

Old stellar populations in distant radio galaxies

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Abstract

I describe the current status of our attempts to determine the age of the oldest known stellar populations at high redshift, in the red mJy radio galaxies 53W091 ($z = 1.55$) and 53W069 ($z = 1.43$). During the past year the original conclusion of Dunlop et al. (1996) – that 53W091 is > 3 Gyr old – has been questioned from two, basically orthogonal directions. First, reports that the near-infrared light from 53W091 is highly polarized have cast some doubt on whether its red colour is genuinely due to an old population of stars. Second, assuming that all the light is indeed due to stars, it has been claimed that 53W091 is in fact only 1-2 Gyr old. Here I present a preliminary analysis of new infrared polarimetric observations of 53W091 which show that the first of these criticisms can be rejected with very high confidence. I then explore why different modellers have derived different ages for 53W091, and present new model fits to the spectrum of 53W069 which demonstrate that different spectral synthesis codes are certainly in good agreement that this galaxy is 3-4 Gyr old. Finally I present a preliminary analysis of the morphologies and scale-lengths of 53W091 and 53W069 as derived from new I-band WFPC2 HST images, and compare the results with those for 3CR galaxies at comparable redshifts. I conclude that the scale-lengths and luminosities of radio galaxies at $z \simeq 1.5$ appear to scale together as would be predicted from the Kormendy relation for low-redshift elliptical galaxies.

1 Introduction

1.1 Cosmic star formation and radio galaxies

The study of ‘normal’ star-forming galaxies at $z > 2$ has developed into a booming astronomical industry over the past 18 months (*e.g.* Steidel et al.

1996; Giavalisco et al. 1996; Steidel et al. 1997). When coupled with the results from complete redshift surveys reaching $z \simeq 1$ (e.g. Lilly et al. 1995) such studies have been used to produce the first estimates of the star formation history of the universe (Madau 1997) as shown in Figure 1. However, a number of lines of evidence suggest that this picture is, perhaps unsurprisingly, biased and incomplete due, at least in part, to the effect of dust. First, as discussed by Dunlop (1997), and shown in Figure 1, the evolving radio luminosity density produced by the radio-loud active-galaxy population traces the ultraviolet luminosity density produced by stars rather well out to $z \simeq 1$, suggesting that, averaged on a large enough scale, both processes may simply scale with a global cosmological fueling rate. There is no real reason to suppose that this should not also apply at higher redshift and so, since the evolving radio luminosity function is now rather well determined out to $z \simeq 4$ and is immune to dust obscuration, Dunlop (1997) argued that the radio based curves shown in Figure 1 should be regarded as our current ‘best bet’ as to the true star-formation history of the Universe. Second, recent attempts to determine the correction due to dust obscuration which should be applied to the high redshift data points in Figure 1 do indeed seem to be sufficient to make them consistent with the radio-based curves; Pettini et al. (1997) suggest they be raised by a factor of $\simeq 3$ while Heckman (this meeting) suggests a factor of $\simeq 7$ may be appropriate, broadly consistent with the results of Sawicki et al. (1997). Finally, it remains unclear whether Figure 1 contains any information at all about the formation of massive elliptical galaxies. Certainly out to $z \simeq 1$ essentially all of the ten-fold increase in star-formation activity occurs in the irregular/spiral population. Furthermore a number of lines of evidence continue to indicate that the majority of stars in massive ellipticals formed in a relatively short-lived (and potentially dust-enriched) burst at high redshift (e.g. Bower et al. 1992, Zepf & Silk 1996). The key question is: how high a redshift?

Studies of radio galaxies remain one of the most effective ways of addressing this question. One of the cleanest results in extra-galactic astronomy is that all powerful ($P > 10^{24} \text{WHz}^{-1} \text{sr}^{-1}$) radio sources in the present-day universe are hosted by giant ellipticals. It is thus not unreasonable to assume that high-redshift radio sources also reside in ellipticals or their progenitors. Thus while Figure 1 indicates that the *radio activity* produced by these objects traces the overall star-formation history, their host galaxies belong to the special subset of giant ellipticals. Furthermore, radio selection is less biased towards actively star-forming objects than is optical selection. The study of the reddest radio galaxies at high-redshift should thus provide an efficient and powerful means of determining the formation epoch of massive ellipticals, provided one can

