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Blazar Observations in Infrared and Optical Regions: Magnetic Field Strength Evaluation

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Abstract. A brief review of the methods to evaluate the strength of magnetic fields in blazars on some examples using observational data is presented.

Key words. Blazars—magnetic fields—polarimetry.

1. Introduction

It is known that blazar radiation consists of several components. In optical region synchrotron radiation produced by the moving of relativistic electrons in the magnetic field of a jet dominates. Magnetic field controls practically all main physical processes in galaxies with active nuclei. This is the reason why one of the main astrophysical task is to evaluate the strength and topology of magnetic field in blazars and related objects. A great number of articles are devoted to the study of magnetic field in cosmic objects. Important contributions to the study of magnetic fields in extragalactic sources are made by astronomers from Russia, USA, Italy, Finland, Germany, Spain, Swiss, China, Japan, India and other countries.

An invaluable contribution in these investigations was made in the last era by brilliant Soviet astronomers: the first Director of the Crimean Astrophysical Observatory academician G. A. Shajn and his collaborators, and I. S. Shklovskii. Shajn was the first to determine the strength of the magnetic field in the vicinity of the Sun and estimated the strength of this field which is in good agreement with recent estimations (Shajn 1955). The other very important work by Shajn was connected with the study of the nature of the Crab Nebula's optical radiation (Shajn *et al.* 1955). Shklovskii proved the synchrotron nature of the Crab Nebula radiation (Shklovskii 1953, 1958). The detection of large linear polarization of the Crab Nebula (Dombrowskij 1954; Waschakidze 1954; Shajn *et al.* 1955) and further investigations completely confirmed Shklovskii's conclusion. Shklovskii has done a great service for the detection of the synchrotron nature of the radiation of radiogalaxies, quasars and Seyfert galaxies (Shklovskii 1964, 1965, 1980, 1982).

The strength of a magnetic field cannot be measured directly. This is the reason why one needs to use observable quantities connected with magnetic field and its structure. The main purpose of this paper is to make a brief review of the methods to estimate the magnetic field strength from optical photopolarimetric observations. I confine myself only to data from observations of linear polarization because the optical circular polarization of these objects is at the level of errors of measurements.

2. Quantities connected with magnetic field

Observable quantities are: wavelength or frequency, characteristics of variability of radiation, amplitudes of flares and their duration, parameters of linear and circular polarization, spectral index of radiation, ratio of apparent velocity of the motion of matter along the jet to the light velocity, red-shift, brightness temperature of the source, frequencies of long-wave and short-wave cutoffs and intensity of radiation. In most cases evident or implicit suggestion is used on the equipartition of kinetic and magnetic energies. It is a very powerful condition. The use of these parameters allows us to determine the characteristics of magnetic field in a jet.

Model parameters are: the Hubble constant z, the Lorentz factor $\Gamma = 1/\sqrt{(1-\beta^2)}$, the Doppler factor $\delta = 1/(\Gamma(1-\beta\cos\theta))$, where β is an intrinsic relativistic velocity, θ is the angle between velocity vector and line-of-site (viewing angle), and the open angle of jet's cone φ.

3. Main models of magnetic field in a jet

A number of rather simple models of the magnetic field configurations were proposed which are applicable for optical region (uniform and isotropic or nonisotropic magnetic fields with regular and chaotic components: Korchak & Syrovatsky 1961; Sazonov 1972; Nordsieck 1976; Björnsson & Blumenthal 1982; Celotti & Matt 1994; Laing 1980, 1981). All these models connect the degree of linear polarization with the spectral index and the magnetic field distribution. An excellent summary of some of these relations was done by Dolginov *et al.* (1979).

Some examples of the comparison of theoretical models with observational data are given by Nordsick (1976); Efimov *et al.* (2002); Efimov & Vovk (2006); Efimov & Primak (2006). However, all these models cannot explain the sharp increase of the polarization with increasing spectral index at any type of magnetic field distribution.

The more sophisticated models were elaborated: shock-in-jet model by Marsher (1980), Marsher & Gear (1985), and the helical-jet model based on the theory of the helical magnetic field structure developed by Villata & Raiteri (1999).

Some of the important model parameters (Lorentz factor Γ and Doppler factor δ) depend on the relativistic velocity β of the plasma in jet which can be measured using the VLBI interferometer in the radio region. To make more easy the selection of the model parameters Γ, δ and θ from the observed β and radio brightness T_b, Lähteenmäki & Valtaoja (1999) constructed the useful diagram connecting observed and model parameters (Fig. 4 in their paper). For observations in the optical region, Fan (1999) proposed the diagram connecting the maximum of observed polarization degree $P\%$ and Doppler factor δ (Fig. 2 in his paper).

Below the magnetic field strength estimation on several blazars is demonstrated.

4. Individual objects

The blazars variability consists of several components: slow component (from several weeks to several years), fast component (from several days to several hours) and flare activity in all spectral ranges. The two components and the irregular fluctuations have natural explanation in the frame of shock-in-jet model (Marscher & Gear 1985; Hughes *et al.* 1989; Qian *et al.* 1991).

However, the flare activity (especially periodical) presents some difficulties in this model. To eliminate these problems, Camenzind & Krockenberger (1992) suggested a more developed model. In this model certain blobs of electrons move along the magnetic field lines of jet rotating around its axis. The cone of radiation from blobs also moves along spiral magnetic field and crosses the line of site in successive time intervals which correspond to the rotation period of the jet (Wagner *et al.* 1993). All details are discussed in Ghisellini *et al.* (1997). A detailed analysis of the evaluation of physical parameters of 140 blazars and quasars with flat spectra (FSQR) and power radiation in the gamma range is given by Ghisellini *et al.* (1997, 1998) and Celotti & Ghisellini (2008). In these papers there are data on the magnetic field strength of these objects. The efficiency of the model is demonstrated by the example of the blazar S5 0716+714.

