A REVISED AGE FOR THE \(z=1.55\) GALAXY LBDS 53W091

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ABSTRACT

Empirical evidence suggests that the stellar population in LBDS 53W091 is significantly younger than that in M32. Population synthesis models indicate that the age of LBDS 53W091 is in the range from 1 to 2 Gyr and depends on the specific model. Older ages require sub-solar metallicity models. The estimates of the age of the dominant population in M32 range from 3 to 5 Gyr and depend not only on the model but also on the SED of this galaxy used in the fits. The same models predict an age of 11 to 13 Gyr for the stars in a typical old E/S0 galaxy. A 1 to 2 Gyr old galaxy at \(z = 1.55\) poses no problem for the \(\Lambda = 0\), \(\Omega = 1\) universe, as long as \(h \leq 0.8\). The most likely reason for the difference between our age estimate and the value of 3.5 Gyr derived by Dunlop et al. (1996), is the fact that these authors did not require that the population synthesis models that they used fitted simultaneously the UV break amplitudes and the observed \(R - J\), \(R - H\), and \(R - K\) colors of this galaxy. As we will discuss elsewhere, a comparison of our results with those by Spinrad et al. (1997) shows that our conclusions still hold. The paper by Spinrad et al. was unknown to us at the time of this Conference.

1. INTRODUCTION

LBDS 53W091, at \(z = 1.552\), is one of the reddest and most distant galaxies with high quality UV spectrophotometry and UV-optical photometry. The discovery spectrum by Dunlop et al. (1996) samples the near UV in the galaxy rest frame and shows clearly several absorption features and the spectral breaks at \(\lambda_{rest} = 2640\) and 2900 Å. Observer frame \(RJHK\) photometry was also performed by Dunlop et al. From a comparison of the amplitude of these breaks with the predictions of various population synthesis models (Guiderdoni & Rocca-Volmerange 1987; Bruzual & Charlot 1993; Bressan, Chiosi, & Fagotto 1994; and their own models), Dunlop et al. estimate that star formation ceased in this galaxy at least 3.5 Gyr before the epoch of the observation and use this number to constrain the value of the density parameter \(\Omega\). For the stellar population in this galaxy not to be older than the \((\Lambda = 0)\) universe at this epoch, \(\Omega < 0.2\) if \(h \equiv H_0/100\) km s\(^{-1}\) Mpc\(^{-1}\) = 0.75, or \(\Omega < 0.8\) if \(h = 0.50\). Since the age of the \(\Omega = 1\) universe at \(z = 1.552\) (\(1.6h^{-1}\) Gyr) is \(< 3.5\) Gyr for the accepted range of values of \(h\) (\(0.50 < h < 0.75\)), Dunlop et al. argue that the \(\Lambda = 0\), \(\Omega = 1\) universe can thus be \textit{formally excluded} as a valid world model.

Given the far reaching astrophysical implications of this conclusion, we repeat Dunlop et al. (1996) analysis of their data in an independent manner. We show below that the age of the stellar population in LBDS 53W091 is most likely in the range 1 to 2 Gyr. Thus, the \(\Lambda = 0\), \(\Omega = 1\) universe is \textit{still viable}, as long as \(h \leq 0.8\).

2. OBSERVATIONAL DATA

In Table 1 we summarize the photometric data available for LBDS 53W091. The \(RJHK\) magnitudes were taken from Dunlop et al. (1996). The \(V\) and \(I\) magnitudes were derived from the synthetic \(V - R\) and \(R - I\) colors computed from the Dunlop et al. spectral energy distribution (SED), kindly made available to us by H. Spinrad, D. Stern, and A. Dey. In Table 1, \(\lambda_{eff}\) and \(\Delta\lambda\) are the effective wavelength and the range covered by each filter when observing a source at \(z = 1.552\). \(\beta(2640)\) and \(\beta(2900)\), defined in §4.2, are not expressed in mag.

As Dunlop et al. did, we also compare the SED of LBDS 53W091 with that of the dwarf elliptical galaxy M32. Additionally, we compare both of these spectra with the SED of a giant E/S0 galaxy, typical of an old stellar population. In Fig 1 the Dunlop et al. (1996) spectrum in the UV below 3700 Å is shown as a histogram. The values of the flux in the \(R, J, H,\) and \(K\) bands were computed from the data in Table 1 and are shown as individual points at \(\lambda_{eff}\). The size of the error bars correspond to \(\pm\sigma\) in Table 1. Including the additional uncertainty introduced by matching the large aperture photometry to the SED (at \(R\)) will increase the size of the error bars. The SEDs of M32 and the E/S0 galaxy given by Bica et al. (1996: E7-M32 and E2-E5 groups in their notation) are also shown in Fig 1. The SED of M32 used by Magris & Bruzual (1993), marked M32(b), is redder than the SED from Bica et al. This difference is due to the uncertainty in matching UV and optical SEDs. These empirical data already suggest that LBDS 53W091 is considerably younger than M32.

