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Properties of CSS radio sources from 102 MHz interplanetary scintillation observations

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Abstract. Interplanetary scintillation observations of 56 compact steep-spectrum radio sources have been carried out at 102 MHz on the Large Phased Array, Russia. Observations have shown that 42 sources have low-frequency cut-offs in their spectra. The physical conditions in the cores of the quasars and radio galaxies studied are estimated.

Key words. radio continuum: galaxies – quasars: general

1. Introduction

Compact steep-spectrum (CSS) radio sources were first distinguished as a separate class in the works of Kapahi (1981), Peacock & Wall (1982). In the 2.7-GHz survey of bright radio sources of Peacock & Wall (1982), ~30% of all the sources observed had angular sizes $< 1''$ and steep spectra at high frequencies (it was previously thought that compact sources chiefly have flat spectra). The linear dimensions of these sources turned out to be smaller than those of the host galaxies. Optical identifications indicate that these sources are quasars and radio galaxies (O'Dea 1998).

The survey of compact radio sources (Artyukh & Tyul'bashev 1996a; Artyukh et al. 1998), carried out at 102 MHz using interplanetary-scintillation measurements, showed that, at meter wavelengths, compact (scintillating) sources with angular sizes $< 1''$ make up ~10% of the total number of radio sources (there are $\sim 10^4$ scintillating sources at a flux density level of 0.2 Jy in the northern sky). Most of these scintillating sources are quasars with steep spectra at low frequencies $\alpha > 0.5, S \sim \nu^{-\alpha}$ (Tyul'bashev 1997) .

Thus, in addition to compact sources with flat spectra, there exists a rather numerous population of compact sources with steep spectra. It is likely that this difference in radio spectra is accompanied by differences in the physical conditions in the nuclei of the galaxies hosting these compact radio sources. It is, therefore, of interest to investigate the physics of the active nuclei in which the compact radio sources are located.

Many CSS sources have been observed with high angular resolution and sensitivity at centimeter and decimeter wavelengths. At the same time, observations of these sources at low frequencies are not so numerous. We decided to observe a sample of CSS sources at meter wavelenghts by interplanetary scintillation method to investigate the nature of CSS sources. For our study, we have chosen the 62 CSS sources in the sample published in Sanghera et al. (1995).

The first paper of our work (Artyukh et al. 1999) contains the results of observations of 12 sources. Our observations have shown that all 12 sources have low-frequency cut-offs in their spectra. Assuming that the low-frequency cut-offs of spectra are the result of synchrotron self-absorption, we have estimated the physical parameters in compact components of sources studied. The absence of energy equipartition between magnetic field and relativistic plasma has been found in most sources.

The second paper of our work (Tyul'bashev & Chernikov 2000) contains the result of observations of 21 sources. The low-frequency cut-offs in the spectra of ~50% of sources studied have been found. The physical conditions in compact components of quasars and radio galaxies were compared. It was shown that most galaxies have the magnetic field energy density much higher than the energy density of relativistic plasma; at the same time most quasars studied showed the opposite situation. The possible correlation between the linear size of the compact component with observed synchrotron self-absorption and other physical parameters has been investigated. It was found that the relativistic particles density increases on the smaller scales, at the same time magnetic field strength increases on the larger scales.

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Table 1. Flux densities of CSS radio sources.

Name	$S_{\rm int}$ (Jy)	$S_{\rm comp}$ (Jy)	Name	$S_{\rm int}$ (Jy)	$S_{\rm comp}$ (Jy)	Name	$S_{\rm int}$ (Jy)	$S_{\rm comp}$ (Jy)	Name	$S_{\rm int}$ (Jy)	$S_{\rm comp}$ (Jy)
3C 43	16	4.4	3C 237	28	7.4	3C 346	19	< 0.8	4C 49.25	3	0.6
3C 48	66	48	3C 241	14.5	2.5	3C 380	90	8	4C 62.22	< 2	0.6
3C 49	20	3.7	3C 258	3.5	0.6	3C 454	13	3.4	4C 66.14	6	2
3C 67	14.6	5.2	3C 266	19	4.2	3C 455	19.5	4.5	4C 68.08	3	1.5
3C 93.1	11	9	3C 268.3	21	5.5	4C 12.50	3.7	0.6	CTA 21	< 6	3.3
3C 119	22	11	3C 277.1	17	3	4C 14.41	4.5	0.4	CTA 102	4.7	1.3
3C 138	31	8	3C 286	28	5	4C 14.82	8.4	3	CTD 93	< 2	0.2
3C 147	84	39	3C 287	31	6.1	4C 29.56	2.5	1	OE 131	3.6	0.8
3C 173	18	4	3C 298	68	12.7	4C 31.04	4.7	2.6	OF 247	< 1.5	1.1
3C 186	33	7.7	3C 299	20.7	6.6	4C 31.38	3	2.6	OI 407	< 1	< 0.3
3C 190	24.5	2	3C 309.1	29	2.5	4C 32.44	4.3	0.9	ON 343	< 1	< 0.2
3C 191	23	4.3	3C 318	23	5.7	4C 34.07	6	2.2	OQ 172	< 1	0.4
3C 213.1	12	< 0.8	3C 343	17	3.5	4C 34.09	11	2.8	OQ 323	7	0.6
3C 216	36	6	3C 343.1	13	3	4C 39.56	4.4	2.6	OZ 438	6.5	0.8

The current article is the final paper of our cycle about the investigation of CSS sources from 102 MHz interplanetary scintillation observations. The aim of our study is to find out the differences between the physical parameters of quasars and radio galaxies, and to perform a statistical analysis of our sample.

2. Observations and data analysis

We carried out our 102 MHz interplanetary-scintillation observations in 1995–1997 with the Large Phased Array of the Lebedev Institute of Physics, Russia. The effective area of the antenna in the zenith direction is 3×10^4 m^2, the beam size is approximately $0.5^\circ \times 1^\circ$, the receiver time constant $\tau = 0.4$ s, and the receiver bandwidth is about 200 kHz. The rms confusion due to extended (nonscintillating) sources is $\sim$1 Jy. The results of observations are presented in Table 1. Columns $S_{\rm int}$ list the integrated flux densities of the sources, columns $S_{\rm comp}$ correspond to the flux densities of compact (scintillating) components. Thus, we observed 56 sources from the sample of 62 sources. Six sources have not been observed because of their high declinations ($\delta > 75^\circ$) or high elongations.

We calibrated the observations using radio sources from the 3C catalog. As a rule, no fewer than five calibrators were recorded during each session. All flux-density estimates were made in the scale of Kellermann (1964). The data reduction method is given in Artyukh (1981), Artyukh & Tyul'bashev (1996b). This method enables us to detect faint scintillating sources, for which the scintillation dispersion is smaller than the noise dispersion on the receiver time constant τ. Note that accuracy of the flux density estimate depends on the fluctuation of flux density and on the elongation of the source. Typical accuracy is 20–25% for elongations smaller than 40° and flux density fluctuations higher than the sensitivity fluctuation of the antenna in a given direction. In the worst cases the accuracy of flux density estimates is still better than 30–50% (see details in Artyukh & Tyul'bashev 1996b; Artyukh et al. 1998).

