

# Induced star formation and morphological evolution in very high redshift radio galaxies

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## Abstract

Near-infrared, sub-arcsecond seeing images obtained with the W. M. Keck I Telescope show strong evolution at *rest-frame optical* wavelengths in the morphologies of high redshift radio galaxies (HzRGs) with  $1.9 < z < 4.4$ . The structures change from large-scale low surface brightness regions surrounding bright, multiple component and often radio-aligned features at  $z > 3$ , to much more compact and symmetrical shapes at  $z < 3$ . The linear sizes ( $\sim 10$  kpc) and luminosities ( $M_B \sim -20$  to  $-22$ ) of the *individual* components in the  $z > 3$  HzRGs are similar to the *total* sizes and luminosities of normal, radio-quiet, star forming galaxies seen at  $z = 3 - 4$ .

'R'-band, 0.1'' resolution images with the Hubble Space Telescope of one of these HzRGs, 4C41.17 at  $z = 3.800$ , show that at *rest-frame UV* wavelengths the galaxy morphology breaks up in even smaller,  $\sim 1$  kpc-sized components embedded in a large halo of low surface brightness emission. The brightest UV emission is from a radio-aligned, edge-brightened feature (4C41.17-North) downstream from a bright radio knot. A narrow-band Ly- $\alpha$  image, also obtained with HST, shows an arc-shaped Ly- $\alpha$  feature at this same location, suggestive of a strong jet/cloud collision. Deep spectropolarimetric observations with the W. M. Keck II Telescope of 4C41.17 show that the radio-aligned UV continuum is unpolarized. Instead the total light spectrum shows absorption lines and P-Cygni type

features that are similar to the radio-quiet  $z = 3 - 4$  star forming galaxies. This shows that the rest-frame UV light in 4C41.17 is dominated by starlight, not scattered light from a hidden AGN. The combined HST and Keck data suggest that the radio-aligned rest-frame UV continuum is probably caused by jet-induced star formation.

The strong morphological evolution suggests that we see the first evidence for the assemblage of massive ellipticals, the parent population of very powerful radio sources at much lower redshifts. The presence of radio-aligned features in many of the  $z > 3$  HzRGs suggests, by analogy with 4C41.17, that jet-induced star formation may be a common phenomenon in these galaxies in their early stages of formation.

## 1 Introduction

Radio sources have allowed the identification of luminous galaxies out to extremely high redshifts. Optical/near-IR campaigns during the past few years by several groups have resulted in the discovery of numerous radio galaxies at  $z > 2$ , including 20 with  $z > 3$ , and 3 with  $z > 4$  (see De Breuck *et al.*, this volume). At lower redshifts powerful radio sources are consistently identified with giant elliptical and cD galaxies, suggesting that at high redshifts we may be observing these massive galaxies in their early stages of evolution. While recently developed techniques for finding very distant star-forming galaxies are yielding substantial ‘normal’ galaxy populations at  $z \gtrsim 3$  (Steidel *et al.* 1996; Dickinson 1998), radio galaxy samples remain the best means of finding, and studying, the most massive galaxies at the highest redshifts. In ‘traditional’ models such galaxies are thought to form early ( $z_F > 5$ ), while in ‘hierarchical’ models this process is thought to take much longer (*e.g.* Kauffmann and Charlot 1998). Observations of HzRGs may therefore provide a unique opportunity to study massive forming galaxies at the highest redshifts and may help discriminate between these two very different cosmogonies.

We discuss the results of our near-IR imaging program with the W. M. Keck Telescope I to investigate the morphological evolution of HzRGs between  $1.9 < z < 4.4$ , and a detailed study of one of these objects (4C41.17 at  $z = 3.800$ ) to determine the nature of its radio-aligned continuum using the Hubble Space Telescope (continuum and emission line imaging) and the W. M. Keck Telescope II (spectroplarmetry).

