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The most distant radio galaxies*

V. K. Kapahi
National Centre for Radio Astrophysics, Tata Institute of Fundamental Research, Poona University Campus, Pune 411 007

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Abstract. The quest for the most distant galaxies in the Universe through deep CCD imaging and spectroscopy of faint objects identified with steep-spectrum radio sources has met with considerable success in the last few years, leading to the discovery of many galaxies at high redshifts. The largest redshift now known is $z = 3.8$. The study of these distant galaxies is of vital importance to our understanding of the epoch of galaxy formation and the early evolution of their stellar populations. Among the major efforts being pursued to find more high redshift galaxies is an international collaborative program to study a southern-sky complete sample of Molonglo 1-Jy radio sources, which is briefly described. One of the most remarkable properties of high redshifts galaxies is the approximate alignment of their optical continuum with the radio axis which may be arising due to star formation induced by the passage of the radio jets through the dense and clumpy medium surrounding the galaxy. It is however unclear if these galaxies are recently formed primeval galaxies or whether they are old and mature stellar systems that have experienced a recent burst of star formation. Future observations, particularly in the IR region of the spectrum, could settle the controversy.

Key words : radio sources—galaxies—redshift—cosmology

1. Introduction

The last few years have seen some exciting developments leading to the discovery and study of galaxies at large redshifts. This has come about principally by the application of modern CCD imaging and spectroscopic techniques to observations of optically faint objects that were first detected through their strong radio emission. As a result, over two dozen galaxies are now known at redshifts exceeding 2. The record for the highest redshift among galaxies currently stands at $z = 3.8$, for the galaxy associated with the radio source 4C 41.17 (Chambers *et al.* 1990). At such high redshifts the light now being

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picked up by the optical and radio telescopes must have been emitted by the galaxy at a time when the Universe had attained only one fifth of its present size and about 10 to 20 percent of its present age since the big bang.

Although quasi stellar objects at even larger redshifts have been known for quite some time, the relatively bright and compact nature of their non thermal emission, believed to arise from active galactic nuclei, provides us very little information about the stellar content of the underlying host galaxies. Apart from giving us vital information on the possible epoch of galaxy formation, the pursuit and study of high redshift galaxies is thus of importance also to our understanding of the history of star formation and the evolution of stellar populations at different epochs. Another strong motivation for finding radio galaxies at large redshifts is the possibility of using them as probes of cosmological world models.

I have briefly outlined in the next section the techniques and samples being used by different groups to find radio galaxies at high redshifts. Some important results obtained from the study of high redshift galaxies, and in particular the observed alignment in the optical and radio morphologies and attempts to understand this phenomenon are discussed in sections 3 and 4.

2. The quest for high redshifts

The potential of radio surveys to pick out the very distant galaxies in the Universe became clear quite early on, when Cygnus-A, one of the strongest radio sources in the sky, was identified with a galaxy at a redshift of $z = 0.056$ (Baade & Minkowski 1954). It was natural to expect that the much weaker and more numerous radio sources in the sky may be at cosmologically greater distances. It is only in the last few few years, however, that the full potential of radio galaxies to be found at large redshifts ($z \gtrsim 1$) has begun to be realized. The march towards higher redshifts in the case of quasars on the other hand, was much more rapid right from their discovery in 1961. While the first radio quasar with $z > 3$ (OH471, $z = 3.40$) had already been found by 1973 (Carswell & Strittmatter 1973), the largest measured redshift for a radio galaxy remained unchanged at $z = 0.45$ (for 3C 295; Minkowski 1960) between 1960 and 1975 and the first redshift in excess of unity was reported only in 1982 (Spinrad 1982). This can be attributed mainly to the much fainter optical magnitudes of radio galaxies compared to quasars at similar redshifts. Even at the relatively modest redshifts of ~ 0.5, the optical counterparts of radio galaxies are generally fainter than the limiting magnitude of the Palomar Sky Survey plates.

The task of optical identification and spectroscopy of complete radio source samples, which is an essential first step towards understanding the astrophysics, space distribution and evolution of powerful radio sources, has therefore been a formidable one, even for the well known 3CR catalogue (Bennet 1962) consisting of the 300 or so brightest radio sources ($S_{178\ \mathrm{MHz}} > 9$ Jy) in the northern sky! A great deal of effort over the last three decades by several groups of astronomers and in particular by Spinrad and his collaborators (Spinrad *et al.* 1985; and later unpublished updates of the compilation on 3CR sources) has finally resulted in almost complete identification and redshift information for the 3CR sources. What has perhaps made it possible at all is the fortunate circumstance that a good fraction of the light emitted by powerful radio galaxies arises in narrow emission lines and in particle in the $Ly-\alpha$ line at λ 1216 Å which gets redshifted to the optical region at large redshifts (see figure 3).

