# AGN spectropolarimetry on the 6-m telescope: observations and results

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# Radiation polarization in AGN

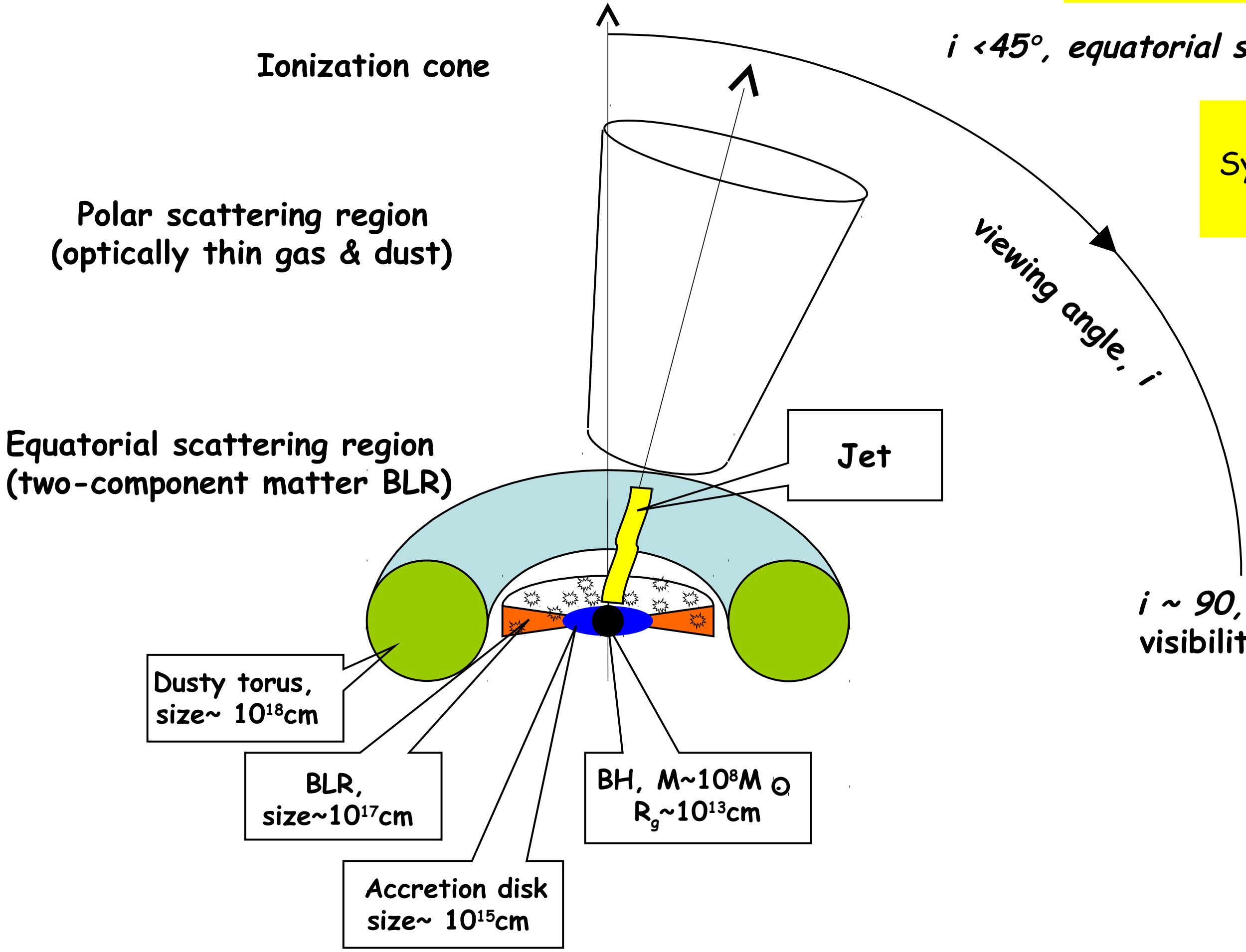
*i ~ 0°, scattering* ~ 0 (E ⊥), direct view of accretion disk (E ||) and jet (E ⊥)

BL Lac, RG, radio-quit QSO,

UV-polarization in cone ionization

*i <45°, equatorial scattering* > 0, (E ||)

Sy1, radio-lobe QSO , Bal QSO




BL Lac, RG, radio-quit QSO,
UV-polarization in cone
ionization

*i ~ 90, polar scattering* > 0 (E⊥),
visibility BLR in polarized light

Sy2,

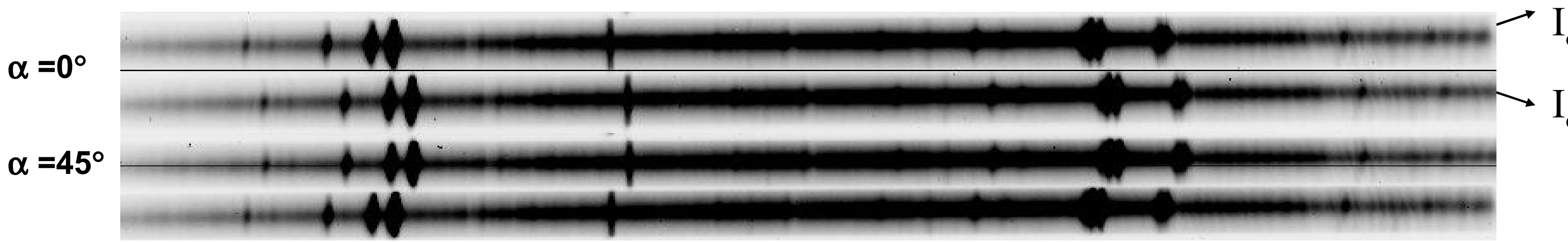
# Possible mechanisms of polarization of radiation in AGN

- *polarization of radiation in the field of a rotating black hole*
- *radiation transfer in* optically thick *accretion disk (electron scattering)*
- *radiation depolarization at Faraday rotation in magnetic field*
- *synchrotron radiation of the jet*
- *scattering in optically thin gas & dust cone ionization*

# Observation tasks in optical range

- *comparison of polarization in continuum and lines, both for NLR and BLR ( to check the unified model )*
- *search for broad lines in polarized light in Sy2*
- *dependence of polarization on redshift ( $L_{\alpha}$-forest )*
- *polarization variability - jet and outflows, nonhomogeneous BLR, instability in accretion disk (AD)*
- *dependence of continuum polarization on wavelength – mechanisms of scattering, estimation of magnetic field in (AD)*

# Polarization measurement.I




**Universal focal reducer SCORPIO in spectropolarimetric mode (Afanasiev & Moiseev, 2005)**

**Analyzer of polarization – turnet on the fixed angle α (0° or 45°) Savart plate**

$$Q = \frac{I_o(\lambda)R(\lambda) - I_e(\lambda)}{I_o(\lambda)R(\lambda) + I_e(\lambda)} = P\cos(\varphi - \varphi_0)\,, \quad \alpha = 0°$$

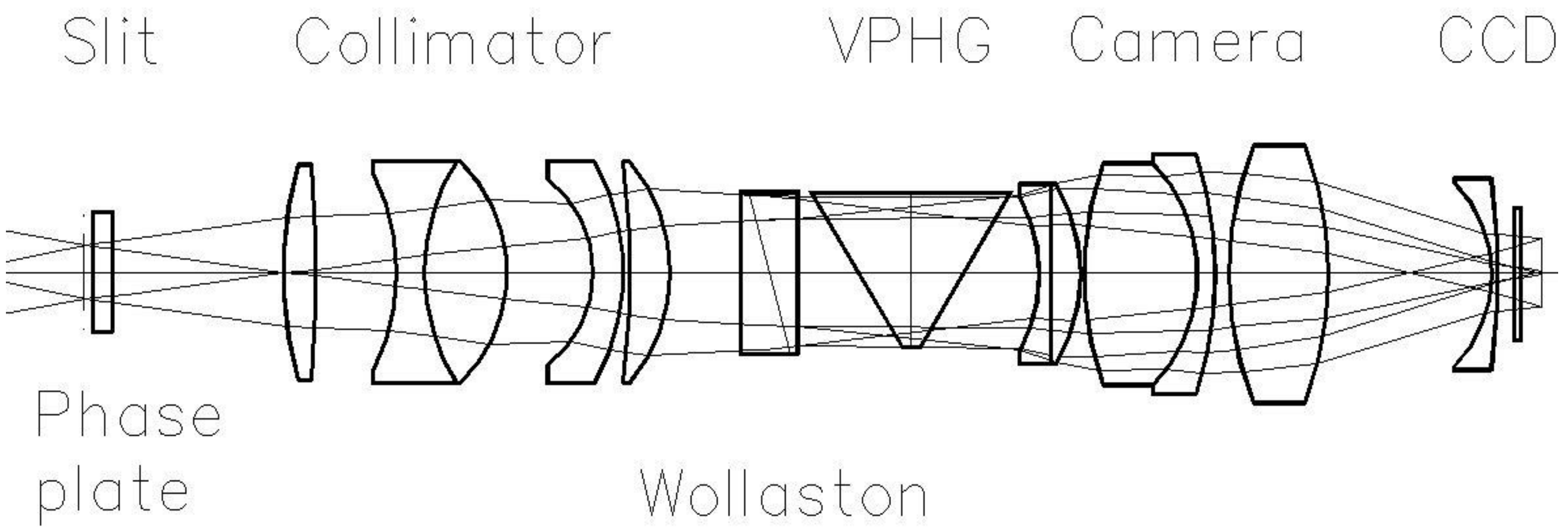
$$U = \frac{I_o(\lambda) - I_e(\lambda)R(\lambda)}{I_o(\lambda) + I_e(\lambda)R(\lambda)} = P\sin(\varphi - \varphi_0)\,, \quad \alpha = 45°$$

