The Wavelength Dependence of Polarization in Active Galactic Nuclei

Fedor V. Prigara

Institute of Microelectronics and Informatics, Russian Academy of Sciences, 21 Universitetskaya, 150007 Yaroslavl, Russia

Abstract. Using the gaseous disk model and the condition for emission based on a stimulated origin of thermal radio emission (Prigara 2003), we received the wavelength dependence of polarization for radio emission from active galactic nuclei consistent with available observational data. The strength of magnetic field required to produce an observable degree of polarization in active galactic nuclei is discussed.

1 Introduction

The degree of polarization for thermal radiation in a magnetic field was obtained by J.C. Kemp in 1970 (for review see Lang 1974). It is given by the formula

\[ p = \frac{eB}{2mc\omega} \]  

where \( e \) and \( m \) are the charge and mass of electron respectively, \( c \) is the speed of light, \( B \) is the strength of magnetic field, and \( \omega \) is the circular frequency of radiation.

According to equation (1), the wavelength dependence of a degree of polarization is determined by the magnetic field profile \( B(r) \), where \( r \) is the distance from a central energy source, and by the relationship between the frequency of radiation and the radius \( r \). The last relationship is given by the condition for emission (Prigara 2003). To introduce the magnetic field profile we consider the gaseous disk model for radio source.

2 The gaseous disk model

It was shown recently (Prigara 2003) that thermal radio emission has a stimulated character. According to this conception thermal radio emission of non-uniform gas is produced by an ensemble of individual emitters. Each of these emitters is a molecular resonator the size of which has an order of magnitude of mean free path \( l \) of photons

\[ l = \frac{1}{n\sigma} \]  

where \( n \) is the number density of particles and \( \sigma \) is the absorption cross-section.

The emission of each molecular resonator is coherent, with the wavelength

\[ \lambda = l, \]  

and thermal radio emission of gaseous layer is incoherent sum of radiation produced by individual emitters.

The condition (3) implies that the radiation with the wavelength \( \lambda \) is produced by the gaseous layer with the definite number density of particles \( n \).

The condition (3) is consistent with the experimental results by Looney and Brown on the excitation of plasma waves by electron beam (see Chen 1987, Alexeev 2003). The wavelength of standing wave with the Langmuir frequency of oscillations depends on the density as predicted by equation (2).
The discreet spectrum of oscillations is produced by the non-uniformity of plasma and the readjustment of the wavelength to the length of resonator. From the results of experiment by Looney and Brown the absorption cross-section for plasma can be evaluated.

The product of the wavelength by density is weakly increasing with the increase of density. This may imply the weak dependence of the size of elementary resonator in terms of the wavelength upon the density or, equivalently, wavelength.

In the gaseous disk model, describing radio emitting gas nebulae (Prigara 2003), the number density of particles decreases reciprocally with respect to the distance $r$ from the energy center

\[ n \propto r^{-1}. \tag{4} \]

Together with the condition for emission (3) the last equation leads to the wavelength dependence of radio source size:

\[ r_\lambda \propto \lambda. \tag{5} \]

The relation (5) is indeed observed for sufficiently extended radio sources. For example, the size of radio core of galaxy M31 is 3.5 arcmin at the frequency 408 MHz and 1 arcmin at the frequency 1407 MHz (Sharov 1982).

## 3 The wavelength dependence of radio source size

In the case of compact radio sources instead of the relationship (4) the relationship

\[ r_\lambda \propto \lambda^2 \tag{6} \]

is observed (Lo et al. 1993, Lo 1982). This relationship may be explained by the effect of a gravitational field on the motion of gas which changes the equation (3) for the equation

\[ n \propto r^{-1/2}. \tag{7} \]

The mass conservation in an outflow or inflow of gas gives $nv=const$, where $v$ is the velocity of flow. In the gravitational field of a central energy source the energy conservation gives

\[ v = \left( v_0^2 + c^2 r_s / r \right)^{1/2} \tag{8} \]

where $r_s$ is the Schwarzschild radius. Therefore, at small values of the radius the equation (7) is valid, whereas at the larger radii we obtain the equation (4). The relationship between linear size and turnover frequency in gigahertz-peaked spectrum sources and steep-spectrum sources (Nagar et al. 2002) is a consequence of the wavelength dependence of radio source size. The turnover frequency is determined by the equation $r_\nu = R$, where $R$ is the radius of a gaseous disk. The same equation determines a turnover frequency for planetary nebulae (Pottasch 1984; Siodmiak & Tylenda 2001).

To summarize, extended radio sources are characterized by the relation (5), and compact radio sources obey the relation (6).