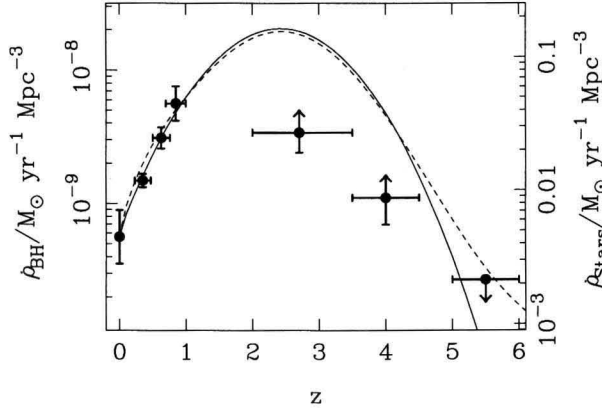


Figure 1. A comparison of the redshift dependence of the rate at which mass is consumed by black holes at the centre of giant elliptical galaxies (and turned into radio luminosity from AGN; curves and left-hand axis) with the rate at which mass is converted into stars per Mpc^3 (and turned into UV-light from primarily disc/irregular galaxies; data points and right-hand axis). The solid and dashed curves are the luminosity-weighted integrals of the pure luminosity evolution (PLE) and luminosity/density evolution (LDE) evolving radio luminosity functions described by Dunlop & Peacock (1990), converted into black hole mass consumption rate per Mpc^3 assuming an efficiency of $\simeq 1\%$. The data-points indicating the star-formation history of the Universe are taken from Madau (1997), and are themselves derived from a low-redshift $H\alpha$ survey ($z \simeq 0$), the Canada France Redshift Survey ($z < 1$), and the number of colour-selected ‘U-dropout’, ‘B-dropout’ and (lack of) ‘V-dropout’ galaxies in the Hubble Deep Field. The upward pointing arrows indicate the fact that the assessment of star-formation rates based on Lyman-limit galaxies is liable to be under-estimated due to the effects of dust.

establish that their optical-infrared properties are not significantly distorted by the presence of an active nucleus.

1.2 Lessons learned from 3C65

The first radio galaxies studied in detail at optical-infrared wavelengths were selected from the 3CR sample (*e.g.* Lilly & Longair 1984), and the reddest 3CR galaxy at $z \simeq 1$ is 3C65. This galaxy has been the subject of several rather detailed studies, the results of which serve to highlight two points of particular relevance to attempts to determine the age of high-redshift radio

galaxies in general. First, while Stockton et al. (1995) showed that this object possesses a strong 4000Å break consistent with a well-evolved population, the Keck spectrum of this most passive of 3CR galaxies at $z \simeq 1$ still contains many emission lines and remains dominated by AGN-related emission shortward of $\lambda_{rest} \simeq 3000\text{Å}$. Second, attempts to date 3C65 have revealed that the spectrophotometric models of Bruzual & Charlot (Chambers & Charlot 1990; Bruzual & Charlot 1993;1997) yield very different ages when applied to individual spectral features as compared to optical-infrared colours; fitting the 4000Å break with the models of Bruzual & Charlot led Stockton et al. (1995) to conclude in favour of an age of 4 Gyr for 3C65, whereas Chambers & Charlot (1990) had previously derived an age of only 1.7 Gyr from its $R - K$ colour.

1.3 Red mJy radio galaxies

By selecting radio galaxies at mJy flux levels we have shown that it is possible to find examples of well-evolved galaxies at $z \simeq 1.5$ whose near-ultraviolet spectrum appears essentially uncontaminated by the direct or indirect effect of AGN activity. The two best examples studied to date are 53W091 at $z = 1.552$ (Dunlop et al. 1996; Spinrad et al. 1997) and 53W069 at $z = 1.432$ (Dey et al. 1997). Keck spectroscopy of these objects has yielded the first detection of stellar absorption features from ‘old’ stars at $z \geq 1.5$ and thus the first ‘reliable’ age-dating of evolved high-redshift objects. However, during the past year the conclusions of Dunlop et al. (1996) and Spinrad et al. (1997) regarding the age of 53W091 have been challenged from two rather different directions. In the next two sections I therefore assess the validity of these criticisms.