We adopt  $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$ ,  $q_0 = 0.0$ , and  $\Lambda = 0$ . The assumed cosmology implies a angular size scale of 13–14 kpc arcsec $^{-1}$  for the redshift range  $z = 1.9 - 4.4$  covered. For  $q_0 = 0.1$  the corresponding angular size scale

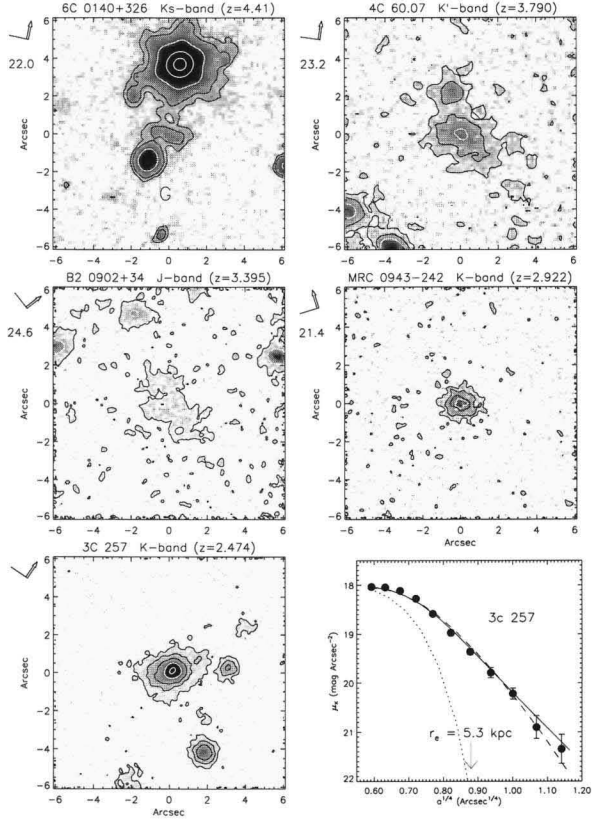
is 14% – 33% less at these redshifts.

## 2 Keck near-infrared imaging of HzRGs

Near-infrared,  $0.4''$  -  $0.7''$  seeing images obtained with the W. M. Keck I Telescope of HzRGs with  $1.9 < z < 4.4$  show strong morphological evolution at rest-frame optical ( $\lambda_{\text{rest}} > 4000\text{\AA}$ ) wavelengths (van Breugel *et al.* 1998; Figure 1). At the highest redshifts,  $z > 3$ , the rest-frame visual morphologies exhibit structure on at least two different scales: relatively bright, compact components with typical sizes of  $\sim 10$  kpc surrounded by large-scale ( $\sim 50 - 100$  kpc) diffuse emission. The brightest components are often aligned with the radio sources, and their *individual* luminosities are  $M_B \sim -20$  to  $-22$ . For comparison, present-epoch  $L_*$  galaxies and, perhaps more appropriately, ultra-luminous infrared starburst galaxies, have, on average,  $M_B \sim -21.0$ . The *total, integrated* rest-frame B-band luminosities are 3 – 5 magnitudes more luminous than present epoch  $L_*$  galaxies.

The presence of radio-aligned optical features suggests a causal connection with the AGN. The most popular explanations for such an alignment effect, which is most prominent at rest-frame UV wavelengths, include induced star formation, nebular continuum emission, or scattered light from a hidden quasar. At  $z \sim 1$  and  $z \sim 2.5$  (Dey, this volume; Cimatti *et al.*, this volume) the presence of strongly polarized light is evidence in support of the latter. However, deep Keck spectropolarimetry of two  $z > 3$  radio galaxies shows that at these higher redshifts the light may be dominated by hot young stars (see section 4; and Dey, this volume).

