

The ages of quasar host galaxies

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ABSTRACT

We present the results of fitting deep off-nuclear optical spectra of radio-quiet quasars, radio-loud quasars and radio galaxies at $z \approx 0.2$ with evolutionary synthesis models of galaxy evolution. Our aim was to determine the age of the dynamically dominant stellar populations in the host galaxies of these three classes of powerful active galactic nuclei (AGN). Some of our spectra display residual nuclear contamination at the shortest wavelengths, but the detailed quality of the fits longward of the 4000-Å break provides unequivocal proof, if further proof were needed, that quasars lie in massive galaxies with (at least at $z \approx 0.2$) evolved stellar populations. By fitting a two-component model we have separated the very blue (starburst and/or AGN contamination) from the redder underlying spectral energy distribution, and find that the hosts of all three classes of AGN are dominated by old stars of age 8–14 Gyr. If the blue component is attributed to young stars, we find that, at most, 1 per cent of the visible baryonic mass of these galaxies is involved in star formation activity at the epoch of observation, at least over the region sampled by our spectroscopic observations. These results strongly support the conclusion reached by McLure et al. that the host galaxies of luminous quasars are massive ellipticals which have formed by the epoch of peak quasar activity at $z \approx 2.5$.

Key words: galaxies: active – galaxies: evolution – quasars: general – galaxies: stellar content.

1 INTRODUCTION

Determining the nature of the host galaxies of powerful active galactic nuclei (AGN) is of importance not only for improving our understanding of different manifestations of AGN activity, but also for exploring possible relationships between nuclear activity and the evolution of massive galaxies. The recent affirmation that black hole mass appears approximately proportional to spheroid mass in nearby inactive galaxies (Magorrian et al. 1998) has further strengthened the motivation for exploring the link between AGN and the dynamical and spectral properties of their hosts.

Over the last few years, improvements in imaging resolution offered by both space- and ground-based optical–infrared telescopes have stimulated a great deal of research activity aimed at determining the basic structural parameters (i.e. luminosity, size and morphological type) of the hosts of radio-loud quasars, radio-quiet quasars and lower-luminosity X-ray-selected and optically selected AGN (e.g. Disney et al. 1995; Hutchings & Morris 1995; Bahcall et al. 1997; Hooper, Impey & Foltz 1997; McLure et al.

1999; Schade, Boyle & Letawsky 2000). However, relatively little corresponding effort has been invested in spectroscopic investigations of AGN hosts, despite the fact that this offers an independent way of classifying these galaxies, and a means of estimating the age of their stellar populations.

Our own work in this field to date has focused on the investigation of the hosts of matched samples of radio-quiet quasars (RQQs), radio-loud quasars (RLQs) and radio galaxies (RGs) at relatively modest redshift ($z = 0.2$). Details of these samples can be found in Dunlop et al. (1993). In brief, the subsamples of quasars (i.e. RQQs and RLQs) have been selected to be indistinguishable in terms of their two-dimensional distribution on the $V-z$ plane, while the subsamples of radio-loud AGN (i.e. RLQs and RGs) have been selected to be indistinguishable in terms of their two-dimensional distribution on the $P_{5\text{GHz}}-z$ plane (and having indistinguishable spectral-index distributions). Deep infrared imaging of these samples (Dunlop et al. 1993; Taylor et al. 1996) has recently been complemented by deep WFPC2 *Hubble Space Telescope* (*HST*) optical imaging (McLure et al. 1999), the final results of which are reported by Dunlop et al. (2001). In addition to demonstrating that, dynamically, the hosts of all three types of luminous AGN appear indistinguishable from normal ellipticals, this work has enabled us to deduce crude spectral

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information on the host galaxies in the form of optical–infrared colours. However, broad-baseline colour information can clearly be most powerfully exploited if combined with detailed optical spectroscopy. Over the past few years we have therefore attempted to complement our imaging studies with a programme of deep optical off-nuclear spectroscopy of this same sample of AGN.

Details of the observed samples, spectroscopic observations and the basic properties of the observed off-nuclear spectra are given in a companion paper (Hughes et al. 2000). As discussed by Hughes et al. (2000), the key feature of this study (other than its size, depth and sample control) is that we have endeavoured to obtain spectra from positions further off-nucleus (≈ 5 arcsec) than previous workers, in an attempt to better minimize the need for accurate subtraction of contaminating nuclear light. This approach was made possible by our deep infrared imaging data, which allowed us to select slit positions ≈ 5 arcsec off-nucleus, which still intercepted the brighter isophotes of the host galaxies [slit positions are shown, superimposed on the infrared images, in Hughes et al. (2000)].

In this paper we present the results of attempting to fit the resulting off-nuclear spectra with evolutionary synthesis models of galaxy evolution. Our primary aim was to determine whether, in each host galaxy, the optical spectrum could be explained by the same model as the optical–infrared colour, and, if so, to derive an estimate of the age of the dynamically dominant stellar population. However, this study also offered the prospect of determining whether the hosts of different classes of AGN differ in terms of their more recent star formation activity.

It is worth noting that our off-nuclear spectroscopy obviously does not enable us to say anything concerning the level of star formation activity in the nucleus of a given host galaxy. Rather, any derived estimates of the level of star formation activity refer to the region probed by our observations ≈ 5 arcsec off-nucleus. However, given the large scalelengths of the hosts, their relatively modest redshift, and the fact that our spectra are derived from long-slit observations, it is reasonable to regard our conclusions as applying to fairly typical regions, still located well within the bulk of the host galaxies under investigation.

The layout of this paper is as follows. In Section 2 we provide details of the adopted models, and how they have been fitted to the data. The results are presented in Section 3, along with detailed notes on the fitting of individual spectra. The implications of the model fits are then discussed in Section 4, focusing on a comparison of the typical derived host-galaxy ages in the three AGN subsamples. Finally, our conclusions are summarized in Section 5. The detailed model fits, along with corresponding chi-squared plots are presented in Appendix A.

2 SPECTRAL FITTING

The stellar population synthesis models adopted for age-dating the AGN host galaxy stellar populations are the solar metallicity, instantaneous starburst models of Jimenez et al. (2001). We have endeavoured to fit each off-nuclear host galaxy optical spectrum by a combination of two single starburst components. For the first component, age is fitted as a free parameter, while for the second component the age is fixed at 0.1 Gyr, and the normalization relative to the first component is the only free parameter. This dual-component approach was adopted because single-age models are not able to adequately represent the data, and because it allows the age of the dynamically dominant component to be determined in a way that is not overly reliant on the level of ultraviolet flux which might be contributed either by a recent burst of star

formation, or by contamination of the slit by scattered light from the quasar nucleus. After experimentation it was found that the spectral shape of the blue light was better represented by the 0.1-Gyr-old (solar metallicity) model of Jimenez than by models of greater (intermediate) age (e.g. 1 Gyr). Moreover, the further addition of a third intermediate age component, ≈ 1 Gyr, did not significantly improve the quality of the fits achieved.

In general, our data are of insufficient quality to tell whether the component that dominates at $\lambda \approx 3000 \text{ \AA}$ is caused really by young stars, or whether it is produced by direct or scattered quasar light. However, while the origin of the blue light is obviously of some interest, it has little impact on the main results presented in this paper, which refer to the age of the dynamically dominant stellar population that dominates the spectrum from longward of the 4000-\AA break through to the near-infrared. The robustness of the age determination of the dominant population is demonstrated by comparing the results of the two stellar-population model fits with the results of a fit allowing for a nuclear contribution in addition to the two stellar populations.

The model parameters determined were therefore the age of the dominant stellar population, which we can reasonably call the age of the galaxy, and the fraction, by (visible) baryonic mass, of the 0.1-Gyr component. For the fit including a nuclear contribution, the fraction of the total flux contributed by quasar light was a third parameter. The red end of each SED was further constrained by

Table 1. Wavelength ranges of observed spectra, and splice regions which were excluded from the fitting process. All wavelengths are in the observed frame. M4M denotes the Mayall 4-m telescope at Kitt Peak, and WHT denotes the 4.2-m William Herschel Telescope on La Palma (see Hughes et al. (2000) for observational details).

IAU name	Telescope	Wavelength range (\AA)	Masked splice region (\AA)
Radio-loud quasars			
0137+012	M4M	3890–6950	
0736+017	M4M	3890–6950	
	WHT	3500–8000	6050–6150
1004+130	WHT	3500–8000	6050–6150
1020–103	M4M	3890–6950	
1217+023	WHT	3500–7500	6000–6100
2135–147	WHT	3500–8500	6000–6100
2141+175	WHT	3500–8500	6000–6100
2247+140	M4M	3890–6950	
	WHT	3500–7500	6050–6150
2349–014	WHT	3500–8300	6000–6100
Radio-quiet quasars			
0054+144	M4M	3890–6950	
	WHT	3500–8000	6000–6100
0157+001	M4M	3890–6950	
	WHT	3500–8000	6050–6150
0204+292	WHT	3500–8000	6050–6150
0244+194	WHT	3500–8500	6000–6100
0923+201	WHT	3500–7000	
1549+203	WHT	3500–8000	6050–6150
1635+119	WHT	3500–7800	6000–6100
2215–037	WHT	3500–8500	6000–6100
2344+184	M4M	3890–6950	
	WHT	3500–8500	6000–6100
Radio galaxies			
0230–027	WHT	3500–8500	6000–6100
0345+337	WHT	3500–8500	6000–6100
0917+459	WHT	3500–8500	6050–6150
1215–033	WHT	3500–7500	6000–6100
1330+022	M4M	3890–6950	
2141+279	M4M	3890–6950	

fitting $R - K$ colour simultaneously with the optical spectral energy distribution. The fitting process is described below.

First, the observed off-nuclear spectra were corrected for redshift and transformed to the rest frame. They were then rebinned to the spectral resolution of the model spectra. The rebinned flux is then the mean flux per unit wavelength in the new bin and the statistical error on each new bin is the standard error in this mean. The data were normalized to a mean flux per unit wavelength of unity across the wavelength range 5020–5500 Å.

The two-component model was built from the instantaneous-burst stellar-population synthesis model (SEDs), so that

$$F_{\lambda,age,\alpha} = \text{constant} \times [\alpha f_{\lambda,0.1} + (1 - \alpha) f_{\lambda,age}],$$

where $f_{\lambda,age}$ is the mean flux per unit wavelength in the bin centred on wavelength λ for a single-burst model of age Gyr, α is the fraction by mass of the young (0.1-Gyr) component, and $F_{\lambda,age,\alpha}$ is then the new, mean twin stellar-population flux per unit wavelength in the bin centred on wavelength λ for a model of age Gyr. This composite spectrum was then normalized in the same way as the observed spectra.

A χ^2 fit was used to determine the age of the older stellar population and the mass fraction, α , of the younger population, for each host galaxy in the sample. The whole parameter space was searched, with the best-fitting values quoted being those parameter values at the point on the grid with the minimum calculated χ^2 . The normalization of the model spectra was allowed to float during the fitting process, to allow the best-fitting continuum shape to be determined in an unbiased way.

The models were fitted across the observed (rest-frame) spectral range, within the wavelength ranges listed in Table 1. As a result of the optimization of the instruments with which the objects were observed, some of the galaxy spectra contain a ‘splice’ region where the red and blue end of the spectrum have been observed separately and then joined together [see Hughes et al. (2000) for details]. These splice regions, defined in Table 1, were masked out of the fit in order to guard against the fitting procedure being dominated by data points the flux calibration of which was potentially less robust. The main emission lines, present because of nuclear light contamination or nebular emission from within the host, were also masked out, over the wavelength ranges given in Table 2.

The fit including a nuclear component was carried out in the same way, with the model flux in this case being

$$F_{\lambda,age,\alpha,\eta} = \text{constant} \times (\alpha f_{\lambda,0.1} + (1 - \alpha) f_{\lambda,age} + \eta f_{0054\lambda}),$$

where η is the fraction contributed to the total model flux by the nucleus, and $f_{0054\lambda}$ is the observed flux of the nucleus of the radio-quiet quasar 0054+144. α is the fraction by mass of the total stellar population contributed by the 0.1-Gyr population. The wavelength range of the observed nuclear flux of 0054+144 is 3890–6950 Å. This was extended to 3500–8500 Å by smooth extrapolation over the wavelength ranges 3500–3890 and 6950–8500 Å in order to carry out the χ^2 fit across the full wavelength range of the observed off-nuclear spectra.

