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# THE SPATIAL DISTRIBUTION AND COSMOLOGICAL EVOLUTION OF SCINTILLATING RADIO SOURCES

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## SUMMARY

An analysis of the scintillation properties of complete samples of extragalactic radio sources indicates:

(i) There exists a correlation between compact physical structure and high radio luminosity and redshift once allowance is made for several observational selection effects.

(ii) Strongly scintillating radio sources exhibit strong cosmological evolution of the form inferred for quasars and powerful radio sources in general. The strong evolutionary effects are found in samples of both 3CR and 4C radio sources.

(iii) Strongly scintillating radio galaxies exhibit strong cosmological evolution as previously inferred by Schmidt.

## 1. INTRODUCTION

The spatial distribution and cosmological evolution of the scintillating radio sources observed by Readhead & Hewish (1974) in a survey of the angular structures of about 1500 radio sources at 81·5 MHz is the subject of this paper. The statistics and physical properties of scintillating radio sources are discussed in a separate paper by Readhead & Hewish (1975). In the present paper, it is shown that scintillating radio sources evolve rapidly with cosmological epoch, in particular that those *radio galaxies* which scintillate strongly partake in strong cosmological evolution of the form already established for quasars. In a future paper (Hewish, Readhead & Duffett-Smith 1975) the redshift-angular diameter test for the strongly scintillating radio sources considered here will be explored.

The property of exhibiting interplanetary scintillation introduces severe selection effects into the statistics of the observed sample of sources. These are considered in detail in Section 2. In the succeeding sections, the luminosity-volume test or $V/V_{\max}$ test and source counts of scintillating sources are employed to extract information relevant to their spatial distribution.

## 2. OBSERVATIONS AND SELECTION EFFECTS

### 2.1 *The observations*

The methods of observation and the reduction of the results have been described in two previous papers (Hewish & Burnell 1970; Readhead 1971) and the results of the survey are included in a catalogue of about 1500 scintillating and non-scintillating sources (Readhead & Hewish 1974). For all the sources in the catalogue estimates of the parameter $R$ could be made, $R$ being the fraction of the flux density of the radio source contained in a compact scintillating component. For the brighter sources in the sample, estimates of $R$ *and* the angular size of the scintillating component could be made because of the wide range in solar elongation for which good observations were available. Thus, the data on sources in the revised 3C catalogue are of uniformly high quality and have justified a more detailed analysis of their spatial distribution. It is convenient to divide the sample of sources into sources exhibiting strong, intermediate and weak scintillation according to the fraction of the flux density in the scintillating component, $R \geqslant 0{\cdot}4$, $0{\cdot}25 < R < 0{\cdot}40$ and $R \leqslant 0{\cdot}25$, respectively.

### 2.2 *The 3CR sample*

We will first restrict attention to the sources belonging to the ' complete 200 ' sample of 3CR sources which consists of all those sources in the region of sky $\delta > 10°$ and $|b| > 10°$ having $S_{178} \geqslant 9 \times 10^{-26}$ W m$^{-2}$ Hz$^{-1}$.

A small number of sources were omitted from consideration for the following reasons:

(a) Four sources consisted of random associations of 4C radio sources and therefore should not be counted in the 3CR sample.

(b) 3C 326 is probably associated with the North Galactic Spur and was therefore excluded.

(c) Thirteen sources having $|b| < 20°$ in the direction of the galactic centre were excluded because it was not clear that their scintillation properties were unaffected by *interstellar* scattering.

### 2.3 *Selection effects in the 3CR sample*

(i) The sample is complete in the sense that all sources have flux densities at 178 MHz greater than, or equal to $9 \times 10^{-26}$ W m$^{-2}$ Hz$^{-1}$ in a particular region of sky. Since the sources span a wide range of redshift and most of them fall into the flux density interval $9 \rightarrow 20 \times 10^{-26}$ W m$^{-2}$ Hz$^{-1}$, an artificial correlation is induced between high radio luminosity and redshift by the selection criteria. One must look to large redshifts before a sufficiently large volume of space is encompassed to include even one of the most powerful radio sources in the sample.

(ii) Sources of a given physical size will only be observed to scintillate when they are beyond the distance at which their observed angular diameter becomes less than or equal to about 1″ arc. This fact, in conjunction with that described in (i) induces an artificial correlation between the more powerful distant sources in the present sample and the presence of a scintillating component.

It is well known that there exists a correlation between high redshift, high luminosity and the presence of scintillating radio components (Harris 1973; Readhead & Hewish 1975). It is important to investigate the importance of the above selection effects in producing a spurious correlation of this type. We would like to answer two questions.

(a) Is there a genuine correlation between compact *physical* structure and high radio luminosity once account is taken of the selection effects?

(b) If such a genuine correlation exists, does it represent a correlation of the presence of small scale structure with luminosity or with redshift?

