COSMOLOGICAL EVOLUTION OF QSOs AND RADIO GALAXIES FROM RADIO - SELECTED SAMPLES

J.V. Wall
Royal Greenwich Observatory, Herstmonceux Castle, Hailsham,
Sussex, U.K.

C.R. Benn
Mullard Radio Astronomy Observatory, Cavendish Laboratory,
Madingley Road, Cambridge, U.K.

We describe recent advances in observation and analysis which lead to improved understanding of the spatial distribution of QSOs and radio galaxies.

1. REVIEW

A severe bias exists in the distribution of powerful radio sources; on a cosmological interpretation of redshifts, they favour the more distant regions of their observable volumes, their space density at earlier epochs of the Universe thus exceeding that at the present day by factors in excess of 1000. The physical basis for this evolution remains elusive, although hints emerge as observations continue to establish the details.

The more recent investigations (e.g. Robertson 1980; Machalski 1981; Wall, Pearson & Longair (WPL) 1980) have used improved statistical techniques and much improved data bases - larger samples of sources with near-complete identification and redshift information, and accurate source counts defined over large flux-density ranges (Fig. 1). The analyses generally assume that extragalactic radio sources belong to one of two sub-populations, the steep-spectrum sources of extended (usually double-lobed) structure identified predominantly with galaxies, and the flat-spectrum sources of compact (VLBI-scale) structure identified predominantly with QSOs. The steep-spectrum sources constitute most sources catalogued at frequencies of 408 MHz and below, and for these, the analyses confirm the degree of evolution and its 'differential' or luminosity-dependent nature found by Longair (1966). The most luminous show drastic evolution, the weaker ones little or none. The flat-spectrum sources occur in similar numbers to steep-spectrum sources in surveys at frequencies of 2.7 GHz and above, and for these, recent analyses suggest mild evolution, with increases in space densities at $z = 1$ of ~100 rather than ~1000 as found for the powerful steep-spectrum sources (Machalski 1981; WPL 1981).

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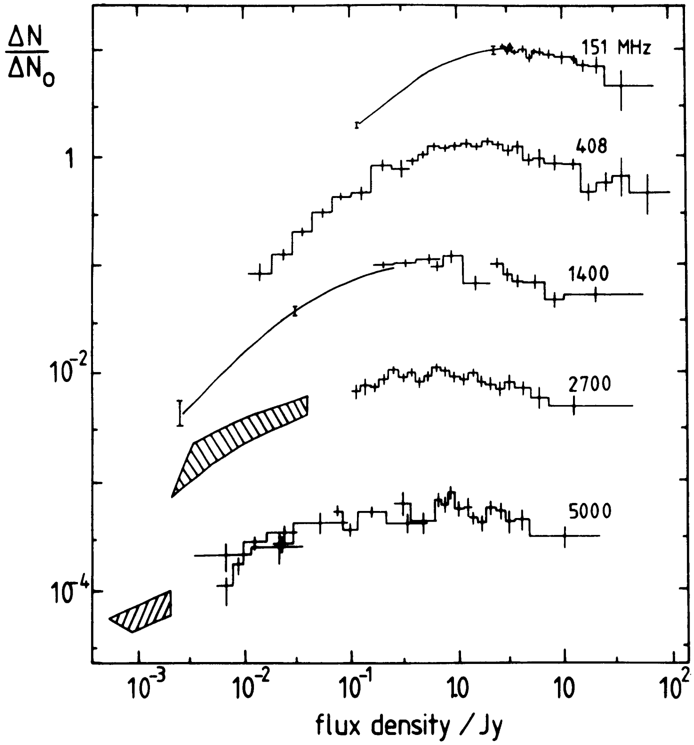

Fig. 1 Source counts in relative differential form, from surveys and P(D) analyses (hatched areas) at 151 to 5000 MHz. References appear in Wall (1980), and further discussion in §2.3 below.

Perhaps the most important result of these analyses was to define new observations crucial to furthering our understanding of the evolution for each population. Three such programmes are described in the next section; the final section discusses an improved technique of evolution-model synthesis which is suitable to incorporate the new data.