$R - K$ colour was fitted in both cases with a typical error of a

Table 2. Rest frame emission lines masked out in the χ^2 fit.

Masked region (Å)	Emission line
3720–3735	O II 3727
3860–3880	Ne III 3869
4840–5020	O III 4959, O III 5007, H β 4861

few per cent. The observed $R - K$ colours for the host galaxies are obtained from *UKIRT* and *HST* images (McLure et al. 1999; Dunlop et al. 2001), and define the basic shape of the host galaxy SED out to $\lambda \approx 2 \mu\text{m}$. The composite model spectra were appropriately redshifted before calculating the colour, so that they could be compared with the observed colours without introducing uncertainties in k -correction. The R -band was simulated using the filter function, including system response and CCD quantum efficiency, for the *HST* WFPC2 F675W filter, and the K -band was reproduced using the filter data for the IRCAM3 K Ocli filter at 77 K combined with Mauna Kea atmosphere.

3 RESULTS

The plots showing fits to individual spectra and χ^2 as a function of fitted age are given in Appendix A. The plots for the two-component fit are presented in Fig. A1, and those for the two stellar-component plus nuclear contribution are in Fig. A2. The results for each object are summarized below, under their IAU names, with alternative names given in parentheses. Objects are listed in order of increasing right ascension, within each AGN class (radio-loud quasars, radio-quiet quasars and radio galaxies). The telescopes with which the spectra were obtained are also noted; M4M denotes the Mayall 4-m telescope at Kitt Peak and WHT denotes the 4.2-m William Herschel Telescope on La Palma. Where there are two spectra, the first plot is for the spectrum observed with the Mayall 4-m telescope, and the second is for the spectrum taken with the William Herschel Telescope.

3.1 Notes on individual objects

3.1.1 Radio-loud quasars

0137+012 (L1093) M4M. The models give a good fit at 13 Gyr, which is clearly improved by the inclusion of a small percentage (0.25 per cent) of young stars. There is no significant nuclear contribution to the spectrum. *HST* imaging has shown that this host galaxy is a large elliptical, with a half-light radius $r_e = 13$ kpc (McLure et al. 1999).

0736+017 (S0736+01, OI 061) M4M, WHT. 0736+017 has been observed with both telescopes, and fits to the two observed spectra are in good agreement. Both indicate an age of 12 Gyr. The M4M spectrum requires a somewhat larger young blue population (0.75 per cent) than the WHT spectrum (0.125 per cent). This may be caused by poorer seeing at Kitt Peak leading to slightly more nuclear contamination of the slit, or to the use of slightly different slit positions at the two telescopes. However, this difference between the observed spectra shortward of 4000 Å leaves the basic form of χ^2 versus age, and the best-fitting age of 12 Gyr unaffected. Inclusion of a nuclear component gives a much better fit to the blue end of the M4M spectrum, without changing the age estimation. The size of the fitted young populations are in much better agreement in this case. *HST* imaging has shown that morphologically this host galaxy is a large elliptical, with a half-light radius $r_e = 13$ kpc (McLure et al. 1999).

1004+130 (S1004+13, OL 107.7, 4C 13.41) WHT. The spectrum of this luminous quasar certainly appears to display significant nuclear contamination below the 4000-Å break. As a result a relatively large young population is required to attempt (not completely successfully) to reproduce the blue end of the spectrum. However, the models predict that the underlying stellar population is old (12 Gyr). Allowing a nuclear component to be fitted reproduces the blue end of the spectrum much more

successfully, without changing the best-fitting age estimation. *HST* *R*-band imaging indicates the morphology of the host galaxy is dominated by a large ($r_e = 8$ kpc) spheroidal component, but subtraction of this best-fitting model reveals two spiral-arm-type features on either side of the nucleus (McLure et al. 1999), which may be associated with the young stellar component required to explain the spectrum.

1020–103 (S1020–103, OL 133) M4M. This object has the second bluest *R* – *K* of this sample, which leads to a much younger inferred age than the majority of the rest of the sample (5 Gyr), despite the presence of a rather clear 4000-Å break in the optical spectrum. Ages greater than ≈ 10 Gyr are rejected by Jimenez’ models, primarily on the basis of *R* – *K* colour. *HST* imaging has shown that this host has an elliptical morphology, and a half-light radius of $r_e = 7$ kpc (Dunlop et al. 2001).

1217+023 (S1217+02, UM 492) WHT. Nuclear contamination can again be seen bluewards of 4000 Å, with a correspondingly large young population prediction for the purely stellar population model, which still fails to account for the very steep rise towards 3000 Å. Hence, a large nuclear contribution is required to reproduce the blue end of the spectrum. The fit achieved by the models suggests that the dominant population is old, with a best-fitting age of 12 Gyr. *HST* imaging has shown that this host has an elliptical morphology, and a half-light radius of $r_e = 11$ kpc (Dunlop et al. 2001).

2135+147 (S2135–14, PHL 1657) WHT. 2135+147 has a very noisy spectrum, but a constrained fit has still been achieved, and an old population is preferred. 2135+147 requires a large α , even when a nuclear contribution is fitted. *HST* imaging has shown that this host has an elliptical morphology, and a half-light radius of $r_e = 12$ kpc (Dunlop et al. 2001).

2141+175 (OX 169) WHT. This is another noisy spectrum, which has a relatively large quasar light contribution. An old population is again indicated by the model fits. From optical and infrared imaging this object is known to be complex, but *HST* images indicate that it is dominated by a moderate sized ($r_e = 4$ kpc) elliptical component [see McLure et al. (1999) for further details].

2247+140 (PKS 2247+14, 4C 14.82) M4M, WHT. 2247+140 has been observed with both telescopes. The model fitting indicates an old population is required by both spectra – although the two observations do not agree precisely, the general level of agreement is very good, the two χ^2 plots have a very similar form, and the difference in χ^2 between the alternative best-fitting ages of 8 and 12 Gyr is very small. No significant nuclear contribution to the flux is present. *HST* imaging has shown that this host has an elliptical morphology, and a half-light radius of $r_e = 14$ kpc (Dunlop et al. 2001).

2349–014 (PKS 2349–01, PB 5564) WHT. This is a very good fit to a good-quality spectrum, showing an obvious improvement when the low-level young population is added. Jimenez’ models clearly predict that the dominant population is old, with a well-constrained age of 12 Gyr. A very small nuclear contribution ($\eta = 0.050$) does not significantly change the results. *HST* imaging of this object strongly suggests that it is involved in a major interaction, with a massive tidal tail extending to the north of the galaxy. However, the dominant morphological component is a spheroid with a half-light radius of $r_e = 18$ kpc (McLure et al. 1999).

3.1.2 Radio-quiet quasars

0054+144 (PHL 909) M4M, WHT. There is evidence of relatively large contamination from nuclear emission in the spectrum of this

luminous quasar taken on both telescopes, and the age is not well-constrained, although the fit to the WHT spectrum derived from the models again suggests an old age. The χ^2 plots serve to emphasize how similar the two spectra of this object actually are (as also discussed by Hughes et al. 2000). Inclusion of a nuclear component in the model better constrains the age and improves the goodness of the fit. *HST* imaging of this object has shown that, morphologically, it is undoubtedly an elliptical galaxy, with a half-light radius of $r_e = 8$ kpc (McLure et al. 1999).

0157+001 (Mrk 1014) M4M, WHT. The age inferred from both the M4M and WHT spectrum of 0157+001 is again 12 Gyr. The apparently more nuclear-contaminated WHT spectrum does not give such a good fit, but 0157+001 is a complex object known to have extended regions of nebular emission, and the slit positions used for the two observations were not identical (Hughes et al. 2000). The age is much better constrained from the more passive M4M spectrum, to which Jimenez’ models provide a very good fit. Again, it seems that the nuclear contamination does not have a great influence on the predicted age of the old population, although the fit to the WHT spectrum is greatly improved by including a nuclear component in the model. Despite its apparent complexity in both ground-based and *HST* images, this host galaxy does again seem to be dominated by a large spheroidal component, of half-light radius $r_e = 8$ kpc (McLure et al. 1999).

0204+292 (3C 59) WHT. Jimenez’ models fit the spectrum of this object well, indicating an old underlying stellar population (>6 Gyr), with a best-fitting age of 13 Gyr for the stellar population plus nuclear component model, and a very small young population. *HST* imaging has shown this galaxy to be an elliptical, with a half-light radius of $r_e = 9$ kpc (Dunlop et al. 2001).

0244+194 (MS 02448+19) WHT. The colour derived from the optical and infrared imaging of this host galaxy is rather blue [$(R - K)_{\text{obs}} = 2.34$] and this in part leads to a fairly young (5 Gyr) age prediction. However, the spectrum is very noisy, and, as indicated by the very flat χ^2 plot, the age is not strongly constrained. No nuclear flux contamination is fitted. *HST* imaging has shown this galaxy to have an elliptical morphology, with a half-light radius of $r_e = 9$ kpc (McLure et al. 1999).

0923+201 WHT. The spectrum of 0923+201 is noisy, and it also appears to have some nuclear contamination. The fit is therefore improved by inclusion of a nuclear component. An old age is strongly preferred by the form of the χ^2 /age plot, with a best-fitting value of 12 Gyr. *HST* imaging has shown this galaxy to have an elliptical morphology, with a half-light radius of $r_e = 8$ kpc (McLure et al. 1999).

1549+203 (1E 15498+203, LB 906, MS 15498+20) WHT. This is a good fit, which is clearly improved by the addition of the younger population. The slope of the χ^2 /age plot strongly indicates an old dominant population, with a best-fitting age of 12 Gyr. There is very little evidence of nuclear contamination. *HST* imaging has shown this galaxy to be a moderate-sized elliptical with $r_e = 5$ kpc (Dunlop et al. 2001).

1635+119 (MC1635+119, MC2) WHT. This is another very successful fit. An old age (12 Gyr) is inferred. Again, *HST* imaging has shown this galaxy to be a moderate-sized elliptical with $r_e = 6$ kpc (McLure et al. 1999).

2215–037 (MS 22152–03, EX 2215–037) WHT. 2215–037 has a noisy spectrum, to which an acceptable fit has nevertheless been possible. Jimenez’ models suggest an old population, with a best-fitting age of 14 Gyr, but this age is not well constrained. This is the only object where the inclusion of a nuclear contribution to the fitted spectrum substantially changes the age predicted of the

Table 3. Results from the simultaneous fitting to the AGN host sample of the two-component model spectra (using the solar metallicity models of Jimenez et al. 2000) and $R - K$ colour. α is the percentage young population, by mass. Results are also presented for the fits including the subtraction of a nuclear component from the observed spectrum. η is the fraction of nuclear flux subtracted, and the corresponding results are denoted by the subscript η .

