RADIO SOURCE-COUNTS AND COSMOLOGY

M. ROWAN-ROBINSON
Queen Mary College, London, Great Britain

Abstract. A review is given of the cosmological implications of radio source-counts.

The source-counts at 178 and 408 MHz can only be understood in the relativistic cosmologies if some subset of radio-sources had different properties in the past. I want to try to answer four basic questions:

(i) Which classes of radio-sources evolve, and, in particular, are the steep source-counts due primarily to the quasars?

(ii) Can any distinction be made between different types of evolution, in particular between the extreme cases of luminosity and density evolution?

(iii) Does the particular mathematical form of evolution chosen influence the interpretation of the counts, and, in particular, do the counts really imply any diminution of number-density of sources at large redshift?

(iv) Is there any hope of learning anything about cosmology from radio source-counts?

Taking question (i) first: we have direct evidence from the luminosity-volume test (Rowan-Robinson, 1968a; Schmidt, 1968) that the quasars must evolve, except perhaps in a small subset of Lemaître models (Rowan-Robinson, 1968b; Petrosian, 1969). This is true even if the redshifts of quasars are nothing to do with distance (Rowan-Robinson, 1969). What about the radio galaxies? An indirect argument that they too must evolve is that over a wide range of flux-density quasars constitute about 20% of identified sources, probably with rather few of them remaining unidentified (Wills and Bolton, 1969; Braccesi *et al.*, 1970). Hence counts of radio galaxies alone are similar to counts of all sources, and thus show evolution.

Some time ago I presented a rather crude direct argument that the stronger radio galaxies show evolution (Rowan-Robinson, 1967). This can now be refined a bit. About 140 of the 3C sources have been identified with galaxies: redshifts are known for sixty. The estimated visual magnitudes of these satisfy a relation of the form

$$V = 20.5 + 5 \log_{10} z + 5z$$

with an rms dispersion of 0.7 mag. Hence redshifts may be estimated for the remaining galaxies with a large, but known, uncertainty. Concentrating attention on 95 unambiguous identifications from the select sample of 220 of the 3C sources studied with the Cambridge one-mile telescope (Macdonald *et al.*, 1968; Mackay, 1969; Elsmore and Mackay, 1969), the distribution of radio luminosity, P, (W ster^{-1} Hz^{-1}), against the quantity

$$x = \mathscr{V}(z)/\mathscr{V}(z_{\max})$$

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where $\mathscr{V}(z)$ is the co-moving volume out to redshift z, and z_{max} is the redshift to which the source would have to be moved to fall below either the 3C limiting flux level, or the Sky Survey limiting magnitude, taken as $V=20$ for galaxies, is shown in Figure 1. Most of these sources are doubles or elongated singles that could be