$$P = \sqrt{U^2 + Q^2}\,, \quad \varphi = \arctan(U/Q)/2 + \text{const}$$

**Instrumental polarization ~ 0.2%**

# Polarization measurement.II

## Focal reducer SCORPIO-2, mode spectropolarimetry

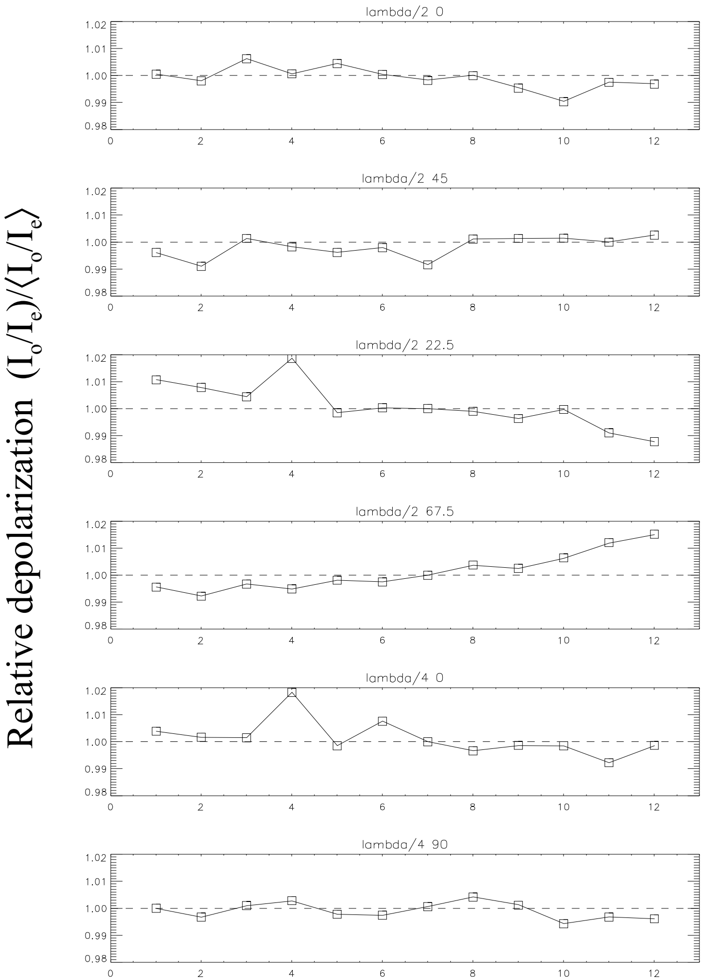



- apochromatic turned phase plate $\lambda/2$ ( phase variation $\pm$ 0.03 rad)

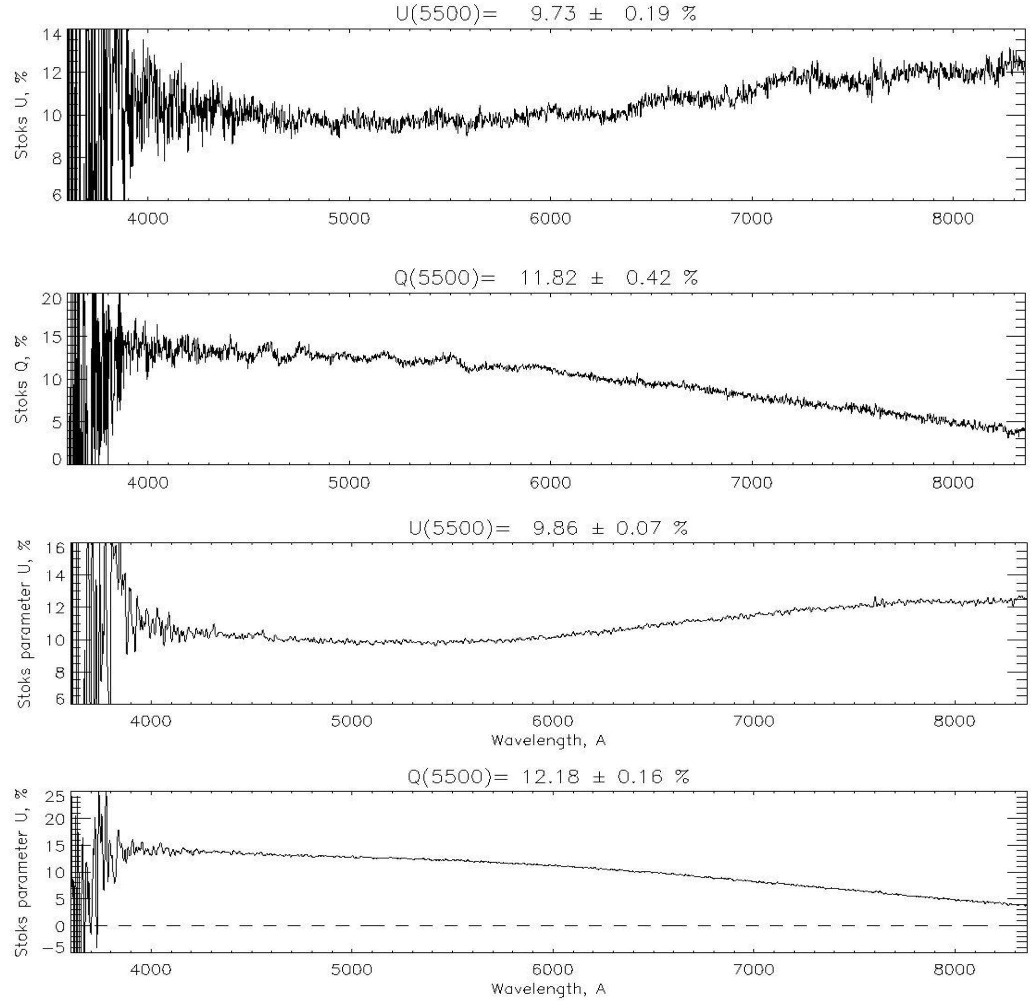
$$Q=0.5\left(\frac{Io-Ie}{Io+Ie}\right)_{0^\circ}-0.5\left(\frac{Io-Ie}{Io+Ie}\right)_{45^\circ} \quad U=0.5\left(\frac{Io-Ie}{Io+Ie}\right)_{22.5^\circ}-0.5\left(\frac{Io-Ie}{Io+Ie}\right)_{67.5^\circ}$$

**Instrumental polarization : linear one < 0.05% circular one <0.01 %**

# Depolarization: effect of the atmosphere of Earth



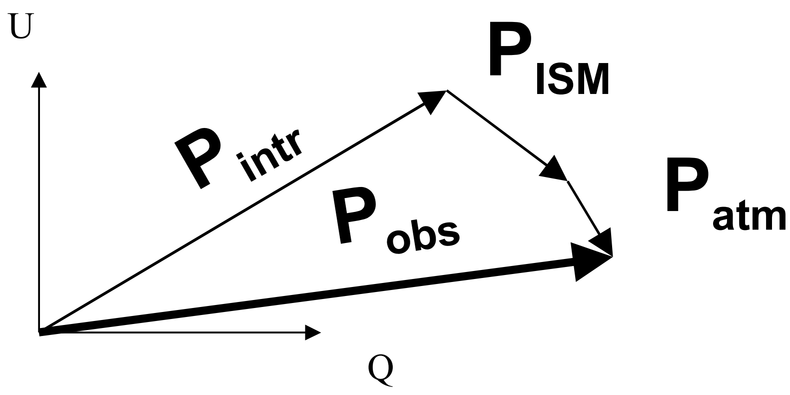

Number of cycle (interval 600 s)