IAU name	Telescope	Best fit age/Gyr	Best fit age $_{\eta}$ /Gyr	α	α_{η}	Reduced χ^2	Reduced χ^2_{η}	$(R - K)_{fit}$	$(R - K)_{fit_{\eta}}$	$(R - K)_{obs}$	η	z
Radio-loud quasars												
0137+012	M4M	13	13	0.2	0.3	3.7	3.6	2.88	2.88	2.82	0.025	0.258
0736+017	M4M	12	12	0.7	0.1	12.0	6.2	2.69	2.89	3.16	0.250	0.191
	WHT	12	12	0.1	0.0	3.3	2.9	2.89	2.93		0.100	
1004+130	WHT	12	12	1.4	0.4	5.4	2.2	2.65	2.96	3.01	0.350	0.240
1020-103	M4M	5	4	0.6	0.0	1.7	1.5	2.33	2.29	2.29	0.125	0.197
1217+023	WHT	12	12	1.1	0.0	11.8	4.9	2.71	3.10	3.18	0.350	0.240
2135-147	WHT	12	11	1.6	1.0	2.2	2.2	2.50	2.50	2.49	0.175	0.200
2141+175	WHT	12	14	1.1	0.5	3.2	2.5	2.66	2.69	2.69	0.500	0.213
2247+140	M4M	8	8	0.3	0.3	1.8	1.8	2.77	2.77	2.81	0.000	0.237
	WHT	12	12	0.9	0.9	2.9	2.9	2.79	2.79		0.000	
2349-014	WHT	12	12	0.5	0.4	3.3	3.0	2.71	2.75	2.87	0.050	0.173
Radio-quiet quasars												
0054+144	M4M	8	12	1.3	0.3	46.9	9.1	2.32	2.78	3.12	0.400	0.171
	WHT	12	12	1.3	0.0	17.7	3.6	2.51	2.86		0.475	
0157+001	M4M	12	12	1.1	1.1	5.9	5.8	2.52	2.52	2.83	0.025	0.164
	WHT	12	12	1.6	0.9	41.0	10.9	2.41	2.58		0.250	
0204+292	WHT	14	13	0.2	0.1	6.3	5.4	2.47	2.45	2.49	0.125	0.109
0244+194	WHT	5	5	0.1	0.1	2.6	2.6	2.37	2.37	2.34	0.000	0.176
0923+201	WHT	12	12	0.6	0.0	5.6	4.0	2.72	2.92	3.24	0.375	0.190
1549+203	WHT	12	12	0.6	0.5	3.8	3.8	2.90	2.95	3.37	0.050	0.250
1635+119	WHT	12	12	0.7	0.5	6.7	6.4	2.57	2.63	3.27	0.100	0.146
2215-037	WHT	14	6	0.6	0.3	2.4	2.4	2.70	2.69	2.68	0.175	0.241
2344+184	M4M	8	11	0.4	0.4	4.8	4.9	2.43	2.57	2.51	0.025	0.138
	WHT	12	12	0.9	0.8	2.1	2.0	2.51	2.54		0.075	
Radio galaxies												
0230-027	WHT	1	1	0.0	0.0	2.0	2.0	2.02	2.02	2.08	0.000	0.230
0345+337	WHT	12	12	0.0	0.0	2.7	2.7	3.13	3.13	3.62	0.000	0.244
0917+459	WHT	12	12	0.2	0.3	4.7	4.6	2.79	2.79	3.42	0.025	0.174
1215-033	WHT	13	13	0.0	0.0	3.4	3.4	2.74	2.74	2.56	0.000	0.184
1330+022	M4M	8	8	0.3	0.1	2.9	2.8	2.70	2.74	2.79	0.050	0.215
2141+279	M4M	12	12	0.1	0.0	3.1	2.5	3.27	3.01	3.25	0.025	0.215

dominant stellar population. However, the χ^2 plots are very flat after an age of 5 Gyr, and the age is not strongly constrained in either case. *HST* imaging has shown this galaxy to have an elliptical morphology, with $r_e = 7$ kpc (Dunlop et al. 2001).

2344+184 (E2344+184) M4M, WHT. 2344+184 has been observed with both telescopes, and the fits to both spectra are in good agreement – although, formally, two different ages are predicted. This is because the χ^2/age plots are fairly flat after about 8 Gyr. The fits to both observations suggest an old dominant population, with a small young blue population improving the fit. There is no significant change in the predictions when a nuclear flux component is included in the model. *HST* imaging has shown this to be one of the few host galaxies in the current sample to be disc-dominated. However, the nuclear component is in fact sufficiently weak that this object should really be classified as a Seyfert galaxy rather than an RQQ (McLure et al. 1999).

3.1.3 Radio galaxies

0230-027 (PKS 0230-027) WHT. 0230-027 has a very noisy spectrum, and the colour of the host as derived from optical and infrared imaging is very blue [$(R - K)_{obs} = 2.09$]. Consequently, the best-fitting age derived using the models is 1 Gyr, with no younger component, but it is clear that little reliance can be placed on the accuracy of this result. Allowing for a contribution from quasar light does not improve the fit. *HST* imaging has shown this galaxy to have an elliptical morphology, with $r_e = 8$ kpc (Dunlop et al. 2001).

0345+337 (3C 93.1) WHT. 0345+337 requires no young component or nuclear flux contribution at all, and an old age, of 12 Gyr, is clearly indicated by the models. *HST* imaging has shown this galaxy to be a large elliptical, with $r_e = 13$ kpc (McLure et al. 1999).

0917+459 (3C 219, 3C 219.0) WHT. This is an excellent fit, with an old age produced by the models (12 Gyr), together with a very small young population. *HST* imaging has shown this galaxy to be a large elliptical, with $r_e = 11$ kpc (McLure et al. 1999).

1215-033 WHT. Jimenez’ models suggest that the population of 1215-033 is universally old (best-fitting age, 13 Gyr), with no young component or nuclear contribution required. *HST* imaging has shown this galaxy to be a large elliptical, with $r_e = 9$ kpc (Dunlop et al. 2001).

1330+022 (3C 287.1) M4M. An excellent fit to the data is produced by Jimenez’ models, indicating that the dominant population is old, with a best-fitting age of 8 Gyr. *HST* imaging has shown this galaxy to be a large elliptical, with $r_e = 16$ kpc (Dunlop et al. 2001).

2141+279 (3C 436) M4M, WHT. This is another very successful, and well-constrained fit, with an inferred age of 12 Gyr. *HST* imaging has shown this galaxy to be a large elliptical, with $r_e = 21$ kpc (McLure et al. 1999).

3.2 Sample overview

The results illustrated in Appendix A are summarized in Table 3. It should be noted that the 4000-Å break typical of evolved stellar populations is present in the majority of the observed spectra (see

Appendix A and Hughes et al. 2000), so we can be confident in fitting stellar population models to the data. The plots clearly show that the addition of even a very small amount of secondary star formation to the simple, near-instantaneous starburst models reproduces the blue end of the observed host galaxy spectra much more successfully (and in most cases very well) than does a single stellar population. Including a nuclear component further improves the fit to the blue end, especially for those spectra not well fitted by purely stellar light. At the same time, the red end of the spectra, plus the observed $R - K$ colours generally require that the underlying stellar populations are old.

The most meaningful output from the model fitting is a constraint on the minimum age of the host galaxies; the χ^2 plots show that often the best-fitting age is not strongly constrained but the trend is clearly towards old (≥ 8 Gyr) stellar populations. In general, young populations are strongly excluded.

The peaks and troughs in χ^2 as a function of model age appear to be the result of real features of the population evolution synthesis, rather than owing to, for example, poor sampling (Jimenez, private communication).

4 DISCUSSION

Fig. 1 shows the distribution of best-fitting ages estimated using Jimenez' models. The left-hand panel shows the ages of the dominant stellar component that result from fitting the two-component (stars only) model, while the right-hand panel shows the ages of the dominant stellar component in the case of the three-component model (i.e. two stellar components + a contribution from scattered nuclear light). The host galaxies of the AGN in each sample are predominantly old, and this result is unaffected by whether or not one chooses to include some nuclear contribution to assist in fitting the blue end of the spectrum. This general result also appears to be relatively unaffected by the precise choice of stellar population model; the models of Bruzual & Charlot (in preparation), fitted to the host galaxies with the same process, reproduce the results for Jimenez' models to within a typical accuracy of 1–3 Gyr. We have not attempted to fit the stellar population models of Yi et al. (2000), because of problems we have found in their main-sequence (MS) rate of evolution (Nolan, Dunlop & Jimenez 2001).

Inclusion of a nuclear contribution in the three-component models obviously raises the question of whether a young stellar population component is really necessary at all. We thus also explored the results of fitting a two-component model consisting of a single stellar population plus nuclear contribution. Such a model adequately reproduces the two-population-plus-nuclear-component results for the *redder* galaxies, but in fact the spectra of the bluest galaxies cannot be adequately reproduced by these models; the resulting serious increase in minimum χ^2 demonstrates that inclusion of a young population component is necessary to achieve a statistically acceptable fit to these data.

Fig. 2 shows the distribution of percentage contribution (by mass), α , of the young (0.1 Gyr) component to the spectra of the hosts. The left-hand panel shows the values of α as derived from fitting the two-component (stars only) model, while the right-hand panel shows the values of α produced by the three-component model (i.e. two stellar components + a contribution from scattered nuclear light).

Where two spectra of the same object have been obtained with alternative telescopes/instruments, the derived ages of the dominant stellar components are reproduced reassuringly well. There are, however, small discrepancies in the estimated

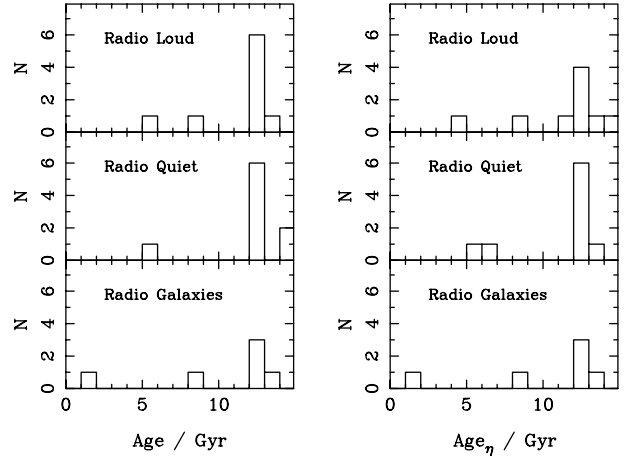


Figure 1. The age distribution of the dominant stellar populations of the sample host galaxies. These are the best-fitting results from Jimenez' solar metallicity models. On the left, results are shown for the fits to the data using a two-component model. The results on the right are those for the two-component model plus a nuclear contribution. The populations are predominantly old (12–14 Gyr) in both cases.

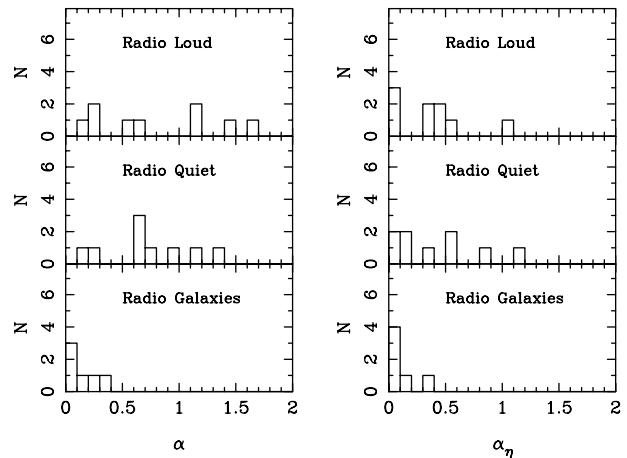


Figure 2. The distribution of α , the percentage contribution (by mass) of the 0.1-Gyr component. Where results have been obtained from two spectra for one object, the best-fitting result has been adopted. Again, the results on the left are for fits using the two-component model, and those on the right are for fits with the two-component model plus a nuclear contribution. Allowing for the possibility of a nuclear contribution means that a smaller α is required to fit the blue end of the spectrum, and the apparent difference between the radio galaxies and radio-loud and quiet quasars is reduced to a statistically insignificant level.

percentage of young population present (see Table 3). This effect is suggestive that at least some of the blue light might be caused by a scattered nuclear contribution, the strength of which would be highly dependent on the seeing at the time of observation, and on the precise repeatability of slit placement relative to the galaxy core. Interestingly, when a nuclear component is included with the stellar flux model, an even smaller percentage of 0.1-Gyr stellar population is required to fit the blue end of the spectra, and (more importantly) the difference in α between two spectra of the same object is generally reduced. This provides further support for the suggestion that some of the bluest quasar host spectra remain contaminated by quasar light at the shortest wavelengths, and indicates that the right-hand panel of Fig. 2 provides a more realistic estimate of the level of on-going star formation in the host galaxies. While this

figure still appears to suggest that at least some quasar hosts display higher levels of ongoing star formation activity than do radio galaxies, statistically this ‘result’ is not significant.

There are three galaxies that have very low age estimates, namely 0230-027, 0244+1944 and 1020-103. These objects have the bluest observed $R - K$ colours, so it may be expected that the fitted ages would be younger than the rest of the sample, and that these populations are genuinely young. As discussed above, it may be that these objects are bluer because of scattered nuclear light contaminating the host galaxy spectrum. However, it seems unlikely that their fitted ages are low simply because of this, because elsewhere in our sample, where two spectra have been obtained of the same object, the amount of nuclear contamination present does not significantly affect the age estimation (e.g. 0736+017 and 0157+001). Moreover, the inclusion of a nuclear component to the fit does not change the estimated age distribution of the host galaxies. If these ages are in error, then a more likely explanation, supported by the relative compactness of these particular host galaxies, is that nuclear and host contributions have been imperfectly separated in the K -band images, leading to an underestimate of the near-infrared luminosity of the host.

