Infrared imaging and off-nuclear spectroscopy of quasar hosts

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Abstract. We present the results of two complementary ground-based programmes to determine the host galaxy properties of radio-quiet and radio-loud quasars and to compare them with those of radio galaxies. Both infrared images and optical off-nuclear spectra were obtained and we discuss the various strategies used to separate the quasar-related emission from that of the underlying galaxy. However, the key feature of this project is the use of carefully matched samples, which ensure that the data for different types of object are directly comparable.

1 Introduction

The paper briefly describes the results of a continuing long-term project to study the host galaxies of powerful AGN. The aim of the project is two-fold: to test the scheme for radio-loud quasars (RLQs) and radio galaxies (RGs) which attempts to unify the two types of object via orientation effects, and to investigate the extent to which the host galaxy influences the radio properties of the AGN by comparing the hosts of radio-loud and radio-quiet quasars (RQQs).

Using ground–based observations we have approached the question of host galaxy properties from two independent directions: near-infrared (K-band) imaging, to determine the host morphologies and luminosities, and off-nuclear optical spectroscopy to investigate their star-formation histories. A more detailed description of the near-infrared imaging can be found in Dunlop et al. (1993) and Taylor et al. (1996).

2 Sample selection

In the past, comparative studies of quasars and radio galaxies have often been hampered by the use of poorly matched samples, sometimes using wildly differing selection criteria. A key feature of the current project was the selection of three carefully matched samples of RQQs, RLQs and powerful (FRII) radio galaxies.

In order to ensure that the samples were directly comparable with each other the RQQs and RLQs were selected to have identical distributions in the $V - z$
plane. Meanwhile the RG sample was chosen to match the radio luminosity – redshift \((L_{5GHz} - z)\) and spectral index - redshift \((\alpha - z)\) distributions of the RLQs. The objects are all of relatively low redshift and cover a narrow range in \(z\) (0.1 < \(z\) < 0.3). Both of the quasar samples were drawn largely from the (optically-selected) Bright Quasar Survey (Schmidt \\& Green 1983) and consist of objects at the fainter end of the quasar luminosity function \((-26 < M_B < -23)\).

3 Near-IR imaging with UKIRT

There are several advantages to working at near-infrared wavelengths. Quasars are, by definition, heavily nuclear-dominated objects in the optical, making galaxy magnitude and morphology determination extremely sensitive to the estimated strength of the core component and the reliability of the adopted form of the point-spread function. Quasars are relatively blue objects \((f_\nu \simeq \text{const})\) whereas the luminosity of the host galaxy is expected to peak at near-infrared wavelengths (Sanders \emph{et al.} 1989), making the near-infrared the waveband of choice for minimising the nuclear:host ratio. Working in the near-infrared also helps to avoid contamination of the images by strong emission lines and/or light from regions of enhanced starformation, both of which could mask the true nature of the underlying galaxy. Finally, the high sky background in the infrared - a major drawback in many ways - does at least mean that the signal:noise ratio of an image is not compromised by subdividing the integration into sufficiently small sub-integrations to avoid saturation of the quasar nucleus, a point of some importance when attempting to determine the correct form of the PSF.

3.1 Observations and modelling

The observations were made in \(K\)-band (2.2 \(\mu\)m) using the 62 \(\times\) 58 array IR-CAM on the United Kingdom Infrared Telescope (UKIRT). A library of \(\sim 100\) standard star images was compiled from which the PSF most suitable for a particular quasar image could subsequently be selected. The procedure adopted for the data reduction is described in detail by Taylor \emph{et al.} (1996).

In our first attempt to analyse the quasar images a simple PSF subtraction was used (Dunlop \emph{et al.} 1993) but this gave rise to a number of problems; most significantly there was an inevitable oversubtraction of galaxy light in the centre of the image. The adopted solution was to use two-dimensional modelling of the surface brightness distribution in order to properly decouple the shape of the host galaxy from that of the PSF (Taylor \emph{et al.} 1996). This allows one to extrapolate smoothly into the central regions of the galaxy and thus estimate the luminosity of each host in a self-consistent manner.