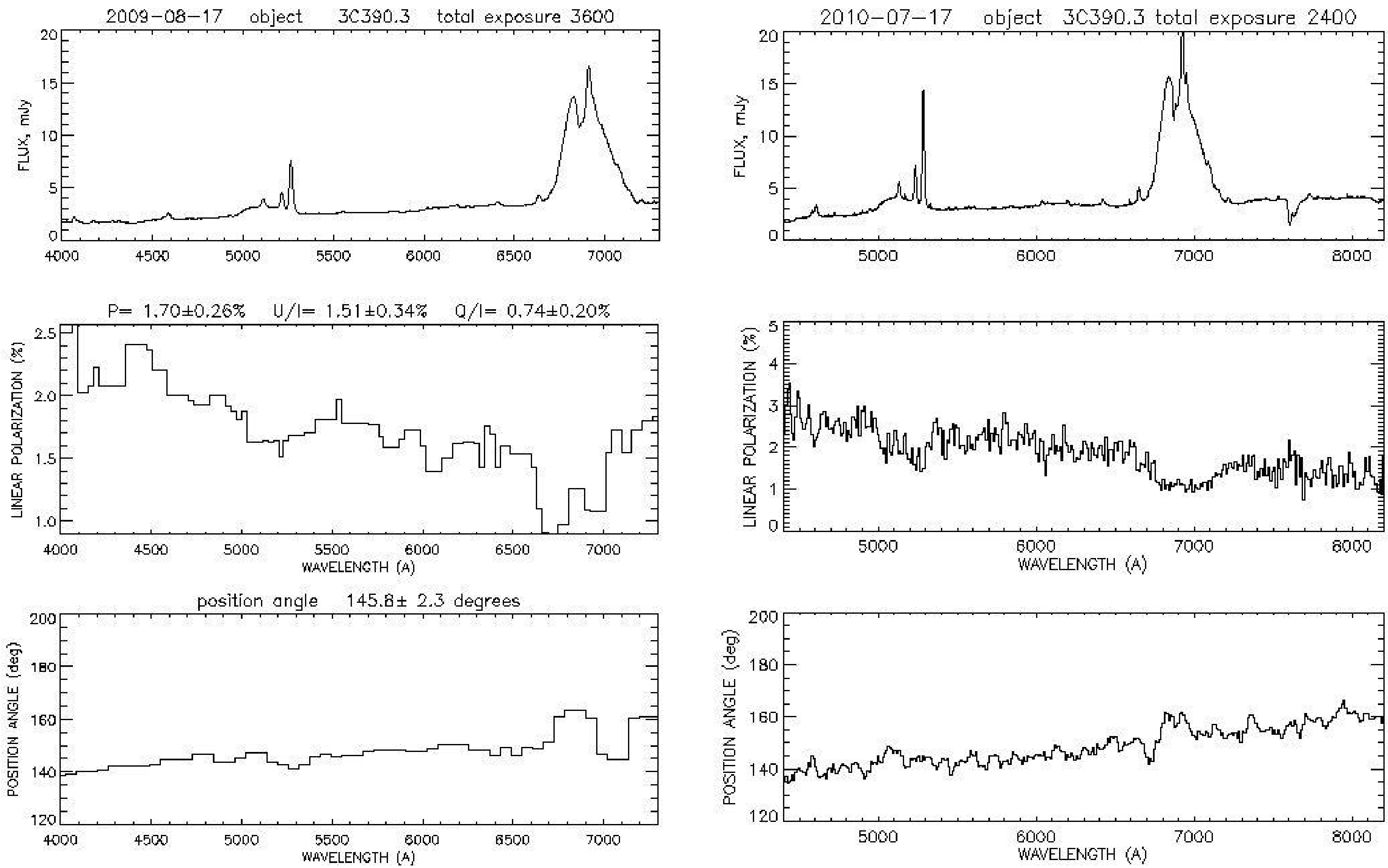

Measurements of Stokes parameters Q and U without correction depolarizations (top) and after corrections (bottom) for blazar S50716+71

# Systematic errors through polarization measurements

- *Instrumental polarization (Mueler matrix is non-diagonal)*
- *Depolarization in the Earth atmosphere depending on zenit distance and a parallactical angle*
- *Interstellar polarization*



# Comparing I and II methods



# Measurement of magnetic field in AGN

## Statement of the problem:

- *The physical conditions in accretion disks around supermassive black holes essentially do not allow a direct method of magnetic field measurement*
- *the value of magnetic field in accretion disk can be estimated on the basis of taking into account depolarization on Faraday rotation (Gnedin & Silantiev, 1997)*
- *polarization measurement in optical continuum of QSO or Sy1, where effects of scattering at dust torus can be neglected*
- *comparison of the received estimates of magnetic field strengths near the BH horizon with various models*

# Measurement of magnetic field in AGN

**Sample objects:**

- *nearby QSO or star-like Sy1 with $z < 0.5$*
- *galactic latitude $b > 30°$*
- *lack of radio emission and bright jets*
- *reliable estimates of mass of the central black holes*
- *measured luminosity of accretion disks and width of hydrogen lines*

# Measurement of magnetic field in AGN

## Observation at 6-m telescope

- observation of the AGN sample were carried out in the autumn 2008 and 2009 in the course of the observation program «Magnetic field in AGN» (PI T.M.Natsvlishvili) during 6 nights
- polarization is measured in continuum at 5100 A (for z=0) and power index n in the relation $P \sim \lambda^n$ for 15 QSO and star-like Sy1 of 14.5-16.3 magnitude in a range of redshifts 0.045-0.466
- accuracy estimates of polarization are 0.15-0.3 %, those for index n of about 0.2

**Measurement of magnetic field in AGN**

**Table 1.** Results of our observations

| Object | $m_V$ | $z$ | Type | Date | $T_{\exp}$, s | $P_V$, % | $PA_V$, deg | $n$ |
|---|---|---|---|---|---|---|---|---|
| PG 0007+106 | 15.2 | 0.089 | Sy1 | Nov. 30, 2008 | 3000 | $1.02 \pm 0.38$ | 83 | $0.15 \pm 0.25$ |
| PG 0026+129 | 15.3 | 0.142 | QSO | Nov. 30, 2008 | 3000 | $1.07 \pm 0.28$ | 99 | $-0.45 \pm 0.33$ |
| PG 0049+171 | 16.1 | 0.064 | Sy1.5 | Sep. 24, 2009 | 2160 | $1.42 \pm 0.31$ | 247 | $-0.28 \pm 0.18$ |
| PG 0157+001 | 15.7 | 0.163 | Sy1.5 | Dec. 1, 2008 | 3000 | $0.78 \pm 0.28$ | 17 | $-0.52 \pm 0.28$ |
| PG 0804+761 | 14.7 | 0.100 | QSO | Dec. 2, 2008 | 3000 | $1.00 \pm 0.38$ | 83 | $0.24 \pm 0.38$ |
| PG 0844+349 | 14.5 | 0.064 | Sy1 | Nov. 29, 2008 | 3000 | $0.85 \pm 0.10$ | 243 | $-1.17 \pm 0.17$ |
| PG 0953+414 | 15.3 | 0.234 | QSO | Dec. 3, 2008 | 3000 | $0.39 \pm 0.12$ | 317 | $0.11 \pm 0.13$ |
| PG 1022+519 | 15.8 | 0.045 | Sy1 | Nov. 30, 2008 | 3000 | $0.83 \pm 0.30$ | 259 | $-2.37 \pm 0.45$ |
| PG 1116+215 | 14.4 | 0.177 | QSO | Nov. 29, 2008 | 3000 | $0.57 \pm 0.12$ | 193 | $-1.26 \pm 0.13$ |
| PG 2112+059 | 15.9 | 0.466 | QSO | Nov. 29, 2008 | 3000 | $1.04 \pm 0.21$ | 258 | $0.45 \pm 0.17$ |
| | | | | Aug. 18, 2009 | 3600 | $1.08 \pm 0.20$ | 243 | $0.35 \pm 0.10$ |
| PG 2130+099 | 14.7 | 0.063 | Sy1 | Nov. 30, 2008 | 3000 | $0.62 \pm 0.15$ | 53 | $-0.05 \pm 0.32$ |
| PG 2209+184 | 15.9 | 0.070 | Sy1 | Sep. 24, 2008 | 3600 | $0.83 \pm 0.29$ | 200 | $-0.75 \pm 0.21$ |
| PG 2214+139 | 15.1 | 0.066 | Sy1 | Nov. 28, 2008 | 3000 | $1.58 \pm 0.18$ | 323 | $-0.69 \pm 0.15$ |
| PG 2233+134 | 16.3 | 0.326 | QSO | Nov. 29, 2008 | 3000 | $0.67 \pm 0.23$ | 253 | $0.28 \pm 0.28$ |
| 3C 390.3 | 15.2 | 0.056 | Sy1 | Nov. 29, 2008 | 3000 | $2.09 \pm 0.22$ | 140 | $-0.57 \pm 0.22$ |
| | | | | Aug. 17, 2009 | 3600 | $1.58 \pm 0.18$ | 146 | $-0.64 \pm 0.07$ |
| | | | | Sep. 24, 2009 | 3600 | $1.80 \pm 0.24$ | 144 | $-0.58 \pm 0.06$ |

