OPTICAL IDENTIFICATIONS OF EXTRAGALACTIC RADIO SOURCES

M.S. Longair,
Mullard Radio Astronomy Observatory,
Cavendish Laboratory, Cambridge, England.

1. THE STATE OF THE ART

The ability to identify the many tens of thousands of extragalactic radio sources now known depends upon the precision with which the radio positions and structures are known as well as the availability of high quality plate material. For the brightest radio sources, positions with accuracy better than 1 arcsec are now routinely available and radio structures with angular resolution 1-5 arcsec can be readily measured with instruments such as the Westerbork Synthesis Radio Telescope, the Cambridge 5-km Telescope and the VLA. The sensitivity of the VLA is such that these observations can be extended to sources in the flux density range $\sim$ 1-10 mJy.

The standard procedure for identifying extragalactic radio sources is first to use the surveys of the northern and southern skies made with Schmidt telescopes, the Palomar-National Geographic Society Sky survey, the U.K. Schmidt survey and the ESO Schmidt survey. For the northern survey, the limiting magnitude on red plates is about 20 and generally speaking identifications of bright radio sources with objects brighter than this limit are easy. The UK Schmidt survey has a somewhat fainter limiting magnitude because of the use of IIIaJ plates. To extend optical identifications to significantly fainter magnitudes requires the use of telescopes in the 4-5 metre class. Until recently, the faintest magnitudes attainable under good seeing conditions was $\simeq$ 23, either by direct prime-focus photography using plates or with an image intensifier. For this work, radio positions with accuracy $\gtrsim$ 1 arcsec and radio structures of comparable angular resolution are essential.

Most recently, CCD cameras have been used on large reflectors and their very high quantum efficiencies in the red and near infrared wavebands ($\sim$ 60%) make them ideal for searching for distant galaxies in the fields of the radio sources. Because of the linearity of the detector, the limiting magnitude attained depends only upon how long one is prepared to integrate. Typically, stellar objects having m $\sim$ 25 can be readily

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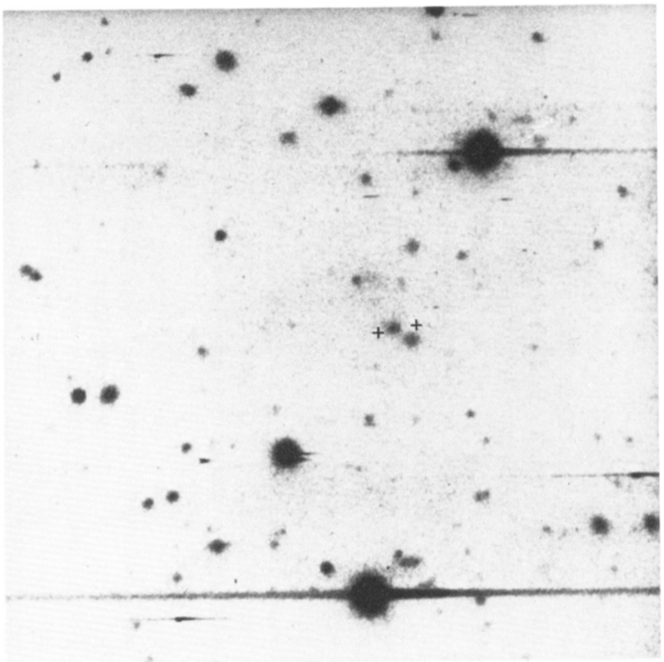
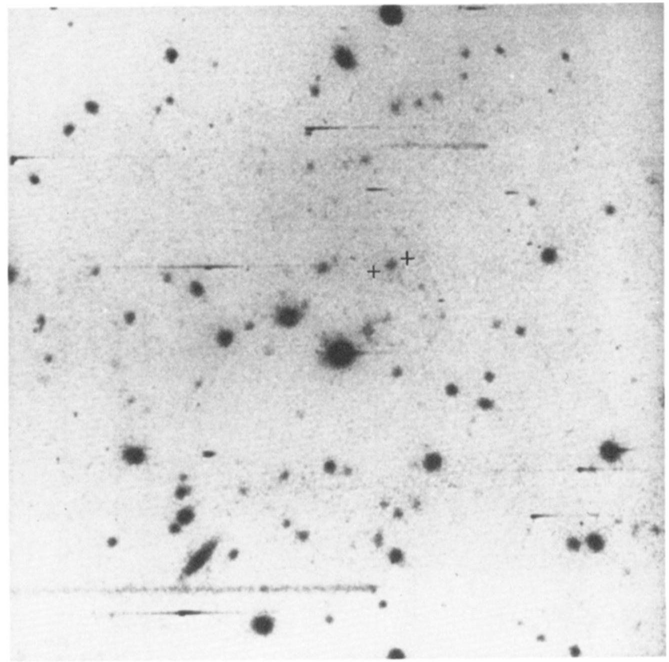


