The Early History of Powerful Radio Galaxies

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Abstract

I briefly review the current status of observations of AGN-powered UV/optical light, starlight, dust and outflow phenomena in high-redshift powerful radio galaxies. The existing data are consistent with the hypothesis that powerful radio galaxies undergo a major episode of star formation at high redshift ($z \sim 4$) during which they form most of their stars, and subsequently evolve ‘passively’, with the UV continuum emission in the $z \sim 1$ galaxies being dominated by AGN-related processes rather than starlight from the underlying, aging population.

1 Introduction

The host galaxies of distant radio sources are of fundamental importance to studies of galaxy formation and evolution primarily because these objects are the best candidates for the progenitors of present-day massive galaxies and represent strongly biased peaks in the matter distribution. This hypothesis is supported at low redshift by the association of powerful radio sources with gE and cD galaxies (Matthews et al. 1964), at intermediate and high redshifts by the tendency for these sources to reside in moderately rich cluster environments (e.g., Hill & Lilly 1991, Dickinson 1997), and by a few direct kinematic measurements of the masses of high-redshift powerful radio galaxies (e.g., 3C265: Dey & Spinrad 1996). In this contribution, I will briefly review the state of the observational data on high-redshift powerful radio galaxies (hereafter HzRGs) and their relevance to our understanding of the evolution of these systems.
Figure 1. Spectropolarimetric observations of two radio galaxies: 3C368 at $z = 1.132$ (left panel) and 3C441 at $z = 0.707$ (right panel). Since 3C368 is unpolarized, with $P < 3\%$, only the Stokes parameters ($Q$ and $U$) and the unbiased percentage polarization ($P_{\text{unb}}$) are shown. In contrast, 3C441 is strongly polarized and shows a monotonically decreasing $P$ and wavelength-independent polarized flux. Note the CaII K stellar absorption in 3C441, and the polarization of the MgII $\lambda 2800$ emission line.

2 AGN–Powered UV and Optical Light

A significant fraction of the observed optical (rest-frame UV) emission from $z \sim 1–2$ radio galaxies is now known to be non-stellar, and dominated by scattered and reprocessed light from the active nucleus. A connection between the AGN and the UV continuum and line emission from HzRGs is clearly evidenced by the ‘alignment effect’, the tendency for the UV emission to be spatially extended along the major axis of the radio emission (McCarthy et al. 1987; Chambers et al. 1987). Several imaging- and spectro-polarimetric studies (Tadhunter et al. 1988; di Serego Alighieri et al. 1989, Jannuzi & Elston 1991, Jannuzi et al. 1995, Dey et al. 1996, Cimatti et al. 1996, 1997) have now convinc-
ingly demonstrated that the extended, aligned UV continuum emission in most
$z \sim 1 - 2$ HzRGs is strongly polarized, with the electric vector oriented per-
pendicular to the major axis of the UV emission. These observations provide
strong evidence that much of the UV light is anisotropically radiated emission
from the AGN scattered into our line of sight by dust and electrons in the
ambient medium.

Our observations of 3C441 (shown in the right panel of figure 1) are fairly
typical of the $z \sim 1 - 2$ radio galaxies: the fractional polarization ($P$) is large
($\gtrsim 5\%$ at $\lambda < 3200\AA$) and blue (i.e., decreasing with increasing wavelength),
but the polarized flux ($P \times F$) is roughly wavelength–independent. Not all
powerful radio galaxies at $z \sim 1 - 2$ are polarized. The aligned radio galaxy
3C368 at $z = 1.132$ remains a notable exception (left panel of figure 1 & table
1); however, even in this case, the extended UV continuum emission (at rest
wavelengths $\lambda 2000–3500\AA$) is largely accounted for by optically thin Balmer
continuum emission from the line-emitting gas (Stockton et al. 1996) powered
by the AGN.

