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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 into 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 Telesc-
scope of 4C41 17 show that the radio-aligned UV continuum is unpolar-
ized. 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 evi-
dence 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 to
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 ex-
tremely 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. 1998,
this volume). At lower redshifts powerful radio sources are consistently identi-
fied 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 of finding very distant star-forming galaxies are
yielding substantial ‘normal’ galaxy populations at z ≥ 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_p > 5), while in ‘hierarchi-
cal’ models this process is thought to take much longer (e.g. Kauffmann and
Charlot 1998). Observations of HzRGs may therefore provide a unique oppor-
tunity 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 (spectropolarimetry).

We adopt H_0 = 50 km s^{-1} Mpc^{-1}, \Omega_0 = 0.0, and \Lambda = 0. The assumed
cosmology implies an 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 (\(\lambda_{\text{rest}} > 4000\)Å) 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 \(M_B \approx -20\) to \(-22\). For comparison, present-epoch \(L_*\) galaxies and, perhaps more appropriately, ultraluminous infrared starburst galaxies, have, on average, \(M_B \approx -21\). 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, nebula continuum emission, or scattered light from a hidden quasar. At \(z \approx 1\) and \(z \approx 2.5\) (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 below; and Dey, this volume).

At lower redshifts, \(z < 3\), the rest-frame optical morphologies become 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 fitting 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...
Figure 1. Selected near-IR images of HzRGs, presented in order of decreasing redshift, and the surface brightness profile of 3C257.

the K-band continuum is due to a radio-aligned component (see De Breuck et al., this volume).

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, \( \lambda_{\text{rest}} \approx 1430 \text{ Å} \), 6.0 hrs exposure), and a Ly-\( \alpha \) image (LRF filter at \( \lambda_{\text{c}} \approx 5830 \text{ Å} \), 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 \( \approx 0.1" \). The central, radio-aligned UV and Ly-\( \alpha \) emission is shown in Figure 2 with the 0.21" resolution radio X-band image from Carilli et al. overlaid. Figure 3 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 ($SFR$) of the various components as deduced from the rest-frame UV HST photometry are listed in Table 1. We have assumed $L_{1500 \AA} \sim 10^{40.1}$ erg s$^{-1}$Å$^{-1}$ for a $SFR = 1$ $M_\odot/yr$ (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

<table>
<thead>
<tr>
<th>4C41 17</th>
<th>Diam</th>
<th>$L_{Ly-\alpha,\lambda}$</th>
<th>$L_{\lambda,\text{em},\lambda}$</th>
<th>$SFR$</th>
</tr>
</thead>
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<tr>
<td>Comp</td>
<td>kpc</td>
<td>10$^{42}$ erg s$^{-1}$</td>
<td>10$^{41}$ erg s$^{-1}$Å$^{-1}$</td>
<td>$M_\odot/yr$</td>
</tr>
<tr>
<td>NW</td>
<td>11</td>
<td>83 ± 0.6</td>
<td>5.7 ± 0.2</td>
<td>60</td>
</tr>
<tr>
<td>NE</td>
<td>11</td>
<td>217 ± 0.7</td>
<td>19.8 ± 0.3</td>
<td>200</td>
</tr>
<tr>
<td>NEE</td>
<td>11</td>
<td>124 ± 0.6</td>
<td>2.8 ± 0.2</td>
<td>30</td>
</tr>
<tr>
<td>S</td>
<td>22</td>
<td>&lt; 3.8 (3σ)</td>
<td>11.3 ± 0.3</td>
<td>110</td>
</tr>
<tr>
<td>Total</td>
<td>65</td>
<td>137 ± 6</td>
<td>65.9 ± 1.1</td>
<td>660</td>
</tr>
<tr>
<td>N-Knots</td>
<td>3</td>
<td>-</td>
<td>0.5 - 4.0</td>
<td>5 - 40</td>
</tr>
<tr>
<td>S-Knots</td>
<td>3</td>
<td>-</td>
<td>0.5 - 1.0</td>
<td>5 - 10</td>
</tr>
</tbody>
</table>

#### 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 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).
Figure 2. HST WFPC2 images of 4C41 17-North through the F702W (‘R’-band), F569W (includes Ly-α) and Ly-α filters. A X-band radio map from Carilli et al. is superimposed.
3.2 The clumpy UV and Ly-α 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 SFR rates 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 SFR 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 blue, 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 so that, 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 $\sim 660 \, M_\odot/yr$ (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 4C41 17 thus seem to suggest that the formation of massive ellipticals may 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-α halo centered on 4C41 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 mass functions. As earlier suggested by Kormendy (1989), hybrid galaxy formation models, involving both dissipationless merging of stellar systems and of 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 4C41.17. 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 (Fig 4). The detection of the S VAl502 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 to 4C 41 17, that jet–induced star formation may be a common phenomenon at these very high redshifts.
Acknowledgments

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