The modelling algorithm fits five parameters to the data: nuclear luminosity, host galaxy luminosity, galaxy scale-length, galaxy position angle and axial ratio. In order to determine the morphological type of the host galaxy one further parameter is required: the index \(\beta\), which describes the form of the galaxy
luminosity profile \( (\mu(r)/\mu_0 = \exp((-r/r_0)^\beta)) \). For the present study we decided to consider only the alternatives of \( \beta = 1 \) (an exponential disc) and \( \beta = 1/4 \) (a de Vaucouleurs law), and thus to confine our morphological investigation to determining whether a given host galaxy is dominated by a disc or a spheroidal component. For each quasar the fitting procedure was carried out twice, once with \( \beta = 1 \) and again with \( \beta = 1/4 \), and the two model fits were then compared with the original image to determine which was the most successful.

In view of the large number of free parameters involved in the model fitting procedure, as well as the notorious sensitivity of such methods to uncertainties in the adopted form of the PSF, the process was subjected to rigorous testing in order to establish the degree of reliability of the fits under a wide range of starting conditions. To this end a series of synthetic quasar+host combinations were constructed and convolved with a range of PSFs. The accuracy with which the modelling algorithm was able to recover the ‘true’ parameters of the artificial galaxies could then be measured in a self-consistent fashion. These tests show that the host galaxy parameters derived from the model fits are typically accurate to within 10%.

However, as expected, the uncertainty increases with the nuclear:host ratio of the quasar and this also has a very strong effect on the degree of confidence with which an exponential disc profile can be distinguished from a de Vaucouleurs law. We decided to adopt a pessimistic approach and to reject as unreliable the morphological classification of objects for which the nuclear:host ratio exceeded a very conservative limit. Effectively, this means that for \( z \approx 0.1 \) objects with \( L_{\text{nuc}} : L_{\text{host}} > 10 \) are excluded; for \( z \approx 0.3 \) the limit becomes an even more stringent \( L_{\text{nuc}} : L_{\text{host}} > 5 \). Fortunately, the low nuclear:host ratio of quasars at near infrared wavelengths means that the majority (31/40) of the objects in our samples survive this selection procedure, and in these cases we are confident that the morphological preference displayed by the fitting algorithm is both valid and meaningful. This would not have been the case in the optical, where typical values of \( L_{\text{nuc}} : L_{\text{host}} \) exceed 10 (in \( B \)-band; see Taylor & Dunlop 1997).

### 3.2 Results

The principal results to emerge from this study can be summarized as follows:

(i) RGs, and the hosts of both RLQs and RQQs are all **luminous galaxies** with \( L \geq L^* \) at \( K \) (\( < M_K > \approx -26 \)).

(ii) RGs and the hosts of RLQs and RQQs are all **large galaxies** with a half-light radius (i.e. the radius containing half of the total galaxy luminosity) \( r_{1/2} \geq 10 \) kpc.

(iii) The basic parameters of the host galaxies are no different from those of other comparably large and luminous galaxies. In particular the hosts of all three types of AGN display a \( \mu_{1/2} - r_{1/2} \) relation which is identical in both slope and normalisation to that displayed by brightest cluster galaxies - objects which are thought to be the product of successive merger events. This suggests that,
regardless of their current interaction status, the host galaxies of powerful AGN have all experienced merger events in the past.

(iv) Essentially all of the RGs and RLQ hosts are best described by a de Vaucouleurs law, consistent with unification of powerful radio-loud AGN via orientation. Thus it appears that an elliptical host galaxy is necessary for an active galaxy to produce a radio luminosity in excess of $L_{5\,\text{GHz}} \approx 10^{24}\,\text{WHz}^{-1}\text{sr}^{-1}$.

(v) Slightly more than half of the RQQs appear to lie in galaxies which are dominated by an exponential disc. Those RQQs which have elliptical hosts are in general more luminous than those which reside in discs. A significant fraction of the RQQ population may at least be capable of producing powerful radio emission.