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Fig. 1. SEDs of LBDS 53W091, M32 and a giant E/S0 in the galaxy rest frame. The SEDs are scaled to the same value of the integrated flux in the range from 2900 to 3150 Å. The wavelength scale is logarithmic.

3. POPULATION SYNTHESIS MODELS

Bruzual & Charlot (1997, hereafter BC97; see also Bruzual & Charlot 1996, and Bruzual et al. 1997) have extended their (1993) evolutionary population synthesis models to provide the evolution in time of the spectrophotometric properties of simple stellar populations (SSPs) of a wide range of stellar metallicity \((Z = 0.0001, 0.0004, 0.004, 0.008, 0.02, 0.05, 0.10)\). The evolutionary tracks are based on the work from the Padova School and an independent set of tracks from the Geneva School for \(Z = 0.02\). The library of synthetic stellar SEDs compiled by Lejeune et al. (1997a,b, hereafter LCB) that covers all the metallicities listed above is used by BC97. The nearly-empirical, extended version of the Gunn & Stryker (1983, hereafter EGS) stellar atlas of BC93 has been updated and used to build the reference \(Z = Z_\odot\) models. In the EGS atlas the IUE stellar library of Fanelli et al. (1996) has been incorporated, and the spectra of the coolest M-type stars have been replaced following LCB. Thus, for \(Z = Z_\odot\) we can compare the predictions of purely-theoretical models (built with LCB) and nearly purely-empirical models (built with EGS) for either the Padova or the Geneva tracks.

| Band | mag | \(\lambda_{eff}\) | \(\Delta\lambda\) | Band | mag | \(\lambda_{eff}\) | \(\Delta\lambda\) |
|------|-----|------------------|----------------|------|-----|------------------|----------------|
| V    | 25.7 ± 0.2 | 2157 | 1861-2900 | H    | 19.5 ± 0.1 | 6413 | 5251-7284 |
| R    | 24.6 ± 0.2 | 2588 | 2175-3429 | K    | 18.7 ± 0.1 | 8716 | 7445-9948 |
| I    | 23.0 ± 0.2 | 3096 | 2743-3487 | \(\beta(2640)\) | 1.9 ± 0.3 | \(\beta(2900)\) | 4.1 ± 0.4 |
| J    | 20.5 ± 0.1 | 4904 | 4075-5643 | \(\beta(2640)\) | \(\beta(2900)\) | \(2800\) | 

4. THE AGE OF LBDS 53W091

4.1. Age from Broad Band Colors

Fig 2 shows the evolution in time of various colors computed in the observer frame, assuming \(z = 1.552\), for a SSP and a 1 Gyr burst model (1GB hereafter). In the latter the star formation rate (SFR) is constant during the first Gyr and zero afterward. The colors computed from the SEDs shown in Fig 1 have been placed at the
Fig. 2. Evolution in time of various colors computed in the observer frame assuming $z = 1.552$ for: (a) a SSP model, and (b) a 1GB model. Both models were computed with the $Z = Z_\odot$ Padova tracks, using the EGS atlas and the Salpeter (1955) initial mass function (IMF).

The amplitude of the spectral breaks at $\lambda = 2640$ and 2900 Å is a function of the age of the stellar population. However, the actual value of the amplitude of the break and of its rate of change depend on the wavelength intervals used to measure the flux above and below the discontinuity. Experimenting with several
TABLE 2

GALAXY AGE DERIVED FROM FITS TO DIFFERENT MODELS (GYR)

| Tracks   | SFR   | IMF    | Z     | Atlas   | LBDS 53W091 | M32 | M32(b) | E/S0 |
|----------|-------|--------|-------|---------|------------|-----|--------|------|
| Padova   | SSP   | Salpeter | Z⊙   | EGS     | 1.4        | 2.75| 3.50   | 12.50|
| "       | "     | "      | "    | "       | 1.4    | 3.00| 3.50   | 12.50|
| "       | "     | 1GB Salpeter | "    | "       | 2.0    | 3.25| 4.00   | 12.75|
| "       | "     | "      | "    | "       | 2.1    | 3.50| 4.25   | 13.00|
| Geneva   | SSP   | Salpeter | "    | "       | 1.2    | 3.25| 4.50   | 11.25|
| "       | "     | "      | "    | "       | 1.3    | 3.50| 4.75   | 11.00|
| "       | "     | 1GB Salpeter | "    | "       | 2.0    | 3.75| 5.00   | 11.50|
| "       | "     | "      | "    | "       | 2.1    | 4.00| 5.25   | 11.75|
| Padova   | SSP   | Z⊙/5   | LCB  | 3.75    | 13.50    | ...| ...    | ...  |
| "       | "     | "      | "    | 4.00    | 13.75    | ...| ...    | ...  |
| "       | "     | 1GB Salpeter | "    | "       | 4.50   | 14.00| ...    | ...  |
| "       | "     | "      | "    | 4.50    | 14.00    | ...| ...    | ...  |

wavelength intervals we found that the 30 Å bins used by Dunlop et al. (1996) to define these amplitudes are too narrow (just a single wavelength point is included in some instances), resulting in break amplitudes with little sensitivity to the evolution of the stellar population. Instead, we define the following spectral properties which provide more sensitivity to the evolution of the population than the break amplitudes defined by Dunlop et al.

