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Determination of magnetic fields in broad line region of active galactic nuclei from polarimetric observations

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HIGHLIGHTS

- Magnetic field values that play an important role in broad line region of active galactic nuclei are estimated.
- Estimates of magnetic fields are based on the observed polarization degrees of broad H_α lines and nearby continuum.
- Values of magnetic fields in broad line region for a number of active galactic nuclei are derived.

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ABSTRACT

Magnetic fields play an important role in confining gas clouds in the broad line region (BLR) of active galactic nuclei (AGN) and in maintaining the stability of these clouds. Without magnetic fields the clouds would not be stable, and soon after their formation they would expand and disperse. We show that the strength of the magnetic field can be derived from the polarimetric observations. Estimates of magnetic fields for a number of AGNs are based on the observed polarization degrees of broad H_α lines and nearby continuum. The difference between their values allows us to estimate the magnetic field strength in the BLR using the method developed by Silant'ev et al. (2013). Values of magnetic fields in BLR for a number of AGNs have been derived.

1. Introduction

In the unified model of AGN the key role belongs to the BLR. Existence of cold clouds embedded in this region allows us to derive the basic physical parameters of supermassive black holes (SMBH) found in central regions of AGN, in particular, the black hole mass. By measuring the time lag between the variations of the AGN continuum and the broad H_β emission line, the radius of the BLR can be derived. Combining these measurements with the FWHM of the H_β line, it is possible to produce the so-called virial estimate of the central black hole mass.

Usually, orbital motion of a cloud is treated as a classical two body system, where the gravitational force of the central black hole and the force of radiation pressure from an accretion disk are determining the total force acting on each cloud and the resulting cloud orbit (Liu and Zhang, 2011; Krause et al., 2012; Shadmehri, 2015). Humi and Carter (2002) studied properties of the orbital motion of a cloud in a central force with a drag force opposite to the velocity vector and proportional to a power law function of the magnitude of the velocity and the distance to the center of attraction. They have demonstrated that orbits decay when the drag force is included.

It appears that magnetic fields play an important role in confining the clouds and maintaining their stability. Without magnetic fields, the clouds would not be stable and soon after their formation they would expand and disperse (Rees, 1987). If the magnetic field is present in the BLR, clouds not only become stable, but also maintain their orbits. This problem was considered in detail by Shadmehri (2015). The problem of magnetized gas clouds was also considered by McCourt et al. (2015).

Observations confirm that the BLR has a typical size of $\sim 0.01 - 0.1$pc and contains a large number of clouds with a very low filling factor ($\sim 10^{-8}$), typical sizes of $\sim 10^{12} - 10^{14}$ cm, and the total mass of $\sim 10^8 M_\odot$ (Rees et al., 1989; Marconi et al., 2008; Plewa et al., 2013). This implies that the BLR clouds are optically thick.

Direct evidence for a flattened BLR comes from the next lines of evidence (Kollatschny and Zetzl, 2013): (a) FWHM of H_β is strongly correlated with the orientation obtained from radio observations; (b) investigation of low-ionization lines showed that there was little material along the line of sight; (c) energy-budget requirements plus absence of BLR absorption also require the BLR to be flattened (Gaskell, 2009; Gaskell et al., 2012; Gaskell and Goosman, 2013).

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Then Kollatschny and Zetzl (2013) have modeled the rotational and turbulent velocities in the line-emitting regions and on the basis of these velocities they estimated the height of the line-emitting regions above the midplane. Their estimates of the ratio of the characteristic thickness of the disk to the radius give the next values: $0.2 \leq H/R \leq 1.7$. It means that the BLR is the geometrically thick disk as compared to the traditional accretion disk.

According to Gaskell and Goosman (2013) the BLR is part of the outer accretion disk and that similar MHD processes are operating. The standard accretion disk is optically thick medium.

The basic goal of our paper is to show that there is a possibility to obtain information about the magnetic field strength, including the turbulent magnetic field, from polarimetric observations of emission lines in the BLR. The main idea is to take into account the effect of Faraday rotation of the polarization plane and Faraday depolarization effect at the distance of the free mean path of a photon (Gnedin and Silant'ev, 1984; 1997; Dolginov et al., 1995; Silant'ev et al., 2009). The difference between the standard (Chandrasekhar, 1950; Sobolev, 1963) and observed polarization degrees allows us to estimate the value of the magnetic field in the radiation region (Silant'ev et al., 2009; 2013; Piotrovich et al., 2015).

There is one problem connected with orientation of the polarization position angle relative to the radio axis in AGNs. There are existed conclusions (Smith et al., 2002) that for ∼ 50% Seyfert 1 galaxies the polarization of E-vector is parallel to the radio jet axis. Unfortunately, this conclusion is made for strongly restricted sample of objects. Smith et al. (2004) used a sample including only 12 objects in which the radio source axis can be determined unambiguously. In the Table 4, presented in Smith et al. (2004), only 7 objects from 42 has the E-vector within ± 20° to be parallel to the radio axis. At the same time, in HST sample with near-IR polarization and broad H_α lines the polarization of E-vector is perpendicular to the radio jet axis for 54% of the sources (Ramirez et al., 2014).