(vi) The majority of the radio galaxies in our sample contain additional nuclear flux at $K$ in excess of that expected from the best fitting $r^{1/4}$-law model. These unresolved nuclear components may simply be indicative of central cusps in their starlight, but their colours and magnitudes are consistent with dust-reddened quasars (Taylor & Dunlop 1997).

3.3 Comparison with HST results

In general the findings of our ground-based imaging programme are in good agreement with those of recent optical HST studies (eg Hutchings et al. 1994, Hutchings & Morris 1995, Disney et al. 1995). The red colours and large scale-lengths of the hosts as determined from our ground-based data almost certainly explain the failure of earlier HST programmes to detect some of these galaxies in the optical (eg Bahcall, Kirhakos & Schneider 1995). Subsequent re-analysis of these HST images has revealed that large, luminous host galaxies are indeed present (McLeod & Rieke 1995, Bahcall, Kirhakos, Saxe & Schneider 1997).

4 Off-nuclear optical spectroscopy

A completely independent way to characterise the host galaxies of AGN is via analysis and classification of their stellar populations. The aim of the observations described in this section is to obtain high signal-to-noise spectra of the quasar hosts which could then be used to determine the composition, age and evolutionary history of their stellar components.

Previous attempts to take optical spectra of quasar ‘fuzz’ were severely hampered by scattered light from the quasar itself which effectively swamped the starlight from the surrounding galaxy and prevented any meaningful analysis from being carried out. However, the deep near-infrared images of our quasar samples presented us with a unique opportunity to circumvent this problem: armed with knowledge of the extent and orientation of the host galaxy on the sky we were able to choose a slit position which was far enough from the nucleus to avoid the worst excesses of scattered quasar light, but which simultaneously maximised the amount of galaxy light falling onto the slit.
Fig. 1. Off-nuclear spectra of three active galaxies: the RQQ 2344+184 ($z = 0.137$), the RLQ 0137+012 ($z = 0.258$) and the radio galaxy 3C436 ($z = 0.215$). Each spectrum is best described by the combination of an old burst model and a very blue component (probably scattered quasar light). The observed spectrum is shown as a heavy line, the model by a thin line and the residuals by dots.

4.1 Observations

Initial observations were carried out on 10 objects using the Mayall 4-m telescope at Kitt Peak and covering a wavelength range of 3500-7500 Å. With the slit positioned 5″ from the nucleus, starlight was easily detected in all 10 objects and the spectra were of sufficient quality to allow us to fit spectrophotometric models to the stellar populations.

Subsequent observations were carried out on the 4.2-m William Herschel Telescope (WHT) on La Palma. The availability of the ISIS double-beam spectrograph on the WHT enabled us to extend our wavelength range into the red down to $\sim 9000$ Å - the extra wavelength coverage being particularly useful for constraining models of galaxy spectrophotometric evolution. To date twenty five of our objects have been observed.

4.2 Initial analysis

For the purposes of this early analysis we have attempted to fit a simple ‘burst’ model (Guiderdoni & Rocca-Volmerange 1987) to the off-nuclear spectrum, varying the age of the model to obtain the best fit. The burst model assumes that
all star formation occurs in a single burst of activity lasting $\sim$1 Gyr, and that the stellar population evolves passively thereafter. We are currently working towards applying more sophisticated and realistic models, but we note that the fits obtained using this very simple scenario are surprisingly good (Figure 1).

Whilst longwards of the 4000Å break the spectra are clearly dominated by starlight, at shorter wavelengths an additional blue component becomes prominent in some of the off-nuclear quasar spectra. This leads to poor fits from the burst model and to extremely young ages for the stellar population.

