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Improved Count of Radio Sources at 1400 MHz

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Summary. New observations at 1400 MHz with the NRAO 300-ft telescope have provided a comparison between the flux-density scales of the BDFL, Davis, Maslowski and Westerbork surveys. The flux-density adjustments determined from these new observations essentially remove the reported clustering of extragalactic sources based on the differences among these surveys at a source density of $\sim 500\,\mathrm{sr}^{-1}$.

The counts at 408, 1400, 2700 and 5000 MHz exhibit significant differences which can be explained by a variation of the effective spectral index of sources with flux density. The required variation is consistent with observations of individual sources.

The corrected count of sources at 1400 MHz between .01 and 100 Jy is compared with evolutionary and steady-state cosmological models. A steady-state model may be compatible with the count only if QSS redshifts greater than 0.5 are mostly not cosmological *and* the relative deficiency of intense sources with steep spectral index is due to local source clustering.

Key words: radio counts — cosmology — clustering

Introduction

The count of extragalactic radio sources at 1400 MHz has recently been measured in surveys covering 4 decades in flux density. The relevant data are shown in Fig. 1. The counts from the Westerbork synthesis survey (Katgert *et al.*, 1973) cover an area of .001 to .008 steradian (depending on the flux density limit) near the position $\alpha = 13^{\mathrm{h}}$, $\delta = +30°$ to a lower limit of .009 Jy and with reasonable statistics up to 0.7 Jy. The other data shown are mainly from the NRAO 300-foot telescope: i) a survey to 0.5 Jy by Davis (unpublished) covering 0.45 sr in the declination strip $24° < \delta < 30°$, ii) a similar survey by Maslowski (1971, 1972a, b, 1973) covering 0.16 sr in the declination strip $48° < \delta < 52°$ in the range $7^{\mathrm{h}}.1 < \alpha < 16^{\mathrm{h}}.2$, and iii) a catalogue of sources brighter than 2.0 Jy in 4.30 sr between declinations $-5°$ and $+70°$ (Bridle *et al.*, 1972b). Errors shown for each data point are proportional to the square root of the number of contributing sources. Also shown are data from the Ohio Survey Installment V, which have not been assigned errors because systematic corrections have not been applied to the survey (Kraus, 1972).

The differences in these published counts between 0.2 and 1.5 Jy have led to suggestions that radio sources may cluster on scale sizes of a few degrees (Katgert *et al.*, 1973) and a few tenths of a steradian (Maslowski, 1973). We have made new observations with the NRAO 300-foot telescope to improve the reliability of the composite Westerbork-NRAO source count and

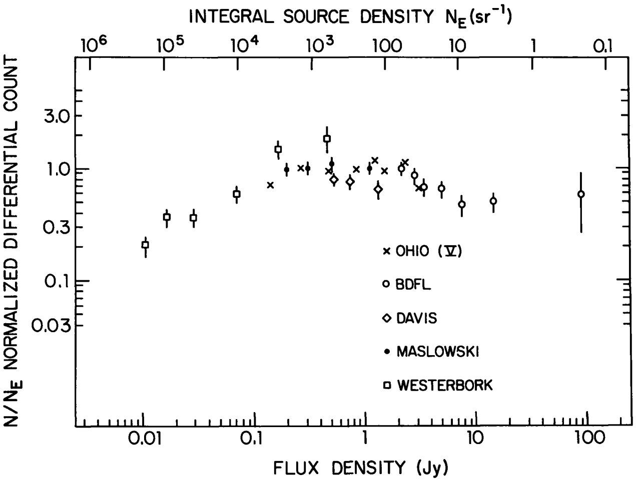

Fig. 1. The original differential counts at 1400 MHz, normalized to the Euclidean count $N_E = 200\,S^{-1.5}\,\mathrm{sr}^{-1}$ shown at the top

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Table 1. Comparison of Westerbork and NRAO flux densities

