The Sun, stellar-population models, and the age estimation of high-redshift galaxies

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ABSTRACT

Given sufficiently deep optical spectroscopy, the age estimation of high-redshift (z > 1) galaxies has been claimed to be a relatively robust process (e.g. Dunlop et al. 1996) due to the fact that, for ages < 5 Gyr, the near-ultraviolet light of a stellar population is expected to be dominated by ‘well-understood’ main-sequence (MS) stars. Recently, however, the reliability of this process has been called into question by Yi et al. (2000), who claim to have developed models in which the spectrum produced by the main sequence reddens much more rapidly than in the models of Jimenez et al. (2000a), leading to much younger age estimates for the reddest known high-redshift ellipticals. In support of their revised age estimates, Yi et al. cite the fact that their models can reproduce the spectrum of the Sun at an age of 5 Gyr, whereas the solar spectrum is not reproduced by the Jimenez et al. models until ≃ 10 Gyr. Here we confirm this discrepancy, but point out that this is in fact a strength of the Jimenez et al. models and indicative of some flaw in the models of Yi et al. (which, in effect, imply that the Sun will turn into a red giant any minute now). We have also explored the models of Worthey (1994) (which are known to differ greatly from those of Jimenez et al. in the treatment of post-MS evolution) and find that the main-sequence component of Worthey’s models also cannot reproduce the solar spectrum until an age of 9-10 Gyr. We conclude that either the models of Yi et al. are not as main-sequence dominated at 4-5 Gyr as claimed, or that the stellar evolutionary timescale in these models is in error by a factor possibly as high as two. Our current best estimate of the age of the oldest galaxies at z ≃ 1.5 thus remains 3 – 4 Gyr, as we confirm with a new analysis of the existing data using the updated solar-metallicity models of both Jimenez et al. and Worthey. Finally, by fitting a mixed metallicity model to the Sun, we demonstrate that, given rest-frame ultraviolet data of sufficient quality, it should be possible to break the age-metallicity degeneracy when analyzing the spectra of high-redshift galaxies.

Key words:

1 INTRODUCTION

For over a decade now, astronomers have attempted to estimate the ages of high-redshift galaxies using broad-band optical-infrared photometry (e.g. Lilly 1988; Dunlop et al. 1989, Chambers & Charlot 1990). Unfortunately, however, the derived ages have been rendered virtually meaningless by disagreements between modellers over post main-sequence evolution (e.g. Charlot, Worthey & Bressan 1996), and by the extreme susceptibility of such relatively crude broad-band data to dust reddening, emission-line contamination etc.

In contrast, it has long been anticipated that relatively robust age constraints for high-redshift galaxies could be derived given rest-frame near-ultraviolet spectra of sufficient quality. This is because, for the potential ages of interest at z > 1 (i.e. ages < 5 Gyr), the ultraviolet light of a stellar population is expected to be dominated by stars close to the turn-off point of the ‘well-understood’ main sequence (MS) (e.g. Magris & Bruzual 1993).

With the advent of deep optical spectroscopy on 10-m class telescopes, it has now proved possible to put this technique into practice. In particular, Dunlop et al. (1996) were able to use a deep Keck spectrum of the z = 1.5 radio galaxy LBDS 53W091 to first confirm that its near-ultraviolet spectrum was indeed dominated by starlight, and then to extract an age constraint of > 3 Gyr based primarily on comparison with a main-sequence only model of an evolving stellar population. Spinrad et al. (1997) explored further the reliability of this age estimate, and confirmed that the best agreement...
between ages derived using alternative evolutionary synthesis models was obtained if fitting was confined to the detailed shape of the near-ultraviolet spectral energy distribution.

