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Analysis of the Astrophysical Significance of Radio Source Counts Obtained in Different Frequency Ranges*

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Abstract

A qualitative analysis of the possible existence in principle of the 'flux density–distance' correlation, which constitutes the basis for a source count test, is presented for samples of radio sources observed at high ($\nu \gtrsim 1000$ MHz) and very low ($\nu < 100$ MHz) frequencies. It has been shown that conditions for the existence of the correlation are best fulfilled at very low frequencies where the source flux densities are conditioned by isotropic radiation from their extended components with steep spectra.

1. Introduction

As is known the radio source count analysis, i.e. that of the $n_\nu(S)$ relations obtained in the course of the radio sky surveys, currently is one of the widely used methods for studying the cosmological evolution of extragalactic radio sources. The problems concerning the interpretation of the source count results, as well as the place and value of the method in observational cosmology, have been discussed many times in the literature (Longair 1966; van Hoerner 1973). At present source counts are available at frequencies covering the entire range used in radio astronomy. From the experimental frequency dependence of the overall shape of the source counts curves, $n_\nu(S)/n_E(S)$, normalised to a Euclidean universe (see Fig. 6 and Table 2 in the paper by Wall 1978), it follows that radio sources found in different frequency ranges have a qualitatively different character for their observed spatial distribution. Thus, at the low finding frequencies $\nu < 408$ MHz, the observed spatial distribution of radio sources differs in principle from the uniform distribution expected for a Euclidean universe. On the contrary, at high frequencies $\nu \gtrsim 1000$ MHz, the observed radio source distribution is consistent with a uniform distribution within a wide interval of flux densities. To explain this effect several artificial suggestions have been put forward concerning this difference in the character of the spatial distribution of radio sources as found at high and low frequencies. The essential need to resolve this cosmological paradox has been pointed out by many authors (Bolton 1971; Kellermann and Pauliny-Toth 1981).

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On the other hand, the analysis available in the literature (Longair 1966; Longair and Sunyaev 1977) suggests the existence of a cutoff in the spatial distribution of the most distant radio sources, specifically at redshifts z_c that corresponds to the epoch of their initial formation. For this reason experimental detection of this cosmological effect is one of the main astrophysical aims in the current source count analysis. However, as shown by Wall *et al.* (1980), Peacock and Gull (1981) and Condon (1984), the source counts obtained at frequencies between 408 and 5000 MHz do not allow an unambiguous detection of the redshift cutoff and can be interpreted both pro and contra the existence of the effect.

The aims of this paper are as follows: (a) a qualitative analysis of the physical reasons determining the source counts obtained in different frequency ranges, and (b) an estimation of the astrophysical significance of the source counts as a test of the extragalactic radio source space distribution.

2. Discussion

An analysis of source counts suggests that the values of the radio source flux densities are indicators of the source distance from the observer in the statistical sense, i.e. there should be a correlation $\langle S_i\rangle = f(\langle \mathbf{D}(z_i)\rangle)$ between average values of the flux densities and source distances for samples of radio sources with various intensities. We consider whether this condition, which forms the basis for an $n_\nu(S)$ test, is satisfied for the experimental data obtained in different frequency ranges.

The flux densities S_i of discrete sources measured at some frequency ν generally are known to result from superposition of the radiation emitted by bright ($T \sim 10^{11-12}$ K) compact components with flat spectra ($l < 1$ kpc, $\alpha < 0\cdot5$ where $S \sim \nu^{-\alpha}$) and extended ($l \sim 100$ kpc) components with low surface brightness and steep spectra ($\alpha > 0\cdot5$). Therefore, an analysis of the possibility in principle of the correlation $\langle S_i\rangle = f(\langle \mathbf{D}(z_i)\rangle)$ should be carried out separately for compact and extended components in the radio source structures. As it follows from the total source spectra obtained in a wide frequency range, the flux density values S_i observed at very low frequencies $\nu < 100$ MHz are conditioned by the radiation from their extended components; in contrast, at high frequencies $\nu \gtrsim 1000$ MHz, the main contribution to the measured values of S_i is due to radiation from the bright central components.

We consider the effect of the radiation characteristics of the compact and extended source components on the average flux densities $\langle S_i\rangle$, and surface density distribution n, for the radio source samples with various mean redshifts $\langle z_i\rangle$ measured in different frequency ranges. The analysis is performed with the assumptions of (*a*) isotropic radiation from the radio source components, and (*b*) a 'unified' radio source scheme.

