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Magnetic fields around AGNs at large and small scales

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Abstract. The dipole structure of the magnetic field on distances ≥1 kpc from an active galactic nucleus is discussed. Two different models of the magnetic field around a supermassive black hole on the scale of the accretion disk are tested. The first model suggests a superstrong field of the order of 10^{10} Gauss (Kardashev 1995), the other one proposed by Field & Rodgers (1993) predicts much lower values ($\sim 10^4$ Gauss).

Key words. galaxies: active – galaxies: nuclei – galaxies: magnetic field

1. Introduction

Active galactic nuclei (AGNs) are known to be associated with highly collimated jets. Their collimation and the polarization of the magnetic field H within them is interpreted as evidence for regular field structures. Observations show that H decreases as one recedes from the nucleus. For distances greater than 1 pc, Lobanov (1998) found in the case of 3C 345 that $H \propto r^{-1}$ out to $r = 500$ pc. For the inner field structure on scales less than 1 pc, observational data are missing, but two competing theoretical models exist. The first (Kardashev 1995) predicts that the field decreases with the cube of the distance from the AGN, $H \propto r^{-3}$; according to the second, $H \propto r^{-1}$ (Field & Rodgers 1993). By extrapolation, the two theories yield values for H at the edge of the accretion disk ($r \sim 0.001$ pc) that are discrepant by a factor of 10^6. The purpose of the present paper is to derive the dependence of the magnetic field at large distances (>1 kpc), and to check which of the two above-mentioned theories is more realistic.

2. Method and results

As a rule, estimates of the magnetic field in AGNs are made for large scales ranging from parsecs to kiloparsecs.

Usually, one applies a modified form of the Slish formula (1963), which connects the perpendicular magnetic field $H_\perp$ to the cutoff frequency ν, the angular size θ and flux density S of the compact component. For a source at redshift z,

$$H_\perp = 2 \times 10^{-11} K(\gamma) \nu^5 \theta^4 S^{-2} (1+z)^{-1} (\mathrm{G}),$$

where $K(\gamma)$ is a coefficient tabulated by Pacholczyk of order one (Pacholczyk 1970). The accuracy of this method is approximately an order of magnitude (for $H_\perp$) mainly due to the uncertainty of the measured angular size of the source (see details in Artyukh 1988, and Tyul'bashev 2001).

Using the above equation, magnetic fields have been calculated for approximately 50 sources with compact components and synchrotron self–absorption (Artyukh 1999; Tyul'bashev 2000; Tyul'bashev 2001; Tyul'bashev 2001a). However, there are only 5 cases for which $H_\perp$ could be estimated on both sides of the nucleus (Tyul'bashev 2000; Tyul'bashev 2001). The parameters of these five sources are listed in Table 1. Column 1 gives the name and type of the source (Q = quasar, G = radio galaxy) plus the relative position of the compact component (W = west, E = east, N = north, S = south). Columns 2 to 7 contain the red shift z; the angular size Ω; the mean linear size L of the compact component; the spectral index α at frequencies where the source is transparent ($S \sim \nu^{-\alpha}$); the magnetic fields strength $H_\perp$; the ratio $E_\mathrm{H}/E_\mathrm{e}$ of the energy of the magnetic field to the energy of the relativistic particles. Question marks indicate doubtful values.

Columns 8 and 9 list for each source the distance between the nucleus and its two compact components; distances are given in arcsec (θ) and parsec (l) and were derived from the original papers (Akujor 1990; Akujor 1991; Zhang 1991; van Breugel 1992; Sanghera 1995).

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Table 1. Parameters of the five sources.

Name 1	z 2	Ω 3	L(pc) 4	α 5	$H_\perp$ (G) 6	$E_{\rm H}/E_{\rm e}$ 7	θ 8	l(pc) 9	n 10	H(100 AU) 11	$H_{\rm min}$(limit) 12
3C 147 (Q) W	0.545	$0.17'' \times 0.05''$	400	1.1	6×10^{-1}	10^8	$0.09''$	400			$>5 \times 10^5$
3C 147 (Q) E	-	$0.5'' \times 0.5''$	2500	1.3	10^{-3}	10^4	$0.49''$	2500	3.8	10^{16}	
3C 241 (G) W	1.617	$0.1'' \times 0.1''$	600	1.1	10^{-2}	4×10^4	$0.36''$	2200			$>4.5 \times 10^4$
3C 241 (G) E	-	$0.1'' \times 0.1''$	600	1.6	6×10^{-3}	10^3	$0.46''$	2800	2.2	10^{18}	
3C 268.3 (G) N	0.371	$0.12'' \times 0.08''$	430	1.2	4×10^{-3}	6×10^2					
3C 268.3 (G) S	-	$0.19'' \times 0.11''$	600	1.1	5×10^3?	10^{25}?					
3C 343.1 (G) W	0.75	$0.17'' \times 0.11''$	780	1.2	10^{-1}	4×10^5	$0.27''$?	1500?		10^{18}?	$>3 \times 10^5$?
3C 343.1 (G) E	-	$0.13'' \times 0.07''$	500	1.2	10^{-1}	3×10^7	$0.27''$?	1500?		10^{18}?	
4C 49.25 (G) W	0.206	$0.23'' \times 0.16''$	560	1.4	6	2×10^{14}	$0.94''$	2700			$>3 \times 10^7$
4C 49.25 (G) E	-	$0.125'' \times 0.09''$	330	0.8	8×10^{-1}	10^{12}	$1.8''$	5600	3.1	10^{21}	

