Optical spectropolarimetry of Seyfert galaxies and the kinematics of the broad line region

Victor L. Afanasiev & Luka Ć. Popović
The study of the kinematics of emitting clouds in the BLR (on scales <0.1pc) is the main source of information the central mass

Assumption of virialization:

\[ M_{BH} = f \frac{R_{BLR}v^2}{G} \]

- Reverberation \( \rightarrow R_{BLR} = c\tau \)-time delay between continuum and broad line

PROBLEMS:
- \( f \) - depends on the BLR geometry (may be very complex - disc, outflows, inflows - combination of these)
- This assumption of virialization cannot be directly verified because the BLRs are spatially unresolved
Polarization of AGNs - a simple (UNIFIED) model

Relation between polarization class and orientation in the generic scattering geometry that broadly explains the optical polarization spectra of Seyfert galaxies Smith et al. (2004)
Polarization in BLR & continuum

- $i \sim 0^\circ$, scattering $\sim 0$ (E $\perp$), view direct to accretion disc (E $\parallel$) and jet (E $\perp$)

- $i < 45^\circ$, equatorial scattering $> 0$, (E $\parallel$)

- $i \sim 90^\circ$, polar scattering $> 0$ (E $\perp$), “hidden” BLR in polarized light

Polarization in continuum
✓ radiative transfer in the AD
✓ Synchrotron radiation in jet
✓ scattering by gas-dust torus

Polarization in lines
✓ scattering by gas-dust torus
✓ radiative transfer in the BLR
Spectropolarimetric observations:

Motivations

➢ To study variability in polarized spectra (continuum and broad lines) of Type 1 AGNs
➢ To measure the dimension and clarify the nature of the polarization region (e.g. is the continuum polarized in the BLR)

Methods

➢ To observe and measure the linear polarization (Stokes parameters) in spectra of radio quiet AGN with low spectral resolution covering a wide spectral range in several epochs
➢ To perform echo mapping (reverberation) in order to find the dimensions of polarization region and compare it with the BLR dimension

Instrument

➢ 6-m telescope + SCORPIO, spectral coverage 4000-8000 AA
➢ Different type analyzer – Savart plate, Single and Double Wollaston prisms
➢ Spectral resolution 5-40AA,
➢ Precision measurement of the polarization 0.1-0.3%
Polarization in the continuum of AGN

- the polarization caused by the Thomson scattering does not depend on the wavelength
- observed wavelength dependent polarization as $P \propto \lambda^n$
- the reason - Faraday rotation in the magnetic field $AD$ on the photon mean free path (Gnedin & Silant’ev, 1997)

Afanasiev, Borisov, Gnedin et al., Astronomy Letters., 2011, v.37,p.307
Spectropolarimetry
Mrk 6

• Sy 1.5 galaxy, z=0.0185,
• m(B)=14.29, M(B)=-20.41

- Observations with 6 -m telescope of SAO RAS in 2010-2013;
- Obtained spectra for 12 epochs in the spectral range from Hβ to Hα with resolution 7-8 Å;
- The interstellar polarization is taken into account
- The resulting accuracy of the measurement of the Stokes parameters is about 0.2% per resolution element

Variability

the characteristic size of the polarized continuum \( \sim 0.002 \) pc, which is much smaller than the BLR (\( \sim 0.2 \) pc)
Polarization in continuum: disk + jet

- Vector addition of the disk and jet polarization
- Polarization in the disk => radiation transfer (electric vector is parallel to the axis of the disc)
- Polarization in the jet => synchrotron radiation - variable (precessing?) Jet (~ electric vector perpendicular to the axis)

Polarization in the broad H\(\alpha\) (BLR). Equatorial scattering - idea

Polarization in the broad Hα. Observation

- The polarization from the disk emission and additional three components A, B and C of the BLR polarized emission at speeds -2000, -6000 and 3000 km/s, respectively.
- Within experimental error (~0.2%) in the polarization of the line has not been changed in a period of two years.
- There is an expansion scattering region inside of the torus at a rate of ~1000 km/s.
Different scattering region in broad Hα

- Rotating BLR disk has an average degree of polarization of ~ 0.5% and shows the change in the angle of the plane of polarization within ± 40° relative to the direction of the disk axis (PA~170°).

- Component A, apparently, is probably the outflow at the velocity of -2000 km/s with a polarization ~ 0.6% and the angle of the plane of polarization ~ 45°; This component is clearly visible in the profile of the broad lines and changes with time.

- For the first time in polarized light detected by the outflow (jet?) of the velocity ~ 6000 km/s with the degree of polarization > 2% and the angle of the plane of polarization about 90°.