Not surprisingly, given its implications for cosmology (for $H_0 = 70\text{km s}^{-1}\text{Mpc}^{-1}$, the age of an Einstein-de Sitter universe at $z = 1.5$ is only 2.3 Gyr), this result has been the subject of subsequent close scrutiny, and claims that 53W091 is in fact less than 2 Gyr old have been put forward by, for example, Bruzual & Magris (1997). Moreover, Dunlop (1999) has argued that such young ages are only deduced using some models if the near-infrared photometry is also included in the fitting process, once again placing undesirable emphasis on the reliability of the modelling of post main-sequence evolution (a point previously also explored by Spinrad et al. 1997). Moreover, Dunlop (1999) has shown that, certainly for the slightly redder $z = 1.43$ galaxy 53W069, if fitting is confined to the Keck spectroscopic data (Dey et al. 2000), the models of Bruzual & Charlot (1993), Worthey (1994), and Jimenez et al. (2000a) all lead to the conclusion that its stellar population is $> 3$ Gyr old (assuming solar metallicity).

Most recently, however, the reliability of even this near-ultraviolet spectroscopic age-dating has been called into question by Yi et al. (2000). Yi et al. (2000), claim to have derived a much younger age for 53W091, but also claim that this age is not due to differences in post-MS evolution, but rather to the fact that the spectrum produced by the main sequence in their models reddens much more rapidly than in the models of Jimenez et al. (2000a). In support of their revised age estimates, Yi et al. cite the fact that their models can reproduce the spectrum of the Sun at an age of 5 Gyr, whereas the solar spectrum is not reproduced by the Jimenez et al. models until 8-10 Gyr. It is unclear to us why a stellar population should be expected to mimic the spectrum of the Sun at its current age ($\simeq 5$ Gyr); even if the light from the stellar population is dominated by stars near the main-sequence turnoff the Sun is not expected to leave the main sequence until an age of $\simeq 10$ Gyr (Jorgensen 1991). Nevertheless this claim has motivated us to explicitly check the calibration of the main-sequence evolution in alternative evolutionary synthesis models of galaxy evolution.

This is the main subject of the present paper. What we have done is to take the 3 alternative and independent models of galaxy evolution developed by Yi et al. (2000), Jimenez et al. (2000a) and Worthey (1994), and to check how rapidly they evolve to mimic the solar spectrum with and (more importantly) without inclusion of their post-MS components. The models are summarized in section 2, and the results of comparison with the solar near-ultraviolet spectrum are presented in section 3. We then proceed, in section 4, to use these models (again with and without post-MS components) to check explicitly the extent to which the age estimates of 53W091 and 53W069 really are affected by different approaches to modelling post-MS evolution. The main remaining uncertainty is the impact of having to assume a value for the metallicity of the stellar population, and in section 5 we explore whether, given near-ultraviolet data of sufficient quality, it may be possible to break the well-known age-metallicity degeneracy. Finally, our conclusions are summarized in section 6.

2 THE MODELS

2.1 The models

This study was motivated by the apparent disagreement reported by Yi et al. (2000) between their own models and those of Jimenez et al. (2000a). We are able to perform our own comparison of these models because Sukyoung Yi has kindly supplied us with his model SEDs up to an age of 5 Gyr (Yi, private communication). We also wanted to compare the predictions of a third independent set of evolutionary synthesis models, and have chosen the models of Worthey (1994) for this purpose. The reason for this choice was that we already knew, from our previous modelling of 53W091 (Dunlop et al. 1996, Spinrad et al. 1997) that the models of Worthey (1994) also appear to yield younger ages than those of Jimenez et al. (2000a), but for reasons which we suspected were primarily due to a different treatment of post-MS evolution (see Charlot et al. 1996).

