THE OPTICAL AND INFRARED PROPERTIES OF 3CR RADIO GALAXIES

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1. INTRODUCTION

For the last 20 years, a huge observational effort has been devoted to the identification of all 3CR radio sources lying in directions away from the Galactic plane. The project is now more-or-less complete thanks to high-resolution radio observations with aperture synthesis radio telescopes, in particular the Cambridge 5-km telescope, and the use of a CCD camera on the Palomar 5-metre telescope (see e.g. Gunn et al 1980).

The aim of the present paper is to assess the reliability of the identifications of distant radio galaxies and to explore their properties using recent infrared observations.

2. THE IDENTIFICATION STATUS OF THE STATISTICAL SAMPLE OF 166 3CR RADIO SOURCES

Most of the effort to complete the optical identifications of 3CR radio sources has been devoted to a statistical sub-sample of 166 sources defined in Jenkins, Pooley and Riley (1977). This sample was selected by C.C. Jenkins, M.S. Longair and J.M. Riley prior to the last major IAU Symposium devoted to extragalactic radio astronomy, IAU Symposium No. 74 "Radio Astronomy and Cosmology". All 3CR sources lying in the declination range $\delta \geqslant 10°$ and $|b| \geqslant 10°$ were re-investigated individually. The flux densities and structures of confused sources were re-assessed by inspecting aperture synthesis maps made with different angular resolutions. All corrected flux densities were reduced to the scale of Kellermann, Pauliny-Toth and Williams (1969) and all those with $S_{178} \geqslant 10$ Jy were included in the statistical sample which amounted to 166 sources. The sources and their adopted flux densities are given by Jenkins, Pooley and Riley (1977).

Besides missing out 3C296 by mistake, the main uncertainty in the sample is discrimination against sources of large angular size and low surface brightness. These "giant radio sources" would have been resolved by

D. S. Heeschen and C. M. Wade (eds.), Extragalactic Radio Sources, 413–422.

the pencil beam of the cylindrical-paraboloid of the radio telescope used to produce the 3CR catalogue. A significant number of these have now been identified in surveys of confused 4C sources and in the 6C radio surveys. There is no definitive figure for how many sources should be added to the sample. It is known that at least 6 giant sources should be added and as many as 20 might have to be included. From the point of view of identifications, most of these sources are associated with relatively bright nearby galaxies and so the inclusion of the giant sources makes little difference to the identification content of the sample.

We wish to estimate how reliable the identifications of the faintest objects in the 166 sample are. Identifications have been claimed for almost all the sources in the sample. Most of those with objects fainter than 20th magnitude are believed to be galaxies on the basis of an extended optical image. The deepest identification surveys using the CCD camera have extended to about $V = 24$ at which the surface density of galaxies exceeds that of foreground stars.

Laing, Riley and Longair (1982) have re-investigated this problem for the 166 sample. The sources were divided into two groups according to whether they were identified with objects having $V \lesssim 19$ or $V > 19$. The sources in each group were then divided according to their radio structures into (i) compact sources with $\theta \lesssim 2$ arcsec, (ii) "classical" double or Fanaroff-Riley class II sources and (iii) the rest, which are Fanaroff-Riley class I sources.

The best criterion for claiming a certain identification results if the source is compact or possesses a compact central component (or radio core) which is coincident within 1 arcsec of an object. Even at $V = 24$, the probability of such a random coincidence is less than 0.2%. Thus, all the compact sources fall in the category of certain identifications. The next best criterion is the observation of a strong emission line spectrum. Only about 15% of elliptical galaxies possess a weak emission line spectrum and only for 1-2% is there a strong emission line spectrum.

For the third class of source, the Fanaroff-Riley class I sources, all of which are brighter than $V = 19$, there is only one source which does not have a radio-core or an emission line spectrum, 3C 314.1, for which the probability of a chance coincidence is 3%. Thus, we can be reasonably confident that these identifications are all correct.

