effect of the Gaussian smoothing on the emission lines and the right-hand panel shows the effect on the CO absorption band.

the observed spectra. However, this step is not relevant in our case, because of the low-resolution models.

Basically, *STARLIGHT* solves the following equation for a model spectrum M_λ (Cid Fernandes et al. 2005):

$$M_\lambda = M_{\lambda_0} \left[\sum_{j=1}^{N_*} x_j b_{j,\lambda} r_\lambda \right] \otimes G(v_*, \sigma_*), \quad (2)$$

where M_{λ_0} is the synthetic flux at the normalization wavelength ($\lambda_0 = 12\,240$ Å); x_j is the j th population vector component of the base set; $b_{j,\lambda} r_\lambda$ is the reddened spectrum of the j th SSP normalized at λ_0 in which $r_\lambda = 10^{-0.4(A_\lambda - A_{\lambda_0})}$ is the extinction term; \otimes denotes the convolution operator and $G(v_*, \sigma_*)$ is the Gaussian distribution used to model the line-of-sight stellar motions, centred at velocity v_* with dispersion σ_* . We choose as normalization wavelength $\lambda_0 = 12\,240$ Å, since this region is free from emission and absorption lines. *STARLIGHT* normalizes all the base spectra by F_{λ_0} and the observed spectrum is normalized by the mean flux measured in a window (we used 80 Å), a region centred at λ_0 defined in order to avoid the effect of a bad pixel (noise spike, cosmic ray, etc.) at λ_0 in the observed spectrum. Finally, the best fit is achieved by *STARLIGHT* as the code searches for the minimum of the equation

$$\chi^2 = \sum_{\lambda} [(O_\lambda - M_\lambda) w_\lambda]^2. \quad (3)$$

The *STARLIGHT* output parameters χ^2 and Adev can be used to measure the robustness of the SP fit. Adev is the percent mean deviation $|O_\lambda - M_\lambda|/O_\lambda$, where O_λ is the observed spectrum and M_λ is the fitted model. The fits are carried out with a mixture of simulated annealing (Kirkpatrick, Gelatt & Vecchi 1983) plus Metropolis scheme, which gradually focuses on the most likely region in parameter space, avoiding (through the logic of the cooling schedule) trapping on to local minimum.

The emission lines and spurious features (noise, telluric regions, cosmic rays) are masked out by using $w_\lambda = 0$ in the regions where they are located. In our case, the emission lines masked were [S III] 9069 Å, [S III] 9531 Å, He I 10 830 Å, Pa γ 10 938 Å, [Fe II] 12 570 Å, Pa β 12 810 Å, [Fe II] 16 444 Å, Pa α 19 570 Å, Br γ 21 650 Å

and H $_2$ 21 213 Å. Spurious data were also masked out. Examples of masked regions are indicated in Figs 8–11.

In summary, after excluding the masked points, the minimization process consists of the following stages: (i) make a broad sweep of the parameter space, starting from a high ‘temperature’ (in statistical mechanics terms) to allow the system to explore all sorts of configuration and then implementing a cooling schedule to gradually reduce the ‘temperature’, therefore letting the system to settle into the lowest energy states, (ii) exclude pixels which could not be fitted by the first stage, once they deviate strongly from the best M_λ found in this first stage, (iii) detailed fit with the full base and (iv) the whole fit is fine-tuned repeating the full loop excluding all irrelevant components ($x_j = 0$) to the fit. A well-detailed discussion of the *STARLIGHT* procedures can be found in Cid Fernandes et al. (2004, 2005) and in *STARLIGHT* manual, available at <http://astro.ufsc.br/starlight/>.

3.1 Uncertainties on the fits

The use of statistics in order to interpret spectral synthesis results is widespread (e.g. Panter et al. 2007), once averaging results tends to reduce the uncertainties (Cid Fernandes et al. 2013). Another good reason to use the statistical interpretation is to produce an estimation of the uncertainties, which *STARLIGHT* does not provide as a standard output. The most straightforward way to achieve this is to perturb the input spectra according to some realistic prescription of the errors involved (Cid Fernandes et al. 2013). In order to estimate these uncertainties, we simulate 100 spectra for each aperture of each galaxy in our sample. The simulated flux for each wavelength (λ_i) is computed assuming a Gaussian distribution of the uncertainties. Therefore, the mean flux in each λ_i corresponds to the measured flux value and the standard deviation is given by the errors provided by *SPEXTOOL*. Thus, we simulate the flux at λ_i according to its normal probability.

STARLIGHT provides a single best-fitting set of parameters among typically many millions trials during its likelihood-guided sampling of the parameter space. These single solutions, however, are not necessarily mathematically unique. In this scenario, we performed

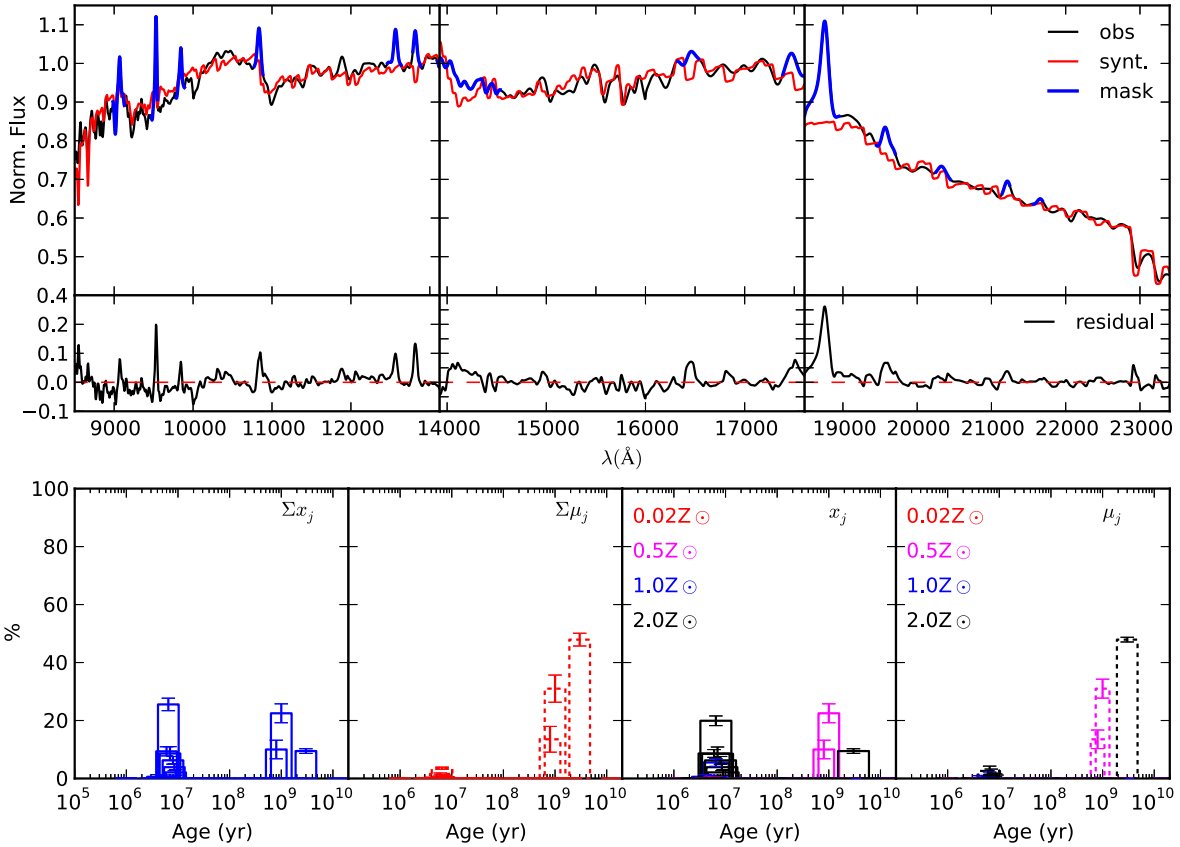


Figure 8. Results for NGC 34. Upper panels: we present the synthesis result (red) and the masked points (blue) overlapping the observed spectra (black), below the residual spectrum is shown (the dashed line in red marks the zero-point in flux). Bottom panels: we display four histograms, the two on the left present the flux-weighted (x_j) and mass-weighted (μ_j) SPs vectors contributions sorted only by age (metallicities summed) and the two on the right show the flux-weighted (x_j) and mass-weighted (μ_j) SPs vectors contributions sorted by age and metallicity. Telluric regions were omitted.

SP synthesis in all the simulated spectra in order to obtain an average result together with the standard deviation associated with each aperture of each galaxy. As a result, we have an estimate of the uncertainties associated with the SP fitting (see Figs 8–11).

4 RESULTS AND DISCUSSION

By making a systematic study over the SP variance along the galaxy, we built a scenario for the star formation in the four SBs studied here. An example of the individual results for the nuclear extraction of each galaxy is shown in Figs 8–11. These plots include (i) in the top panel are the synthesis result (red) and the masked points (blue) overlapping the observed spectra (black); (ii) the residual spectrum (the dashed line in red marks the zero-point in flux) and (iii) the bottom panel shows four histograms, the two on the left present the flux-weighted (x_j) and mass-weighted (μ_j) SP vectors contributions sorted only by age (metallicities summed) and the two on the right show x_j and μ_j sorted by age and metallicity. In these figures, we can analyse the results individually for each aperture of each galaxy, controlling the quality of the fits and improving the mask files when necessary.

On the other hand, grouping the population vector in age bins should thus provide a coarser but more powerful description of the SFH of the galaxies (Cid Fernandes et al. 2001; Cid Fernandes, Leão & Lacerda 2003; Riffel et al. 2010, 2011b, among others.).

Actually, Cid Fernandes et al. (2001) show that measurement errors as well as the use of reduced sets of observables are responsible for spreading a strong contribution in one component preferentially among base elements of same age. In this sense, we used their definition of binned population vectors as follows: young: x_y ($t \leq 50 \times 10^6$ yr), intermediate-age: x_i ($50 \times 10^6 < t \leq 2 \times 10^9$ yr) and old: x_o ($t > 2 \times 10^9$ yr).

In addition to this, in order to describe the metallicity behaviour of the SP mixture along the galaxy, we have used the flux- and mass-weighted mean metallicity defined by Cid Fernandes et al. (2005) as

$$\langle Z_\star \rangle_F = \sum_{j=1}^{N_\star} x_j Z_j, \quad (4)$$

for the flux-weighted mean metallicity and

$$\langle Z_\star \rangle_M = \sum_{j=1}^{N_\star} m_j Z_j \quad (5)$$

for the mass-weighted mean metallicity. Both definitions are bounded by the $\frac{1}{50} - 2 Z_\odot$ range.