\[
\beta(2640) = \frac{(\lambda_4 - \lambda_3)^{-1} \int_{\lambda_3}^{\lambda_4} F_\lambda(\lambda) d\lambda}{(\lambda_2 - \lambda_1)^{-1} \int_{\lambda_1}^{\lambda_2} F_\lambda(\lambda) d\lambda}, \quad \beta(2900) = \frac{(\lambda_6 - \lambda_5)^{-1} \int_{\lambda_5}^{\lambda_6} F_\lambda(\lambda) d\lambda}{F_\lambda(2800)},
\]

where (\(\lambda_1, \lambda_2\)) = (2200, 2400), (\(\lambda_3, \lambda_4\)) = (2640, 2750), and (\(\lambda_5, \lambda_6\)) = (2900, 3150) Å. \(F_\lambda(2800) = F_\lambda(\text{Mg II 2800})\) measures the flux at the bottom of the Mg II absorption line at 2800 Å.

Fig 4 shows the evolution of \(\beta(2640)\) and \(\beta(2900)\) for the same models used in Fig 2. The dotted lines join the points corresponding to individual stars at the MS turnoff. The dots representing M32 and the E/S0 galaxy have been placed at the age at which the model produces the best fit to the observed colors (Fig 3). The height of the boxes representing LBDS 53W091 correspond to 2\(\sigma\). The width of these boxes represents the range of age allowed by the model. The triangles, from left to right, represent the position of stars of 1.8, 1.5, 1.3, 1.15, and 1\(\text{M}_\odot\). The effective temperature at the turnoff was obtained from the Padova tracks. From this figure we conclude that: (a) \(\beta(2900)\) is a good age indicator for young stellar populations up to 3 Gyr. LBDS 53W091 and M32 fall on top of the model prediction at the age determined from fitting the colors. For LBDS 53W091, \(\beta(2900)\) indicate again an age in the range from 1 to 2 Gyr, considerably younger than M32. (b) The predicted \(\beta(2640)\) agrees very well with the observed values for M32 and E/S0 at the age derived from broad band colors. Because of its flatter slope, \(\beta(2640)\) is not as useful an age indicator as \(\beta(2900)\). Despite the wide range of possible age, the value of this break for LBDS 53W091 indicates that this galaxy is younger than M32. (c) The values of \(\beta\) for the integrated populations are higher at early ages than the corresponding value for the star at the MS turnoff (dotted lines in Fig 4). The contribution from stars cooler than the turn-off star is noticeable even in the near UV. This happens because \(\beta\) increases with decreasing stellar mass and low mass stars are present in large numbers in the MS according to any realistic IMF. The age derived from \(\beta(2900)\) for LBDS 53W091 is about 1.5 Gyr younger than the MS turnoff for the same amplitude of this break. At the age of M32, the age of the population agrees fairly well with the turnoff. (d) The E/S0 galaxy shows a value of \(\beta(2900)\) higher than predicted by the models. All the dwarf and giant stars of type later than G8 in the Fanelli et al. (1996) IUE library (used by BC97) show chromospheric emission at Mg II 2800, filling in the absorption line, and decreasing \(\beta(2900)\) with time in the models. In real E/S0 galaxies chromospheric emission must also occur, but most likely there is a distribution of emission line intensity at each spectral type, not taken into account in our models. This fact may explain the apparent discrepant value of \(\beta(2900)\) for the E/S0 galaxy in Fig 4.

4.3. Age from the Galaxy SED
Fig. 3. (a) $m(\lambda) - R$ vs $\lambda$ for LBDS 53W091 (dashed line), M32 (dotted line), and E/S0 (dot-dashed line). (b,c,d) Colors predicted by the SSP model (Salpeter IMF, EGS atlas), at 1.4, 2.75, and 12.5 Gyr, respectively (solid line). The effective wavelengths seen by the $VRIJHK$ filters for $z = 1.552$ are indicated in the two bottom frames.

