OLD GALAXIES AT HIGH REDSHIFT

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The most passive galaxies at high redshift are unlikely to be identified by either narrow-band emission-line searches, or by Lyman limit searches (both techniques which have been highlighted at this meeting) simply because such selection methods rely on the presence of a strong ultraviolet component. Selection on the basis of extreme radio power has also proved to yield optically active objects with the majority of high-redshift objects studied to date displaying complex elongated optical/UV morphologies, relatively blue optical-ultraviolet continuum colours, and strong emission lines. These features, coupled with the failure to detect any spectral signatures of old stars at $z > 1$, has led to the suggestion that these galaxies are being observed close to or even during a general epoch of formation. However, we have recently demonstrated that radio selection at significantly fainter (mJy) flux densities can be used to identify apparently passively evolving elliptical galaxies at high redshift. Deep Keck spectra have now been obtained for two such objects yielding absorption line redshifts $z \simeq 1.5$; 53W091 at $z = 1.552$ (Dunlop *et al.* 1996)[1] and most recently 53W069 at $z = 1.432$. The ultraviolet SEDs of these galaxies indicate minimum ages > 3 Gyr while, as stressed in this article, the strength of the reddenning-independent ultraviolet spectral breaks actually indicate a greater minimum age of 5 Gyr for both objects assuming solar metallicity. Since the spectra comprise the integrated light of each galaxy to radii greater than r_e, I argue that it is difficult to justify the adoption of significantly super-solar metallicity in interpreting these data. It thus seems hard to escape the conclusion that $\Omega_0 < 1$ and that, irrespective of the adopted cosmology, at least some massive ellipitical galaxies were formed at high redshift ($z > 5$).

1 Background: locating passively evolving galaxies at high z

The recent discovery of a substantial population of star-forming galaxies at ($3.0 < z < 3.5$) has revolutionised the study of radio quiet galaxies at high redshift, as evidenced by a number of contributions at this meeting[2]. However a selection method which depends on a Lyman continuum break superimposed on an otherwise blue far-UV continuum can shed little light on the evolutionary state of the most passively evolving systems which exist at a given epoch. This is unfortunate since, given the ease with which a relatively small starburst can mask the true properties of an underlying galaxy, it is the reddest/most-passive systems at any redshift which are of greatest interest for constraining the first epoch of galaxy formation and indeed the age of the Universe.

Radio-based selection has long provided an alternative and effective method of locating high redshift galaxies which, at least in principle, should not be so directly biassed towards star-forming sources. Indeed, if anything it should be biassed towards the precursors of old elliptical galaxies since at low-redshifts it is well-established that the hosts of powerful radio sources are elliptical galaxies with well-evolved stellar populations. Despite this, identification of high-redshift objects on the basis of extreme radio power has also yielded optically active objects with the majority of high-redshift radio galaxies studied to date displaying complex elongated optical/UV morphologies, relatively blue optical-ultraviolet continuum colours, and strong emission lines[3]. However, the fact that the optical-ultraviolet properties of high-redshift radio galaxies are known to correlate with radio power[4] suggests that any radio-based search for 'normal' elliptical galaxies at high redshift should be confined to milli-Jansky flux levels. Accordingly, over the past few years we have investigated the properties of weak radio galaxies with $S_{1.4GHz} > 1$ mJy from the Leiden Berkeley Deep Survey, and have isolated a sample of 10 extremely red objects that have $R - K > 5$ and $z_{est} > 1$ for intensive spectroscopic study.

2 Keck Spectroscopy

While a red $R-K$ colour can be taken as indicative of an old stellar population, deep optical spectroscopy is vital for the reliable dating of these objects for four reasons. First, a spectroscopic redshift is required. Second, it is necessary to show that the red colour of the object arises from a lack of young stars rather than, for example, from a dust-reddened active nucleus. Third, the shape of the rest-frame ultraviolet spectrum of a galaxy is extremely sensitive to the age of the stellar population[5]. Fourth, for high-redshift galaxies it should be possible to use evolutionary synthesis models to derive relatively robust age estimates from ultra-violet SEDs because, for the potential age range of interest (*i.e.* age < 8 Gyr for $z > 1$) the ultraviolet SED is completely dominated by stars near the main-sequence turnoff point on the HR diagram[6] (*i.e.* disagreements over, for example, the strength and colour of the AGB or HB are unimportant).