We can give a fairly complete answer to (a) (Section 2.4) but it is impossible as yet to make any statement about (b) because of the small statistical sample for sources of a given radio luminosity.

### 2.4 *The radio luminosity–redshift diagram*

The complete radio luminosity–redshift diagram for identified sources in the 3CR sample is shown in Fig. 1, the symbols indicating the three classes of scintillating source, strong, intermediate and weak. For a number of radio galaxies in the sample no redshifts have been measured and so they have been estimated

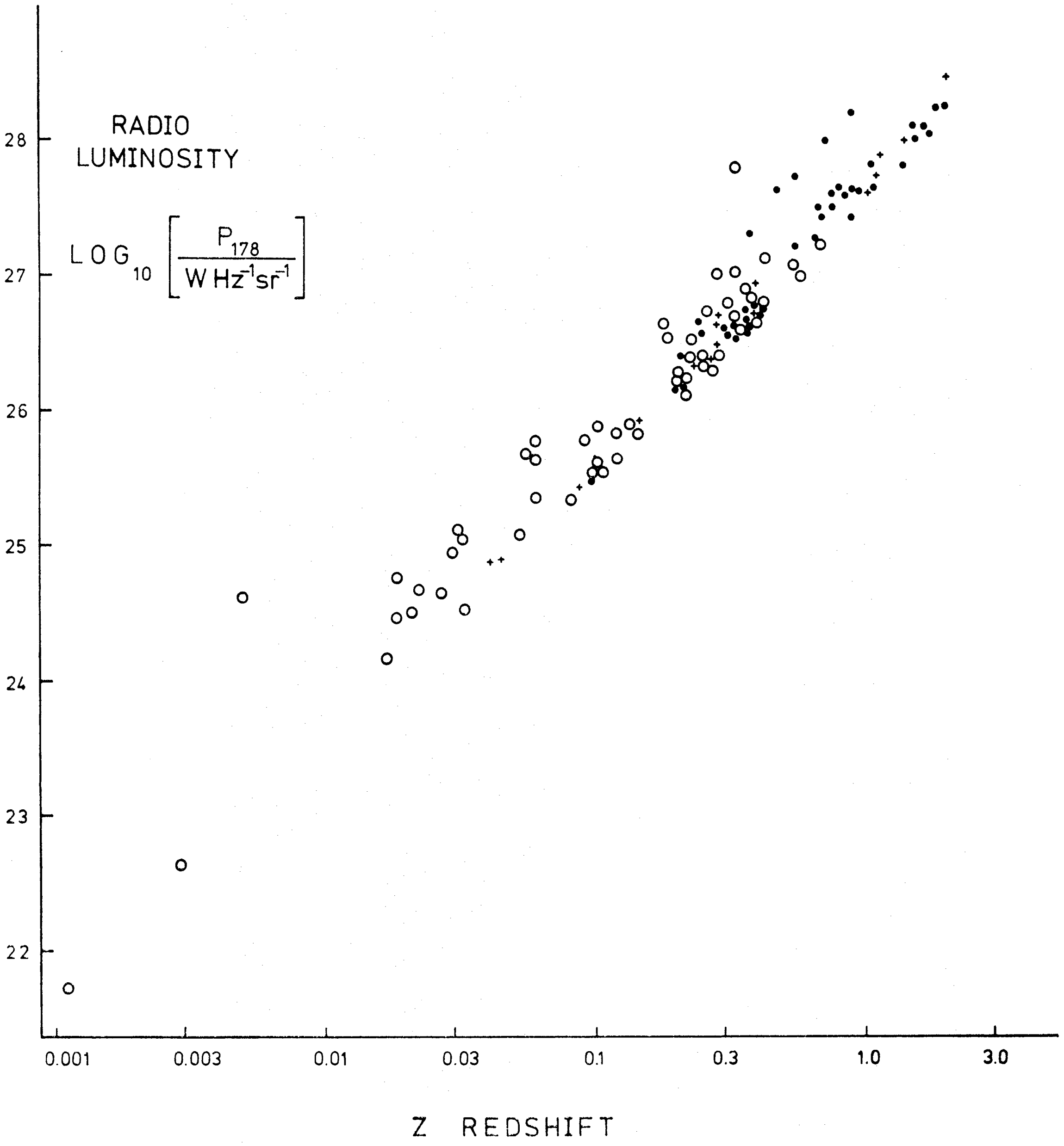


FIG. 1. *The luminosity–redshift diagram for all identified sources in the complete 200 3CR sample. Different classes of scintillating sources are indicated as follows;* ●, *strongly scintillating sources;* +, *intermediate scintillating sources;* ○, *weakly scintillating sources.*

assuming that the absolute optical magnitude of radio galaxies corresponds to $V = -23$. A value of 50 km $\mathrm{s^{-1}}$ $\mathrm{Mpc^{-1}}$ has been adopted for the Hubble constant.