Westerbork source(s)	S_W (Jy)	Westerbork beam correction factor	S_{FBD} (Jy)	$S_W - S_{FBD}$	Comments
1245+34 W 3	0.405 ± .008	3.81	0.41 ± 0.03	−.01	Possibly confused by 1245+34 W 1 (.027 Jy)
1247+33 W 1 1247+33 W 2 1247+33 W 5	0.911 ± .025	1.43	1.29 ± 0.06	−.38	Variable? Large-scale structure ∼3′?
1248+35 W 1 1247+35 W 1 1248+34 W 1	0.464 ± .025	8.3	0.45 ± 0.03	.01	
1253+35 W 9	0.280 ± .005	1.11	0.31 ± 0.03	−.03	Possibly confused by 1253+35 W 3 (.071 Jy) and 1253+35 W 4 (.013 Jy). Not a good flux density comparison.
1253+37 W 5 1253+37 W 4	0.698 ± .086	2.15	0.69 ± 0.03	.01	Possibly confused by 1254+37 W 2 (.031 Jy).
1255+37 W 1 1254+37 W 4	0.787 ± .010	1.4	0.68 ± 0.05	.11	Possibly confused by 1254+37 W 3 (.012 Jy) and 1255+37 W 3 (.024 Jy).
1256+36 W 1	0.433 ± .023	1.51	0.45 ± 0.04	−.02	Nearby sources 1257+36 W 2 (.077 Jy) and 1255+36 W 1 (.132 Jy) resolved from 1256+36 W 1 by 300′.
1257+34 W 2	0.460 ± .009	1.51	0.44 ± 0.03	.02	Possibly confused by 1257+35 W 2 (.012 Jy)
1301+38 W 1	0.800 ± .120	8.01	0.61 ± 0.03	.19	Nearby source 1301+38 W 2 (.146 Jy) resolved from 1301+38 W 1 by 300′.
1301+35 W 1	0.492 ± .013	5.12	0.47 ± 0.05	.02	
1301+37 W 3	0.286 ± .004	1.78	0.30 ± 0.03	−.01	Nearby source 1302+37 W 2 (.094 Jy) resolved from 1301+37 W 3 by 300′.
1302+35 W 1	0.489 ± .008	1.56	0.45 ± 0.03	.04	
1307+34 W 2 1307+34 W 1	0.626 ± .004	∼22	0.75 ± 0.05	−.12	Sources barely resolved by 300′.
1307+37 W 1	0.408 ± .065	3.26	0.32 ± 0.03	.08	Possibly confused by 1307+37 W 2 (.016 Jy) and 1307+37 W 5 (.016 Jy).

to test whether the suggested source anisotropy can be attributed to systematic differences in the flux densities measured by the 1400-MHz surveys.

Observations

In May and August 1973, the NRAO 300-ft telescope was used with the 4-feed 21-cm system to remeasure the flux densities of sources from the Westerbork, Davis and Maslowski surveys. The observation method and reduction technique were similar to that used for the 1400-MHz intense source catalogue (Bridle *et al.*, 1972b, hereafter referred to as BDFL) and the resulting flux densities are on the KPW (Kellermann *et al.*, 1969) flux-density scale.

The results of comparing the newly-measured flux densities (S_{FBD}) with those measured at Westerbork (S_W) for the most intense sources of the Westerbork survey are listed in Table 1 and plotted in Fig. 2. In most cases the 300-ft measurements correspond to blends of close Westerbork sources. The few ambiguous fields where it is not certain if a Westerbork source has

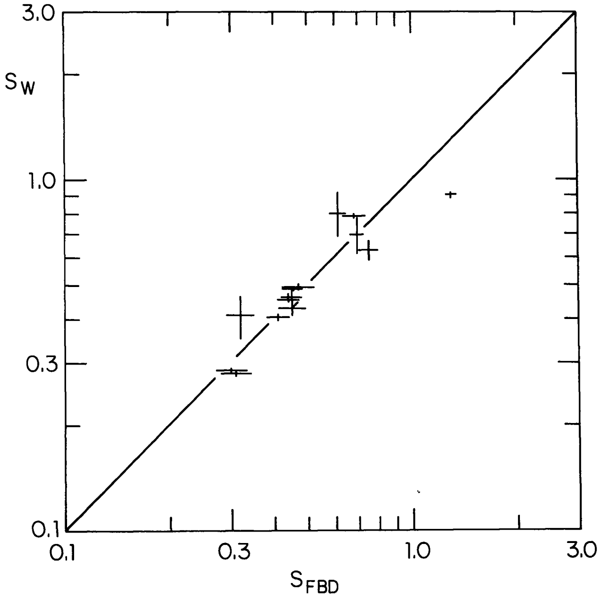

Fig. 2. The Westerbork flux density measurements S_W compared with the present measurements S_{FBD}. Observational errors are shown for each point