2. NEW OBSERVATIONS

2.1 The 5C12 Survey

WPL (1980) showed that powerful constraints on permissible models of evolution for steep-spectrum sources could be provided by a faint steep-spectrum sample for which optical identifications and redshifts are obtained. The conclusion has led to 5C12.

The 5C (Fifth Cambridge) surveys are carried out with the 3-element One-Mile Telescope, 64 days of observing yielding concentric maps at 408 and 1407 MHz. Respectively, these maps have diameters of 4 deg and

1 deg, reach apparent flux densities of 10 mJy and 1 mJy, and contain ~250 sources and ~100 sources. The 5C12 survey is centered at 13^h, $+35^{\circ}$, close to the North Galactic Pole to minimize optical obscuration and chance coincidences with foreground stars. It coincides with the first Westerbork deep survey at 1415 MHz (Katgert et al. 1973), and with one of the original Sandage-Véron-Braccesi fields searched for radio-quiet QSOs. The catalogue from the survey (Benn et al. 1981) contains 299 sources with $S_{408} > 10$ mJy. Improved phase-calibration and super-cleaning techniques have resulted in positions accurate to 3 arcsec and a noise level of 1.8 mJy, parameters significantly better than for previous 5C surveys.

The complementary optical survey for 5C12 consists of repeated, sky-limited plates, some 5 in each of 3 broad-band colours, taken with the 48-in Schmidt telescope of Hale Observatories. Magnitude calibration was achieved with a Racine wedge ($\Delta m = 5.0$ mag), and by taking deep plates of SA57, plates which overlap the 5C12 area plates by a strip 1.5 deg wide. Most of the 299 sources have been observed with the VLA, and the final identifications will be made using the VLA accurate positions. But a preliminary examination of all fields has yielded the following two results:

(i) A first estimate of 33 percent for total identification rate down to $m_b = 22.5$ mag has been obtained using a new statistical procedure (Benn 1981). This rate is higher than that found by Perryman (1979a,b) for the 5C6 and 5C7 surveys, and the difference may be due to some underestimation of position errors in these surveys. The 5C12 identification rate is in good agreement with predictions from evolution models in which 'transition power' between the evolving and non-evolving sources is not a function of epoch (e.g. model 4, WPL 1980). Models which ascribe a significant amount of evolution to sources of lower powers (e.g. model 5, WPL 1980) predict many more identifications at the 10-mJy level than appear in 5C12, and such models are therefore rejected.

(ii) An initial investigation of the colours of 5C12 radio galaxies is shown in Fig. 2. The fainter galaxies have magnitudes

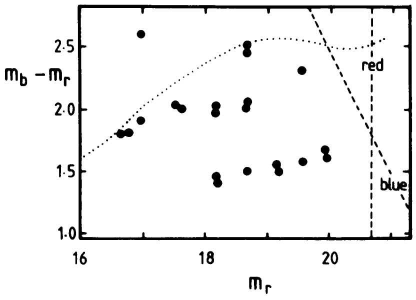

Fig. 2 The colours of 21 5C12 radio galaxies; $m_r = 20$ corresponds to $z \simeq 0.4$. Dashed lines represent red and blue plate limits, while the dotted line is the variation in colour with magnitude predicted from a redshifted E-galaxy spectrum.

corresponding to $z \simeq 0.4$, and these show some blue excess. But the effect does not exceed $\Delta(m_b - m_r) = 0.7$ mag, in disagreement with the suggestion by Katgert *et al.* (1979) that at $z \simeq 0.3$ radio galaxies become drastically bluer by some 2 magnitudes in $(m_b - m_r)$. Problems with magnitude calibration near their plate limit may be responsible.