The result of the three-component fitting process that also allows a contribution from scattered nuclear light is that there are in fact only three host galaxies in the sample for which there is evidence that $\alpha > 0.5$. One of these is the host of a radio-loud quasar (2135-147) but, as can be seen from Fig. A2, this spectrum is one of the poorest (along with 0230-027, the only apparently young radio galaxy) in the entire data set. The two convincing cases are both the hosts of radio-quiet quasars, namely 0157+001 and 2344+184.

Within the somewhat larger sample of 13 RQQs imaged with the *HST* by McLure et al. (1999) and Dunlop et al. (2001), four objects showed evidence for a disc component in addition to a bulge, namely 0052+251, 0157+001, 0257+024 and 2344+184. Since we do not possess spectra of 0052+251 and 0257+024 this means that there is a 1:1 correspondence between the objects that we have identified on the basis of this spectroscopic study as having recent star formation activity, and those which would be highlighted on the basis of *HST* imaging as possessing a significant disc component. This straightforward match clearly provides us with considerable confidence that the spectral decomposition attempted here has been effective and robust. Finally, we note that it is almost certainly significant that 0157+001, which has the largest starburst component ($\alpha = 1.1$) based on this spectroscopic analysis, is also the only *IRAS* source in the sample.

5 CONCLUSIONS

We conclude that the hosts of all three major classes of AGN contain predominantly old stellar populations (≈ 11 Gyr) by $z \approx 0.2$. This agrees well with the results of McLure et al. (1999) and Dunlop et al. (2001) who compare host galaxy morphologies, luminosities, scalelengths and colours in the same sample, and conclude that the hosts are, to first order, indistinguishable from ‘normal’ quiescent giant elliptical galaxies.

The best-fitting age of the dominant stellar population is *not* a function of AGN class. For the purely stellar models, the fitted percentage contribution of the blue component is, however, greater in the quasar hosts than in the radio galaxies; the median values are 0.6 per cent for the nine radio-loud quasars, 0.6 per cent for the nine radio-quiet quasars and 0.05 per cent for the six radio galaxies. However, when a nuclear component is included, the median values

are 0.3 per cent for the radio-loud quasars, 0.3 per cent for the radio-quiet quasars and 0.00 per cent for the radio galaxies. Performing a Kolmogorov–Smirnov test on these results yields a probability greater than 0.2 that the percentage of young stellar population in host galaxies is in fact also not a function of AGN class.

These results strongly support the conclusion that the host galaxies of all three major classes of AGN are massive ellipticals, dominated by old stellar populations.

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APPENDIX A: SPECTRA AND χ^2 PLOTS

The fits for all the off-nuclear spectra are given. In Fig. A1, the rest frame spectra are in the first column (light grey), with the best-fitting two-component model spectra (Jimenez et al. 2000) superimposed (black). The spectra of the single-aged old population (mid-grey) is given for comparison. In Fig. A2, the fits allowing for an additional contribution to the flux from the nucleus are presented. The key is the same as in A1, with the additional dotted line representing the best-fitting two-component model flux plus the nuclear flux contribution.

The second column of plots shows the χ^2 evolution with age for the dominant older population. The third column shows the best-fitting χ^2 as a function of percentage young population, α , for fixed ages of the dominant component. The models have solar metallicity. The subscript η denotes results obtained by including the nuclear contribution.

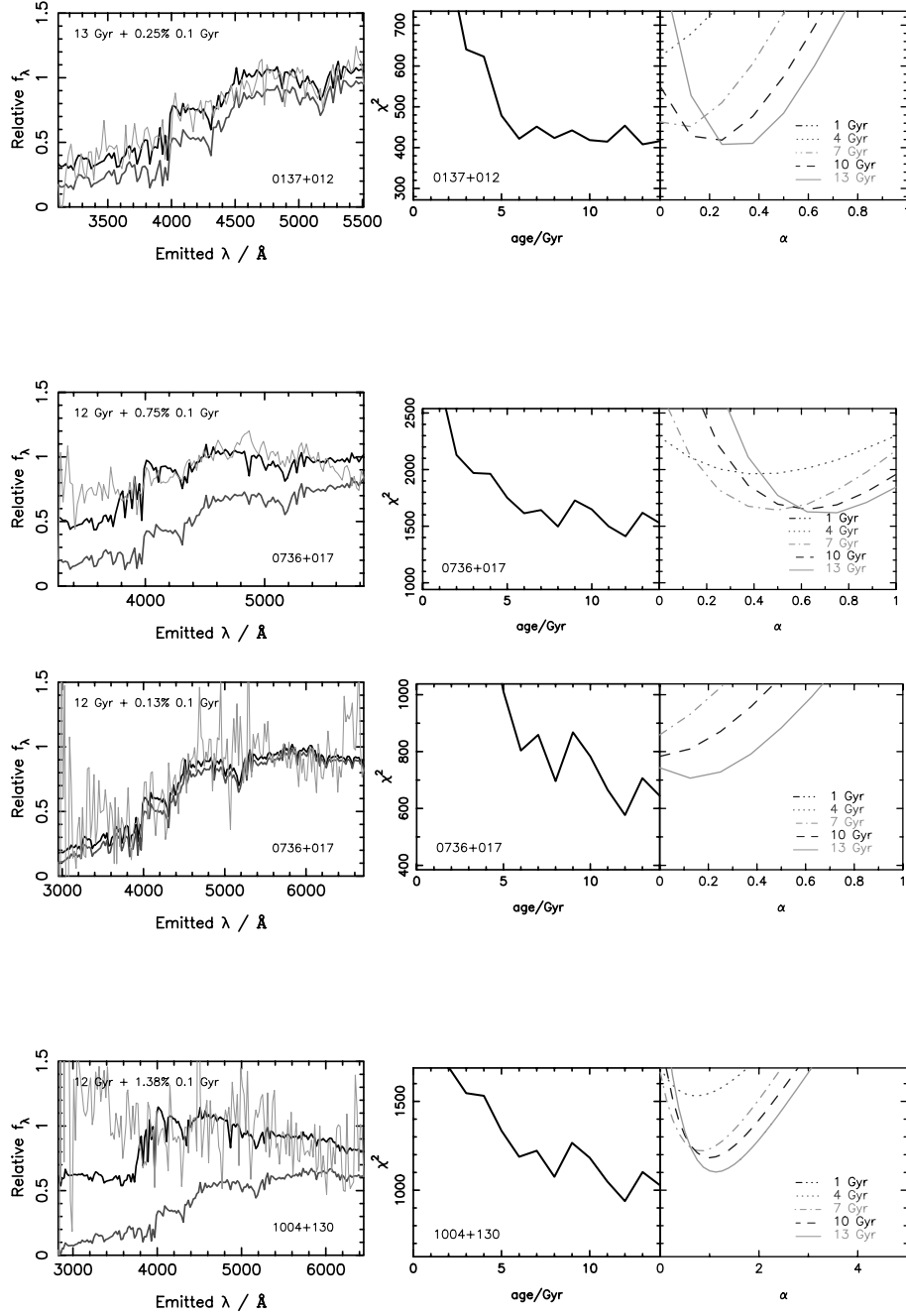


Figure A1. Model fits to the off-nuclear rest frame spectra, for each object, with the corresponding χ^2 plots. The rest-frame host-galaxy spectra are in the first column (lightest grey), with the best-fitting two-component model spectra (Jimenez et al. 2000) superimposed (black). The spectra of the single-aged old population (mid-grey, lowest line) is given for comparison. The second column shows the χ^2 evolution with age for the dominant older population and the third column shows the best-fitting χ^2 as a function of percentage young population, α , for fixed ages of the dominant component. All models have solar metallicity. Where there are two spectra of the same object, the spectrum given first is that observed on the Mayall 4-m telescope, and the second is that observed using the William Herschel Telescope. The data for the following objects have been smoothed using a Hanning function: 2135+147 (RLQ), 2141+175 (RLQ), 0244+194 (RQQ), 0923+201 (RQQ), 1549+203 (RQQ), 2215-037 (RQQ), 0230-027 (RG) and 0345+337 (RG).