3C 280



3C 289

Figure 1. CCD images of the fields of the radio sources 3C 280 and 289. Each field is 3 arcmin in size. The observations were made with the 500 x 500 pixel CCD camera at the prime focus of the Hale 5-metre telescope. The black crosses indicate the positions of the maxima in the radio brightness distributions of these double sources.

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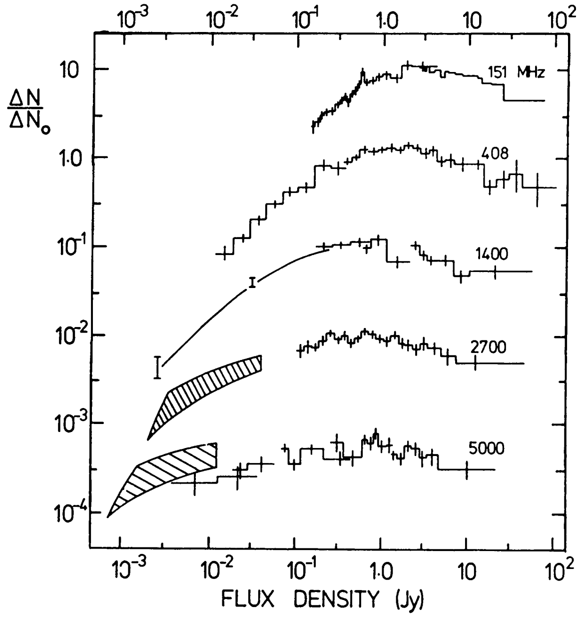
detected in a 1000-sec exposure. Our experience in identifying very faint radio galaxies and quasars shows that one can obtain about 1-1½ magnitude improvement in identifying these objects with a 1000-sec exposure over what we have been able to achieve with an image intensifier and IIIaJ plates on the Hale 5-metre telescope (see e.g. Figure 1).

The astrophysical objectives of these studies are multifold. First, the optical identifications are an essential first step in trying to disentangle how the radio source population has evolved with cosmological epoch. Figure 2(a) shows a recent compilation of different counts of radio sources by Wall (1979). It is well known that the counts at all the frequencies shown in Figure 2(a) disagree with the predictions of uniform world models, as is illustrated in Figure 2(b) for the counts at 408 MHz. Second, the optical identification of distant radio sources is one of the most successful methods of discovering distant massive galaxies and quasars. These may be used to study how the properties of massive galaxies have evolved with cosmological epoch and may conceivably eventually lead to an estimate of q_o. The question of a redshift cut-off for quasars may be studied using unbiased radio selected samples. Third, the optical identifications are often objects exhibiting evidence of other high energy astrophysical activity such as strong emission-line spectra, strong continuum radiation and X-ray emission. Optical identifications have also led to unexpected discoveries such as quasars themselves and more recently the spectacular double quasar, 0757+561.