We have thoroughly investigated the structure of each source from the published VLBI-maps. We checked whether the spectra of compact components have cut-offs at high frequencies. These components cannot dominate at low frequencies and could be excluded from further consideration. We also excluded components which have a low flux density and flat spectrum. Among the remaining compact components we tried to find those which have a comparatively high flux density and steep spectrum at high frequencies. Such an analysis allows us to reveal one or several components of known angular size dominating at 102 MHz.

Few sources have two components which both dominate at 102 MHz. We assumed that the flux density ratio of such components does not depend on frequency. For example, the western component of 3C 343.1 has a flux density at high frequencies two times greater than the flux density of the eastern one. At 102 MHz, 3C 343.1 has $S_{\rm comp} = 3$ Jy, so we assumed that the flux density of the western component at 102 Mhz is 2 Jy, and the eastern one is 1 Jy. However, this case is an exception.

Note that the angular sizes derived from interstellar scintillation cannot be used as a guide to understand which, among the various components, is dominating at 102 MHz. The estimation of sizes from scintillation depends on the velocity of the solar wind at the moment of observation, the turbulence spectrum of the interstellar medium, signal-to-noise ratio of the source, etc. As is shown in the work of Artyukh (1988), angular size of a source with a flux density of several Jy and which is smaller than $0.1''$ cannot be derived from scintillation with uncertainty better than 100%. Additionaly, we cannot separate scintillation from several compact components in a complex source.

The spectra of the sources involved in the present paper are given in Fig. 1. Circles correspond to integrated flux density, N, S, W, E – spectra of northern, southern, western or eastern component, C – spectrum of a core, K – spectrum of a knot in a jet. In these figures, it is shown that in spite of inaccuracy of flux density estimates, the low-frequency cut-offs have been detected very clearly in several cases. We decided not to present here the complete description of every source, because it is not informative. As an example, we only give, below, a description of the source ON 343.

3. ON 343

The radio source ON 343 is a quasar with redshift $z = 1.974$. This source has previously been observed with high angular resolution, but observations were not numerous (Dallacasa 1993; Dallacasa et al. 1995; Hodges et al. 1984; Kulkarni & Romney 1990). ON 343 has a jet-like structure extending from east to west with angular size $0.035'' \times 0.01''$. A relatively weak spot is also visible on the west. The angular size of this spot is $0.01'' \times 0.01''$ (at 1.6 GHz). In the work of Dallacasa (1993), this source has been resolved into 8 components with typical angular size $\sim 0.003''$. It is not possible to separate the scintillation of these components. We considered them as one single complex source, which should have strong scintillation due to its small angular size.

Our observations of ON 343 were obtained during four days, at elongations $\sim 36°$. The right ascension of the source $\alpha = 12^{\rm h}24^{\rm m}40^{\rm s}$ has been measured. It is about $1^{\rm m}$ smaller than the catalogued right ascension of ON 343 ($\alpha = 12^{\rm h}25^{\rm m}30^{\rm s}$). Nevertheless, we consider that we have detected the source ON 343 because the difference in right ascension of $1^{\rm m}$ for the antenna beam size of $7^{\rm m}$ is acceptable. The integrated flux density of ON 343 could not be measured, so we give an upper limit $S_{\rm int} < 1$ Jy (the confusion level of our antenna). We have measured weak ($\Delta S \simeq 0.15$ Jy) scintillation on levels below the sensitivity fluctuation of the antenna (for $\tau = 0.4^{\rm s}$, $\Delta S_{\rm noise} \sim 0.20-0.25$ Jy in the source direction). Therefore we set an upper limit of $S_{\rm comp} = 0.22$ Jy to the flux density of the scintillating components of ON 343. We did not take into account the orientation of this source because of its small angular size. As was mentioned before, we carried out our observations in 1995–1997 during the minimum of sun activity. Thus, we obtained the estimates of flux density with accuracy better than 30–40%. There are only two measurements for the compact structure in the spectrum of ON 343, given in Fig. 1 (Dallacasa et al. 1995). We can see from the spectrum that this source should be more correctly classified as a GHz-Peaked-Spectrum (GPS) radio source. The extended structure of GPS sources (if it exists) contributes about 5–10% to integrated flux density (Stanghellini et al. 1990; Baum et al. 1990; Stanghellini et al. 1997). Thus, we assumed that the integrated flux density at high frequencies is equal to the flux density of the compact (scintillating) component, so we could use the integrated spectrum as the spectrum of compact components.

Thus, high-frequency observations allowed us to reveal the compact component of ON 343 which should scintillate at 102 MHz. We also estimated the flux density of this component and an upper limit of the integrated flux density.

4. Physical conditions in the compact structures of the sources studied

Our observations have shown that 32 of 56 sources studied have more or less defined low-frequency cut-offs in the spectra of their compact components. Compact components of another 10 sources have GHz-peaked spectra. The low-frequency spectral cut-offs carry information about the physical conditions in the compact structures of the host galaxies. The analysis of possible mechanisms for the cut-offs, presented for instance in the work of Artyukh (1988), indicated the synchrotron self-absorption of radio emission as the most probable.

In the work of Artyukh (1988) it was pointed out that the formula suggested by Slysh (1963) for estimation of the angular size of compact radio sources from their spectra can be used to determine the strength of the magnetic field in the source once its angular size and flux density have been measured:

$$H_\perp = 2 \times 10^{-11} K(\gamma) \nu^5 \Omega^2 S^{-2} (1+z)^{-1}, \qquad (1)$$

where $K(\gamma)$ is the coefficient tabulated in the work of Pacholczyk (1970), ν is a frequency in MHz at which optical depth $\tau > 1$, S is the flux density in Jy of the source at this frequency, Ω is the solid angle in square arcseconds, and z is the redshift of the source.

When the redshift z is known, the linear size L of the source can be determined from its angular size, and, substituting the resulting H and L, we can estimate the relativistic electron density N_0 ($N(E){\rm d}E = N_0 E^{-\gamma}{\rm d}E$).

Note that the formula (1) can only be used for homogeneous sources which have low-frequency cut-off $S_\nu \propto \nu^{2.5}$. The details of spectra of inhomogeneous sources are discussed in the work of Artyukh & Chernikov (2001). To avoid the influence of a possibly inhomogeneous magnetic field we tried to choose for calculations the observations in the opaque region of the spectrum but near the maximum. In addition, the source is optically transparent at the maximum of spectrum, so we can estimate the magnetic field strength of the whole source.