Therefore, to best analyse our results, we create a series of histograms for each galaxy shown in Figs 12–15. Each figure includes seven plots: (i) panels (a) and (b) present a global analysis of each source by plotting the average contribution in flux and mass,

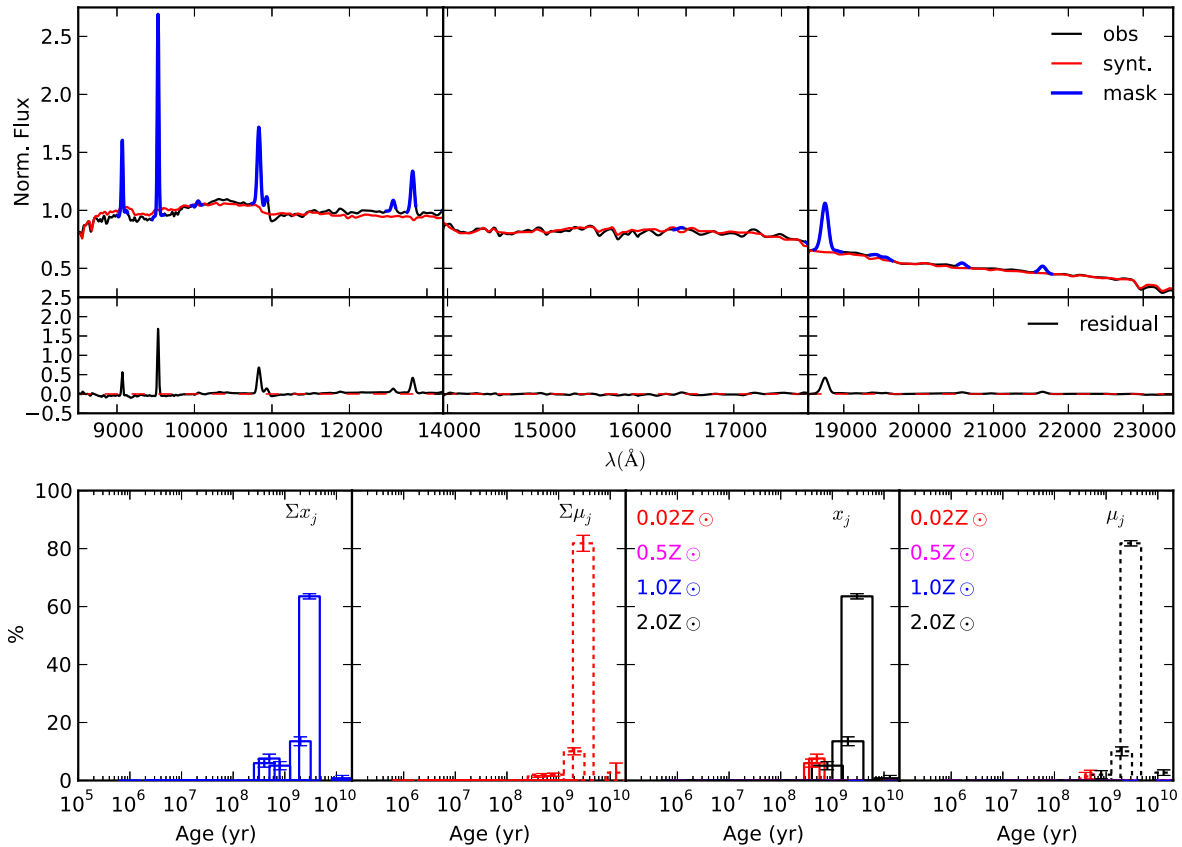


Figure 9. The same as Fig. 8 but for NGC 1614.

respectively, of the binned vectors along the apertures; (ii) panel (c) shows the mean-metallicity-weighted by flux (Z_F) and by mass (Z_M); (iii) the extinction (A_v) is plotted along the apertures in panel (d); (iv) the average χ^2 and A_{dev} are plotted in panel (e); (v) the continuum profile at $\lambda_{cent} = 12\,230\text{ \AA}$ is shown in panel (f); (vi) the signal-to-noise ratio (SNR) in panel (g), which was estimated as being the ratio between the mean values of the F_λ points (in a window of 60 \AA) and their standard deviation. These histograms will enable us to construct the star formation scenario for each galaxy, revealing the predominant ages of the population as well as indicating the possible presence of nuclear structures.

It is important to mention that the uncertainties increase with decreasing SNR (higher error bars in the outer apertures – see Figs 12–15). Nevertheless, we decided to include these results (for $SNR \leq 10$) in the analysis, as they follow the same tendency of the SP distribution along the galaxy. The average results from the SP synthesis are in Table 2.

Below we describe the results obtained through our SP analysis for each galaxy and compare them with the results found in the literature.

4.1 NGC 34

Panels (a) and (b) of Fig. 12 show a predominance of younger ages in the nuclear region shifted towards the south direction, while the intermediate-age SP is more pronounced towards north of the nucleus. The contribution of the old SP is enhanced in the mass fraction histogram as expected, once the older the SP is, less light

it will radiate, decreasing the flux contribution and increasing the mass contribution of this age in the SP components. These results are in agreement with the literature. For example, studying the optical properties of NGC 34 (on a larger field of view), Schweizer & Seitzer (2007) conclude that this source supports a rich system of young massive star clusters, a blue exponential disc and a strong gaseous outflow, all signatures of a recent gas-rich merger accompanied by a strong starburst. This source was also studied by R08 in the NIR part of the spectrum. Analysing the 230 central parsecs of this galaxy, they found a dominating intermediate-age SP ($\sim 1\text{ Gyr}$).

In Fig. 12(c), we show the mass- and flux-weighted mean metallicities along the apertures of NGC 34. Our results point to above-solar mean metallicity values along the galaxy. Moreover, the apertures displaying higher mass-weighted mean metallicity values than the flux-weighted ones are those in which the contribution of the old SP increases. Such discrepancy can be associated with the well-known age–metallicity degeneracy, i.e. for a fixed mass, a high-metallicity SP looks cooler – and older – than a low-metallicity SP, thus resulting in a higher M/L ratio. In this context, one can interpret that the flux-weighted metallicity is more sensitive to the young component, while the mass-weighted metallicity is more sensitive to the old one.

The north side of the galaxy displays lower visual extinction ($A_v < 2.0\text{ mag}$) than the nuclear ($A_v \sim 3.0\text{ mag}$) and southern region ($A_v \sim 2.0\text{ mag}$), suggesting a differential reddening. To better compare our results with those found in the literature, we estimated a weighted average of the visual extinction values derived by

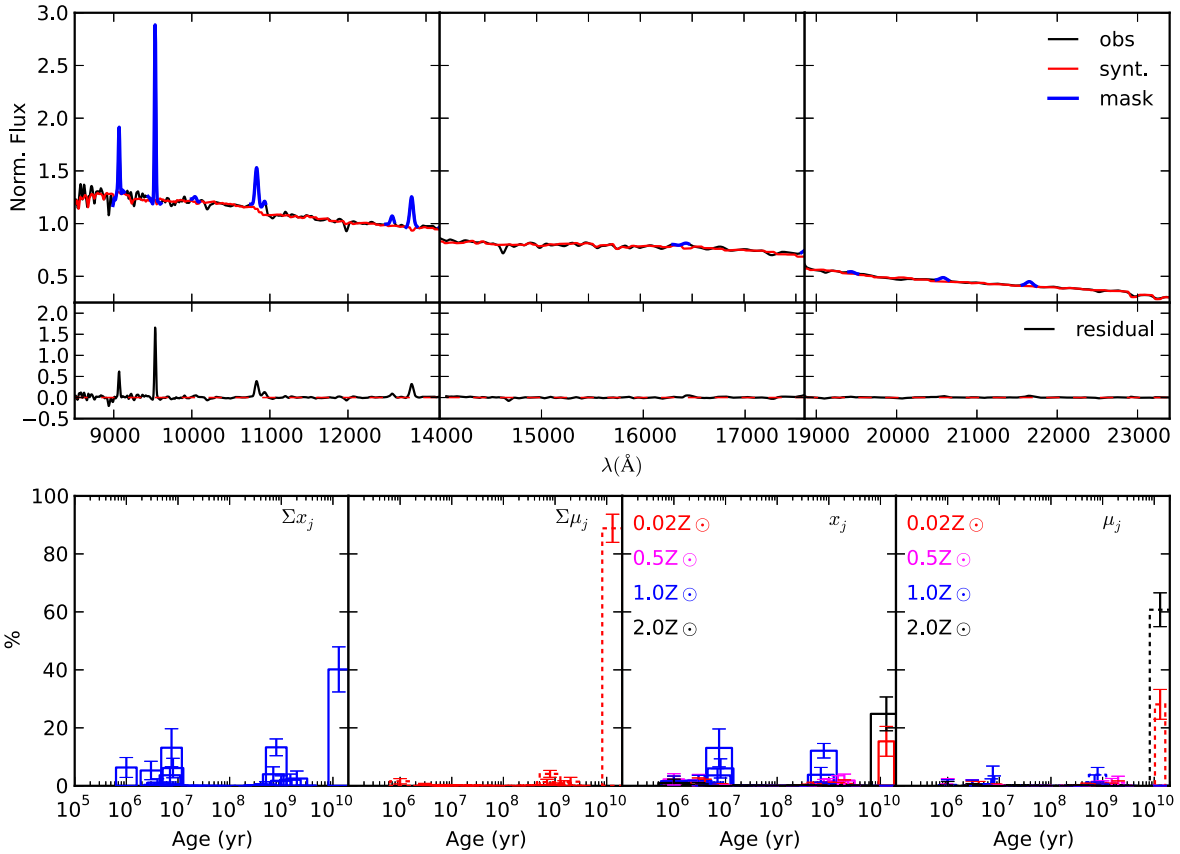


Figure 10. The same as Fig. 8 but for NGC 3310.

STARLIGHT, resulting in $\bar{A}_v = 2.49 \pm 0.10$ mag for NGC 34. Using the values of $E(B - V)$ quoted by Veilleux et al. (1995), Goldader et al. (1997a) derived $A_K = 0.67$ mag (in a $1.5 \text{ arcsec} \times 4.5 \text{ arcsec}$ beam), which results in $A_v = 6.2$ mag when using the relation $A_K = 0.108A_v$ (Mathis 1990).

In order to assess the robustness of the fit, we display the χ^2 and Adev (per cent mean deviation) along the apertures in Fig. 12(e), the continuum profile at $\lambda_{\text{cent}} = 12\,230 \text{ \AA}$ in Fig. 12(f) and the SNR along the galaxy in Fig. 12(g). As the SNR drops to values below 10, the per cent mean deviation (Adev) reaches higher values (see Figs 13 e–g).

4.2 NGC 1614

From Fig. 13(a), we can see a peak of old SP in nucleus at 219 pc south, while the off-nuclear northern apertures present a dominant young-/intermediate-age SP component. The fact that we are not detecting a contribution of the young SP ($t \leq 50 \times 10^6 \text{ yr}$) in the nuclear aperture can be explained in two different scenarios: (i) the presence of an AGN, which would quench star formation in the nuclear region (Nesvadba et al. 2006), or (ii) that the NIR still cannot reveal the young stars embedded in dustier nuclear regions (Imanishi & Nakanishi 2013). By modelling the starburst of this galaxy, Alonso-Herrero et al. (2001) associated the strong CO concentrations found in the nucleus with an older part of the starburst (10^9 yr old or older stars), which is similar to the dominant SP age we found in the nuclear aperture.

Moreover, we found evidence of a circumnuclear ring-like structure⁵ of young-/intermediate-age SP with a diameter of about 600 pc. In fact, Olsson et al. (2010) detected a ring-like structure traced out by 1.4 and 5 GHz MERLIN contours with a radius of around 310 pc, which is consistent with our results. This also has been reported by Alonso-Herrero et al. (2001), which have stated that the relation between the strong stellar CO bands to surrounding ionized gas rings to molecular gas suggests that the luminous starburst started in the nucleus and is propagating outwards into a molecular ring. Väisänen et al. (2012), through the analysis of L -band IFU observations of the inner kpc of NGC 1614, detected a ring that extends from 200 to 500 pc from the nucleus, from the equivalent width map of $3.3 \mu\text{m}$ polycyclic aromatic hydrocarbon emission. It is worth mentioning that such kind of nuclear rings are quite common in AGNs, but rarely found in these systems (e.g. Riffel et al. 2011b, 2010; Storch-Bergmann et al. 2012).

The increase in the young-/intermediate-age SP component at ~ 300 pc north from the nucleus can also be interpreted as being an evidence of the secondary nucleus (see Fig. 13 a), also reported by Alonso-Herrero et al. (2001) as the remnant of the merger with a smaller galaxy, which has by now largely been destroyed. In a

⁵ As we used an unidimensional slit, we can only see an increase in the young-/intermediate-age SP in both sides of the nucleus, in this sense we cannot assert if this pattern surrounds the nuclear region. Although, from Alonso-Herrero et al. (2001, Fig. 4) we can see that the Pa α emission image reveals a nuclear ring-like structure with approximate diameter of 650 pc, possibly formed by H II regions. A deeper analysis will be made using integral field unit (IFU) data of this source.