2. OPTICAL IDENTIFICATION SURVEYS

Low frequencies Most effort has been devoted to the identification of the brightest radio sources at low frequencies because historically these sources were among the first to be detected and most subsequent work with high resolution aperture synthesis telescopes has concentrated on these samples because most of the sources are extended with resolvable radio structures. Until the beginning of this year, the optical identification content of a statistical sample of 166 3CR radio sources was about 85-90%, this work using prime focus photography, either direct or with an image intensifier (Longair and Gunn 1975, Smith, Spinrad and Smith 1976, Laing et al. 1978, Riley et al. 1980). This spring, Jim Gunn and I had access to the 500 x 500 pixel CCD camera built by JPL as part of the development programme of the Space Telescope. With this device, we were able to identify all the remaining unidentified sources in a complete sample of 60 sources which was a subset of the 166 3CR statistical sample (see Figure 1 for an example of the quality of this material). The apparent magnitude distribution of this sample is indicated in figure 3a. Most of the objects fainter than m = 20 are galaxies. As can be seen from the figure, a problem in interpreting these results is that there are very few redshifts available for objects fainter than about m = 20, essentially all of which are radio galaxies. The redshift distribution for the 41 objects with redshifts is shown in Figure 3(b). It is likely that the redshifts of the remaining radio

(a)



(b)

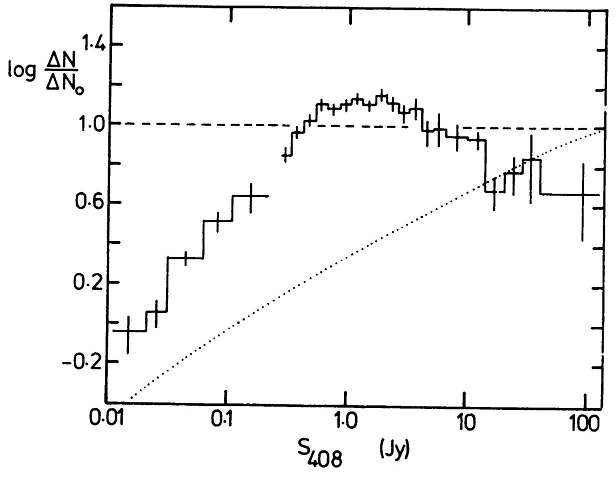
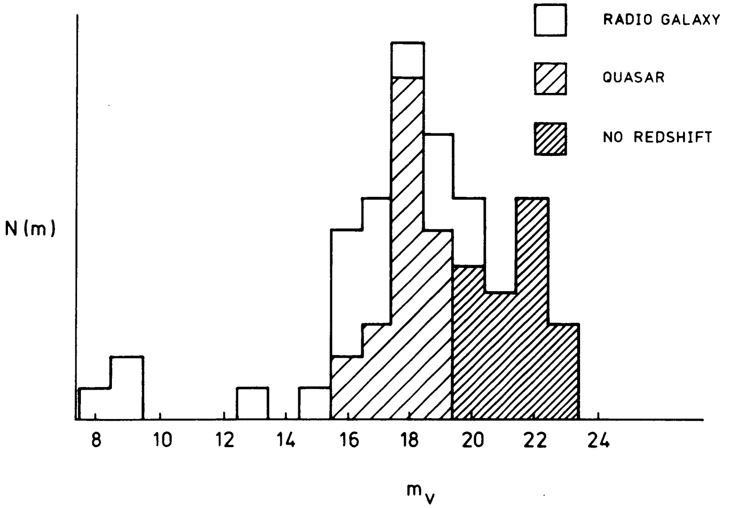


Figure 2(a) Counts of radio sources at five frequencies in differential form. ΔN is the number of sources in the flux density interval S to S+ΔS and ΔN_o is the expected number in a Universe in which $N(\geq S) \propto S^{-1.5}$ (Wall 1979).

(b) The differential source counts at 408 MHz compared with the law $N(\geq S) \propto S^{-1.5}$ (dashed line) and the expected relation for a Friedmann world model having Ω= 1 assuming the sources are uniformly distributed (dotted line). (Wall 1979).