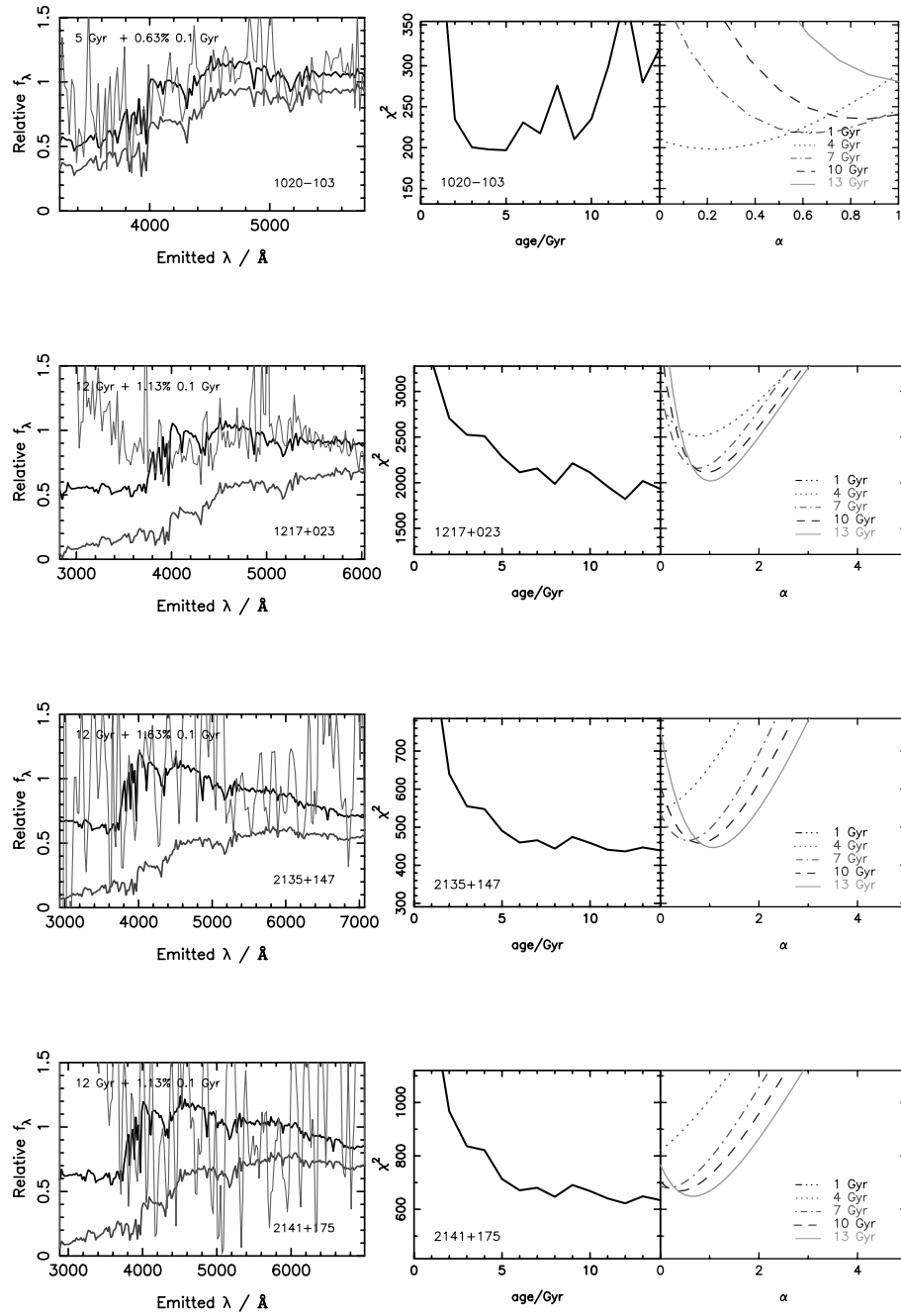


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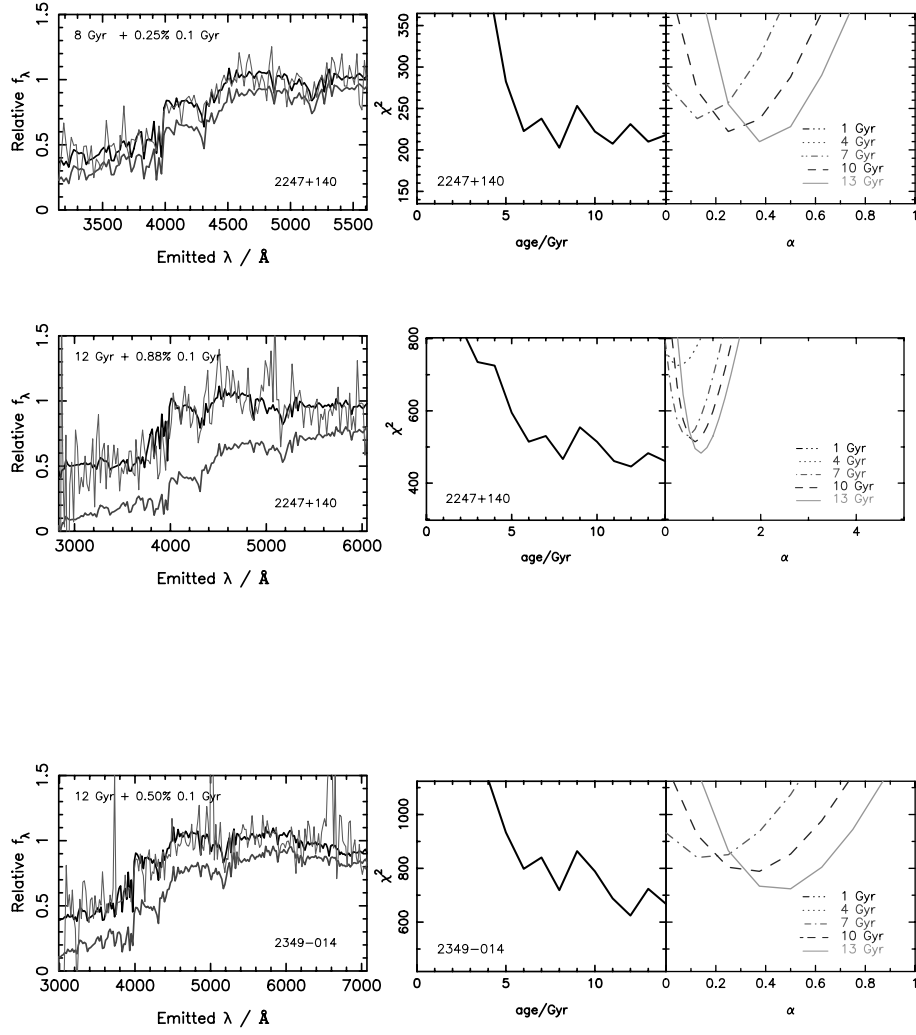


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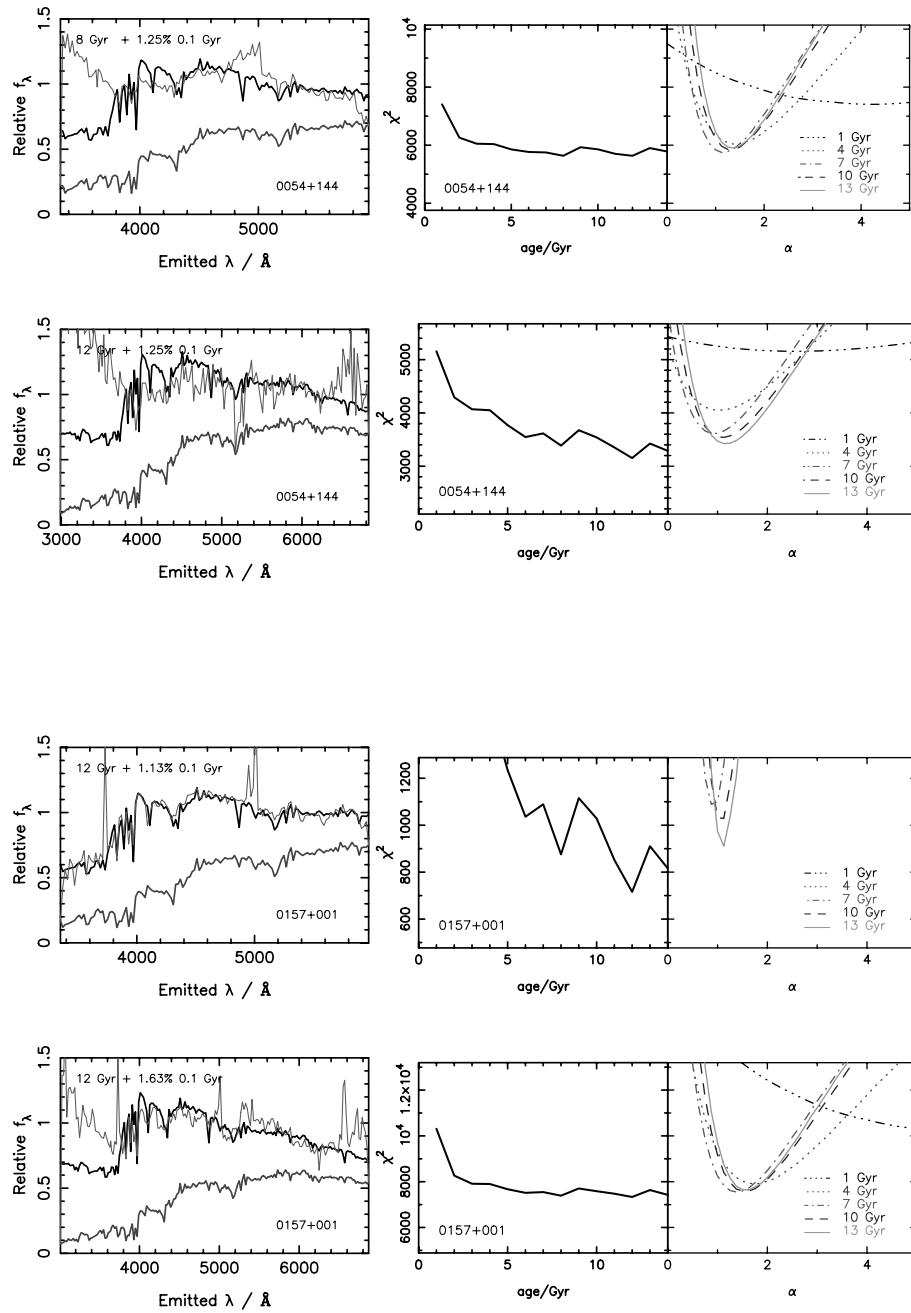


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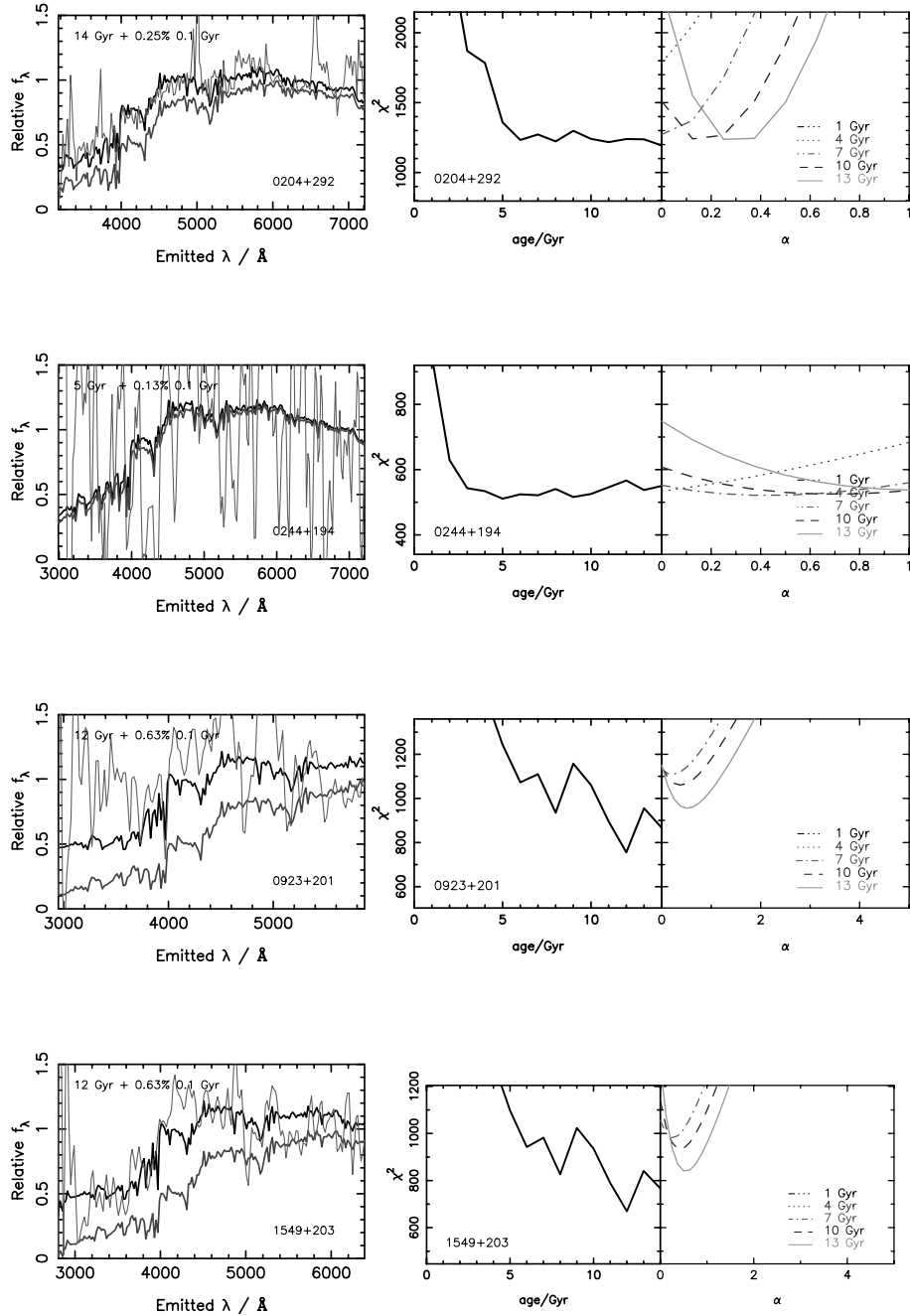


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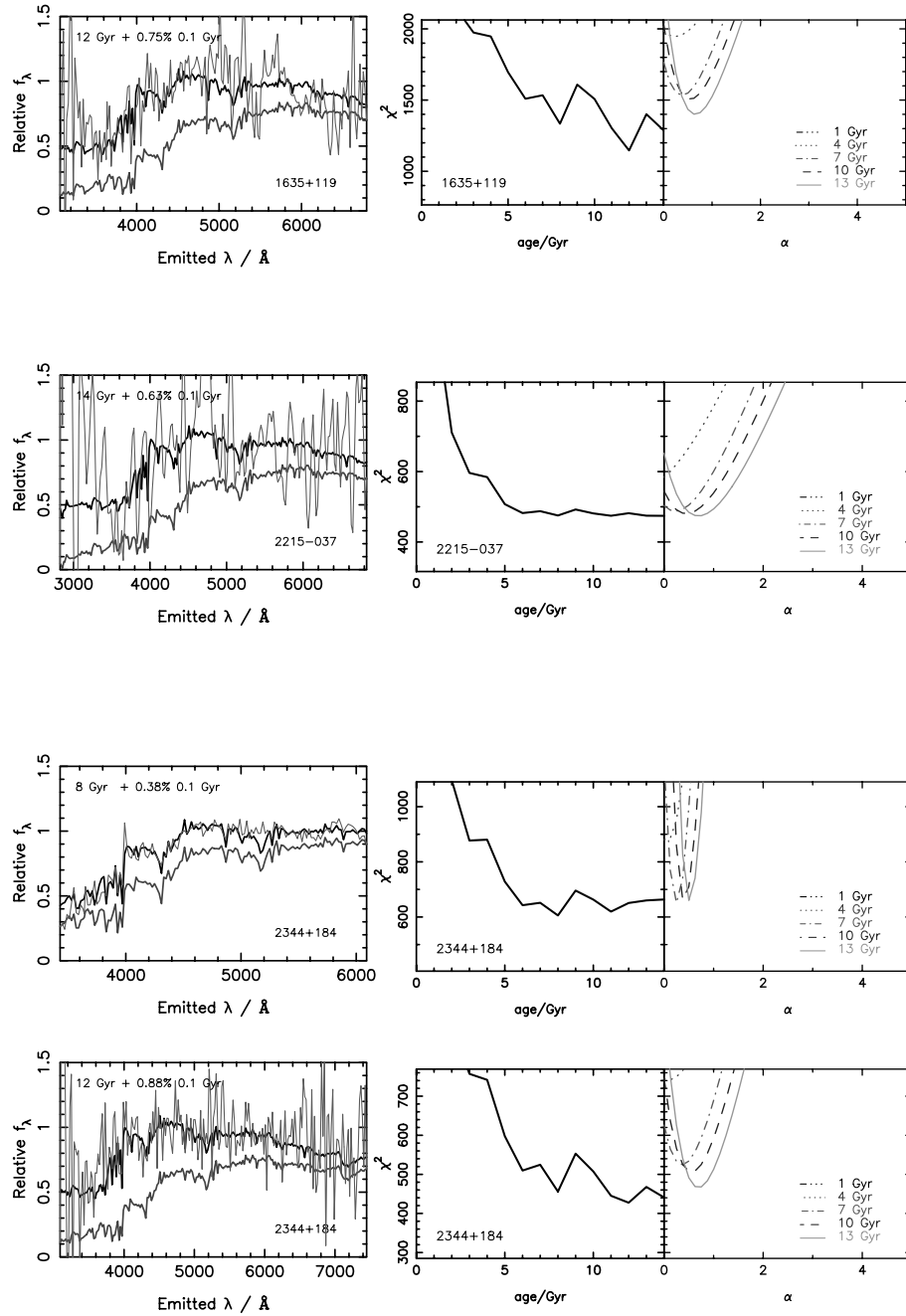