Since the presence of this blue component is often accompanied by the appearance of broad emission-lines, particularly H$\beta$, we conjectured that it was probably the result of residual scattered quasar light which, although relatively low-level, was still sufficient to dominate the combined spectrum at $\lambda_{\text{rest}} < 4000$Å. In order to test this theory we took a nuclear spectrum of the RQQ 0054+144 and scaled it to match the height of the broad H$\beta$ feature in the off-nuclear spectrum of the same object. Subtraction of the scaled nuclear spectrum caused a marked improvement in the quality of the resulting fit and, as expected, a substantial increase in the age of the best fitting model (from 5 to 13 Gyrs).

We therefore decided to carry out a two-component fit to the off-nuclear spectra, using a combination of a burst model and a flat-$f_{\nu}$ component to simulate scattered quasar light, and allowing the age of the burst and the amplitude of the flat component to vary freely. For the sake of consistency this procedure was used on all the objects in our sample, including the radio galaxies and those quasars which appeared to lack a strong blue component. This approach appears to have been vindicated by the fact that in cases where a blue component was not obviously present in the spectrum the modelling algorithm invariably achieved a good fit without resorting to the addition of a strong ‘scattered quasar’ component. As a final check, we applied the same procedure to spectra of M32, a dwarf elliptical companion of the Andromeda galaxy, and M33, a nearby late-type spiral. In both cases a good fit was obtained without recourse to a flat-$f_{\nu}$ component, and sensible ages were obtained from the models (old for the dwarf elliptical and relatively young for the spiral).

4.3 Preliminary results

The galaxy ages obtained from the best fitting models are shown in Figure 2 along with the derived ages for M32 and M33. The histograms for the RLQs and RGs are statistically indistinguishable and the host galaxies are generally rather old, red systems, consistent with unification of the two types of AGN. The histogram for the RQQs shows a prominent tail of younger, bluer galaxies - three galaxies have ages < 6 Gyr even after the removal of any scattered quasar light. A comparison with our near-infrared images shows that all of these ‘young’, blue galaxies appear to have close companions and/or display distorted morphologies, implying that they are currently (or have recently been) involved in interactions or mergers.
Fig. 2. Age distributions of the stellar populations in our three matched samples. Note that the RQQ sample contains a significant proportion of young, blue hosts whereas the RLQ and RG samples have distributions which are indistinguishable from each other and consist of older, redder galaxies. Also indicated in this figure are our fits to M33 (a late-type spiral) and M32 (a dwarf elliptical).
However, the general trend is that the hosts of all three types of AGN are dominated by an old stellar population. In the RG and RLQ samples 80% and 75% respectively of the host galaxies have ages \( \geq 11 \) Gyr, whilst for the RQQ sample the proportion with ages \( \geq 11 \) Gyr is still 50% (with the current, rather crude level of analysis, distinguishing between ages greater than 11 Gyr is a highly model-dependent affair). Other than the fact that the youngest RQQ hosts appear to be interacting galaxies there is no obvious correlation between the age of the hosts and their morphological type.

5 Summary

This has proved to be a very fruitful project. Many interesting (and some unexpected) results have emerged from the near-infrared imaging study and, although the off-nuclear spectroscopy is still very much a work in progress, the fact that we have been able to isolate starlight in all of the spectra taken so far is a very encouraging result.

A consistent picture is emerging from the data. It appears that RLQ hosts and RGs are indeed the same type of galaxy - large luminous spheroidal systems with old, red stellar populations - consistent with the unified scheme. The hosts of RQQs are also large and luminous, and can be either disc-dominated or spheroidal systems. There seems to be a tendency for the most luminous RQQs to occur in elliptical hosts. Ages of the RQQ hosts cover a wide range and the bluest galaxies all seem to be undergoing interactions.

In the immediate future we have been awarded 34 orbits on the HST to observe our three AGN samples in R-band. Not only will these images enable us to determine the optical morphologies of the hosts with a level of detail which is impossible from the ground, but by providing us with reliable optical luminosities for the host galaxies they will enable us to bridge the gap between our two ground-based datasets, allowing us to calculate \( R - K \) colours for the galaxies and thus to test whether a particular spectrophotometric model can explain the shape of a galaxy spectrum from optical through to near-infrared wavelengths.

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