2 Polarized near-infrared light in 53W091 ?

It has recently been claimed that new polarimetric observations of 53W091 show that it is strongly polarized at near-infrared wavelengths with $p \simeq 40\%$ (Chambers, priv. comm.). The full details of this observation have yet to appear in the literature, but nevertheless we felt that it was important to attempt an independent check of the validity of this result because of its obviously important implications for the interpretation of the red colour of 53W091.

Therefore, on the nights of 17/18 August 1997 we observed 53W091 at K with the dual-beam polarimeter IRPOL2 on UKIRT for a total integration time of 6 hours. Full details of these observations will be presented by Leyshon et al. (1998) while the data reduction method is described in detail by Leyshon

& Eales (1997). The result of this observation is that the (debiased) percent-age polarization of the K -band light from 53W091 is $p = 0.31\%$, with a $1\text{-}\sigma$ confidence range of $0 < p < 9.6\%$. We therefore find no evidence of significant polarization in the near-infrared light from 53W091, consistent with our original conclusion that the light from 53W091 is dominated by an old stellar population from $\lambda_{rest} \simeq 2000\text{\AA}$ to $\lambda_{rest} \simeq 1\mu\text{m}$.

3 Age controversy

3.1 Comparison of 53W091, 53W069 and stars

In Plate 3 I show the rest-frame ultraviolet spectra of 53W091 and 53W069 as derived from our Keck spectroscopy, overlaid with the average IUE spectrum of the spectral type of star which best fits the near-ultraviolet spectral energy distribution of each galaxy. 53W091 is essentially indistinguishable from an F5V star, while 53W069 is even redder, and is best described by an F9V star. The redder ultraviolet SED of 53W069 is consistent with the fact that it is 0.5 magnitudes fainter in R than 53W091 while having the same K magnitude (18.7 in a 4 arcsec aperture). The spectra in Plate 3 have been scaled to reflect this 0.5 mag difference in the R -band, and are compared directly in the bottom panel. This plot illustrates rather graphically how many of the features in the spectra of these galaxies are real, rather than due to noise or poor sky subtraction (the galaxies having of course been shifted from different redshifts). Also shown is a smoothed version of the difference between the two SEDs, which is rather flat (in f_λ). The origin of this additional low-level blue component in 53W091 is unclear. It may or may not be starlight, but as shown it is broadly consistent with the SED of an F0V star. Shortward of 2300\AA it appears to contribute approximately half of the emission from 53W091, a fact of importance when considering some of the recent controversy over the age of this galaxy (see next section).

3.2 Spectral Features

The shape of the ultraviolet SED is potentially sensitive to both low-level AGN contamination and to reddening by dust. However, the strengths of individual spectral features defined over a relatively short baseline in wavelength should be more robust. It is therefore useful to compare the strengths of the spectral features (absorption lines and breaks) in 53W091 and 53W069 with the strengths

Table 1. The strengths of the near-UV spectral features in the radio galaxies 53W091 and 53W069 as defined by Fanelli et al. (1992), and quantified in terms of the spectral type of solar-metallicity star which displays comparable feature strength (as determined from average IUE spectra by Fanelli et al.). In terms of typical feature strength, both galaxies are essentially indistinguishable from the Sun.

Feature	53W091	53W069
2609/2660Å break	$G0 \rightarrow G5$	$G0 \rightarrow G5$
2828/2921Å break	$G0 \rightarrow G5$	$G0 \rightarrow G5$
FeII 2402Å	$F8 \rightarrow G9$	$G0 \rightarrow G5$
FeII 2609Å	$F8 \rightarrow G9$	$F8 \rightarrow G9$
MgII 2800Å	$A0 \rightarrow A2$	$A5 \rightarrow A8$
MgI 2852Å	$A9 \rightarrow F3$	$G0 \rightarrow G5$
FeI 3000Å	$G0 \rightarrow G5$	$G6 \rightarrow G9$
BL 3096Å	$G0 \rightarrow G5$	$G0 \rightarrow G5$
Mg Wide	$G0 \rightarrow G5$	$G6 \rightarrow G9$

of the same features in stars of different spectral class as determined from their IUE spectra.

For 53W091 this comparison was performed by Spinrad et al. (1997) for the two prominent spectral breaks at 2640Å and 2900Å. Here I have extended the measurement/comparison to include all of the most prominent features in the IUE spectra of stars as defined by Fanelli et al. (1992) and have also performed the same analysis for 53W069.