At lower redshifts,  $z < 3$ , the rest-frame optical emission becomes smaller, more centrally concentrated, and less aligned with the radio structure. Galaxy surface brightness profiles for the  $z < 3$  HzRGs are much steeper than those of at  $z > 3$ . We attempted to fit the  $z < 3$  surface brightness profiles with a de Vaucouleurs  $r^{1/4}$  law and with an exponential law, the forms commonly used to fit elliptical and spiral galaxy profiles, respectively. We demonstrate the fit for our best resolved object at  $z < 3$ , 3C 257 at  $z = 2.474$  (Figure 1). Within the limited dynamical range of the data, both functional forms fit the observed profiles—neither is preferred. Interestingly, despite this strong morphological evolution, the  $K - z$  ‘Hubble’ diagram for the most luminous radio galaxies remains valid even at the highest redshifts, where a large fraction of the K-band continuum is due to a radio-aligned component (see De Breuck *et al.*, this volume).



**Figure 1.** Selected near-IR images of HzRGs, presented in order of decreasing redshift, and the surface brightness profile of 3C257.

### 3 HST imaging of 4C 41.17

4C41.17 at  $z = 3.800$  was one of the first truly HzRGs discovered (Chambers *et al.* 1990). Previous observations with the aberrated HST showed that the optical continuum of 4C41.17 is very clumpy and aligned with the inner radio source (Miley *et al.* 1992). Much improved observations were subsequently obtained with the refurbished HST, including a deep rest-frame UV image (F702W filter,  $\lambda_{rest} \sim 1430\text{\AA}$ ; 6.0 hrs exposure), and a Ly- $\alpha$  image (LRF filter at  $\lambda_c \sim 5830$

Å; 2.0 hrs exposure). One of the field objects in the HST images was also seen at near-IR (Graham *et al.* 1994; object # 16) and radio wavelengths (Carilli *et al.* 1994). This was used to align the HST and radio frames with an estimated relative accuracy of  $\sim 0.1''$ . The central, radio-aligned UV and Ly- $\alpha$  emission is shown in Plate 1 with the  $0.21''$  resolution radio X-band image from Carilli *et al.* overlaid. Plate 2 shows the HST continuum image of the entire 4C41.17 system smoothed to  $0.3''$  resolution to enhance low surface brightness features. The star formation rates (*S.F.R.*) of the various components, as deduced from the rest-frame UV HST photometry, are listed in Table 1. We have assumed  $L_{1500\text{Å}} \sim 10^{40.1} \text{ erg s}^{-1} \text{Å}^{-1}$  for a *S.F.R.* of  $1 M_{\odot}/\text{yr}$  (Conti *et al.* 1996) and no dust reddening (which is surely a lower limit, given the detection of dust at sub-mm wavelengths in 4C41.17 by Dunlop *et al.* 1994).

Table 1  
Luminosities and Star Formation Rates

4C41.17 Comp.	Diam. kpc	$L_{Ly-\alpha,c}$ $10^{43} \text{ erg s}^{-1}$	$L_{\lambda em,c}$ $10^{41} \text{ erg s}^{-1} \text{Å}^{-1}$	<i>S.F.R.</i> $M_{\odot}/\text{yr}$
NW	11	$8.3 \pm 0.6$	$5.7 \pm 0.2$	60
NE	11	$21.7 \pm 0.7$	$19.8 \pm 0.3$	200
NEE	11	$12.4 \pm 0.6$	$2.8 \pm 0.2$	30
S	22	$< 3.8 (3\sigma)$	$11.3 \pm 0.3$	110
Total	65	$137 \pm 6$	$65.9 \pm 1.1$	660
N-Knots	3	–	$0.5 - 4.0$	$5 - 40$
S-Knots	3	–	$0.5 - 1.0$	$5 - 10$