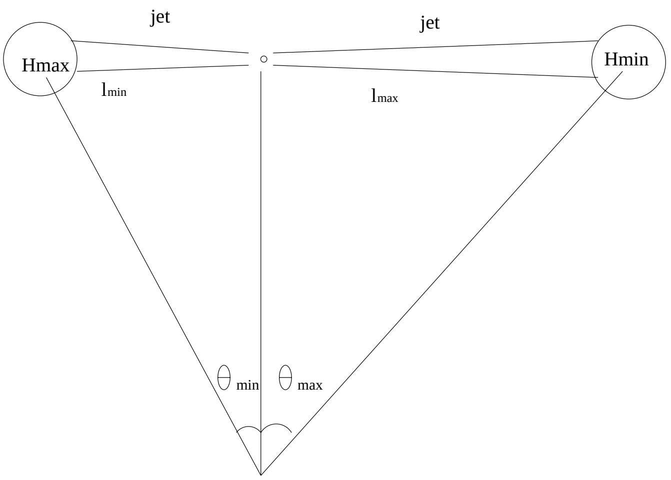

Fig. 1. In all sources of Table 1, the magnetic field is stronger in the component that is closer to the nucleus ($H_{\rm max}$) corresponds to short distances ($l_{\rm min}, \theta_{\rm min}$) from the nuclei.

As we have no information on the location of the nuclei for 3C 268.3 and 3C 343.1, we will assume that they are located halfway between the components with spectral cutoff. In the absence of high spatial resolution data at low frequencies, the value for the magnetic field in 3C 268.3 (S) is doubtful and likely to be an overestimate (Tyul'bashev 2001). Apparently this large value of magnetic field can be explained by incorrect determination of the spectra maximum ($H \sim \nu^5$) or an incorrect value of the flux density at low frequency points.

Table 1 allows a number of interesting conclusions: *a)* the larger the distance from the nucleus, the smaller the magnetic field in the compact components; *b)* the energy of the magnetic field is always greater than the energy of the relativistic particles; *c)* four out of five sources are radio galaxies; *d)* the size of the compact components is not correlated to the distance from the nucleus.

As usual, we assume that the strength of the magnetic field increases towards the nucleus. Let us write the relation between the magnetic field and the distance to nucleus in the form (see Fig. 1)
$H_{\rm max} = H_{\rm min} \times (\theta_{\rm max}/\theta_{\rm min})^n = H_{\rm min} \times (l_{\rm max}/l_{\rm min})^n$.
Using the values of the magnetic field ($H_\perp$) and the angular distance (θ) from Table 1, we find the exponent n as given in Col. 10 of Table 1.

We must keep in mind that our method of estimating magnetic fields is very rough. To determine the exponent n, we selected only 3 sources (see Table 1). Nevertheless, it is suggestive that the average value $\langle n \rangle = 3$, which is characteristic for a dipole magnetic field. If the magnetic field is indeed dipolar, we may extrapolate the field strength to small scales and then find for the outer edge of the accretion disk (∼100 AU) the numbers listed in Col. 11 of Table 1. They imply unrealistically strong magnetic fields. It is more likely that the collimation of jets changes the $H \sim l^{-3}$–law at large distances into a weaker decline at small scales. However, where the break in the exponent n occurs is unknown.

We speculate that the $H \sim l^{-3}$–law is applicable only at $l > 1$ kpc, while at medium (1 pc $< l <$ 1 kpc) (Lobanov 1998) and small scales ($l < 1$ pc) (Field 1993) a $H \sim l^{-1}$–dependence operates. In this case, we have rather accurate lower limits for the field in the nucleus. These lower limits are given in Col. 12, but they are still higher than the theoretical predictions by Field & Rogers (1993). We therefore propose that $H \sim l^{-3}$ for $l < 1$ pc, as suggested by Kardashev (1995). Because the observational errors are comparable to the amount by which the measurements exceed the estimates of Field & Rogers, we cannot strongly rule out this model.

3. Conclusion

We show that on distances >1 kpc from nucleus the magnetic field has a dipole structure. Because of very poor statistics (3 sources), additional tests of our conclusion are needed. New observations of compact symmetric objects (CSOs) have been carried out at the Large Phased Array using the interplanetary scintillation method.

We expect to find additional confirmation of dipole magnetic fields in AGNs at large scales from these observations.

We have outlined a method that allows us to probe the magnetic field strength at small scales. If magnetic fields on small and large scales are closely linked and there are no processes at large scales which essentially amplify the magnetic fields then we expect strong collimation, highly regular and strong magnetic fields. This should give rise to Faraday rotation with rotation measured in excess of 10^7 rad/m^2, as already proposed by Kardashev (1995). Suitable objects for testing such strong fields would be intraday variability sources.

The present study makes an additional prediction for the position of the nucleus of 3C 343.1. As the magnetic fields in the two compact components are the same, they should be equidistant with respect to the nucleus.

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