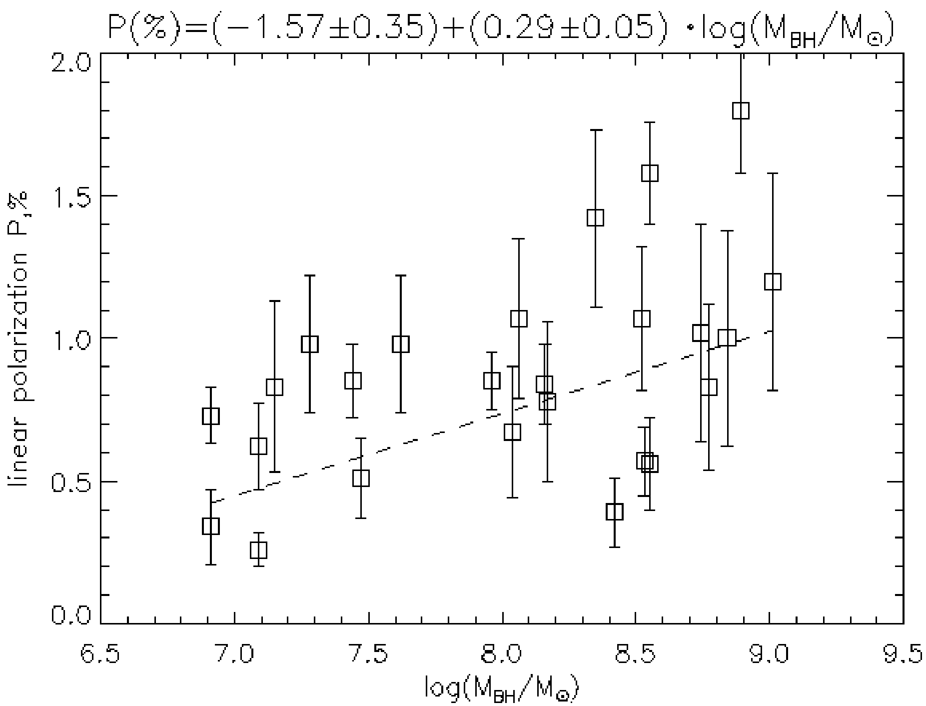
**Measurement ofmagnetic field in AGN**

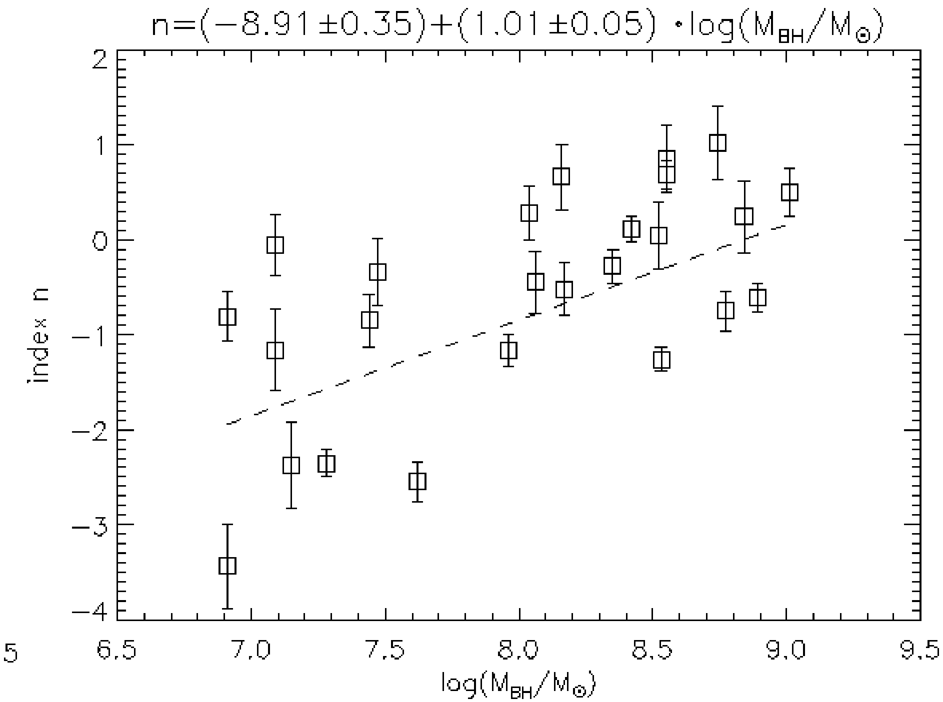
**Table 2.** Masses of the central black holes and polarization in continuum

| Object | Type | $\log \lambda L_\lambda$, erg $s^{-1}$ (opt.) | $\log \frac{M_{BH}}{M_\odot}$ | References | $P_V$, % | $n$ | References |
|---|---|---|---|---|---|---|---|
| PG 0007+106 | Sy1 | 44.82 | $8.73^{+0.08}_{-0.10}$ | 6 | $1.02 \pm 0.38$ | $0.15 \pm 0.25$ | 1 |
| PG 0026+129 | QSO | 45.02 | $8.59^{+0.07}_{-0.12}$ | 7 | $1.07 \pm 0.28$ | $-0.45 \pm 0.33$ | 1 |
| PG 0049+171 | Sy1.5 | 44.00 | $8.35^{+0.08}_{-0.10}$ | 6 | $1.42 \pm 0.31$ | $-0.28 \pm 0.18$ | 1 |
| PG 0157+001 | Sy1.5 | 44.98 | $8.17^{+0.08}_{-0.10}$ | 6 | $0.78 \pm 0.28$ | $-0.52 \pm 0.28$ | 1 |
| PG 0804+761 | QSO | 44.94 | $8.84^{+0.05}_{-0.06}$ | 7 | $1.00 \pm 0.38$ | $0.24 \pm 0.38$ | 1 |
| PG 0844+349 | Sy1 | 44.35 | $7.97^{+0.15}_{-0.23}$ | 7 | $0.85 \pm 0.10$ | $-1.17 \pm 0.17$ | 1 |
| PG 0953+414 | QSO | 45.40 | $8.42^{+0.08}_{-0.10}$ | 6 | $0.39 \pm 0.12$ | $0.11 \pm 0.13$ | 1 |
| PG 1022+519 | Sy1 | 43.70 | $7.15^{+0.09}_{-0.11}$ | 6 | $0.83 \pm 0.30$ | $-2.37 \pm 0.45$ | 1 |
| PG 1116+215 | QSO | 45.40 | $8.53^{+0.08}_{-0.10}$ | 6 | $0.57 \pm 0.12$ | $-1.26 \pm 0.13$ | 1 |
| PG 2112+059 | QSO | 46.18 | $9.00^{+0.09}_{-0.11}$ | 6 | $1.06 \pm 0.21$ | $0.40 \pm 0.15$ | 1 |
| PG 2130+099 | Sy1 | 44.46 | $8.66^{+0.05}_{-0.06}$ | 7 | $0.62 \pm 0.15$ | $-0.05 \pm 0.32$ | 1 |
| PG 2209+184 | Sy1 | 44.47 | $8.77^{+0.08}_{-0.10}$ | 6 | $0.83 \pm 0.29$ | $-0.75 \pm 0.21$ | 1 |
| PG 2214+139 | Sy1 | 44.66 | $8.55^{+0.09}_{-0.12}$ | 6 | $1.58 \pm 0.18$ | $-0.69 \pm 0.15$ | 1 |
| PG 2233+134 | QSO | 45.33 | $8.04^{+0.08}_{-0.10}$ | 6 | $0.67 \pm 0.23$ | $0.28 \pm 0.28$ | 1 |
| 3C 390.3 | Sy1 | 43.99 | $8.85^{+0.09}_{-0.11}$ | 6 | $1.80 \pm 0.22$ | $-0.61 \pm 0.15$ | 1 |
| I Zw 1 | Sy1 | 44.80 | $7.44^{+0.09}_{-0.12}$ | 6 | $0.85 \pm 0.13$ | $-0.85 \pm 0.28$ | 2 |
| Mrk 509 | Sy1 | 44.28 | $8.16^{+0.04}_{-0.04}$ | 7 | $0.84 \pm 0.14$ | $0.66 \pm 0.35$ | 2 |
| Mrk 573 | Sy1 | 44.40 | $7.28^{+0.08}_{-0.10}$ | 8 | $0.98 \pm 0.24$ | $-2.35 \pm 0.14$ | 3 |
| Mrk 841 | Sy1.5 | 44.29 | $8.52^{+0.08}_{-0.10}$ | 6 | $1.07 \pm 0.25$ | $0.05 \pm 0.35$ | 2 |
| NGC 3227 | Sy1.5 | 42.38 | $7.63^{+1.1}_{-1.9}$ | 7 | $0.98 \pm 0.24$ | $-2.55 \pm 0.21$ | 4, 9 |
| NGC 3783 | Sy1 | 43.26 | $7.47^{+0.07}_{-0.09}$ | 7 | $0.51 \pm 0.14$ | $-0.34 \pm 0.35$ | 2 |
| NGC 4593 | Sy1 | 43.09 | $6.73^{+0.03}_{-0.09}$ | 7 | $0.34 \pm 0.13$ | $-3.44 \pm 0.45$ | 2, 9 |
| NGC 5548 | Sy1 | 43.51 | $7.83^{+0.02}_{-0.02}$ | 7 | $0.73 \pm 0.10$ | $-0.81 \pm 0.26$ | 5, 9 |
| NGC 7469 | Sy1 | 43.72 | $7.09^{+0.05}_{-0.05}$ | 7 | $0.26 \pm 0.06$ | $-1.16 \pm 0.43$ | 2 |

# Measurement of magnetic field in AGN

## Empirical relation




Significant correlation of the polarization properties with masses of SMBH specifies that observed dependences are produced by physical mechanisms in accretion disk