(a)



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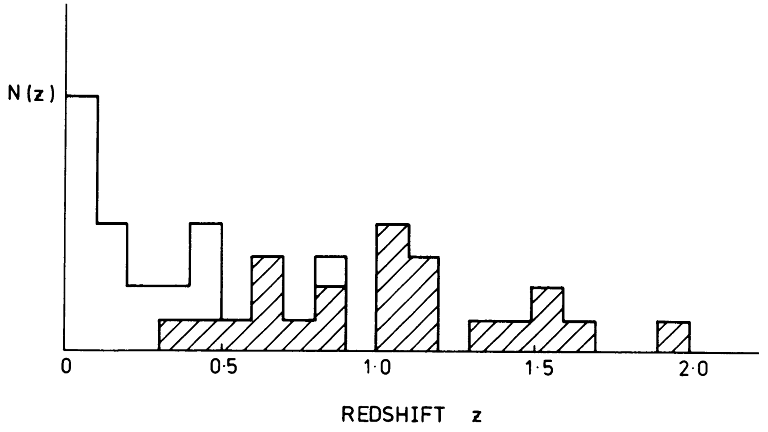

Figure 3(a) The apparent magnitude distribution for a complete sample of 60 3CR radio sources all of which now have optical identifications (Gunn et al. 1980).

(b) The redshift distribution for the sample of 60 3CR radio sources. Redshifts are only available for 41 of these, the apparent magnitudes of those without redshifts being indicated in Figure 3(a).

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galaxies fall in the redshift range $0.5 < z \lesssim 1.5$. In fact, for the complete 166 sample of sources, there are only 4 sources for which there is at present not even a tentative identification, 3C 65, 68.2, 294 and 437. None of these fields has been studied using the CCD camera.

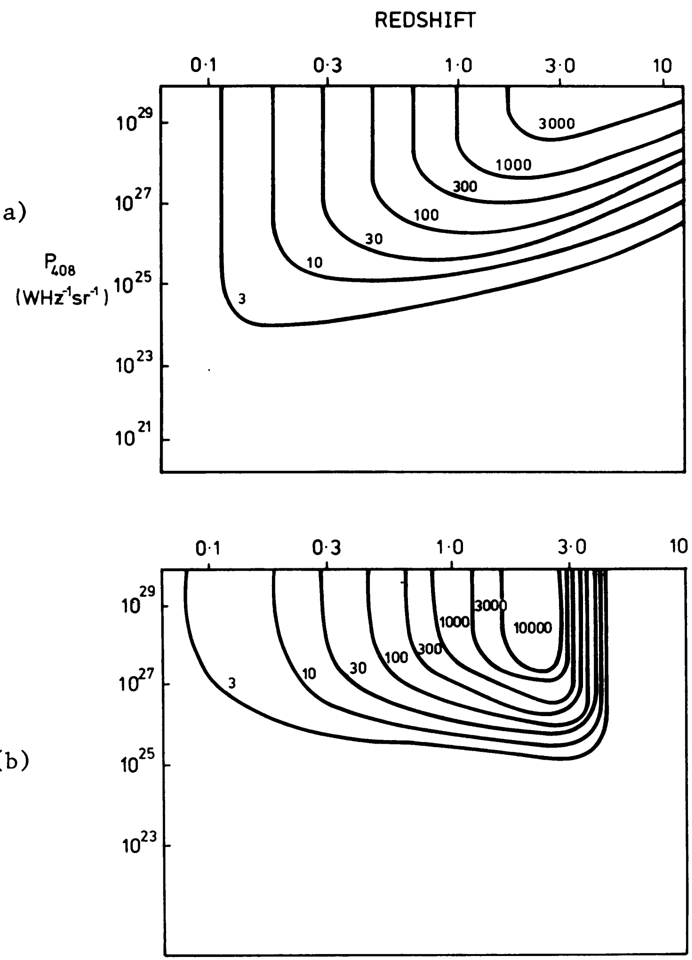
It is the combination of optical identification and redshift information at high flux densities combined with radio source counts known with excellent statistical precision that enable models for the cosmological evolution of the radio source population to be constructed (e.g. Wall, Pearson and Longair, 1977). It is instructive to present these models in terms of "enhancement factors", $f(P,z)$ which indicate the increase in comoving space density of sources as a function of radio luminosity P and redshift z. If the world model were uniform $f(P, z) = 1$. Figures 4(a) and (b) show two models which can account for the source counts at 408 MHz (Figure 2(b)) and the V/V_{max} data for quasars in the sample (Wall et al. 1977). Some models have cut-offs at redshifts $z \sim 3$-4 and others have different rates of evolution of the strongest sources. Notice that the strongest evolution is only associated with the most luminous sources - intrinsically weak radio sources show at best weak cosmological evolution.