(a) Isotropic Radiating Components

For an isotropically radiating source with the radio luminosity P_0 the relation $S = f(\mathbf{D}(z))$ is determined by the well known formula

$$S_0 = \frac{P_0}{4\pi \mathbf{D}^2(z)} (1+z)^{1-\alpha}, \tag{1}$$

where $\mathbf{D}(z)$ is the bolometric luminosity distance, $(1+z)^{1-\alpha}$ is the K-correction factor, and $P_0/\{4\pi\mathbf{D}^2(z)\} = S_{\mathrm{D}}$ is the flux density which depends only on z and the model assumed for the universe. Note that with equal (or known) values of the luminosities P_i for distant radio sources, it is the statistical relation $\langle S_{\mathrm{D}}\rangle = \mathbf{S}(\langle\mathbf{D}(z_i)\rangle)$ which reflects the model of the universe.

As can be seen from (1), the effect of the K-correction on the observed correlation $\langle S_i\rangle = f(\langle\mathbf{D}(z_i)\rangle)$ for extended sources is either negligible (if $\alpha \approx 1$) or emphasises the correlation observed in contrast to the $S_{\mathrm{D}} = \mathbf{S}(\mathbf{D}(z))$ relationship expected for the model universe (if $\alpha > 1$). In contrast, for samples of compact sources ($\alpha < 0 \cdot 5$) the K-correeection makes the observed correlation $\langle S_i\rangle = f(\langle\mathbf{D}(z_i)\rangle)$ a less pronounced function of z in comparison with $S_{\mathrm{D}} \approx \mathbf{S}(\mathbf{D}(z))$. Thus, even with equal values of P_i assumed for the compact and extended sources, the dependence $\langle S_i\rangle = f(\langle\mathbf{D}(z_i)\rangle)$ is more distinct for samples of extended steep-spectrum sources.

But the main reason for the lack of statistically significant experimental $\langle S_i\rangle = f(\langle\mathbf{D}(z_i)\rangle)$ relations lies in the large scatter in the luminosities P_i actually observed; e.g., for the compact components observed at high frequencies the average estimate of the ratio $P_{\max}/P_{\min}$ is evaluated as more than 10^3–10^4 (Peacock and Wall 1981; Hutchings *et al.* 1988). On the other hand, as follows from the paper by Fanaroff and Longair (1973), as well as the analysis of the 3CR source samples (see e.g. Chambers *et al.* 1988), the extended sources observed at low frequencies are characterised by the least scatter in their luminosities.

Thus, simultaneous allowance for the K-correction and the scatter in source luminosities brings us to the conclusion that the $\langle S_i\rangle = f(\langle\mathbf{D}(z_i)\rangle)$ dependence should manifest itself most distinctly at very low finding frequencies where the observed flux densities S_i are dominated by the radiation from extended components with steep spectra.

(b) Unified Source Model

According to the unified scheme (Blandford and Königl 1979; Perley *et al.* 1980; Browne *et al.* 1982; Kellermann and Pauliny-Toth 1981) all extragalactic radio sources are characterised by the classical double structure with a bright compact nucleus at the centre, while the variety of the observed structures and the corresponding classification of radio sources are exclusively determined by their orientation with respect to the line-of-sight. The radiation from the compact and the extended components are different in principle. The bright compact components radiate anisotropically in a narrow beam of half-width $\sim 1/\gamma$ [where $\gamma = (1-\beta^2)^{-1/2}$ is the Lorentz factor of the relativistic jet and $\beta = v/c$] and their measured flux densities are subject to the Doppler enhancement:

$$S_{\mathrm{obs}} = S_0 A = S_0\{\gamma(1-\beta\cos\theta)\}^{-(3+\alpha)}, \tag{2}$$

where S_0 is the flux density expected for isotropic radiation and θ is the angle between the line-of-sight and the jet direction. The Doppler enhancement factor A can reach values of the order of $\sim 10^4$ (if $\langle\gamma\rangle \sim 5$). The extended components radiate isotropically. This model allows the variety of the observed structures and properties of radio sources to be explained without separation of the extended and compact sources into physically distinct classes, and to establish statistical relations between them. The conformity of the unified scheme with experimental source counts was shown by Orr and Browne (1982). Over recent years the unified scheme has received considerable experimental support (Fanti *et al.* 1984).

The conclusions that can be drawn from the unified scheme are:

(i) the values of n and $\langle S_i \rangle$ for compact radio sources observed at high frequencies are conditioned mainly by the relativistic effects of beamed radiation and Doppler boosting;

(ii) in contrast, the values of n and $\langle S_i \rangle$ measured at low frequencies do not depend on the orientation of radio sources owing to the isotropic radiation from their extended components.

