The multi-component UV continuum of powerful radio galaxies

Clive N. Tadhunter

Department of Physics, University of Sheffield, Sheffield S3 7RH, UK

Abstract

Observations of a complete sample of southern 2Jy radio galaxies show that at least four components contribute to UV continuum in powerful radio galaxies: scattered AGN light, nebular continuum, direct AGN light and the light of young stellar populations. The relative contributions of the various components vary markedly from object to object, but the incidence of the scattered AGN component is lower than reported in previous surveys of high redshift radio galaxies. The young stellar populations provide a potentially valuable tool for investigating the timescales for the formation of radio sources in galaxy mergers.

1 Introduction

When the high redshift radio galaxies were first studied in detail in the early 1980's it was demonstrated that they show UV excesses compared with passively evolving early-type galaxies (Lilly & Longair 1984). Given that one of the original motivations for studing high redshift radio galaxies was to search for signs of galaxy evolutionary processes, it is no surprise that the UV excesses were initially interpreted in terms of starbursts in the host galaxies.

If the UV excess is due to starbursts, what is the nature of these starbursts? The discovery of the UV continuum alignment effect in the late 1980's provided evidence that the UV excesses are directly related to the non-thermal radio activity (McCarthy et al. 1987). This led to the suggestion that the alignment effect is a manifestation of a jet-induced star formation process in which the starbursts are triggered by the passage of the radio jets through the ISM (e.g. Rees 1989, Begelman & Cioffi 1989). However, there is a distinct lack of direct observational evidence for young stellar populations in the aligned structures.

It is also important to recognise that a significant fraction of the total UV light of the host galaxies originates in the circumnuclear regions rather than in the extended, aligned structures. Thus, the starbursts, if they exist, need not necessarility be an effect of the activity.

With the parallel development of the unified schemes for radio sources in the 1980's, it was recognised that many radio galaxies may contain powerful quasars in their cores (e.g. Barthel 1989). This paved the way for an alternative explanation for both the UV excesses and the alignment effect in terms of scattering of the anisotropic radiation fields of quasars hidden in the cores of the host galaxies (Tadhunter et al. 1988, Fabian 1989). There is now considerable evidence to support the anisotropic scattering model in form of polarization measurements which show that a significant fraction of the high-z radio galaxies are highly polarized in the UV, with their E-vectors aligned perpendicular to the axis of the aligned UV structures (e.g. Tadhunter et al. 1992, Cimatti et al. 1993); the detection of scattered broad lines in the polarized spectra demonstrates that the illuminating sources are quasars (e.g. Young et al. 1996, Cimatti et al. 1996, Ogle et al. 1997). The main debate concerning the scattered component now centres on its general importance: does the scattered quasar light dominate the UV excess in every object, or do other components make a significant contribution? Other activity-related components which are now known contribute to the UV excess include the nebular continuum emitted by the warm emission line gas (Dickson et al. 1995), and direct AGN light (Shaw et al. 1995).

Most recently, events have turned full circle with the direct detection of young stellar populations in at least some powerful radio galaxies (e.g. Tadhunter et al. 1996, Melnick et al. 1997). The continuum emission from the young stars can be difficult to detect because is be masked to some extent by the activity-related components, and also because the spectral features of young stellar populations can be subtle. This is illustrated by the case of 3C321 which shows evidence for a significant scattered quasar component, with scattered broad lines and a large UV polarization, but also shows evidence for a starburst component in the form of a Balmer break and Balmer absorption lines (Tadhunter et al. 1996). Note that the starburst component in 3C321 only came to light through detailed modelling of the optical/UV continuum using a combination of spectrophotometry and spectropolarimetry measurements.

Clearly, the UV continuum of powerful radio galaxies is multi-component in nature. In this contribution I will attempt to quantify the relative contributions of the components which make up the UV excess in the general population of powerful radio galaxies. In particular, I will concentrate on the starburst component which has the potential to provide important information about the origins and evolution of the activity in radio galaxies.

2 The scattered AGN component: a new survey

The first surveys of the polarization properties of high and intermediate redshift radio galaxies — using imaging polarimetry measurements — revealed that a significant fraction of radio galaxies at $z > 0.5$ are polarized at the $5 - 20\%$ level when measured at optical wavelengths (Tadhunter et al. 1992, Cimatti et al. 1993). The polarization E-vectors were found to be aligned close to perpendicular to the axes of the UV continuum structures, as expected in the case of scattered light in a reflection nebula. There were also strong indications of a rise in the measured optical polarization with redshift.