In a few cases where the data are of high enough signal-to-noise ratio (e.g.,
3C265 — Dey & Spinrad 1996, Tran et al. 1998; 3C324 — Cimatti et al. 1996;
3C441 — figure II 3C277.1 - Tran et al. 1998), there is some evidence that
the hidden nuclear source has quasar-like broad emission lines. It is important
to note, however, that the total number of $z \gtrsim 1$ radio galaxies for which high
quality data exist is small (the observations require long exposures of $\gtrsim 1$
night per object even on the largest telescopes) and hence concluding that all
powerful radio galaxies contain quasars hidden from direct view is premature.

At higher redshifts ($z > 3$), the data are even more sparse: polarimetry exist
for only two $z > 3$ powerful radio galaxies as of this writing, and both of these
are unpolarized (see table). Instead, the spectra of these galaxies show strong
resonance absorption features typically observed in nearby starburst galaxies
($\S$ 3). At least in the case of 4C41.17 ($z = 3.8$; Chambers et al. 1990), the lack
of polarization, the absorption lines, and the inadequacy of alternative emis-
sion processes (e.g., Balmer continuum emission) to account for the observed
extended UV continuum emission together imply that starlight dominates the
UV light from this system (Dey et al. 1998).

An important question is whether or not there is any evidence for evolution in
the fractional AGN contribution to the UV continuum emission in high redshift
radio galaxies. Although we remain in the preliminary stages of investigating
this problem, the existing data (see table), albeit limited, hint at a decrease in $P$
with increasing redshift. One has to be cautious in interpreting the current data:
at different redshifts, the current observations sample different rest wavelength
ranges, and the observed differences with redshift could result from a wavelength dependent emergent fractional polarization (either due to the intrinsic nature of the scattering process or to dilution by an unpolarized component) rather than an evolutionary phenomenon. The existing observations only permit us to compare the same rest wavelength range in a few objects in the redshift range where evolution may be expected. Clearly, optical polarization observations of objects (with similar radio luminosities) in the intermediate redshift range between 2 and 3 and near-IR polarimetry of the $z > 3$ galaxies will provide the critical tests of the reality of any evolution in $P$ (e.g., Cimatti et al. 1998).

However, if the decrease in $P$ (at a fixed rest wavelength) with redshift proves to be real, it is most likely to be due to a variation in the relative dominance of
the scattered, polarized component over the diluting, unpolarized components at rest-frame UV wavelengths. An evolutionary picture in which the unpolarized component decreases in intensity relative to the polarized component is consistent with the present observations, and may be expected if the diluting component is dominated by starlight from an aging population. For instance, the time elapsed between $z=3.8$ and $z=2.5$ is nearly 1.2 Gyr ($H_0=50$, $q_0=0.1$, $\Lambda=0$), and would provide ample time for a starburst to age sufficiently so as to contribute negligible flux to the UV spectrum. This hypothesis is also supported by the evidence for stars in HzRGs, which is discussed in the next section, and provides a natural explanation for the uniformity observed in the $K-z$ Hubble diagram (e.g., Lilly & Longair 1984).

3 Starlight

Until recently, the arguments for the presence of stars in distant radio galaxies were based primarily on near-IR observations, which showed symmetric rest-
frame optical morphologies (similar to normal elliptical galaxies) in contrast to the peculiar, elongated, multi-component rest-frame UV structures observed at optical wavelengths (McCarthy et al. 1987, Chambers et al. 1987, Eisenhardt & Chokshi 1990, Rigler et al. 1992, Dunlop & Peacock 1993; see McCarthy 1993 for a review). In addition, the landmark study of Lilly & Longair (1984) demonstrated that the photometric properties of HzRGs form a homogeneous redshift sequence (the 'K-z Hubble diagram'), which is well-modeled by the 'passive' evolution of a stellar population formed at high redshift (e.g., McCarthy 1993). The small scatter in the K-z diagram exhibited by the host galaxies of at least the powerful radio sources has been generally taken to suggest that these objects are the progenitors of the present-day giant ellipticals and cD galaxies. However, given the faintness of the distant radio galaxies and the limitations of current near-IR spectrographs, direct spectroscopic evidence for starlight in HzRGs has proved elusive.