Since the primary objective in this paper is to check the calibration of MS evolution using the Sun, we have confined our attention only to models which assume solar metallicity. However, we are interested in removing any potential confusion introduced by different treatments of post-MS evolution, because it is hard to be sure that the UV spectrum of an instantaneous starburst really is completely dominated by MS stars in all alternative models beyond an age of 2-3 Gyr (and beyond 5 Gyr it is not expected to be). We have therefore constructed a MS-only version of the models of Jimenez et al. (2000a), and have also been supplied with a MS-only version of the models of Worthey (1994) (Worthey, private communication). In both the Jimenez and the Worthey models the isochrones have been cut off at the same point (corresponding to point 55 in the Vandenberg grid in the case of Worthey’s models). A pure MS-only version of the Yi et al. models was not available to us, but we do have access to a main-sequence + giant branch (MSGB) version, which is stripped of Horizontal Branch and Asymptotic Giant Branch contributions, and should be an excellent approximation to an MS-only model, at least in the near-ultraviolet for ages $< 5$ Gyr, as Yi et al. themselves claim.

2.2 $\chi^2$ minimization

Since our main aim in this paper was to calibrate the age-dating of distant stellar populations based on the rest-frame near-ultraviolet spectra, fitting was deliberately restricted to the spectral range 2000 – 4000Å. The best fit was determined by binning the data to the same spectral resolution as the model in question, and then varying the age and normalization as free parameters until $\chi^2$ was minimized.

For the high-redshift galaxies 53W091 and 53W069, the error on each binned spectral datapoint was derived from propagation of the original errors in the Keck optical spectra (see Dunlop et al. 1996; Dey et al. 2000). In the case of the Sun, we are using the theoretical spectrum of Kurucz as the best available representation of the true solar SED, and have simply assumed a constant flux-density error (i.e. independent of wavelength), adjusted in size until reduced chi-squared ($\chi^2$) equalled unity for the very best fitting model. It is thus only possible to compare the relative (rather than absolute) ability of the different models to
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Figure 1. Reduced $\chi^2$ as a function of age for the six alternative solar metallicity stellar population models fitted to the solar spectrum. On the left-hand panel are the results for the full stellar population models, and on the right-hand side are those for Worthey and Jimenez et al. main sequence (MS) only models and Yi et al. main sequence plus red giant branch (MSGB) models. Solid lines - Yi et al. (2000); dashed lines - Worthey (1994); dotted lines - Jimenez et al. (2000a). The MS / MSGB models result in a better fit than the full models. The best-fit age of Yi et al.’s MSGB models differ from the best-fit ages of both Worthey’s and Jimenez et al.’s MS only models by a factor of order two, implying a MS-turnoff age for the Sun of only 4-5 Gyr, compared with 9 or 11 Gyr implied by the MS-only models of Worthey and Jimenez et al. respectively.

reproduce the solar ultraviolet spectrum as the age of each model is varied.

3 COMPARISON WITH THE SOLAR SPECTRUM

3.1 Full models

In Figure 1a we show reduced $\chi^2$ as a function of age for each of the full stellar population models when age is varied in an attempt to best reproduce the solar spectrum. The models of Yi et al. predict the youngest age, indicating that the near-ultraviolet spectrum produced by these models best mimics that of the sun after an age of only 4 Gyr. The models of Worthey yield a best-fit age of 5 Gyr, while those of Jimenez et al. predict an age of 8 Gyr. From this plot it might appear that it is the models of Jimenez et al. that are most unusual, but it is important to note that i) it is the models of Jimenez et al. which yield the best quality of fit to the solar spectrum, and ii) it is to be expected that the full stellar population models will underestimate the main-sequence turn-off (MSTO) age of the sun, because of the inclusion of post-MS stars. Moreover, from this plot it is completely unclear how much of the (substantial) difference between the derived best-fit ages can be attributed to differing contributions of post-MS stars to the galaxy ultraviolet SEDs.

3.2 Main-sequence only models

For a meaningful comparison between galaxy synthesis models and the expected MS turn-off age of the sun, we really require to ensure that the ultraviolet spectra produced by the models are completely MS dominated. Therefore, in Figure 1b we show reduced $\chi^2$ as a function of age in an analogous way to Figure 1a, but this time using models, stripped as far as possible of post-MS contributions. This allows not only a sensible comparison with the Sun, but also makes it possible to assess the relative impact of post-MS contributions to the full model fits shown in Figure 1a.