We emphasize that this method of estimating the physical parameters does not assume equipartition between the energies of the magnetic field and of the relativistic plasma, which is commonly assumed in estimations of relativistic-electron densities and magnetic field strengths. This circumstance is extremely important. In fact, the broad high-excitation emission lines, superluminal motions, and appreciable short-period variability observed in many active galaxies reflect the presence of violent and

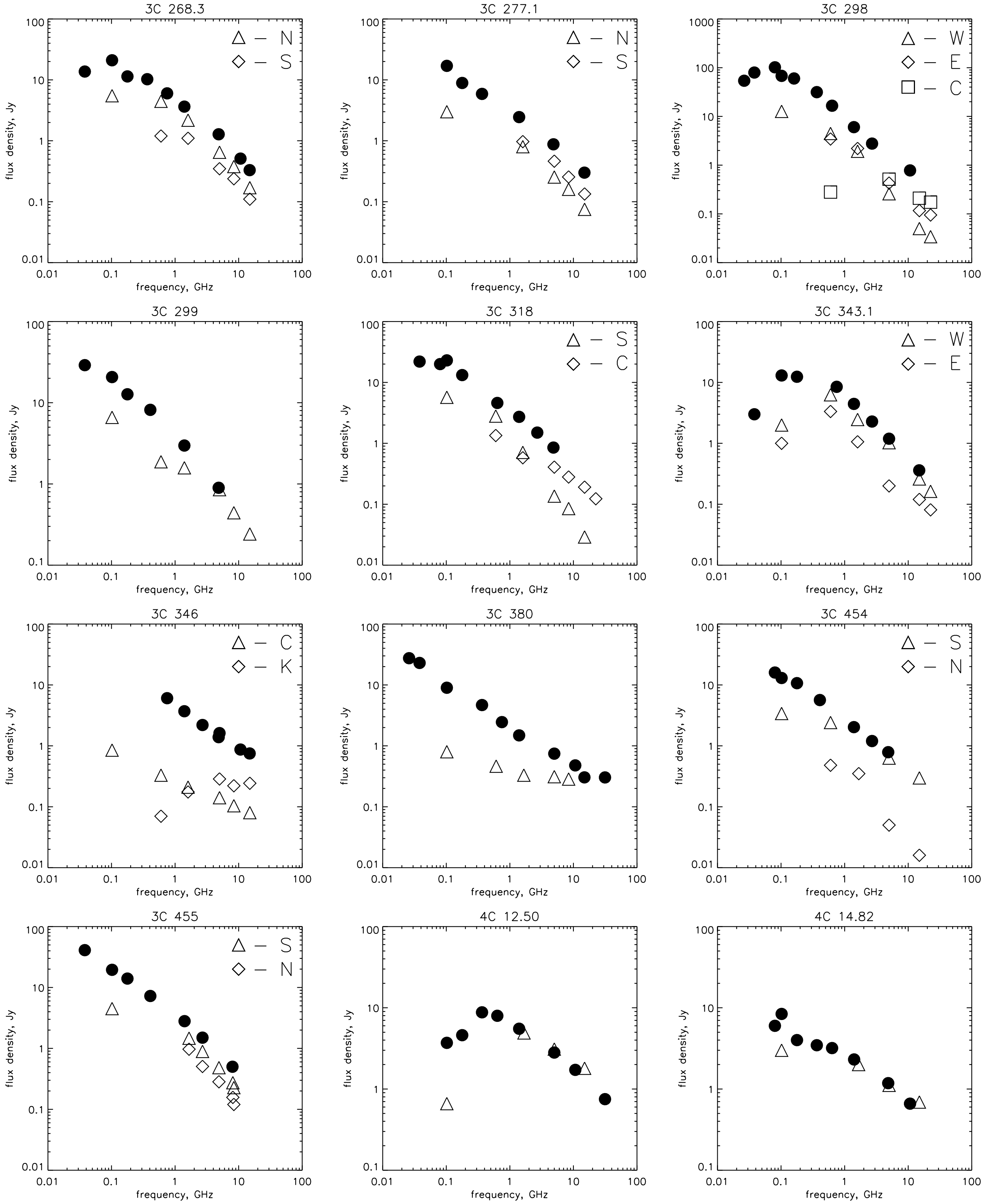

Fig. 1. The spectra of the sources.

rapidly variable processes in their nuclei; therefore, it is quite possible that equipartition had no time to be established.

In principle the frequency ν makes practically no contribution to the error in the estimated H, since the frequency of observation is always known to high accuracy

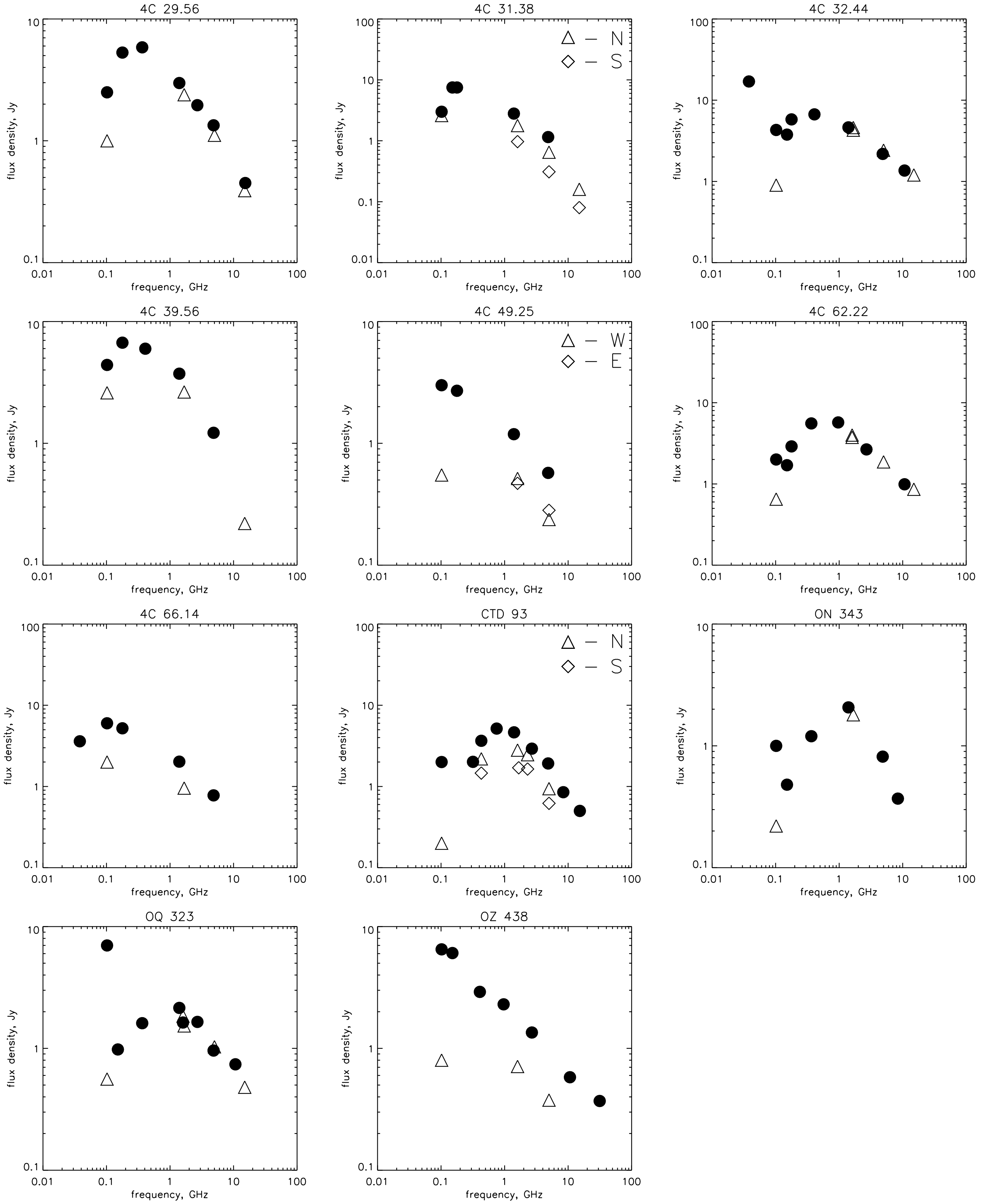

Fig. 1. continued.