High signal-to-noise ratio, moderate resolution spectroscopic studies have become possible using the new, large aperture telescopes. Our group's spectropolarimetric and spectroscopic observations at the W. M. Keck Observatory have resulted in the detection of the CaII K absorption line in several HzRGs (e.g., Dey & Spinrad 1996; also right panel of figure 1); the strength of this line suggests that it arises in stellar photospheres rather than in the interstellar media of the host galaxies. Stockton et al. (1996) have presented deep Keck spectroscopy of 3C65 (z = 1.175) and attempted to subtract the strong emission lines and then fit a population synthesis model to the underlying continuum spectrum.

The strongest evidence to date that at least some HzRGs contain stars is provided by the spectra of three objects: LBDS 53W091 at z = 1.55 (Dunlop et al. 1996, Spinrad et al. 1997), LBDS 53W069 at z = 1.43 (Dey et al. 1998), and 4C41.17 at z = 3.8 (Dey et al. 1997, Chambers et al. 1990). The first two objects are radio galaxies which have lower radio luminosities than similar redshift 3CR galaxies, but are, nevertheless, powerful radio sources (i.e., more luminous than the break in the radio luminosity function). The last, 4C41.17, is a powerful radio galaxy which exhibits an unpolarized UV continuum and absorption lines similar to those observed in nearby starbursts.

The two LBDS radio galaxies have very weak (insignificant) AGN contributions at rest-frame UV wavelengths, and their spectra at these wavelengths show unmistakable signatures of an old stellar population. In fact, the spectra of both LBDS galaxies are well represented by the IUE spectra of individual F-type main sequence stars (figure 3). Since the rest-frame UV light in a simple instantaneous burst stellar population is dominated by the main sequence turn-
Figure 3. Population synthesis model fits to the spectrum of 4C41.17. The curves show Bruzual & Charlot (1996) constant star-forming models (assuming a Salpeter IMF $1 < M < 100 \, M_\odot$, $Z_\odot$, and reddened by $E_{B-V} = 0.1$) at ages of $10^7$, $7.2 \times 10^7$, and $4 \times 10^8$ yrs, superimposed on the rest-frame UV spectrum and optical broad-band colours. The models are normalized to the spectra at $\lambda_{\text{rest}} = 1500$\AA.

Off stars for ages between 1 and 7 Gyr (e.g., Bruzual & Charlot 1996, Spinrad et al. 1997), the implied colour of the turn-off can be used to place a stringent lower limit to the age of the galaxy. The implied rest-frame $B-V$ colors of the two galaxies can be used in conjunction with the Revised Yale Isochrones to determine a lower limit to the age of the stellar population that dominates the UV light as a function of metallicity. More sophisticated population synthesis modelling (Dunlop et al. 1996, Spinrad et al. 1997, Dunlop 1998) reinforce this simple analysis, and provide age estimates of between 3 – 5 Gyr (for relatively normal IMFs) for the stellar populations in the two LBDS galaxies.

A similarly detailed analysis is difficult to perform for the more luminous 3CR radio galaxies, since the spectrum of the UV starlight is diluted by strong emission lines and nonstellar continua (e.g., scattered light and Balmer continuum emission). However, the symmetric, ‘elliptical’ near-IR morphologies of
most $z \sim 1 - 2$ 3CR galaxies suggests that their stellar components are also dynamically old (Rigler et al. 1992; Best et al. 1997). The similarity in $K$-band morphologies of the LBDS and 3CR galaxies may provide weak support for generalizing the results derived for LBDS 53W069 and LBDS 53W091 to the more luminous 3CR systems, suggesting that most luminous radio galaxies at $z \sim 1.5$ contain evolved populations as old as $3 - 5$ Gyr. These large ages imply a high formation redshift ($z_f$) for the dominant UV population of the $z \sim 1 - 2$ powerful radio galaxies, and may also pose stringent lower limits on the age of the Universe. For instance, the age of 4 Gyr for LBDS 53W069 derived using population synthesis techniques implies a $z_f > 5$ ($\Omega = 0.2$).