### 3.1 Aligned UV and Ly- $\alpha$ emission: jet-induced star formation?

The HST images show that the 4C41.17 system consists of two components: 4C41.17-North with a bright string of UV knots and Ly- $\alpha$  emission along the radio axis, and 4C41.17-South with several much fainter knots, distributed in a random fashion throughout a low surface brightness halo. The brightest radio knot in 4C41.17-North is associated with the brightest UV knot and arc-like Ly- $\alpha$  emission. Downstream from this knot (NEE, Table 1) the radio source curves towards a faint, very steep spectrum NE lobe (see Carilli *et al.* 1994), while upstream (NE, Table 1) from this knot, towards the central radio core, the UV continuum appears edge-brightened. These morphological features suggest a strong interaction between the radio jet and dense ambient gas and, in fact,

are as expected in jet-induced star formation models where sideways shocks induce star formation in the dense medium of forming galaxies (*e.g.* De Young 1989; Bicknell *et al.* 1998).

### 3.2 The clumpy UV and Ly- $\alpha$ halo: a forming massive galaxy?

The entire 4C41.17 system is embedded in a common halo of diffuse, low surface brightness emission which extends over a very large area of  $54h_{50}^{-1}$  kpc  $\times$   $76h_{50}^{-1}$  kpc ( $5'' \times 7''$ ). This includes a faint region, 4C41.17-South, with half a dozen compact knots distributed in random fashion. Spectroscopic observations have shown that 4C41.17-South is indeed at the same redshift as 4C41.17-North (Dey *et al.* 1999). The range of UV luminosities and *S.F.R.* for the individual knots in 4C41.17-South is lower than in 4C41.17-North, and very similar to the ‘normal’ (radio-quiet) Lyman-break galaxies discovered by Steidel *et al.* (1996). The random distribution and on average lower *S.F.R.* in the 4C41.17-South knots suggests that star formation here is unaided by bowshocks from the radio jet.

The Keck near-IR images have shown that the entire 4C41.17 system (North + South) has a very blue (line-free) continuum, with  $R - K_s = 2.7 \pm 0.1$  in a  $3''$  circular aperture (Graham *et al.* 1994). From these same data we have estimated that 4C41.17-South itself may even be bluer, with  $R - K_s \sim 2.2 \pm 0.2$  in a  $1.9''$  circular aperture. Such colors are commonly found for galaxies in the  $3 < z < 4$  range, and are thought to indicate ongoing star formation (see for example Eisenhardt and Dickinson 1992 [B2 0902+34]; Steidel *et al.* 1996 [‘Ly-break’ galaxies]). In 4C41.17-South perhaps as much as 80% of the continuum is due to low surface brightness emission, and so, on the basis of its blue colors, it appears that star formation occurs not only in compact, kpc-sized starbursts, but also throughout the 4C41.17-South region, and indeed perhaps the entire 4C41.17 system. The total integrated UV luminosity of 4C41.17, over a region approximately 60 kpc in diameter and including the compact and low surface brightness regions, then implies a total SFR of at least  $\sim 660 M_{\odot}/\text{yr}$  (Table 1). Of this perhaps as much as 2/3 of the star formation may be occurring in the inter-knot regions. If the total star formation would continue at this rate for  $2 \times 10^8 - 2 \times 10^9$  yrs an entire massive elliptical galaxy of  $10^{11} M_{\odot} - 10^{12} M_{\odot}$  might be assembled between  $z \sim 4$  and  $z \sim 2.5$ , consistent with the morphological evolution for HzRGs seen in the near-IR Keck observations (Section 2).