been included in the 300-ft measurement are noted in Table 1. Within the statistical uncertainty, the Westerbork flux densities are seen to be on the same scale as those from the 300-ft telescope. The absence of any systematic trend in the data verifies the accuracy of the correction adopted by Katgert *et al.* (1973) to correct observations of sources well beyond the half-power response of the Westerbork primary beam. The one discordant comparison is for the source blend 1247+33 W 1, W 2 and W 5; the additional flux density observed by the 300-ft telescope may correspond to structure that was resolved by the Westerbork observations.

Although there is good agreement between our flux densities and those measured at Westerbork, the Westerbork count has been renormalized in its highest flux density interval ($S \geqq 0.465$ Jy). Katgert *et al.* chose the upper limit of this interval to be 0.72 Jy, the flux density of the strongest source observed in the Westerbork survey. This *a posteriori* choice produces an artificially high normalized differential count in this interval and a correspondingly low count of zero above 0.72 Jy. We have changed the highest flux density interval for their count to $0.465 < S < \infty$, and have renormalized the count accordingly.

The comparison with the Davis survey (S_D) in Figs. 3 and 4 shows that flux densities of sources between 0.5 and 0.8 Jy have been systematically underestimated in the Davis Survey. The error is very nearly that suggested by Schmidt (1972) to account for a discrepancy by a factor of about 1.3 between the Davis 1400 MHz counts and the count predicted by a model of radio sources derived from lower-frequency data. In reviewing the data reduction procedure used in the Davis survey, an error was found which caused a ten percent underestimate in the flux density for all sources $\leqq 0.62$ Jy (dashed line in Fig. 4). Above this flux density the expected error drops abruptly to nearly zero. This idealized correction curve does not, however, include the effects of gain variations and of confusion and noise errors, so we prefer to use the empirically determined corrections based on our new measurements, shown as the solid line in Fig. 4.

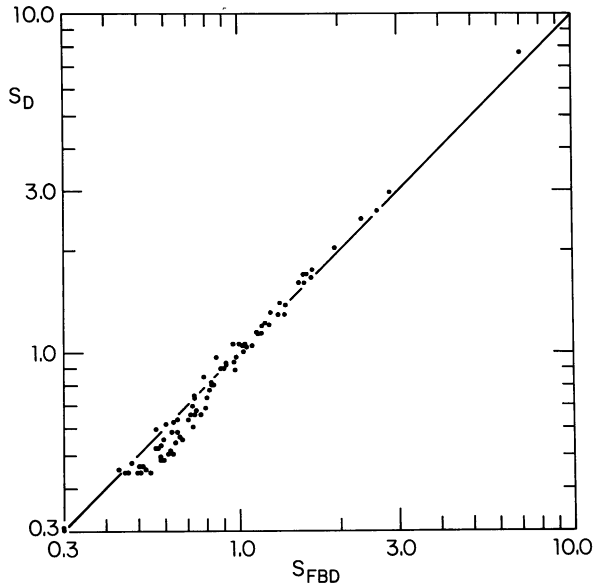

Fig. 3. The Davis flux density measurements S_D compared with the present measurements S_{FBD}

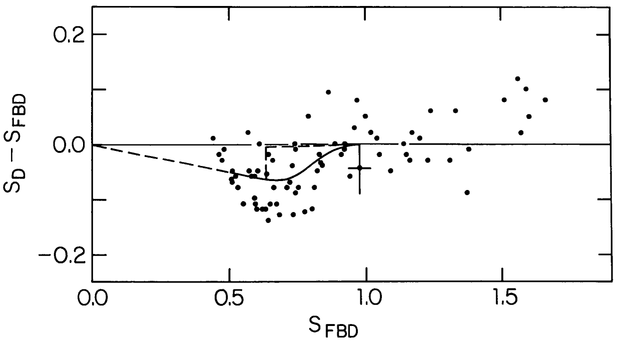

Fig. 4. The residual $S_D - S_{FBD}$. The solid curve gives the adopted empirical correction based on these new observations. The dashed curve is the residual expected from the error in the baseline procedure for a noise-and-confusion-free source. One typical measurement error is shown