These high formation redshifts for the $z \sim 1 - 2$ powerful radio galaxies imply that their counterparts at $z \sim 4$ should be observed to contain stellar populations a few hundred million years old. It is therefore very intriguing that 4C41.17, the only $z \sim 4$ powerful radio galaxy for which sufficiently detailed data permit a fairly reliable age estimate, has a population not older than a few hundred Myr (Dey et al. 1997; see also figure 3). The star-formation rate derived for 4C41.17 from its rest-frame 1500 Å luminosity is $\sim 140 - 1100 M_\odot$ yr$^{-1}$, and a factor of 3 larger if the galaxy is reddened by $E_{B-V} \sim 0.1$. Sustained for a period of order 0.5 Gyr, this rate will produce a gE’s equivalent of stars.

4 Dust

There are now several lines of evidence that point to the existence of significant quantities of dust in HzRGs. At least four $z > 2$ objects (8C1435+635 at $z = 4.25$ – Ivison et al. 1997; 4C41.17 at $z = 3.8$ – Dunlop et al. 1994; MG1019+0535 at $z = 2.8$ – Cimatti et al. 1998b; 53W002 at $z = 2.4$ – Hughes et al. 1997) have robust detections of sub-mm continuum flux in excess of the expected nonthermal component (extrapolated from radio wavelengths). In addition to this direct evidence, the presence of dust in HzRGs can also be inferred by the reddening of the line emission and starlight and from the measured UV / optical polarization. For instance, the stellar components in both 3C324 and 3C368 are clearly observed at near-IR wavelengths (i.e., rest-frame optical $\lambda$s), but are invisible in the deep HST WFPC2 imaging data (rest-frame UV $\lambda$s); the upper limits suggest dust reddening in excess of $E_{B-V} \sim 0.3$ (e.g., Dickinson, Dey & Spinrad 1995). Finally, as discussed in § 2, the observed UV / optical polarization measurements are generally interpreted in terms of scattering of anisotropically radiated AGN light, and dust particles can provide an efficient scattering population. However, since the scattering and polarizing properties
of dust grains depend on their chemistry, size distribution, optical depth and spatial distribution, at present it is only possible to derive very crude constraints on the global properties of the scattering population from the polarization observations. These observations suggest that there is a large quantity of dust which is distributed over a fairly large volume which scatters and redens the observed optical continuum emission. Estimates of the dust mass range from $M_{\text{dust}} \sim 0.2 - 2 \times 10^8 \ M_\odot$ derived from the sub-mm continuum emission to $\sim 10^5 - 10^6 \ M_\odot$ derived from reddening / scattering data. The sub-mm data also provide crude estimates of the effective temperature of the dust which range between 30 – 200 K (Hughes et al. 1998, Ivison et al. 1998, Cimatti et al. 1998).

The existence of large amounts of dust in the highest redshift radio galaxies known poses a puzzle: since dust formation is predicated on the existence of metals (and therefore on star-formation), how did so much dust form in such a short time from the Big Bang? Very little is known about the formation and evolution time-scales of dust, especially under the extreme conditions that may prevail in ISM of HzRGs. However, it is intriguing to note that simply scaling the dust injection rate due to supernovae inferred for our Galaxy (e.g., Whittet 1992) by the star-formation rate observed in the the high-redshift systems can account for in the large amounts of dust observed ($M_{\text{dust}} \sim 7 \times 10^8 [M/10^3 \ M_\odot \ yr^{-1}] [t/1\ Gyr] \ M_\odot$; where $M$ is the star-formation rate and $t$ is the duration of the starburst). Another important question concerns the ultimate fate of the dust grains. Low redshift cD and gE galaxies, which are thought to be the evolutionary products of the HzRGs, do not contain large quantities of dust. One way to efficiently destroy dust may be through sputtering processes in the shocks associated with the radio source (DeYoung 1998).

