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REDSHIFT DEPENDENCE OF THE LOW-FREQUENCY TURNOVER OF QUASARS

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ABSTRACT

I have identified a sample of quasars whose spectra exhibit clearly defined maxima at low frequencies. The turnover frequencies are found to increase with redshift, but the equipartition angular sizes, deduced on the assumption of a synchrotron self-absorption model, decrease much faster than is predicted by any simple cosmological model. I show that this variation may be due to the steep density gradient of the gas in the nuclear regions of the parent galaxies and to the increase in number density or luminosity of the sources at earlier epochs.

I. INTRODUCTION

Low-frequency turnovers in the spectra of extragalactic radio sources have generally been ascribed to self-absorption of the synchrotron radiation from the source. On this interpretation, the frequency of maximum flux density, ν_T, is related to the magnetic field, B (Gauss), and the redshift, z, by the relation (Kellermann 1974):

$$\nu_T \approx f(\gamma) S_m^{2/5} \theta^{-4/5} B^{1/5} (1+z)^{1/5}\,\mathrm{GHz}, \tag{1}$$

where S_m is the flux density in Jy at the turnover frequency, and θ is the angular size in milliarcsec. The function $f(\gamma)$ depends only weakly on γ, the energy index of the electron distribution, and has a value of the order of 8 for $\gamma = 2$.

This paper is concerned with the relationship between ν_T and other parameters of the sources in a sample selected from the large numbers presented in the literature, and with the cosmological significance of the observed trends.

II. DATA AND ANALYSIS

For the purposes of this study I have selected a group of 19 quasars, mostly from the compilation of radio spectra by Kühr *et al.* (1979), using the following criteria: (1) The spectrum had a clear maximum at the low-frequency end of the available range and a well-defined power law shape above the turnover frequency. (2) The source had a measured redshift. The sources are listed in Table I together with their parameters. The turnover frequency was determined graphically from the flux densities given by Kühr *et al.* (1979) and the luminosities, F_R (5), at the emitted frequency of 5 GHz were calculated following the procedure given by Willis and Lynds (1978) taking $q_0 = 0.5$ and $H_0 = 50$ km s^{-1} Mpc^{-1}.

The plot of z against the emitted turnover frequency, ν_T $(1 + z)$, shows a high degree of correlation between the two parameters (Fig. 1). I now consider selection effects which may influence this correlation. All sources included in the present sample are radio-selected ob-

TABLE I. The sample of quasars.

Source	z	ν_T (GHz)	S_m (Jy)	S_5 (Jy)	α	$\log F_R$	$\log \theta_{\mathrm{Eq}}$ (MAS)
1442 + 10	3.53	0.917	2.5	1.2	0.67	28.856	1.1387
0537 − 28	3.11	5.0	1.02	1.02	0.8	28.755	0.2227
0457 + 02	2.382	1.4	1.89	1.20	0.53	28.439	0.8242
0552 + 39	2.365	5.0	4.92	4.92	0.70	29.136	0.4947
2251 + 24	2.328	0.6	2.40	0.79	0.93	28.448	1.2779
0237 − 23	2.224	1.4	7.18	3.59	0.70	28.944	1.1100
0400 + 25	2.109	1.4	1.87	1.79	0.10	28.300	0.8874
1148 − 00	1.982	0.47	3.90	1.90	0.37	28.409	1.4037
0711 + 35	1.62	1.4	1.92	1.52	0.31	28.127	0.7784
1421 + 12	1.604	0.318	1.95	0.48	0.57	27.726	1.4227
1416 + 06	1.439	0.08	102.0	1.7	0.93	28.322	2.8360
0333 + 32	1.263	0.613	2.45	2.4	0.01	27.946	1.2363
1328 + 25	1.055	0.186	18.1	3.26	0.59	28.204	2.0701
2230 + 11	1.037	0.375	8.5	3.65	0.50	28.210	1.6113
1634 + 62	0.988	0.178	13.8	1.5	0.95	27.917	2.0479
1328 + 30	0.849	0.272	18.5	7.48	0.53	28.360	1.8908
0518 + 16	0.759	0.178	22.0	4.16	0.69	28.048	2.1082
0538 + 49	0.545	0.119	70.0	8.18	0.76	28.060	2.4983
0134 + 32	0.367	0.064	89.0	5.35	0.85	27.533	2.7959