We have now obtained deep optical spectra of two red mJy radio galaxies using LRIS on the Keck telescope. Our redshift determination and spectral dating of the first of these (53W091; $z = 1.552$) have been published[1] and will be described in more detail elsewhere[7]. In brief, the ultraviolet SED of this source is, as illustrated in Figure 1, very similar to those of low-redshift ellipticals such as M32, and essentially identical to that of an F6V star. Both these comparisons suggest an age of $\simeq 3.5$ Gyr, a result confirmed by spectral synthesis modelling. We have recently (June 1996) obtained a deep LRIS spectrum of a second red mJy radio galaxy, 53W069. This object also lies at $z \simeq 1.5$ ($z = 1.432$) and has an ultraviolet SED which is in fact slightly redder,

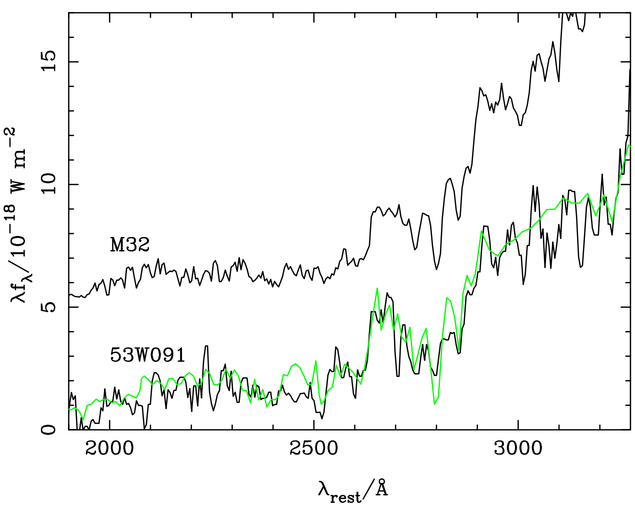

Figure 1: The rest-frame spectrum of 53W091 compared with an instantaneous starburst at an age of 3.5 Gyr (dotted line) and a transposed IUE spectrum of the elliptical M32.

indicating an age of $\simeq 4.5$ Gyr[8].

3 Galaxy ages from ultraviolet spectral breaks

While the large number of stellar absorption features detected in the spectra of both these objects proves that their UV light is dominated by stars, dating on the basis of the overall shape of their UV SED is susceptible to distortion either by dust reddening or by low-level direct/indirect AGN contamination. However the strengths of the spectral breaks at 2640Å and 2900Å being relatively immune from such complications should yield more robust age estimates. Certainly the strength of these breaks in the IUE spectra of stars is well studied[9], and despite misgivings over the understanding of the relevant opacities, evolutionary synthesis models based on both observed and theoretical stellar spectra do indeed seem to produce reasonably consistent results from both breaks. As indicated in Table 1, this analysis indicates that in both galaxies $\simeq 5$ Gyr has elapsed since the last era of significant star-formation activity.

The most attractive way to reconcile an Einstein-de Sitter Universe with such large ages at $z \simeq 1.5$ is to assume that the strong breaks in both 53W069 and 53W091 are due to high metallicity rather than age. However, the metal-

Table 1: Minimum ages deduced from the break strengths in the rest-frame spectra of 53W091 and 53W069 using 3 alternative models of galaxy spectral evolution. The evolution of the 2640Å break in Worthey's model is anomolously rapid (*e.g.* it yields a MS turnoff age of < 3 Gyr for the sun). The other ages in the table are consistent with 5 Gyr.

Ages (Gyr)		Model	Average Age
2640Å	2900Å		
(1.8)	4.6	Worthey (1994)[11]	4.6
4.0	6.5	Jimenez *et al.* (1996)[12]	5.3
6.2	4.6	Bruzual & Charlot (1993)[13]	5.4

licity dependence of these breaks does not appear to be strong[1,9], and in any case the *mean* metallicities of comparably massive giant ellipticals at low redshift are at most only mildly super-solar when averaged out to $r \simeq r_e$ ($\simeq 0.5$ arcsec at $z \simeq 1.5$ and thus within the LRIS slit)[10]. Taken at face value an age > 5 Gyr at $z \simeq 1.5$ implies $\Omega_0 < 0.2$ for $H_0 > 55 \mathrm{kms}^{-1} \mathrm{Mpc}^{-1}$ unless $\Lambda > 0$.

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