The results are presented in Table 1, where the strength of each feature has been quantified in terms of the range of spectral classes which display features of comparable strength (Fanelli et al. 1992).

This comparison demonstrates that, in terms of spectral feature strength, both galaxies are consistent with the spectrum of a G0V-G5V star. Only the MgII absorption line is too weak to be consistent with such a spectral classification, but this line is particularly likely to be weakened by some emission in a radio galaxy. The similarity of the strengths of the features in 53W091 and 53W069 strengthens the conclusion of the previous subsection that the ultraviolet SED of 53W091 only differs from that of 53W069 through the presence of an additional low-level blue component. These results also indicate that 53W069 is a particularly ‘clean’ object, in which the spectral type of star which best de-

Table 2. A comparison of age estimates for the stellar populations in 53W091, 53W069 and M32 as derived from the instantaneous burst models of Bruzual & Charlot (B&C) and Jimenez et al. (1997; J97), when used to fit different spectral indicators of age.

	53W091		53W069		M32	
Feature	B&C	J97	B&C	J97	B&C	J97
UV-SED	2.5 Gyr	3.5 Gyr	3.3 Gyr	4.3 Gyr	2.8 Gyr	3.5 Gyr
$R - K$	1.4 Gyr	3.0 Gyr	1.6 Gyr	4.0 Gyr		
2640Å	5.0 Gyr	4.0 Gyr	5.0 Gyr	4.0 Gyr		
2900Å	4.5 Gyr	4.0 Gyr	4.5 Gyr	4.5 Gyr		

scribes the strength of its spectral features is consistent with the spectral type which best fits the overall shape of its ultraviolet SED.

This conclusion is obviously independent of any spectral synthesis modelling, and helps to clarify the basic question which spectral modelling must aim to answer - *i.e.* how quickly can the spectrum of a galaxy evolve to be indistinguishable from that of a G0 star (or, within the errors, identical to that of the Sun)?

3.3 Model Fitting

Recently Bruzual & Magris (1997) have reported that the spectral energy distribution of 53W091 is bluer than that of M32 and, using the models of Bruzual & Charlot, that it can be reproduced by an instantaneous starburst with an age of only 1-2 Gyr. The former conclusion is basically in agreement with the comparison of 53W091 and M32 performed by Dunlop et al. (1996), but the latter conclusion is not.

In order to clarify the origin of this discrepancy, I have performed properly weighted chi-squared fits to the ultra-violet SEDs of 53W091, M32 and 53W069 using the models of Bruzual & Charlot and the new revised models of Jimenez et al. (1997) (based on new isochrone calculations performed on the Cray T3D at Edinburgh). The results are listed in Table 3, where for 53W091 and 53W069 I also give the ages derived from the $R - K$ colour and the strength of the breaks at 2640Å and 2900Å.

This table helps to clarify a number of important points. First, I should emphasize that the Bruzual & Charlot models to which I had access when

performing these fits was not the latest (1997) version used by Bruzual & Magris (1997). However, the age I have derived by fitting the Bruzual & Charlot models to the ultraviolet SED of M32 is 2.8 Gyr, in excellent agreement with that reported by Bruzual & Magris (1997), indicating that in the age-range and spectral-range of interest the models have changed very little.

Second, columns 2 and 4 re-emphasize that, as already discussed in section 1 in the context of 3C65, the Bruzual & Charlot models seem to be internally inconsistent in the sense that they are capable of reproducing very red $R - K$ colours at a much younger age than they can reproduce the ultraviolet SED or the spectral breaks in 53W091 and 53W069. However, it is well-known that the correct prediction of $R - K$ colours at young ages depends crucially on the treatment of the late stages of evolution, whereas prediction of the UV-spectrum at such times depends mainly on the correct prediction of the main sequence turn-off point. As discussed by Jimenez et al. (1997), it appears that the more consistent $R - K$ ages produced by the Jimenez et al. (1997) models (see columns 3 and 5) result from a more sophisticated treatment of mass-loss on the red giant branch which prevents the production of a very red horizontal branch, or such a red and luminous asymptotic branch. Whatever the precise origin of the apparently excessively red colours produced at young ages by the Bruzual & Charlot models, we believe it is much safer to focus on ages determined from the fits to the UV-SED and spectral features, which are less sensitive to our precise knowledge of the latter stages of stellar evolution. Indeed, not to do so is tantamount to throwing away the new, more robust information which can be gleaned from the spectroscopy (note that Bruzual & Magris 1997 cite the ability of their models to reproduce the entire SED of M32 at a single age (2.8 Gyr) as a success. However, this could in fact be regarded as problematic since the spectrum of a present-day elliptical is expected to be consist of a number of components of different ages which will dominate at different wavelengths. Arguably a more important test of the internal consistency of such models is their ability to reproduce the entire SED of a high-redshift galaxy whose population is more likely to be coeval).

