THE RADIO GALAXY $K-z$ RELATION TO $z \sim 4.5$

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Abstract

Using a new radio sample, 6C* designed to find radio galaxies at $z > 4$ along with the complete 3CRR and 6CE sample we extend the radio galaxy $K-z$ relation to $z \sim 4.5$. The 6C* $K-z$ data significantly improve delineation of the $K-z$ relation for radio galaxies at high redshift ($z > 2$). Accounting for non-stellar contamination, and for correlations between radio luminosity and estimates of stellar mass, we find little support for previous claims that the underlying scatter in the stellar luminosity of radio galaxies increases significantly at $z > 2$. This indicates that we are not probing into the formation epoch until at least $z \gtrsim 3$.

Why radio galaxies?

Radio galaxies provide the most direct method of investigating the host galaxies of quasars if orientation based unified schemes are correct. The nuclear light which dominates the optical/near-infrared emission in quasars is obscured by the dusty torus in radio galaxies, therefore difficulties surrounding the psf modelling and subtraction are not required to determine the properties of the underlying host galaxy. Unfortunately compiling samples of radio loud AGN is a long process, because of the radio selection there is no intrinsic optical magnitude limitation, making follow-up observations extremely time consuming, especially when dealing with the faintest of these objects. However, low-frequency selected radio samples do now exist with the completion of 3CRR (Laing, Riley & Longair 1983) along with 6CE (Eales et al. 1997; Rawlings et al. 2001) and the filtered 6C* sample (Blundell et al. 1998; Jarvis et al. 2001a; 2001b). We can now use these radio samples to investigate the
underlying stellar populations through the radio galaxy $K - z$ Hubble diagram.

**Previous radio samples and the $K - z$ Hubble diagram**

There has been much interest in the $K - z$ relation for radio galaxies in the past decade. Dunlop & Peacock (1993) using radio galaxies from the 3CRR sample along with fainter radio sources from the Parkes selected regions demonstrated that there exists a correlation between radio luminosity and the $K$-band emission. Whether this is due to a radio luminosity dependent contribution from a non-stellar source or because the galaxies hosting the most powerful radio sources are indeed more massive galaxies has yet to be resolved. Eales et al. (1997) confirmed this result and also found that the dispersion in the $K$-band magnitude from the fitted straight line increases with redshift. This result, along with the departure to brighter magnitudes of the sources at high redshift led Eales et al. to conclude that we are beginning to probe the epoch of formation of these massive galaxies. Using the highest redshift radio galaxies from ultra-steep samples of radio sources van Breugel et al. (1998) found that the near infrared colours of radio galaxies at $z > 3$ are very blue, consistent with young stellar populations. They also suggest that the size of the radio structure is comparable with the size of the near infrared region, and the alignment of this region with the radio structure is also more pronounced at $z > 3$. Lacy et al. (2000) using the 7C-III sample found evidence that the hosts of radio galaxies become more luminous with redshift and are consistent with a passively evolving population which formed at high redshift ($z > 3$). Thus, all of this work points to a radio galaxy population which formed at high redshift and has undergone simple passive evolution since. However, all of these studies were made with only a few high-redshift ($z > 2$) sources. With the 6C* sample we are now able to probe this high redshift regime with increased numbers from samples with well-defined selection criteria.

**The 6C* filtered sample**

The 6C* sample is a low-frequency radio sample ($0.96 \text{Jy} \leq S_{151} \leq 2.00 \text{Jy}$) which was originally designed to find radio sources at $z > 4$ using filtering criteria based on the radio properties of steep spectral index and small angular size. The discovery of 6C*0140+326 at $z = 4.41$ (Rawlings et al. 1996) and 6C*0032+412 at $z = 3.66$ (Jarvis et al. 2001a) from a sample of just 30 objects showed that this filtering was indeed effective in finding high-redshift objects. Indeed, the median redshift of the 6C* sample is $z \sim 1.9$ whereas for complete samples at similar flux-density
levels the median redshift is \( z \sim 1.1 \) (Willott et al. in prep.). We can now use this sample to push the radio galaxy \( K-z \) diagram to high redshift \( (z > 2) \) where it has not yet been probed with any significant number of sources (e.g. Eales et al. 1997; van Breugel et al. 1998; Lacy et al. 2000). Fig. 1 shows the radio luminosity-redshift plane for the 3 samples used in this analysis.

Figure 1. Rest-frame 151 MHz luminosity \( (L_{151}) \) versus redshift \( z \) plane for the 3CRR (circles), 6CE (triangles) and 6C* (stars) samples. The rest-frame 151 MHz luminosity \( L_{151} \) has been calculated according to a polynomial fit to the radio spectrum (relevant radio data from Blundell et al. 1998). The curved lines show the lower flux-density limit for the 3CRR sample (dotted line; Laing et al. 1983) and the 7CRS (solid line; Blundell et al. in prep; Willott et al. in prep). The dashed lines correspond to the limits for the 6CE sample (Rawlings et al. 2001) and the shaded region shows the 6C* flux-density limits (all assuming a low-frequency radio spectral index of 0.5). Note that the area between the 3CRR sources and 6CE sources contains no sources, this is the area which corresponds to the absence of a flux-density limited sample between the 6CE \( (S_{151} \leq 3.93 \ Jy) \) and 3CRR \( (S_{178} \geq 10.9 \ Jy) \) samples. The reason why some of the sources lie very close to or below the flux-density limit of the samples represented by the curved lines is because the spectral indices lie very close to or below the assumed spectral index of the curves of \( \alpha = 0.5 \).