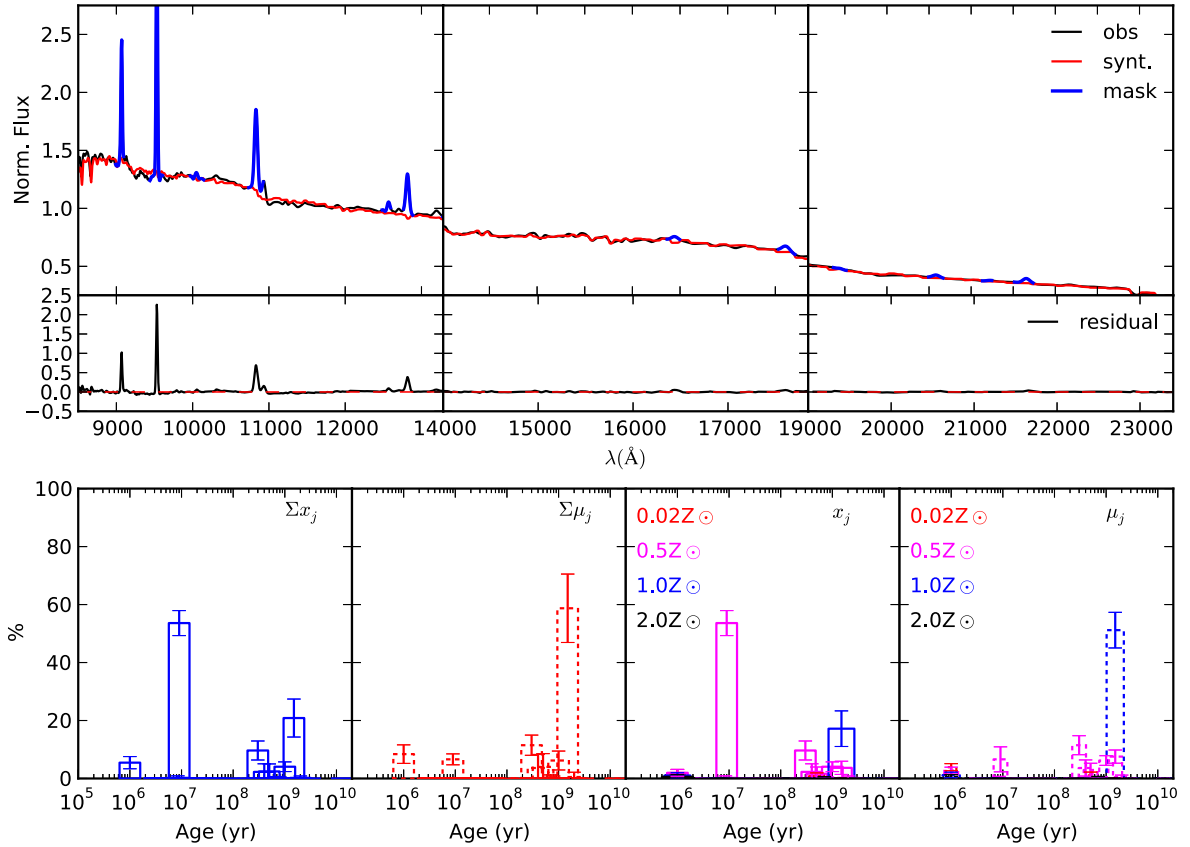


Figure 11. The same as Fig. 8 but for NGC 7714.

previous work, R08 found a 1 Gyr old SP dominating the light in the inner 154 pc of this source.

We found above solar values for the flux- and mass-weighted mean metallicity along the galaxy (see Fig. 13 c). As the contribution of the young SP component grows north, the metallicity tends to decrease, suggesting a metal-poor young SP at this side of the galaxy. In this scenario, the modest-sized galaxy which merged with NGC 1614 in the past (Alonso-Herrero et al. 2001) would have diluted the gas in the remnant, thus giving rise to a metal-poor SP, poorer than the old SP component already present in NGC 1614.

The values derived by us for the extinction (A_v) range from 1.7 to 3.9 mag ($\bar{A}_v = 2.66 \pm 0.08$). Results found in the literature are in agreement with ours, for example Neff et al. (1990) derived $A_v = 3\text{--}5$ mag assuming a foreground dust screen model, from optical and IR colours (in an ~ 20 arcsec \times 20 arcsec beam), as well as IR emission lines (in a 2.7 arcsec \times 4.3 arcsec beam). Using NIR colours, Shier, Rieke & Rieke (1996) found $A_v = 4.9$ mag (in a 2.4 arcsec \times 4.8 arcsec beam), while Kotilainen et al. (2001) (in a 2 arcsec \times 2 arcsec beam) derived $A_v = 1.8$ mag south-east of the nucleus and $A_v = 3.5$ mag north-west. Assuming an intrinsic stellar colour $H - K = 0.2$, Oliva et al. (1995) derived $A_v \sim 4$ mag (in a 2.2 arcsec \times 4.4 arcsec beam). Moreover, Alonso-Herrero et al. (2001), using the flux of two [Fe II] emission lines at 1.257 and 1.644 μm as well as the hydrogen recombination lines Pa β and Br γ and a foreground dust screen model, derived the extinction to the gas in the K band as $A_K = 0.40\text{--}0.49$ mag (in a 19.5 arcsec \times 19.5 arcsec beam), corresponding to $A_v \sim 4$ mag, using the Mathis (1990) relation of A_v and A_K . Also using recombination lines, Kotilainen et al. (2001) found

$A_v = 3.8$ mag (in a 3.5 arcsec \times 3.5 arcsec beam), a similar value than the one Bushouse (1986) derived ($A_v \sim 3$ mag) for a similar beam. Likewise, Goldader et al. (1995, see section 1614) derived $A_v = 2.96$ mag (in 3 arcsec \times 12 arcsec beam), using the values of $E(B - V)$ quoted by Veilleux et al. (1995).

On the other hand, Puxley & Brand (1994) present discrepant values when compared to those we derived and those found in the literature. Using hydrogen recombination line fluxes, they inferred a total visual extinction of $A_v = 15 \pm 2.5$ mag (in 9 arcsec \times 3 arcsec beam) assuming a composite model (a mixture of dust, gas and foreground screen) and claimed that the extinction on NGC 1614 could not be modelled with a simple foreground dust screen model, for which they found visual extinction values ranging from 4.7 to 9.5 mag.

4.3 NGC 3310

Our results point out to a predominant young-/intermediate-age SP southwards (see Fig. 14a). An increase in the older component can be seen in both flux and mass contribution towards the opposite direction. Similar to our study, several previous works in the optical region (Balick & Heckman 1981; Telesco & Gatley 1984; Schweizer & Seitzer 1988) estimated the starburst age on this source in the range of $10^7\text{--}10^8$ yr.

The nucleus and six surrounding H II regions, four of which are located at less than 400 pc from the galaxy nucleus (a wider range than the one analysed in this work, which comprehend only the

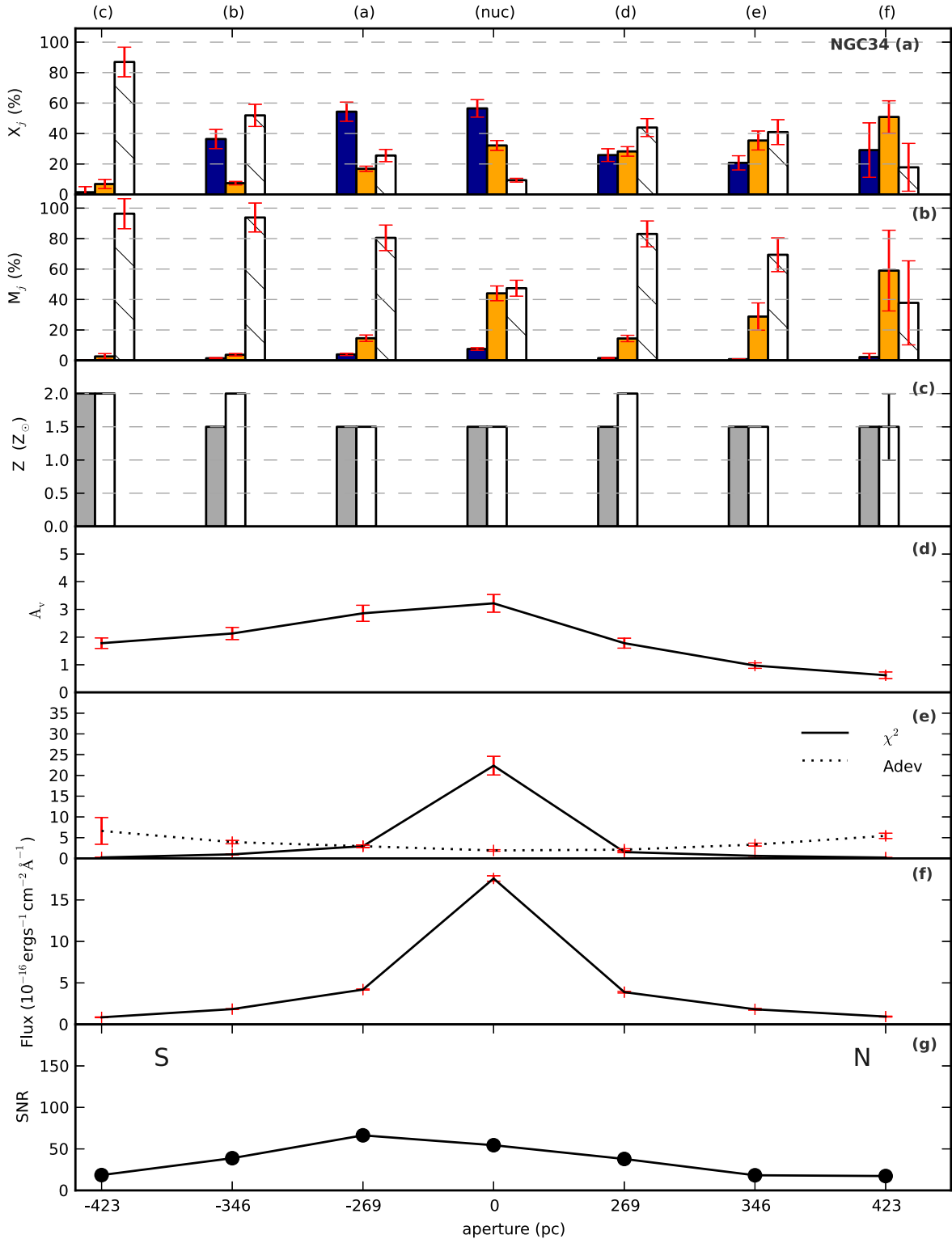


Figure 12. Global analysis for NGC 34. Panels (a) and (b) present the average contribution in flux and mass, respectively, of the population vectors along the apertures. Blue, yellow and red represent young (x_y), intermediate (x_i) and old (x_o) SP contributions, respectively; panel (c) shows the average metallicity weighted by flux (Z_F – filled) and by mass (Z_M – empty); the extinction (A_v) is plotted along the apertures in panel (d); the average χ^2 and Adev are plotted in panel (e); the continuum profile at $\lambda_{\text{cent}} = 12230 \text{ \AA}$ in panel (f) and for last, the SNR along the galaxy in panel (g). The letters on the top of the figure correspond to those of Fig. 1. North (N) and south (S) direction are indicated in the bottom panel.