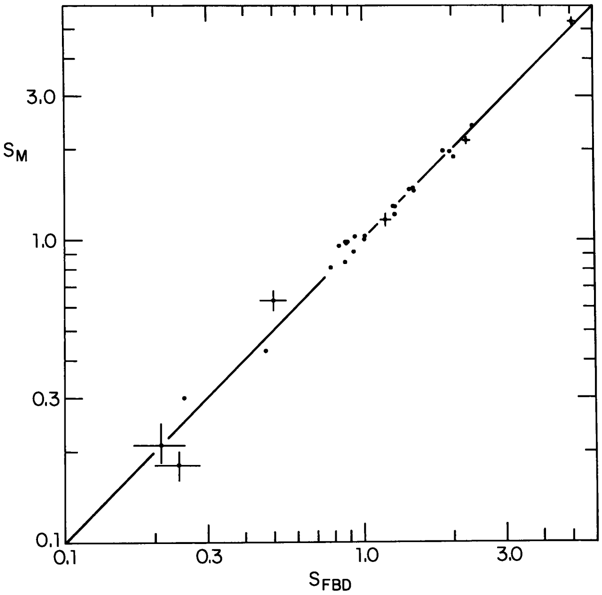

Fig. 5. The Maslowski flux density measurements S_M compared with the present measurements S_{FBD}. Typical observational errors are given for a few points

The Maslowski survey (S_M) flux densities agree well with the present observations, as shown in Fig. 5. There is possibly a slight difference for sources between 0.7 and 1.0 Jy. Data are sparse below this flux density, but the systematic error found in the Davis survey should not be present in the Maslowski Survey as a different data reduction procedure was used.

Discussion of the Improved Count

i) Agreement among the Surveys

The improved count of radio sources at 1400 MHz is given in Table 2 and plotted in Fig. 6. The changes

Table 2. Differential counts of sources

Flux density range [Jy]	N No. of sources	N/N_E ratio	Flux density range [Jy]	N No. of sources	N/N_E ratio	Flux density range [Jy]	Area (10^{-3} ster.)	N No. of sources	N/N_E ratio
BDFL, 10.22 ster.			Davis, 0.450 ster.			Westerbork			
56.47 –∞	3	0.62	1.063–1.994	34	0.68	0.465 –∞	7.6	6	1.25
10.00 –56.469	31	0.52	0.705–1.062	84	1.20	0.300 –0.464	7.6	6	1.35
6.461– 9.999	28	0.47	0.550–0.704	67	0.98	0.193 –0.299	6.1	13	1.87
						0.124 –0.192	5.4	15	1.25
BDFL, 4.30 ster.			Maslowski, 0.1586 ster.			0.081 –0.123	4.9	13	0.64
						0.0520–0.0800	4.7	21	0.56
4.124– 6.460	34	0.69	0.700–∞	57.3	1.05	0.0335–0.0519	3.4	25	0.47
3.161– 4.123	35	0.70	0.400–0.699	82.1	1.15	0.0216–0.0334	2.8	19	0.22
2.615– 3.160	41	0.81	0.250–0.399	135.1	1.05	0.0140–0.0215	1.54	32	0.36
1.995– 2.614	104	1.03	0.160–0.249	247.2	1.02	0.0090–0.0139	0.995	21	0.19

N_E is the normalized Euclidean count determined from $N_E(S) = 200\,S^{-1.5}\,\mathrm{sr}^{-1}$.

made to the count in Fig. 1 are: the addition of three sources to the BDFL catalogue above 2.0 Jy (Bridle and Fomalont, 1974); the correction to the Davis survey flux density measurements between 0.5 and 1.0 Jy; and a renormalization of the Westerbork count above 0.465 Jy.

The evidence for clustering of radio sources based on differing counts among the Davis, Maslowski and Westerbork surveys at a source density of $\sim 500\,\mathrm{sr}^{-1}$ is now less compelling, as the revised differential counts from the three surveys are generally in agreement to within the statistical errors. The ratio of source densities in the Maslowski and Davis surveys below 1 Jy has decreased from 1.43 ± 0.18 to 1.18 ± 0.16 with the correction to the Davis survey. In the range 1 to 2 Jy the ratio remains 2.2 ± 0.6.