While these early surveys demonstrated that scattered light makes a significant contribution to the UV excess in *some* high-z radio galaxies, uncertainties remain about the significance of this component in the *general population* of powerful radio galaxies. This is because: (a) the polarization measurements are difficult to make, and the early measurements were biased towards the brightest, most spectacular objects; and (b) whereas the optical measurements for the high-z radio galaxies sample the rest-frame UV, where the scattered component is expected to be strong relative to the light of the old stellar populations of the host galaxies, the optical measurements for the low-z radio galaxies sample the rest-frame optical, where the dilution by starlight is expected to be significant. This latter point helps to explain the apparent redshift dependence of the optical polarization. Indeed, recent spectropolarimetry measurements of individual radio galaxies show that there is often a sharp decline in the measured polarization from UV to optical (e.g. Tadhunter et al. 1996), as expected in the case of dilution by the old stellar populations in the host galaxies.

In order to avoid the problems of the previous surveys we have recently undertaken a B-band polarization survey of a complete sample of 20 southern 2Jy radio galaxies with redshifts in the range $0.15 < z < 0.7$ (see Tadhunter et al. 1997 for details). The completeness of our sample allows us to avoid the biases of the previous studies and, by making the measurements in the B-band, we sample the rest-frame UV for the redshift range of the sample. The imaging polarimetry data were taken using the ESO Faint Object Spectrograph and Camera (EFOSC) on the ESO 3.6m telescope. Typically, the polarization measurements were made through 3 – 5 arcsecond diameter circular apertures centred on the nuclei of the host galaxies. Deep optical spectra, taken at the same time as the polarization measurements, have enabled us to investigate the

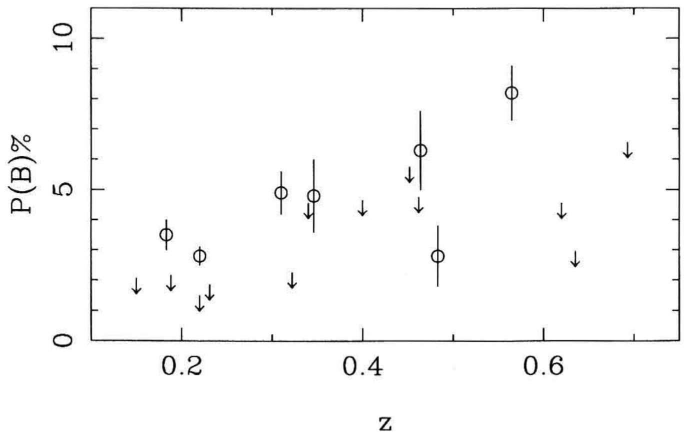

Figure 1. B-band percentage polarization plotted against redshift for the objects in the complete sample of southern radio galaxies (see Tadhunter et al. 1997 for details). Note the relatively low levels of polarization measured in most of the objects.

relationship between the optical spectra and the UV polarization properties.

In contrast to the previous studies we find that the rate of incidence of large UV polarization is relatively low in our sample (see Figure 1). Only 5 (25%) of the sources — all narrow line radio galaxies (NLRG) — are highly polarized in the UV ($P_B > 3\%$), but even for these sources the level of polarization is lower ($P_B < 10\%$) than would be expected in the case of pure scattered quasar light. We conclude that *scattered quasar light cannot be the dominant cause of the UV excess in the overwhelming majority of the sources in our sample.*

How do we explain the difference with the previous results? One possibility is that some of the difference may result from the fact that the selection frequency of our 2Jy sample (2.7GHz) is higher than for the 3C radio galaxies which form the majority of objects in the previous surveys. However, we do not believe that the higher selection frequency can explain all the difference, since many of the more northerly sources in our sample *are* 3C radio galaxies. Moreover, despite the high selection frequency, all but one of the sources in our sample would be selected in the 2Jy sample on the basis of their extended radio emission alone, and the relative proportions of broad and narrow line objects in our 2Jy sample are similar to those in the 3C sample.

An alternative possibility is that the difference reflects a genuine evolution in the UV polarization properties of powerful radio galaxies with radio power or redshift, given that our sample extends to much lower redshifts than the previous surveys of high-z radio galaxies. The strong correlation between radio power and redshift in a flux limited sample has the consequence that the high redshift sources are more powerful radio sources than their low redshift counterparts. Since the luminosities of the illuminating quasars are thought to be strongly correlated with the radio power (e.g. Saunders et al. 1989), we might naturally expect the scattered component to be stronger in the higher redshift samples.