**Emission-line contamination**

The most-luminous sources at high redshift may be contaminated by the bright optical emission lines redshifted into the infrared. This is particularly true for sources in radio flux-density limited samples. The high redshift sources in these samples are inevitably some of the most luminous, and we also know there is a strong correlation between low-frequency radio luminosity and emission-line strength (e.g. Rawlings...
& Saunders 1991; Willott et al. 1999; Jarvis et al. 2001a) which will increase the contribution to the measured K-band magnitudes from the emission-lines in the most radio luminous sources.

To subtract this contribution we use the correlation between [OII] emission-line luminosity $L_{[\text{OII}]}$ and the low-frequency radio luminosity $L_{151}$ from Willott (2000), where $L_{[\text{OII}]} \propto L_{151}^{1.00 \pm 0.04}$. Then by using the emission-line flux ratios for radio galaxies (e.g. McCarthy 1993) we are able to determine the contribution to the K-band magnitude from all of the other emission-lines. This is illustrated in Fig. 2 where the emission-line contamination to the K-band flux is shown for various radio flux-density limits and a range of redshifts.

![Figure 2](image-url)  
*Figure 2. Emission line contribution to the K-band magnitudes for various radio flux-densities assuming the power-law relation of $L_{[\text{OII}]} \propto L_{151}^{1.00}$.]*

**The $K - z$ relation**

Following the prescription of Eales et al. (1997) we split the data into three redshift bins: $z < 0.6$, the redshift above which the alignment effect is readily observed (e.g. McCarthy 1993); $0.6 \leq z \leq 1.8$, the medium-redshift bin to compare 3CRR and 6CE/6C* sources at the same redshift; and $z > 1.8$, the redshift above which there are no 3CRR sources. A least-squares fit line to the K-band magnitudes is plotted on the K–z diagram for the three samples used in our analysis (Fig 3). The main results from this plot are:

(i) We confirm the previous results of Dunlop & Peacock (1993) and Eales et al. (1997) and find a correlation between radio luminosity and near infrared magnitude. Sources from the new 6C* sample occupy a similar range in K-band magnitudes as the 6CE sources, which are
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Figure 3. The $K-z$ Hubble diagram for radio galaxies from the 3CRR (circles), 6CE (triangles), 6C* (stars) and 7C-III (squares) samples. $K_{63.9}$ denotes the $K-$band magnitude within a comoving metric aperture of 63.9 kpc (c.f. Eales et al. 1997; Jarvis et al. 2001b). The two vertical lines show the redshift above which the alignment effect begins to be seen ($z = 0.6$) and the higher redshift at which we chose to split the data beyond which there are no 3CRR sources ($z = 1.8$). The solid lines are the fits to the 3CRR data points at $z < 0.6$ and $0.6 < z < 1.8$. The dashed line is the fit to the 6CE and 6C* sources at $0.6 < z < 1.8$ and $z > 1.8$. 6C*0031+403 probably has an AGN component contributing to the $K-$band magnitude and is labelled. The filled stars represent the objects in 6C* which do not yet have completely secure redshifts.

A factor of two brighter in radio luminosity than the 6C* sources. The 3CRR sources, which are a factor of six brighter than the 6CE sources occupy $K-$band magnitudes approximately 0.7 magnitudes brighter than the 6CE/6C* sources at $0.6 < z < 1.8$ (A Mann-Whitney U-test shows that the distribution in magnitudes between the 6CE/6C* and 3CRR sources are different at $> 99.9\%$ level).

(ii) We find that the dispersion in the $K-$band magnitudes for the 3CR sources decrease from the $z < 0.6$ bin ($\sigma = 0.52$) to the $0.6 \leq z \leq 1.8$ bin ($\sigma = 0.36$). This may be because of a non-stellar component linked to the radio luminosity becoming more important at the higher redshifts as the sources are necessarily more radio luminous than their low-redshift counterparts and such a luminosity dependent effect would reduce the observed dispersion. However, an alternative explanation in which these extreme objects can only exist in specific physical conditions
also needs to be explored. It is not inconceivable that the most luminous radio galaxies need some of the narrowest set of conditions to form and exist, whereas the lower luminosity radio galaxies may be able to form and exist in a broader range of physical environments.

(iii) The dispersion in the $K - z$ diagram does not increase from $z < 0.6$ ($\sigma = 0.57$) out to $z \sim 3$ ($\sigma = 0.51$) for the sources in the 6CE and 6C* samples. This is in opposition to results in which the dispersion was found to increase, which led previous authors to conclude that we are probing the epoch of formation at $z \sim 2$. The lack of an apparent increase in dispersion toward high redshift may be due to the possibility outlined above in which non-stellar emission may be contributing to the $K$-band flux at these high redshifts, and thus high luminosities. Alternatively, the lack of scatter may be informing on the lack of ongoing star formation at these redshifts, and would mean that the period of star formation has come to an end. If this scenario is correct then it does fit in with other results concerning the epoch at which these massive galaxies first formed. First, Archibald et al. (2001) have found that the dust mass in radio galaxies appears to increase with redshift, at least out to $z \sim 3$, thus implying that the majority of star-formation activity in these galaxies is occurring at high redshift. Second, the discovery of six extremely red objects at $1 < z < 2$ in the 7C redshift survey Willott et al. (2001; these proceedings) with inferred ages of a few Gyrs implies that the bulk of their stellar population formed at $z \simeq 5$.

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