# Computation of magnetic field

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

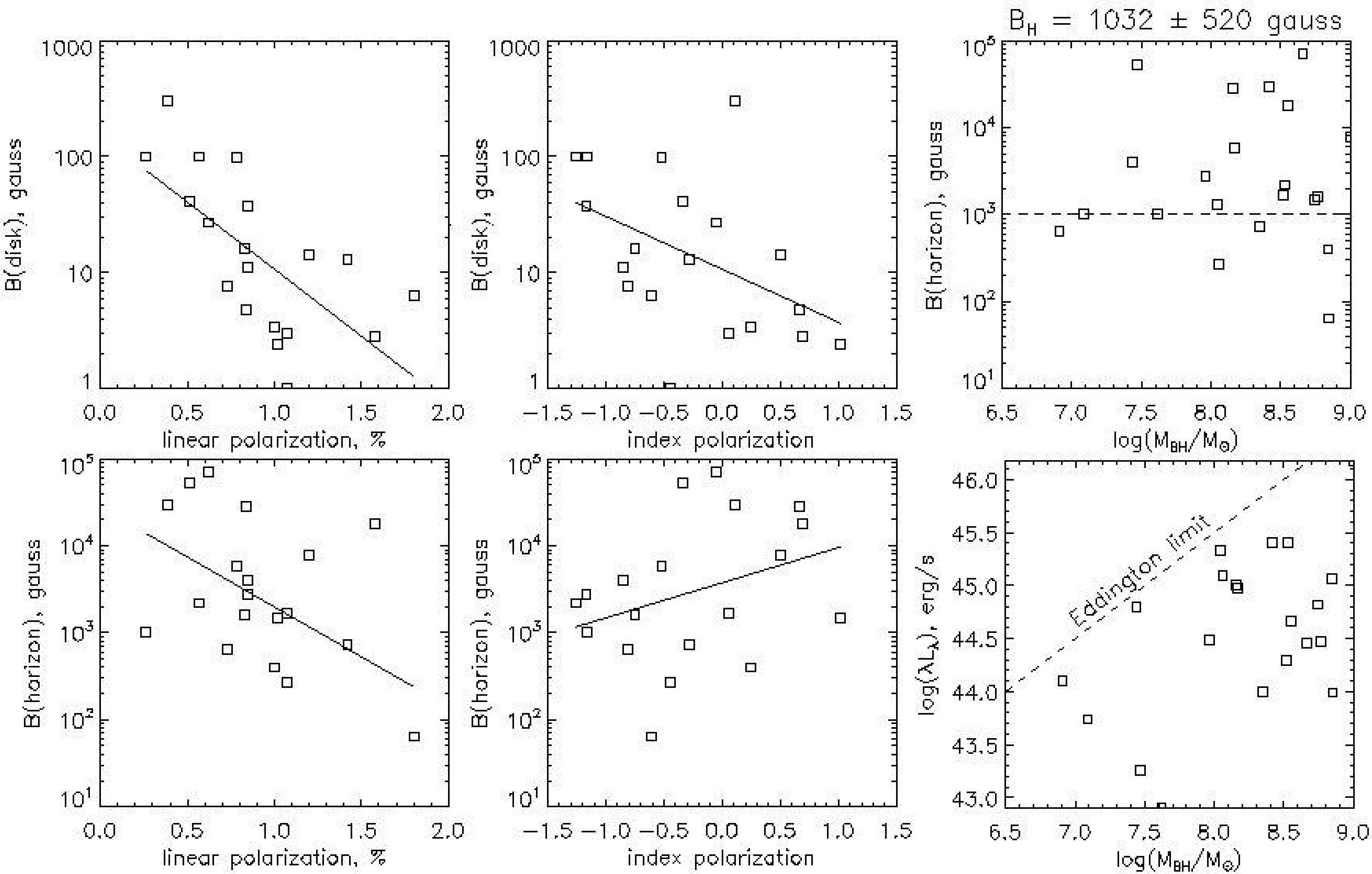
✓ If the magnetic field is not strong ($B < 10^6$ G ) to provide optical anisotropy of the medium, then the real optical anisotropy can result from the Faraday rotation of the polarization plane on the photon mean free path in the medium (Gnedin and Silant'ev 1984), that results in strong dependence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

# Estimation of the magnetic field strength for the AGN sample




$B_H \sim 1000$ G !!

(Afanasiev at al., 2011, Astron.Letter, v.37, p. 302)

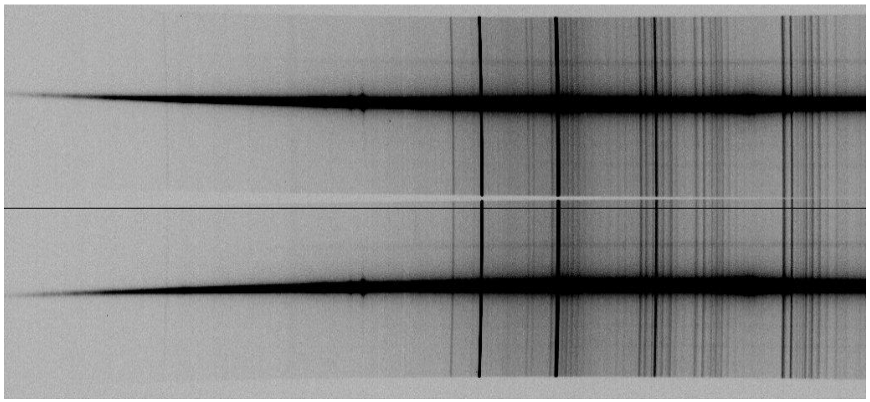
# Variability of the polarization properties For some Sy1

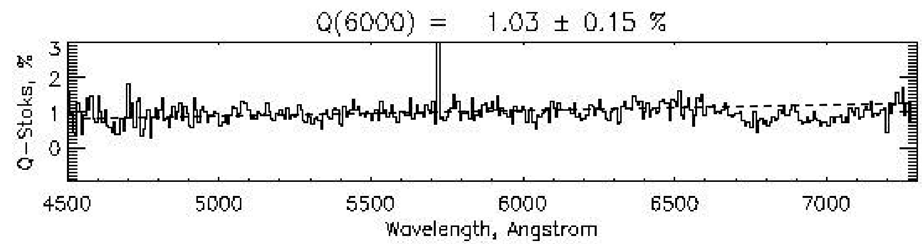
Observations of variability of the spectropolarimetric properties of AGN were carried out within three observation programs at the 6-m telescope during 2008- 2012:

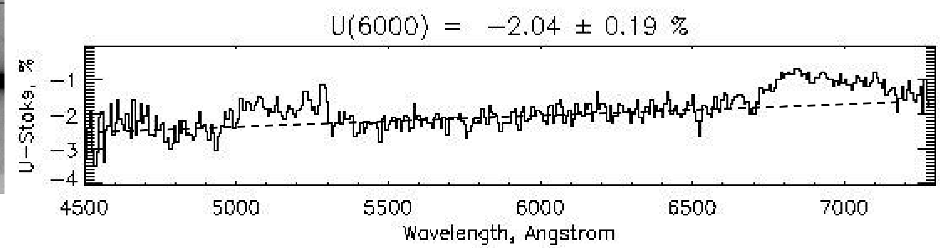
- «Magnetic field in AGN» (Natsvlishvili)
- AGN spectropolarimetry' (Shapovalova)
- 2D-spectrophotometry of SyG (Afanasiev)

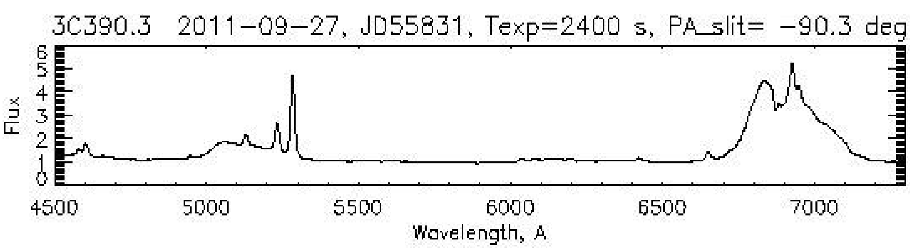
Below results of spectropolarimetry for two objects - 3C390.3 and Mkn6 - are presented

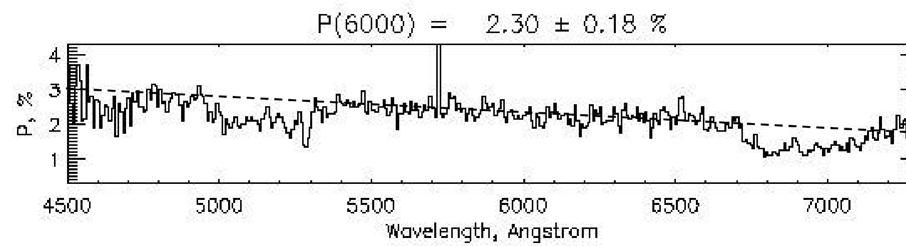
# Variability in 3C390.3. Example spectra

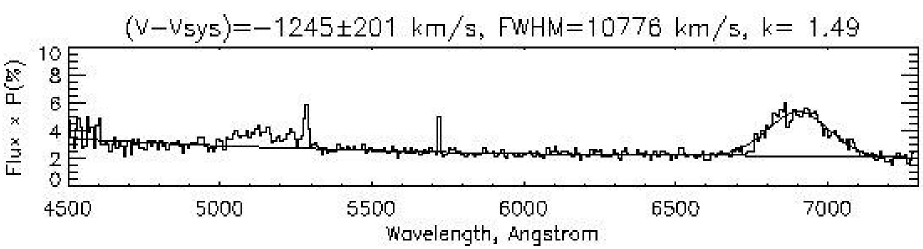


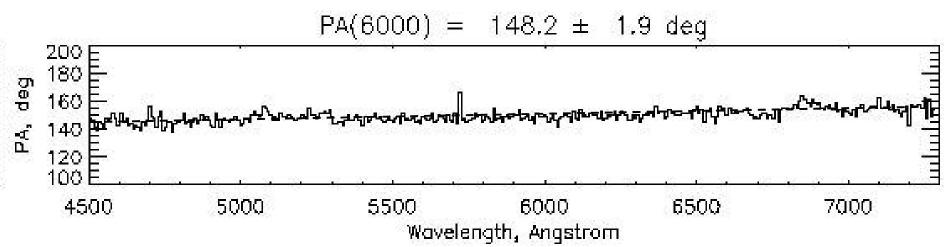


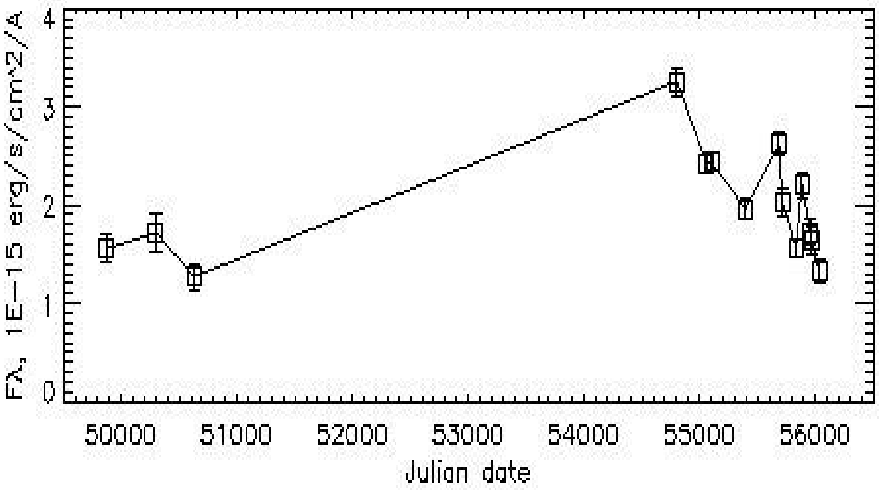
# Variability in 3C390.3. Resulted table