The distributions of redshifts for both radio galaxies as well as quasars among the 178 radio sources with $S \geqslant 10$ Jy at 178 MHz in the more restricted but better defined 3CRR sample (Laing *et al.* 1983) are shown in figure 1. A remarkable feature of the sample is the wide spread in the radio galaxy redshifts ranging from about 0.001 to 2. This is in sharp contrast to the situation at optical wavelengths where the brightest objects in the sky even at high Galactic latitudes are all nearby stars in our Galaxy. The large range in redshift comes about because of the strong evolution in the space density of powerful radio sources with look-back time and the critical slope of the near power-law radio luminosity function which means that the fall in the number density of sources with increasing radio luminosity is approximately compensated for by the increasing volume in which such sources can be located. It is also interesting to note that with the recent completion in spectroscopic measurements of faint galaxy identifications in the 3CR sample, the highest measured redshifts of ~ 2 for radio galaxies are now quite similar to those that had been measured earlier for quasars in the sample. This is one of the important factors that has led to models suggesting the unification of radio galaxies and quasars based on relativistic beaming effects and the orientation of their radio jet axes with respect to the observer's line of sight (Barthel 1989; Kapahi 1990; Kapahi & Murphy 1990).

In order to find powerful radio galaxies at redshifts even larger than 2, it is clearly necessary to concentrate on radio samples that go considerably fainter in their lower flux density limit than the 3CRR sample. There is also another important reason for going to fainter radio samples. The rather limited range of flux density in flux limited samples