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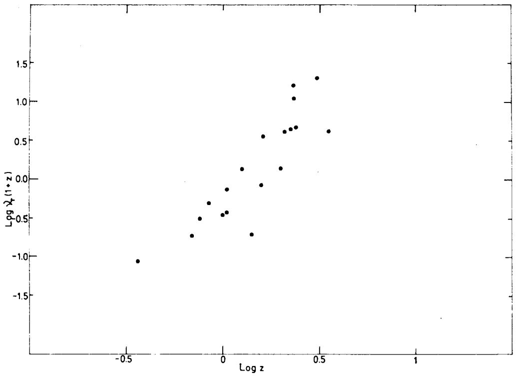

FIG. 1. Distribution of the emitted low-frequency turnover ν_T $(1+z)$ as a function of redshift.

jects. Since the observations of the radio-frequency spectra are available generally only between about 38 MHz and 10 GHz, there is at each redshift an observational limit to the intrinsic turnover frequency of an object. Objects with intrinsic turnover frequencies such that their redshifted turnover frequencies are above or below the limit will not be included in the sample. If objects with lower turnover frequencies do in fact exist they would appear as sources with steep straight line spectra in low flux density, low-frequency surveys. All the sources in Table I have measured angular diameters of less than a second of arc, so that the missing sources should appear compact with steep spectra in low-frequency surveys. The only systematic surveys of angular sizes at low frequencies are by interplanetary scintillation surveys (e.g., Readhead and Hewish 1974). Duffett-Smith (1980), in a discussion of the data of Readhead and Hewish (1974), has pointed out that there are hardly any sources with a value of R, the fraction of the total flux density in a scintillating component, greater than about 0.6, and concludes that there are probably no compact sources at low frequencies down to the limiting flux density of the 4C survey. This is consistent with the results of Fanti *et al.* (1979) who found only one source with a low-frequency turnover in a sample of the 74 B2 quasars detected at 0.4 GHz. Furthermore, most of the high-redshift quasars which have been identified in optical or radio surveys have either flat radio spectra or no radio emission. Hence it seems unlikely that the selection effect introduced by the restriction of the observed frequency range discriminates against any high-redshift quasars with turnovers at or below the low end of the observable range.

Our selection critera will also have excluded sources with turnover frequencies greater than about 5 GHz. Such sources would have positive spectral indices in surveys of faint radio sources at centimeter wavelengths. In a study by Machalski and Condon (1979) of 196 flat spectra sources from the GB2 survey, there are no sources with spectra of the type described above. In the confusion-limited survey of Condon and Ledden (1981) at 4.755 GHz there are a total of 186 sources in a complete sample and 26 have spectral indices greater than 0.1 between 1.415 and 4.755 GHz, for which four may be spurious. It is worth noting that 15 of the remaining 22 sources have a mean flux density of 14.7 mJy, very close to the completeness limit of 15 mJy. Hence the uncertainty in the determination of their spectral indices is likely to be very high. Of the 26 sources only three have suggested identifications with blue stellar objects, whose magnitudes range from 18 to 18.5. These three sources are also the strongest of the group. No redshift measurements are available, however, and, on the basis of the correlations to be discussed below, they are likely to be very distant objects. I conclude that the data of Table I and Fig. 1 are not likely to be influenced by any major selection effects.

