Variability in AGN polarized spectra - a view to the BLR and torus structure

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AGN Reverberation Mapping, Lijiang, Oct. 24-26
Polarization in AGNs

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

- $i < 45^\circ$, equatorial scattering $> 0$, (E $\parallel$), Sy 1

- $i \sim 90$, polar scattering $> 0$ (E $\perp$), “hidden” BLR in polarized light, Sy 2

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

**Polarization in lines**
- ✓ scattering by gas-dust torus
- ✓ radiative transfer in the BLR
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)

Orientation is important!
Optical emission of AGNs

The structure can be more complex. Emission in the optical is coming from different regions.

- Optical jet
- Torus
- Outflowing BLR
- Disc-like BLR
- BH
- AD
- Radio jet
- Star-light, starbursts, etc.

The graph shows the rest wavelength (Å) on the x-axis and the Specific Flux (arbitrary units) on the y-axis.
Expected variability of polarization parameters in AGN spectra - scales?

Small scales (order of the BLR)
- Radiative transfer in the accretion disk (electron scattering)
- Synchrotron radiation of the jet

Larger scales (> the BLR)
- Scattering in optically thick gas-dust torus
- Scattering in optically thin gas cone ionization

Star-light, starbursts, etc.
Spectropolarization of the broad line AGNs – our observations
Spectropolarimetric observations:

Motivations

- To study variability in polarized spectra (continuum and broad lines) of Type 1 AGNs
- To measure the dimension and investigate the nature of the polarization regions in Ty1 AGNs

Methods

- To observe and measure the linear polarization (Stokes parameters) thype 1, radio quiet AGNs. Low spectral resolution covering a wide spectral range in several epochs
- Reverberation - to find the dimensions of polarization region and compare it with the BLR dimension
- To model observations using STOKES code (also variability of PP)

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%
Broad line AGNs (Sy 1) – Smith et al. 2004, polar vs equatorial pol.
Type 1 AGN: Equatorial polarization in broad lines: (Smith et al. 2004, 2005)

Broad line shapes

- Direct (unpolarized) light
- Scattered (polarized) light
- E-vectors of scattered rays
- Rotating broad-line emitting disc
- Equatorial scattering element (part of an entire ring of scatterers)
- Rotating emission ring/disc
- Equatorial scattering ring/disc

Broad line P.A.
Equatorial polarization – Keplerian disk – polarization in the broad line

Sketch showing a possible far-field scattering geometry in which Hα photons from BLR clouds undergoing bi-polar outflow are scattered by dust or free electrons in the inner wall of a surrounding torus.

Equatorial polarization – Keplerian disk – polarization in the broad line
Polarization in the broad Hα of Mrk6: 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
- The shape of polarization angle (PA)
Polarization in the broad Hα (BLR). Equatorial scattering - idea

Afanasiev et al. 2014 (Mrk 6); Afanasiev & Popovic 2015, ApJL, 800, L35

\[ \log(V/c) \]

\[ \log[\tan(\text{PA})] \]

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

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

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

\[ a = 0.5 \log\left(\frac{G M_{\text{BH}} \cos^2(\theta)}{c^2 R_{\text{sc}}}\right), \]

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

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

Estimated size by interferometry is about two times larger than by variability

M. Kishimoto et al., A&A 527, A121 (2011)
Results: Observed 9 AGNs, Popovic & Afanasiev 2015

\[ \Delta \varphi, \text{ degrees} \]

\[ \text{Velocity, km/s} \]

3C273, \( R_s = 95.3 \) light days

\[ \log(V/c) = \alpha + 0.5 \log(\tan \varphi) \]

\[ \alpha = -2.19 \pm 0.13 \]

\[ \log(M_{BH}/M_\odot) = 8.85 \pm 0.27 \]

NGC4051, \( R_s = 38 \) light days

\[ \log(V/c) = \alpha + 0.5 \log(\tan \varphi) \]

\[ \alpha = -2.80 \pm 0.09 \]

\[ \log(M_{BH}/M_\odot) = 6.23 \pm 0.18 \]
Comparison polarization and reverberation

![Graph showing comparison between log(M) from polarization and log(M) from reverberation with data points for Mkn6, Mkn817, Mkn335, Akn120, NGC5548, NGC4151, NGC3227, NGC4051, and 3C273]
BH mass vs. central velocity dispersion

Black hole mass estimates – polarization in the broad line profiles vs. reverberation

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

- 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
Variability in the continuum and broad lines – Mrk 6 and 3C390.3


Spectropolarimetry
Mrk 6 (IC 450)

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 H\( \beta \) to H\( \alpha \) 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.