This plot makes it clear that it is the models of Yi et al. that are unusual, and apparently in error by a factor of two in terms of rate of MS evolution. Stripped of HB and AGB contributions the predictions of the Yi et al. models are little changed, indicating a best-fit age of 4-5 Gyr. In contrast, stripped of post-MS evolution the models of Worthey and Jimenez et al. appear to be in good agreement not only with each other (9 Gyr and 11 Gyr respectively) but also with the generally accepted MS turnoff age of the Sun (10.5 Gyr - Jorgensen 1991).

It is hard to assess the likely impact on the predictions of the Yi et al. models if the GB was also removed, but the lack of any dramatic change upon removal of HB and AGB contributions does tend to support their own claim that their models are already highly MS dominated at ages < 5 Gyr. In contrast the contribution of post-MS stars in the models of Worthey must be relatively strong, even at 5 Gyr, because removal of HB + AGB moves the derived age from 5 to 7 Gyr, and subsequent removal of remaining post-MS stars completes the shift to 9 Gyr as shown in Figure 1b. This therefore backs up the suggestion made in Jimenez et al. (2000a) that the main difference between the models of Jimenez et al. and Worthey lies in the strength of the AGB and RGB, but that the MS evolution in both models is very similar, and yields sensible values for the turn-off age of the Sun.

These results are tabulated in Table 1, and in Figure 2 we show the best-fit model spectra superimposed on the solar spectrum. It is worth noting (from both Figure 2 and Figure 1) that, as one would hope, the MS-only models in
Figure 2. Best fits to the solar spectrum (black lines) for the various solar metallicity models (grey lines).
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Figure 3. Reduced $\chi^2$ as a function of age for the six alternative solar metallicity stellar population models fitted to the near-ultraviolet spectrum of the $z = 1.55$ radio galaxy 53W091 (Dunlop et al. 1996; Spinrad et al. 1997). On the left-hand panel are the results for the full stellar population models, and on the right-hand side are those for Worthey and Jimenez et al. main sequence (MS) only models and Yi et al. main sequence plus red giant branch (MSGB) models. Solid lines - Yi et al. (2000): dashed lines - Worthey (1994): dotted lines - Jimenez et al. (2000a).

every case yield a better quality of fit to the solar spectrum than do the full models which include some contribution from more evolved stars. Interestingly, the MS-only models of Jimenez et al. yield both the best overall fit in terms of reduced $\chi^2$, and a MS-turnoff age which most closely matches the accepted value of 10.5 Gyr (Jorgensen 1991).

In summary, either the timescale of MS evolution in the models of Yi et al. is too short by a factor $\approx 2$, or the GB contribution to the UV spectrum at an age of 4 Gyr is unexpectedly large, in which case these models would again be extremely unusual and the comparison with the age of the Sun as suggested by Yi et al. must inevitably be meaningless.

4 COMPARISON WITH THE SPECTRA OF RED GALAXIES AT $Z \approx 1.5$

4.1 LBDS 53W091

The age implications of the deep Keck optical spectrum of the red mJy radio galaxy 53W091 have been previously discussed in some detail by Dunlop et al. (1996) and Spinrad et al. (1997). However it is interesting and important to revisit the age-determination of this object for a number of reasons. First, the models of Jimenez et al. have been updated in the intervening years. Second, the Yi et al. models did not exist in 1996/1997. Third, we have only recently obtained the MS-only versions of the Worthey models. We also felt it was important to re-analyze this spectrum given the claims made by Bruzual & Margris (1997) and Yi et al. (2000) that the most recent models yield best-fit ages for the stellar population in 53W091 of less than 2 Gyr.