Afanasiev, Popovich & Shapovalova et al.
Variability of broad Hα on the scale of 10 years

Various angular velocities and the spin orientation of the three areas of the accretion disk with jet, BLR-disk of gas and dust torus
Rotation of the plane of polarization in the BLR

\[ V_i = V_i^{\text{rot}} \cos(\theta) = \sqrt{\frac{GM_{\text{BH}}}{R_i}} \cos(\theta), \]

\[ R_i = R_{\text{sc}} \cdot \tan(\varphi_i), \]

\[ \log\left(\frac{V_i}{c}\right) = a - 0.5 \log(\tan(\varphi_i)), \]

\[ a = 0.5 \log\left(\frac{GM_{\text{BH}} \cos^2(\theta)}{c^2 R_{\text{sc}}}ight). \]
Estimating of the inner radius of the torus

- Direct measurements of the size by interferometry in the near-IR (2–3 mkm)
- Estimation by delay variability radiation in K with respect to V
- Estimating the size of the calibration by relation {size – UV luminosity}

\[ R_{in} \approx 1.3 \cdot \sqrt{L_{AGN}^{46}} \cdot T_{1500}^{-2.8} \text{ [pc]} \]

Estimated size by interferometry is about two times larger than by variability
Numerical simulation (by Goosmann)

The method is weakly dependent on the angle of inclination of the galaxy!!
AGN sample with the observed equatorial scattering

<table>
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<th>Object</th>
<th>Type</th>
<th>z</th>
<th>R_{SC} [pc]</th>
<th>−a</th>
<th>log(M_{POL})[M_{\odot}]</th>
<th>log(M_{REV})[M_{\odot}]</th>
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<td>7.67±0.21</td>
<td>7.64±0.11</td>
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Masse BH in AGN by spectropolarimetry of broad Hα

Comparison masses by polarization with reverberation

\[ M_{BH} = f \frac{R_{BLR} V^2}{G} \]

\[ f \approx 5.5 \]

Spectropolarimetry
AGN 3C390.3

24 epochs observation at 2010-2014 years

- decrease of the degree of polarization with the wavelength ("flat spectrum")
- depolarization in the broad lines Hβ and Hα (like a "suitcase")
- blue shift of the broad lines in polarized light (-1200 km/s)
- Variability polarization and spectral properties:
  - small delay (~10 days) between the unpolarized and polarized continuum
  - the delay for the broad emission lines (lag(Hα) ~138 and lag(Hβ) ~60 days)
  - The delay of the polarized light in the line, lag(Hα) ~ 89 days
Variability polarized continuum: disk+jet

- **Vector addition** of the polarization disk and jet

- **Polarization in the disk** => radiation transfer. **Electric vector parallel to the disk axis**

- **Polarization in the jet** => synchrotron radiation variable jet. **Electric vector ~ perpendicular to the disk axis with accuracy up to pitch angle**

![Graph showing polarization data with annotations](image-url)
Polarization in broad Hα 3C390.3

- Depolarization in broad lines => depolarization in the mist of cloudelets thick disk BLR in the direction of the disk axis
- Shift broad Hα -1200 km/s and FWHM ~ 6000 km/s

Afanasiev, Popovic et all., MNRAS, 2015, v. 448,
CONCLUSION

✓ Spectropolarimetric monitoring of the AGN allows to resolve regions with different polarization mechanisms and determine their sizes.

✓ Using the optical spectropolarimetry enables to determine the type of gas clouds kinematics in the BLR (Keplerian motion, outflows).

✓ There is a sample of SyG's, with equatorial scattering, which show a Keplerian rotation at <0.2 pc from the center. This can be used for AGN BH mass estimates (a new method).
Thank you for your attention!

Спасибо за внимание!

Хвала на пажњи!

1945-2015
Magnetic fields in sample AGN

B(disk), gauss

linear polarization, %

B(disk), gauss

index polarization

B_H = 1032 \pm 520\; \text{gauss}
Computation of magnetic field

✓ Anisotropy in the hot-gas density distribution in AD => Thompson scattering => linear polarization;

✓ If the magnetic field is not strong ($B < 10^6 \, G$) to provide optical anisotropy of the medium, then the real optical anisotropy can result from the Faraday rotation of the polarization plane on the photon mean free path in the medium (Gnedin and Silant’ev 1984), that results in strong dependence of the polarization on a wavelength;

✓ For accretion disk with the temperature distribution $T_e( R ) \sim R^{-p}$ and of a magnetic field dependence on radius $B( R ) \sim B_H( R_H/R )^s$

$$ P_l \sim \frac{P_l(0, \mu)}{B_{z,\perp} \lambda^2} \sim \lambda^{(s/p-2)} \) (Silant’ev at al., 2007) $$

the quantity $P_l(0, \mu)$ is well known from the theory of polarized radiation transfer (Sobolev 1949) and can reach 11.7%. Strength of a magnetic field at the horizon $B_H$ was calculated within the magnetic coupling model $B_H = c_B (2M)^{1/2}/R_g$ (Ma et al., 2007)