To eliminate the effects of selection effect (i) on the observed distribution we have adopted the following procedure.

In real cosmological models the observed angular diameter of a rigid rod (i.e. its metric angular diameter) does not vary rapidly with redshift $z$ for $z \gtrsim 0{\cdot}3$. It is well known that this is due to the combined effects of space curvature and to the fact that a rigid rod occupies a larger fraction of the celestial sphere at large redshifts.

$$\theta = \frac{D(1+z)}{\left(\frac{\sin Ar}{A}\right)} \quad \text{where } z \text{ is redshift,}$$

and

$$\left(\frac{\sin Ar}{A}\right) = \frac{2c}{H_0\Omega^2(1+z)}\{\Omega z + (\Omega-2)\{(\Omega z+1)^{1/2}-1\}\}$$

$\Omega$ = density parameter = $8\pi G\rho_0/3H_0{}^2$. This formula assumes that the cosmological constant $\Lambda$ is zero.

This results in the well-known minimum in the relation between angular diameter and redshift for all models having $\Omega$, the density parameter greater than 0. Even in the $\Omega = 0$ model, the relation flattens off at $z \geqslant 1$. Since the quasars in the sample have redshifts in the range $0{\cdot}1 < z < 2$, and most of them have $z \sim 1$, there is little bias against observing scintillation in quasars towards the small end of this redshift range and in any case, all the quasars belong to the highest classes of radio luminosity. Quasars are therefore of little value in estimating the importance of selection effect (i).

However, the effect is important for the radio galaxies in the sample, all of which have redshifts $z < 0{\cdot}5$. They span a redshift range from 0·001 to 0·5 over which the angular diameter of a rigid rod varies by a factor of 500 according to the Euclidean formula. We have therefore considered the cases of *radio galaxies* which exhibit strong and weak scintillation (i.e. we have specifically excluded sources showing intermediate scintillation). The results are shown in Fig. 2. We have asked how close to the Earth we would have to bring each of the strongly scintillating sources before it would have $R < 0{\cdot}4$. In performing this calculation it is assumed that the observed flux density of the source remains unchanged because we wish to ask whether radio galaxies observed at smaller redshifts could have compact components of the same intensity relative to the total flux density of the radio galaxy as the powerful sources. The lines attached to each strongly scintillating source in Fig. 2 show the range over which the source would be classified as strongly scintillating.

Fine scale structure of the *physical* size observed in powerful sources can be detected to redshifts as small as $\approx 0{\cdot}08$, i.e. there is no observational bias against detecting strong scintillation in intrinsically weaker radio galaxies having $z \geqslant 0{\cdot}08$. It is evident from the diagram that at redshifts greater than 0·08 there is a strong correlation between high luminosity, and the presence of scintillation. Only one of the 12 radio galaxies in the redshift range 0·08 to 0·20 scintillates strongly whereas in the range 0·20 to 0·45, 10 out of 27 exhibit strong scintillation.