Therefore in Figure 3 we show the results of fitting the same six models (as fitted to the Sun above), to the rest-frame near-ultraviolet SED of 53W091. The results, summarized in Table 1, are that both the Jimenez et al. (2000a) models (full and MS only) yield a best-fit age of 3 Gyr (with ages as young as 2 Gyr formally excluded), both the Yi et al. models (full and MSGB) yield a best fit age of 2 Gyr, while the best-fit age yielded by the Worthey models changes from 2 Gyr to 3 Gyr if post-MS contributions are excluded. Given the fact that we have already shown that the MS clock in the Yi et al. models appears to be running up to a factor of 2 too fast, this means that the argument over whether the age of 53W091 can or cannot be younger than 3 Gyr comes down to a debate over the validity of the stronger AGB and GB contributions in the Worthey models compared with the more MS-dominated Jimenez et al. models. Jimenez et al. (2000a) argue that their models include a better treatment of mass-loss in evolved stars which results in less luminous RGB and AGB contributions. In summary, the available evidence still appears to favour a minimum age of 3 Gyr for this galaxy, subject to remaining uncertainties over the impact of possible non-solar metallicity (see section 5).

4.2 LBDS 53W069

As discussed by Dunlop (1999), the Keck spectrum of the even redder mJy radio galaxy 53W069 ($z = 1.43$; Dey et al. 2000) appears to offer the best example discovered to date of a highly-evolved coeval stellar population at a redshift as high as $z \approx 1.5$. Dunlop (1999) found, from a comparison of their near-ultraviolet SEDs, that 53W069 is significantly redder than 53W091, and that the SED of the latter galaxy can be decomposed into that of 53W069 plus a low-level blue component which is approximately flat in $f_\lambda$. It is therefore to be expected that model-fitting to the near-ultraviolet SED of 53W069 might yield even older age limits than those derived above for 53W091.

In Figure 4 we show the results of fitting the same six models as before to the near-ultraviolet SED of 53W069. The results can again be found in tabulated form in Table 1. In summary, for this object 5 out of the 6 models yield a
minimum age > 3 Gyr, with only the Yi et al. full models allowing an age as young as 2 Gyr. Since these models appear flawed based on the solar comparison discussed in section 3, we conclude that it is extremely hard to escape the conclusion that 53W069 is at least 3 Gyr old. For this object the debate over whether the post-MS treatment of Jimenez et al. (2000a) is to be preferred over that of Worthey (1994) translates into an uncertainty over whether the best-fit age is in fact > 3 or > 4 Gyr (see Table 1).

For $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, the age of an Einstein-de Sitter Universe at $z = 1.43$ is only 2.5 Gyr. Therefore, given the apparently flawed nature of the Yi et al. models, we conclude that the only way that the age of 53W069 at $z = 1.43$ can be contained within an Einstein-de Sitter Universe is if varying the assumed metallicity from solar can in fact reduce the best-fit age to < 2.5 Gyr.

5 BREAKING THE AGE-METALLICITY DEGENERACY

The potential severity of the age-metallicity degeneracy was highlighted in the work of Worthey (1994), and acknowledged by Dunlop et al. (1996) in their original attempts to determine the age of 53W091. It is clear that assuming a metallicity of twice solar for the entire stellar population results in the lower limit to the derived age of both 53W091 and 53W069 falling below 2.5 Gyr.

Spinrad et al. (1997) presented arguments that, even assuming these galaxies possess a high-metallicity core, adoption of a universally high metallicity is inappropriate when analyzing the integrated light from the central $\simeq 10$ kpc of an elliptical galaxy (as sampled at $z > 1$ by the Keck spectroscopic slit). Moreover, both Jimenez et al. (2000b) and Yi et al. (2000) have now attempted to produce more realistic mixed-metallicity models and have independently found that such mixed-metallicity models in fact yield very similar ages to simple solar metallicity models (despite the basic disagreement between model timescales detailed above). This appears to be true, even when the average metallicity is twice solar, simply because it is the low metallicity component which dominates the light shortward of 3000Å (Jimenez et al. 2000b).

Ideally, however, we would like to be able to fit both metallicity mix and age to the data. The extent to which this is possible obviously depends both on the quality of the spectroscopic data available, and on the presence of (primarily) metallicity-dependent and age-dependent features within the available spectral range.