(with an error equal to the receiver bandwidth, ∼1%). At meter wavelengths the flux density can be measured to within 10–20%, which leads to a factor of 1.5 error in H. Some flux density, instead, might be lost in VLBI observations due to resolution. The largest error is the one due to the uncertainty in the measured angular size of the source.

Thus, the accuracy of this method could be approximately an order of magnitude (for $H_\perp$). In most cases we might have an accuracy better than one order of magnitude because angular sizes of the sources obtained vary in different VLBI-observations within 30% ÷ 50%. We consider that the possibility of confusing the component dominating at 102 MHz is unlikely.

For several sources, low-frequency measurements found in the literature are quite sparse and the frequency of observations used for calculations may differ strongly from the peak frequency. In these cases a major contribution to the uncertainty on the magnetic field arises from the difference in the low-frequency spectrum from the law $\nu^{2.5}$. For example, if the spectrum in the opaque region is flat, the difference in frequency used for calculations from the frequency at which optical depth $\tau = 1$ by a mere factor of two implies an error of about 30 in H. In practice, however, low-frequency spectra of the sources are steep, so the uncertainty of H may remain within one order of magnitude.

Assuming that the emission of the radio sources studied is synchrotron radiation and that the low-frequency cut-offs in the spectra are the result of synchrotron self-absorption, we have estimated the physical parameters for 42 sources from the sample studied. The remaining 14 sources have straight spectra down to 102 MHz and therefore could not be used. We adopted $H_0 = 75$ km s^{-1}Mpc^{-1} and $q_0 = 1/2$ in our estimates.

We used angular sizes of the sources taken from high-frequency VLBI observations. In the work of Marscher (1983) it was shown that the angular size of the homogeneous spherically symmetric synchrotron source is a factor of 1.8 times the HPW, usually adopted as size measure. We decided not to make such a correction because we did not find any source with low-frequency cut-off $S_\nu \propto \nu^{2.5}$, therefore most of the sources are not spherically symmetric. The sizes were also presented in different papers at different brightness levels and they are often different for one source at the same frequency. Therefore we decided not to confuse the results by making the correction proposed by Marscher, although we are aware that this may lead to a wrong estimate of H in a number of objects.

The results of our estimates for all sources of the sample studied are given in Table 2. Columns one to five list the source name, redshift (z), adopted solid angle (Ω)and mean linear size of the compact component (L), spectral index in the optically thin region of the spectrum (α). Columns six to ten list our estimates of the physical parameters in the compact components of the sources: magnetic field strength, magnetic field energy density, density of relativistic electrons, energy density of relativistic electrons, density of the thermal electrons (n_e). The frequencies and the flux densities used to derive the parameters of several sources are given in Table 3. For other sources we used the data of our observations presented in Table 1. References to the origin of the component angular size and to the origin of spectra are given in Tables 4 and 5.

For the sources with unknown redshift (4C 14.41, 4C 34.07, CTA 21, OI 407, OQ 323), we adopted $z = 2$ (typical for quasars). Note that the value of redshift has no significant influence on the results because $H \sim (1+z)^{-1}$. In several cases we have estimated the physical parameters for different components in one source, so in Fig. 1 and in Table 2 these components differ from each other by labels N, S, E, W, C, K (standing for northern, southern, eastern or western component, core, knot in a jet). Compact components of 3 sources (3C 119, 4C 31.04, OI 407) consist of two substructures. The solid angles and flux densities of these substructures were summed to obtain the total values of Ω.

In Table 2 it is shown that the energy density of the magnetic field may differ significantly from the energy density of relativistic particles. We consider that sources have equipartition between the energy of magnetic field (E_H) and the energy of relativistic particles (E_e) if $10^{-3} < \frac{E_\mathrm{e}}{E_H} < 10^3$. Thus, energy equipartition is only observed in 8 of 42 sources (3C 119, 3C 138, 3C 237, northern component of 3C 268.3, 3C 286, 4C 29.56, 4C 31.04, 4C 32.44). In most cases the magnetic fields vary within an interval from 10^{-4} to 10^{-2} G. Extremely strong magnetic fields in sources 3C 186, 3C 190, 3C 213.1, 3C 346 and the western component of 4C 49.25 may be due to the overestimation of angular sizes of the sources. As it was mentioned before, angular sizes of the sources were taken from high-frequency VLBI-observations. However, there are sources in our sample with little data available in the literature, so in some cases we could only obtain the upper level estimates of angular size. The possible reason for such strong magnetic field estimates may also be the presence of the errors in spectra of sources. For example, spectra of 3C 286, 3C 298, 3C 454 and others have one low-frequency point which indicates the possible cut-off. We consider such cut-offs to be doubtful, so in cases of absence of cut-off our estimates may be inaccurate. In the case of extremely weak magnetic fields (4C 34.07, CTA 21, CTA 102, OE 131) we may possibly have to deal with superluminal motions (Artyukh, private communications), which also lead to errors in estimates of magnetic field strength. However, for a number of sources there is no obvious explanation for the very high or very low values of H and these are likely to be genuine sources far from equipartition.

Several sources (for example, 4C 12.50, 4C 32.44, 4C 62.22) had been studied quite thoroughly at low frequencies, so we could obtain a reliable frequency of the maximum of the flux density spectrum. This allowed us to compare the estimates of physical parameters obtained at the frequency of maximum with ones obtained by our method. The differences in magnetic field strengths have proved to be one or two orders of magnitude, and in all cases the absence of energy equipartition has been additionally reinforced.

We calculated the total energy of relativistic particles by integration of the electron energy spectrum. For the limits of integration we chose energies of the electrons

Table 2. Physical parameters in compact components of the radio sources.