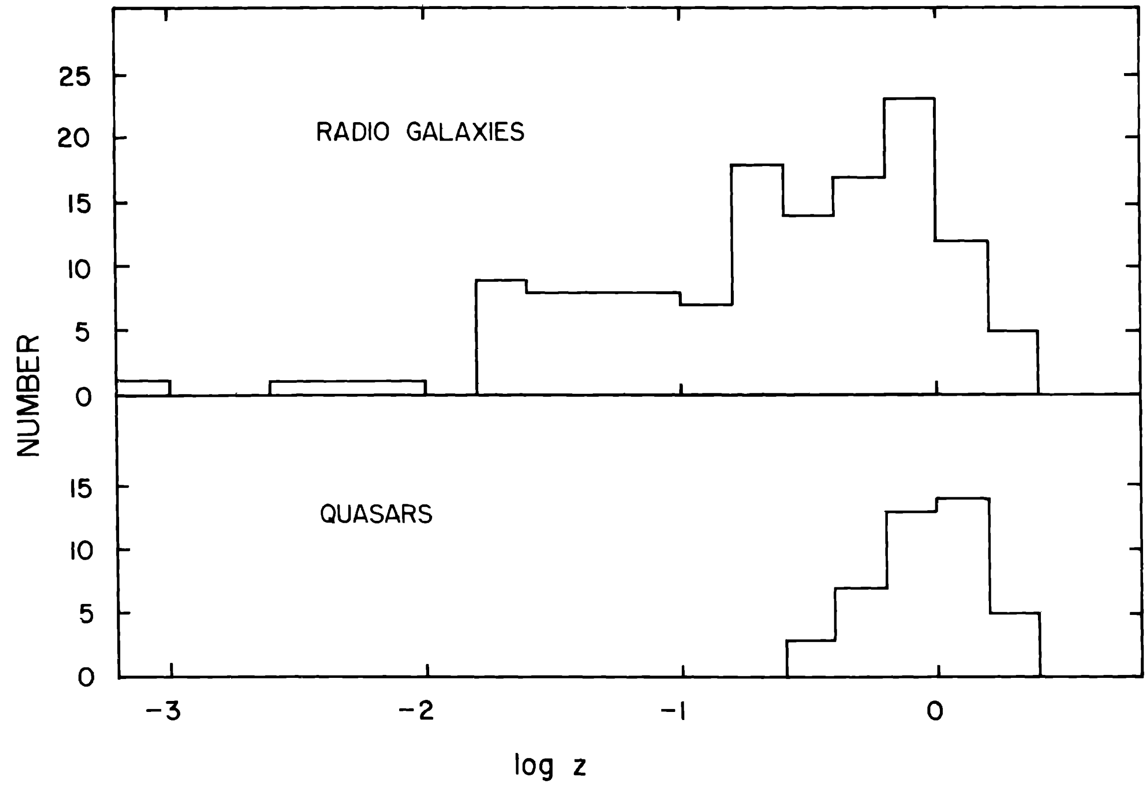

Figure 1. The redshift distributions of radio sources in the 3CRR catalogue, identified with galaxies and quasars.

such as 3CRR (about 90% of the sources have a 178 MHz flux density between 10 and 30 Jy), compared to the range in redshifts, introduces a strong artificial correlation between redshift and radio luminosity as illustrated in figure 2. Many observed properties of radio sources are known to depend on their redshift, but it is almost impossible to decide whether the primary dependence is on cosmic epoch or radio luminosity. The best way to resolve such ambiguities is to form additional samples of sources at substantially lower flux densities so that the sources span a large range of luminosities at any given redshift.

The rapid rise in the number of radio sources with decreasing flux density makes it all the more difficult and time consuming to look for radio galaxies at high redshifts because most of the radio sources in fainter samples have no optical counterparts to the limits of the Palomar Sky Survey and there is limited availability of time on the large optical telescopes for imaging and spectroscopy of extremely faint objects. Two different approaches have been tried in the quest for high redshifts among the weaker radio sources. The first approach was to concentrate on complete but small samples in restricted regions of the sky such as the 408 MHz 1-Jy B2-sample (Allington-Smith 1982; Allington-Smith *et al.* 1988), the LBDS mJy and sub-mJy samples at 1.4 GHz (Windhorst *et al.* 1984, 1991) and the 2.7 GHz Parkes Selected Area Samples (Dunlop *et al.* 1989). These have led to the discovery of several galaxies at $z > 1$ and a few at $z > 2$, including B2 0902 + 34 at $z = 3.395$ (Lilly 1988).

In the second approach, first used by Chambers & Miley (1990), a small subset of the sources from large samples are first preselected to have a high probability of being at