Clearly, it is now essential to obtain UV polarization measurements of a complete, *unbiased* sample of $z > 0.7$ radio galaxies, in order to determine whether there is a real evolution in the UV polarization properties of radio galaxies with radio power/redshift, or whether the apparently high incidence of large UV polarization at $z > 0.7$ is a consequence of selectional biases in the samples of high redshift objects.

3 Other activity-related components

In the course of our survey of southern 2Jy radio sources we have identified a further two activity-related components which contribute to the UV excess: direct AGN light and nebular continuum. These two components will now be considered in turn.

Direct AGN light. Our deep spectra reveal weak broad permitted lines in the spectra of 9 (45%) of the sources in our sample. Given that none of these sources is highly polarized in the UV, we conclude that they are broad line radio galaxies (BLRG) in which we are observing the AGN directly. The direct AGN light is likely to dominate the UV excess in these objects.

Nebular Continuum. Until recently, the nebular continuum emitted by the warm emission line gas was surprisingly neglected as a component contributing to the UV excess of radio galaxies. The optical spectra of our 2Jy sample allow us to determine the contribution of the nebular continuum accurately using measurements of the Balmer emission lines. In the near-nuclear regions sampled by the spectra we find that the nebular continuum comprises 5 — 40% of the total UV light below the Balmer break for the objects in our sample. Note, however, that the contribution of the nebular continuum could be much higher than this in the extended aligned structures where the emission line equivalent widths are larger (see Dickson et al. 1995). Indeed, recent observations have shown that this component dominates the extended UV continuum of at least two powerful radio galaxies: 3C368 ($z = 1.135$; Stockton et al. 1996) and 3C171

($z = 0.235$; Clark et al. 1998).

4 Young stellar populations

For the reasons outlined in the introduction, young stellar populations can be difficult to detect in the presence of the other activity-related components. Nonetheless, evidence in now accumulating that young stars make a significant contribution to the UV excess in several powerful radio galaxies. In our sample of southern 2Jy radio galaxies we find that young stellar populations are significant in at least three objects — 3C459, PKS1549-79 and PKS2135-20 — for which we have been able to identify the young stars unambiguously by detecting the Balmer break characteristic of a starburst of age $t_{sb} > 10^8$ years. Starbursts younger than $\sim 10^8$ years are more difficult to detect in the presence of the activity-related components, because of the lack of detailed features in their spectra. Thus we cannot rule out the presence of young stellar populations in the other radio galaxies in our sample, even in those objects which show polarimetric evidence for scattered light in the UV. Other powerful radio galaxies with reported detections of young stellar populations in the literature include 3C305 (Heckman et al. 1982), Hydra A (Melnick et al. 1997), 3C321 (Tadhunter et al. 1996), Perseus A (Holtzman et al. 1992) and Cygnus A (Jackson et al. 1998). It is likely that more evidence for young stellar populations will be revealed in the future by spectropolarimetric observations which have the ability to distinguish between the scattered AGN light and the young stellar populations.

It is crucial to understand the origins of the young stellar populations: are they related to evolutionary processes in the host galaxies, or are they an effect of the activity? I now consider the possibilities.

4.1 Merger-induced star formation

At low redshifts, the host galaxies of powerful FRII radio galaxies frequently show morphological evidence for recent mergers and interactions (Heckman et al. 1986). Given that there is also independent evidence from studies of IRAS galaxies that the galaxy mergers can trigger starbursts, a plausible explanation for the presence of starburst components in radio galaxies is merger-induced star formation (Smith & Heckman 1989). If the mergers also trigger the nuclear activity and the radio jets (see Heckman et al. 1986), then one exciting possibility is to use the starbursts to estimate the timescale for the formation and evolution of the radio jets.

It is notable that three of the radio galaxies which show good spectroscopic evidence for starbursts — 3C305, 3C321 and 3C459 — all show clear signs of galaxy interactions/mergers in the form of large scale tidal tails and shells (Heckman et al. 1986). In all of these objects the strength of the Balmer break suggests an age for the starbursts of $t_{sb} > 10^8$ years, which is significantly larger than the ages of the radio sources based on standard spectral ageing arguments ($t_{rad} < 10^7$ years). This difference may indicate that there is a significant time lag between the start of the merger and the onset of activity or, alternatively, that the spectral ageing arguments severely underestimate the ages of the radio sources. Either way, the starburst components are a potentially valuable tool for investigating the timescales of the radio activity in powerful radio galaxies.