Name	z	Ω (arcsec $\times$ arcsec)	L (pc)	α	H (G)	E_H (erg cm^{-3})	$n_{\rm e}$ (cm^{-3})	$E_{\rm e}$ (erg cm^{-3})	$n_{\rm e\ thermal}$ (cm^{-3})
3C 43	1.46	0.013×0.013	60	0.8	2×10^{-6}	10^{-13}	11	5×10^{-2}	25
3C 48	0.367	0.4×0.1	800	0.9	3×10^{-3}	10^{-6}	10^{-5}	10^{-9}	15
3C 49	0.621	0.03×0.015	100	0.7	3×10^{-5}	3×10^{-11}	10^{-1}	10^{-4}	45
3C 119	1.023	$0.03 \times 0.15+$ $+0.025 \times 0.1$	300	0.6	10^{-3}	10^{-8}	4×10^{-4}	10^{-7}	35
3C 138	0.759	0.05×0.07	300	0.8	3×10^{-4}	10^{-8}	10^{-3}	10^{-6}	25
3C 147 W	0.545	0.17×0.05	400	1.1	10^{-1}	10^{-3}	10^{-6}	10^{-11}	100
3C 147 E	0.545	0.5×0.5	2500	1.3	10^{-3}	10^{-7}	7×10^{-7}	6×10^{-11}	3
3C 186	1.063	0.224×0.083	800	1.6	10^{4}	4×10^{6}	10^{-12}	7×10^{-20}	60
3C 190	1.197	0.03×0.017	100	0.8	10^{5}	3×10^{8}	5×10^{-12}	10^{-19}	380
3C 213.1	0.194	0.2×0.2	600	0.8	5	1	6×10^{-10}	10^{-15}	15
3C 237	0.877	0.2×0.1	800	1.4	4×10^{-3}	7×10^{-7}	3×10^{-5}	10^{-9}	10
3C 241 W	1.617	0.1×0.1	600	1.1	10^{-2}	4×10^{-6}	3×10^{-6}	10^{-10}	16
3C 241 E	1.617	0.1×0.1	600	1.6	6×10^{-3}	10^{-6}	2×10^{-5}	10^{-9}	16
3C 268.3 N	0.371	0.12×0.08	430	1.2	4×10^{-3}	6×10^{-7}	4×10^{-5}	10^{-9}	12
3C 268.3 S	0.371	0.19×0.11	600	1.1	5×10^{3}	10^{6}	3×10^{-12}	10^{-19}	52
3C 286	0.849	0.05×0.03	200	0.3	10^{-3}	10^{-8}	10^{-3}	10^{-6}	30
3C 287	1.055	0.06×0.03	250	0.5	10^{-4}	10^{-9}	3×10^{-3}	10^{-6}	30
3C 298 E	1.439	0.1×0.083	530	1.4	30	30	10^{-8}	10^{-14}	30
3C 309.1	0.904	0.032×0.008	100	0.4	10^{-4}	10^{-10}	10^{-1}	10^{-4}	45
3C 318	0.752	0.062×0.043	280	1.5	10^{-4}	10^{-9}	4×10^{-3}	10^{-6}	15
3C 343	0.988	0.039×0.018	150	0.9	6×10^{-5}	10^{-10}	6×10^{-2}	4×10^{-5}	45
3C 343.1 W	0.75	0.17×0.11	780	1.2	10^{-1}	3×10^{-4}	6×10^{-7}	7×10^{-12}	14
3C 343.1 E	0.75	0.13×0.07	500	1.2	10^{-1}	3×10^{-4}	10^{-6}	10^{-11}	17
3C 346 K	0.161	0.065×0.03	100	0.1	7×10^{5}	10^{10}	4×10^{-14}	10^{-21}	500
3C 454	1.757	0.15×0.02	300	1.4	10^{2}	10^{3}	10^{-9}	6×10^{-16}	80
4C 12.50	0.122	0.06×0.02	60	0.8	10^{-3}	10^{-7}	3×10^{-3}	3×10^{-17}	70
4C 14.41	2(?)	0.01×0.01	60	0.4	10^{-4}	7×10^{-10}	6×10^{-2}	7×10^{-5}	70
4C 14.82	0.237	0.1×0.1	330	0.6	3×10^{-2}	4×10^{-5}	10^{-6}	4×10^{-11}	15
4C 29.56	0.842	0.1×0.01	170	0.9	10^{-3}	6×10^{-8}	10^{-3}	3×10^{-7}	50
4C 31.04	0.059	$0.03 \times 0.02+$ $+0.043 \times 0.024$	20	0.4	10^{-3}	10^{-7}	10^{-3}	4×10^{-7}	140
4C 31.38	1.577	$< 0.04 \times < 0.04$	230	1.2	$< 3 \times 10^{-4}$	$< 3 \times 10^{-9}$	$> 7 \times 10^{-3}$	$> 10^{-6}$	25
4C 32.44	0.369	0.06×0.03	170	0.7	3×10^{-3}	3×10^{-7}	4×10^{-4}	5×10^{-8}	40
4C 34.07	2(?)	0.006×0.003	20	0.4	10^{-7}	6×10^{-16}	10^{3}	50	110
4C 39.56	0.4	0.12×0.015	580	1.1	6×10^{-2}	10^{-4}	10^{-6}	10^{-11}	30
4C 49.25 W	0.206	0.23×0.16	560	1.4	6	1	3×10^{-9}	4×10^{-15}	21
4C 49.25 E	0.206	0.125×0.09	330	0.8	8×10^{-1}	3×10^{-2}	6×10^{-9}	4×10^{-14}	28
4C 62.22	0.431	0.06×0.02	140	1.0	4×10^{-2}	7×10^{-5}	10^{-4}	10^{-9}	60
CTA 21	2(?)	0.003×0.004	20	1.0	10^{-8}	10^{-18}	10^{6}	3×10^{4}	270
CTA 102	1.037	0.001×0.005	10	0.0	10^{-7}	10^{-15}	10^{4}	4×10^{2}	140
CTD 93	0.473	0.005×0.005	20	1.4	10^{-4}	10^{-9}	10	5×10^{-3}	280
OE 131	2.67	0.0012×0.0002	3	0.5	10^{-10}	6×10^{-22}	10^{9}	10^{9}	300
OF 247	0.219	0.02×0.01	50	1.1	6×10^{-2}	10^{-4}	4×10^{-3}	7×10^{-8}	90
OI 407	2(?)	$0.008 \times 0.004+$ $+0.008 \times 0.004$	30	0.8	6×10^{-5}	10^{-10}	1	10^{-3}	140
ON 343	1.974	0.035×0.01	100	1.3	3×10^{-2}	4×10^{-5}	7×10^{-4}	10^{-8}	120
OQ 172	3.54	0.01×0.01	45	0.8	5×10^{-5}	10^{-10}	1	10^{-3}	210
OQ 323	2(?)	0.04×0.015	110	0.8	7×10^{-2}	10^{-4}	5×10^{-5}	10^{-9}	100
OZ 438	0.145	0.11×0.09	230	0.6	4×10^{-1}	6×10^{-3}	6×10^{-8}	8×10^{-13}	30

radiating in the frequency range 10 MHz and 100 GHz. The same integration limits have been assumed in Artyukh et al. (1999), Tyul'bashev & Chernikov (2000).

5. Discussion

1) Figure 2 shows magnetic field strength vs. linear size dependence (on the left) and relativistic particles density vs. linear size dependence (on the right) for all galaxies

Table 3. Frequencies and flux densities used to derive the parameters.