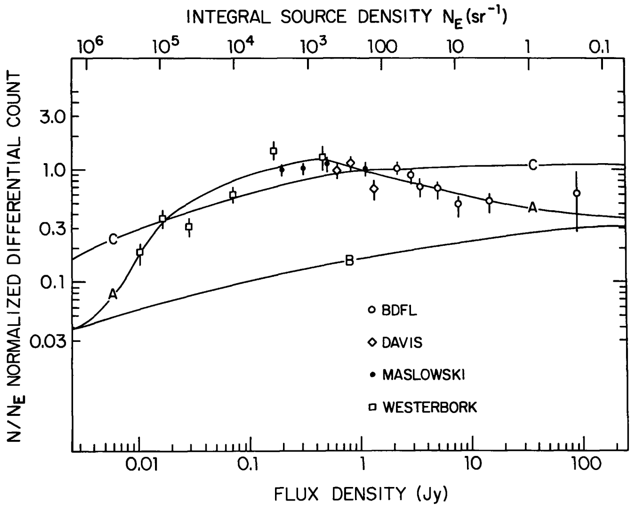

Fig. 6A—C. The improved differential source counts at 1400 MHz, normalized to the Euclidean count $N_E = 200\,S^{-1.5}\,\mathrm{sr}^{-1}$ shown at the top. The data are given in Table 2 with some Westerbork data averaged over several entires. Various models are shown by the solid lines: (A) A standard evolutionary model. (B) The steady-state model using the standard luminosity function. (C) The steady-state model using a modified luminosity function

ii) Comparison of the Counts at Frequencies from 408 to 5000 MHz

The counts at frequencies of 408, 1400, 2700 and 5000 MHz, each covering about four decades in flux density and each having comparable statistical errors, are plotted in Fig. 7. These differential counts have been normalized to the *same* Euclidean count assuming an "effective" spectral index $\bar{\alpha} = -0.7$ $\left(\bar{\alpha}\text{ is defined by } S(N, \nu_2) = \left(\frac{\nu_2}{\nu_1}\right)^{\bar{\alpha}} S(N, \nu_1)\right)$.

The four counts are in qualitative agreement, each displaying: 1) a dearth of sources at source densities $< 10\,\mathrm{sr}^{-1}$, 2) an approximately Euclidean slope between source densities 30 to $3000\,\mathrm{sr}^{-1}$ and 3) a convergence at higher source densities. Parameters of the counts at the four frequencies are given in Table 3. The counts do however display systematic changes over the frequency range 408 to 5000 MHz that can be explained by the dependence of the spectral index distribution on flux density at each frequency. The variation in the effective spectral index necessary to reproduce the frequency dependence of the count (Column 6, Table 3) is consistent with spectral measurements of individual sources (e.g., Condon and Jauncey, 1974).

Interpretation of the Counts

The interpretation of the counts of extragalactic sources has been a subject of continuing controversy (e.g. Hoyle, 1967; Ryle, 1968; Bridle *et al.*, 1972a; Schmidt, 1972; von Hoerner, 1973). Although the improved 1400 MHz counts are among the most statistically accurate now available, little of the controversy can be settled by an exhaustive analysis. We consider it worthwhile only to compare the counts to two simple models: a "typical" evolutionary cosmological model and the steady-state model.

To illustrate the ability of an evolutionary model to fit the counts, the world model $q_0 = 1/2$, $\sigma = 1/2$ was used. The luminosity function shown in Fig. 8 was

