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Determining the Star-formation History of Elliptical Galaxies

L. A. NOLAN
University of Birmingham, U.K.

Abstract

We investigate the star-formation history of elliptical galaxies at high and low redshift via spectral fitting, using the latest version of the Jimenez et al. (1998) stellar population evolutionary synthesis models. For the high-redshift galaxies, with predominantly co-eval stellar populations, we find that high S:N rest-frame Keck UV spectra contain sufficient information to determine their age and mean metallicity. For the more complex low-redshift ellipticals, we find that fitting to long-baseline UV+optical spectrophotometry is a powerful tool for disentangling the unambiguous star-formation history of multiple stellar population components (age, metallicity and relative baryonic mass). The results are consistent with the hypothesis that there are two routes for the formation of elliptical galaxies: those that are formed at low redshift (z<1) via major mergers, with associated star formation, and those that are assembled at high redshift, with predominantly passive evolution. With robustly constrained ages of stellar populations at known redshift, we are also able to put constraints on cosmological models, and find that our results strongly favour a Λ-dominated Universe.

1.1 Red Galaxies at z > 1.5

We have fitted variable-metallicity co-eval models to the high signal:noise, deep, optical spectra of the $z \simeq 1.5$ mJy radio galaxies 53W091 and 53W069 obtained with the Keck telescope (Dunlop et al. 1996; Spinrad et al. 1997). The best fitting ages and mean metallicities for the two galaxies were determined via χ^2 minimisation. Figure 1.1 presents the results for LBDS 53W091. The best fitting model to this spectrum has an age of 3 Gyr and solar metallicity ($Z_\odot$). For LBDS 53W069, the age is less well-constrained, but must be > 2 Gyr, with a metallicity ~ 3.8 $Z_\odot$. (Nolan et al. 2003). These robust results resolve the disagreement over the precise age of LBDS 53W091 (e.g. Bruzual & Magris 1997, Yi et al. 2000) and indicate that these objects have mature stellar populations already in place at high redshift (z $\sim$ 1.5).

1.2 Low-redshift Elliptical Galaxies

NGC 3605 and NGC 5018 are two low-z elliptical galaxies (z = 0.002 and 0.009 respectively). We have used archived UV+optical spectrophotometry to create a single long-baseline, high-quality spectrum for each object. The UV spectra of NGC 3605 and NGC 5018 (2250 – 4750 , Ponder et al., 1998) were observed using the Faint Object Spectrograph on the Hubble Space Telescope. The optical spectrum of NGC 3605 (3481 – 7375 , Jansen et al., 2000) was observed with the F. L. Whipple Observatory's 1.5m Tillinghast telescope.

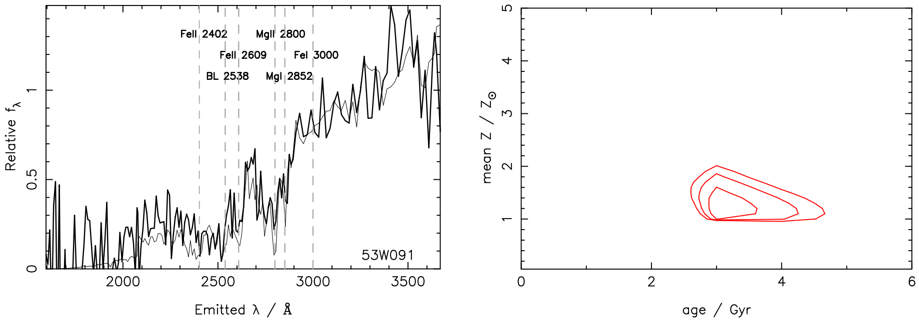

Fig. 1.1. LHS: the best-fitting, six-component, mixed-metallicity, co-eval model (3 Gyr, $Z_\odot$, thin line) to the spectrum of the z = 1.55 galaxy LBDS 53W091 (Dunlop et al. 1996; Spinrad et al. 1997, thick line). The central wavelengths of the mid-UV spectral features identified by Fanelli et al. (1992) are marked on the spectra for comparison (dashed lines). RHS: contour plots of constant relative likelihood for the marginalised distribution of mean metallicity with age. The contours contain 68%, 90% and 95.4% relative likelihood (Nolan et al. 2003).

For NGC 5018, the optical spectrum (3700 − 8000 , Bica & Alloin, 1987a) was observed with the ESO 1.52m telescope at La Silla. The infrared (IR) spectrum (6300 − 9700 , Bica & Alloin, 1987b) was observed with the ESO 2.2m telescope. In each case, the sections of the spectra for each object were normalised to unity in the overlap region and spliced.

