On the Age Estimation of High Redshift Galaxies

Sukyoung Yi

Yonsei University, Korea & Caltech, USA

Thomas M. Brown, Sara Heap, Ivan Hubeny, Wayne Landsman, Thierry Lanz, Allen Sweigart

NASA/Goddard Space Flight Center, USA

Abstract.

The recent spectral analysis of LBDS 53W091 by Spinrad and his collaborators has suggested that the red galaxy at $z = 1.552$ is at least 3.5 Gyr old. This imposes an important constraint on cosmology, suggesting that this galaxy formed at $z \geq 6.5$. Because of its large impact to cosmology, we have performed our own test using our population models and the available rest-frame UV to near-IR data. Using the same configuration as in Spinrad et al. (solar abundance), our analysis suggests an age of $\approx 1.4 - 1.8$ Gyr. More realistic, metal-rich composite models with the effect of convective core overshoot suggest only slightly larger ages. The discrepancy between Spinrad et al.’s age estimate (based on the Jimenez models) and ours originates from the large difference in the model integrated spectrum: the Jimenez models appear much bluer than the Yi models and the Bruzual & Charlot models, and indicate larger ages by sometimes more than 100 %. The source of this difference is under investigation. Yi et al. (1999) present the results in detail.

1. LBDS 53W091: a 3.5 Gyr-old galaxy at $z=1.552$?

Precise age estimates of high redshift galaxies directly constrain the epoch of galaxy formation, $z_f$, where $z_f$ is defined as the epoch when the majority of stars formed. Constraining $z_f$ is important to cosmology. For example, one of the key questions in modern cosmology has been whether the majority of stars in giant elliptical galaxies form at high redshifts in monolithic starbursts or during rather recent merger/interaction activities between smaller galaxies. In addition, the age of a merger galaxy is a unique product of just a few cosmological parameters; thus, it can be used to constrain cosmological parameters as well.

Spinrad and his collaborators recently obtained the rest-frame UV spectrum of LBDS 53W091, a very red galaxy at $z = 1.552$, using the Keck Telescope (Spinrad et al. 1997). Based on their analysis on two UV breaks and the continuum, they have concluded that LBDS 53W091 is at least 3.5 Gyr old already at $z = 1.552$, which suggests $z_f \geq 6.5$, using recently measured cosmological parameters (e.g., $H_0 = 65$, $\Omega = 0.3$, $\Lambda = 0.7$). Their results have been disputed

© Astronomical Society of the Pacific • Provided by the NASA Astrophysics Data System
by two independent studies, however. Bruzual & Magris (1997) reached an age estimate of 1.4 Gyr, mainly matching the overall visible-IR photometric data with the recent Bruzual & Charlot models. Heap et al. (1998) interpreted the UV spectral breaks, using model atmosphere results specifically constructed for their study and the new Yale isochrones, and reached an age estimate of 1 – 2 Gyr. Such discordant age estimates undermine our efforts to use this important technique as a probe of cosmology. Thus, we have carried out a similar exercise using our independent models (Yi et al. 1997), hoping to achieve a more accurate age estimate.

2. Population Synthesis Models

An important advantage of working with the spectra of elliptical galaxies at \( z \approx 1 – 2 \) (age \( \approx 1 – 5 \) Gyr) comes from the fact that their major light sources in the UV and visible, i.e., the stars on the main sequence (MS) and the red giant branch (RGB), are all relatively well understood. The rapid spectral evolution in that age range makes them even more vulnerable to age estimations.

One of the largest uncertainties in modeling 1-5 Gyr-old stellar populations is in the extent of convective core overshoot (OS). Stars develop convective cores if their masses are larger than approximately 1.3 – 1.5 \( M_\odot \), typical for the MS turn-off stars in 1 – 5 Gyr-old populations, such as LBDS 53W091. There has been a consensus for the presence of OS, but its extent has been controversial. Thus, conventional stellar models often do not include OS. After the advent of the OPAL opacities, however, various studies have rather unanimously suggested a modest amount of OS; that is, OS \( \approx 0.2H_p \), where \( H_p \) is the pressure scale height.

OS has many effects on stellar evolution and to the integrated spectrum, but the most notable one appears in the luminosity function. Inclusion of a modest amount of OS causes a longer MS lifetime and an earlier departure from the RGB, as shown in Fig 1-(a). Because most of the visible-IR flux comes from red giants, a decrease in the RGB lifetime results in a lower visible-IR flux. Fig 1-(b) shows the integrated spectra (including all evolutionary phases) with and without OS. We use the Kurucz (1992) spectral library in this study. When the models with OS are used in the population synthesis, the same observed integrated spectrum indicates a larger age by \( \approx 25\% \) when the age is near 1 Gyr.