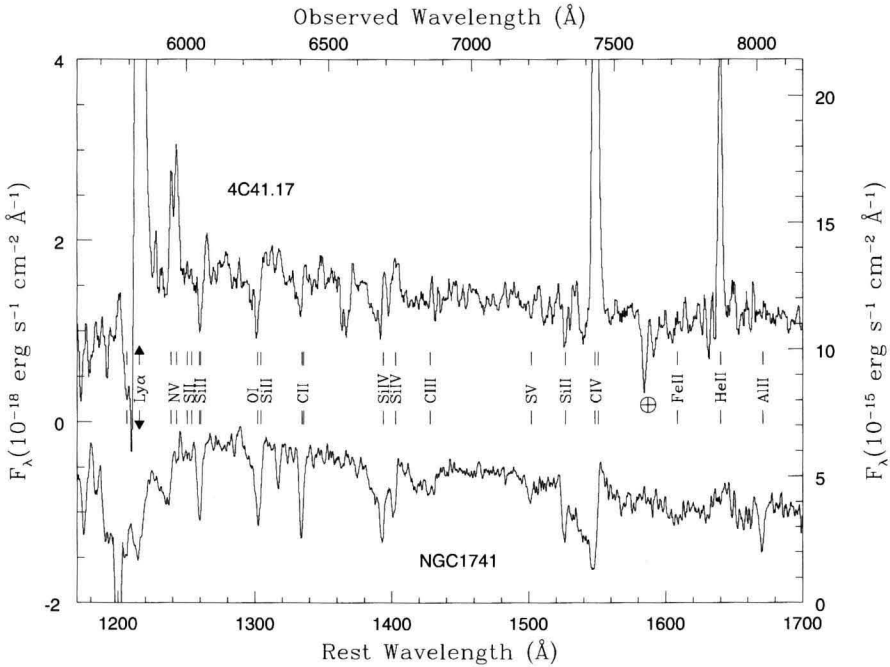
The HST observations of 4C 41.17 thus seem to suggest that the formation of massive ellipticals might occur on two different length scales. One in which

relatively dense, 1–10 kpc-sized star forming regions evolve separately and then merge, and one which involves star formation on a very much larger ( $\sim 70$  kpc) scale. The latter may be more dissipative in nature, as suggested by huge ( $\sim 200$  kpc), turbulent and possibly slowly rotating Ly- $\alpha$  halo centered on 4C 41.17 (Chambers *et al.* 1990; Dey *et al.* 1999). Quite possibly the star formation on these small and large scales proceeds on different time scales and with different initial mass functions. As earlier suggested by Kormendy (1989), hybrid galaxy formation models, involving both dissipationless merging of stellar systems and dissipative collapse, may be needed to understand the formation of very massive galaxies.

## 4 Keck spectropolarimetry of 4C41.17

The deep spectropolarimetric observations with the Keck II telescope by Dey *et al.* (1997) have provided strong evidence in support of the jet-induced star formation model for 4C41.17-North suggested above on the basis of the HST and radio morphologies. These observations showed that the bright, radio-aligned rest-frame UV continuum is unpolarized ( $P_{UV}(2\sigma) < 4\%$ ). This implies that scattered AGN light, which is generally the dominant contributor to the rest-frame UV emission in  $z \sim 1$  radio galaxies, is unlikely to be a major component of the UV flux from 4C 41.17. Instead, the total light spectrum shows absorption lines and P-Cygni-like features that are similar to those detected in the spectra of the recently discovered population of star forming galaxies at slightly lower ( $z \sim 2 - 3$ ) redshifts (Figure 2). The detection of the S V $\lambda$ 1502 stellar photospheric absorption line, the shape of the blue wing of the Si IV profile, the unpolarized continuum emission, the inability of other AGN-related processes to account for the UV continuum flux, and the overall similarity of the UV continuum spectra of 4C 41.17 and the nearby star forming region NGC 1741B strongly suggest that the light from 4C 41.17 is dominated by young, hot stars. The presence of radio-aligned features in many of the  $z > 3$  HzRGs suggests, by analogy with 4C41.17, that jet-induced star formation may be a common phenomenon at these very high redshifts.

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**Figure 2.** Keck spectrum (Dey *et al.* 1997) of the radio-aligned component 4C41.17-North, compared with a UV spectrum of the Wolf-Rayet starburst galaxy NGC 1741 (Conti *et al.* 1996).

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