## 4 The wavelength dependence of polarization

At first, consider extended radio sources for which the equation (5) is valid. Assuming the magnetic field profile $B \propto r^{-2}$, which is characteristic for the field of two-dimensional magnetic dipole, from equation (1) we obtain

\[ p \propto B(r_\lambda) \lambda \propto \lambda^{-1}. \tag{9} \]

This relationship is qualitatively consistent with observational data. The degree of linear and circular polarization in active galactic nuclei typically decreases with the increase of wavelength (Bower et al. 1999; Bower et al. 2001). In the case of Cen A the law (9) is valid in the decimeter range.
For compact radio sources the law (6) is valid, and the magnetic field profile is also changed to
\[ B \propto r^{-3/2} \] (Prigara 2003). Now the equation (1) gives
\[ p \propto \lambda^{-2}. \] (10)

The degree of linear polarization in 3C 84 is \( p = 0.03\% \) at the frequency 4.8 GHz and \( p \approx 0.2\% \) at the frequency 14.5 GHz (Bower et al. 1999), in agreement with the equation (10). The degree of linear polarization in Cen A in centimeter range also follows the equation (10).

It is known that the synchrotron theory predicts a change in the polarization position angle across the spectral peak of gigahertz-peaked source. No such a change was found for the six gigahertz-peaked sources (Mutoh et al. 2002).

5 The strength of magnetic field

According to equation (1) the field \( B = 20 \, \text{G} \) is required to produce the degree of polarization \( p = 0.2\% \) at the frequency 14.5 GHz, as in the case of 3C 84 (Bower et al. 1999). If we assume, for compact radio sources, that \( r_\lambda = r_0 \) at the wavelength \( \lambda = 1 \, \text{mm} \), where \( r_0 \) is the radius of the photosphere of a central energy source (e.g., the Schwarzschild radius), then \( B_0 = B_\lambda (\lambda/\lambda_0)^2 = 2 \times 10^5 \, \text{G} \). Zakharov et al. (2003) have obtained an estimate \( B < 10^{10} - 10^{11} \, \text{G} \) for the Seyfert galaxy MCG-6-30-15.

The existence of regular magnetic fields in active galactic nuclei is supported by the geometry of radio jets following the lines of a magnetic field. In many cases jets have a significant curvature, sometimes up to 90 degrees or more (Kellermann et al. 1998). The stable handedness of circular polarization in Sgr A* and M81* requires stable global magnetic field components (Beckert & Falcke 2002, Bower, Falcke & Mellon 2002). This suggests the existence of regular magnetic fields in accretion flows too.

One of the possible explanations for line widths in active galactic nuclei is a magnetic broadening. A magnetic broadening of spectral lines is produced by the Zeeman splitting in a non-uniform magnetic field changing its strength in the emitting region. The magnetic broadening in AGN is supported by broader \( H_\alpha \) lines in polarized emission than in total emission (Nagar et al. 2002; Hes, Barthel & Fosbury 1993). However, the magnetic broadening of broad emission lines in AGNs encounters some difficulties. First, a change in the continuum flux produces an earlier response in the red wing of the line than in the blue wing (e.g., Konigl 2003). Second, some AGNs show double-peaked broad emission lines (Strateva et al. 2003). Both these features are indicative of a convection in the disk corona. In particular, the double-peaked emission lines are observed in planetary nebulae (Pottasch 1984). Nevertheless, a magnetic broadening can be applied to the narrow emission lines in AGNs. It may also participate in the width of each component of a double-peaked emission line.

A magnetic broadening may be a solution to the well-known problem of line broadening in A, B and O stars (Bohm-Vitense 1980). The \( \text{Ca} \, \text{II} \) lines in B stars usually assumed to be interstellar alternatively may be interpreted as a result of a non-uniform shift of spectral lines (Ebbets 1980) together with the Zeeman splitting. The latter produces the several (6 to 10) components of \( \text{Ca} \, \text{II} \) lines.

The phase diagram for the matter in ultrastrong magnetic fields is virtually unknown. The phase transitions in sufficiently strong magnetic fields may be responsible both for hard gamma-ray flares (Kellermann et al. 1998) and cosmic rays of ultrahigh energies. The origin of the latter is not elucidated up to date.

The effect of the strong magnetic field on the matter is produced by the magnetic pressure. In magneto-hydrodynamics it is assumed that the magnetic pressure is proportional to the \( B^2 \). One-fluid magneto-hydrodynamics is, however, poorly justified (Kadomtsev 1988). Alternatively, the magnetic pressure in a hot plasma may be suggested to be proportional to the strength of a magnetic field as follows
\[ p_B = eBv_0/\sigma c, \] (11)
where \( \sigma \) is the collisional cross-section in the high-temperature limit (when \( e^2/kT < h^2/Zm^2 \)), and \( v_0 \) is a constant.