Name	ν (MHz)	S (Jy)	Reference	Name	ν (MHz)	S (Jy)	Reference
3C 147 W	329	11	Simon et al. (1980)	4C 12.50	178	4.60	Gower et al. (1967)
3C 147 E	329	12	Simon et al. (1980)	4C 32.44	151	3.77	Waldram et al. (1996)
3C 186	610	0.32	Rendong et al. (1991a)	4C 62.22	365	5.56	Douglas et al. (1996)
3C 190	1660	0.06	Spencer et al. (1991)	CTD 93	430	2.19	Phillips & Mutel (1980)
3C 268.3 S	610	1.20	Rendong et al. (1991a)	OF 247	430	3.42	Phillips & Mutel (1980)
3C 298 E	610	3.44	Rendong et al. (1991a)	ON 343	365	1.20	Douglas et al. (1996)
3C 346 K	1660	0.21	Spencer et al. (1991)	OQ 323	365	1.61	Kuehr et al. (1981)
3C 454	610	0.48	Rendong et al. (1991a)				

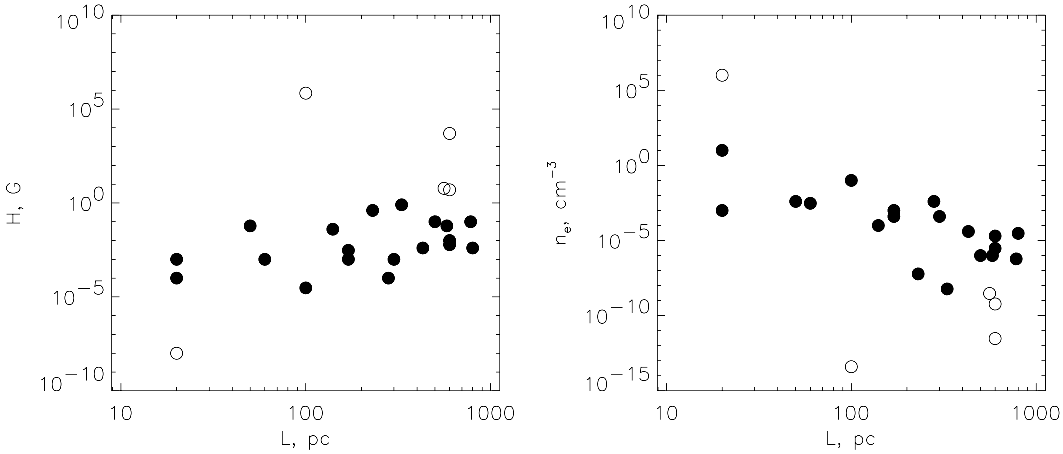

Fig. 2. Magnetic field strength (left) and relativistic plasma density (right) vs. linear size for radio galaxies.

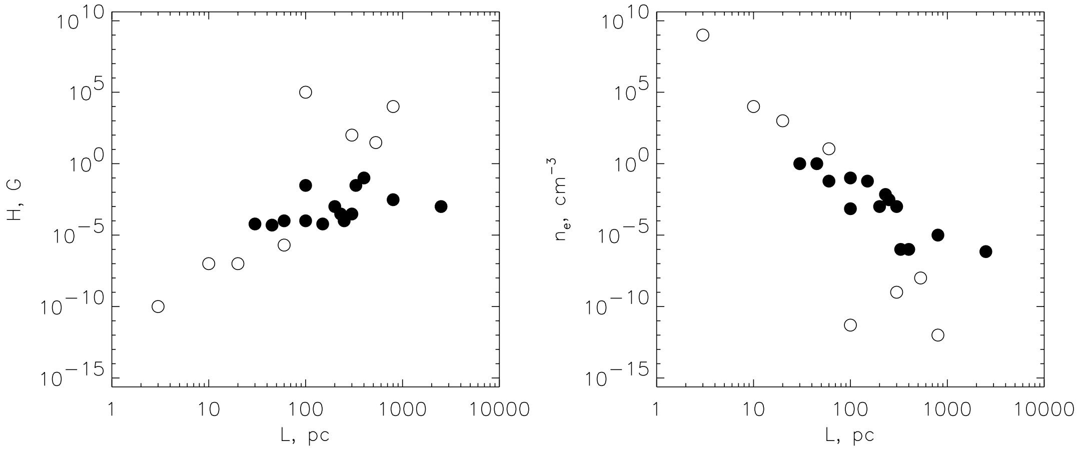

Fig. 3. Magnetic field strength (left) and relativistic plasma density (right) vs. linear size for quasars.

from the sample studied. Figure 3 shows the same dependences for all studied quasars. In each figure, the empty circles correspond to estimates of magnetic field strength greater than 1 G (which seems to be doubtful) or less than 10^{-5} (weaker than the mean magnetic field strength of our Galaxy) which reflect uncertain values of physical parameters. We have obtained the empirical relations for quasars:

$$H = 6 \times 10^{-10\pm2} L^{3\pm1}, n_{\rm e} = 2 \times 10^{9\pm2} L^{-6\pm1}, \tag{2}$$

and for galaxies:

$$H = 2 \times 10^{-7\pm2} L^{2\pm1}, n_{\rm e} = 2 \times 10^{5\pm3} L^{-4\pm1}. \tag{3}$$

We used all our estimates including the doubtful ones for calculations, but the slope of the relation does not change much if they are rejected. Given the large dispersion of the data points, we do not think that the differences in the relations (2) and (3) are statistically significant. The magnetic field intensity increases with increasing linear size.

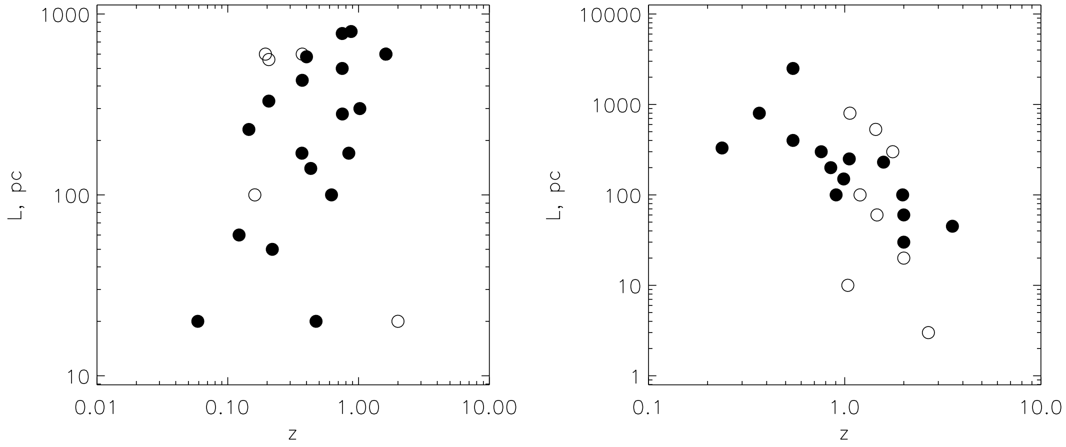

Fig. 4. Linear size vs. redshift for galaxies (left) and for quasars (right).