| Julian date | Q(6000), % | U(6000), % | P(6000), % | PA(6000), degrees | Continuum(5100), $10^{-15}$erg/s/cm$^2$/Å | $V_{sys}$-$V_{polarized}$, km/s |
|---|---|---|---|---|---|---|
| 49875 | 0.59 ± 0.10 | -0.94 ± 0.10 | 1.12 ± 0.07 | 156.0 ± 1.9 | 1.56 ± 0.15 | (300 ± 300) |
| 50302 | 0.74 ± 0.10 | -1.17 ± 0.10 | 1.51 ± 0.15 | 160.0 ± 2.9 | 1.72 ± 0.20 | 437 ± 200 |
| 50628 | 0.54 ± 0.05 | -1.47 ± 0.05 | 1.57 ± 0.05 | 150.0 ± 2.0 | 1.27 ± 0.13 | (300 ± 300) |
| 54799 | 0.38 ± 0.25 | -2.06 ± 0.25 | 2.09 ± 0.22 | 140.2 ± 1.1 | 3.26 ± 0.14 | 1200 ± 400 |
| 55060 | 0.82 ± 0.20 | -1.60 ± 0.34 | 1.81 ± 0.26 | 148.6 ± 2.8 | 2.42 ± 0.10 | 1100 ± 350 |
| 55099 | 0.60 ± 0.24 | -1.70 ± 0.28 | 1.80 ± 0.24 | 144.7 ± 1.7 | 2.44 ± 0.09 | 800 ± 300 |
| 55394 | 1.21 ± 0.34 | -1.38 ± 0.24 | 1.85 ± 0.29 | 155.6 ± 3.9 | 1.96 ± 0.11 | 874 ± 200 |
| 55682 | 0.90 ± 0.11 | -1.38 ± 0.08 | 1.65 ± 0.09 | 151.6 ± 2.1 | 2.62 ± 0.12 | 915 ± 276 |
| 55713 | 1.39 ± 0.15 | -0.90 ± 0.10 | 1.66 ± 0.09 | 163.3 ± 1.8 | 2.03 ± 0.14 | 913 ± 220 |
| 55831 | 1.04 ± 0.09 | -2.03 ± 0.16 | 2.28 ± 0.12 | 148.5 ± 1.3 | 1.56 ± 0.10 | 1250 ± 193 |
| 55885 | 1.52 ± 0.22 | -1.83 ± 0.40 | 2.45 ± 0.29 | 155.1 ± 3.9 | 2.21 ± 0.13 | 1246 ± 418 |
| 55959 | 1.26 ± 0.41 | -1.09 ± 0.49 | 1.89 ± 0.42 | 160.4 ± 7.1 | 1.72 ± 0.13 | 1294 ± 201 |
| 55971 | 0.97 ± 0.34 | -1.95 ± 0.47 | 2.22 ± 0.42 | 147.8 ± 4.0 | 1.65 ± 0.14 | 1012 ± 304 |
| 56032 | 1.03 ± 0.18 | -1.80 ± 0.19 | 2.10 ± 0.10 | 149.6 ± 2.6 | 1.33 ± 0.12 | 1170 +201 |

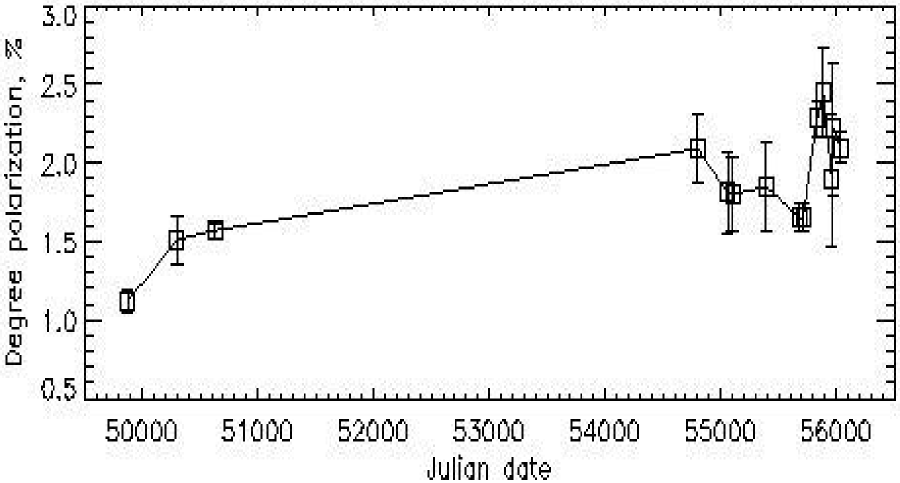
(*) Corbett at al., 2000, MNRAS, v.319, 685
(**) Kay at al., 1999, ASP Conference Series, v.175, 205