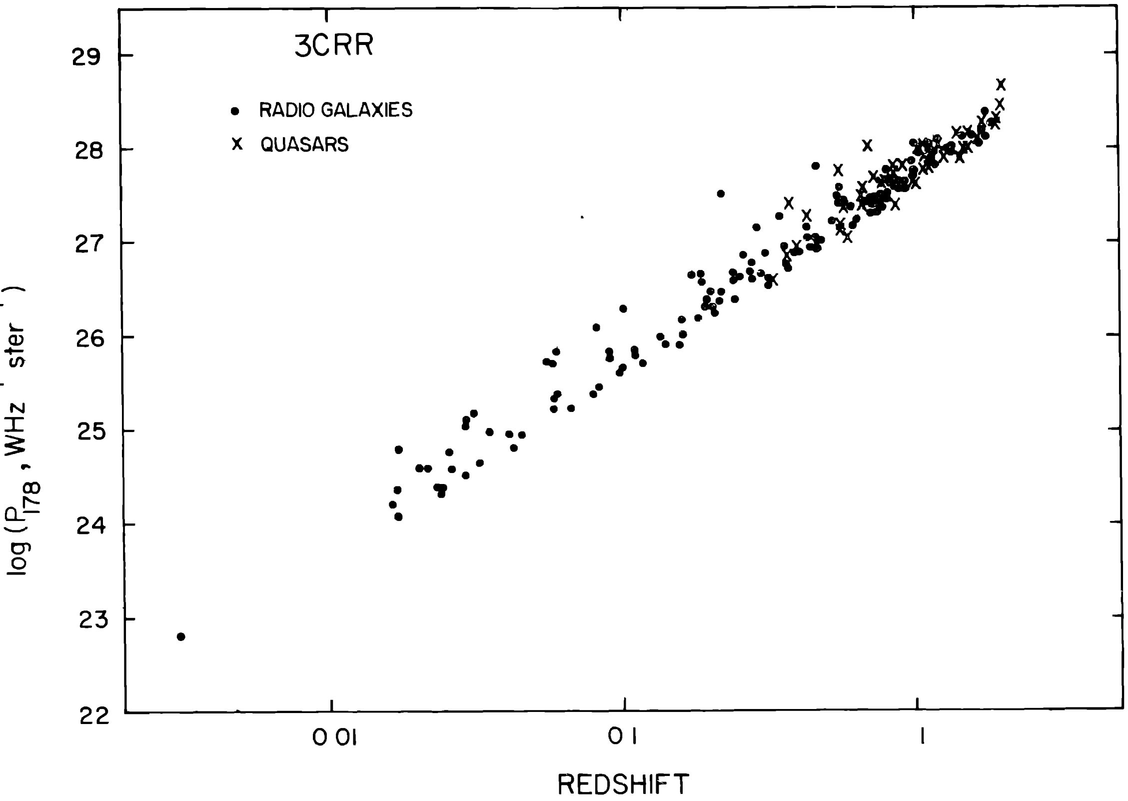

Figure 2. The strong correlation between radio luminosity and redshift for radio galaxies and quasars in the 3CRR catalogue.

large redshifts. The criterian of steep radio spectral index ($\alpha > 1$; defined as $S(\nu) \propto \nu^{-\alpha}$) for such a preselection has been remarkably successful in bringing about a rapid increase in the number of known high redshift galaxies over the last few years. The spectral indices of 3CR sources are known to become steeper with increasing radio luminosity (Laing and Peacock 1981) or with increasing redshift in view of the tight correlation between P and z. It was shown earlier (Tielens & Miley 1979; Gopal-Krishna & Steppe 1981) that the fraction of intermediate flux density radio sources that can be optically identified with objects above the plate limit of the Palomar Sky Survey decreases significantly with steepening spectral index. It is therefore reasonable to expect that sources with the steepest spectral indices may be the most radio luminous and therefore at large redshifts. By concentrating on a subsample of 4C source with $\alpha > 1$, Chambers and Miley have indeed been successful in finding several galaxies at $z > 2$ (Chambers & Miley 1990). The source 4C 41.17 with the highest known redshift of 3.80 for a radio galaxy was also found by this technique (Chambers *et al.* 1990).

Another major ongoing program that has already resulted in the finding of over a dozen radio galaxies at $z > 2$ is also based on sources with steep spectral indices (McCarthy *et al.* 1990, 1991). This is a collaboration between P.J. McCarthy of the Carnagie Institution in Pasadena, USA, W. van Breugel of the Lawrence Livermore Laboratory in Livermore, USA and C. R. Subrahmanya, R. M. Athreya and the author from TIFR, India. The samples being investigated in this program are a subset of the 408 MHz Molonglo Reference Catalogue (Large *et al.* 1981) complete to $S_{408} \geqslant 1$ Jy. The first step in this project was the observations by Subrahmanya of about 700 sources in a restricted declination range ($-30° < \delta < -20°$) using the Molonglo Synthesis Telescope at 843 MHz, which enabled accurate radio positions to be determined and optical identifications to be attempted from the SRC-J Sky Survey plates. A further subset of about 150 sources, comprising those with no optical identifications or plate limit identifications ($m_J > 21$) and having steep spectral indices between 408 and 843 MHz ($\alpha_{408}^{843} > 0.9$), was then selected for further radio and optical observations.

Optical CCD imaging (generally in the r band) for our Molonglo 1-Jy sample is being carried out with the Las Campanas 2.5 m Du Pont telescope in Chile and optical spectroscopic observations of the faint galaxies considered identified with the radio sources are being made using the Cerro Tololo 4 m telescope and its Folded-Schmidt spectrograph. The highest redshift recorded in the program so far is $z = 3.13$ for the source 0316-257: this is now the most distant galaxy known in the southern sky.

In order to make a comparison of their optical and radio properties the sources in the Molonglo sample are also being imaged in the radio with high angular resolution (~ 1 arcsec) using the Very Large Array (Napier *et al.* 1980) in New Mexico, USA. This is being done in the snap-shot mode at a frequency of 5 GHz to start with. More detailed imaging for sources at $z > 1.5$ is also being carried out using the VLA at several wavelengths and angular resolutions.

Another systematic program to find high z radio galaxies has been undertaken by Gopal-Krishna (of TIFR) and his collaborators in the European Southern Observatory in Munich, Germany. The search list for this program has been compiled from the radio sources in the Lunar Occultation Surveys made using the Ooty Radio Telescope that have been found to have ultra-steep spectral indices (Gopal-Krishna & Steppe 1981). Apart from finding some high redshift radio galaxies, this program has led to the discovery of a powerful radio galaxy (at $z = 0.477$) having an unusually low-excitation emission line spectrum (Gopal-Krishna *et al.* 1992).