This approach will be explored further in a separate paper, but here we present evidence that the age metallicity degeneracy can, at least in principle, be broken with data in the spectral range 2000Å–4000Å, using the Sun as a test case.

A mixed-metallicity model was constructed from the 0.2$Z_{\odot}$, $Z_{\odot}$ and 2.5$Z_{\odot}$ full models of Jimenez et al., with the relative contributions of the different metallicity models allowed to vary as free parameters. The ability of this mixed-metallicity model to reproduce the metallicity and MSTO age of the sun is a test of the stellar population synthesis models’ ability to break the age-metallicity degeneracy given data in this near-ultraviolet spectral range.

The solar spectrum was rebinned in the same way as for the solar-metallicity only fitting process. The mixed-metallicity model flux was built from normalised SED’s, so that

$$F_{\lambda, \text{age}} = \lambda \frac{X_{0.2Z_{\odot}} f_{0.2Z_{\odot}, \lambda, \text{age}} + X_{Z_{\odot}} f_{Z_{\odot}, \lambda, \text{age}} + X_{2.5Z_{\odot}} f_{2.5Z_{\odot}, \lambda, \text{age}}}{X_{Z_{\odot}} f_{Z_{\odot}, \lambda, \text{age}}}$$

where $F_{\lambda, \text{age}}$ is the mixed metallicity flux per unit wavelength in the bin centred on wavelength $\lambda$ at age Gyr, $f_{Z_{\odot}, \lambda, \text{age}}$ is the flux per unit wavelength in the bin centred...
Table 1. A summary of the best fit ages produced by fitting the 6 alternative models discussed in the text to the near-ultraviolet spectral energy distribution of i) the sun (see Figures 1 and 2), ii) the \( z = 1.55 \) galaxy 53W091 (see Figure 3), and iii) the \( z = 1.43 \) galaxy 53W069 (see Figure 4). In the case of the sun, the result of fitting the mixed metallicity model discussed in section 5 is also given (see Figure 5). The value of reduced \( \chi^2 \) is also given in each case, although in the case of the fits to the Sun, the values of reduced \( \chi^2 \) can only be used to judge the relative quality of the alternative model fits.

| object    | model | best fit / Gyr | reduced \( \chi^2 \) |
|-----------|-------|----------------|----------------------|
| SUN       | J Full| 8              | 1.67                 |
|           | J MS  | 11             | 1.00                 |
|           | W Full| 5              | 2.72                 |
|           | W MS  | 9              | 1.57                 |
|           | Y Full| 4              | 2.06                 |
|           | Y MSGB| 4              | 1.67                 |
|           | J 3Z  | 8              | 1.37                 |
| LBDS 53W091| J Full| 3              | 1.25                 |
|           | J MS  | 3              | 1.22                 |
|           | W Full| 2              | 1.38                 |
|           | W MS  | 3              | 1.22                 |
|           | Y Full| 2              | 1.30                 |
|           | Y MSGB| 2              | 1.25                 |
| LBDS 53W069| J Full| 5              | 1.63                 |
|           | J MS  | 6              | 1.72                 |
|           | W Full| 3              | 1.54                 |
|           | W MS  | 4              | 1.78                 |
|           | Y Full| 2              | 1.63                 |
|           | Y MSGB| 3              | 1.69                 |

on wavelength \( \lambda \) of the model at age Gyr, and metallicity \( Z \), and \( X_{0.2Z} \) is the fractional contribution to \( F_{\lambda Z, \text{age}} \) by \( f_{\lambda Z, \text{age}} \).

A \( \chi^2 \)-fit was used to determine the best-fit age, total normalization, and values of \( X_{0.2Z} \), \( X_{Z} \), and \( X_{2.5Z} \).