2.2 A Large-area Sample at 2.7 GHz

The technique advocated by WPL (1980) to derive cosmological information from radio-source statistics demands a well-defined *luminosity distribution* for each class of object. In a preliminary analysis of 2.7-GHz data to determine evolution for flat-spectrum sources (WPL 1981), the luminosity distribution used contained only 20 objects. To provide a more satisfactory sample, Peacock & Wall (1981) compiled a Northern Hemisphere catalogue of the brightest sources at 2.7 GHz. The sample is complete to limits $S_{2.7} \geqslant 1.5$ Jy, $\delta \geqslant +10^\circ$, and $|b| \geqslant 10^\circ$; it is intended as a high-frequency counterpart to the 3CR '166 sample' (Jenkins, Pooley & Riley 1977). The 2.7-GHz sample contains 168 sources of which 161 (96 per cent) are identified, and 108 (64 per cent) have measured redshifts. All sources in the sample have been mapped with the Cambridge 5-km telescope at 2.7 or 5.0 GHz.

There are 51 flat-spectrum sources in the sample, of which 49 are optically identified and 41 have measured redshifts. As a result, an improved luminosity distribution (Fig. 5 of Peacock & Wall 1981) is now available. Other points of interest have emerged from the study:

(i) The sample contains 33 sources with relatively *steep* spectra and yet with *compact* morphologies in the sense that they were not resolved by the 2 arcsec beam of the 5-km telescope. The sources show some spectral curvature in the sense of flattening towards lower frequencies, enough to keep them all out of the 3CR sample. Their nature is unknown. Are they powerful, very distant doubles, extreme Cyg A's, in which self-absorption in the hot-spots bends the spectra? Or are they 'semi-compact', either single component or very small double-component sources, some kind of missing link between extended and compact sources? High-resolution observations are necessary.

(ii) There are 39 flat-spectrum QSOs in the sample, and for these, Peacock *et al.* (1981) found $\langle V/V_{max} \rangle = 0.68 \pm .04$. This is higher than the early values found for such objects (Schmidt 1976; Masson & Wall 1977); contrary to these results and to the results from preliminary source-count analysis (WPL 1981), it suggests that the flat-spectrum QSOs do partake in the strong cosmological evolution exhibited by the most powerful steep-spectrum sources. We return to the point in §3.

2.3 Construction and Dissection of the 5-GHz Source Count; 5C12 Again

Surveys at 5 GHz give a still greater yield of flat-spectrum sources. To extract information on their spatial distribution, the WPL (1980, 1981) analyses indicate that prime reqirements are (i) a luminosity distribution from a large-area sample, the 5-GHz analogue of the 2.7-GHz sample of §2.2, (ii) definition of the *total* source count down to mJy levels, and (iii) samples at different intensity levels with complete radio spectral data, so that sub-counts for both steep- and flat-spectrum populations can be constructed.

With regard to (i), Kühr (1980) has compiled a large-area sample at 5 GHz for which identifications approach completeness. Requirement (ii) has now been met via recent deep surveys and P(D) analyses at 5 GHz carried out on the NRAO 91-m and the MPIfR 100-m telescopes. The deep surveys (Ledden et al. 1980; Pauliny-Toth, Steppe & Witzel 1980; Maslowski et al. 1981) provide direct counts down to 15 mJy, while the P(D) analyses (Ledden et al. 1980; Maslowski et al. 1981; Wall et al. 1981) yield source surface densities near 1 mJy. The new results are consistent, and demonstrate that below 0.1 Jy, the source surface density decreases monotonically from the Euclidean law (Fig. 1; hatched area, 5 GHz, from Wall et al. 1981). In particular, they confirm that the estimate of 5-GHz surface density by Wall (1978) is too high for reasons discussed by Wall et al. (1981).