Although the criterian of steep spectral index has been highly successful in the search for high redshift galaxies, the nature of the $\alpha - P$ or $\alpha - z$ relation is not fully understood and remains somewhat controversial. The strongest correlation between α_{observed} and P is seen in the low-frequency 3CR sample (Laing & Peacock 1980). Samples selected at higher radio frequencies (*e.g.* 2.7 GHz) show little evidence of such a correlation (Peacock 1985; Kapahi & Kulkarni 1990). Besides, a substantial fraction of the extended radio sources are known to have curved radio spectra; spectral indices getting steeper at higher frequencies. This makes high-z (and hence high-P) sources appear steeper between fixed frequencies in the observed frame even if there is no intrinsic correlation between P and alpha (*e.g.* Gopal-Krishna 1988). Indeed, a reexamination of the $\alpha - P$ correlation for 3 CRR sources after transforming the spectral indices to a fixed rest frame frequency of 1.4 GHz by van Breugel & McCarthy (1990), shows only a weak residual trend for α with P.

It has also been noted by Kapahi & Kulkarni (1990) that a trend of α and P in the 3CR sources could arise in part from a selection effect related to the steepening slope of the radio luminosity function at high P that could result in the preferential selection of ultra steep spectrum sources of high radio luminosity in a bright low frequency catalogue. It is therefore necessary to be aware that the high-z galaxies found using the ultra steep spectrum filter may not be entirely representative of the high-z radio galaxy population. In order to assess the importance of this possible bias, we have recently taken up another subset of the Molonglo 1 Jy sample for investigation that consists of about 120 sources that have no optical counterparts (or are at plate limits) on the SRC-J films and have $\alpha_{408}^{843} < 0.9$.

3. Radio-optical correlations and the alignment effect

One of the most remarkable properties of radio galaxies at high redshifts has turned out to be the so called 'alignment effect'. It was found (McCarthy *et al.* 1987; Chambers *et al.* 1987) that the optical continuum emission of radio galaxies at high redshifts ($z \gtrsim 0.5$) often showed an elongated morphology with one or more regions of emission sometimes extending to distances as large as 50 to 100 Kpc. The major axis of this elongation showed a strong tendency to be approximately aligned with the axis defined by the twin lobes of the radio emission associated with the galaxy. A good example of the alignment in the case of the radio source 0406 − 244 from the Mologlo 1-Jy sample is shown in figure 3. This tendency for the radio and optical axes to be approximately aligned is in complete contrast to the case for radio sources identified with ellipticals at small redshifts ($z < 0.1$) where the radio axis is found to be generally aligned with the minor axis of the light distribution (*e.g.* Kapahi & Saikia 1981).

The alignment effect appears to become progressively stronger with increasing redshift (McCarthy 1989) and at $z > 0.5$ the effect is seen in a majority of all radio galaxies. So strong is the effect in fact that even blind spectroscopy (without any knowledge of the optical continuum) with a long slit at the position of the radio source and aligned along the radio axis has been shown to be quite successful in obtaining redshifts of unidentified steep spectrum radio sources (Rawlings *et al.* 1990). Because of the strong correlation between P and z in the 3CR sample as mentioned earlier, it is of