In the case of flat-spectrum active galactic nuclei (Bower & Backer 1998; Nagar, Wilson & Falcke 2001; Ulvestad & Ho 2001) the density, temperature, and pressure profiles have a form \( n \propto r^{-1/2} \), \( T \propto r^{-1} \), \( P = nkT \propto r^{-3/2} \). Since for compact radio sources \( B \propto r^{-3/2} \), from equation (11) we obtain \( P \propto P_B \). The latter relationship confirms equation (11). Here the density, temperature and pressure profiles are the same as those in the convection-dominated accretion flow (CDAF) models (Nagar et al. 2001). The magnetic field profile is different since the expression for the magnetic pressure is changed. The ratio of magnetic to gas pressure will be fixed similar to the CDAF models.

6 Conclusions

The maser theory of thermal radio emission (Prigara 2003) can explain the wavelength dependence of polarization in active galactic nuclei, if we only assume the existence of sufficiently strong magnetic fields in AGN. The other indications of strong magnetic fields in AGN are a magnetic broadening of spectral lines and possibly the hard gamma-ray flares.

References

Alexeev B.V. (2003) Usp. Fiz. Nauk 173, 145.
Beckert T., Falcke H. (2002) Astron. Astrophys. 388, 1106.
Bohm-Vitense E. (1980), in Stellar Turbulence, IAU Colloq. 51, eds. D.F.Gray, J.L.Linsky, Springer.
Bower G.C., Backer D.C. (1998) Astrophys. J., Lett. 507, L117.
Bower G.C., Falcke H., Mellon R.R. (2002) Astrophys. J., Lett. 578, L103.
Bower G.C., Wright M.C.H., Backer D.C., Falcke H. (1999) Astrophys. J. 527, 851.
Bower G.C., Wright M.C.H., Falcke H., Backer D.C. (2001) Astrophys. J., Lett. 555, L103.
Chen F.F. (1984), Introduction to Plasma Physics and Controlled Fusion, Vol. 1: Plasma Physics, Plenum Press.
Ebbets D. (1980) in Stellar Turbulence, IAU Colloq. 51, eds. D.F.Gray, J.L.Linsky, Springer.
Hes R., Barthel P.D., Fosbury R.A.E. (1993) Nature 361, 326.
Kadomtsev B.B. (1988), Cooperative phenomena in plasmas, Nauka.
Kellermann K.I., Vermeulen R.C., Zensus J.A., Cohen M.H. (1998) Astron. J. 115, 1295.
Konigl A. (2003) in Active Galactic Nuclei: from Central Engine to Host Galaxy, ASP Conf. Series 290, eds. S.Collin, F.Combes, I.Shiosman, ASP.
Lang K.R. (1974), Astrophysical Formulae, Springer.
Lo K.Y. (1982) in AIP Proc. 83: The Galactic Center, eds. G.Riegler, R.Blandford, AIP.
Lo K.Y., Backer D.C., Kellermann K.I., Reid M., Zhao J.H., Goss M.H., Moran J.M. (1993) Nature 361, 38.
Mutoh M., Inoue M., Kameno S., Asada K., Fujisawa K., Uchida Y. (2002), astro-ph/0201144.
Nagar N.M., Wilson A.S., Falcke H. (2001) Astrophys. J., Lett. 559, L87.
Nagar N.M., Wilson A.S., Falcke H., Ulvestad J.S., Mundell C.G. (2002) in Issues in Unification of AGNs, ASP Conf. Series 258, eds. R.Maiolino, A.Marconi, N.Nagar, ASP.
Pottasch S.R. (1984), Planetary Nebulae, D.Reidel Reinhold Company.
Prigara F.V. (2003), Astron. Nachr., Vol. 324, No. S1, Supplement: Proceedings of the Galactic Center Workshop 2002 - The central 300 parsecs of the Milky Way, eds. A.Cotera, H.Falcke, T.R.Geballe, S.Markoff.
Sharov A.S. (1982), The Andromeda Nebula, Nauka.
Siodmiak N., Tylenda R. (2001) Astron. Astrophys. 373, 1032.
Strateva I., Strauss M.A., Hao L. (2003) in Carnegie Observatories Astrophysics Series, Vol.1: Coevolution of Black Holes and Galaxies, ed. L.C.Ho, Carnegie Observatories.
Tadhunter C., Wills K., Morganti R., Oosterloo T., Dickson R. (2001) Mon. Not. R. Astron. Soc. 327, 227.
Ulvestad J.S., Ho L.C. (2001) Astrophys. J., Lett. 562, L133.
Zakharov A.F., Kardashev N.S., Lukash V.N., Repin S.V. (2003) Mon. Not. R. Astron. Soc. 342, 1325.