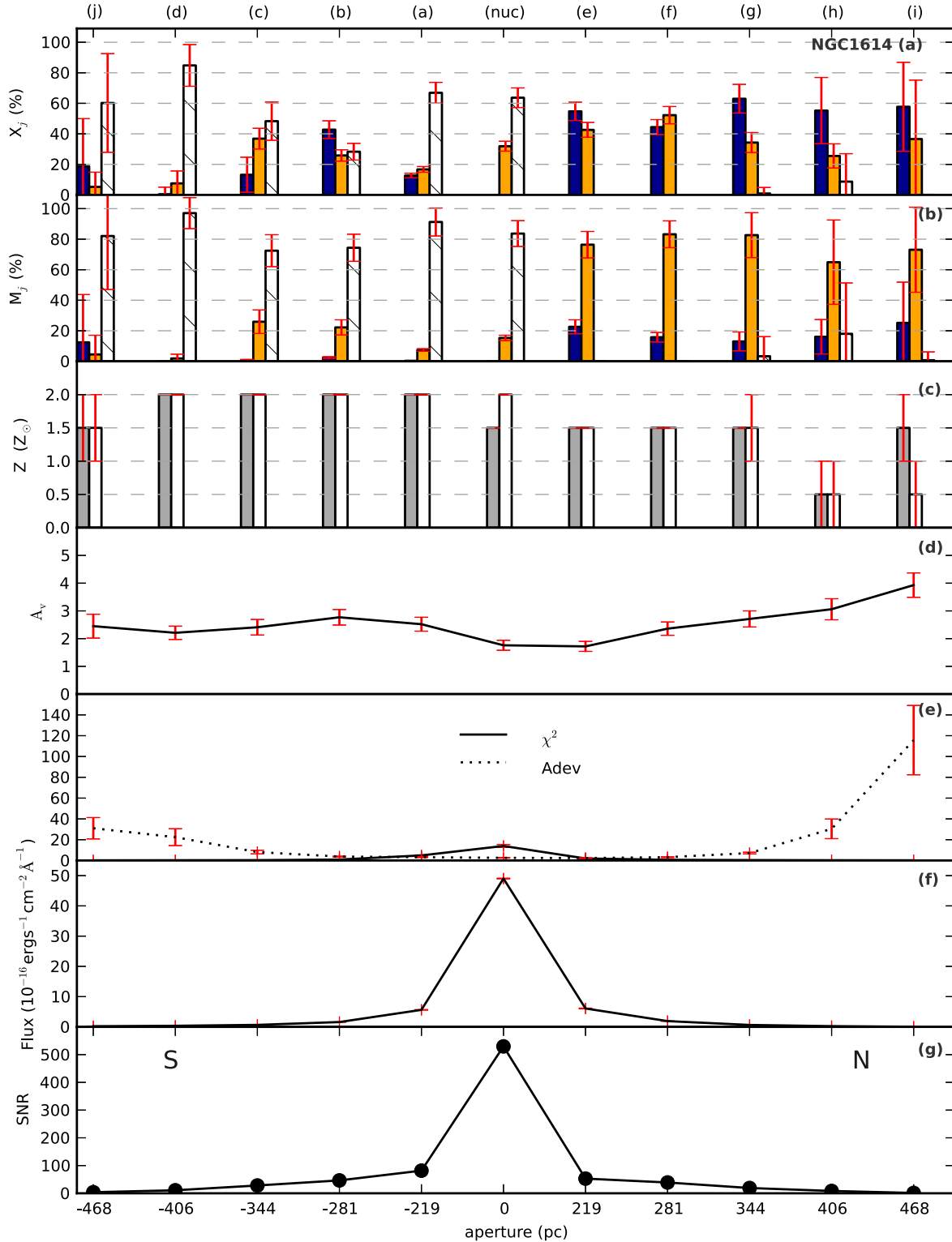


Figure 13. The same as Fig. 12, but for NGC 1614. North (N) and south (S) direction are indicated in the bottom panel.

nuclear region studied by these authors⁶), were investigated by Pastoriza et al. (1993) between 3600 and 9600 Å. In this study, they propose a two-age model (5 and 15 Myr) for the starburst

activity and low-metallicity values (0.2–0.4 Z_\odot) for the circum-nuclear (400 pc from the centre) and disc H II regions, while the nucleus presented solar abundances, in agreement with our results ($Z \sim Z_\odot$ along the galaxy – see Fig. 14c). R08 also studied the inner 56 pc of NGC 3310 in the NIR part of the spectrum, detecting a dominant 1 Gyr old SP. Similar to the scenario we propose for NGC 1614, the low-metallicity SP derived for this source

⁶ It is worth mentioning that the apertures used in this source are the most inner ones in the sample, ranging only up to 106 pc from the nucleus.

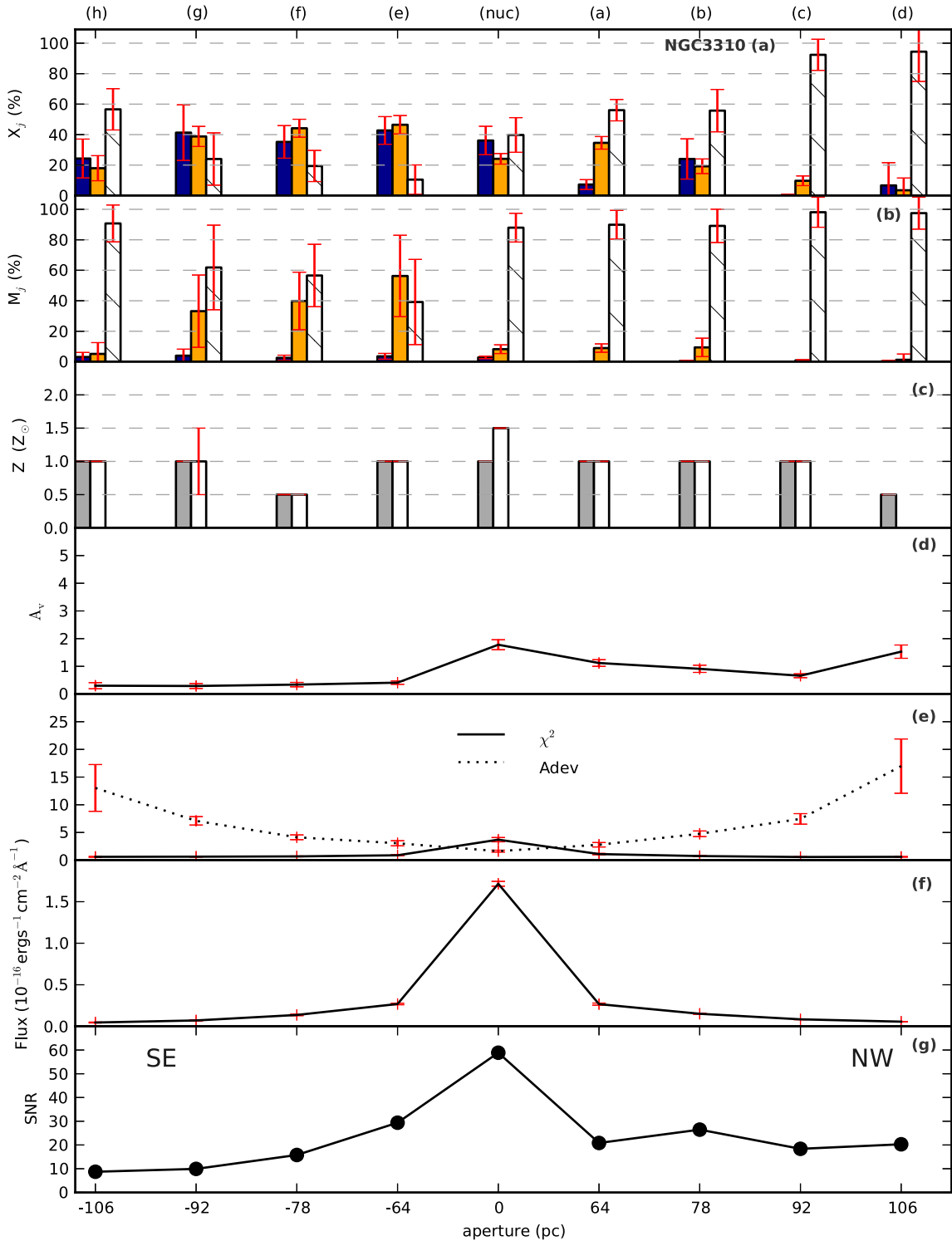


Figure 14. The same as Fig. 12, but for NGC 3310. North-west (NW) and southeast (SE) direction are indicated in the bottom panel.

suggests that the gas present in the galaxy interacting with NGC 3310 (Balick & Heckman 1981) should be metal poor, giving rise to a metal poorer SP.

We found a extinction of $A_v \sim 1.7$ mag in the nucleus, ranging from 0.27 mag southwards to 1.5 mag towards the north direction

($\bar{A}_v = 1.43 \pm 0.06$). As for NGC 1614, Goldader et al. (1995) derived the extinction for this source and found $A_v = 2.69$ mag (in $3 \text{ arcsec} \times 9 \text{ arcsec}$ beam), a slightly larger value than those we found. It is worth mentioning that this is the less interacting galaxy of the sample.

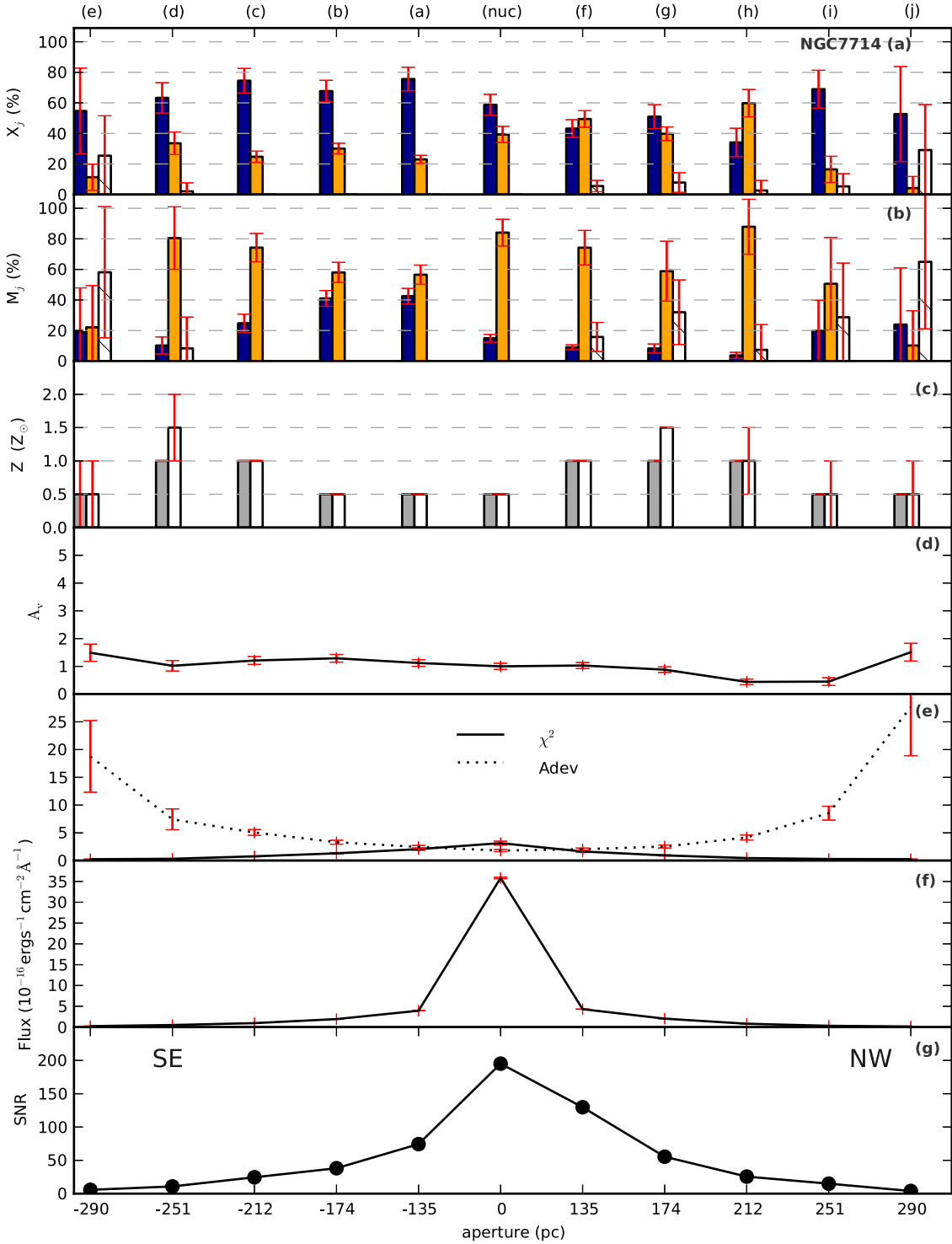


Figure 15. The same as Fig. 12, but for NGC 7714. North-west (NW) and southeast (SE) direction are indicated in the bottom panel.