4.2 Star formation associated with cooling flows

cD galaxies at the centres of cooling flows frequently show the spectroscopic signatures of young stellar populations (e.g. McNamara & O'Connell 1989, Crawford et al. 1995). Although the estimated star formation rates are generally less than the spatially integrated mass deposition rates from the cooling flows as a whole, the star formation rates may be comparable with the mass deposition rates in the central regions of the clusters where the young stellar populations are detected. Thus, it is at least possible that the young, massive stars which generate the UV excess in the cD galaxies form directly from the cooling flows, although other mechanisms such as merger-induced star formation or jet-induced star formation cannot be ruled out (e.g. Crawford & Fabian 1993, McNamara & O'Connell 1983).

In this context it is relevant that three of the radio galaxies which show strong evidence for young stellar populations — Cygnus A, Hydra A, Perseus A — are situated at the centre of cluster cooling flows with large mass deposition rates. In these cases star formation associated with cooling flows is a plausible alternative to other star formation mechanisms. Note that cooling flow star formation may be particularly important in the high redshift radio galaxies ($z > 0.5$), since X-ray observations of at least some high-z radio galaxies show direct evidence for massive hot X-ray haloes (Crawford & Fabian 1996), and there is also evidence that the environments of powerful, FRII radio galaxies become generally richer as the redshift increases (Hill & Lilly 1991).

4.3 Jet-induced star formation

Although jet-induced star formation has been proposed as a means of explaining the aligned UV structures in high redshift radio galaxies, the observational evidence for this mechanism remains limited. At low redshifts, starburst regions are found along the radio axes of Minkowski's Object (van Breugel et al. 1985), 3C285 (van Breugel & Dey 1993) and two central cluster galaxies (McNamara & O'Connell 1993); at moderately high redshifts, 3C34 ($z = 0.690$) shows a linear continuum-emitting feature closely aligned with the radio axis (Best et al. 1997); and at the highest redshifts, Keck spectroscopy shows direct evidence for a starburst component in 4C41.17 ($z = 3.8$; Dey et al. 1997). However, it is possible that some of the apparent associations between the starburst regions and the radio axes are due to a chance superpositions of foreground or background galaxies on the radio axes, while in the case of the spectroscopic detection of a starburst in 4C41.17, it is not yet clear whether the starburst is associated with a single bright region close to the centre of the galaxy, or with the aligned UV structure as a whole. It is also important to stress that, in none of the cases mentioned above in which the detection of the starburst is based on imaging or spectroscopy of the near-nuclear regions, is there any clear evidence for an association between the starburst and the radio axis.

Another problem with the jet-induced star formation model is that the jet-induced shocks are likely to be as disruptive as they are conducive to the formation of stars in radio galaxies (see also contribution by V. Icke in these proceedings). As well as being compressed as they enter the shocks driven by the radio jets, the clouds will be be directly heated by the shocks, by the EUV radiation from the AGN, by EUV radiation from the hot post-shock gas, and possibly also by cosmic rays associated with the radio sources. The warm clouds are also likely to be severely disrupted by their interaction with the fast, hot wind behind the shock front (e.g. Klein, McKee & Colella 1994).

Finally I note that, of the several nearby examples of jet-cloud interactions which have now been studied in depth using spectroscopic techniques, only Minkowski's object shows clear evidence for star formation at the site of the interaction. In the other jet-cloud interaction candidates most of the extended UV light comprises nebular continuum emitted by the warm emission line clouds (Clark 1996).

5 Conclusions

There is no single continuum emission mechanism which dominates the UV excess in powerful radio galaxies: scattered AGN light, nebular continuum, direct AGN light and the light from young stellar populations all contribute to the UV continuum to varying degrees. Although many of these components are directly related to the *effects* of the activity, the presence of the young stellar populations is more likely to be related to its *causes*. Future investigations of the young stellar populations in powerful radio galaxies are likely to lead to new insights into the evolution of the host galaxies and the origins of the radio activity.

Acknowledgements I would like to thank my collaborators Neil Clark, Bob Dickson, Montse Villar-Martin, Raffaella Morganti and Bob Fosbury who have contributed to this work at various stages.