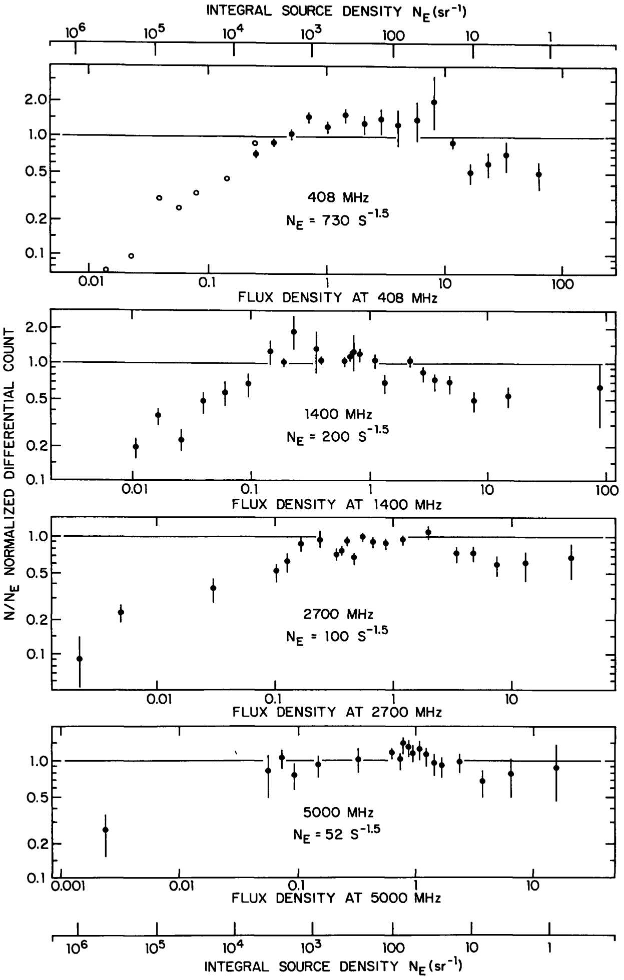

Fig. 7. The differential counts at 408, 1400, 2700 and 5000 MHz. Each count has been normalized to the same Euclidean integral source density shown at the top. Data from: 408 MHz: Pooley and Ryle, 1968; Mills *et al.*, 1973. 1400 MHz: this paper. 2700 MHz: Ekers, 1969; Wall *et al.*, 1971; Shimmins, 1971; Shimmins and Bolton, 1972; Bolton and Shimmins, 1973; Fomalont, 1974. 5000 MHz: Davis, 1971; Pauliny-Toth and Kellermann, 1974

taken from von Hoerner (1973) and scaled to 1400 MHz using a spectral index -0.7 for all sources. This "standard" luminosity function has a critical slope ($\phi(L) \sim L^{-1.5}$) at high luminosities so that a relatively small uncertainty in it significantly affects the count. An excellent fit to the count using this luminosity function with an evolutionary model is shown in Fig. 6 Curve A. The evolution model was defined by three parameters e, z^* and L^* such that

$$\left.\begin{aligned}\varrho(z) &= (1+z)^e, 0<z<z^* \\ &= (1+z^*)^e, z>z^*\end{aligned}\right\} L>L^*$$
$$= 1 \qquad L<L^*$$

where $\varrho(z)\cdot\phi(L)$ gives the *density* of radio sources with redshift z per cubic megaparsec per radio magnitude[1]). The best fit was obtained with the parameters $e=5.1\pm0.1$, $z^*=3.6\pm0.8$, $L^*=10^{26.2\pm0.2}$ (W · Hz^{-1}). In addition, the luminosity function published by von Hoerner had to be adjusted slightly in the luminosity range $10^{23.1}<L<10^{28.1}$. A slope of $1.36\pm.04$ was necessary to fit the count for the intense sources. More complicated and detailed models are available in the literature; we wish only to emphasize that a suitably-selected evolutionary model fits the count extremely well.

Table 3. Frequency dependence of the counts

Euclidean source density N_e(sr^{-1})	Differential count N/N_E 408 MHz	1400 MHz	2700 MHz	5000 MHz	"Effective" spectral index $\bar{\alpha}$
<10	0.55	0.55	0.65	0.80	-0.6
30–3000	1.40	1.20	0.95	1.05	-0.8
2×10^5	0.10	0.15	0.20	0.25	-0.6

The count cannot be fit with a steady-state model ($q_0=-1$, $\sigma=0$) using the "standard" luminosity function [see Fig. 6(B)]. However, a significant change of the luminosity function for the most luminous radio sources is possible if the quasar redshifts above $\sim$0.5 are not entirely of cosmological origin. With this in mind we have formed a hypothetical luminosity function which is identical to the standard function at low luminosities and departs as little as possible at high luminosities. An acceptable fit was obtained with the luminosity function labelled "steady-state" in Fig. 8, the resultant count using a steady-state model being shown in Fig. 6 (C). The fit is good below about 3 Jy, corresponding to a source density of 40 sr^{-1}. It could be improved slightly by using a luminosity function for which *all* sources have a luminosity of $10^{25.1}$ W Hz^{-1} and a space density of $10^{-4.34}$ Mpc^{-3} mag^{-1} (cf. Hoyle, 1967). However, such a luminosity function would be physically implausible.