4.4 NGC 7714

The analysis of the flux contribution of the SP vectors from Fig. 15(a) clearly shows the predominance of the young SP component along the galaxy. While the contribution of this young SP component increases towards south-east, the intermediate-age SP

component increases in the opposite direction. Bernlöhr (1993) has presented an evolutionary model for the pair NGC 7714 and NGC 7715 and stated that NGC 7715 is in the post-burst phase, starting its star formation around 10^8 yr ago, similar to our results. A tidal tail between these two galaxies can be seen in Smith

Table 2. Average synthesis results.

| Galaxy | Aperture (pc) | X_y (per cent) (1) | X_i (per cent) (2) | X_o (per cent) (3) | M_y (per cent) (4) | M_i (per cent) (5) | M_o (per cent) (6) | $Z_F (Z_\odot)$ (7) | $Z_M (Z_\odot)$ (8) | A_v (mag) (9) | Adev (per cent) (10) | χ^2 (11) |
|----------|---------------|----------------------------|----------------------------|----------------------------|----------------------------|----------------------------|----------------------------|------------------------|------------------------|--------------------|----------------------------|------------------|
| NGC 34 | (c)423 S | 2 ± 5 | 7 ± 3 | 87 ± 11 | – | 3 ± 2 | 96 ± 10 | 2.0 | 2.0 | 1.79 ± 0.19 | 6.3 ± 1.6 | 0.2 |
| | (b)346 S | 36 ± 6 | 7 ± 1 | 52 ± 7 | 1 | 4 ± 1 | 94 ± 9 | 1.5 | 2.0 | 2.13 ± 0.22 | 3.9 ± 0.4 | 1.0 ± 0.1 |
| | (a)269 S | 54 ± 6 | 17 ± 2 | 26 ± 4 | 4 ± 1 | 15 ± 2 | 81 ± 8 | 1.5 | 1.5 | 2.86 ± 0.29 | 2.9 ± 0.3 | 2.9 ± 0.3 |
| | Nuc | 49 ± 5 | 31 ± 3 | 18 ± 2 | 5 ± 1 | 30 ± 3 | 64 ± 7 | 1.5 | 1.5 | 3.23 ± 0.32 | 2.2 ± 0.2 | 30.4 ± 3.1 |
| | (d)269 N | 26 ± 4 | 28 ± 3 | 44 ± 6 | 2 | 14 ± 2 | 83 ± 9 | 1.5 | 2.0 | 1.78 ± 0.18 | 2.1 ± 0.2 | 1.5 ± 0.2 |
| | (e)346 N | 21 ± 5 | 35 ± 6 | 41 ± 8 | 1 | 29 ± 9 | 69 ± 11 | 1.5 | 1.5 | 0.97 ± 0.10 | 3.3 ± 0.4 | 0.6 ± 0.1 |
| | (f)423 N | 29 ± 18 | 51 ± 11 | 18 ± 16 | 2 ± 2 | 59 ± 27 | 38 ± 28 | 1.5 | 1.5 ± 0.5 | 0.62 ± 0.12 | 5.4 ± 0.6 | 0.2 |
| NGC 1614 | (j)468 S | 19 ± 31 | 5 ± 10 | 60 ± 32 | 12 ± 31 | 5 ± 13 | 82 ± 35 | 1.5 ± 0.5 | 1.5 ± 0.5 | 2.45 ± 0.43 | 31 ± 10 | 0.2 |
| | (d)406 S | 1 ± 5 | 8 ± 8 | 85 ± 14 | – | 2 ± 3 | 97 ± 10 | 2.0 | 2.0 | 2.21 ± 0.24 | 22 ± 8 | 0.2 |
| | (c)344 S | 13 ± 11 | 37 ± 7 | 48 ± 13 | 1 ± 1 | 26 ± 8 | 72 ± 10 | 2.0 | 2.0 | 2.41 ± 0.28 | 8 ± 2 | 0.3 |
| | (b)281 S | 43 ± 6 | 26 ± 4 | 28 ± 5 | 2 ± 1 | 22 ± 5 | 74 ± 9 | 2.0 | 2.0 | 2.77 ± 0.28 | 4 | 0.9 ± 0.1 |
| | (a)219 S | 13 ± 2 | 17 ± 2 | 67 ± 7 | – | 7 ± 1 | 91 ± 9 | 2.0 | 2.0 | 2.52 ± 0.25 | 3 | 4.9 ± 0.5 |
| | Nuc | – | 32 ± 3 | 64 ± 6 | – | 15 ± 2 | 84 ± 8 | 1.5 | 2.0 | 1.76 ± 0.18 | 3 | 14.0 ± 1.4 |
| | (e)219 N | 54 ± 6 | 43 ± 5 | – | 22 ± 4 | 77 ± 9 | – | 1.5 | 1.5 | 1.73 ± 0.18 | 2 | 2.0 ± 0.2 |
| | (f)281 N | 44 ± 5 | 52 ± 6 | – | 16 ± 3 | 83 ± 9 | – | 1.5 | 1.5 | 2.36 ± 0.24 | 3 | 1.0 ± 0.1 |
| | (g)344 N | 63 ± 9 | 34 ± 7 | 9 ± 4 | 13 ± 6 | 83 ± 15 | 3 ± 13 | 1.5 | 1.5 ± 0.5 | 2.71 ± 0.29 | 7 ± 1 | 0.4 ± 0.1 |
| | (h)406 N | 55 ± 22 | 26 ± 8 | 8 ± 18 | 16 ± 11 | 65 ± 28 | 18 ± 33 | 0.5 ± 0.5 | 0.5 ± 0.5 | 3.06 ± 0.38 | 30 ± 9 | 0.3 |
| | (i)468 N | 49 ± 29 | 48 ± 40 | – | 18 ± 21 | 81 ± 23 | 1 ± 3 | 1.0 ± 0.5 | 0.5 ± 0.5 | 3.93 ± 0.41 | 116 ± 30 | 0.2 ± 0.1 |
| NGC 3310 | (d)106 N | 7 ± 15 | 4 ± 8 | 94 ± 20 | 0 ± 1 | 1 ± 4 | 97 ± 11 | 0.5 | – | 1.53 ± 0.24 | 17 ± 5 | 0.6 ± 0.1 |
| | (c)92 N | 0 ± 1 | 10 ± 3 | 92 ± 10 | – | 1 | 98 ± 10 | 1.0 | 1.0 | 0.66 ± 0.07 | 7 ± 1 | 0.6 ± 0.1 |
| | (b)78 N | 24 ± 13 | 19 ± 5 | 56 ± 14 | – | 9 ± 6 | 89 ± 11 | 1.0 | 1.0 | 0.91 ± 0.13 | 5 ± 1 | 0.7 ± 0.1 |
| | (a)64 N | 6 ± 3 | 39 ± 5 | 53 ± 7 | – | 13 ± 3 | 86 ± 9 | 1.5 | 1.0 | 1.09 ± 0.11 | 3 | 1.2 ± 0.1 |
| | Nuc | 22 ± 4 | 22 ± 3 | 56 ± 7 | 2 | 5 ± 2 | 92 ± 9 | 1.0 | 1.0 | 1.73 ± 0.17 | 2 | 5.0 ± 0.5 |
| | (e)64 S | 39 ± 9 | 47 ± 6 | 14 ± 11 | 3 ± 2 | 48 ± 26 | 48 ± 27 | 1.0 | 1.0 ± 0.5 | 0.39 ± 0.07 | 3 ± 1 | 1.0 ± 0.1 |
| | (f)78 S | 35 ± 11 | 44 ± 6 | 19 ± 10 | 3 ± 2 | 40 ± 19 | 57 ± 20 | 0.5 | 0.5 | 0.34 ± 0.08 | 4 | 0.7 ± 0.1 |
| | (g)92 S | 34 ± 19 | 43 ± 8 | 28 ± 17 | 3 ± 3 | 39 ± 21 | 57 ± 23 | 1.0 | 1.0 ± 0.5 | 0.27 ± 0.08 | 7 ± 1 | 0.6 ± 0.1 |
| | (h)106 S | 24 ± 13 | 18 ± 8 | 57 ± 14 | 3 ± 3 | 5 ± 7 | 91 ± 12 | 1.0 | 1.0 | 0.30 ± 0.11 | 13 ± 4 | 0.6 ± 0.1 |
| | NGC 7714 | (e)290 S | 55 ± 28 | 11 ± 9 | 25 ± 26 | 19 ± 29 | 22 ± 27 | 58 ± 43 | 0.5 ± 0.5 | 0.5 ± 0.5 | 1.49 ± 0.31 | 19 ± 6 |
| (d)251 S | | 63 ± 10 | 34 ± 7 | 2 ± 6 | 10 ± 6 | 81 ± 20 | 8 ± 20 | 1.0 | 1.5 ± 0.5 | 1.02 ± 0.19 | 7 ± 2 | 0.3 |
| (c)212 S | | 75 ± 8 | 25 ± 4 | – | 25 ± 6 | 74 ± 9 | – | 1.0 | 1.0 | 1.21 ± 0.14 | 5 ± 1 | 0.8 ± 0.1 |
| (b)174 S | | 68 ± 7 | 30 ± 3 | – | 41 ± 5 | 58 ± 7 | – | 0.5 | 0.5 | 1.29 ± 0.14 | 3 | 1.3 ± 0.1 |
| (a)135 S | | 76 ± 8 | 23 ± 3 | – | 42 ± 5 | 56 ± 6 | – | 0.5 | 0.5 | 1.12 ± 0.12 | 2 | 2.1 ± 0.2 |
| Nuc | | 59 ± 7 | 39 ± 5 | – | 15 ± 3 | 84 ± 9 | – | 0.5 | 0.5 | 1.00 ± 0.11 | 2 | 3.2 ± 0.4 |
| (f)135 N | | 43 ± 6 | 49 ± 5 | 6 ± 4 | 9 ± 2 | 74 ± 11 | 16 ± 10 | 1.0 | 1.0 | 1.03 ± 0.11 | 2 | 1.6 ± 0.2 |
| (g)174 N | | 51 ± 8 | 40 ± 5 | 8 ± 6 | 8 ± 3 | 59 ± 20 | 32 ± 21 | 1.0 | 1.5 | 0.88 ± 0.10 | 3 | 0.9 ± 0.1 |
| (h)212 N | | 34 ± 9 | 60 ± 9 | 3 ± 7 | 3 ± 2 | 88 ± 18 | 7 ± 17 | 1.0 | 1.0 ± 0.5 | 0.44 ± 0.10 | 4 | 0.4 ± 0.1 |
| (i)251 N | | 69 ± 12 | 16 ± 9 | 5 ± 8 | 20 ± 20 | 51 ± 30 | 29 ± 35 | 0.5 | 0.5 ± 0.5 | 0.45 ± 0.14 | 9 ± 1 | 0.3 |
| (j)290 N | | 53 ± 31 | 4 ± 8 | 29 ± 30 | 24 ± 37 | 10 ± 23 | 65 ± 44 | 0.5 | 0.5 ± 0.5 | 1.51 ± 0.32 | 28 ± 9 | 0.3 |

Notes: (1), (2), (3): average contribution in flux of the young ($t \leq 50 \times 10^6$ yr), intermediate-age ($50 \times 10^6 < t \leq 2 \times 10^9$ yr) and old ($t > 2 \times 10^9$ yr) SP component, respectively; (4), (5), (6): average contribution of the SP components in mass; (7), (8): flux- and mass-weighted mean metallicities; (9) visual extinction; (10) percent mean deviation $|O_\lambda - M_\lambda|/O_\lambda$, where O_λ is the observed spectrum and M_λ is the fitted model and (11) reduced chi square. Whenever there are no error values, the uncertainties are zero.

& Wallin (1992), and we suggest that the SP distribution northwards (increasing intermediate-age SP component) can be related to this post-starburst population in NGC 7715. In fact, such an age is consistent with the scenario proposed by González-Delgado et al. (1999), where the presence of RSGs is associated with the Ca II triplet, present in the galaxy spectrum. Besides, this result is further supported by the fact that this is the side in which NGC 7714 interacted with NGC 7715 in the past (Smith, Struck & Pogge 1997; Struck & Smith 2003). Several previous studies in the UV and optical part of the spectrum (González-Delgado et al. 1995, 1999; Lançon et al. 2001; Cid Fernandes et al. 2003) detected young-age SP from the inner hundreds to thousands of parsecs, in agreement with our work. R08 also found a dominant star formation burst with 1 Gyr old studying the inner 115 pc of this source.

The metallicity, as can be seen from Fig. 15(c), increases with the increase of the intermediate SP, as expected. The lower mean

metallicity values derived for this source can be explained in the scenario proposed by González-Delgado et al. (1995), in which the unprocessed gas from the companion NGC 7715 could be the source of fuel to the starburst in NGC 7714.

As we can see from Fig. 15(d), the visual extinction is nearly constant along the galaxy with $\bar{A}_v = 1.13 \pm 0.04$, similar to the results found in the literature. For example, Kotilainen et al. (2001) derived $A_v = 1.2$ mag (in a 6 arcsec \times 7 arcsec beam) from NIR colours and $A_v = 1.7$ mag from recombination line fluxes, while Oliva et al. (1995) found $A_v = 1\text{--}2$ mag (in a 2.2 arcsec \times 4.4 arcsec beam) assuming an intrinsic stellar colour $H - K = 0.2$. Moreover, Puxley & Brand (1994) found $A_v = 1.8 \pm 0.7$ mag for a point-source model or $A_v = 3.9 \pm 1.7$ mag if sources and dust are homogeneously distributed. They claim, however, that different from NGC 1614, NGC 7714 presents low-extinction values and can indeed be modelled with a simple foreground dust screen model.