We cannot explain this dependence. We must also bear in mind that these dependences may be inaccurate because of the inaccuracies in estimates of physical parameters. Moreover our method leads to $L \sim \theta$ and $H \sim \theta^4$, so obtained empirical dependences $H \sim L^{2\div 3}$ and $n_{\rm e} \sim L^{-4\div -6}$ may be partially induced. It is necessary to additionally verify the results obtained and to investigate the sources with doubtful values of the magnetic field strength, to test if these dependences are real.

2) Figure 4 shows linear size vs. source redshift dependence for galaxies (on the left) and for quasars (on the right). We cannot give the exact interpretation of these dependences. In the case of quasars, for example, we might have to deal with evolution of sources: at high redshifts we could observe young compact sources, which increase angular size during evolution. In the case of galaxies, selection effects could take place – we cannot observe compact sources at great distances because sources in galaxies are much weaker than sources in quasars. On the other hand, such an interpretation can be incorrect because we observed spectral cut-offs in the cores and jets of quasars and in the lobes and hot spots of radio galaxies. So, the sources have different physical natures and we cannot compare any correlations.

3) We have also studied correlations between the physical parameters obtained and source redshifts. There is no evidence for correlations between magnetic field strength, relativistic particles density and source redshift. Therefore, there seems to be no evidence for evolution of the parameters until $z \sim 2{-}3$. However, the reason for this result may be also the fact that the nature of the source scintillating component is significantly different (hot spots, jets, cores, radiolobes).

4) It is also interesting to compare the magnetic field strengths of quasars and radio galaxies. We have rejected the sources with extremely strong magnetic field strengths (> 1 G) and the sources with extremely weak strengths ($< 10^{-5}$ G). We have also rejected the sources having different values of magnetic field strength in different components. It was found that 6 galaxies and 2 quasars have 10^{-2} G $< H <$ 1 G, 6 galaxies and 2 quasars have 10^{-3} G $< H < 10^{-2}$ G, 3 galaxies and 8 quasars have 10^{-5} G $< H < 10^{-4}$ G (Fig. 5). Therefore, the mean magnetic field strength in quasars ($\sim 10^{-4}$ G) is weaker than mean magnetic field strength in galaxies ($\sim 10^{-3}$ G).

5) Additional information about physical parameters may be obtained from high-frequency breaks of the spectrum. It was shown in the works of Kardashev (1962), Pacholczyk (1970), Deeg et al. (1993) that electrons with different energies have different energy losses. For the low-energy electrons, the ionization losses are common, for the high-energy electrons the synchrotron emission losses dominate; at the same time middle-energy electrons have mainly free-free losses. Thus, the function of the relativistic electron distribution has two breaks. The spectrum of relativistic electron radio emission also has two breaks. Ten sources of our sample show evidence of high-frequency spectral breaks (3C 286, 3C 287, 3C 343, 3C 67, OF 247, 3C 190, 3C 191, 3C 268.3, ON 343, 3C 299). For seven of these sources we estimated the values of physical parameters from low-frequency spectral cut-offs. Our estimates of magnetic field strength lead to the conclusion that all radio emitting relativistic electrons only lose their energy for synchrotron emission, and other losses are negligible. In this case, the high-frequency spectral break could be interpreted within the model of one-time injection of electrons. We have estimated the age of 3C 286, 3C 287, 3C 343, OF 247, 3C 268.3, ON 343 with the method suggested in the work of Kardashev (1962). For the source 3C 190 we have obtained doubtful estimates of magnetic field strength, therefore we have not estimated the age of this source. We have found that the typical age of sources is $10^4{-}10^5$ years. For OF 247 we obtained 0.1 year. In this case we probably have overestimated the magnetic field strength and, as a consequence, underestimated the age of the source. So, all the sources with high-frequency spectral breaks have been found to be very young. 6) The low-frequency cut-offs in the spectra of the radio sources considered could be the result of absorption by thermal (non-relativistic) plasma. In the work of Artyukh et al. (1999)

Table 4. The sample of sources which have low frequency cut-off of the spectrum.

Name	Type	References to the origin of the component angular size	References for the spectrum of compact component	References for the integrated spectrum
3C 43	Q	1, 2, 3	2, 3, 4, 5, 6	7, 8, 9
3C 48	Q	5, 6, 10, 11, 12	6, 11, 12, 13, 14	7, 9, 15, 16
3C 49	G	1, 5, 6, 11, 17, 18, 19	6, 11, 17	8, 20
3C 119	G	6, 19, 21, 22, 23, 24	6, 11, 19	8, 25, 26, 27, 28
3C 138	Q	1, 5, 6, 18	5, 6, 18, 29	7, 9, 30
3C 147	Q	1, 10, 11, 12, 13, 29, 31, 32, 33, 34, 35, 36	10, 11, 31, 34, 35	1, 7, 8, 9, 11, 15, 26, 31
3C 186	Q	2, 4, 6, 11, 29	2, 4, 6	8, 26, 27, 37
3C 190	Q	1, 2, 6, 11	1, 2, 6, 11, 29	8, 20, 26, 28, 37, 38
3C 213.1	G	5, 13, 29	5, 13, 29	8, 26, 39
3C 237	G	1, 6, 11, 13, 19, 29, 40	1, 6, 11, 13, 29	7, 9, 20, 37
3C 241	G	1, 5, 6, 11, 13, 17, 19, 29	6, 11, 17, 29	8, 20
3C 268.3	G	5, 6, 13, 19	5, 6, 13, 19, 29	7, 9, 15, 26, 41, 42
3C 286	Q	2, 13, 34, 43	1, 2, 10, 11, 34, 43	7, 9, 16, 37, 44
3C 287	Q	11, 18, 45, 46	1, 6, 10, 11, 18	7, 9, 37
3C 298	Q	5, 6, 11, 13	5, 6, 11, 13	9
3C 309.1	Q	6, 10, 12, 47, 48, 49, 50, 51	1, 6, 10, 12, 48, 51	7, 9, 37
3C 318	G	2, 5, 6, 11, 13, 29	2, 5, 6, 11, 29	8, 20, 26, 37
3C 343	Q	6, 19, 52, 51	5, 6, 11	7, 8, 9
3C 343.1	G	6, 11, 13, 19, 29	6, 11, 13, 19	7, 9, 42
3C 346	G	2, 5, 6, 11, 29	2, 5, 6, 11, 29	7, 8, 9, 37
3C 454	Q	2, 4, 5, 6	4, 6	8, 20, 26
4C 12.50	G	10, 13, 53, 54	13, 54	9, 28, 55
4C 14.41	Q	17, 56, 57	17, 57	9, 16, 20
4C 14.82	Q	2, 4, 5, 6	6, 13	8, 9, 16, 20
4C 29.56	G	13, 58, 59	13, 58	8, 9, 16, 39, 60
4C 31.04	G	46, 61	46, 61	8, 9, 16, 39, 60, 62
4C 31.38	Q	10, 13	13	8, 39, 63, 64
4C 32.44	G	13, 26, 58, 59, 65	13, 58	8, 9, 16, 26, 37, 39, 64
4C 34.07	Q	13, 17, 59	13, 59	8, 9, 39, 44, 66
4C 39.56	G	13, 58, 59	13, 58	8, 26, 27, 39
4C 49.25	G	17	17	8, 26, 28
4C 62.22	G	57, 58, 59	13, 57, 58	9, 28, 67, 68, 69
CTA 21	G	21, 70, 71	13, 70	9, 15, 20, 72
CTA 102	Q	10, 13, 47, 58, 70, 73, 74	10, 13, 58, 70, 75	13, 46, 70
CTD 93	G	13, 43, 76, 77	43, 76, 77	8, 9, 16, 20
OE 131	Q	58, 59	58, 59	9, 16, 38, 62
OF 247	G	13, 78	13, 78	9, 62, 79
OI 407	Q	17, 80	17, 80, 81	8, 26, 27
ON 343	Q	58, 59, 65, 82	58, 59	8, 25, 67, 83
OQ 172	Q	13, 58	10, 13, 52, 58	38, 67
OQ 323	?	13, 58, 59, 82	13, 58	8, 9, 15, 58, 60, 64
OZ 438	G	17, 51, 84, 85	17	9, 27, 86, 87