2. Basic equations

According to Silant'ev et al. (2009, 2013), the approximate analytical formulae for the degree of linear polarization $p(B, \mu, q)$ and the position angle χ of broad emission lines in the optically thick disk-like BLR take a form:

$$p(B,\mu,q) = \frac{p(\mu,q)(1-k\mu)}{[g^4+2g^2(a^2+b^2)+(a^2-b^2)^2]^{1/4}}, \tag{1}$$

$$\tan 2\chi = \frac{2ag}{\left(\frac{P(\mu,q)(1-k\mu)}{P(B,\mu,q)}\right)^2+(g^2+b^2-a^2)}, \tag{2}$$

where $\mu = \cos i$ and i is the BLR inclination angle, $g = 1 - k\mu + C$, k is the solution to the characteristic equation for classical Milne problem with absorption (Silant'ev et al., 2014), $q = \sigma_a/(\sigma_s + \sigma_a)$ is the absorption coefficient, σ_s is the cross-section of scattering, σ_a is the absorption cross section. The polarization degree $p(\mu, q)$ is determined by solving the classical Milne problem in an unmagnetized atmosphere with absorption. The position angle $\chi = 0$ corresponds to the oscillations of the electric vector of the electromagnetic wave in the plane of the disk-like atmosphere.

The dimensionless parameters a and b describe the effect of Faraday depolarization:

$$a = 0.8\lambda^2\mu B_z;\ \ b = 0.8\lambda^2\sqrt{1-\mu^2}B_\perp, \tag{3}$$

where B_z and $B_\perp$ are the magnetic field components perpendicular and parallel to the plane of the flattened BLR, respectively, and λ is the emission line wavelength in μm. B_z and $B_\perp$ are in Gauss.

The dimensionless parameter C describes the contribution of the turbulent magnetic field and characterizes a new effect – an additional absorption of polarized radiation due to the incoherence of Faraday rotations in small scale turbulent vortices (Silant'ev, 2005; Silant'ev et al., 2013):

$$C = 0.64\tau\lambda^4\langle B_t^2\rangle\frac{f_B}{3}, \tag{4}$$

where τ is the average Thomson optical depth of a turbulent vortex ($\tau \leq 1$), $\langle B_t^2\rangle$ is the average magnetic field fluctuation, and $f_B \approx 1$ is the parameter that describes the correlation of B_t values at two neighboring points of the BLR.

For turbulent magnetic field in the BLR with $q = 0$ the degree of polarization is derived by the following expression:

$$p(B_t,\mu) = \frac{p(\mu)}{1+C};\ \ \chi = 0. \tag{5}$$

Below we consider two important cases: $B_t \neq 0$ and $B_\perp \neq 0$. It seems that in the distant regions of the accretion disk, especially at distance R_{BLR}, the global magnetic field has generally a toroidal shape ($B_\perp \gg B_z$). A contributing factor is the Keplerian rotation in the accretion disk, which transforms the poloidal magnetic field into a toroidal one (Bonanno and Urpin, 2007).

3. Determining magnetic field strength in BLR for AGNs from polarimetric data

In their atlas Smith et al. (2002) presented polarimetric data both for the continuum and for the H_α emission line. It is interesting that for many observed objects there is a marked difference between polarization degrees of the continuum and the H_α emission line, and in most cases $p(H_\alpha) < p(cont)$. The basic reason for such difference is the depolarization effect according to Eqs. (1) and (5).

Let's consider some specific examples.

We are beginning with Akn 564. According to Smith et al. (2002), the polarimetric data are as follows: the continuum polarization degree is $p(cont) = (0.52 \pm 0.02)\%$ and the degree of polarization of the H_α emission line is $p(H_\alpha) = (0.34 \pm 0.05)\%$. We are suggesting that the lower polarization degree of the H_α emission line is due to the existence of magnetic field in the BLR. That implies that $p(cont) = p(\mu)$. It is very important that the position angles are practically the same for the continuum emission and for the H_α emission and they are perpendicular to radio axis (Smith et al., 2004). Assuming the existence of the intrinsic global magnetic field $B_\perp$ in the accretion disk, one obtains the estimate for the value of $B_\perp$ using Eqs. (1) and (3):

$$P(B,\mu) = \frac{P(\mu)}{\sqrt{1+b62}},\ \ b = \left[\left(\frac{p(cont)}{p(H_\alpha)}\right)^2 - 1\right]^{1/2},$$

$$b = 0.345\sqrt{1-\mu^2}B_\perp. \tag{6}$$

For Akn 564 we have $b = 1.16$. The value $\mu = \cos i$ can be obtained from $p(\mu)$ that corresponds to the standard polarization degree from multiple electron scatterings in the optically thick disk-like medium (Chandrasekhar, 1950; Sobolev, 1963). The results of the calculations of the polarization degree as a function of $\mu = \cos i$ are presented in Table 1. It should be noted that the function describing the angular distribution of outgoing radiation, that is dependent on the absorption coefficient, is presented in Silant'ev (2002). For the polarization degree $p(\mu) = 0.52\%$, the appropriate values are $\mu = 0.842$ and the inclination angle $i = 32.5°$. Then we have $\sin i = \sqrt{1-\mu^2} = 0.537$. As a result, we obtain the estimate of the intrinsic magnetic field in the BLR of $B_\perp(R_{BLR}) = 6.27$G.

Let's consider another possible situation when in the BLR the magnetic field is highly turbulent. In this case the degree of polarization is determined by Eq. (5) and the parameter C is determined according to Eq. (4). We are suggesting that $\tau \approx f_B \approx 1$. In