In Figure 5 we show the results of this mixed-metallicity fitting procedure. Comparison of the left-hand plot with the dotted line in Figure 1a demonstrates the extent to which allowing metallicity to vary has weakened the constraint on age. However, the best-fit age is still 8 Gyr, as for the full solar-metallicity only models. Figure 5b shows the evolution of the fractional contributions to the flux of the different metallicity SED’s. At the best-fit age of 8 Gyr, the flux is clearly completely dominated by the solar metallicity SED, as it should be. \( X_{0.2Z} \) is 0.01, \( X_{Z} \) is 0.99 and there is no contribution from the 2.5Z model. This gives a mean metallicity of 0.99 Z⊙. In summary, given data of this (obviously excellent) quality, the mixed-metallicity model can return both the correct metallicity and the correct age to high accuracy (where here the correct age does not mean the turnoff age of the Sun, but rather the age of 8 Gyr which was returned using the full model with the correct metallicity).

6 CONCLUSION

In this paper we have not attempted a model-maker’s comparison of different evolutionary synthesis models, deliberately not entering into the debate over which model uses the most trustworthy components, such as isochrones, stellar atmospheres etc. These issues will be addressed in a future paper (Jimenez et al., 2000c). Instead, we have addressed the simple issue of whether the near-ultraviolet spectral energy distribution of the Sun is reproduced by the main-sequence only components of three independent models at an age commensurate with current estimates of the MS-turnoff age of the Sun. This test was suggested by Yi et al. (2000), but in fact leads us to the conclusion that the evolutionary timescale of the main sequence in the Yi et al. models is anomalous when compared with the either the models of Worthey (1994), Jimenez et al. (2000a) or the current best estimate of the MS turn-off age of the Sun.

We have also re-addressed the issue of the extent to which varying contributions from post-MS phases of stellar evolution can affect the age estimation of galaxies at \( z \simeq 1.5 \) from rest-frame ultraviolet spectra. We find that (assuming solar metallicity) the minimum age of the dominant stellar population in the \( z = 1.55 \) radio galaxy 53W091 is 2 Gyr if one invokes the relatively strong AGB/RGB components included in the models of Worthey (1994), and 3 Gyr is one
adopts the weaker post-MS contributions included in the models of Jimenez et al. (2000a). In the case of the even more passive $z = 1.43$ radio galaxy 53W069, these numbers become 3 Gyr and 4 Gyr respectively.

Finally, as stated above, these figures are derived on the assumption of approximately solar metallicity. Yi et al. (2000) and Jimenez et al. (2000b) have in fact shown that the age metallicity degeneracy in a realistic mixed-metallicity population is probably not nearly as severe as previously feared. Nevertheless, ideally it is clearly desirable to determine both age and metallicity directly from the observations. Using the spectrum of the Sun, we have shown that, given data of sufficient quality, it should in principle be possible to break the well-known age-metallicity degeneracy using data covering only the near-ultraviolet spectral range which is accessible when observing galaxies at $z > 1$ with optical spectrographs. The possibility of breaking the age metallicity degeneracy will be explored further in a subsequent paper.

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| object  | model | best fit age / Gyr | reduced $\chi^2$ |
|---------|-------|-------------------|----------------|
| SUN     | J Full| 8                 | 1.67           |
|         | J MS  | 11                | 1.00           |
|         | W Full| 5                 | 2.72           |
|         | W MS  | 9                 | 1.57           |
|         | Y Full| 4                 | 2.66           |
|         | Y MSGB| 5                 | 1.67           |
|         | J 3Z  | 8                 | 1.37           |
| LBDS 53W091 | J Full| 3                 | 1.25           |
|         | J MS  | 3                 | 1.22           |
|         | W Full| 2                 | 1.38           |
|         | W MS  | 3                 | 1.22           |
|         | Y Full| 2                 | 1.30           |
|         | Y MSGB| 2                 | 1.25           |
| LBDS 53W069 | J Full| 5                 | 1.63           |
|         | J MS  | 6                 | 1.72           |
|         | W Full| 3                 | 1.54           |
|         | W MS  | 4                 | 1.78           |
|         | Y Full| 2                 | 1.63           |
|         | Y MSGB| 3                 | 1.69           |