It also follows from the unified model that the large apparent spread in the luminosities of compact sources is conditioned by Doppler enhancement and beamed radiation as well, i.e. it does not reflect the scatter in their intrinsic radio luminosities.

(c) Reality of the $\langle S_i \rangle = f(\langle \mathbf{D}(z_i) \rangle)$ Correlation

With regard to the reality of the $\langle S_i \rangle = f(\langle \mathbf{D}(z_i) \rangle)$ correlation underlying the $n_\nu(S)$ test we are now able to make the following conclusions:

(1) the conditions for the existence of the correlation are best fulfilled at frequencies $\nu \ll 100$ MHz where the source flux densities are determined mainly by the isotropic radiation from their extended components with steep spectra;

(2) at frequencies where the source flux densities S_i are dominated by the radiation from their bright compact components ($\nu > 1000$ MHz) the correlation cannot exist in principle, since the observed values $\langle S_i \rangle$ are determined mainly by relativistic effects rather than distance.

These conclusions are supported by the observational results obtained at both high and low frequencies. According to the data available in the literature (see e.g. Windhorst *et al.* 1985), the relative content of radio galaxies and quasars in statistically complete samples of sources observed at high frequencies remains practically constant over the whole flux-density range where the corresponding source counts have been analysed. This suggests that the probability of detecting most distant objects such as quasars or relatively close radio galaxies does not depend on the mean values $\langle S_i \rangle$ of the source samples considered. Therefore, at frequencies $\nu \gtrsim 1000$ MHz the $\langle S_i \rangle = f(\langle \mathbf{D}(z_i) \rangle)$ correlation does not exist. On the one hand, this confirms the conclusion which we obtained above from independent considerations, while on the other, it contradicts the very idea of using high frequency $n_\nu(S)$ data as a test of radio source spatial distribution. Actually, this also implies that an increase in the instrumental sensitivity of high frequency surveys would not lead to the detection of objects that are on average more distant. As follows from model simulations, it rather would be the case that sources with weaker intrinsic luminosities and/or objects with greater angles between their radiation and the line-of-sight would be observed.

Conversely, studies of extended source samples indicate the possibility for the $\langle S_i \rangle = f(\langle \mathbf{D}(z_i) \rangle)$ correlation to exist at low frequencies; e.g., as shown by Spinrad *et al.* (1985) samples of radio sources with different intensities at 178 MHz were characterised by quite different values of $\langle z_i \rangle$. Another piece of indirect evidence for the existence of the correlation in question at low frequencies is given by the detection of a correlation between the S_i values of the sources measured at 408 MHz and their visual magnitudes m_V (Browne and Wright 1985). These data can be regarded as experimental evidence for the existence of the correlation $\langle S_i \rangle = f(\langle \mathbf{D}(z_i) \rangle)$ for extended radio sources. Hence, the counts of extended sources obtained at very low frequencies can reflect the main properties of the extragalactic radio source spatial distribution.

(d) Effect of Source Component Lifetimes on the Source Counts

The conclusions above suggest equal lifetimes for the bright compact and extended components in the source structure. Consider the case of different duration for these main stages in the intrinsic radio source evolution. A lower limit to the compact component lifetime $t_{cc} \sim 10^6$–10^7 yr (Komberg and Sunyaev 1971) can be derived from the lifetime of optically bright quasars which they are generally identified with. The extended components have lifetimes t_{ec} as long as 3×10^9 yr (Cordey 1986). It should be noted that redshifts $z_c \approx 3$–4 which are supposed to relate to the source formation epoch correspond to the lookback time $\tau \approx (10\text{–}16) \times 10^9$ yr (assuming $1 > q_0 \geq 0$ and $H_0 = 50$ km s^{-1} Mpc^{-1}); i.e. the lifetime of extended components is comparable with the period passed from the suggested epoch of the source triggering. Hence, extended sources of low surface brightness can be regarded as long-lived 'imprints' of the corresponding bright compact sources on the cosmological time (distance) axis.