This result shows that there is a genuine physical correlation between high

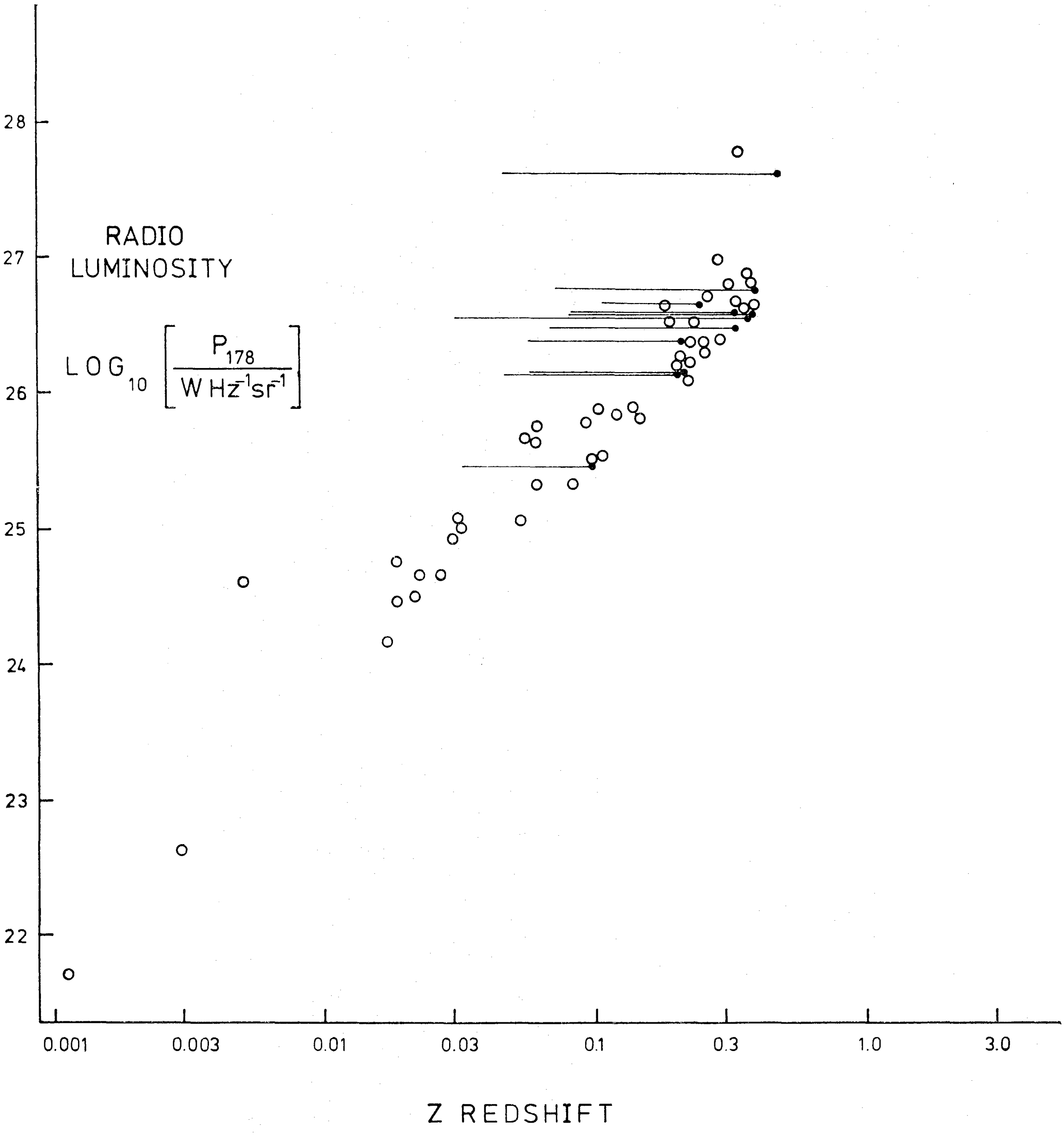


FIG. 2. *The luminosity redshift diagram for the strongly and weakly scintillating radio galaxies in the complete 200 3CR sample. Filled and open circles indicate strongly and weakly scintillating sources, respectively. The line attached to each filled circle indicates the range of redshifts over which the radio source would be classed as a strongly scintillating source, if it were brought closer to the observer assuming the observed flux density remains the same.*

radio luminosity, large redshift radio galaxies and the presence of compact physical structure.

## 3. THE $V/V_{\max}$ TEST FOR SCINTILLATING RADIO SOURCES

### 3.1 *The overall $V/V_{max}$ test*

The $V/V_{\max}$ test has been used to test the uniformity of the spatial distribution of sources which exhibit strong and weak scintillation in the complete 3CR sample. The test has been performed in the normal manner (see e.g. Schmidt 1968;

Longair & Scheuer 1970) but in the present analysis it has been applied to *all identified* sources in the sample.

It is necessary to know the optical and radio spectra of the quasars and galaxies in the sample. For the quasars, we have used the ' synthesized composite compromise ' spectrum of Sandage (1966) which has been shown to be an adequate approximation for this test. For radio galaxies, we have employed the absolute optical energy distribution for elliptical galaxies of Oke & Sandage (1970). Radio spectral indices are taken from Kellermann, Pauliny-Toth & Williams (1969). Because of uncertainties in the knowledge of the optical magnitude to which the sample is complete, we have evaluated $\langle V/V_{\max}\rangle$ for a number of limiting apparent magnitudes.

TABLE I

| | Strong scintillators | | Weak scintillators | |
|---|---|---|---|---|
| $m_V$ | No. of sources | $\langle V/V_{\max}\rangle$ | No. of sources | $\langle V/V_{\max}\rangle$ |
| 18·0 | 11 | 0·71 | 33 | 0·45 |
| 18·5 | 18 | 0·71 | 44 | 0·53 |
| 19·0 | 22 | 0·71 | 45 | 0·51 |
| 19·5 | 24 | 0·68 | 46 | 0·50 |
| 20·0 | 26 | 0·68 | 49 | 0·52 |
| 20·5 | 30 | 0·70 | 52 | 0·53 |

The calculations were repeated for a range of world models but, as is usually found in these calculations, there is little variation in the results as a function of $\Omega$. The results for the Einstein–de Sitter world model ($\Omega = 1$) are shown in Table I, for successively fainter limiting optical apparent magnitudes.