The models differ in the predicted identification content and redshift distributions at low flux densities. An example of these differences for the three successful models described by Wall et al. is shown in figure 4(c) from which it can be seen that the differences between the models are large. Detailed optical identification searches have been made by Grueff and Vigotti to $S_{408} \gtrsim 1$ Jy and by Perryman (1979 a, b), both of whom used IIIaJ plates taken with the Palomar 48-inch Schmidt telescope. Grueff and Vigotti (1977) achieved an overall identification percentage of about 63% consisting of 40% galaxies and 23% quasars. At 408 MHz, Perryman achieved an identification percentage of only about 20% at $S_{408} \geq 0.01$ Jy. Even assuming that all the latter objects are radio galaxies with $z \lesssim 0.6$, it is evident that these statistics are as yet inadequate to discriminate between models.

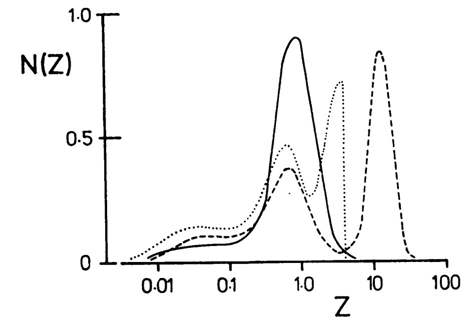
<u>Deep identifications at 1400 MHz</u> In contrast deep optical identification surveys at 1.4 GHz by de Ruiter et al. (1977) and Perryman (1979a, b) have found significantly higher identification rates at the lowest flux densities, $S_{1.4} \gtrsim 2$ mJy. De Ruiter et al. find more than 40% of the faint sources to be identifiable on deep 4-metre plates while Perryman achieved a figure $\sim$ 35-40% for the 5C6 and 7 surveys using very high quality IIIaJ 48-inch Schmidt plates taken by Dr. M.V. Penston. The cause of this difference in optical identification rate as compared with 408 MHz is attributed by Perryman to the fact that there is a larger fraction of sources with spectral indices $0.4<\alpha< 0.7$ in the 1.4 GHz sample which are of larger angular size than 5C sources in general. These sources are more readily identifiable optically. This result is consistent with the known correlation between radio luminosity and spectral index for radio galaxies recently re-analysed by Laing and Peacock (1980). Originally, Wall et al. (1977) hoped that this high

(a)

(b)



(c)



Figures 4(a) and (b). Two models for the evolution of the radio source population as a function of cosmic epoch (or redshift z) and radio luminosity. These models, which are designed to account for the source counts at 408 MHz, are models 5 and 4b (Figure 4(a) and (b) respectively) of Wall et al. (1977). For radio quasars at low frequencies $f(P,z) = \exp\{M(t_o - t)/t_o\}$ where $M \approx$ 10-12 and t is cosmic epoch.

(c) The predicted redshift distributions at $S_{408} \geq 10$ mJy for models 4a, 4b and 5 of Wall et al. (1977).

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identification percentage would enable a tentative discrimination to be made between the models illustrated in figure 4(c) but this new result indicates that the sample of identified 5C sources at 408 MHz, the frequency at which the models were constructed, is only 20%. A noteworthy feature of the recent Westerbork work (Katgert et al. 1979) is the indication that the faintest identifications are significantly bluer than those down to $m = 20$. They interpret this as evidence for colour evolution of massive galaxies at redshifts $z \sim 0.5$-0.6.