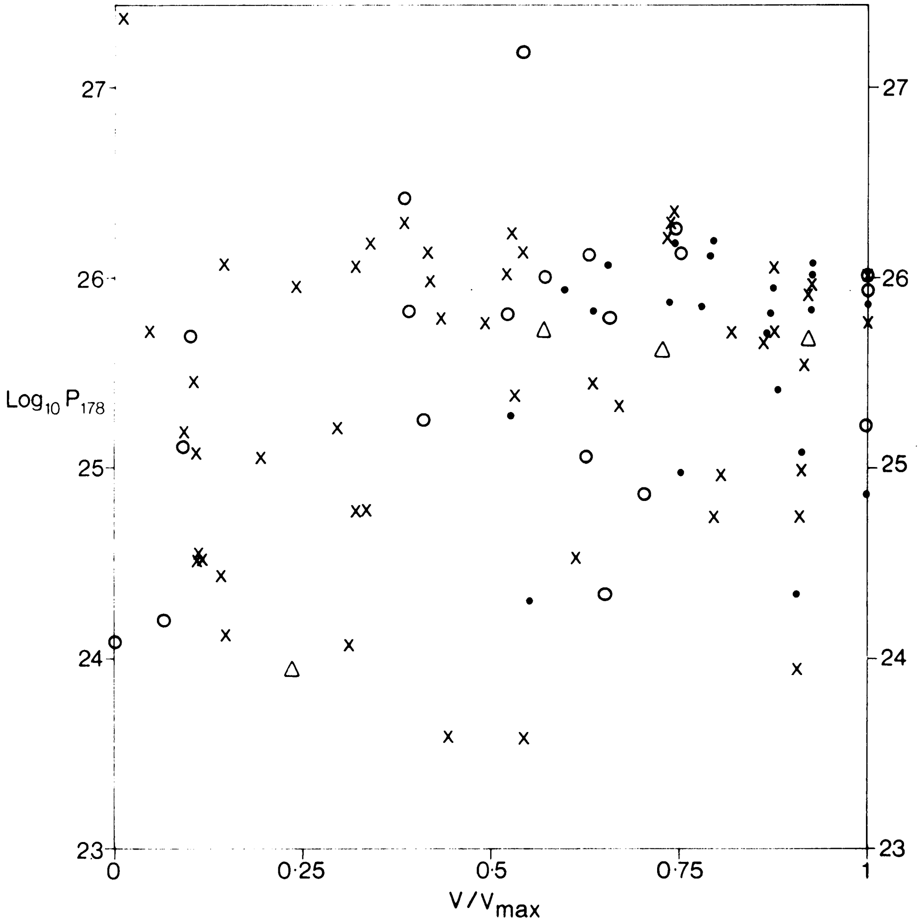

Fig. 1. Radio luminosity against $\mathscr{V}/\mathscr{V}_{max}$ for radio galaxies from the Cambridge select sample. Triangles denote single sources (A), crosses denote doubles (B), circles denote elongated singles (AB), and dots denote unresolved sources.

incompletely resolved doubles, or are completely unresolved. The associated galaxies are basically ellipticals or N-types.

The mean values of x both for all radio galaxies, and for the stronger sources ($P>10^{25.5}$ W ster^{-1} Hz^{-1}), are shown in Table I for various values of limiting optical magnitude, together with the corresponding probabilities that the distribution of x is uniform, estimated by means of Student's t-test. The distribution is significantly non-uniform, even if attention is confined to galaxies brighter than 19 or even

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TABLE I

Limiting visual magnitude	20	19.5	19	18.5	18
Number of radio-galaxies	95	81	72	60	50
$\bar{x}$	0.622	0.589	0.584	0.564	0.542
$t=\sqrt{12}\,n(\bar{x}-0.5)$	4.1	2.8	2.45	1.7	1.0
Probability	$\leqslant 0.1\%$	0.6%	2%	10%	25%
For sources stronger than $10^{25.5}$ W ster^{-1} Hz^{-1}					
$\bar{x}$	0.700	0.661	0.698	0.693	0.670
t	5.1	3.5	3.7	3.3	2.2
Probability	$\leqslant 0.1\%$	$<0.1\%$	0.1%	0.3%	5%

18.5 mag. Note the nearly vertical line of sources on the right of Figure 1. These all have the same radio flux, just above the 3C limit, in fact, but visual magnitudes ranging from 14 to 20. Although the slope of lines of this form increases slightly as we increase the radio-flux, $(\partial x/\partial \mathscr{V})_S$ ranges from zero to only about 0.02. Even if all the magnitude estimates need to be changed by two magnitudes, $\bar{x}$ remains significantly different from 0.5. The possibility of chance identifications is much reduced for these sources for which detailed radio-maps are available.

The evolution clearly affects sources brighter than about $10^{25.5}$ W ster^{-1} Hz^{-1} and is stronger for unresolved than for resolved sources. This is partly because the un-