4.5 Emission gas

The sample of galaxies analysed in this work display strong emission lines in their spectra, as we can see from Figs 2–5. Apart from the absorption features that shape the continuum emission, these sources have been classified as star-forming/H II galaxies by several previous works, particularly in the optical region (e.g. González-Delgado et al. 1999; Alonso-Herrero et al. 2001; Wehner et al. 2006; Schweizer & Seitzer 2007). Thus, we measured these nebular atomic emission lines ([S III] λ 9530, He I λ 10 830, [Fe II] λ 12 570, Pa β λ 12 810, [Fe II] λ 16 440 and Br γ λ 21 650) and the H₂ λ 21 210 line. It is important to mention that the standard procedure to properly measure emission lines consist of subtracting the stellar continuum fitted by SP synthesis methods. However, we did not subtract the stellar continuum, because the emission lines were severely diluted as a result of the smoothing done in the observed spectra to match the resolution of M05 models ($R \leq 250$ – see Section 3).

The emission-line fluxes can be used, for example, to estimate the reddening effects on the emission gas. Therefore, we derived the interstellar extinction c , the colour excess $E(B - V)$ and the visual extinction A_v (equation 6) for each aperture of the galaxies by means of the emission lines. To this purpose, we assume the ratio of total to selective extinction as $R_v = 4.05 \pm 0.80$, from Calzetti et al. (2000), which is the most suitable one when dealing with SBs (Calzetti et al. 2000; Fischera, Dopita & Sutherland 2003). Moreover, we adopt the intrinsic value of 5.86 for the emission-line ratio Pa β /Br γ , following the case B ($T = 10\,000$ K, $N = 10^2$ cm⁻³; Osterbrock & Ferland 2006). Using the above values, one can determine A_v following the equation:

$$A_v = -15.24 \log \left(\frac{1}{5.88} \frac{\text{Pa}\beta}{\text{Br}\gamma} \right). \quad (6)$$

The measured fluxes are listed in Table 3 and the reddening parameters in Table 4. In a previous work, as we have already mentioned, R08 performed SP synthesis in the nuclear region of the four galaxies studied here. They derived lower values for the colour excess $E(B - V)$ than those present in Table 4. We suggest that this difference can be related to the use of Cardelli et al. (1989) extinction law by R08 when fitting the SP, which is not the most suitable one for SBs (Calzetti, Kinney & Storchi-Bergmann 1994; Fischera et al. 2003).

In fact, when comparing the results for A_v obtained with the emission-line ratio Pa β /Br γ (Table 4 – column 2) and those derived by STARLIGHT code (Table 4 – column 3), we can see that the mean values derived from the emission lines are larger than those obtained from the spectral fitting. A possible explanation for this discrepancy is to consider that the hot ionizing stars could be associated with a dustier region with respect to the cold SP (Calzetti et al. 1994). Another important aspect is that as the merger progresses, tidally induced gas motions and outflows from galactic winds become more frequent (e.g. Heckman, Armus & Miley 1990). In this scenario, shocks induced by large-scale gas flows have an influence on the emission-line gas (e.g. Colina & Montañol-Ibero 2005) and can contaminate the line ratios.

The emission lines can also be used to estimate the SFR of the sources. Adopting $\text{SFR} = L(\text{H}\alpha) \times 7.9 \times 10^{-42}$ and $L(\text{H}\alpha) = 103L(\text{Br}\gamma)$ (Kennicutt 1998), we derived the SFR for each aperture of our galaxy sample using their reddening-corrected Br γ luminosities. The SFRs are listed in Table 4. Since STARLIGHT outputs the mass that have been processed into stars over the last t years (M_*^t), this can be used to estimate the mean SFR over a period of time t .

We have estimated the mean SFR * over the last $t \leq 10$ Myr as being the ratio of M_*^t/t . The obtained values are also listed in Table 4.

As we can see from Table 4, the nuclear SFRs derived through Br γ (column 5) are those that exhibit the major discrepancies when compared to those calculated through STARLIGHT output. In fact, since our sample comprises only SBs, it is likely that a significant fraction of the star formation occurs in dusty regions (Imanishi & Nakanishi 2013). In this sense, our results of the SFR may suggest that the NIR spectral range would probe weaker obscured star-forming regions. Thus, we may miss dustier starburst regions, once our values tend to be smaller than those calculated in larger wavelengths.

For NGC 34, Fernández et al. (2010) calculated the SFR from radio luminosity and found a value of $64 M_\odot \text{ yr}^{-1}$ (in a $3 \text{ arcmin} \times 2 \text{ arcmin}$ beam), in agreement with $\text{SFR} \sim 50 M_\odot \text{ yr}^{-1}$ derived by Prouton et al. (2004) from the FIR luminosity for similar beam. For NGC 1614, Alonso-Herrero et al. (2001) found $\text{SFR} = 52 M_\odot \text{ yr}^{-1}$ from integrated FIR luminosity (in a $45 \text{ arcsec} \times 250 \text{ arcsec}$ beam) and assuming that 70 per cent of this star formation occurs in the nucleus, they predict a nuclear SFR of $36 M_\odot \text{ yr}^{-1}$. For NGC 1614 and NGC 7714, assuming a constant star formation model, Kotilainen et al. (2001) derived SFRs ranging from 2.1 to $4.8 M_\odot \text{ yr}^{-1}$ (in a 3.9 arcsec aperture) and 0.1 to $3.9 M_\odot \text{ yr}^{-1}$ (in a 11.2 arcsec aperture), respectively, while assuming a model of an instantaneous burst of star formation (ISF) they derived SFRs ranging from 11 to $25 M_\odot \text{ yr}^{-1}$ and 0.4 to $16 M_\odot \text{ yr}^{-1}$, respectively. The results derived assuming an ISF are closer to the values derived by us for NGC 1614 and NGC 7714 and we believe that the reason for that is the resembling spacial scale used in their work in relation to this study. Moreover, we suggest that the negligible value derived for the nuclear SFR of NGC 1614 by STARLIGHT can be explained if we consider the LINER classification of this source. In this scenario, the strong emission lines present in the nuclear spectra of this source can be associated with an AGN activity, which would quench the star formation (Nesvadba et al. 2006) in the nucleus and limit it to the outer regions.⁷ It is important to reinforce the scenario in which shocks induced by large-scale gas flows in merging systems affect the emission-line gas and may contaminate the line ratios used to determine the SFRs and A_v for example.

4.6 Comparison between M05 and M11 models

In order to deepen our analysis, we performed SP synthesis for the four galaxies using the new models computed by Maraston & Strömbäck (2011, hereafter M11). These higher resolution models have been constructed in the same way as M05 (e.g. stellar energetics, the atmospheric parameters, the treatment of the TP-AGB phase and horizontal branch morphology), but are based on different stellar spectral libraries (empirical libraries). The set of templates that extend to the NIR are those based on the Pickles (1998) library. Rather than including spectra of individual stars, it practically averages out spectra from several sources. However, since there are not enough spectra to cover all evolutionary phases to a tolerable degree for other than solar metallicities, models were computed with $Z = Z_\odot$. Moreover, above $\sim 1 \mu\text{m}$ about half of the spectra lack spectroscopic observations leading the authors to construct a smooth energy distribution from broad-band photometry, resulting in a featureless region on the M11 spectra. This may imply that some NIR absorption features are not well resolved, even for these

⁷ A proper analysis of this evidence would require an IFU study of the nuclear region of this galaxy.

Table 3. Measured fluxes in units of 10^{-15} erg cm $^{-2}$ s $^{-1}$.

| Galaxy | Aperture | [S III] 0.953 μ m (1) | He I 1.083 μ m (2) | [Fe II] 1.257 μ m (3) | Pa β 1.281 μ m (4) | [Fe II] 1.644 μ m (5) | H $_2$ 2.121 μ m (6) | Br γ 2.165 μ m (7) |
|----------|-----------------|---------------------------------|------------------------------|---------------------------------|------------------------------------|---------------------------------|--------------------------------|-------------------------------------|
| NGC 34 | (c)423 S | 0.54 \pm 0.21 | 0.46 \pm 0.17 | – | 0.23 \pm 0.08 | 0.25 \pm 0.14 | 0.25 \pm 0.03 | 0.09 \pm 0.03 |
| | (b)346 S | 1.15 \pm 0.31 | 0.65 \pm 0.26 | 0.38 \pm 0.12 | 0.37 \pm 0.13 | 0.00 \pm 0.00 | 0.73 \pm 0.11 | 0.22 \pm 0.06 |
| | (a)269 S | 1.46 \pm 0.30 | 2.24 \pm 0.52 | 1.63 \pm 0.15 | 1.23 \pm 0.11 | 1.78 \pm 0.45 | 2.08 \pm 0.22 | 0.81 \pm 0.12 |
| | Nuc | 10.60 \pm 0.84 | 12.00 \pm 1.66 | 8.41 \pm 0.82 | 7.58 \pm 0.71 | 9.32 \pm 2.34 | 8.21 \pm 0.75 | 4.45 \pm 0.54 |
| | (d)269 N | 2.77 \pm 0.32 | 2.92 \pm 0.59 | 1.74 \pm 0.17 | 1.06 \pm 0.11 | 1.65 \pm 0.48 | 1.48 \pm 0.12 | 0.68 \pm 0.08 |
| | (e)346 N | 0.70 \pm 0.21 | – | 0.48 \pm 0.14 | 0.38 \pm 0.11 | – | 0.63 \pm 0.07 | – |
| (f)423 N | – | – | – | – | – | – | – | |
| NGC 1614 | (j)468 S | 0.80 \pm 0.19 | 1.13 \pm 0.20 | 0.41 \pm 0.15 | 0.57 \pm 0.09 | 0.28 \pm 0.06 | 0.08 \pm 0.03 | 0.15 \pm 0.04 |
| | (d)406 S | 1.55 \pm 0.28 | 1.89 \pm 0.26 | 0.50 \pm 0.08 | 0.92 \pm 0.08 | 0.74 \pm 0.08 | 0.14 \pm 0.03 | 0.36 \pm 0.03 |
| | (c)344 S | 4.14 \pm 0.36 | 3.20 \pm 0.23 | 1.12 \pm 0.09 | 2.68 \pm 0.10 | 1.28 \pm 0.11 | 0.53 \pm 0.06 | 1.12 \pm 0.07 |
| | (b)281 S | 14.40 \pm 0.36 | 11.00 \pm 0.32 | 2.78 \pm 0.18 | 9.46 \pm 0.17 | 3.33 \pm 0.24 | 0.83 \pm 0.09 | 3.47 \pm 0.11 |
| | (a)219 S | 46.20 \pm 0.44 | 33.90 \pm 0.64 | 7.11 \pm 0.27 | 25.80 \pm 0.27 | 8.17 \pm 0.84 | 1.36 \pm 0.17 | 9.67 \pm 0.20 |
| | Nuc | 227.00 \pm 1.79 | 187.00 \pm 3.60 | 28.20 \pm 1.49 | 97.30 \pm 1.32 | 17.80 \pm 4.40 | – | 32.00 \pm 1.68 |
| | (e)219 N | 64.40 \pm 0.33 | 51.00 \pm 0.59 | 7.79 \pm 0.34 | 29.80 \pm 0.32 | 8.84 \pm 0.85 | 1.35 \pm 0.15 | 10.40 \pm 0.17 |
| | (f)281 N | 27.90 \pm 0.35 | 21.30 \pm 0.23 | 4.12 \pm 0.17 | 13.90 \pm 0.16 | 4.61 \pm 0.24 | 0.98 \pm 0.08 | 4.63 \pm 0.08 |
| | (g)344 N | 9.61 \pm 0.31 | 7.01 \pm 0.22 | 1.48 \pm 0.14 | 5.21 \pm 0.14 | 1.93 \pm 0.11 | 0.65 \pm 0.07 | 1.71 \pm 0.07 |
| | (h)406 N | 3.37 \pm 0.31 | 2.24 \pm 0.25 | 0.57 \pm 0.10 | 1.87 \pm 0.10 | 0.57 \pm 0.09 | 0.43 \pm 0.07 | 0.65 \pm 0.07 |
| (i)468 N | 0.65 \pm 0.17 | 0.91 \pm 0.21 | 0.36 \pm 0.09 | 0.73 \pm 0.10 | – | 0.24 \pm 0.07 | 0.13 \pm 0.05 | |
| NGC 3310 | (d)106 N | – | – | – | – | – | – | – |
| | (c)92 N | 0.09 \pm 0.03 | – | – | 0.03 \pm 0.02 | – | – | – |
| | (b)78 N | 0.26 \pm 0.06 | 0.13 \pm 0.04 | – | – | – | – | 0.03 \pm 0.01 |
| | (a)64 N | 0.73 \pm 0.04 | 0.40 \pm 0.03 | 0.07 \pm 0.02 | 0.28 \pm 0.02 | 0.13 \pm 0.03 | – | 0.10 \pm 0.01 |
| | Nuc | 6.58 \pm 0.10 | 3.57 \pm 0.11 | 0.75 \pm 0.07 | 2.44 \pm 0.07 | 0.86 \pm 0.13 | – | 0.77 \pm 0.05 |
| | (e)64 S | 0.74 \pm 0.05 | 0.38 \pm 0.05 | 0.09 \pm 0.02 | 0.19 \pm 0.02 | 0.11 \pm 0.03 | 0.06 \pm 0.02 | 0.06 \pm 0.01 |
| | (f)78 S | 0.31 \pm 0.06 | 0.25 \pm 0.08 | – | 0.07 \pm 0.03 | 0.05 \pm 0.02 | – | – |
| | (g)92 S | 0.15 \pm 0.06 | – | – | – | – | – | – |
| (h)106 S | – | – | – | – | – | – | – | |
| NGC 7714 | (e)290 S | 3.61 \pm 0.25 | 1.82 \pm 0.19 | 0.36 \pm 0.08 | 1.21 \pm 0.07 | 0.33 \pm 0.08 | 0.10 \pm 0.04 | 0.30 \pm 0.05 |
| | (d)251 S | 7.17 \pm 0.37 | 4.27 \pm 0.18 | 0.48 \pm 0.14 | 2.58 \pm 0.14 | 0.69 \pm 0.13 | – | 0.47 \pm 0.05 |
| | (c)212 S | 15.90 \pm 0.27 | 10.10 \pm 0.17 | 0.66 \pm 0.16 | 5.24 \pm 0.12 | 0.71 \pm 0.13 | 0.17 \pm 0.05 | 1.14 \pm 0.05 |
| | (b)174 S | 37.30 \pm 0.33 | 23.50 \pm 0.25 | 1.98 \pm 0.16 | 11.20 \pm 0.13 | 1.96 \pm 0.21 | – | 2.78 \pm 0.08 |
| | (a)135 S | 59.90 \pm 0.40 | 41.10 \pm 0.41 | 2.98 \pm 0.20 | 18.50 \pm 0.17 | 2.59 \pm 0.27 | – | 4.55 \pm 0.11 |
| | Nuc | 195.00 \pm 1.89 | 132.00 \pm 2.40 | 17.00 \pm 0.91 | 63.30 \pm 0.97 | 17.10 \pm 2.83 | 2.56 \pm 0.63 | 15.90 \pm 0.66 |
| | (f)135 N | 24.40 \pm 0.28 | 14.90 \pm 0.33 | 4.06 \pm 0.17 | 9.12 \pm 0.15 | 3.76 \pm 0.34 | 0.55 \pm 0.08 | 2.51 \pm 0.09 |
| | (g)174 N | 14.60 \pm 0.20 | 8.67 \pm 0.20 | 2.43 \pm 0.16 | 5.69 \pm 0.13 | 2.24 \pm 0.17 | 0.39 \pm 0.07 | 1.44 \pm 0.06 |
| | (h)212 N | 5.40 \pm 0.21 | 3.21 \pm 0.14 | 0.85 \pm 0.08 | 2.14 \pm 0.08 | 1.00 \pm 0.08 | 0.19 \pm 0.06 | 0.57 \pm 0.04 |
| | (i)251 N | 1.27 \pm 0.18 | 0.98 \pm 0.14 | 0.29 \pm 0.07 | 0.74 \pm 0.08 | 0.29 \pm 0.07 | – | 0.09 \pm 0.03 |
| | (j)290 N | 0.25 \pm 0.10 | 0.14 \pm 0.07 | – | 0.14 \pm 0.04 | 0.14 \pm 0.06 | – | – |