it was shown that this mechanism is unlikely, because the thermal electron density required should be close to the thermal-plasma densities in superluminous IR galaxies. However, we have estimated the density of thermal electrons which is necessary to provide the observed low-frequency spectral cut-offs; the results are given in the last column of Table 2. We can see that our estimates of n_e are several orders of magnitude higher than the density of thermal electrons on the same scales in our Galaxy (Downes & Maxwell 1966).

7) The Razin effect (Razin 1960; Tsytovich 1967) also has been considered in Artyukh et al. (1999), and it was shown that this mechanism is unlikely.

6. Conclusions

Interplanetary-scintillation observations of 56 compact steep-spectrum radio sources have been carried out at 102 MHz with the Large Phased Array of the Lebedev Institute of Physics, Russia. 28 sources are galaxies, 26 are quasars and 2 sources have no optical identification (4C 66.14, OQ 323). Our observations indicate the

Table 5. References for Table 4.

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85. Zensus et al. (1984)
86. Witzel et al. (1978)
87. Hales et al. (1993)

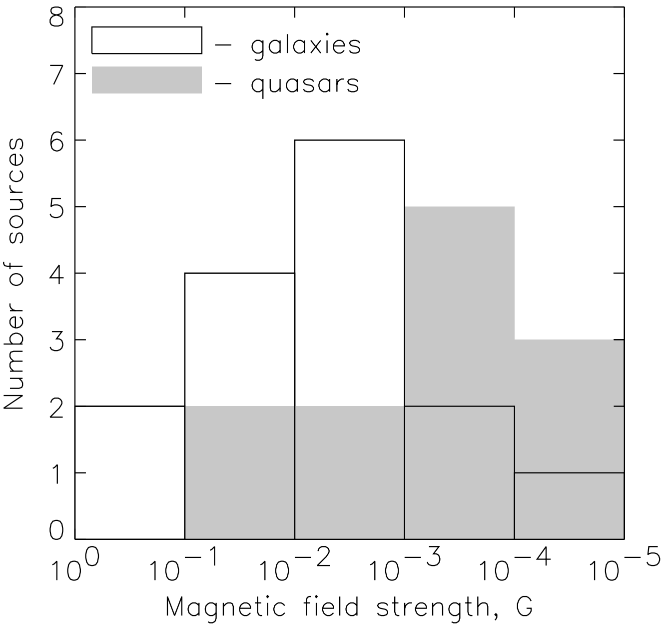

Fig. 5. Histogram of distribution in magnetic field strength.

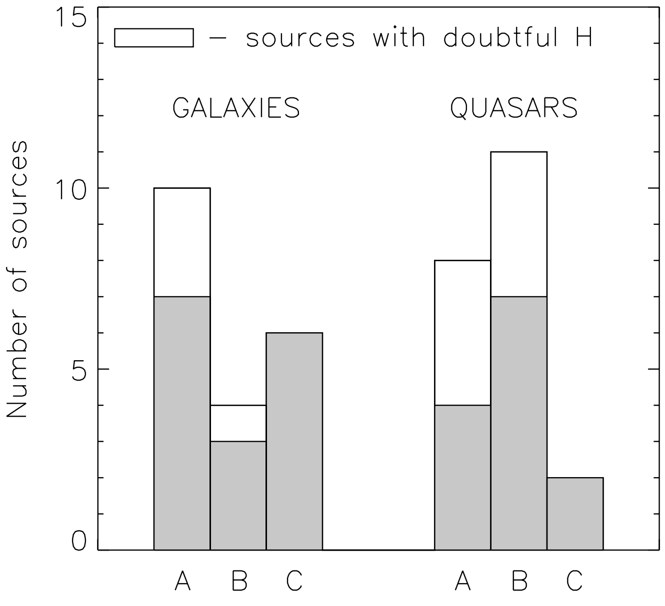

Fig. 6. Histogram of distribution in the ratio of energies A: $E_H \gg E_e$, B: $E_H \ll E_e$, C: $E_H \approx E_e$.

presence of low-frequency cut-offs in the spectra of 42 sources. 20 sources with spectral cut-off are galaxies, 21 are quasars and 1 has no identification (OQ 323).

Assuming that the low-frequency cut-offs in the spectra are the result of synchrotron self-absorption, we have estimated magnetic field strength, relativistic particle density and the energy densities of the magnetic field and of the relativistic plasma in the compact structures of the galaxies hosting compact radio sources. Energy equipartition is observed in 8 of 42 sources. 6 sources are galaxies and 2 are quasars. 10 galaxies and 8 quasars have the energy of their magnetic field several orders of magnitude higher than the energy of relativistic particles. 4 galaxies and 11 quasars show the opposite situation (Fig. 6). The source OQ 323, which has no optical identification, has $E_H \gg E_{\rm e}$. Therefore, it seems that the energy of the magnetic field may dominate in the main part of the galaxies; at the same time, the quasars may have different balances between energies, including equipartition. The situation does not change if we remove sources with doubtful estimates of the magnetic field strength (Fig. 6).

There is a possible correlation between the linear size and some physical parameters of the compact components. The relativistic particle density increases on the smaller scales, at the same time that magnetic field strength increases on the larger scales. There is also a possible correlation between linear size of the compact component and source redshift. Quasars have smaller linear size at higher redshifts, at the same time, radio galaxies may show the opposite correlation. There is no evidence for correlation between other physical parameters and redshifts of compact sources.

The mean magnetic field strength in galaxies is one order of magnitude higher than the mean magnetic field strength in quasars. The age of sources with a high-frequency spectral break is 10^4–10^5 years.

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