Several of the new surveys contribute to (iii), the construction of sub-counts, or the question of population mix as a function of 5-GHz flux density. A further deep survey at 5 GHz with the MPIfR 100-m telescope (Wall, Benn, G. Grueff & M. Vigotti, in preparation) covers the 16 deg^2 area of 5C12 and is complete to 18 mJy. It contains a wealth of information relevant to requirement (iii), because the 408-MHz survey (5C12 itself) provides radio spectral data over a long frequency baseline, while the 5C12 deep Schmidt plates permit faint optical identifications to be made. Fig. 3b depicts the two-point spectral-index distribution from the 5-GHz survey of 5C12. It shows that as flux density at 5 GHz is decreased, an astonishing change in the population content takes place. The spectral-index distribution for bright sources

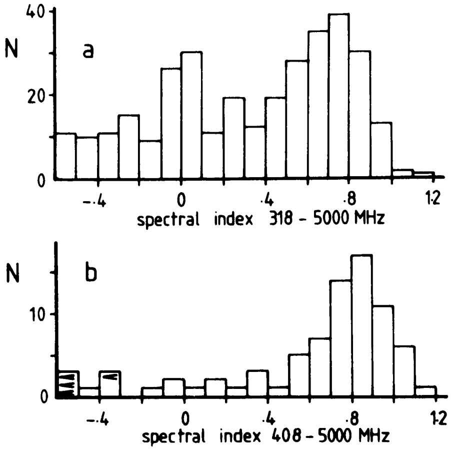

Fig. 3 Spectral-index ($S \propto \nu^{-\alpha}$) distributions for samples selected at 5 GHz: (a) $S_5 > 0.6$ Jy (Condon & Jauncey 1974), and (b) $S_5 > 18$ mJy (5C12 area).

(Fig. 3a) shows the well-known double peak, with similar contributions from steep- and flat-spectrum sources. At low flux densities, only a single peak remains; the flat-spectrum sources have almost disappeared, the remnants of this population spilling out in a tail to negative spectral indices. In parallel, the proportion of QSO identifications has fallen drastically; of the 99 sources in the 5C12 5-GHz sample, a preliminary search (Benn 1981) finds 25 with galaxies as optical counterparts, and only 6 with QSOs. Thus the count for flat-spectrum sources - which are QSOs for the most part - drops off below 0.1 Jy at a rate very much faster than that for steep-spectrum sources. Indeed, spectral-index distributions for 5-GHz samples at intermediate flux-density levels confirm the trend and provide some further detail of the form of the flat-spectrum source count (Kellermann 1980).

A further point of interest is the shift to higher indices of the steep-spectrum peak in Fig. 3b. Via the P - α correlation, this suggests that the steep-spectrum sources dominating the 5-GHz count at faint intensity levels are of relatively high luminosity.

We thus have the following picture for the 5-GHz source count. Of the two sub-counts comprising it, that of the flat-spectrum sources has its plateau centered on $\sim$1 Jy and drops rapidly from Euclidean values below 0.1 Jy, while that of the steep-spectrum sources has its plateau centered on $\sim$0.2 Jy and its decrease with respect to Euclidean is mapped essentially by that of the total count, Fig. 1. The increasing width of plateau of the total counts, so apparent (Fig. 1) as survey frequency is raised, is thus due to the increasing prominence of the flat-spectrum count, whose plateau centre is displaced to higher flux densities than that for the count of steep-spectrum sources.

3. MULTI-FREQUENCY / DUAL-POPULATION MODELS OF EVOLUTION

How best to synthesize these new data into descriptions of the spatial distribution of radio sources? The analyses mentioned in §1 are all flawed in some sense. The WPL (1980) technique, for instance, requires guessed analytical functions to describe the evolution of steep-spectrum sources. Robertson's (1980) generalization of the method is 'free-form' only in a restricted sense, in that it assumes a particular type of transition between evolving (high-luminosity) and non-evolving components of the steep-spectrum population. None of the analyses explores the question of differential evolution for the flat-spectrum sources.

A new procedure (Peacock & Gull (PG) 1981) considers both steep- and flat-spectrum populations simultaneously, and represents the closest possible approach to truly free-form analysis. PG write the luminosity functions for both populations as power series expansions over the (radio-power - redshift) or (P - z) plane. The coefficients of expansion are then determined by optimization using an algorithm in which the χ^2 statistic tests goodness-of-fit between model prediction and data. As input data, PG used (i) published observations of bright galaxies to establish the local radio-luminosity function at low luminosities, (ii) source counts at 408, 1400, 2700, and 5000 MHz, with sub-counts constructed at the latter two frequencies from radio spectral data to subdivide steep- and flat-spectrum populations, (iii) luminosity or redshift distributions from complete samples at several frequencies and flux-density levels, (iv) V/V_{max} results from complete samples, again at several different frequencies and flux-density levels, and (v) a $P - \alpha$ correlation to relate the steep-spectrum populations at low and high frequencies.