Fig. 4. Evolution in time of $\beta(2640)$ and $\beta(2900)$ for: (a) a SSP model, and (b) a 1 Gyr Burst model, both for the $Z = Z_\odot$ Padova tracks and the Salpeter IMF.
Fig 3 of Bruzual & Magris (1997; hereafter Fig 3bm), not included here due to lack of space, shows the SEDs for the $Z = Z_\odot$ SSP model together with the observed SEDs. The ages derived from fitting broad band colors agree with the ages derived from fitting the complete SEDs from 2000 to 9600 Å. The quality of the fits in Fig 3bm is remarkable. We also show in Fig 3bm the contribution from different stellar groups to the total SED. We see from this figure that despite the relatively similar value of $\beta(2640)$ for the 3 galaxies (Fig 4), the relative contribution of the MS and subgiant branch stars is quite different for each galaxy. It is important to use models that include all phases of stellar evolution to study these systems.

5. CONCLUSIONS

Empirical evidence suggests that the stellar population in LBDS 53W091 is significantly younger than the dominant population in M32 (Fig 1). We have used evolutionary population synthesis models to estimate the age of the dominant population in these stellar systems. The age of LBDS 53W091 is in the range from 1 to 2 Gyr and depends on the specific model (Table 2). Older ages require sub-solar metallicity models. The estimates of the age of the dominant population in M32 range from 3 to 5 Gyr and depend not only on the model but also on the SED of this galaxy used in the fits. The same models predict an age of 11 to 13 Gyr for the stars in a typical old E/S0 galaxy. This age is consistent with the age of the metal-rich galactic bulge globular clusters NGC 6553, NGC 6528, and Terzan 5, estimated by Bruzual et al. (1997).

 Passive evolution seems an adequate scenario for the evolution of the stellar population in E galaxies from $z = 1.6$ to $z = 0$. The dominant population in M32 is genuinely young (3 to 5 Gyr), independently than an older stellar population may be present in this galaxy. Thus, M32 may not be representative of galaxies that evolve passively. The length of time for which these galaxies have existed as individual dynamical entities is not determined by our models.

The age of the $\Lambda = 0$, $\Omega = 1$ universe at $z = 1.552$ is $1.6h^{-1}$ Gyr. Hence, a 1 to 2 Gyr old galaxy at $z = 1.552$ poses no problem for this universe as long as $h \leq 0.8$. In this universe, the 13 Gyr limit for the E/S0 galaxy at $z = 0$ requires $h \leq 0.5$.

The most likely reason for the difference between our age estimate of 1 to 2 Gyr for LBDS 53W091 and the value of 3.5 Gyr derived by Dunlop et al. (1996), is the fact that these authors did not require that the population synthesis models that they used fitted simultaneously the UV break amplitudes and the observed $R - J$, $R - H$, and $R - K$ colors of this galaxy. When we prepared the poster for this Conference the paper by Spinrad et al. (1997) was not known to us. A preliminary comparison of our results with those by Spinrad et al. shows that our conclusions still hold. This will be discussed in detail elsewhere.

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Fig. 5. (a,b,c) SED for the $Z = Z_\odot$ SSP model at 1.4, 2.75, and 12.5 Gyr (heavy solid lines and points) together with the SED of LBDS 53W091 in the galaxy rest frame, M32, and the E/S0 galaxy (light solid lines).

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6. APPENDIX

For the benefit of the interested reader, in Fig 5 of this Appendix we reproduce Fig 3bm, i.e., Fig 3 from Bruzual & Magris (1997) together with the corresponding discussion.

Fig 5 shows the SEDs for the $Z = Z_\odot$ SSP model together with the observed SEDs. The ages derived from fitting broad band colors agree with the ages derived from fitting the complete SEDs from 2000 to 9600 Å. The quality of the fits in Fig 5 is remarkable. The observed SEDs have been scaled to match the model flux by minimizing the residuals $\log F_\lambda(obs) - \log F_\lambda(model)$ over the entire SED. The resulting fluxes correspond to a galaxy of mass $1 M_\odot$. To illustrate the effects of spectral evolution more clearly, the SEDs in panels (b) and (c) have been multiplied by a scaling factor $\alpha$. The value of $\alpha^{-1}$ reflects the amount of spectral evolution from 1.4 to 12.5 Gyr. Thus, at 5500 Å, the M32 model is half as bright as the LBDS 53W091 model, and the E/S0 model is 7 times fainter than LBDS 53W091. These numbers refer only to the dimming effects of passive evolution in galaxies of identical mass. No attempt has been made to scale the flux according to the mass of each galaxy. In each panel of Fig 5 the contribution of each stellar group to the total SED is shown as follows: main sequence (dotted line), subgiant branch (short-dashed line), red giant branch (long-dashed line), horizontal branch (dot and short-dashed line), asymptotic giant branch (dot and long-dashed line). Despite the relatively similar value of $\beta(2640)$ for the 3 galaxies (Fig 4), the relative contribution of the MS and subgiant branch stars differs for each galaxy. It is important to use models that include all phases of stellar evolution to study these stellar systems.