# Variability in 3C390.3

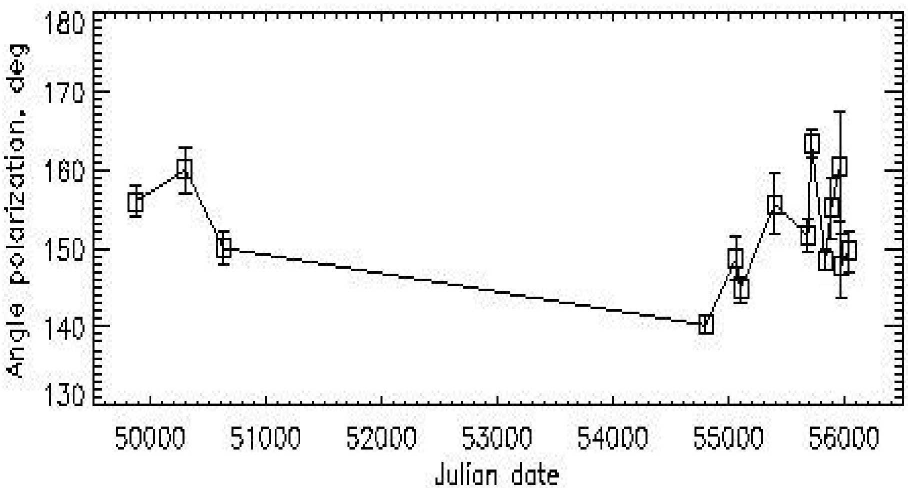
Continuum Flux at 5100Å for z=0



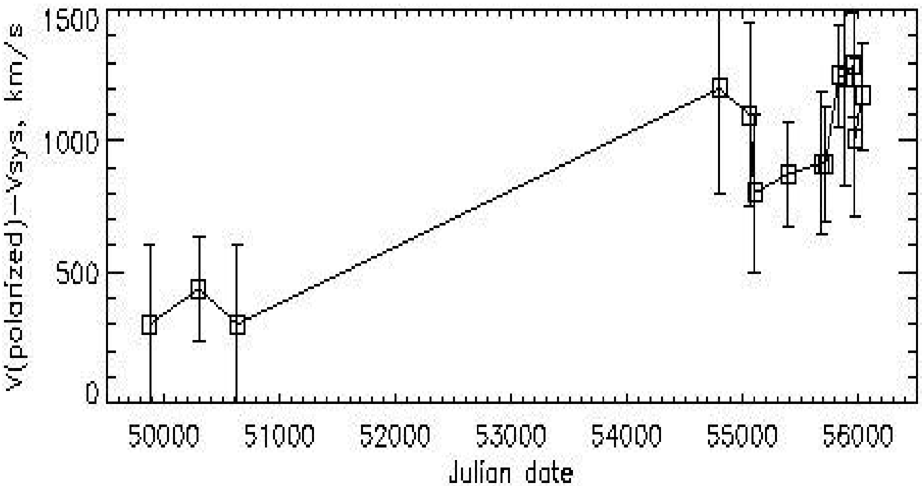

Linear polarization of continuum



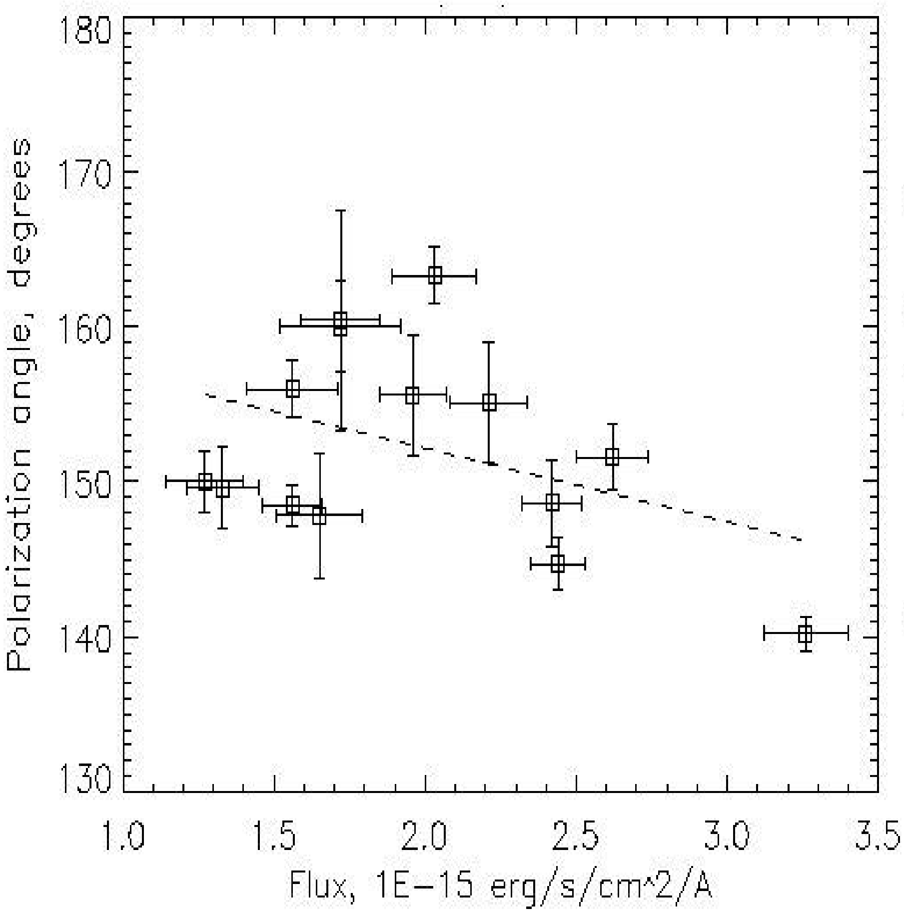

Angle plane of polarization of continuum

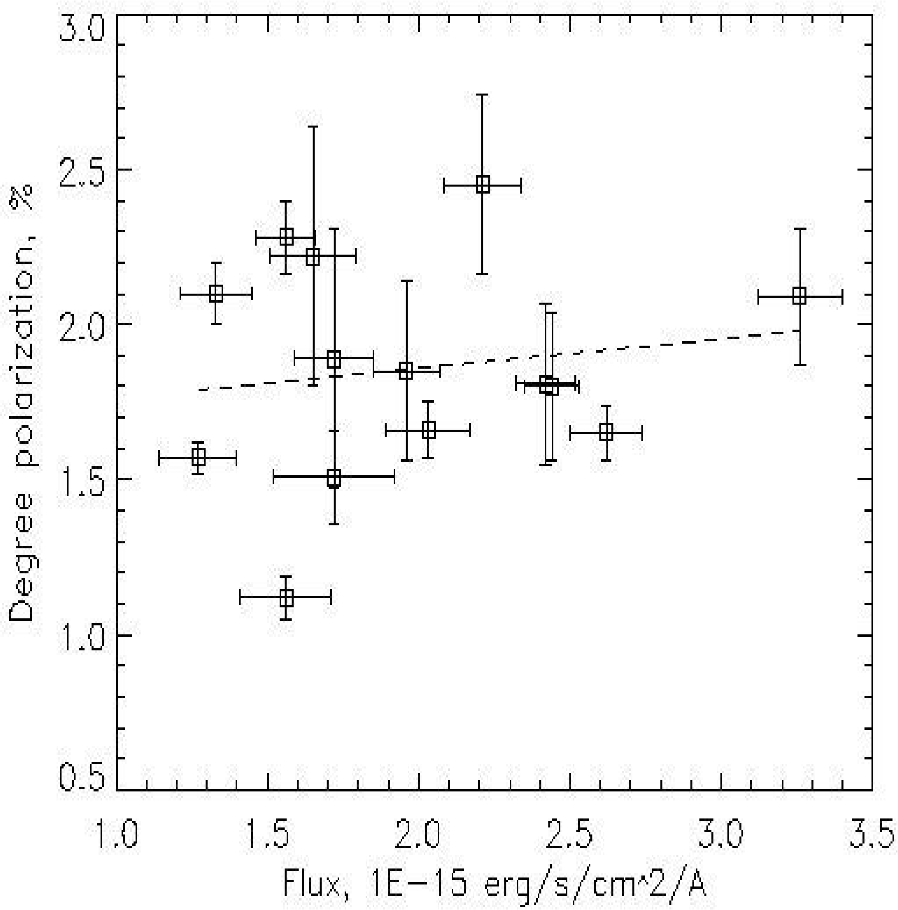



Velocity shift polarized broad Hα emission



# Variability in 3C390.3. Relation

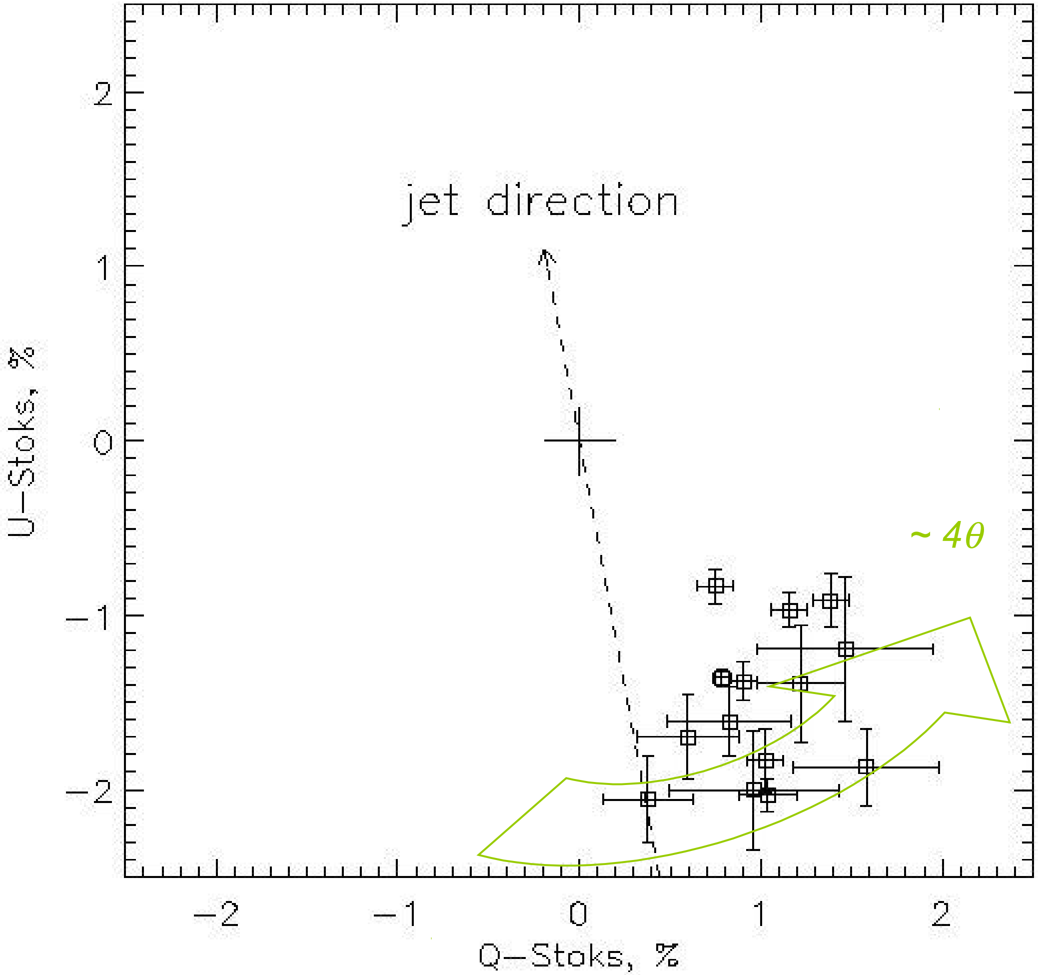


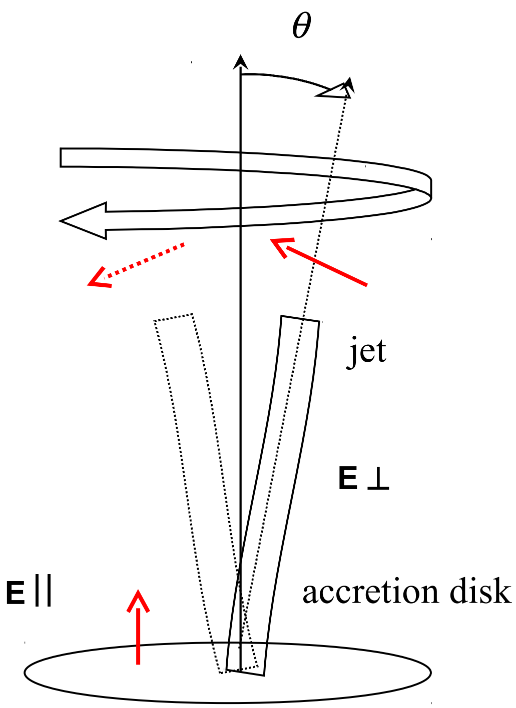



# Variability in 3C390.3. Turn of the polarization plane

**Direct view of the accretion disk and jet in continuum**

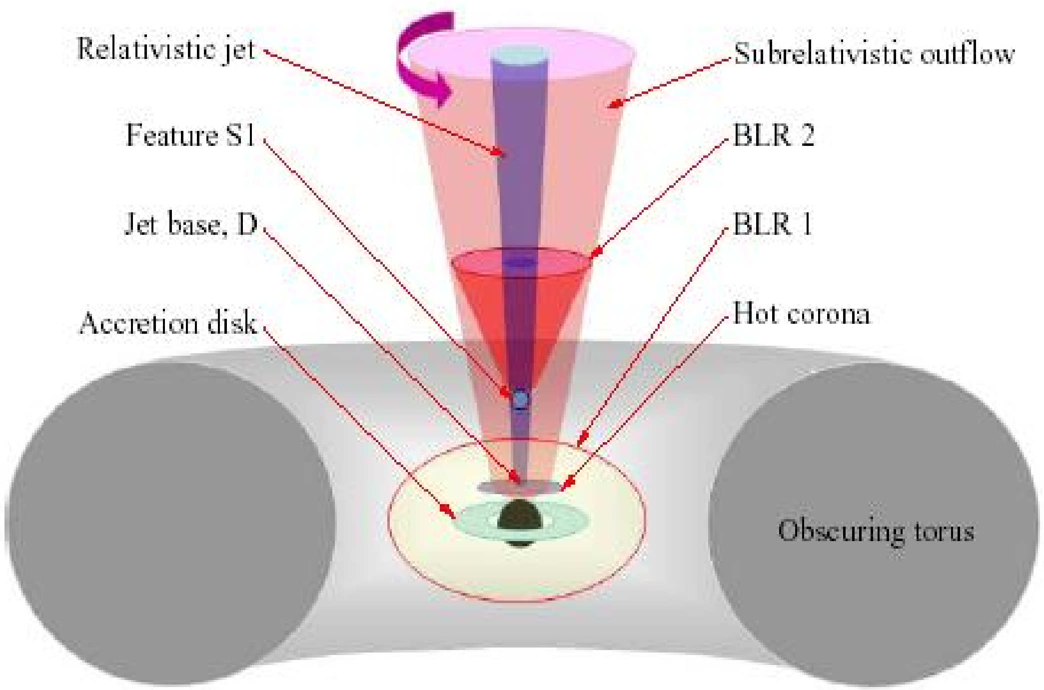
**observed polarization is superposition of two non-colinear vectors**

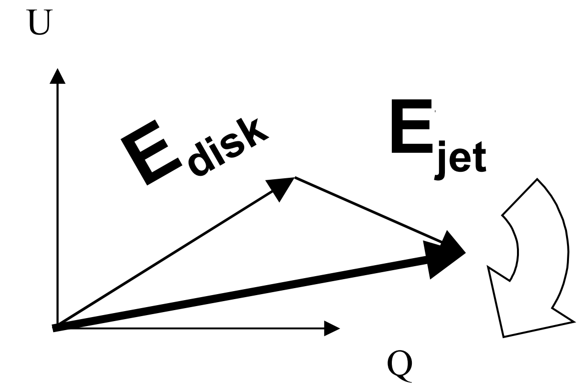



$\theta \approx 8°$