This leaves the double sources which have been considered in three parts. First, sources with radio cores and identifications having $V \lesssim 19$ within 1 arcsec of this component have been selected and the position of the identification with respect to the outer maxima of the double source plotted. For these certain identifications, it was found that all but one lay within a circle of radios 0.2θ centred on the mid point of the double, where θ is the separation of the double. The analysis was repeated for the 25 double sources with $V \lesssim 19$ which do not possess radio cores and it was found that only 3 of the proposed identifications lay outside the search area. In no case did the probability of a random coincidence within this search area exceed 0.01 and all but 6 have strong emission line spectra. Of those objects which lie outside the error circle, 3C254 is perhaps most remarkable in that the identification, a quasar, is almost, but not quite, coincident with one of the double source components. Laing (private communication) has found a weak radio core associated with the quasar in a recent observation with the VLA. Another problem source is 3C340 which lies outside the 0.2θ circle (although on the axis of the source) and there are no emission lines in the optical spectrum. The chance of a random coincidence with the radio source is only 0.6%. Thus, for all doubles with $V \leqslant 19$, 55 out of 59 lie within the 0.2θ circle indicating that it is a very good criterion for assessing the reliability of the identification.

Of the remaining 68 double sources with $V > 19$, 2 proposed identifications are well outside the 0.2θ circle, 3C68.2 and 3C470 and, unless they are anomalous doubles like 3C254, are probably not correct identifications. Two fields are obscured by bright stars, 3C268.1 and 3C294. There is no identification for 3C437. Of the 68 sources, the chances of a random coincidence within the 0.2θ error circle exceeds 0.01 in 24 cases and is greater than 0.1 in 8 cases. Thus, it is likely that at most one or two of the identifications which satisfy the identification criterion are chance associations with the radio source. An obvious programme of importance is the search for weak radio cores in all sources in which they have not yet been found.

In summary, of the fields which are not obscured, there are no optical identifications for 3C68.2 and 437. The identifications of 3C340 and 470 are uncertain. Others require further spectroscopic and radio observations to resolve which of a number of galaxies is the correct identification, in particular 3C61.1 and 469.1. Thus, the sample is almost certainly more than 95% complete.

From the point of view of studying a homogeneous sample of distant radio galaxies, those in the 3CR catalogue thus provides a more or less complete sample to the faintest magnitudes. This is the sample we have selected for study at infrared wavelengths.

3. INFRARED OBSERVATIONS OF 3CR RADIO GALAXIES

The infrared waveband holds great potential for many different types of extragalactic and cosmological research. The advantages of observing very distant galaxies in the near infrared have been discussed by Grasdalen (1980) and Lebofsky (1980), and arise because the K-correction for the K waveband (2.2μm) is increasingly negative for redshifts up to and greater than 1. We describe below the first results of a systematic survey of the near infrared properties of 3CR radio galaxies which we have carried out with the UKIRT 3.8m infrared telescope.

The galaxies selected for study are from the 166-source sub-sample. Additional constraints are imposed that limit the declination to less than 55° and the redshift to greater than 0.03. These limit the number of galaxies to 87 and includes the 2 empty fields. The apparent optical magnitudes of these galaxies range from 14 to 23, the magnitude distribution being shown in Fig. 1. Spectroscopic redshifts are available for about 66% of the galaxies, and range from 0.03 to in excess of 1.0. The optical morphologies of these identifications are very similar to those of first ranked elliptical galaxies, including some cD systems and N-galaxies, the latter being associated with broad-line radio galaxies (BLRGs).

The bulk of the observations were carried out during six nights of excellent observing conditions on Mauna Kea during March 1981. 35 3CR galaxies, selected from throughout the magnitude range of the 87-source sub-sample have now been studied, and their magnitude distribution is shown in Figure 1. In addition, we have confirmed the detection of 3C68.2 reported by Grasdalen (1980), and have obtained a marginal detection of 3C437.

All sources were observed at K, and for all but the faintest at H(1.65μm) and J(1.2μm) as well. For most of the observations a 10.8" aperture was used, except for three cases when a 7.2" aperture was used to avoid nearby objects visible on the best plate material.

4. THE COLOUR-REDSHIFT DIAGRAMS

From our observations it is straightforward to construct the infrared colour-redshift diagrams. In Figures 2 and 3 we show the observed (H-K) and (J-K) colours for the galaxies. The redshifts are taken from the compilation of Smith and Spinrad (1980) or from recent work by Spinrad (private communications).