Spectral dating is even more vulnerable to the uncertainty in the adopted metallicity. Most of the previous age estimates of LBDS 53W091 were based on the single abundance population models, typically for the solar composition. However, LBDS 53W091 would be brighter than any ellipticals in the local universe (\( M_V \approx -23.9 \) at \( z = 0 \), Spinrad et al. 1997); thus, if the conventional luminosity-metallicity relation is assumed, the mean metallicity of this galaxy should be much higher than solar. Most chemical evolution theories predict that giant ellipticals would reach the current metallicity level within a few tenths of a Gyr of the initial starburst (e.g., Kodama & Arimoto 1997). This means that 1 – 5 Gyr-old giant ellipticals may already have stars of various metallicities ranging \( Z \approx 0 \) through perhaps 3 – 4 times solar.
Adopting an arbitrary value of metallicity is dangerous because the age estimate based on continuum fits is quite sensitive to it. Fig 2-(a) shows it clearly. If we assume an arbitrary metallicity between $Z = 0.25$ and $2Z_\odot$, the age estimate would vary between 5 Gyr and less than 1 Gyr, respectively. This difference is caused by the opacity effects that increase with increasing metallicity. As a result, the same observed spectrum can indicate significantly different ages when the true metallicity is unknown.

One can guess the effect of the use of metallicity mixtures even with a cursory inspection of Fig 2. The fraction of metal-poor stars in conventional metallicity mixture models of elliptical galaxies is small. However, even with such small fractions of metal-poor stars, a combination of coeval stars of various metallicities may have a substantial UV light contribution from metal-poor stars because of the opacity effects. We have adopted the metal-rich ($< Z > \approx 2Z_\odot$) “infall” model of Kodama & Arimoto (1997) that reasonably match the observed properties of present epoch giant ellipticals. Fig 2-(b) illustrates the likely light contributions from various metallicity groups of stars when the galaxy is 2 Gyr old. As we expected, metal-poor stars are more efficient UV sources than metal-rich stars, while the opposite is true in the visible-IR. Such metal-rich ($< Z > \approx 2Z_\odot$) composite models always suggest much larger ages than single abundance ($Z = 2Z_\odot$) models but only slightly different ages from the conventional solar abundance models.

3. Age Estimates from $\chi^2$ Tests: $t(\text{uv}) \approx 1.9$ Gyr, $t(\text{vis}) \approx 1.5$ Gyr

We have carried out reduced $\chi^2$ tests to the UV spectrum and the visible-IR photometric data of LBDS 53W091. Fig 3 shows the measured values of reduced
Figure 2.  (a) The 2 Gyr models for different metallicities are shown with the observed data of LBDS 53W091. The four photometric data (filled circles) have been derived from $R$, $J$, $H$, & $K$ magnitudes. Their y-axis error bars are observational errors, and the x-axis ones show the effective band widths. (b) A sample light contribution from the stars of various metallicities in a composite (infall) model, whose mass-mean metallicity is $\approx 2Z_\odot$.

$\chi^2$ of various models. A smaller value of $\chi^2$ indicates a better fit. The spectra are normalized by the mean flux in the 3000 – 3300 Å range, but the test was quite insensitive to the choice of the normalization point, as long as the normalizing flux is defined over a reasonably wide wavelength range ($\geq 50$ Å). The results of the $\chi^2$ tests are summarized as follows, where we define $t(\text{uv})$ as the age estimate based on the UV continuum fitting and $t(\text{vis})$ as the age estimate based on the visible-IR photometric data fitting.

- Inclusion of OS raises $t(\text{vis})$ by $\approx 25\%$, when the age $\approx 1$ Gyr.
- Composite models suggest larger ages by up to 100%, when $< Z > \approx 2Z_\odot$.
- Solar composition models reasonably approximate young metal-rich ellipticals.
- $t(\text{uv}) \approx 1.9 \pm 0.2$ Gyr and $t(\text{vis}) \approx 1.5 \pm 0.2$ Gyr: our estimates are inconsistent with that of Spinrad et al. (1997) with more than a five $\sigma$ confidence level.
- $t(\text{uv}) > t(\text{vis})$

Fig 4 shows that the UV spectrum of LBDS 53W091 indicates a larger age than the visible-IR data: $t(\text{uv}) > t(\text{vis})$. This can provide us with useful information. First, this may indicate the presence of at least some reddening. For example, with a Galactic reddening of $E(B - V) = 0.04$, both the UV spectrum and the photometric data become consistent with an age of 1.3 Gyr (Fig 4-[b]). It is also probable that some of this age difference comes from the fact that the light sources of the UV data are older and/or more metal-rich than those of the visible-IR data, because the UV spectroscopy covered a smaller area near the center of this galaxy (Spinrad et al. 1997): aperture effects.
Figure 3. The results of weighted, reduced-$\chi^2$ tests to (a) the UV spectrum and (b) the visible-IR photometric data of LBDS 53W091. Only shown are the models with OS.