5 Outflows

Outflow phenomena have now been observed in nearly all $z > 2$ radio galaxies for which high-resolution, high signal-to-noise ratio data exist. 3C256 shows an absorption feature in its spectrum, most likely CIV $\lambda 1550$ absorption arising in gas moving at a velocity of 14300 km s$^{-1}$ relative to the radio galaxy (Dey et al. 1996). Absorbing gas associated with lower velocity outflows has now been observed in several HzRGs, almost all of which show asymmetric Ly$\alpha$ profiles suggesting the presence of blue-shifted absorbing gas which appears to be spatially extended over the entire emission line region (figure 4; see also van Ojik et al. 1997). One of the most spectacular cases is shown in figure 5, where the
Figure 4. Lyα emission profiles of four HzRGs. The triangular-shaped profiles result from spatially extended absorption which is blue-shifted relative to the systemic velocity. The zero velocity in all cases is determined either from the HeIIλ1640 line or the CIIIλ1909 line. Note that the Lyα emission from 4C41.17 extends over >200 kpc.

absorption is likely to be spatially extended, modifying the off-nuclear emission line profiles. In the cases for which the data exist, the outflows extend over tens of kpc, and exhibit equivalent widths of \( \sim 10 \ \text{Å} \) and FWHM \( \gtrsim 2000 \ \text{km s}^{-1} \). In many cases, P Cygni–like features are observed in both low- and high-ionization lines suggesting that the outflowing material has a wide range of ionization.

Evidence for outflows is also observed in the more normal (i.e., non-AGN) \( z \sim 3 \) star-forming galaxies. For example, 0000-263 D6, a ‘normal’ (i.e., non-AGN) star-forming galaxy at \( z = 2.96 \), also shows P-Cygni like features associated with both the low-ionization and high-ionization lines, perhaps suggesting the presence of a galaxian wind (e.g., Spinrad et al. 1998). If the outflow phe-
nomena are indeed ubiquitous, could they be a fundamental part of the AGN / galaxy formation process? A telling analogy may be made to the low mass star–formation process, where large–scale outflows are thought to provide a mechanism for angular momentum loss, which is necessary to enable accretion.

6 Conclusions

I have attempted to present an overview of our observations of $z > 1$ radio galaxies and describe our present observational understanding of the evolution of the different components in these objects. The preliminary evidence suggests that the AGN contribution to the UV light is less important at $z \sim 4$ than at $z \sim 1$ and may reflect the spectral evolution of the stellar component which dominates the UV light at higher redshifts. Indeed, the present data, albeit sparse, qualitatively supports an evolutionary scenario in which powerful radio galaxies form the bulk of their stars before $z \sim 3.5 - 4$, and then evolve relatively quiescently (i.e., with little or no continuing star-formation) to $z \lesssim 1$.

This subject remains in its infancy and is still photon-starved. The spectroscopic and polarimetric observations that are necessary to elucidate the content and evolution of HzRGs require long exposures on the largest telescopes, and
our understanding will therefore improve considerably during the next decade with the availability of sensitive instruments on the Keck, VLT and Gemini telescopes.

Acknowledgements I thank my collaborators Wil van Breugel, Hy Spinrad, Bill Vacca, Daniel Stern, Ski Antonucci, Mark Dickinson, Andrea Cimatti, Andrew Bunker and Huub Röttgering for permitting me to present some of our results prior to publication. Much of the data presented here were obtained at the W. M. Keck Observatories, and I thank the Observatory staff for their expert assistance. I am very grateful to the KNAW and to NOAO for financial support that made it possible for me to attend the conference. In particular, I thank Huub Röttgering, Philip Best, Matt Lehnert and George Miley for providing me with the opportunity to visit Amsterdam, for a stimulating conference, and particularly for their extreme patience in waiting for this contribution.

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