Two-component model spectra were fitted to the long-baseline data, via χ^2 minimisation. The age and metallicity of each component, together with the relative normalisation of the two components were allowed to vary freely. The results are presented in table 1.1 and Figure 1.2. It is evident that, despite the apparent similarity of the spectra of these two ellipticals, they have very different star-formation histort (SFH). NGC 3602 is dominated by a young (2 Gyr), high metallicity (5 $Z_\odot$) stellar population, whereas NGC 5018 has a predominantly old (12 Gyr) population, with a metallicity 2.5 $Z_\odot$. This suggests that NGC 3605 is the present-day result of a major merging event at low redshift (z_{merg} = 0.2, for H_0= 65 kms^{-1} Mpc^{-1}, Ω_m= 0.3 and Ω_Λ= 0.7) which triggered a massive starburst, whereas NGC 5018 has evolved predominantly passively from high redshift ($z_{form} \sim 3$, for the same cosmology), with a small amount of later star formation, probably triggered by a mild interaction with the neighbouring spiral galaxy NGC 5022 (Dunlop et al., 2003, in preparation).

Figure 1.3 demonstrates the power of our UV+optical spectral fitting method. Fitting to the optical spectra alone is unable to lift the age-metallicity degeneracy. However, with the additional constraints imposed by inclusion of the UV spectrum, age and metallicity can be tightly constrained (Dunlop et al., 2003, in preparation).

1.3 Conclusions

We have achieved the robust, unambiguous disentanglement of SFH for low and high-z galaxies. The results are consistent with the locations of these objects in the Fundamental Plane(Figure 1.4). In summary:

NGC 3605: is a power-law galaxy, with a predominantly young stellar population, arising from star formation associated with formation via a major low-z galaxy-galaxy merging event.

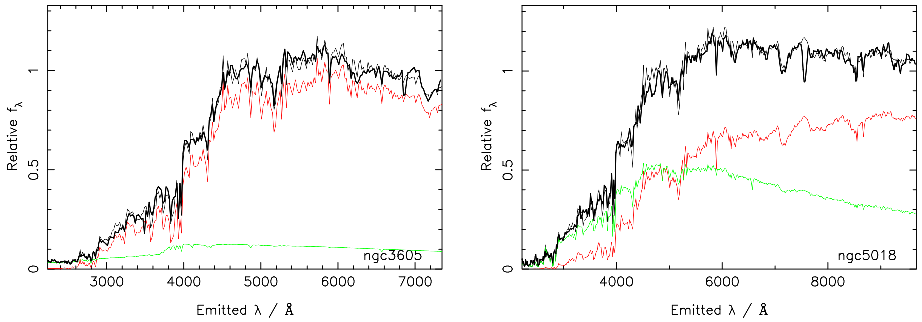

Fig. 1.2. Best-fitting two-component stellar population model (thin black line) superimposed on the combined HST-UV + ground-based optical spectra of the elliptical galaxies NGC 3605 and NGC 5018 (thick lines). We note that results for NGC 5018 do not conflict with the recent report by Leonardi & Worthey (2000) that NGC 5018 contains an intermediate-age stellar population. Rather, our analysis confirms the presence of this component, but also reveals that it does not dominate the mass of the stellar population (Dunlop et al. 2003, in preparation). See table 1.1 for the best-fitting parameters.

Table 1.1. *Best-fitting results from analysis of the UV+optical spectra of NGC 3605 and NGC 5018. NGC 5018 is dominated by an intermediate-age stellar population (2 Gyr), whereas NGC 5018, a larger elliptical with boxy isophotes, is dominated by an old component (12 Gyr).*

	Age / Gyr	$Z / Z_\odot$	M / M_{gal}
NGC 3605	2.0	5.00	0.88
	14.0	0.01	0.12
NGC 5018	12.0	2.50	0.78
	4.0	1.00	0.22

NGC 5018: a core galaxy, with most of its star formation completed at high redshift, and predominantly passive evolution thereafter.

LBDS 53W091 and 53W069: massive galaxies with mature stellar populations already in place by $z \sim 1.5$. Star formation in these objects was therefore completed somewhere in the redshift range $3<z<5$. This suggests that star formation activity in radio galaxies, and potentially all massive ellipticals, is largely complete at $z > 3$. These massive galaxies are the plausible progenitors of low-z core galaxies like NGC 5018.