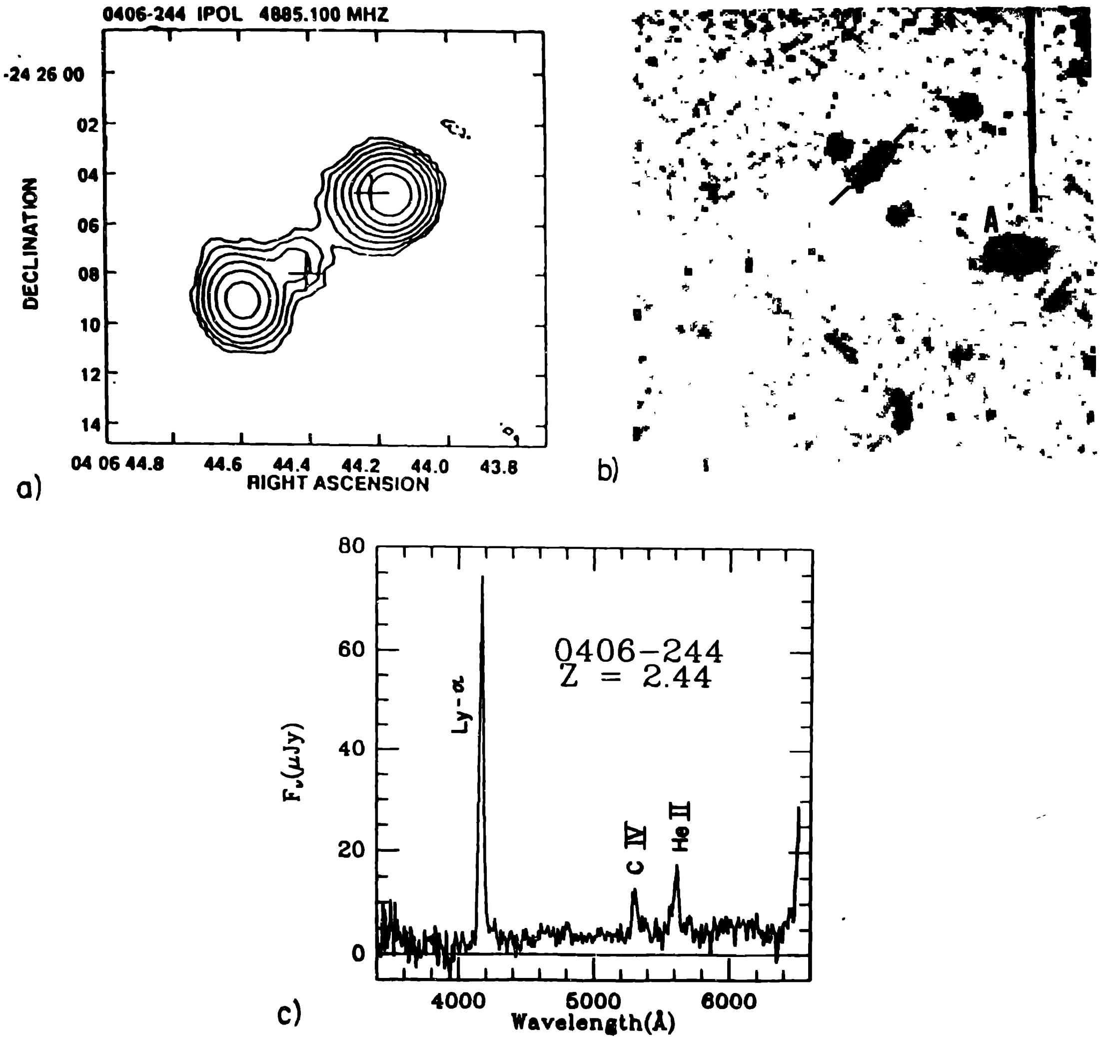

Figure 3. The Molonglo radio source 0406-244 at a redshift of $z = 2.44$. (a) contour plot of the brightness distribution at 5 GHz determined using the VLA; (b) optical r band CCD image obtained using the 2.5m telescope of the Las Campanas Observatory. The field shown covers a region of 65 × 65 arcsec. The orientation of the radio axis is shown by the two short lines on either side of the elongated optical image; (c) identification of the strong lines in the spectrum obtained using the 4m telescope of the Cerro Tololo Inter-American Observatory.

course possible that the alignment effect is related primarily to radio luminosity or beam power rather than to z; recent studies of the effect in the fainter Molonglo 1 Jy sample suggest, however, that the effect may primarily be related to redshift (McCarthy *et al.* 1990).

Some radio galaxies have been known also to contain extended emission line regions that appear to be related to the radio structure (*e.g.* van Breugel 1989). Detailed narrow band line imaging of larger samples (generally in $H\alpha$, [OIII] λ5007, [OII] λ3727 or $Ly - \alpha$ lines) has now shown (*e.g.* Baum *et al.* 1988; McCarthy 1989) that such extended line emitting regions are a fairly common phenomenon associated with powerful radio galaxies. Although the line emitting regions do not show a one-to-one morphological correspondence with the radio emission, they are roughly aligned with the radio axes. The alignment is rather loose at small redshifts but becomes progressively stronger at higher redshifts (Baum & Heckman 1988; McCarthy 1989). An important aspect of the extended line emission is the finding of a strong correlation between the emission line luminosity and the total radio luminosity in both low redshift radio galaxy samples (Baum and Heckman 1989; Saunders *et al.* 1990) as well as in samples at high redshifts (McCarthy 1989; McCarthy *et al.* 1991; Rawlings & Saunders 1991) covering over four orders of magnitude in radio luminosity.

