Active Galactic Nuclei in polarized light

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Polarization!

Why?

How to?

What?
1. Non-thermal emission with radio, IR, UV and X-ray excess.

The emission is concentrated in <1 pc region and contains up to 90% of the galaxy luminosity.
2. Emission lines.

Broad emission lines – up to 10,000 km/s (Balmer, MgII, OI, NII...) + highly ionized narrow lines – up to 1000 km/s ([OII], [OIII]...)
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Observational properties of AGN

3. Rapid variability
   Long-term (years+), short-term (hours!), spectral. The key point – small sizes.

e.g. S5 0716+714:

credit: VO of SPbSU

Shapovalova+19: NGC 3516
4. Polarization

Polarization is an additional parameter of the radiation helping to resolve the structure.
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- Physical state
- Kinematics
- Volume distribution

NGC 5793
HST image

AGN <1 pc

0.1″ = 25 pc

1″ = 250 pc
Polarization mechanisms

INSIDE
- GR effects near spinning SMBH
- Thomson scattering in AD
- Scattering in hot corona
- Jet synchrotron radiation
- Faraday rotation

OUTSIDE
- Polar scattering by ionization cone
- Equatorial scattering by dusty torus
Polarization in Sy

Unpolarized Seyfert 1
($i \sim 0^\circ$)

Equatorially-scattered Seyfert 1
($0 < i < 45^\circ$)

Polar-scattered Seyfert 1
($i \approx 45^\circ$)

Polar-scattered Seyfert 2
($i > 45^\circ$)

Torus

Equatorial scattering region

Broad-line emitting disc

Smith+14

Depends on orientation!
Polarization in Sy

NGC 1068

Hidden broad lines

Optically thin cone

Point-source scattering → 2D distribution

3D clouds distribution

Kishimoto+99

Miller+91
Polarization is a marker of inner physics

• Polarization is a unique tool to resolve the structure and kinematics

• Polarization helps to reconstruct 3D image
Observational techniques

Wollaston prism

Double Wollaston prism

\[ Q(\lambda) = \frac{1}{2} \left( \frac{I_0(\lambda) - I_{90}(\lambda)}{I_0(\lambda) + I_{90}(\lambda)} \right)_{\phi=0} - \frac{1}{2} \left( \frac{I_0(\lambda) - I_{90}(\lambda)}{I_0(\lambda) + I_{90}(\lambda)} \right)_{\phi=22.5}, \]

\[ U(\lambda) = \frac{1}{2} \left( \frac{I_0(\lambda) - I_{90}(\lambda)}{I_0(\lambda) + I_{90}(\lambda)} \right)_{\phi=0} - \frac{1}{2} \left( \frac{I_0(\lambda) - I_{90}(\lambda)}{I_0(\lambda) + I_{90}(\lambda)} \right)_{\phi=67.5}, \]

\[ I(\lambda) = \sum_{\phi} \left[ I_0(\lambda) + I_{90}(\lambda) \right]_{\phi}, \quad \phi = 0, 45, 22.5, 67.5 \]

\[ P(\lambda) = \sqrt{Q(\lambda)^2 + U(\lambda)^2}, \quad \varphi(\lambda) = \frac{1}{2} \arctg \left[ \frac{U(\lambda)}{Q(\lambda)} \right] \]

Afanasiev&Amirkhanyan12
Observational techniques

1. Depolarization in atmosphere

Rayleigh: \[ p = \frac{\sin^2 \theta}{1+\cos^2 \theta} \]

Ice crystals: 20-30%
Observational techniques

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Observational techniques

2. ISM

\[ P_{\text{obs}} = P_{\text{obj}} + P_{\text{ISM}} \]
«How to» conclusions:

- ISM and atmosphere are the sources of depolarization
- *Polarization is a vector*
Afanasiev+11: if the Faraday rotation on the photon mean free path in the process of scattering by electrons is taken into account, then the polarization and its dependences on the wavelength are completely determined by the magnetic field.

$$P(\lambda) \sim \lambda^n$$

$$T_e(R) \sim R^{-p}$$

$$B(R) \sim B_H(R_H/R)^s$$

$$P_l \sim \frac{P_l(0, \mu)}{B_{z,\perp} \lambda^2} \sim \lambda^{(s/p-2)}$$
Afanasiev+11: *if the Faraday rotation on the photon mean free path in the process of scattering by electrons is taken into account, then the polarization and its dependences on the wavelength are completely determined by the magnetic field.*

| Object          | $p$  | $s$  | $B(R_\lambda)$ [G] |
|-----------------|------|------|---------------------|
| PG 0007+106     | 1/2  | 1    | 2.43                |
| PG 0026+129     | 3/4  | 5/4  | 1                   |
| PG 0049+171     | 3/4  | 5/4  | 13                  |
| PG 0157+001     | 3/4  | 5/4  | 98                  |
| PG 0804+761     | 3/4  | 3/2  | 3.4                 |
| PG 0844+349     | 3/4  | 1    | 37                  |
| PG 0953+414     | 3/4  | 1    | 300                 |
| PG 1116+215     | 3/4  | 3/4  | 100                 |
| PG 2112+059     | 3/4  | 2    | 14.4                |
| PG 2130+099     | 1/2  | 1    | 27                  |
| PG 2209+184     | 1/2  | 3/4  | 16                  |
| PG 2214+139     | 1/2  | 5/4  | 2.8                 |
| PG 2233+134     | 3/4  | 3/2  | 0.37                |
| 3C 390.3        | 3/4  | 1    | 6.4                 |
Afanasyev+18: SMBH spins

$$\mu^{3/2} l_E = 0.201 \left( \frac{L_{5100}}{10^{44} \text{erg s}^{-1}} \right)^{3/2} \frac{\varepsilon(a)}{M_8^2}$$