I have calculated the Spearman Rank Correlation Coefficients (Siegel 1956) among the various parameters of Table I in order to test for possible correlations. The coefficients and their levels of significance are given in Table II. The correlations between z and F_R is undoubtedly due to a selection effect inherent in all flux-density-limited surveys as pointed out by Wills and Lynds (1978). The question then arises as to whether the high degrees of correlation found between z and ν_T and between z and ν_T $(1+z)$ are due to subsidiary correlations among other parameters. This can be tested by the method of partial correlations (Siegel 1956) and their significance tested by the method described by Macklin (1982). In the observed correlation r_{z,ν_T}, the obvious candidate for the third parameter is F_R. The relevant partial correlations and their significance are given in Table III in the notation of Macklin (1982), from which it is clear that the correlation of ν_T $(1+z)$ with z is independent of F_R.

If all the objects had the same intrinsic turnover frequency we would expect the observed turnover frequency to decrease with increasing redshift. Yet we find an increase of turnover frequency with z which must be attributed to changes in other intrinsic properties of these sources. If the turnover is due to synchrotron self-absorption, the observed variation of ν_T with z can be due only to changes in the quantities S_m, θ, or B (Eq. 1). The value of ν_T is not very sensitive to the range of magnetic fields which are usually derived from equipartition arguments, and following Scott and Readhead (1977), we can assume that the magnetic field is the same as the equipartition magnetic field to obtain the following expression for θ_{Eq} which contains only observa-

TABLE II. Spearman rank correlation coefficients.

Correlations	ν_T/z	$\nu_T(1+z)/z$	F_R/z	θ_{Eq}/z	$\nu_T(1+z)/F_R$
Coefficients	0.837	0.930	0.804	−0.814	0.790
t	6.3	10.4	5.6	5.78	5.30

TABLE III. Correlation of $\nu_T(1+z)$ with z.

Correlation	r_{AX}	t	$r_{AX,Y}$	$D_{AX,Y}$
$\nu_T(1+z)/z$	0.928	10.3	0.808	4.4
F_R/Z	0.804	5.6	0.308	1.2
$\nu_T(1+z)/F_R$	0.790	5.3	0.195	0.8

tional parameters

$$\theta_{\mathrm{Eq}} = F(\alpha)[1-(1+\alpha)^{-1/2}]^{-1/17} (1+z)^{(2\alpha+15)/34} \cdot S_m^{8/17} \cdot \nu_T^{(2\alpha-35)/34}, \qquad (2)$$

where θ is in arcseconds, S is in Jy, and ν_T in MHz. (An Einstein-de Sitter cosmology is assumed with $H_0 = 50$ km s^{-1} Mpc^{-1}). $F(\alpha)$ can be computed using the expressions derived by Scott and Readhead (1977) and ranges from 3.33 to 5.47 for the sources in Table I. The θ_{Eq} computed from Eq. (2) are given in column 8 of Table I. The occurrence of a turnover at low frequency with a normal power-law spectrum at high frequency implies that the angular size θ_{Eq} is the largest unresolved radio structure in the source. VLBI studies with resolutions of the order of milliarcseconds suggest that many of these sources contain structures on angular scales much smaller than are inferred from the turnover frequency. However, most VLBI observations have been made at frequencies much higher than the turnover frequency, and hence at lower optical depths, so that the VLBI structures may not be directly comparable to the θ_{Eq} derived here. For example, studies of the source 0538 + 49 (3C 147) by Wilkinson *et al.* (1977) and Preuss *et al.* (1982) have shown the existence of structures on scales between a milliarcsecond and half an arcsecond. The relative positions of the brightest centimeter-wave component and the low-frequency turnover component are not known but the optical and low-frequency radio positions agree to within an arcsecond in all cases. It has been suggested by Readhead and Wilkinson (1980) that the larger component in 3C 147 may be the outer component of a double source and the high brightness region observed may then be considered the "working surface" of the beam impinging on the interstellar medium of the galaxy. In their model, the outer lobe may be either in front of or behind the central component seen at high frequencies. The model implies that the largest angular sizes in such sources are the "working surfaces," or hot spots, of double sources observed at small angles to the line of sight. The angular size of the hot spot will then be determined by the angle subtended by the beam and the distance of the working surface from the central source of energy. Detailed studies of a large number of sources during the last few years have shown that there is a high degree of collimation of the beam and, hence, the linear size of the hot spot may not significantly vary among sources of comparable luminosity. According to Duffett-Smith and Purvis (1981) the hot spots have an average size of about 3.5 kpc in the luminosity ranges of the 3C and 4C catalogs at low redshifts. On the other hand Kapahi and Schilizzi (1979) have argued, on the basis of their VLBI observations of hot spots in the lobes of more distant radio sources, that the sizes of hot spots decrease with increasing redshift.