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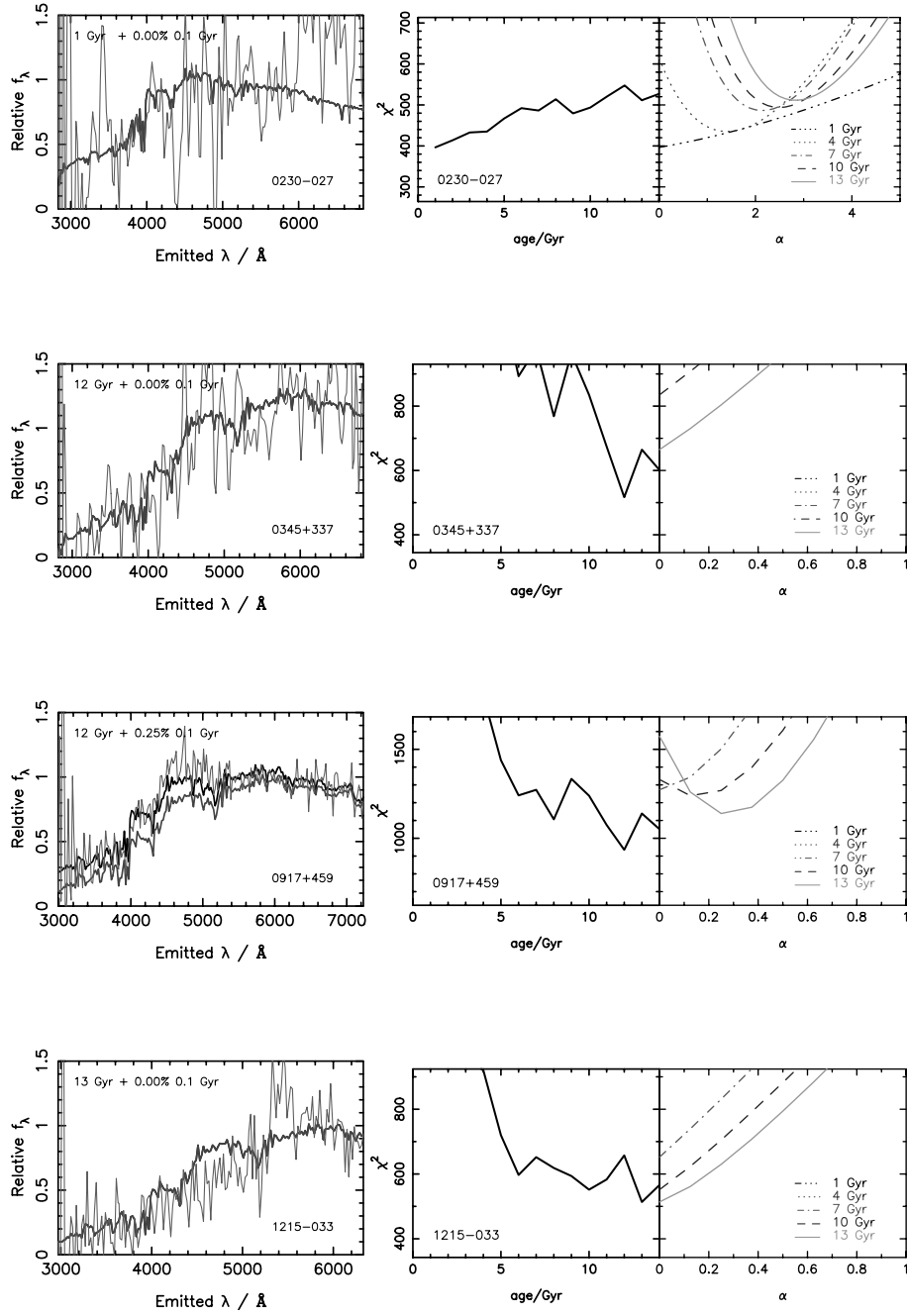


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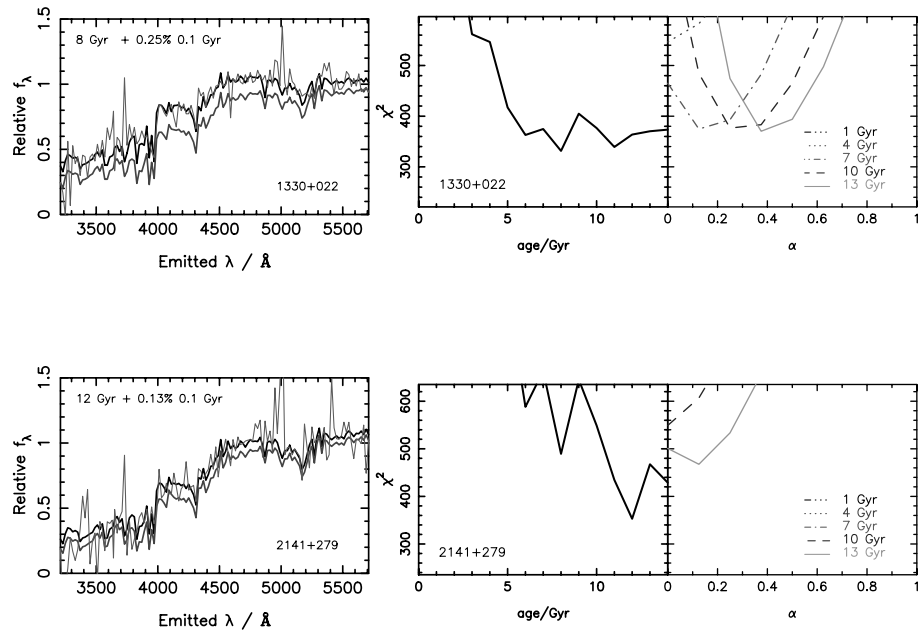


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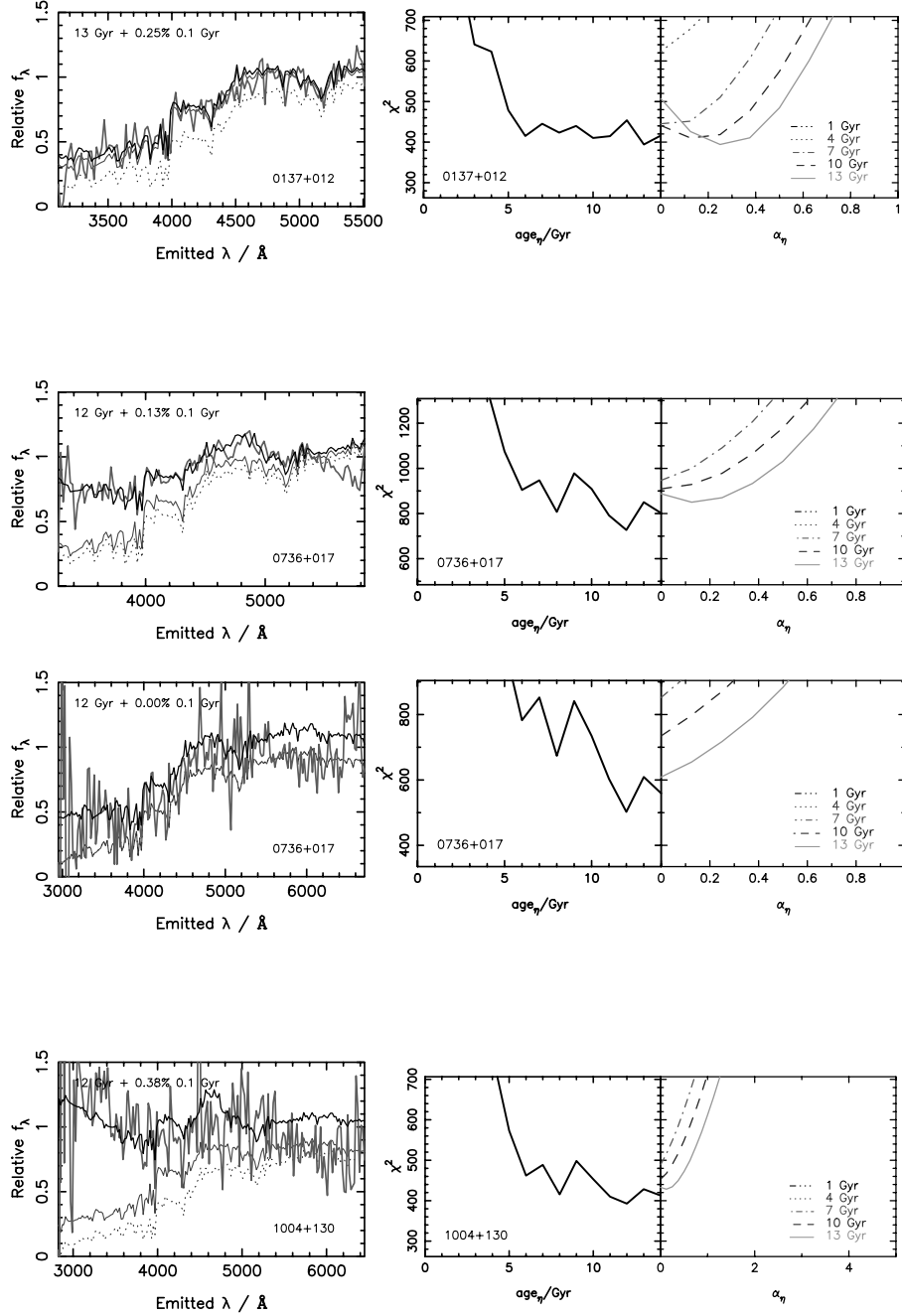


Figure A2. Model fits to the off-nuclear rest frame spectra, including the modelling of a nuclear contribution, for each object, with the corresponding χ^2 plots. The rest frame host galaxy spectra are in the first column (light grey), with the best-fitting two-component model flux plus the nuclear flux contribution (black) and the best-fitting two-component model spectra (Jimenez et al. 2000) superimposed (thin mid-grey). As in Fig. A1, the spectra of the single-aged old population (dotted line) is given for comparison. The second column shows the χ^2 evolution with age for the dominant older population and the third column shows the best-fitting χ^2 as a function of percentage young population, α , for fixed ages of the dominant component. The subscript η denotes results obtained by including the nuclear contribution. All models have solar metallicity. Where there are two spectra of the same object, the spectrum given first is that observed on the Mayall 4-m telescope, and the second is that observed using the William Herschel Telescope. The data for the following objects have been smoothed using a Hanning function: 2135+147 (RLQ), 2141+175 (RLQ), 0244+194 (RQQ), 0923+201 (RQQ), 1549+203 (RQQ), 2215-037 (RQQ), 0230-027 (RG) and 0345+337 (RG).