Considering first the low redshift galaxies ($z < 0.4$), it is clear that with the exception of the four galaxies classified as BLRG by Grandi and Osterbrock (1977), and represented by crosses on the diagram, the infrared colours of the radio galaxies occupy a well defined locus on the colour-redshift planes. This implies that they may all be represented, with small cosmic scatter, by a single energy distribution. This was derived using the observed infrared colours of the galaxies with $z < 0.4$ and is shown by the solid line on the diagrams.

The zero redshift intercepts of the colours predicted from this energy distribution are very similar to those found in a large sample of nearby elliptical galaxies by Frogel et al (1978), (hereafter FPAM). We can therefore conclude that the infrared energy distributions of these galaxies are essentially the same as those of normal elliptical galaxies, and that any additional component associated with the active nucleus must be small. There is no obvious relation between emission line strength and infrared properties amongst the NLRGs.

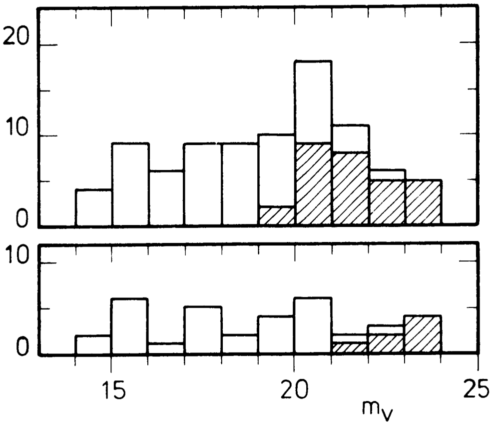

Figure 1. The apparent magnitude distribution for 87 radio galaxies from the statistical samples of 3CR radio sources and that for the 35 radio galaxies studied here. Galaxies without redshifts are shown by hatched boxes.

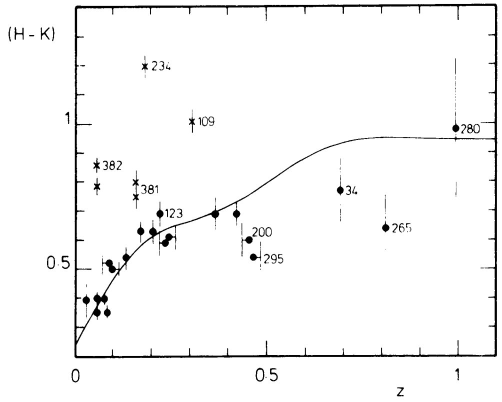

Figure 2. The (H-K) - redshift relation for 3CR radio galaxies. The crosses are N-galaxies with strong non-thermal components.

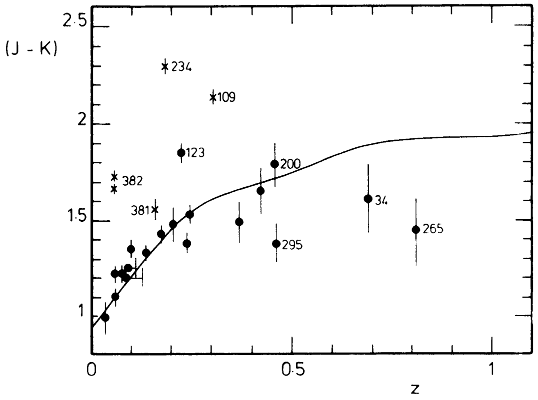

Figure 3. The (J-K) - redshift relation for 3CR radio galaxies. The crosses are N-galaxies with strong non-thermal components.

At higher redshifts, the galaxies broadly follow the predicted relations computed on the basis of the infrared spectrum constructed earlier and the energy distribution shortward of 1μm of Coleman et al (1980). There is no strong evidence for colour evolution in the infrared, and this is as predicted by conventional evolutionary models of elliptical galaxies, for example those of Bruzual (1981). Lebofsky (1981) has recently published (H-K) colours of gE galaxies over a similar redshift range. We remark that the two high z 3CR galaxies considered by her to have anomalous (H-K) colours are not anomalous on our diagram, because of our improved determination of the mean galaxy spectrum, and that we do not find evidence for the large scatter in low z galaxies.