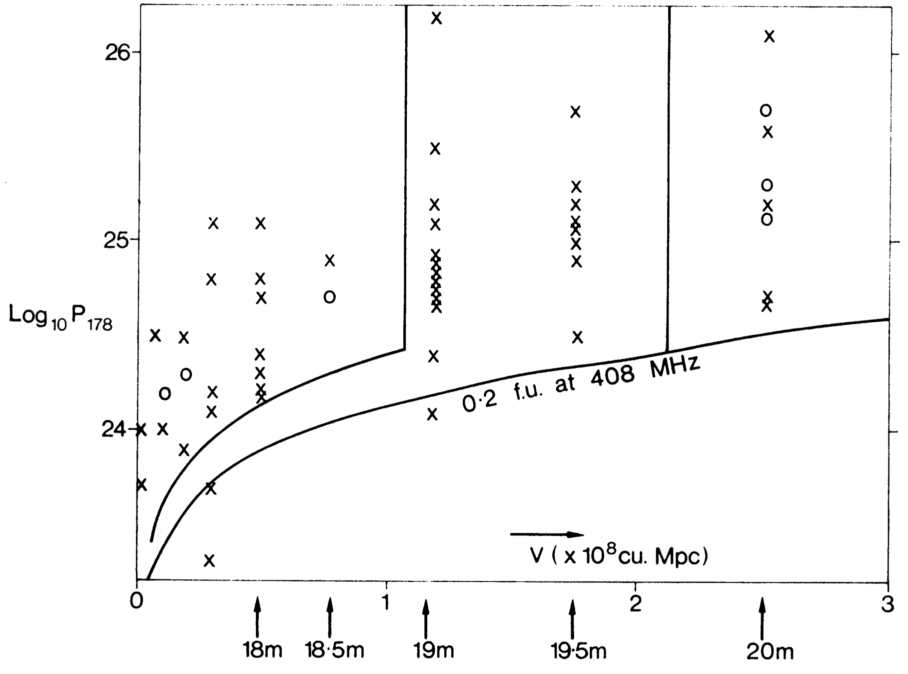

Fig. 2. Radio luminosity against volume for radio galaxies in the Windram and Kenderdine survey, for which identifications are believed to be complete to 19.5 mag. Circles denote doubtful identifications.

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resolved sources tend to be at greater redshifts, but there does seem to be a real effect, since the resolved doubles with intrinsic separations less than 100 kpc show stronger evolution than those with separations $\geqslant 100$ kpc. This casts doubts on the idea that the evolution is due to interaction of the radio components with a medium whose properties change with epoch, since in this case we might expect the evolution to appear mainly in the more extended sources. The evolution seems to be due to changes with epoch of the probability or strength of an outburst. Interaction with a universal gas or with the black-body radiation may then have the effect of reducing the apparent evolution for the more extended sources.

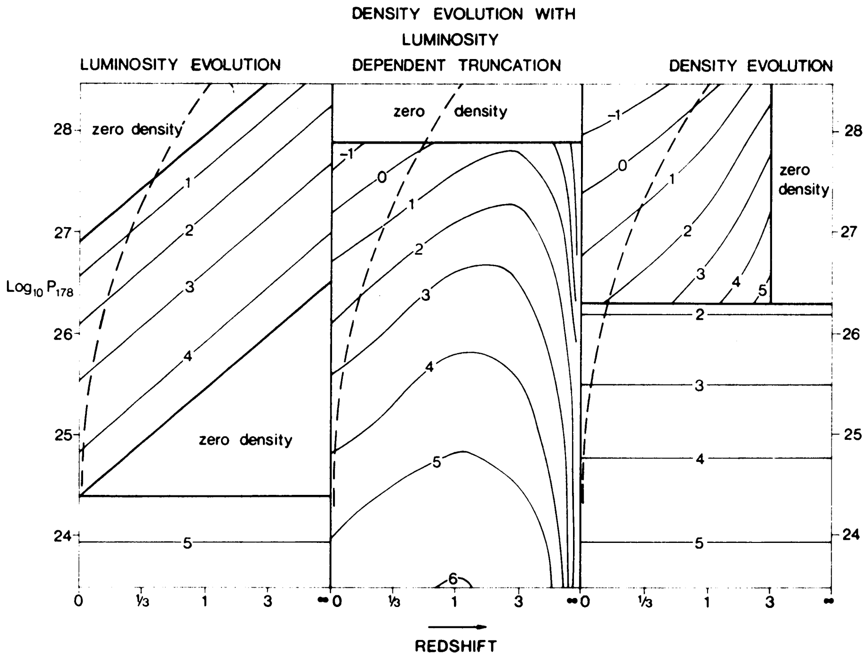

Fig. 3. Loci of constant coordinate number-density per unit radio luminosity for three different types of evolution (see text). The broken line corresponds to the 3C limit. The curves are labelled with the value of $\log_{10}\eta(P)$.

The 3C sources weaker than $10^{25.5}$ W ster^{-1} Hz^{-1} have to be so near to us that it is unlikely that we would see evolution in them. But if we turn to a set of identifications made by Windram and Kenderdine (1969) of sources brighter than 0.2 f.u. at 408 MHz, then the distribution of radio luminosity against volume (Figure 2) for the galaxies brighter than 19.5 m looks as if evolution extends down to luminosities of $10^{24.5}$ W ster^{-1} Hz^{-1} at least.