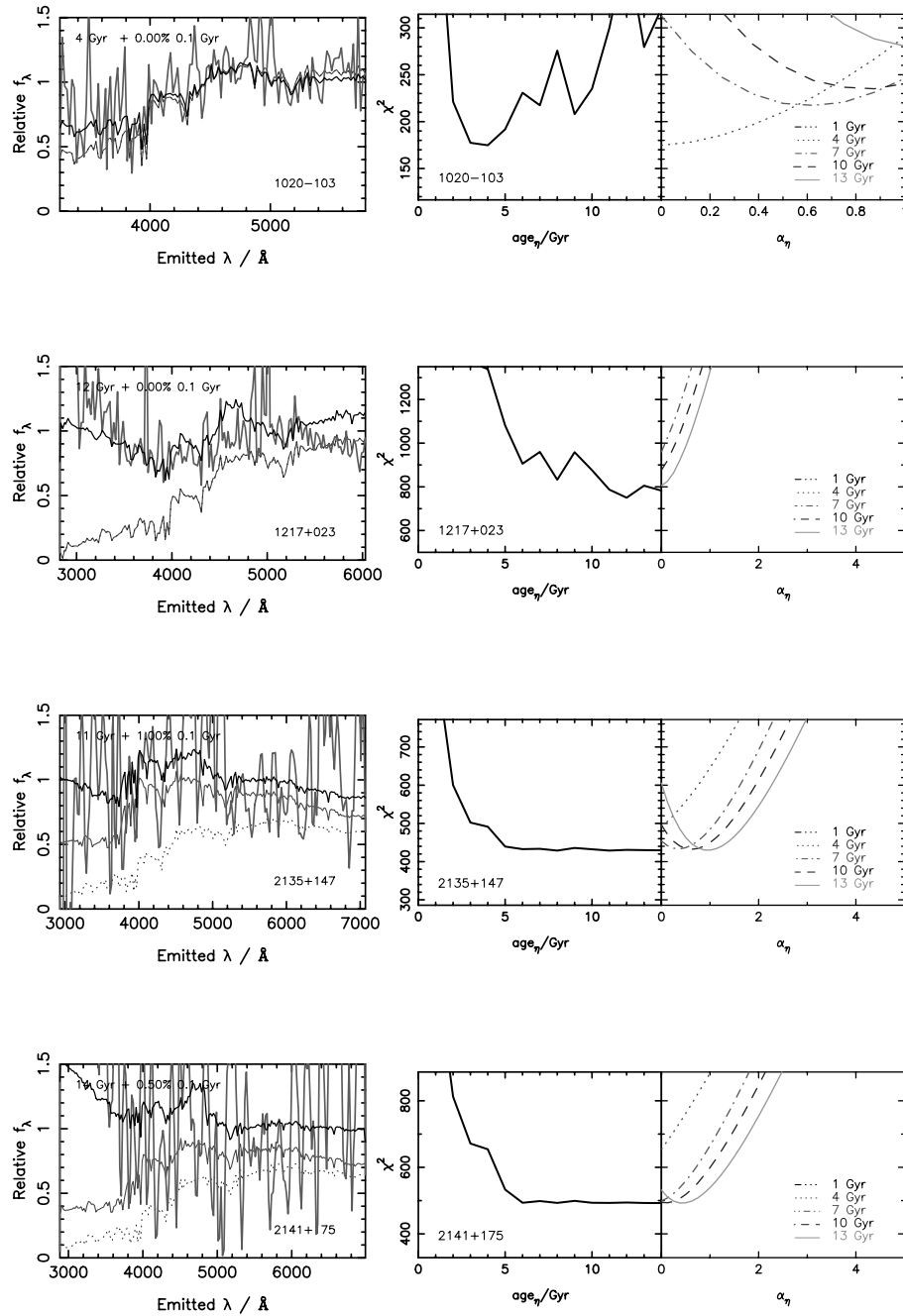


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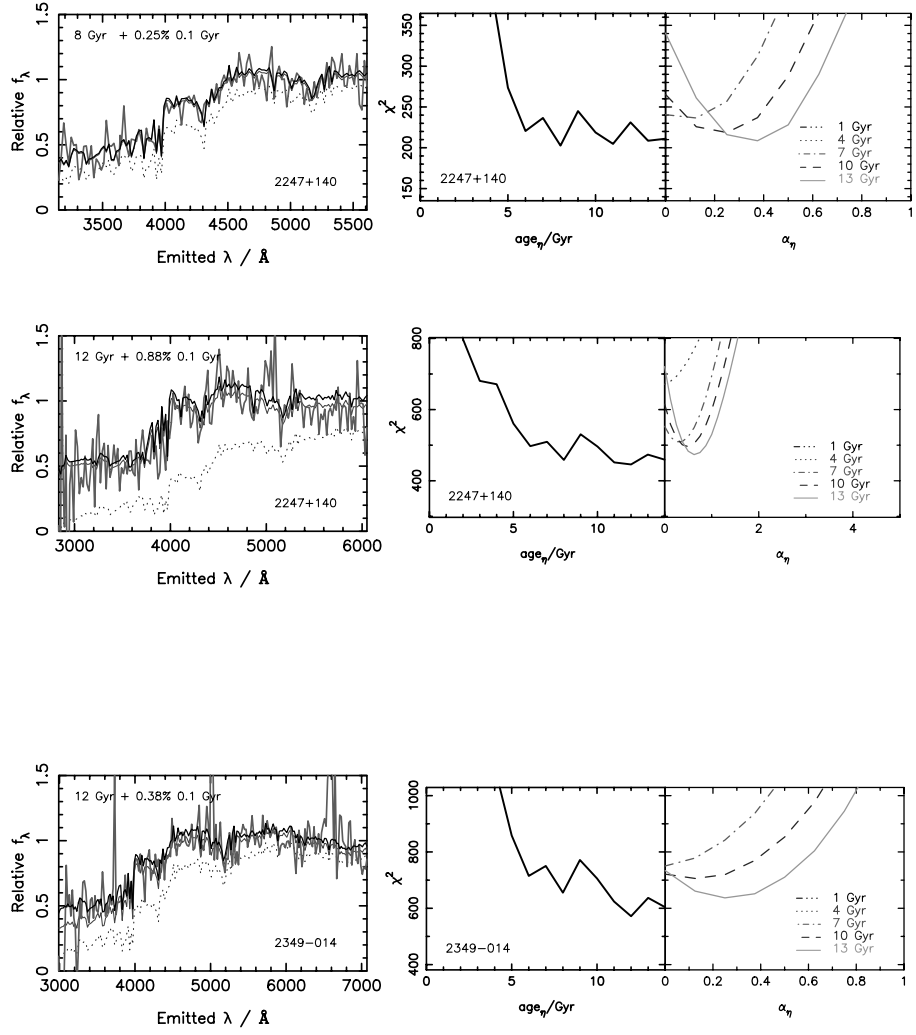


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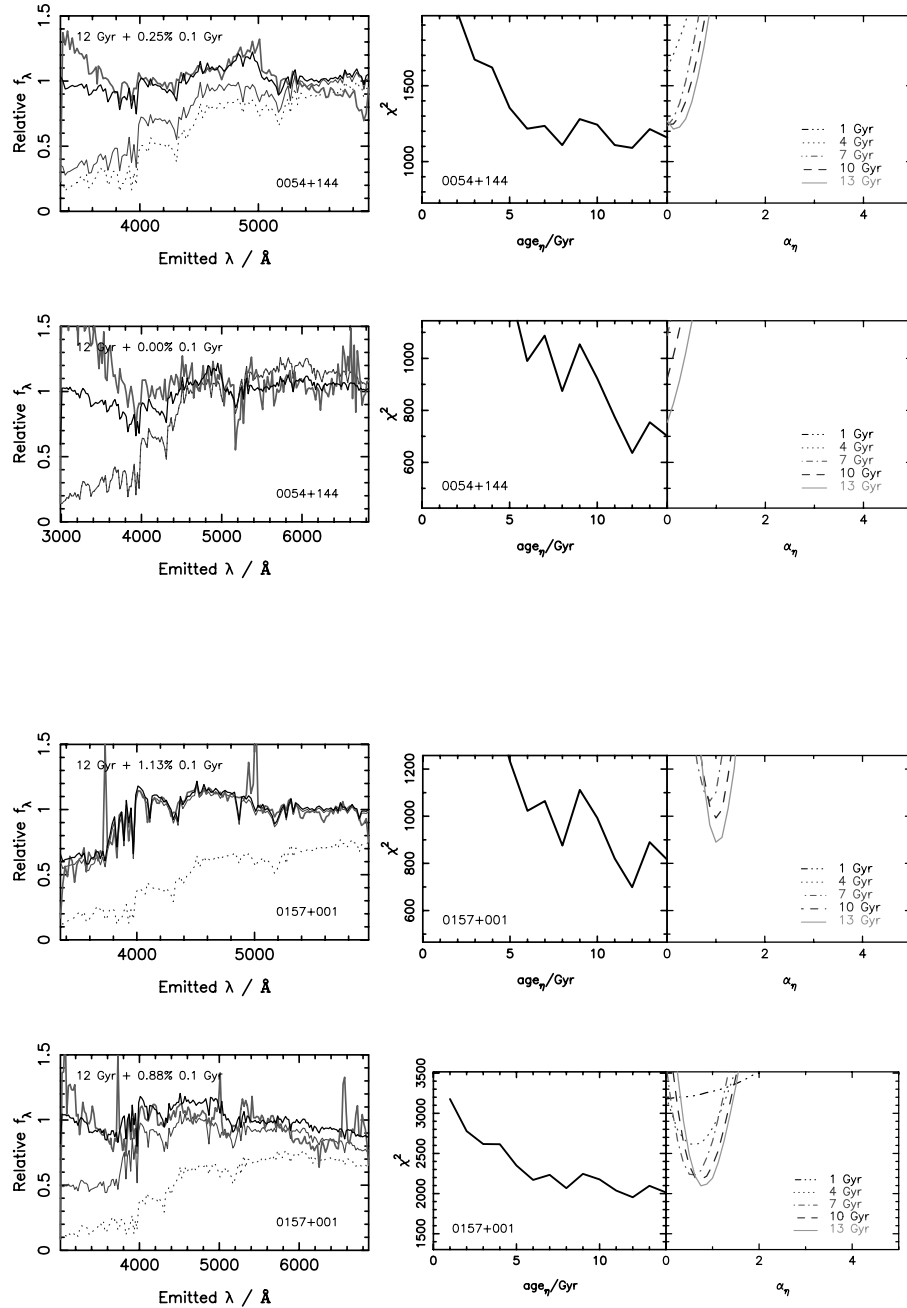