For a uniform distribution of objects the expected value of $\langle V/V_{\max}\rangle$ is 0·5 and for a sample of $N$ randomly chosen sources from this uniform distribution the probability distribution of the value of $\langle V/V_{\max}\rangle$ has standard deviation $1/(12\,N)^{1/2}$. From Table I it can be seen that strongly scintillating sources are significantly non-uniformly distributed in space whereas the weakly scintillating sources have values of $\langle V/V_{\max}\rangle$ consistent with their distribution being uniform.

It is appropriate at this point to note the way in which we have misused the strict $V/V_{\max}$ test in the above analysis. To employ the test in its strict form, we should be certain that all sources in the sample have been identified to a given limiting optical magnitude but we are not at all certain about this for the present sample in the magnitude range 18–20. However, this uncertainty is unlikely to have much effect upon the present results for the following reasons.

(i) Most of the unidentified sources, some of which could in fact have apparent magnitudes in the above range, have flux densities close to the limiting flux density of the 3CR sample since virtually all sources having $S_{178} \geqslant 20 \times 10^{-26}$ W m$^{-2}$ Hz$^{-1}$ have been identified; therefore if they have been missed they will on average have values of $V/V_{\max}$ greater than 0·5 on the basis of the radio data alone. Inclusion of optical information can only *increase* the value of $V/V_{\max}$ if the source is optically limited.

(ii) Most of the sources are radio limited and therefore the $V/V_{\max}$ test reflects closely the counts of the different classes of radio source. We could have thrown away all the optical information concerning apparent magnitudes and we would then have a lower limit to the value of $\langle V/V_{\max}\rangle$ which would not be significantly different from the values listed in Table I.

In essence, we have employed the $V/V_{\max}$ test as a means of making counts of radio sources but including the redshift information which increases the divergence of the observed distribution from uniformity.

The value of $\langle V/V_{\max}\rangle$ for scintillating radio sources agrees closely with the values found for quasars alone (Schmidt 1968; Schmidt 1974; Wills 1974). This is certainly partly due to the fact that 20 of the 30 strongly scintillating sources are quasars. However, the sample of scintillating sources involves only a sub-sample of all 3CR quasars and includes scintillating radio galaxies. There is therefore no immediate reason to expect the values of the two $\langle V/V_{\max}\rangle$ tests to give exactly the same result.

It is to be expected that the cosmological evolution necessary to explain the present results should be similar to that found by earlier workers. We have included various forms of evolution into the $V/V_{\max}$ test as listed in Table II using a limiting optical magnitude $m_V = 19{\cdot}0$.

TABLE II

| Evolution | $z$ | $\langle V/V_{\max}\rangle$ for strongly scintillating sources | $\langle V/V_{\max}\rangle$ for weakly scintillating sources |
|---|---|---|---|
| $(1+z)^4$ | 2·4 | 0·59 | 0·47 |
| $(1+z)^6$ | 2·4 | 0·55 | 0·46 |
| $(1+z)^8$ | 2·4 | 0·51 | 0·44 |
| exp | — | 0·56 | 0·44 |

The evolution of the comoving space density of sources is taken to be of the form

(a)
$$\rho(z) = \rho(z=0)(1+z)^{\beta}, \quad z<2{\cdot}4$$
$$= 0, \quad z>2{\cdot}4$$

cases with $\beta = 4$, 6 and 8 are considered;

(b) exponential evolution of the form

$$\rho(z) = \rho(z=0)\exp\left[m\left(\frac{t_0-t}{t_0}\right)\right]$$

$m = 8$; $t = (2/3H_0)(1+z)^{-1{\cdot}5}$ for Einstein–de Sitter model, $\Omega = 1$, $t_0$ = present epoch.

Strong evolution is necessary to reduce $\langle V/V_{\max}\rangle$ to 0·5 for strongly scintillating sources, but for weakly scintillating sources the evolution must be weak or absent. These results are consistent with previous analyses which have suggested that strong cosmological evolution is primarily associated with powerful radio sources (Longair & Pooley 1969; Doroshkevich, Longair & Zeldovich 1970; Fanaroff & Longair 1973).

### 3.2 *The $V/V_{max}$ test for quasars and radio galaxies separately*

In Fig. 3(a) and (b) the distributions of $V/V_{\max}$ for all the quasars and radio galaxies in the complete sample are shown, strongly scintillating sources being indicated by hatched boxes.

In Fig. 3(a) it is apparent that there is very little difference in the distributions for strongly and weakly scintillating quasars so that although the latter were classed as part of a uniform distribution of weakly scintillating sources, this arose because their small numbers were diluted by the much larger numbers of weakly scintillating radio galaxies.

A particularly striking result is the similarity of the distribution of strongly scintillating *radio galaxies* to that of the quasars. All the strongly scintillating radio galaxies have values of $V/V_{\max}$ greater than 0·4 with 8 out of 10 having values of $V/V_{\max}$ greater than 0·75. We emphasize that this cannot be due to the selection effect that sources at large redshifts have smaller angular sizes. Inspection of Fig. 1 shows that there are no radio galaxies which have radio luminosities in the same range as the strongly scintillating radio galaxies and which are at sufficiently small redshifts to escape proper study by the scintillation technique (see the vacant area in the region of Fig. 1 $P_{178} \geqslant 10^{25 \cdot 5}$ W Hz$^{-1}$ sr$^{-1}$, $z < 0 \cdot 08$).