Another very interesting correlation between the optical line emission and the radio structure is the finding (McCarthy, van Breugel & Kapahi 1991) that the shorter of the two arms of the double radio structures is almost invariably located on the side with the stronger optical line emission. This provides strong support to the idea that asymmetry in the radio structure may be related primarily to different gas densities on the two sides (Swarup & Banhatti 1981).

In order to understand the radio-optical alignment effect it is important first to ascertain if the optical continuum is indeed starlight from the underlying elliptical galaxy. Nonthermal synchrotron emission from relativistic electrons responsible for the radio emission, as well as inverse compton scattering of the cosmic microwave background off the relativistic electrons fail to account for the high brightness of the observed light (Chambers & Miley 1990) and for the observed spectral energy distributions which are very different from nonthermal power laws. Several authors have considered the possibility of the continuum emission arising from either electron scattering or dust scattering of nonthermal emission from an obscured active QSO nucleus (*e.g.* Fabian 1989; Rawlings and Eales 1989; di Serego Alighieri *et al.* 1989). These mechanisms cannot easily explain the observed SEDs and do not readily explain the small observed scatter in the infrared K-magnitude Hubble diagram over the entire redshift range extending up to 3.8. Although it is not yet possible to rule out scattering processes being responsible for atleast a part of the observed continuum, the general consensus appears to be that most of the observed emission is starlight from the galaxy. One of the strongest pieces of evidence in support of starlight comes from the superposition of the observed spectra of several high redshift radio galaxies by Chambers & McCarthy (1990) which shows up the presence of weak stellar absorption features.

Gravitational lensing has sometimes been suggested as making an important contribution to the morphology and luminosity of high redshift radio galaxies (e.g. Hammer & Le Fevre 1990), but it is difficult to explain the alignment as arising from lensing effects. The simplest explanation for the optical-radio alignment is that the galaxies have undergone a burst of star formation triggered by the action of radio jets (McCarthy *et al.* 1987; Chambers *et al.* 1987). A possible mechanism for such star formation has been proposed independently by Rees (1989) and Begelman Cioffi (1989) in which cocoons of shocked gas surrounding radio lobes engulf and compress preexisting circumgalactic gas clouds, driving them over the Jeans limit leading to powerful bursts of star formation. As the life time of radio jets in powerful radio galaxies is unlikely to exceed about 10^8 years, the alignment effect puts strong constraints on the ages of the stars responsible for the aligned light as discussed in the next section.

The approximate alignment of the line emitting region with the radio axis could alkso be related to the radio jet. The source of ionizing photons responsible for the line emission could be the young hot stars, radiative shocks or the active nucleus of the galaxy. The line ratios appear to be best explained by photoionization by a powerlaw-uv continuum from the nucleus (*e.g.* van Breugel & McCarthy 1990) which is hidden from direct view due to obscuration or beaming effects required also in the 'unifying schemes' based on source orientation (Barthel 1989). It is also interesting to note that the presence of gaseous halos around high redshift galaxies suggested by the presence of extended line emitting regions could be responsible for the strong cosmological evolution observed in the linear sizes of double radio galaxies (*e.g.* Kapahi 1989) if the halos had a higher gas density at earlier epochs (Subramanian & Swarup 1990; Gopal-Krishna & Wiita 1991).

4. Old or Young?

At redshifts of $z \gtrsim 1$, the observed light in the visible and red parts of the spectrum corresponds to uv and blue regions in the rest frames of the galaxies and most of this light arises from young massive stars formed in a recent star formation episode. The older and less massive stars emit most of their light in the red region which wwould be redshifted to the IR region. If the alginment effect is indeed related to recent jet-induced star formation, one expects the effect to be much less prominent in the IR images. Infrared imaging, which is now coming of age with the development of large multidetector arrays, has thus acquired great importance. Although IR images of some of the high red-shift galaxies do show extended emission roughly aligned with the radio axis, recent imaging of larger samples appears to indicate that the IR images may be less elongated than those at optical wavelengths and also may show a weaker alignment effect (Eisenhardt & Chokshi 1990; Chokshi & Eisenhardt 1991; Riegler *et al*] 1992). Future studies should provide more definitive answers to the basic questions that would help choose between the two opposing hypotheses that have been put forward concerning the nature and ages of high redshift radio galaxies.