The "steady-state" luminosity function has a smaller density of luminous sources with $L\sim10^{28.0}$ W Hz^{-1} and a larger density of sources with $L\sim10^{24.5}$ W Hz^{-1} than the "standard" luminosity function. The difference could be accommodated if most quasi-stellar sources having a redshift of $z\sim0.5$ or greater were actually at distances corresponding to a cosmological Doppler redshift of 0.02 to 0.10.

The "deficiency" of the number of observed sources above 3.16 Jy compared with the steady-state model of Fig. 6(C) is shown in Table 4. Only about half of the number of sources required by the model are observed. The "deficiency" calculated by Bridle *et al.* (1972a) was somewhat less because 1) the deficiency was that relative to a static Euclidean universe rather than a detailed model and 2) the revision to the Davis Survey and the inclusion of the Maslowski and Westerbork data in the count increases the number of intense sources required by the steady-state model.

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[1]) A Hubble constant of $H=75$ km · S^{-1} · Mpc^{-1} was used throughout.

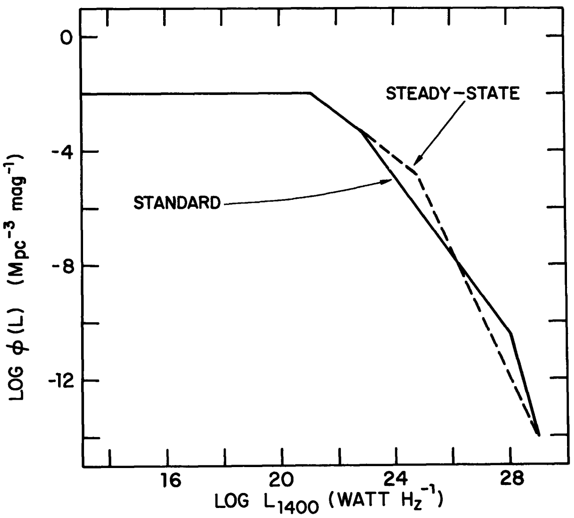

Fig. 8. Two luminosity functions used for model calculations: (A) Standard luminosity function taken from von Hoerner (1973). (B) A luminosity function for which a steady-state model fits the count except at large flux density

Table 4. Deficiency of intense sources compared with a steady-state model using a revised luminosity function

Flux density range Jy	Area Sr	Number observed	Number expected	Number missing
3.161–6.460	4.30	62	133	71
6.461–∞	10.22	69	125	56

Conclusions

i) There is no evidence for *large-scale* anisotropy of the count at 1400 MHz at a source density of $\sim 500 \text{ sr}^{-1}$.

ii) The counts at frequencies from 408 to 5000 MHz display systematic changes which can be explained by a dependence of the spectral index distribution on flux density consistent with that observed for individual sources. This implies that the radio luminosity function is appreciably frequency-dependent, and any fully satisfactory analysis of the counts must take account of this.

iii) If QSS redshifts greater than about 0.5 are mostly not of cosmological origin, then the count may be compatible with a steady-state universe. However, the dearth of intense sources at 408 and 1400 MHz must still be explained by a local deficiency of radio sources with relatively steep spectral indices.

At higher frequencies where more of the intense sources have flat spectra and are high-redshift stellar objects, there is no significant dearth of strong sources. Two explanations of this are possible, depending on the assumption of the origin of the redshifts of these stellar objects. If their redshifts are cosmological, these sources are so distant that the cutoff of evolution at $z \sim 3$ is dominating their count even at the highest flux densities (e.g. Schmidt, 1972; Fanti *et al.*, 1974). If their redshifts are not cosmological, the sources may be local objects. The choice between these alternatives will depend on the construction of a reliable luminosity function for the high radio frequencies.

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