The BLGRs are clearly red in both (J-K) and (H-K), and from the (K,z) relation it is deduced that these are brighter than the typical galaxies in our study, at all the wavelengths observed. Sandage (1973a) has shown that these systems may be successfully decomposed into a central nuclear component situated in a normal galaxy, and we have followed a similar procedure, for 3C 109, 234 and 382, using our observations of the other galaxies to define the colours and magnitudes of the underlying galaxy. To within the uncertainties of this subtraction procedure, we find that the additional component has a power-law spectrum, and that in the case of 3C382 this extends to 3.5μm. In addition, the variability of this latter source which we observed over a 6 month timebase is compatible with a nuclear component of approximately constant spectral index ($\alpha \approx 1.5$) but of varying intensity. In the small sub-sample for which there exists good spectrophotometry we find that the BLRGs displaying an infrared excess have more than 10 times the Hβ flux as compared with those other galaxies which do not.

The optical-infrared colours may be similarly constructed from published optical photometry (e.g. Sandage (1972b, 1973b), Kristian et al (1978), Smith et al (1979), Spinrad et al (1981)), although greater uncertainty will be introduced. The (R-K) and (V-K) colours as a function of redshift are plotted in Figures 4 and 5. At high redshift the CCD r magnitudes were transformed to the R system using an extension of the colour equation given by Wade et al (1979). In the diagrams, the solid lines are the predicted colour-redshift relations based upon the infrared energy distribution derived earlier and the optical spectrum from Coleman et al (1980). The other lines are various evolutionary models from Bruzual (1981). The reddest model assumes no evolution, the others representing different histories of the star formation rate (SFR), being either a constant burst of duration 1 Gyr (the C model) or an exponential decay of the SFR, with 0.7, and 0.5 respectively, of the mass of the galaxy in stars at the end of the first 1 Gyr. At high redshifts it is clear on both diagrams that there are large deviations from the relations predicted by the non-evolving models. We have included the colours derived from the K magnitudes of the high z 3CR galaxies observed by Lebofsky (1981), and these are represented by open circles. We cannot exclude the possibility that part of the blue colours of 3C299, 318 and 265 have a non-thermal origin, since the first two of these do not have "classical double" radio structure, and

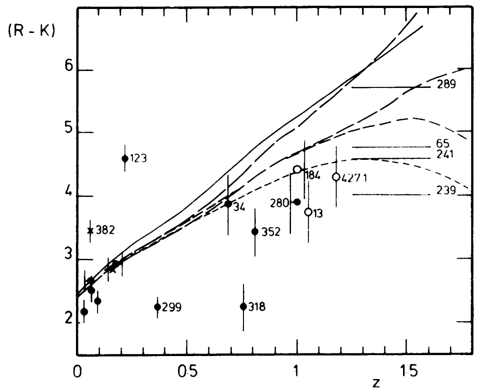

Figure 4. The (R-K) redshift relation for radio galaxies. The straight lines show the (R-K) values for galaxies of unknown redshift. Open circles are data from Lebofsky (1981).

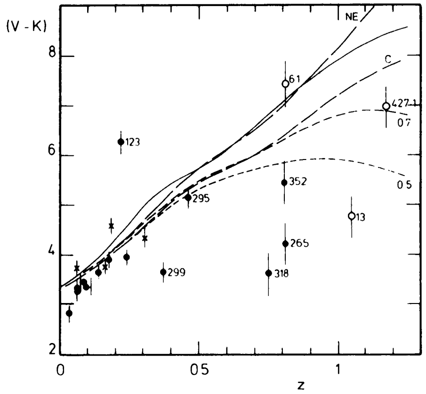

Figure 5. The (V-K) redshift relation for radio galaxies. The uppermost lines show the predicted relation if the galaxies undergo no colour evolution.

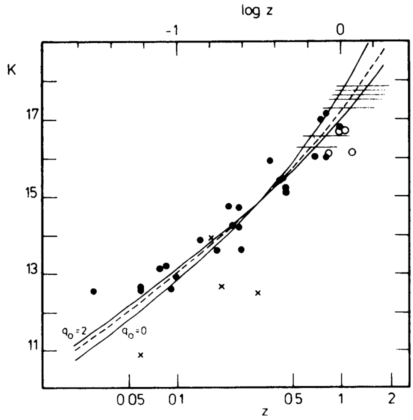

Figure 6. The redshift - K magnitude relation for radio galaxies. Crosses are N-galaxies and the open circles are data due to Lebofsky (1981).