The first hypothesis, pioneered by Lilly and his associates (*e.g.* Lilly 1990), is that these are mature galaxies with an old stellar population in which there has been a fresh burst of star formation, possibly triggered by the radio jet, and involving only a small fraction of the total mass of the galaxy. Photometric observations in the optical and the infrared regions for a few high redshift galaxies indicate that their spectral energy distributions (SEDs) are remarkably similar, being characterised by a nearly flat portion in the emitted uv and a steep bump in the emitted red (Lilly 1988; Chambers *et al*] 1990; Rigler *et al*] 1992). Standard stellar population synthesis models (*e.g.* Bruzual 1983; Guiderdoni & Rocca-Volmerange 1987) can provide reasonable fits to the red bump in the observed SEDs requiring the bulk of the strs in the galaxy to be atleast ~ 10^9 years old. This advanced age at the epochs corresponding to the high redshifts of the galaxies, in turn implies that most of the galaxies must have formed quite early on with the epoch of formation $z_f > 5$ (Lilly 1988). The flat part of the SED at the uv end can also be readily modeled by a small population of young and massive stars contributing less than a few percent of the galaxy mass.

Apart from the fairly uniform SEDs, powerful radio galaxies also show a remarkably small dispersion (~ 0.4 mag) in their infrared K-magnitudes (Lilly & Longair 1984; Spinrad & Djorgovski 1987; Lilly 1990) over the entire range of redshift from ~ 0.1 to 3.8, inspite of the wide variation in their optical magnitudes and morphologies with z. This can also be considered to indicate a mature and homogeneous population of stars in the host galaxies, together with a tight mass selection effect in radio galaxies and a uniform M/L ratio.

In this 'old galaxy' interpretation the optical-radio alignment is attributed entirely to the small population of young stars presumably formed as a result of the radio jets. Based on multicolour images of 13 3CR radio galaxies, it has recently been suggested by Rigler *et al.* (1992) that the active aligned component could contribute typically about 10% of a galaxy's infrared light, which, though not large enough to seriously affect the K-magnitude Hubble diagram, can nevertheless introduce a weak elongation and alignment of the continuum IR light with the radio jet axis.

The other hypothesis for the alignment effect is that one is looking mainly at young galaxies in which the bulk of the star formation is related to the radio jet (Chambers & Charlot 1990; Bithel & Rees 1990). We have little direct knowledge of the history of star formation at early epochs. Unlike the standard stellar population synthesis models in which the initial formation of stars is spread out over a considerable amount of time, Chambers and Charlot have proposed a model in which most of the star formation is assumed to take place in a strong initial bust lasting $\lesssim 10^8$ years which is roughly the free fall time. The model produces reasonably good fits to the observed SEDs for ages of $\sim 3 \times 10^8$ years, comparable to the radio jet time scales. In this model the galaxies are being observed soon after the completion of the main star formation episode and the epoch of formation can extend to relatively small redshifts of $z \sim 1$. The model appears, to first approximation, to preserve the low dispersion in the K-mag Hubble diagram as the red luminosity stays roughly constant over $\sim 10^9$ years. It also predicts both the optical and infrared images to be coeval and hence aligned with the radio jet direction. Future infrared imaging and colour maps of larger samples of galaxies should therefore help to decide between the old and young galaxy interpretations.

5. Conclusion

The development of high efficiency imaging and spectroscopic instrumentation in the optical and IR wavebands has led to rapid advances in the study of the earliest radio galaxies to have formed in the Universe.

These studies have revealed several optical-radio correlations, including the so called alignment effect, which points to the importance of radio jets in triggering bursts of star formation. Systematic observational efforts currently being pursued by several groups are expected to lead to a substantial increase in the number of known galaxies at high redshifts. Apart from serving as important probes of the physical conditions in the Universe at different epochs, studies of high redshift galaxies could tell us if the bulk of galaxy formation took place in a relatively short span of time at early epochs or whether the process was much more spread out in time, extending to relatively recent epochs. One can look forward in the near future to finding answers to several unanswered questions and to generating many new questions in the process.

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