higher resolution models. The authors also call attention for the youngest ages (below ~ 100 Myr), which should be used somewhat more cautiously, once their spectra are significantly attenuated by dust absorption in the UV.

To allow a proper comparison between both models sets, avoiding the discrepancies due to different metallicity ranges, we used a reduced base including only the solar metallicity SSPs from M05 models with the same age range used in Section 4. Figs 16 and 17 present the differences in STARLIGHT output parameters X_y , X_i , X_o , A_v , A_{dev} and χ^2 between M05 and M11 models.

In general, M11 models enhance the old-/intermediate-age SP component in favour of younger ages when compared to M05, leading to small contributions of X_y (the young component would not cross the limit of 40 per cent along the galaxies with the exception of the nucleus of NGC 34 in which the young component reaches ~ 48 per cent). This could be related with M11 models issue regarding younger ages, as mentioned before. The intermediate-age

SP component is the less affected by the choice of the model; however, this SP component tends to get higher values with M11 models, mainly in two galaxies, NGC 34 and NGC 7714. These two sources are the ones that display higher young SP contribution when using M05 models with the full range in metallicities of our base set.

The extinction A_v results are in good agreement (see Figs 16 and 17 – middle panels). NGC 3310 and NGC 7714 though, tend to be less reddened when using M11 models, as well as they present higher A_{dev} and χ^2 values (indicators of the quality of the fit – see Section 3), as we can see by analysing the middle and left-hand panels in Figs 16 and 17.

Due to the limitations of M11 models as discussed above, it is not clear whether the use of these higher resolution models would bring an improvement capable of compensating the fact that they are only available for solar metallicities. Thus, we conclude that the use of low-resolution M05 models are still the best option in this wavelength range.

Table 4. Emission-line ratio and Pa β /Br γ derived quantities: c , A_v , $E(B - V)$ and SFR.

| Galaxy | Aperture | c (1) | A_v (mag) (2) | A_v^* (mag) (3) | $E(B - V)$ (mag) (4) | SFR ($M_{\odot} \text{ yr}^{-1}$) (5) | SFR* ($M_{\odot} \text{ yr}^{-1}$) (6) |
|----------|----------|-----------------|--------------------|----------------------|-------------------------|--|---|
| NGC 34 | (c)423 S | 2.21 ± 1.28 | 5.52 ± 0.32 | 2.86 ± 0.29 | 1.36 ± 0.22 | 0.13 ± 0.08 | 3.65 ± 0.60 |
| | (b)346 S | 3.32 ± 1.18 | 8.28 ± 0.29 | 2.13 ± 0.22 | 2.05 ± 0.33 | 0.48 ± 0.26 | 0.65 ± 0.21 |
| | (a)269 S | 3.59 ± 0.46 | 8.96 ± 0.11 | 1.79 ± 0.19 | 2.21 ± 0.35 | 1.97 ± 0.46 | 0.02 ± 0.06 |
| | Nuc | 3.28 ± 0.41 | 8.20 ± 0.10 | 3.23 ± 0.32 | 2.02 ± 0.32 | 9.63 ± 1.93 | 34.64 ± 3.68 |
| | (d)269 N | 3.52 ± 0.42 | 8.79 ± 0.10 | 1.78 ± 0.18 | 2.17 ± 0.34 | 1.62 ± 0.32 | 2.43 ± 0.65 |
| | (e)346 N | – | – | 0.97 ± 0.10 | – | – | 0.28 ± 0.10 |
| | (f)423 N | – | – | 0.62 ± 0.12 | – | – | 0.20 ± 0.18 |
| | Mean | 2.99 ± 0.24 | 7.45 ± 0.06 | 2.49 ± 0.10 | 2.01 ± 0.13 | | |
| NGC 1614 | (j)468 S | 1.16 ± 0.82 | 2.89 ± 0.20 | 2.52 ± 0.25 | 0.71 ± 0.12 | 0.09 ± 0.04 | 1.11 ± 0.14 |
| | (d)406 S | 2.21 ± 0.32 | 5.52 ± 0.08 | 2.77 ± 0.28 | 1.36 ± 0.22 | 0.34 ± 0.05 | 1.28 ± 0.20 |
| | (c)344 S | 2.38 ± 0.19 | 5.95 ± 0.05 | 2.41 ± 0.28 | 1.47 ± 0.23 | 1.13 ± 0.11 | 0.18 ± 0.16 |
| | (b)281 S | 2.04 ± 0.10 | 5.09 ± 0.02 | 2.21 ± 0.24 | 1.26 ± 0.20 | 3.04 ± 0.15 | 0.00 ± 0.03 |
| | (a)219 S | 2.09 ± 0.06 | 5.23 ± 0.02 | 2.45 ± 0.43 | 1.29 ± 0.20 | 8.67 ± 0.28 | 0.08 ± 0.14 |
| | Nuc | 1.75 ± 0.14 | 4.36 ± 0.04 | 1.76 ± 0.18 | 1.08 ± 0.17 | 25.06 ± 1.93 | – |
| | (e)219 N | 1.91 ± 0.05 | 4.76 ± 0.01 | 1.73 ± 0.18 | 1.17 ± 0.19 | 8.66 ± 0.23 | 12.44 ± 1.9 |
| | (f)281 N | 1.78 ± 0.06 | 4.45 ± 0.01 | 2.36 ± 0.24 | 1.10 ± 0.17 | 3.67 ± 0.10 | 6.60 ± 1.43 |
| | (g)344 N | 1.74 ± 0.13 | 4.35 ± 0.03 | 2.71 ± 0.29 | 1.07 ± 0.17 | 1.34 ± 0.09 | 0.89 ± 0.15 |
| | (h)406 N | 1.89 ± 0.32 | 4.73 ± 0.08 | 3.06 ± 0.38 | 1.17 ± 0.18 | 0.54 ± 0.09 | 0.24 ± 0.14 |
| | (i)468 N | 0.12 ± 1.08 | 0.30 ± 0.27 | 3.93 ± 0.41 | 0.08 ± 0.02 | 0.06 ± 0.03 | 0.04 ± 0.03 |
| | Mean | 1.17 ± 0.03 | 2.94 ± 0.01 | 2.66 ± 0.08 | 1.19 ± 0.02 | | |
| | NGC 3310 | (d)106 N | – | – | 1.09 ± 0.11 | – | – |
| (c)92 N | | – | – | 0.91 ± 0.13 | – | – | – |
| (b)78 N | | – | – | 0.66 ± 0.07 | – | – | – |
| (a)64 N | | 1.97 ± 0.33 | 4.91 ± 0.08 | 1.53 ± 0.24 | 1.21 ± 0.19 | – | – |
| Nuc | | 1.64 ± 0.19 | 4.09 ± 0.05 | 1.73 ± 0.17 | 1.01 ± 0.16 | 0.02 | 0.12 ± 0.02 |
| (e)64 S | | 1.64 ± 0.52 | 4.10 ± 0.13 | 0.39 ± 0.07 | 1.01 ± 0.16 | – | – |
| (f)78 S | | – | – | 0.34 ± 0.08 | – | – | – |
| (g)92 S | | – | – | 0.27 ± 0.08 | – | – | – |
| (h)106 S | | – | – | 0.30 ± 0.11 | – | – | – |
| Mean | | 1.74 ± 0.16 | 4.35 ± 0.04 | 1.43 ± 0.06 | 1.08 ± 0.01 | | |
| NGC 7714 | (e)290 S | 1.00 ± 0.47 | 2.49 ± 0.12 | 1.12 ± 0.12 | 0.62 ± 0.10 | 0.06 ± 0.01 | 2.58 ± 0.31 |
| | (d)251 S | 0.18 ± 0.32 | 0.45 ± 0.08 | 1.29 ± 0.14 | 0.11 ± 0.02 | 0.07 ± 0.01 | 1.63 ± 0.24 |
| | (c)212 S | 0.65 ± 0.13 | 1.63 ± 0.03 | 1.21 ± 0.14 | 0.40 ± 0.06 | 0.20 ± 0.01 | 0.36 ± 0.09 |
| | (b)174 S | 1.00 ± 0.08 | 2.50 ± 0.02 | 1.02 ± 0.19 | 0.62 ± 0.10 | 0.56 ± 0.02 | 0.15 ± 0.05 |
| | (a)135 S | 0.98 ± 0.07 | 2.44 ± 0.02 | 1.49 ± 0.31 | 0.60 ± 0.10 | 0.90 ± 0.03 | 0.07 ± 0.05 |
| | Nuc | 1.03 ± 0.12 | 2.58 ± 0.03 | 1.00 ± 0.11 | 0.64 ± 0.10 | 3.23 ± 0.20 | 15.48 ± 2.35 |
| | (f)135 N | 1.28 ± 0.10 | 3.19 ± 0.03 | 1.03 ± 0.11 | 0.79 ± 0.12 | 0.56 ± 0.03 | 1.70 ± 0.26 |
| | (g)174 N | 1.05 ± 0.13 | 2.63 ± 0.03 | 0.88 ± 0.10 | 0.65 ± 0.10 | 0.30 ± 0.02 | 0.48 ± 0.11 |
| | (h)212 N | 1.19 ± 0.21 | 2.97 ± 0.05 | 0.44 ± 0.10 | 0.73 ± 0.12 | 0.12 ± 0.01 | 0.07 ± 0.03 |
| | (i)251 N | – | – | 0.45 ± 0.14 | – | 0.01 ± 0.00 | 0.01 ± 0.01 |
| | (j)290 N | – | – | 1.51 ± 0.32 | – | – | 0.03 ± 0.02 |
| | Mean | 0.86 ± 0.04 | 2.15 ± 0.01 | 1.13 ± 0.04 | 0.64 ± 0.02 | | |

Notes: (1) interstellar extinction; (2) visual extinction derived by the emission-lines ratio; (3) visual extinction derived by STARLIGHT; (4) colour excess; (5) SFR derived by the emission-lines ratio; (6) SFR derived from STARLIGHT output parameters. Whenever there are no error values, the uncertainties are zero.