3C265 does not have stellar absorption features in its optical spectrum (Smith et al (1979)). For the remainder of the galaxies, however, the V-K colours can be accounted for by the evolving galaxy models, with relatively slowly decaying SFR. We have also plotted on the (R-K) diagram the colours of 4 very faint galaxies of unknown redshift, and it may be seen that these galaxies have colours that are consistent with this conclusion. This result has implications for attempts to derive the redshifts of distant galaxies from their colours alone.

The red colours of 3C123 are almost certainly due to galactic absorption, the colours being consistent with an Av of 2 magnitudes.

At low redshift, it may be seen that there is a systematic trend for the (V-K) colours as observed to be some 0.2 magnitudes too blue, as compared with the predictions which themselves intercept the axis at the value of 3.3 found by FPAM in their study of nearby giant ellipticals. The reasons for this deviation, which is probably also present in (R-K) is not known at the present time. This discrepancy does however mean that it would be imprudent to use the K magnitudes of these very low redshift giant ellipticals to anchor the low redshift end of the (K,z) Hubble diagram considered in the next section.

5. THE INFRARED HUBBLE DIAGRAM FOR RADIO GALAXIES

Because essentially all the observations were made through the same aperture, we plot on the Hubble diagram, figure 6, the magnitudes as observed, and incorporate the K-corrections (which differ in the evolving and non-evolving models) and aperture corrections (which are different for different world models) into the predicted magnitude-redshift relations for different values of q_o. The aperture corrections were derived from the beam profiles and from the curve of growth given by Sandage (1972a). The best fit model may then be determined by a Chi-squared test, with the absolute magnitude/Hubble constant combination a free parameter in each world model. This method also gives the certainty with which other models may be rejected. Also shown on the diagram are the sources with unknown redshifts, and the high z data from Lebofsky (1981), as horizontal lines and open circles respectively.

With the exclusion of the BLRGs, the radio galaxies form a well defined Hubble relation, the cosmic scatter about the best fit models being 0.40 mag, which is very similar to that found at optical wavelengths by Smith (1977). For the unevolving energy distribution, the apparent, uncorrected, value of q_o is considerably in excess of 1. The best fit value occurs at 2.8, and the $q_o = 1$ model may be rejected with 70% confidence. The relations for $q_o = 0$ and 2 models are shown in Figure 6. However, the lack of infrared colour evolution does not imply a lack of luminosity evolution in the infrared. The effect of the $\mu = 0.5$ model discussed in connection with the optical-infrared colour diagrams is to increase the predicted K luminosity at a redshift of 1 by 0.8 mag. Application of the K-corrections appropriate to this model result in a best fit value of $q_o = 0.5$. Therefore, if lower values of q_o are preferred for other reasons, then the Hubble diagram provides further evidence of substantial evolution over lookback times of half the Hubble time.

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DISCUSSION;

WEISTROP: Can you tell from the CCD frames whether those galaxies with blue excess in the color-redshift diagrams have a bright, blue nucleus?

LONGAIR: The CCD images were taken in r and i and so it is difficult to say whether there is a blue excess or not. Our analysis of the images indicates that most of the faint identifications are radio galaxies, and we could set limits to the contribution of a point-like object at their nuclei.

ROBERTSON: At high redshifts, most galaxies with known redshifts have emission lines, because these are the ones that can be measured. How does this affect your results?

LONGAIR: We find that the broad-line radio galaxies are clearly separable on the infrared color diagrams. For the others, the continuum radiation is much weaker than the stellar radiation from the galaxy, and we can find no correlations between the infrared colors and the properties of the narrow line region.

WINDHORST: What is the typical value of the IR aperture correction applied to the Hubble diagram in k? Is it very uncertain due to the fact that the Hubble profile of ellipticals is not well known in the k band?

LILLY: The aperture correction incorporated into the predicted (k,z) relations changes by 1.2 magnitudes over the entire redshift range, 0.03 to 1.0, with half of this change occurring below a redshift of 0.1. Unfortunately, the k growth curve of Frogel et al. (1978) does not extend to sufficiently large metric diameters to be used here. In the region of overlap, their growth curve is similar to the v growth curve of Sandage used in this paper.