Besides, since extended sources (components thereof) are also characterised by a minimal scatter in their luminosities, the widely used assumption of the pure density cosmological evolution is strictly valid only for the source counts obtained at very low frequencies. At higher frequencies, where the observed objects are in the active stage of their evolution, the source counts are also affected by the evolution of their luminosities. Numerical simulations show that the strength of the space density evolution, i.e. values of the function $E(z)$ in the equation for the radio luminosity function,

$$\rho(P, z) = \rho(P, z{=}0)\, E(z)\,, \tag{3}$$

where $\rho(P, z{=}0)$ denotes the space density at the present epoch, should be proportional to the ratio $t(z)/\Delta T(z)$ of the typical radio source lifetime to the period of their formation for corresponding values of z. It should be noted that, generally speaking, only the $\Delta T(z)$ relationship reflects the real (rather than the observed) space density evolution. In the case where $t_{ec} \gg t_{cc}$ the nonuniformity in the extended source distribution is increased compared with that determined from the $\Delta T(z)$ relation. This intensification of the density evolution is due to the 'accumulation' effect [if $t_{ec}(z) > \Delta T(z)$] of long-lived extended radio sources at large redshifts. Numerical simulations show that if the redshift cutoff effect exists this accumulation should produce a peak in the spatial distribution of extended sources at some redshift value $z_m < z_c$, i.e.

an absolute decrease in their space density should be observed at $z_c > z > z_m$. Such a distribution would correspond to an evolution function $E(z)$ similar to that considered in the 'successful' evolution model 5 of Wall *et al.* (1980). The position of the space density maximum on the z-axis and the value of $E(z_m)$ are determined both by the time required for the formation of extended components and by their lifetimes. Obviously, such a distribution of extended radio sources should favour the observational detection of the redshift cutoff in the analysis of the radio source counts obtained at very low frequencies.

3. Conclusions

As can be seen from the qualitative analysis presented, the conditions for the existence of the correlation $\langle S_i \rangle = f(\langle \mathbf{D}(z_i) \rangle)$, which constitutes a basis for every source count analysis, are best satisfied for extended radio sources of low surface brightness and with steep spectra. Hence, the general properties of the extragalactic radio source spatial distribution should manifest themselves most distinctly in the source counts obtained at the lowest observational frequencies. This conclusion is in agreement with the one made by Fanaroff and Longair (1973) obtained on the basis of a radio source spectrum analysis. Moreover, it is qualitatively confirmed by the experimental frequency dependence of the overall shape of the source counts (Wall 1978). From this experimental dependence, it also follows that the effects of cosmological evolution begin to emerge more distinctly as the observation frequency is decreased. On the other hand, the analysis also suggests that high-frequency source counts ($\nu \gtrsim 1000$ MHz) cannot in principle reflect the real space distribution of radio sources, since the values of n and $\langle S_i \rangle$ observed in that frequency range show no correlation with distance. The overall shape of the high-frequency source counts, where the radio source flux densities observed are dominated by radiation from the bright compact components in the source structures, is determined mainly by the convolution of the real source space distribution and the following effects: (1) Doppler enhancement of their observed flux densities; (2) beamed radiation; and (3) intrinsic luminosity evolution. As a result the observed spatial source distribution cannot be distinguished from a universal uniform (Euclidean) distribution within a wide range (10^3–10^4) of the observed flux densities. As follows from model estimates, allowance for the effects of Doppler enhancement and beamed radiation alone, for compact sources placed in a narrow layer corresponding to some redshift, results in a wide 'Euclidean' section on the observed source count curve. This imposes restrictive limitations on the possibility of unambiguously deriving the real spatial distribution of radio sources, and particularly the redshift cutoff, from the high-frequency sources count analysis. Thus, parameters of the $n_\nu(S)$ relations and, accordingly, of the radio source spatial distribution observed at a frequency ν, are determined mainly by the ratio of fractional flux densities from the extended and compact source components in the total flux density S_i measured at the same frequency. In the framework of the present analysis a natural explanation can be given to: (i) the frequency dependence of the source counts; and (ii) the paradox caused by the qualitatively different character of the spatial source distributions observed over different frequency ranges. As is known, these distinctions in the observed distribution of objects found at high and low frequencies, as well as in the optical range, are confirmed by the results of the V/V_{max} test (Schmidt 1976, 1978; Masson and Wall 1977; Wills and Lynds 1978). As has been pointed out above, the main reason for it is the detection in significantly different ranges of different components in the structures of the objects whose radiation characteristics differ in principle. Note that the V/V_{max} test is equally based on the assumption of the $\langle S_i \rangle = f(\langle \mathbf{D}(z_i) \rangle)$ correlation. The possibility in principle for the existence of such a correlation has been considered above. The problem of the mutual dependence of the results obtained for the $n_\nu(S)$ and V/V_{max} tests has been discussed more than once in the literature (Carswell and Weymann 1972). From the present analysis, it also follows that the parameters of the $n_\nu(S)$ relations and $\langle V/V_{max} \rangle$ values determined for a certain class of objects are not independent.

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