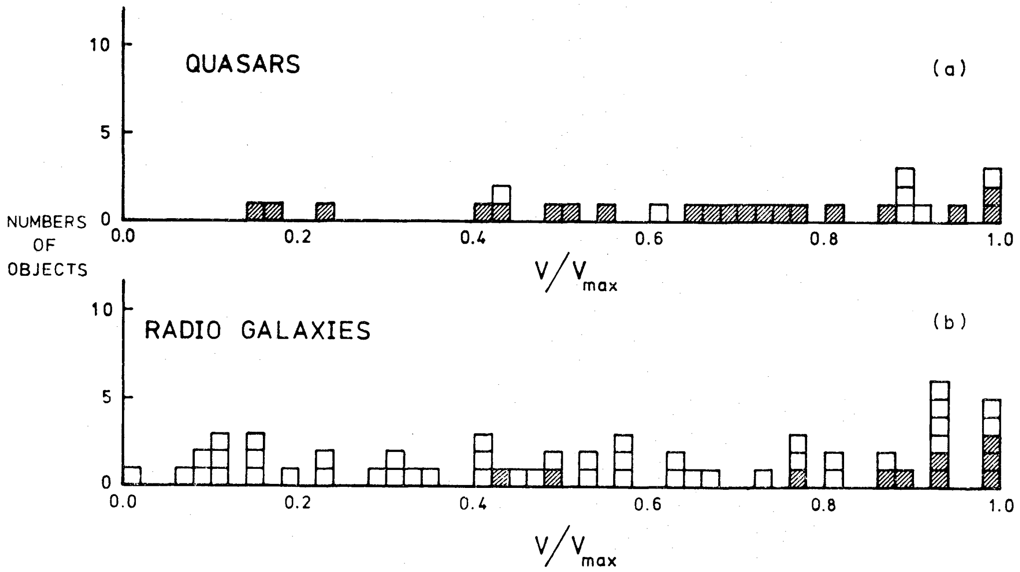


FIG. 3. *The distributions of $V/V_{max}$ for all the identified strongly and weakly scintillating sources in the complete sample for (a) quasars and (b) radio galaxies. Strongly scintillating sources are indicated by hatched boxes.*

This result provides strong evidence for the cosmological evolution of powerful radio galaxies and is direct evidence for Schmidt's inference (Schmidt 1972) that radio galaxies must evolve rapidly with epoch to account for the overall counts of radio sources. Direct evidence for the cosmological evolution of radio galaxies was previously discussed by Rowan-Robinson (1971) who applied the $V/V_{\max}$ test to all 3CR radio galaxies. The present result for strongly scintillating radio galaxies provides more conclusive evidence for their strong cosmological evolution by restricting attention to a particular high radio luminosity sample of 3CR radio galaxies.

## 4. COUNTS OF SCINTILLATING SOURCES IN THE 4C CATALOGUE

It is possible to make a reasonable estimate of the absolute numbers of scintillating sources expected in the 4C catalogue on the basis of the evolution derived for the sources in the 3CR catalogue. In view of the observational problems discussed below we have not attempted the most refined calculation (which could certainly be attempted). The procedure we have adopted is the following.

We assume that scintillating sources evolve according to either of the satisfactory models of the evolution of the radio source population, noting incidentally that these models can account for the overall counts of sources in the 4C catalogue. The complete sample of scintillating sources down to the limit of the 3CR catalogue includes unidentified sources, and these must be included in order to make proper estimates. This is done empirically by assuming these sources to have redshifts of 0·2, 0·5 and 1·0 in three successive runs of the programme. It is generally found that the overall predicted counts of scintillating sources resulting from these three assumptions differ by less than 10 per cent because the extrapolation is over a relatively small range of flux density ($9 \rightarrow 2 \times 10^{-26}$ W m$^{-2}$ Hz$^{-1}$ at most).