Identifications at 2.7 GHz and higher At high radio frequencies, 2.7 GHz and greater, the fraction of sources with flat radio spectra, $\alpha < 0.5$, is very much larger and continues to increase to the very highest frequencies. Recently, Peacock and Wall (1980) have defined various statistical samples of the brightest sources at 2.7 GHz and the optical identification content of a high flux density sample is shown in Table 1. The problems of interpretation of the source counts are different at 2.7 GHz.

Table 1

Identification statistics at 2.7 GHz for a sample of 155 sources having $S_{2.7} \geq 1.5$ Jy (Peacock and Wall 1980)

	Extended sources $\alpha > 0.5$	Compact sources $\alpha < 0.5$
Galaxies	66	19
Quasars	8	43
No identification	2	4
Neutral objects	-	2
New CCD survey		11*
	76	79

* 7 identifications roughly half of which are galaxies and 4 empty fields.

The sources with steep radio spectra are similar to those found in surveys at low radio frequencies and their source counts are also consistent with the low frequency counts. However, the flat spectrum sources have a much flatter count. If the counts are interpreted in terms of exponential evolution models, $f(z) = \exp\{M(t_o-t)/t_o\}$ where t is cosmic time and t_o the present epoch, $M \approx 10$-12 for sources with steep spectra but only ≈ 3-5 for flat spectrum sources. Wall et al. (1980) show that there are further complications in understanding the 2.7 GHz counts at lower flux densities at which it may be necessary to invoke the presence of an evolving low-luminosity source population.

Thus, the need for further identifications and redshifts for high as well as low frequency samples is pressing at all flux densities since it is clear that the evolution of the overall radio source population cannot be wholly understood from observations at a single frequency.

3. PROSPECTS FOR FUTURE OPTICAL WORK

I believe the prospects for future optical identification work and for measuring the redshifts of distant radio sources are good. First of all, studies of samples of bright radio sources associated with galaxies and quasars show a number of encouraging trends (Hine and Longair 1979). For example, the fraction of sources with strong non-thermal optical continua from their nuclear regions increases with increasing radio luminosity and correspondingly, even for radio galaxies alone the fraction of galaxies with strong emission line spectra increases to about 70% at the highest radio luminosities (for a brief survey of these and other optical properties of radio sources, see Longair 1979). Inspection of figures 4(a) and (b) shows that the models predict that it is sources of these properties which are the main cause of the "excess" of faint sources in the counts. Second, there is increasing evidence that at redshifts $z \gtrsim 0.5$, galaxies and, in particular the brightest galaxies in clusters, are significantly bluer than comparable nearby objects. Thus, Butcher and Oemler (1978) find distant clusters to be bluer, Tinsley (1979) reports an excess of blue galaxies in the most recent galaxy counts, Oke (1979) has reported that the fraction of brightest galaxies in clusters with a blue excess increases rapidly at redshifts $z \gtrsim 0.55$ and Katgert et al. (1979) find directly that the faintest radio galaxies are excessively blue. These trends make the problem of identifying the most distant radio galaxies significantly easier since the K-correction which is mostly responsible for the faintness of distant galaxies in, say, the V-band, no longer increases so rapidly with increasing redshift.

These programmes are prime candidates for study with the new generation of CCD cameras on ground-based telescopes and with the Space Telescope.

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DISCUSSION

Rees: You presented a correlation between optical line width and the fraction of the radio flux coming from a central component. Do you get a better or worse correlation between line width and the radio luminosity of the compact component?

Longair: There is definitely a trend for the sources with greater intrinsic central component luminosities to have greater line widths. We have not quantified our correlations because as yet the data are very sparse. We work in terms of ratios of luminosities because these tend to be less sensitive to distance-dependent selection effects in a sample selected by flux density.

Wills: So far as you can tell, do the new faint optical identifications of 3C sources continue to be exclusively galaxies?

Longair: For objects well above the limits of detectability, the new 3CR identifications are all with extended objects. Close to the plate limits, it is obviously difficult to distinguish stars and galaxies.