Figure 4. (a) The model (composite, OS) spectra compared to the observed data of LBDS 53W091. In the UV, only the best matching model is overplotted, while in the longer wavelength range multiple models with various ages (shown in Gyr on lines) are shown. The UV spectrum indicates somewhat larger age than the the visible-IR data. (b) If it is dues to a modest reddening (E(B-V)=0.04), a 1.3 Gyr model matches both UV and visible-IR data reasonably.
Figure 5. Comparison between the Yi models and the Jimenez models for solar composition. From the top in (a), 1, 2, 5 Gyr models are shown. In (b), age increases from the bottom. Note the substantial disagreement.

Any $t(\text{uv})$ is in principle a lower limit of the mean age of the majority of stars if there is any age spread among stars, because the UV spectrum is likely to be dominated by the youngest population. For example, if a galaxy experiences a starburst that lasts for 1 Gyr at a constant rate centered at 2 Gyr before the observation, its integrated UV spectrum would indicate $t(\text{uv}) = 1.8 - 1.9$ Gyr instead of 2.0 Gyr. In some ad hoc star formation scenarios, the age underestimation can of course be larger. However, in the case of LBDS53W091, $t(\text{uv})$ is larger than $t(\text{vis})$, which is opposite to the expectation from the population with any age spread. Thus, $t(\text{uv}) > t(\text{vis})$ likely implies very little age spread in LBDS53W091 and thus the presence of some reddening, unless it is entirely due to the aperture effect. Then, our $t(\text{uv})$ is in practice more an upper limit than a lower limit.

4. Origin of the Disagreement among Various Models

The large difference in age estimate from Spinrad et al. and from this study is mainly due to the significant difference in the model integrated spectrum. Fig 5 shows the comparison between the Jimenez models (used in Spinrad et al.) and the Yi models, both for the solar composition with no OS. In the UV, Yi’s 2, 3, 5 Gyr models are close to Jimenez’ 3, 5, 10 Gyr models. In the visible-IR, the difference is even larger. Fig 5-(b) compares their 1, 2, 5, and 10 Gyr models. Jimenez’ 1 and 2 Gyr models are very close to one another, while Yi’s models are quite well separated. Jimenez’ 5 and 10 Gyr models are quite close to Yi’s 2 and 4 Gyr models, respectively. If such a large disagreement is due to the uncertainties in the input physics, we would have to admit that we are not
ready to estimate ages of stellar populations via continuum fitting. Currently, Yi's models are all in good agreement with the Bruzual & Charlot models.

A notable disagreement can easily be introduced by the details in the population synthesis technique. For example, inaccurate interpolations between tracks, whether they take place during the isochrone construction or directly in the population synthesis, may cause significant difference especially in the visible-IR spectrum. The mass interpolation must be carried out with particular caution. A small error in the mass interpolation can cause a seriously inaccurate luminosity function near the tip of the RGB, which will in turn affect the integrated spectrum substantially. For example, when 60 points define one isochrone of ages \( \leq 5 \) Gyr from the zero-age MS through RGB, an error in mass in the 4th (or 5th if age \( \geq 5 \) Gyr) digit below the decimal (in \( M_\odot \)) causes a noticeable difference in the integrated magnitudes in the near-IR, but not in the shape of the isochrone. The tip of the RGB should also be defined with care, because the visible-IR flux is dominated by bright red giants.

Despite all these complexities in modeling the visible-IR flux, it is not true that model spectra in the visible-IR are generally unreliable (see Dunlop 1998 for a different opinion). For example, the age estimate using the old (1987) Revised Yale Isochrones, where RGB tips were computed less accurately than in the Yale Isochrones 1997, is different from our current estimate only by 20%. In short, the visible-IR flux is more sensitive to the uncertainties in the stellar models and in the population synthesis (including isochrone construction), but the level of uncertainty is less than 20% or so in age.