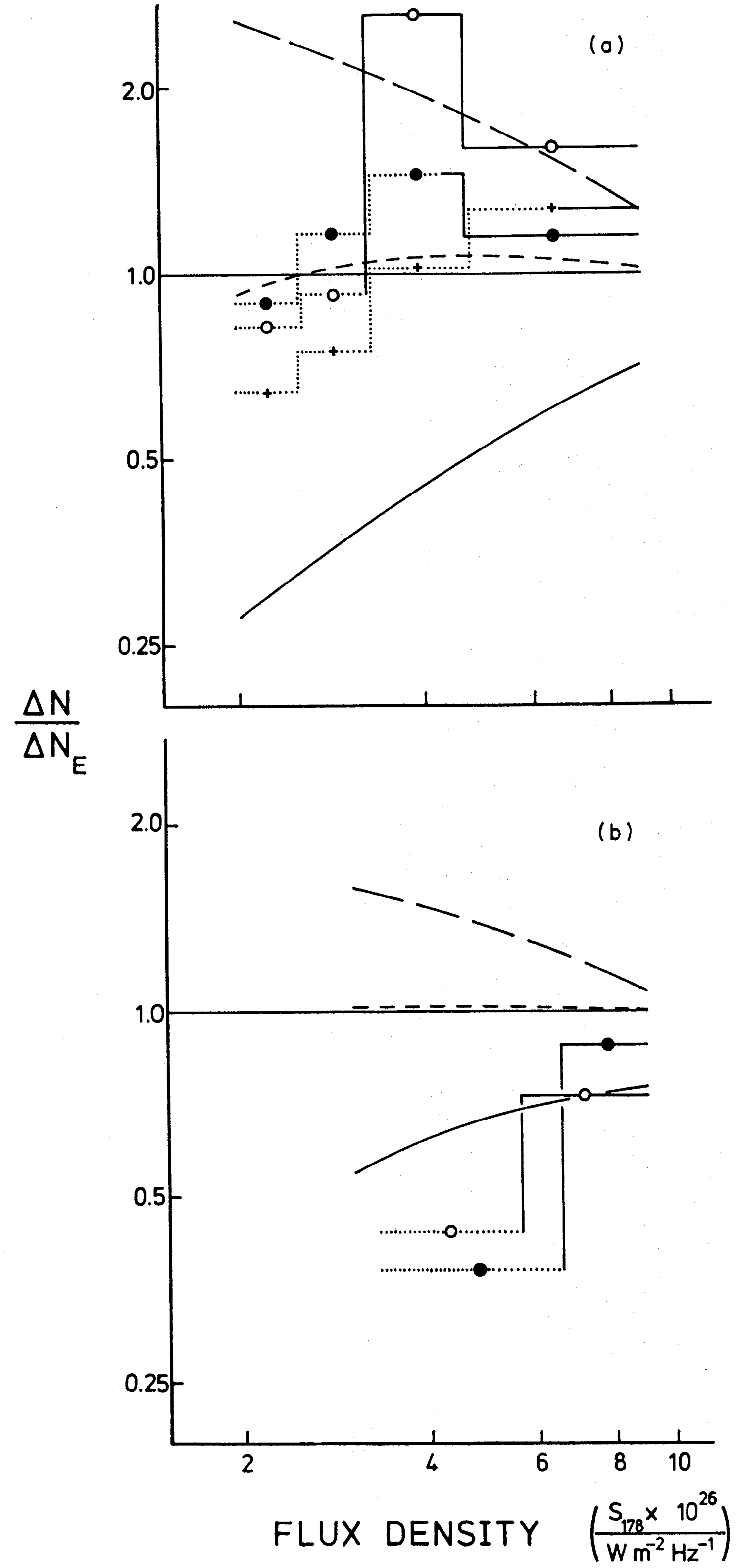
It is necessary to consider how to allow for the varying angular diameter of sources with increasing redshift. We make use of the fact that in most world models beyond redshifts of $\sim 0{\cdot}3$, out to about $z = 3$, the angular diameter of a rigid rod varies little with redshift, and hence we make little error by neglecting the variation of angular size with redshift over the flux density range considered. However, no account is taken of more nearby classes of source which are just too large to scintillate at $9 \times 10^{-26}$ W m$^{-2}$ Hz$^{-1}$, the 3CR limit, but which would have angular size $< 1''$ at $2 \times 10^{-26}$ W m$^{-2}$ Hz$^{-1}$.

The observational evidence suggests that there are few of these sources but in any case they will merely serve to increase the predicted number of scintillating sources in the 4C catalogue. Therefore our computations should give *lower* limits to the expected number of scintillating sources in the 4C catalogue but we do not expect it to be a gross underestimate, in view of the small range of flux densities over which predictions are made. The procedure used is the same as that described by Longair (1974).

There are two further effects, due to observational limitations which complicate the comparison of these predictions with the observations:

(i) No complete survey of radio sources at 81·5 MHz exists, and there may well be systematic differences between the 81·5 MHz flux densities used in the survey for the fainter sources. The safest course is to use extrapolated 178 MHz fluxes assuming $\alpha = 0{\cdot}75$. Pooley & Ryle (1968) and Fanaroff & Longair (1973) have shown that the mean spectral index changes very little with frequency below about 400 MHz. The principal error in adopting this procedure may be to overestimate the 81·5 MHz flux densities of some of the scintillating sources, as these in general have flatter low frequency spectra (Readhead & Hewish 1975), and thus to underestimate $R$. Thus we will tend to underestimate the observed number of strongly scintillating sources which we see below the 3CR limit, but this effect is probably small.