Observations

continuum

continuum and line

$H\alpha$
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 broad lines

Three regions of polarization

- Torus – equatorial polarization
- Two additional polarization components probably polar polarization (outflows).
Variability of broad H\(\alpha\) on the scale of 10 years

BLR size, optical depth of SR, precession of jet-like motion (outflow)?
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 H\(\beta\) and H\(\alpha\) (like a “suitcase”)
- blue shift of the broad lines in polarized light (~1200 km/s)
- Variability polarization and spectral properties:
  - small delay (~10 light days) between the unpolarized and polarized continuum
  - the delay for the broad emission lines (lag(H\(\alpha\)) ~138 and lag(H\(\beta\)) ~60 light days)
  - The delay of the polarized light in the line, lag(H\(\alpha\)) ~ 89 light days
Variability

**Continuum at 5100Å**

**Polarized continuum at 5100Å**

**Broad Hβ**

**Broad Hα**

**Polarized broad Hα**

**Normalized Flux**

- 55000 55500 56000 56500 57000

**Lag**

- $10^{13}_{-12} \text{ day}$
- $60^{17}_{-16} \text{ day}$
- $138^{47}_{-35} \text{ day}$
- $89^{77}_{-16} \text{ day}$
Variability polarized continuum: disk+jet

- the polarization disk and jet

- Polarization in the disk => Electric vector parallel to the disk axis

- Polarization in the jet => synchrotron from the jet. Electric vector ~ perpendicular to the disk axis with accuracy up to pitch angle
Polarization in broad $\text{H}_\alpha$ 3C390.3

- Depolarization in broad lines $\Rightarrow$ depolarization in the hot material above thick disk BLR in the direction of the disk axis
- Shift broad $\text{H}_\alpha$ -1200 km/s and FWHM $\sim$ 6000 km/s

Radio jet (VLBI)
Outflow BLR
Optical jet
Torus
Rotated BLR
BH
AD

Radio jet

Outflow BLR

Optical jet

Torus

Rotated BLR

BH

AD

$\theta$ $\sim$ 20°
Future work

✔ Observation of a number of Sy 1 AGNs (we still observed around 40 broad line AGNs)

✔ Model the AGN polarization (R. Goosmann, PhD student Dj. Savic)

✔ Some first results for NGC 4051

✔ BLR (ld) 4.3 – 15 ld, torus 38 – 54 ld,  V =400 km/s, tau 0.5 and 0.8 and theta 30 degrees
Observations NGC 4051

-log(V/c) = α + 0.5 log(φ)

α = -2.57 ± 0.11

Log(MBH/M☉) = 6.69 ± 0.21
Change in the optical depth from 0.5 to 0.8
BLR 4.3-10 ld

\[ \vartheta = 28.96^\circ \]

- \[ a = -2.692 \]

\[ \Delta \varphi \]

Doppler velocity [km s\(^{-1}\)]

\[ \log(Y/c) \]

\[ \log(\tan \Delta \varphi) \]

- blue part
- red part
BLR 4.3-20ld

\[ \theta = 28.96^\circ \]

\[ a = -2.752 \]

[Graph showing Doppler velocity and log(tan Δφ) plots with annotations for blue and red parts.]
CONCLUSION

- Spectropolarimetric monitoring of the AGN allows to resolve regions with different polarization mechanisms and determine their sizes.
- Using the high-resolution 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).
- Work is in progress.
The observed polarization in the continuum – the result of the vector addition disk and jet polarization
Polarization in broad lines

Broad lines region BLR:
- Mist of clouds with $N \sim 10^8 \div 10^{12} \text{ cm}^{-3}$
- Size $\text{BLR} \sim 0.1-1 \text{ pc}$, $\varepsilon \sim 0.001$

Equatorial scattering

BLR - an indication of the BH in AGN

- The size of the BLR is measured at time delay $\tau$ of variability flux broad $H\alpha$ relative to the continuum $R_{\text{BLR}} = c\tau$
- Line width $V$ is estimated from the observed width $V = V_{\text{obs}}/\sin i$, where $i$ - unknown angle of inclination BLR disk to the line of sight
- **PROBLEMS**: $f$ - depends on the BLR geometry (may be very complex - disc, outflows, inflows - combination of these)
- It is believed that the area of broad line (BLR) in active galactic nuclei (AGN) are virialized.

This assumption cannot be directly verified because the BLRs are spatially unresolved

Rotation of the plane of polarization in the BLR

\[ V_i = V_i^{\text{rec}} \cos(\theta) = \sqrt{\frac{G M_{\text{BH}}}{R_i}} \cos(\theta). \]

\[ R_i = R_{sc} \cdot \tan(\varphi). \]

\[ \log\left(\frac{V}{c}\right) = a - b \cdot \log(\tan(\varphi)). \]

\[ a = 0.5 \log\left(\frac{G M_{\text{BH}} \cos^2(\theta)}{c^2 R_{sc}}\right). \]

Estimation $M_{\text{BH}}$ does not depend on the inclination of the BLR.
BH masses by polarization in broad line Hα

Observation at 6-m telescope sample SyG with equatorial scattering in Hα

- Depolarization polarized flux of accretion disk because of the "mist" halo BLR clouds in the direction of the disk axis with PA~152° => -U (PA=135°)
- The halo of clouds in Hα, extends along an axis at velocity -1200 km/s
E.g. -Polarization in broad Hα 3C390.3
Afanasiev et al. 2015, MNRAS

- 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

Radio jet (VLBI)
Outflow BLR
Optical jet
Torus
Rotating BLR
Accretion disk

\( i \sim 20^\circ \)