It is still unclear where the difference in the model spectra comes from. It is unlikely to be caused by the difference in the input physics in the stellar models, because the stellar evolution theory is already quite well established. The difference between the estimates of Bruzual & Magris and ours is very small, even though the two groups use different stellar evolution tracks. Because all these three groups use the Kurucz spectral library or some hybrid versions originated from it, it is not likely that much of the difference can be attributed to the spectral library, either. The source of the discrepancy will be known only when these models are compared step by step with each other.

While it may be difficult to directly compare different population models and to find a better model, it should be possible to test models by matching the observational properties of the objects whose ages are reasonably well known. Good examples include the sun, M32, and globular clusters. M32 is a good test to any spectral synthesis model, as we now have resolved CMDs that suggest an age of \( \approx 8 \) Gyr (Grillmair et al. 1996). Yi's composite models \((< Z> \approx Z_\odot)\) match the visible spectrum of M32 at 7.2 - 8.1 Gyr, which is consistent with the CMD results. Yi's models also match the solar spectrum in the 2000 - 3500 Å range at a reasonable age, i.e., 5.0 Gyr. This slight disagreement in the age estimate from the generally accepted solar age (\( \approx 4.5 - 4.7 \) Gyr) is perfectly expected because we are matching a single stellar spectrum with those of composite (in the sense of containing main sequence, red giants, and etc.) stellar populations. This proximity in age estimates once again demonstrates the high reliability of the UV-based age estimates for intermediate-age, composite populations. As one can easily expect from the inspection of Fig 5, the current Jimenez models would suggest much larger ages for both M32 and the sun.
Figure 6. For given cosmological parameters, the age estimates of high-z galaxies can effectively constrain \( z_f \).

5. Conclusion

The pioneering studies of Spinrad and his collaborators have demonstrated the power of precise age estimates of distant galaxies in constraining \( z_f \). Their age estimate of LBDS 53W091, \( \geq 3.5 \) Gyr, suggests \( z_f \geq 6.5 \) when recent cosmological measurements are adopted (Fig. 6). When we use the same input parameters, however, we reach age estimates of \( 1.5 - 2.0 \) Gyr, substantially smaller than theirs. Our estimate suggests \( z_f \geq 2 - 3 \) for this galaxy. The implication on \( z_f \) from different age estimates is illustrated in Fig 6.

The disagreement between the age estimates mainly originates from the difference between the population synthesis models: the Jimenez model spectra (used by Spinrad et al.) look systematically and substantially bluer than the Yi models, resulting in larger age estimates sometimes by more than 100%. The reasons for such disagreements should be understood first in order for this powerful cosmology probe to be useful. The Yi models are currently in reasonable agreement with the Bruzual & Charlot models.

We have improved our estimates over previous ones by adopting convective core overshoot (OS) and realistic metallicity mixtures. Both OS and metallicity mixture raise the age estimates substantially and should be included in modeling.

The slightly larger age estimates from the UV continuum fit than from the visible-IR fit may indicate an evidence of some reddening (e.g., \( E(B-V), \) Galactic\(] = 0.04 \), and/or of radial age/metallicity gradient in this galaxy. It also suggests that the age spread among the stars is not substantial.

Population synthesis models are products of intricate treatments with numerous parameters, thus it is difficult to directly compare different models. Instead, we suggest population synthesis modelers apply their models first to some standard objects, whose ages have been independently determined, for calibration purpose. Good examples include the sun, M32, and globular clusters. The
Yi models currently reproduce the observed spectra of M32 and the sun and the colors of globular clusters at their accepted ages.

Our smaller age estimate for this one galaxy does not contradict work that suggests galaxies generally formed at high redshifts, regardless of the rarity of massive ellipticals at z=1.5. Furthermore, we are just beginning to expand our observations of galaxies to high redshift, and so the existence of a few old galaxies at high redshifts does yet prove any galaxy formation scenario, although it can potentially constrain cosmological parameters (in the sense that the ages of a few objects can provide lower limits on the age of the Universe at that redshift). Finding no old galaxies at high redshift would support a low zf for the general population. Building a larger database of observations is therefore crucial to achieve a unique and statistically significant solution.

Acknowledgments. We are grateful to the LBDS 53W091 team (in particular, Hyron Spinrad, Dan Stern, Raul Jimenez, Arjun Dey) for providing the data, models, and stimulating discussions. We also thank Gustavo Brusual for sending me his models and for constructive comments. Part of this work was supported by the Creative Research Initiative Program of the Korean Ministry of Science & Technology grant.

References

Dunlop, J. 1998, in “The most distant radio galaxies” KNAW Colloquium, eds. Best et al. (Amsterdam: Kluwer), in press