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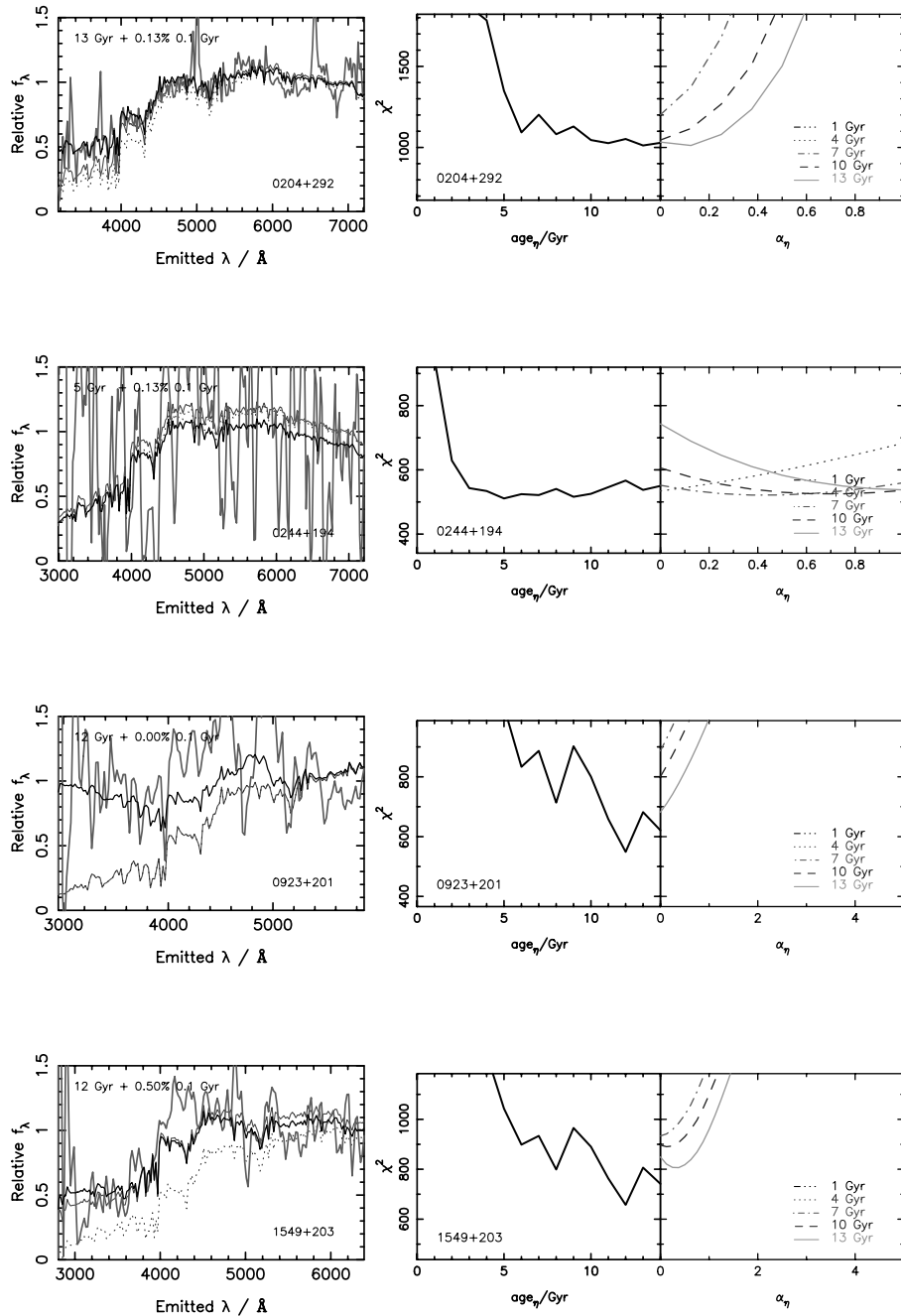


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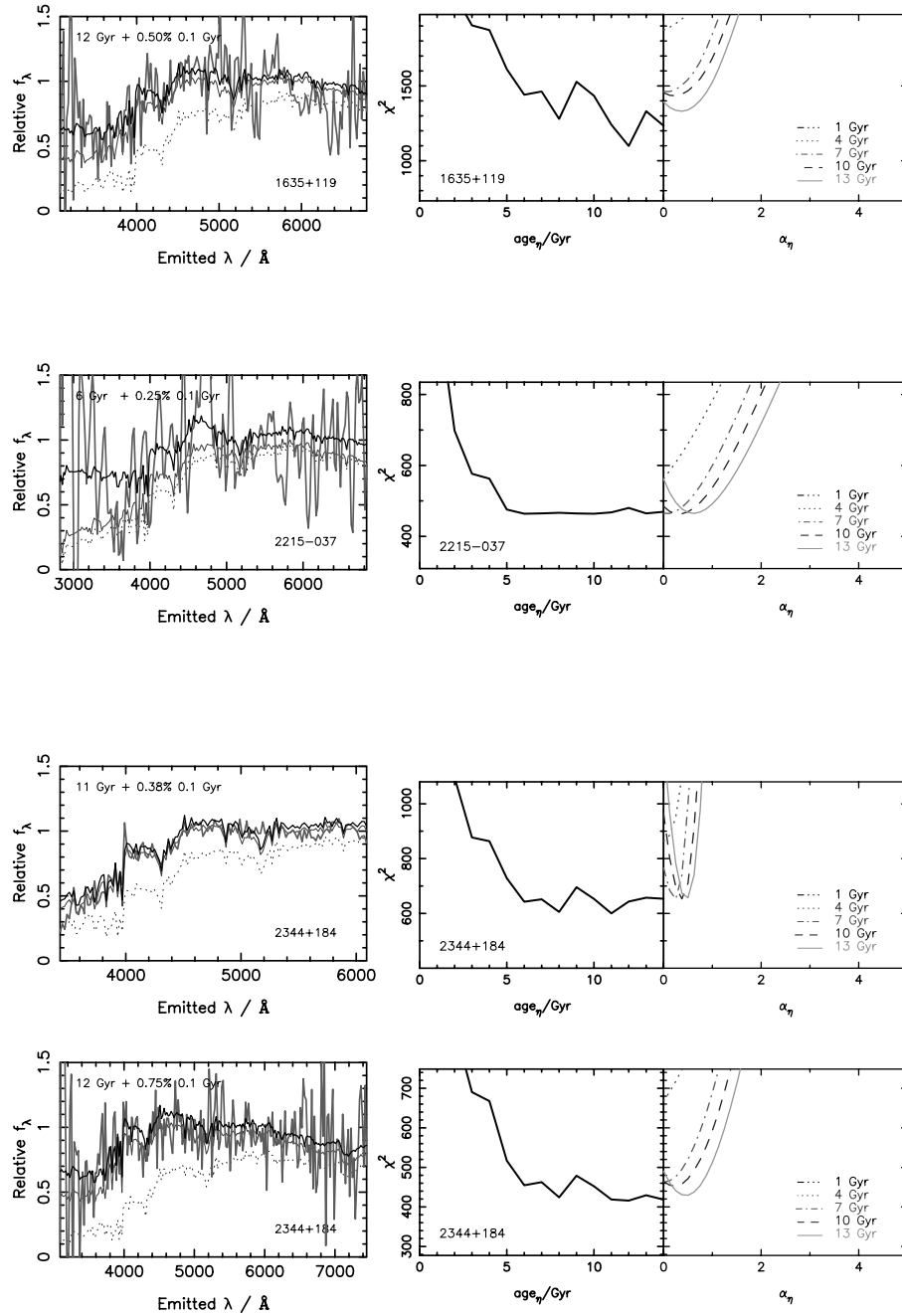


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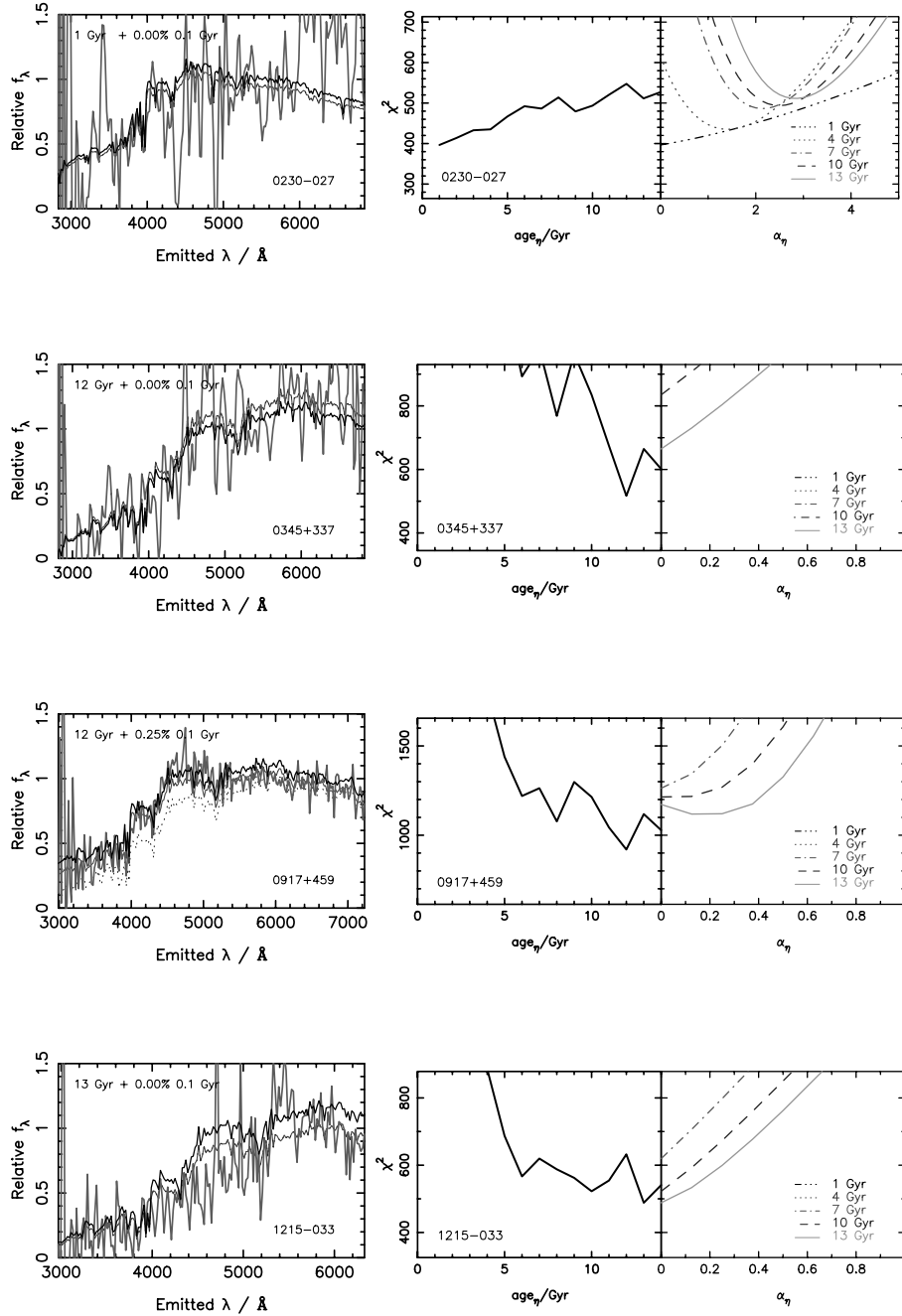
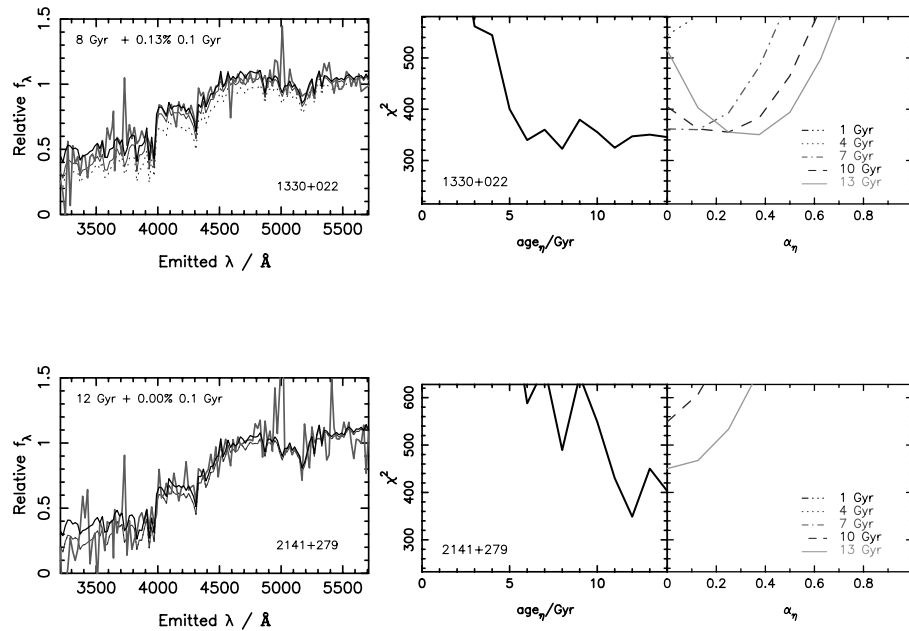


Figure A2 – continued

Figure A2 – *continued*

Where there are two spectra of the same object, the spectrum given first is that observed on the Mayall 4-m telescope, and the second is that observed using the William Herschel Telescope. The data for the following objects have been smoothed using a Hanning function: 2135 + 147 (RLQ), 2141 + 175 (RLQ),

0244 + 194 (RQQ), 0923 + 201 (RQQ), 1549 + 203 (RQQ), 2215 – 037 (RQQ), 0230 – 027 (RG) and 0345 + 337 (RG).

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