Focussing, therefore, on UV dating it is clear that both sets of models agree that 53W091 is marginally bluer/younger than M32 but that 53W069 is redder/older. Also, the ages derived from the Bruzual & Charlot models are, in each case, $\simeq 0.9$ Gyr younger than those derived from the new Jimenez models. Tracing the origin of this second discrepancy is harder and needs detailed investigation, but we suggest that it may be primarily due to the difference between the isochrones produced by the Padova tracks (used by Bruzual & Charlot) and those of Jimenez et al. (1997). The former are typically 100K cooler than the

latter at the epochs of interest, which translates to a difference in inferred age of up to 1 Gyr. Jimenez et al. (1997) present evidence based on Hipparcos data that the Padova tracks are in fact too red.

Whatever the precise origin of this disagreement, it is in any case not so severe as to affect our basic conclusion. If one focusses on the results for 53W069 then, ignoring the anomalously young $R - K$ age produced by the Bruzual & Charlot models, both models are basically in good agreement that the overall shape of the UV SED and the strengths of the main spectral features are consistent with an age in the range $3.5 \rightarrow 4.5$ Gyr. In Plate 4 I compare the spectrum of 53W069 with both the best-fitting Bruzual & Charlot model (3.3 Gyr) and the best-fitting Jimenez et al. (1997) model (4.3 Gyr).

Finally, I note that Table 2 indicates that while on the basis of fits to its ultraviolet SED 53W091 appears to be about a Gyr younger than 53W069, dating based on spectral breaks yields an age more similar to that of 53W069, again consistent with the conclusion that 53W069 is a cleaner example of a genuinely passively evolving galaxy.

In summary, the new data on 53W069 coupled with this more detailed analysis appears to basically re-affirm and strengthen the original conclusion of Dunlop et al. (1996) that, assuming solar metallicity, 3 – 4 Gyr have elapsed since the cessation of the major burst of star-formation in these galaxies at $z \simeq 1.5$.

4 HST observations

4.1 Morphology and scale-lengths

Spectroscopically, 53W091 and 53W069 thus appear to be the best known examples of old, passively-evolving elliptical galaxies at redshifts as high as $z \simeq 1.5$. It is therefore obviously of interest to determine whether this is also true morphologically, and to attempt to determine their scale-lengths. To address this issue we were awarded 9 orbits of Cycle 7 HST time to obtain WFPC2 and NICMOS images of both galaxies below and above the 4000Å break (through the F814W and F110W filters respectively). Full details of these observations and our results will be presented in Peacock et al. (1998b), but here I briefly discuss the results of a preliminary analysis of the WFPC2 data.

I have used a modified version of the 2-dimensional fitting code developed by Taylor et al. (1996) to determine whether both galaxies are better described by a de Vaucouleurs $r^{1/4}$ law, or by an exponential disc. As illustrated by the

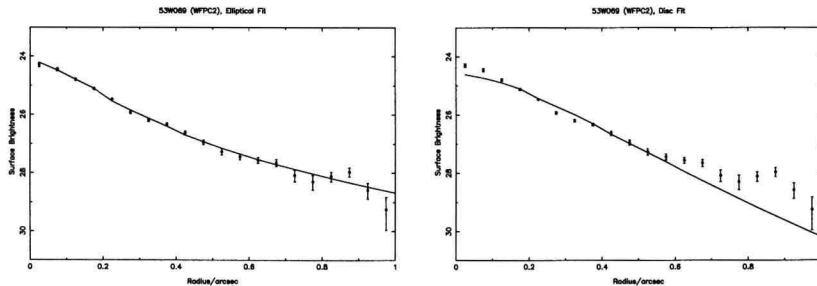


Figure 2. Left panel: the high-quality fit to the I -band (F814W) luminosity profile of 53W069 which is produced using a de Vaucouleurs law convolved with the HST F814W point spread function. Right panel: the inadequate fit to the same data which is provided by the best-fit disc model convolved with the HST F814W point spread function.