4.1 *S5 0716+714*

It is supposed that the duration of the flare does not exceed *R/c*, where *R* is the radius of the source, the equipartition hypotheses is valid and β is the relativistic velocity of the moving blob. In this case the evaluation of the strength of the magnetic field B and the Lorenz factor $\Gamma = 1/\sqrt{(1-\beta^2)}$ can be made by the formulae: $B \geq 0.67\nu^{-1/3}t^{-2/3}2^{-2/3}[(1+z)/\delta)]^{1/3}$, $\Gamma_0 \leq 2 \times 10^4 \nu^{2/3}[2t(1+z)/\delta]^{1/3}$, where B is in Gauss, t in days, ν in the units of 10^{15} Hz and the Doppler factor $\delta = 1/(\Gamma(1-\beta\cos\theta))$. With $\delta/(1+z) = 10$, $t = 1$ day we have $B \geq 0.2$ G, $\Gamma_0 \leq 10^4$.

More precise estimations of B and δ may be obtained by taking into account the ratio of frequencies of picks of synchrotron ν_s and Compton radiation ν_C and the ratio of corresponding fluxes. A detailed analysis of the evaluation of physical parameters of 140 blazars and quasars with flat spectra (FSQR) and power radiation in the gamma range is given by Ghisellini *et al.* (1997, 1998, 2002) and Celotti & Ghisellini (2008). In these papers, there are data on the magnetic field strength in these objects. For example, the strength of the magnetic field in blazar S5 0716+714 is estimated as $B = 0.5$ G at the Doppler factor $\delta \approx 11$ (Ghisellini *et al.* 1997).

4.2 *S5 0917+62*

For the distant quasar ($z = 1.446$), Qian *et al.* (1991) estimated the geometrical and physical parameters of the variable source of radiation on the base of shock-in-jet model using observations in the centimeter range. Accepting variability time as 1.3 days, the Lorenz factor $\Gamma = 14$, the Doppler factor $\delta \approx 20$ and the view angle $\theta \leq 0.1$ rad, the authors obtained $B \approx 5 \times 10^{-4}$ and the electron density 0.1 cm^{-3}.

4.3 *Mkn 501*

The estimation of the magnetic field strength in blazar MKN 501 was made using only data from optical photometry of fast flares of this blazar in the infrared (K band) by Kidger *et al.* (1992). They suggested the synchrotron nature of these flares in the course of which the strong magnetic field penetrates into limited area of the accretion disk. Amplitudes of these flares may be different in different spectral ranges and depend on the flare mechanism. Using the formula $\nu = 1.07 \times 10^{24} B^{-3} t^{-2}$ Hz, where t is the duration of the flare in seconds, and the frequency ν is the central frequency of the K band (the wavelength is 2.2μ), the authors have found $B = 13$ G.

4.4 *AO 0235+164*

The method of evaluation of the magnetic field strength using the duration of the optical flare in the blazar AO 0235+164 and the polarization maximum in December 2006 is given by Hagen-Thorn *et al.* (2008). Observational data are the degree of linear polarization $P\%$ in the flare maximum, the spectral index α, the duration of the flare t in days, the Lorenz factor Γ and the frequency ν. These data are used to determine the compression of the plasma η in the shock, the angle ψ between the line of site and the direction of the shock-wave front, the angle ϕ between the line of site and the velocity vector of radiation matter, and the Doppler factor δ. Accepting flare duration t = 1.7 hours, the wavelength of observation (R band), the red-shift $z = 0.940$, determined Doppler factor $\delta = 23.3$ and using formula $t \approx 4.75 \times 10^2[(1 + z)/\delta\nu B^3]^{1/2}$, they found $B = 0.5$ G.

4.5 *3C 273*

The magnetic field strength in the quasar 3C 273 has been measured firstly in the optical range by Courvoisier *et al.* (1988) during enhanced activity of the object in 1988. During this time there occurred several flares of different amplitudes and marked variations of linear polarization. The data on maximal flare on March 9, 1988 in the J band (1.2μ) were used to estimate the strength of the magnetic field in the assumption of equipartition between magnetic and kinetic energy of relativistic electrons in the jet. Accepting the time of energy release equal to 2 days, the magnetic field strength B was found to be 0.7 G.

5. Radio regime

Putting into operation the radiointerferometer with a very long base (VLBI) made it possible for direct measurements of the size of blobs in the projection to sky plane and the determination of their velocities. Thereby it is possible to determine the Lorenz and Doppler factors, and at minimum number of input parameters the strength of magnetic field and polarization parameters in various places of the jet can be evaluated. A detailed description of the method is given by O'Sullivan & Gabuzda (2009). The observations in different frequencies of VLBI allow us to study the changing of the strength of magnetic field along the jet. The authors evaluated the magnetic field strengths and model parameters for BL Lac, S5 2007+777, GC 1418+546 (OQ 530) and S4 0954+658. They found that the magnetic field strength decreased with increased distance from several hundred gauss to several dozen of milligauss with increased distance from the core. For example, Fig. 5 in the paper by

O'Sullivan & Gabuzda (2009) illustrates the changing of magnetic field strength B *versus* distance r in parsecs for BL Lac.

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