5 CONCLUSIONS

We have studied, by means of NIR spectroscopy (from 0.8 to 2.4 μm), the spatial variation of the SPs in the central region of the local universe SBs NGC 34, NGC 1614, NGC 3310 and NGC 7714. Therefore, we employed the STARLIGHT code updated with M05 EPS models, which are the most suitable ones, once they include a proper treatment of the TP-AGB phase crucial to model the SPs in the NIR (M05; Riffel et al. 2011a). Our main conclusions are as follows.

(i) The NIR light dominating the off-nuclear apertures of the galaxies is due to young-/intermediate-age stars ($t \leq 2 \times 10^9$ yr), summing from ~ 40 per cent up to 100 per cent of the light contribution.

(ii) A predominance of young-/intermediate-age SP ($t \leq 2 \times 10^9$ yr) is observed also in the central region of the galaxies, except for NGC 1614 in which the old SP ($t \geq 2 \times 10^9$ yr) prevails in the nucleus, but the younger ages predominate the nuclear surroundings of this source.

(iii) Evidence of a ring-like structure of about 600 pc and a secondary nucleus at ~ 300 pc north from the nucleus was detected in NGC 1614.

(iv) The increase in the intermediate-age SP component north from the nucleus in NGC 7714 could be related to the SP present in its companion, NGC 7715.

(v) The merger experienced by NGC 1614, NGC 3310 and NGC 7714 can explain the discrepancy in its metallicity values, once the fresh unprocessed metal poorer gas from the

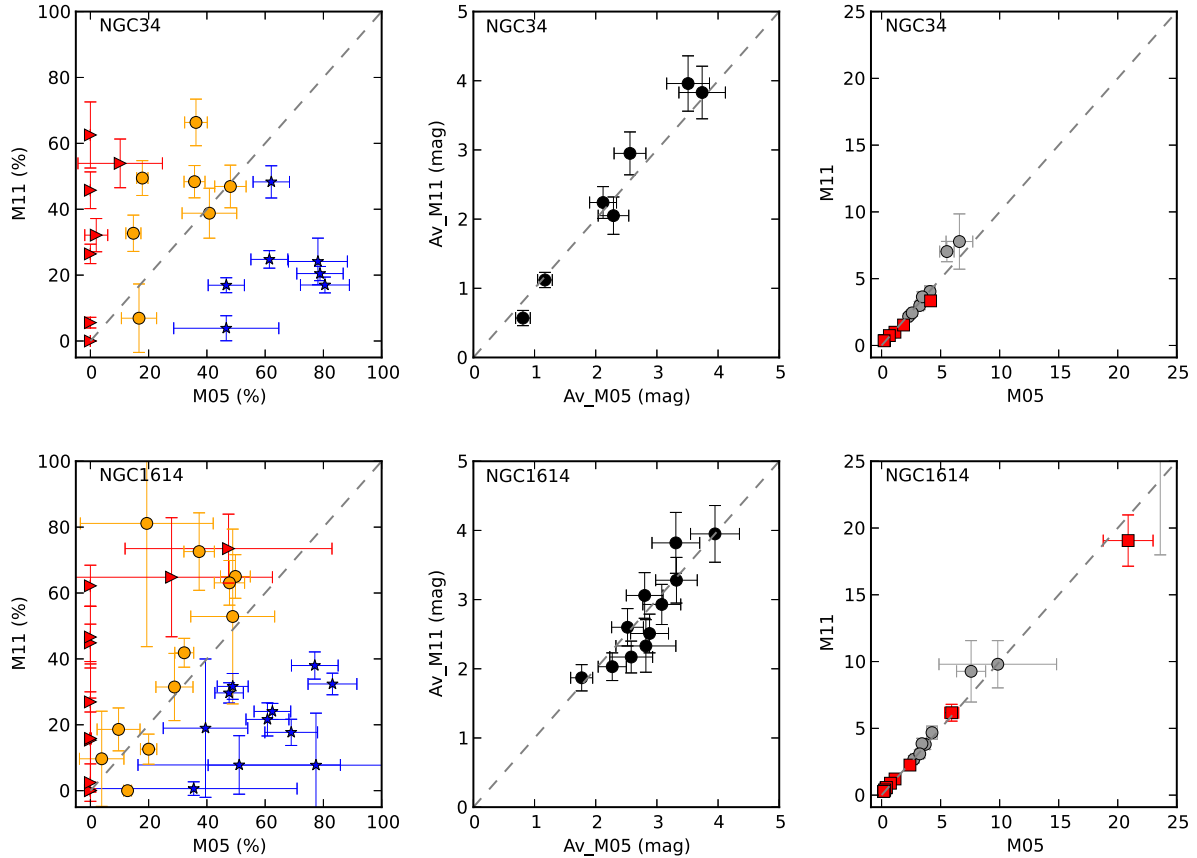


Figure 16. Comparison between the results obtained using **M05** and **M11** models for galaxies NGC 34 (upper panels) and NGC 1614 (bottom panels). Left-hand panels: SP distribution. The different markers indicate the SP age component: X_y (star), X_i (filled circle), X_o (triangle). Middle panels: optical extinction (A_V). Right-hand panels: quality of the fit. The square markers represent the χ^2 and the filled circles the A_{dev} .

destroyed/interacting companion galaxy is driven to the centre of the galaxies and mixed with the central region gas, before star formation takes place. In this context, the lower metallicity values derived for the young SP component ($t \leq 5 \times 10^6$ yr) can be understood as the diluted gas of the remnant.

(vi) As our sample present strong emission lines in their spectra, we measure these nebular lines ($[S\text{III}] \lambda 9530$, $\text{He I } \lambda 10\ 830$, $[\text{Fe II}] \lambda 12\ 570$, $\text{Pa}\beta \lambda 12\ 810$, $[\text{Fe II}] \lambda 16\ 440$, $\text{H}_2(1.0)\text{S}(1)_o \lambda 21\ 210$ and $\text{Br}\gamma \lambda 21\ 650$) and derived values for the visual extinction (A_V) and SFR along the galaxies. Our results on the interstellar extinction tend to agree with those found in the literature. We derived $\bar{A}_V = 7.45 \pm 0.06$, 2.94 ± 0.01 , 4.35 ± 0.04 and 2.15 ± 0.01 for NGC 34, NGC 1614, NGC 3310 and NGC 7714, respectively. Our values for the SFRs tend to be smaller than those calculated in other wavelengths.

(vii) The comparison between **M05** and **M11** models indicates that **M11** models tend to enhance the old-/intermediate-age SP contribution in favour of younger ages. This could be related to the fact that the templates representing the youngest ages (below ~ 100 Myr) are significantly attenuated by dust absorption in the UV (**M11**). Moreover, above $\sim 1 \mu\text{m}$ about half of the spectra lack spectroscopic observations leading the authors to construct a smooth energy distribution from broad-band photometry. This may imply that some NIR absorption features are not well resolved, even for these higher resolution models. Due to these limitations of **M11** models, it is not clear whether the use of these higher resolution models would

bring an improvement capable of compensating the fact that they are only available for solar metallicities. Thus, we conclude that the use of low-resolution **M05** models is still the best option in the NIR wavelength range.

Therefore, the study of the distribution of the SP using the NIR spectral range is a useful tool in order to build a scenario for the star formation along the sources. Moreover, the results for these star-forming interacting systems in the local universe can provide further support to the study of high- z sources, which are of great importance for understanding the history of star formation in the early universe.

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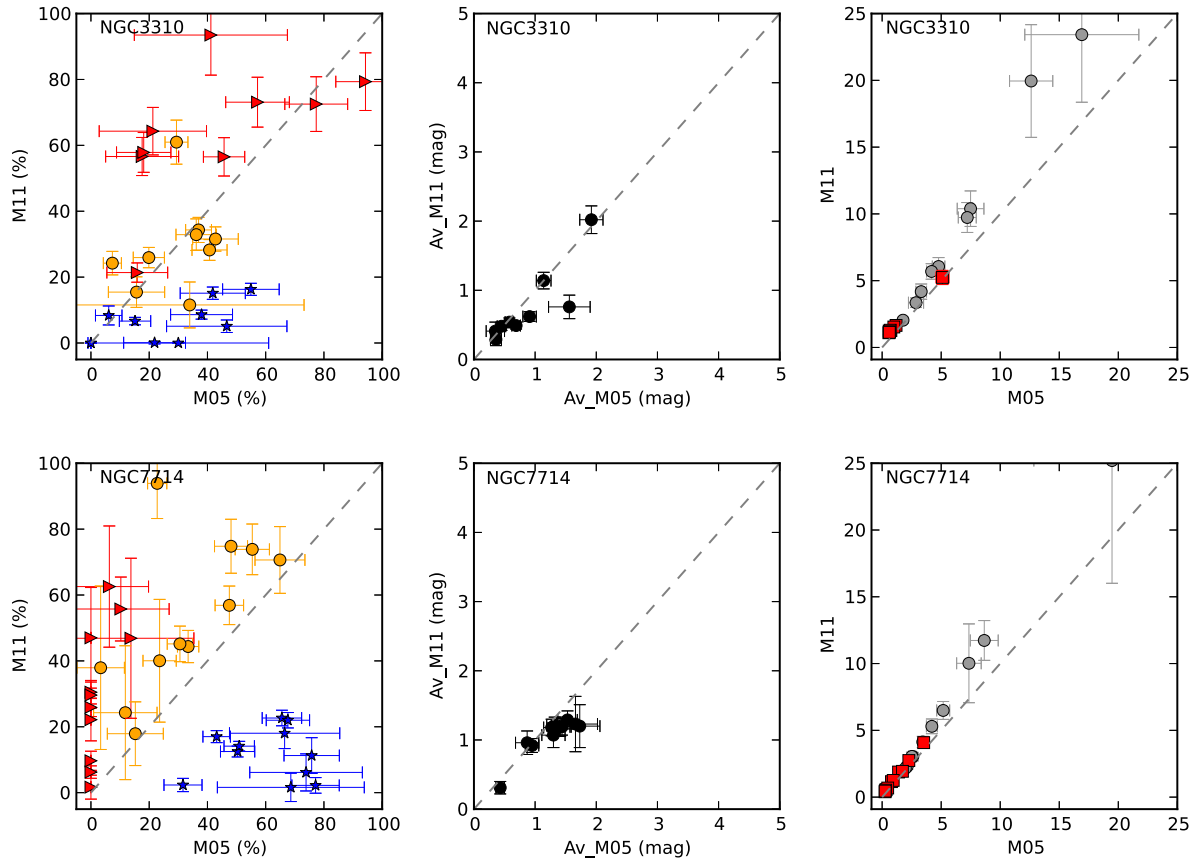


Figure 17. Same as Fig. 16 but for galaxies NGC 3310 (upper panels) and NGC 7714 (bottom panels).

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