References

Barthel, P.D., 1989, ApJ, 336, 606
Best, P.N., Longair, M.S., Röttgering, H.J.A., 1997, MNRAS, 286, 785
Begelman, M.C., Cioffe, D., 1989, Apj, 345, L21
Cimatti A., di Serego Alighieri S., Fosbury R., Salvati M., Taylor D., 1993, MNRAS, 264, 421
Cimatti, A., Dey, A., van Breugel, W., Antonucci, R., Spinrad, H., 1996, ApJ, 465, 145
Clark, N.E., 1996, PhD Thesis, University of Sheffield
Clark, N.E., Axon, D.J., Tadhunter, C.N., Robinson, A., O'Brien, P., 1998, ApJ, 494, 546
Crawford, C.S., Fabian, A.C., 1993, MNRAS, 265, 431
Crawford, C.S., Edge, A.C., Fabian, A.C., Allen, S.W., Bohringer, H., Ebeling, H., McMahon, R.G., Voges, W., 1995, MNRAS, 274, 75
Crawford, C.S., Fabian, A.C., 1996, MNRAS, 382, 1483
Dey, A., van Breugel, W., Vacca, W.D., Antonucci, R., 1997, ApJ, 490, 698
Dickson, R., Tadhunter, C., Shaw, M., Clark, N. & Morganti, R., 1995, MNRAS, 273, L29
Fabian, A.C., 1989, MNRAS, 238, 41p

Heckman T.M., Smith E.P., Baum S.A., van Breugel W.J.M., Miley G.K., 1986, 311, 526
Holtzman, J.A., et al., 1992, AJ, 103, 691
Hill, G.J., Lilly, S.J., 1991, ApJ, 367, 1
Jackson, N., Tadhunter, C.N., Sparks, W., 1998, MNRAS, in preparation.
Klein, R., McKee, C., Colella, P., 1994, ApJ, 420, 213
Lilly, S.J., Longair, M.S., 1984, MNRAS, 211, 833
McCarthy, P.J., van Breugel, W., Spinrad, H., Djorgovski, S. 1987, ApJ, 321, L29
McNamara, B.R., O'Connell, R.W., 1989, AJ, 98, 2018
McNamara, B.R., O'Connell, R.W., 1993, AJ, 105, 417
Melnick, J., Gopal-Krishna, Terlevich, R., 1997, A&A, 318, 337
Miller, J.S., 1981, PASP, 93, 681
Ogle, P.M, Cohen, M.H., Miller, J.S., Tran, H.S., Fosbury, R.A.E., Goodrich, R.W., 1997, ApJ, 482, 370
Rees, M.J., 1989, MNRAS, 239, 1p
Saunders, R., Baldwin, J.E., Rawlings, S., Warner, P.J., Miller, L., 1989, MNRAS, 238, 777
Shaw M., Tadhunter C., Dickson R., Morganti R., 1995, MNRAS, 275, 703
Smith, E.P., Heckman, T.M., 1989, ApJ, 341, 658
Stockton, A., Ridgway, S.E., Kellogg, M., 1996, AJ, 112, 902.
Tadhunter C., Fosbury, R.A.E., di Serego Alighieri S., 1988, in Maraschi L., Maccacaro T., Ulrich M.-H., eds, Proc. Como Conf., BL Lac Objects. Springer-Verlag, Berlin, p.79
Tadhunter, C., Scarrott S., Draper P., Rolph C., 1992, MNRAS, 256, 53p
Tadhunter, C., Shaw, M.A., Morganti, R., 1994, MNRAS, 271, 807
Tadhunter, C.N., Dickson, R.C., Shaw, M.A., 1996, MNRAS, 281, 591
Tadhunter, C.N., Dickson, R., Morganti, R., Villar-Martin, M., 1997, Proceedings of the ESO Workshop on Quasar Hosts, Clements, D & Perez-Fornoun,I. (eds), Springer-Verlag, p311
van Breugel, W.M., Dey, A., 1993, ApJ, 414, 563.
van Breugel, W.J.M., Filippenko, A.V., Heckman, T.M., Miley, G.K., 1985, ApJ, 293, 83
Young, S. Hough, J.H., Efstathiou, A., Wills, B.J., Axon, D.J., Bailey, J.A., Ward, M.J., 1996, MNRAS, 279, L72