In Fig. 2 I have plotted the angular sizes, θ_{Eq}, as a function of $(1+z)$ for the sources in the present sample. A least-square-fitted straight line has a slope of about -4.2. Such a slope is not predicted in any simple cosmological model such as that assumed in deriving Eq. 2.

It has been known for some time that the observed angular size/redshift variation for well-resolved double sources cannot be interpreted on the basis of any simple cosmological model without allowing for evolutionary effects on the linear sizes or luminosities (Kapahi and Subramanya 1982; Downes *et al.* 1981). For the sources in the present sample the calculated linear sizes, in an Einstein-de Sitter cosmology, range from 12 parsecs to 5.9 kpc. Most beaming models of hot spots involve the conversion of the beam energy into relativistic electrons at the working surface, which then produce the radio hot spots. In such models the linear size of the hot spot will be a function of the distance of the working surface from the base of the beam. The efficiency of conversion of the beam energy may be expected to depend on the ambient density. Spectroscopic studies of radio galaxies and quasars have shown that their nuclear regions contain very large amounts of gas with a steep density gradient towards the center. Hence, as the beam interacts with the gas and progresses outwards, we may expect a gradual increase in linear size and decrease in emissivity of the head of the beam. For the sources in the present sample, the seven orders of magnitude range in emissivity may be attributed to the combined effect of the ambient density variation and the beam energy conversion efficiency.

A number of studies of the counts of radio sources have shown that either the number density or the luminosity of sources must be a steep function of z. Since the lifetime of the compact stage of a radio source is very

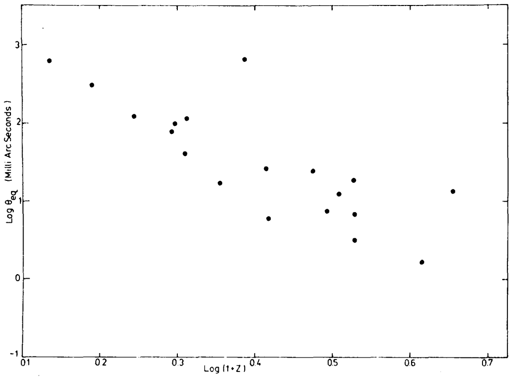

FIG. 2. Distribution of equipartition angular size θ_{Eq} as a function of redshift.

much smaller than the look-back time for the sources in the present sample the probability of observing them in their compact stage will be determined by their number density and luminosity at various epochs. The increase in compactness with redshift of the sources of comparable luminosity discussed here implies an increase in their number density or luminosity with z.

III. CONCLUSION

I have identified a sample of quasars whose spectra exhibit clearly defined maxima at low frequencies. The turnover frequencies of these quasars are found to increase with redshift, but the equipartition angular sizes, deduced on the assumption of a synchrotron self-absorption model, decrease much faster than is predicted by any simple cosmological model. The self-absorbing component is interpreted as the head of a beam advancing into the ambient medium in the central region of the parent galaxy. The emissivity of the working surface of the beam varies by seven orders of magnitude. I suggest that this variation may be due to the steep density gradient of the gas in the nuclear regions of the parent galaxies and to the increase in number density or luminosity of the sources at earlier epochs.

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