Cosmological constraints from the ages of stellar populations at known z (Figure 1.5) strongly favour a Λ-dominated Universe, consistent with observational constraints from, for example, the Wilkinson Microwave Anisotropy Probe (Spergel et al. 2003).

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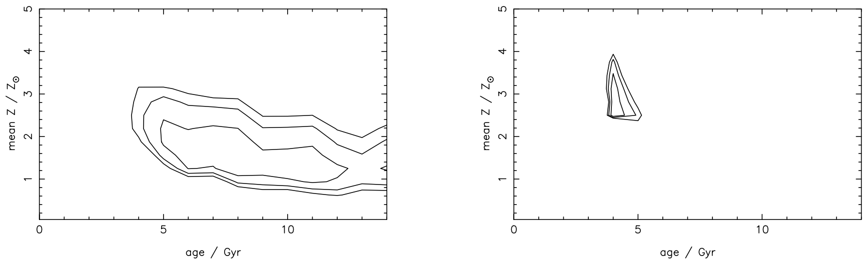

Fig. 1.3. Confidence intervals on mean age and metallicity (for a co-eval, mixed-metallicity model) of NGC 3605, from fitting to only the optical data (LHS) and from fitting to the combined UV+optical spectrum. When only the optical data are included, the age-metallicity degeneracy is clearly evident. When the spectrum is extended into the near-UV, the degeneracy is lifted, and an unambiguous result is achieved, which clearly shows that the stellar mass of NGC 3605 is dominated by an intermediate-age population of fairly high metallicity. Contour levels are 1, 2 and 3 σ (Dunlop et al. 2003).

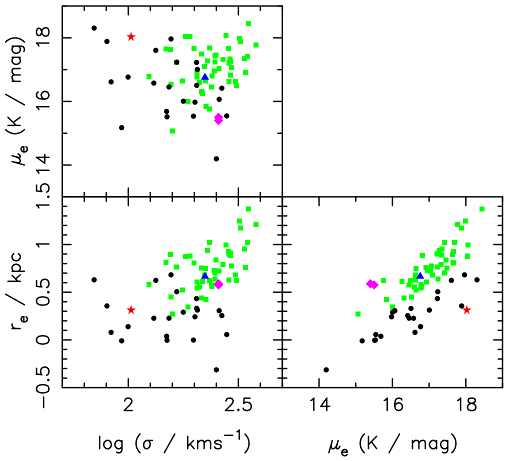

Fig. 1.4. Projections of the Fundamental Plane. NGC 5018 (triangle), LBDS 53W069 and LBDS 53W091 (diamonds) are associated with the population of massive boxy ellipticals (squares). NGC 3605 (star) is associated with the intermediate-mass disky ellipticals (circles). This is consistent with the SFH we have derived for these objects. Parameters are calculated with $H_0 = 65 kms^{-1}, \Omega_m = 0.3, \Omega_\Lambda = 0.7$. Fundamental Plane data is from Bender et al. (1992), Faber et al. (1989), Faber et al. (1997), Dunlop (1999) and Peacock et al. (1998).

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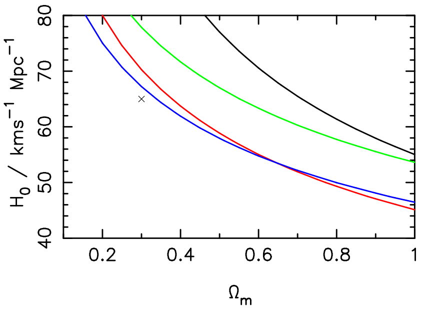

Fig. 1.5. Lines of constant age for cosmologies where $\Omega_m + \Omega_{Lambda} = 1$. The lines represent cosmologies for which the Universe has an age equal to that determined for the stellar populations in this work, at the redshift of the galaxy hosting that population. Cosmologies to the upper right of the lines are therefore excluded, as, in the cosmologies represented in these regions, the Universe would be younger than the ages of the stellar populations at the corresponding redshifts. From left to right along the top x-axis: NGC 3605 sub-population, 14 Gyr at z = 0.009; typical low-z AGN host galaxy, 11 Gyr at z = 0.2 (Nolan et al. 2001); NGC 5018 dominant population, 12 Gyr at z = 0.002; LBDS 53W091, 3Gyr at z = 1.5; Cross: cosmology with $H_0 = 65 kms^{-1}, \Omega_m = 0.3, \Omega_\Lambda = 0.7$.

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