1-dimensional luminosity profiles of 53W069 shown in Figure 2, both galaxies are perfectly consistent with a de Vaucouleurs law and inconsistent with a disc. Moreover, the fitted observed half-light radii of both galaxies are very similar; $r_e = 0.43$ arcsec for 53W069, and $r_e = 0.42$ arcsec for 53W091. Assuming $\Omega_0 = 1$ and $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$ this implies a physical half-light radius of $r_e \simeq 4$ kpc for both objects.

4.2 K - z diagram and the Kormendy relation at high z

These first reliable scale-length detections for weak radio galaxies at high redshift, when coupled with the HST-based scale-length determinations for the 3CR galaxies of Best et al. (1997), allow a first attempt to determine whether high-redshift radio galaxies still follow the Kormendy relation for giant ellipticals, as they do at low redshift (Taylor et al. 1996).

Both 53W091 and 53W069 have basically identical K -band magnitudes of 18.3 within an 8 arcsec aperture. Reference to the most recent version of the $K - z$ diagram for radio galaxies as presented by Eales et al. (1997) shows that these 2 galaxies lie $\simeq 0.7 - 0.8$ mag faintward of the mean $K - z$ relation for the 3CR galaxies at comparable redshift. The more radio-luminous 3CR galaxies are therefore on average brighter, but if this were generally due to an enhanced nuclear contribution as suggested by Eales et al. (1997), they would be expected to be more nucleated. In fact, the opposite is true; they are larger (Best et al. 1997) providing further circumstantial evidence that their infrared emission is

indeed dominated by starlight.

This baseline in magnitude allows us to test, for the first time, whether the magnitudes and scale-lengths of radio galaxies at $z > 1$ are consistent with the Kormendy relation. The answer is that they are. Best et al. (1997) have determined that the average half-light radii of the 3CR radio galaxies at $z > 1$ is $r_e \simeq 10$ kpc (note that Best et al. were not able to constrain the scale-lengths of the 3CR galaxies to sufficient accuracy to prove that they follow the Kormendy relation, but did at least manage to show that their average position on the $\mu_e - r_e$ diagram was consistent with a passively evolved version of the low-redshift Kormendy relation for ellipticals). If we simply ask what scale-length would then be predicted for an elliptical 0.8 mag fainter, the answer is 4 kpc, exactly consistent with that derived from our new HST images of 53W091 and 53W069.

5 Conclusion

Our Keck and HST data on the mJy radio galaxies 53W091 and 53W069 basically re-affirm the usefulness of high-redshift radio galaxies as probes of the evolution of massive ellipticals, although it is clear that one needs to avoid the most radio-luminous sources to obtain an uncontaminated view of the underlying stellar population in the rest-frame optical-ultraviolet. Our new infrared polarimetric observations of 53W091 coupled with detailed modelling of the Keck spectra of 53W091 and especially 53W069 allow the original conclusions of Dunlop et al. (1996) to be re-affirmed with increased confidence – the observed optical-infrared light of these galaxies is dominated by an evolved stellar population with a minimum age of 3 – 4 Gyr. Analysis of the *I*-band WFPC2 HST images of both galaxies confirm that, morphologically, they are relaxed elliptical galaxies with a scale-length $r_e \simeq 4$ kpc, exactly as would be predicted by the Kormendy relation for elliptical galaxies given that they are 0.8 mag fainter at *K* than the 3CR galaxies which have an average scale-length of $r_e \simeq 10$ kpc. Our results therefore still point towards a very high formation redshift for massive elliptical galaxies, and continue to place a severe strain on an Einstein de-Sitter cosmology. However, as discussed elsewhere in this volume by John Peacock (see also Peacock et al. 1998a), provided one adopts a present-day age of the universe of $\simeq 14$ Gyr, it is perfectly reasonable to expect a small number of L^* ellipticals to be as old as 3–4 Gyr by $z \simeq 1.5$. The next important step will be to determine the true space density of comparably old objects from infrared-based surveys.

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