The different types of evolution consistent with the source-counts down to the 5C level can be illustrated by looking at the loci of constant number-density per unit luminosity, $\eta(P, z)$, as a function of luminosity and redshift. Figure 3(a) shows exponential luminosity evolution (Rowan-Robinson, 1970a) which is relevant if it is the strength of outbursts which was greater in the past. Figure 3(c) shows power-law density evolution (Doroshkevich *et al.*, 1970). Lastly Figure 3(b) shows an intermediate type where there is density evolution ($\eta \propto \exp(-10t/\tau_0)$), but with a luminosity dependent truncation due to interaction of the relativistic electrons in the radio components with the black-body radiation, where the luminosity is related to the magnetic field in sources, e.g. $P \propto B^n$ (Rowan-Robinson, 1970b). This last case arises in expanding plasmon models of radio galaxies, with $n = 1 + 2\alpha$.

I maintain that the density evolution model is ruled out by the luminosity-volume test for radio galaxies, which showed that evolution operates down to a luminosity of $10^{25.5}$ W ster^{-1} Hz^{-1}, and probably to $10^{24.5}$, whereas Doroshkevich *et al.* (1970) have evolution for sources brighter than $10^{26.3}$ only (i.e. primarily due to quasars).

The intermediate type of evolution fits the counts satisfactorily with *all* radio galaxies evolving. The weakest sources, with magnetic fields of a microgauss or less, could be the source of the isotropic X-ray background. With exponential luminosity evolution there is an appreciable dependence on the cosmological model, firstly in

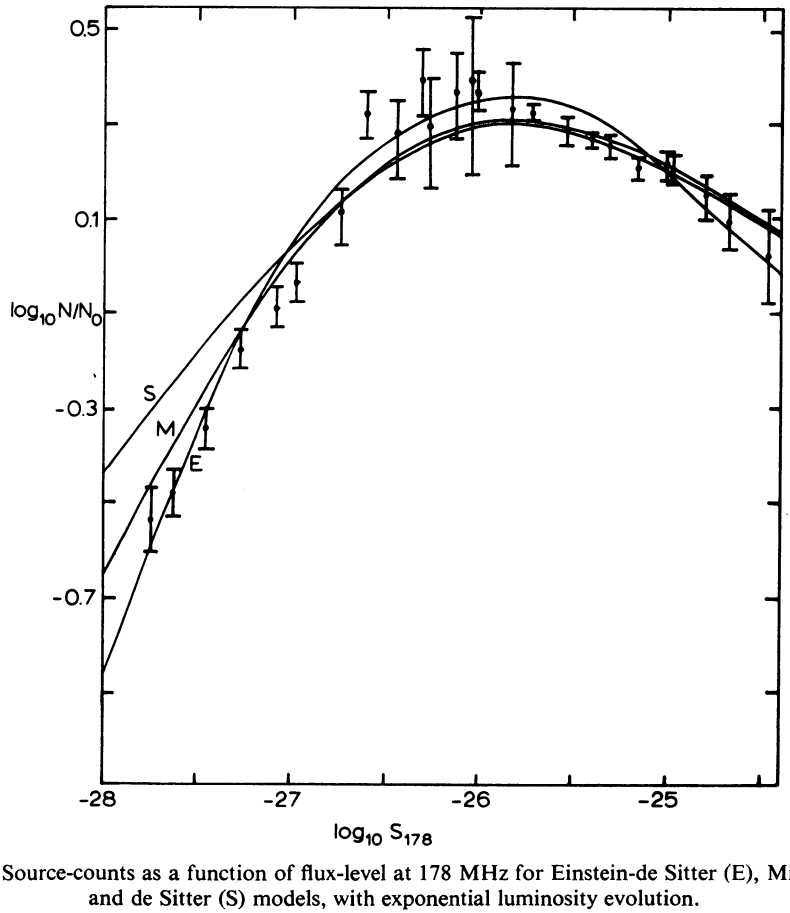

Fig. 4. Source-counts as a function of flux-level at 178 MHz for Einstein-de Sitter (E), Milne (M), and de Sitter (S) models, with exponential luminosity evolution.

the luminosity above which evolution must be assumed to operate. For this to correspond to the transition from radio galaxies to normal galaxies, i.e. $P \sim \sim 10^{24 \pm 0.5}$ W ster^{-1} Hz^{-1}, $q_0 \geqslant 0.5$ is necessary. Secondly, in the asymptotic number-count slope, illustrated in Figure 4, which shows $\log_{10}(NS^{1.5}) - \log_{10} S_{178}$ for the Einstein-de Sitter, Milne and de Sitter models. Only models with $\sigma_0 = 0$ give a non-zero asymptotic slope. For these three models the total number-density of radio galaxies is the same at all epochs, so it is clear that the counts do not imply any diminution of the number-density at large redshift.

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