The initial achievements are impressive. The first of these is to delineate quantitatively the areas of the (P - z) planes in which our knowledge of space density is deficient. These uncertainty maps for steep- and flat-spectrum populations can be used to reflect the impact of each succesive new data set, and are therefore invaluable in defining the next generation of observational programmes.

The second achievement is to demonstrate conclusively that strong cosmic evolution is a feature of the flat-spectrum source population as well as the steep. As noted in §2.2, the result is in apparent disagreement with earlier indications from source counts at cm-wavelengths and V/V_{max} data on flat-spectrum QSOs. But a strength of the PG scheme is that it examines compatibility of all data sets via the χ^2 statistic; and in this instance PG show that all observations are reconcilable on a picture of differential evolution for the flat-spectrum sources - evolution identical in style to that of the steep-spectrum sources in which only the most powerful have had dramatic enhancement of their space densities at the earlier epochs.

Fig. 4 indicates the qualitative similarity in evolution of the luminosity functions for one of PG's models. This similarity suggests that factors peculiar to one population or the other, e.g. confinement

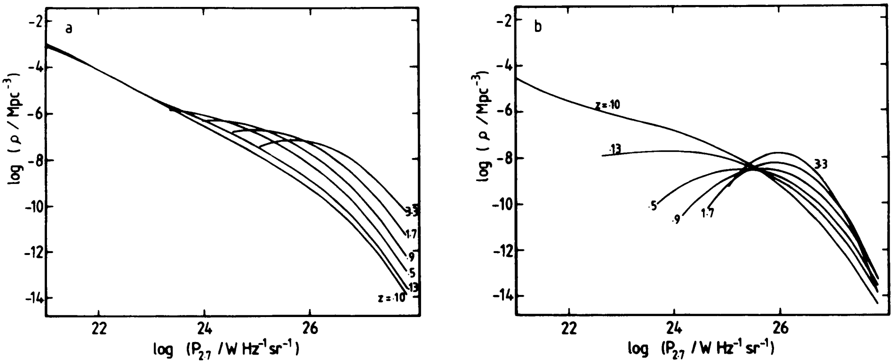

Fig. 4 Luminosity functions and their epoch dependence as given by one of the free-form evolution models of Peacock & Gull (1981), (a) for steep-spectrum sources, and (b) for flat-spectrum sources.

of extended (steep-spectrum) sources by the IGM, or preferential 'Compton snuffing' of the weaker such sources by the MWBG, cannot play a major role in determining the spatial distribution. Something common to both steep- and flat-spectrum objects such as fuel supply must dominate. On the other hand, Fig. 4 suggests that there are quantitative differences between the evolutions. The question is complex, requiring consideration of the uncertainty maps for both populations together with K-corrections and the frequency at which the evolution enhancements are specified.

Should such considerations and/or further analyses show that the evolutions are very similar, it might suggest that the steep- and flat-spectrum sources comprise a single population. Moreover, optically-selected QSOs are now known to exhibit differential evolution (M. Schmidt, this volume) although again quantitative differences may exist in that the rate of evolution appears to exceed that of the powerful radio sources. Possibly gravitational lensing (Turner 1980) has boosted the apparent evolution over that of the luminous radio sources, on which it has little effect (J.A. Peacock, this volume). Similar spatial distributions for all these populations would point to a common origin, and would lend support to scenarios in which they are related perhaps by orientation and a range in jet speed from non-relativistic to extreme-relativistic (Scheuer & Readhead 1979; I.W.A. Browne, this volume).

Speculation aside, we conclude that the sequence (evolution-model synthesis) → (improved data) → (improved synthesis) yields systematic advances in our understanding of the gross properties of radio-source populations.

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