(ii) Nearly all of the sources in the 3CR strongly scintillating sample have measured angular diameters, and thus $R$ is well determined. However, for fainter sources, the lower limit to $R$ has been set by comparing the observed scintillation with that of a point source. While this method provides a strict lower limit to $R$ for individual sources, in general it will mean that we underestimate $R$, and hence again underestimate the observed numbers of strongly scintillating sources below the limit of the 3CR catalogue. A better estimate of $R$, when dealing with a large sample of sources, is obtained by assuming a mean angular diameter of $0''{\cdot}5$ for those sources for which we do not have a good diameter determination. This estimate of $R$ has been used in the following discussion.


(a)
2.0
1.0
0.5
0.25
$\frac{\Delta N}{\Delta N_E}$
(b)
2.0
1.0
0.5
0.25
2
4
6
8
10
FLUX DENSITY $\left(\frac{S_{178} \times 10^{26}}{\mathrm{W\,m^{-2}\,Hz^{-1}}}\right)$

In Fig. 4(a) the differential source counts for strongly scintillating sources are shown for three separate areas of sky. The limits of sensitivity for the three areas are also indicated. Also shown are the predicted source counts assuming no cosmological evolution of the luminosity function, and assuming evolution of the comoving space density of sources as $(1+z)^4$ and $(1+z)^6$. The results are seen to be consistent with evolution of the form $(1+z)^6$ down to the sensitivity limit in each area. In the area of highest sensitivity this extends to $3\cdot5\times10^{-26}$ W m$^{-2}$ Hz$^{-1}$ at 178 MHz.

In Fig. 4(b) the results for weakly scintillating sources are shown. Unfortunately the data are more limited than for the strongly scintillating sources ($R \geqslant 0\cdot4$) since we require the sources to have nearly twice the flux density to determine whether a source belongs to the weakly scintillating class ($R \leqslant 0\cdot25$). The observations are consistent, however, with no evolution or with weak evolution of the weakly scintillating sources down to $6\times10^{-26}$ W m$^{-2}$ Hz$^{-1}$ at 178 MHz.

## 5. CONCLUSION

We have found good evidence for the rapid cosmological evolution of strongly scintillating radio galaxies. The distribution of these sources with $V/V_{\mathrm{max}}$ is significantly different from that of weakly scintillating radio galaxies, and similar to the distribution for all quasars and powerful radio sources in general. The rapid evolution of all strongly scintillating sources persists at least to a flux density of $3\cdot5\times10^{-26}$ W m$^{-2}$ Hz$^{-1}$ at 178 MHz. No evidence of cosmological evolution of weakly scintillating sources is found to $6\times10^{-26}$ W m$^{-2}$ Hz$^{-1}$ at 178 MHz.

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FIG. 4. (*a*) *The differential counts of* strongly *scintillating* 4C *sources*, $\Delta N$, *normalized to the Euclidean value*, $\Delta N_E$, *for three separate regions of sky which have different sensitivity limits. The statistical error on each point is shown in the last column of the Table.*

| Area symbol | Region of sky $\alpha$ | $\delta$ | Limiting sensitivity to which survey complete ($10^{-26}$ W m$^{-2}$ Hz$^{-1}$) | Statistical error on numbers of sources in each flux density interval (%) |
|---|---|---|---|---|
| 1 | $0^{\mathrm{h}} \rightarrow 16^{\mathrm{h}}$ | $47^\circ \rightarrow 54^\circ$ | 3·3 | ±30 |
| 2 | $0^{\mathrm{h}} \rightarrow 4^{\mathrm{h}}\,30^{\mathrm{m}}$, $6^{\mathrm{h}} \rightarrow 14^{\mathrm{h}}$ | $34^\circ \rightarrow 47^\circ$ | 4·2 | ±20 |
| 3 | $0^{\mathrm{h}} \rightarrow 5^{\mathrm{h}}$, $8^{\mathrm{h}} \rightarrow 16^{\mathrm{h}}$ | $10^\circ \rightarrow 34^\circ$ | 6·5 | ±15 |

*Dotted lines indicate the flux density range in which the sample cannot be considered complete because of inadequate sensitivity. The curves indicate the expected variation of the differential counts in an Einstein–de Sitter universe with no evolution* (——) *and with evolution of the forms* $(1+z)^4$ (––––)$^2$ *and* $(1+z)^6$ (– –). *The theoretical curves are normalized to the same Euclidean prediction as the observations.* (*b*) *The same as Fig.* 4(*a*), *but for* weakly *scintillating sources. The statistical errors for areas* 1 *and* 2 *are* ±45 *per cent and* ±35 *per cent respectively.*

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