$P_l$: observations vs. Sobolev-Chandrasekhar theory $\Rightarrow \mu = \cos(i)$

47 type 1 active galaxies

Kerr supermassive black holes
Polarization in continuum: variability

**Sy1.5 Mrk 6**
- Spectropolarimetric monitoring in 12 epochs 2010-2014;
- Polarized continuum region - 2 days (0.002 pc);
- BLR H\(\alpha\) - 22 days (0.02 pc)

**Sy1 3C390.3**
- Spectropolarimetric monitoring in 23 epochs 2009-2015;
- Polarized continuum region - 10 days (0.01 pc);
- BLR H\(\beta\) - 60 days (0.06 pc), BLR H\(\alpha\) - 120 days (0.1 pc)

Afanasiev+14, Afanasiev+15

The polarized continuum region is 10 times smaller than BLR.
The observed polarization in continuum is the vector sum of the disk and jet polarization.
Polarization in broad lines

Savic+19, in print

Broad-line region (BLR):
- $n \sim 10^8 \div 10^{12}$ cm$^{-3}$
- 0.1 pc
- clumpy structure
Broad lines are originally unpolarized. The polarization is produced by equatorial scattering.
Polarization in broad lines

In case of Keplerian-like motion:

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

\[ \log \left( \frac{V_i}{c} \right) = a - b \cdot \log(\tan(\phi_i)), \quad a = 0.5 \log \left( \frac{G M_{BH} \cos^2(\theta)}{c^2 R_{sc}} \right) \]

STOKES modelling (Marin18)
Polarization in broad lines

**Mrk 6 (IC 450)**

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

- observations with SCORPIO-2 at 6-m BTA in 2010-2013;
- 12 spectra (Hα + Hβ) with 2800-3600 sec exposures and 7-8Å resolution;
- Stokes parameters accuracy $\sim 0.2%$.

Afanasiev+14
Polarization in broad lines

Afanasiev+19: 35 Sy galaxies

Figure 9. The same as in Fig. 4, but for PG 1700+518, 3C 390.3, Mkn 509, Mkn 304 and 3C 445.
Polarization in broad lines: mass estimation

SMBH mass – *reverberation mapping*

- Gas is virialized.
- BLR size as a time-delay in Balmer line: $R_{BLR} = c\tau$.
- $v$ is obtained from the line width: $v = v_{obs}/\sin(i)$ - $i$ is unknown.
- $f$ is totally unknown.

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

Too many parameters are unknown and unobserved.
Polarization in broad lines: mass estimation

SMBH mass – *spectropolarimetry*

- Gas is virialized.
- Only geometrical effects.
- Direct and indirect measurements of $R_{sc}$.
- Only 1 epoch is needed.

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

Independent from the inclination!
As the mass is estimated, the inclination angle could be found:

\[ \sin^2(i) = \frac{R_{BLR} v^2}{G M_{SMBH}^{pol}} \]

The dependence between BLR inclination angle and galaxy inclination

In the frame of equatorial scattering model:

\[ R_{max} = R_{sc} \tan(\phi_{max}) \]
\[ R_{max} \propto R_{BLR} \]
\[ R_{BLR} = c \tau = \langle R \rangle = \frac{\int_{R_{min}}^{R_{max}} I(R) R dR}{\int_{R_{min}}^{R_{max}} I(R) dR} \]
\[ \langle R \rangle \approx \frac{(1 + \alpha)}{(2 + \alpha)} R_{max} \]
\[ I(R) \propto R^\alpha \]

Constant luminosity disk (\( \alpha = 0 \)) \( R_{BLR} = 0.5 R_{max} \)
Shakura-Sunyaev disk (\( \alpha = -3/4 \)) \( R_{BLR} = 0.2 R_{max} \)

Observations \( R_{BLR} = (0.31 \pm 0.17) R_{max}, \alpha \approx -0.57 \)
Type 1 AGN SBS 1419+538  \( z = 1.862 \)

- Spectropolarimetry with SCORPIO-2 at 6-m BTA
- Double Wollaston prism
- Exposures: 16 x 300\(^s\)

\[
\log \left( \frac{M_{BH}}{M_\odot} \right) = 9.59 \pm 0.29
\]
The observer looks into the jet, where polarization has the synchrotron origin. The polarization vector is connected with the plasma trajectory and thus with the magnetic field structure.

The rotation of the polarization vector = The plasma rotation in the magnetic field inside the jet
Short-term polarization variability

Helical magnetic field structure at $< 10^{-2}$ pc from the core.

(Marscher05)
**Conclusions**

- The polarization in *continuum* is produced in magnetized AD (0.001-0.01 pc) and depends on:
  - MF in AD $B(R)$;
  - $M_{SMBH}$ and BH spin.
- The polarization in *continuum* consists of the constant $\overrightarrow{disk}$ and the variable $\overrightarrow{jet}$.
- The polarization in *broad lines* resolves the gas kinematics in BLR ($\sim$0.1 pc) $\Rightarrow$ more accurate SMBH mass estimation, independent from the inclination angle.
- *Short-term variability* of the polarization vector in BL Lac type objects marks the plasma kinematics inside the jet $\Rightarrow$ the jet magnetic field structure.