# Variability in 3C390.3. Composition of two polarizations

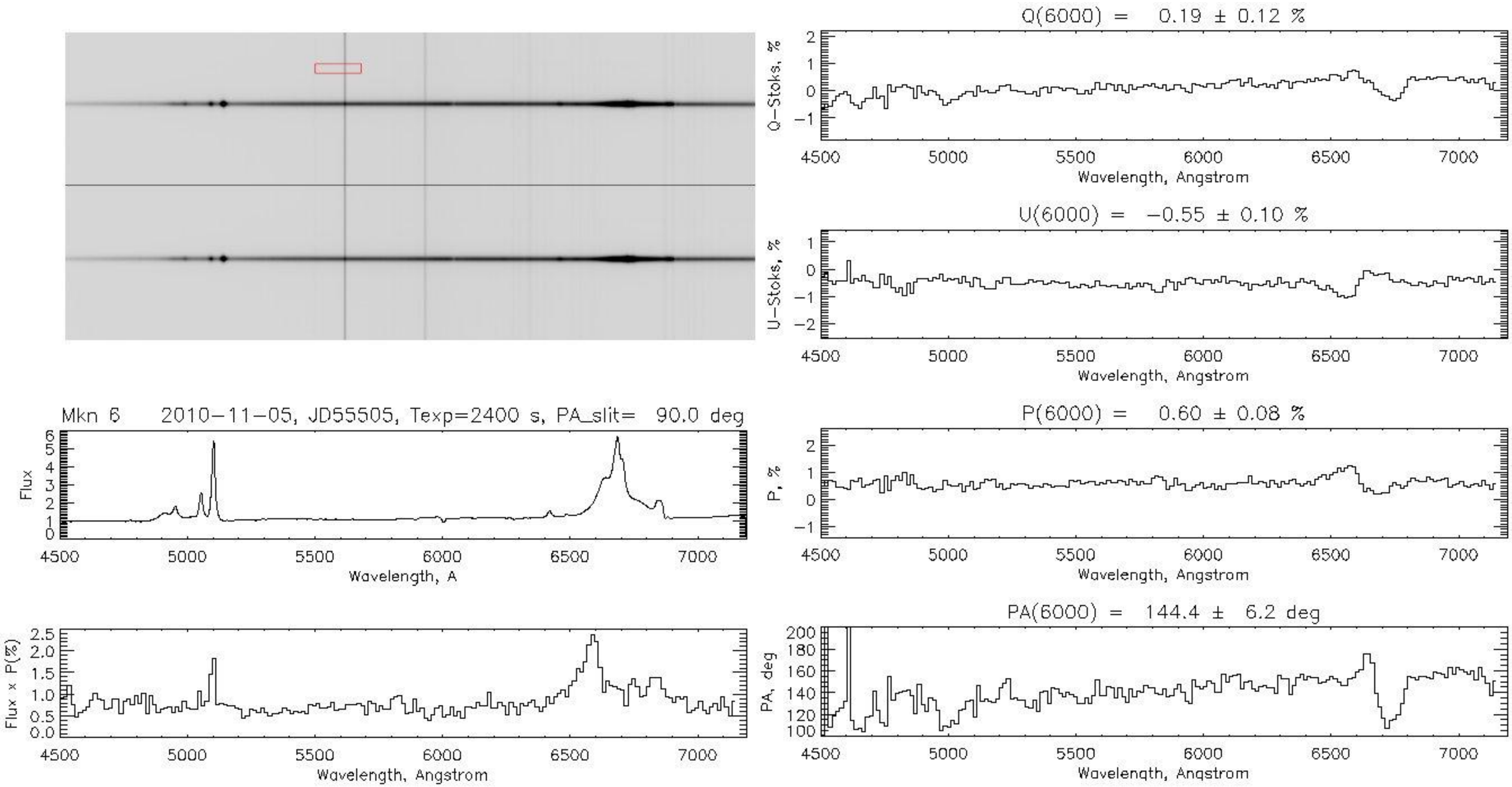



**A sketch of the nuclear region in 3C 390.3.**
***The conical shape of the BLR2 associated with the outflow arises from a large fraction of the continuum radiation being beamed into a cone with a half-opening angle ~ 30 deg. (Shapovalova et al., 2010)***

- ***In continuum - composition of TWO VARIABLE polarization vectors from disk (||) and jet (⊥)***
- ***In Hα - polar scattering (depolarization) in plane ⊥ jet direction at hot subrelativistic outflow with velocity ~10³ km/s***

# Polarization Mkn6. Example spectra



# Polarization variability of Mkn 6 in continuum

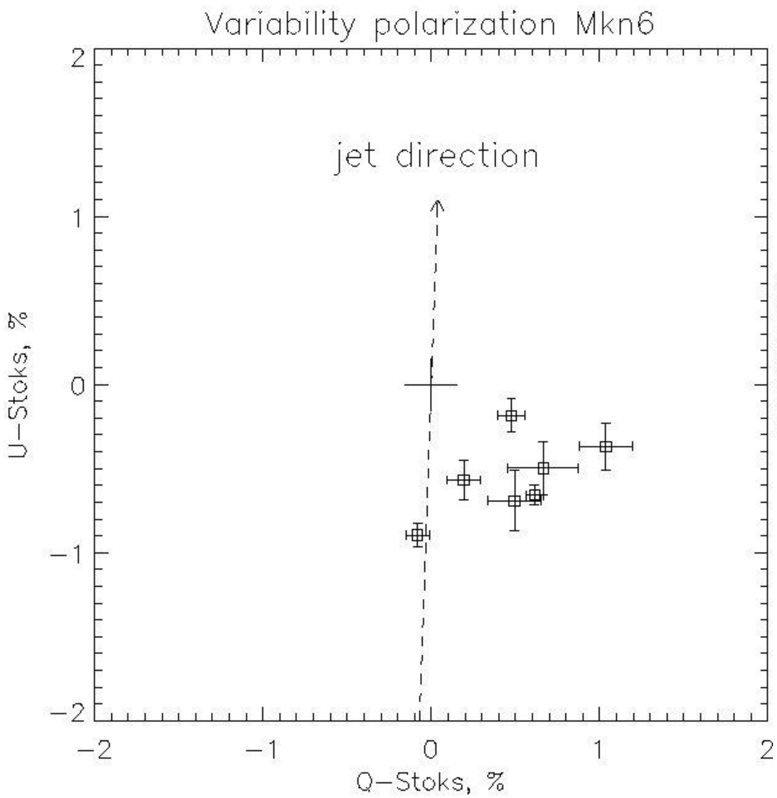
Data of spectropolarimetry Mkn 6

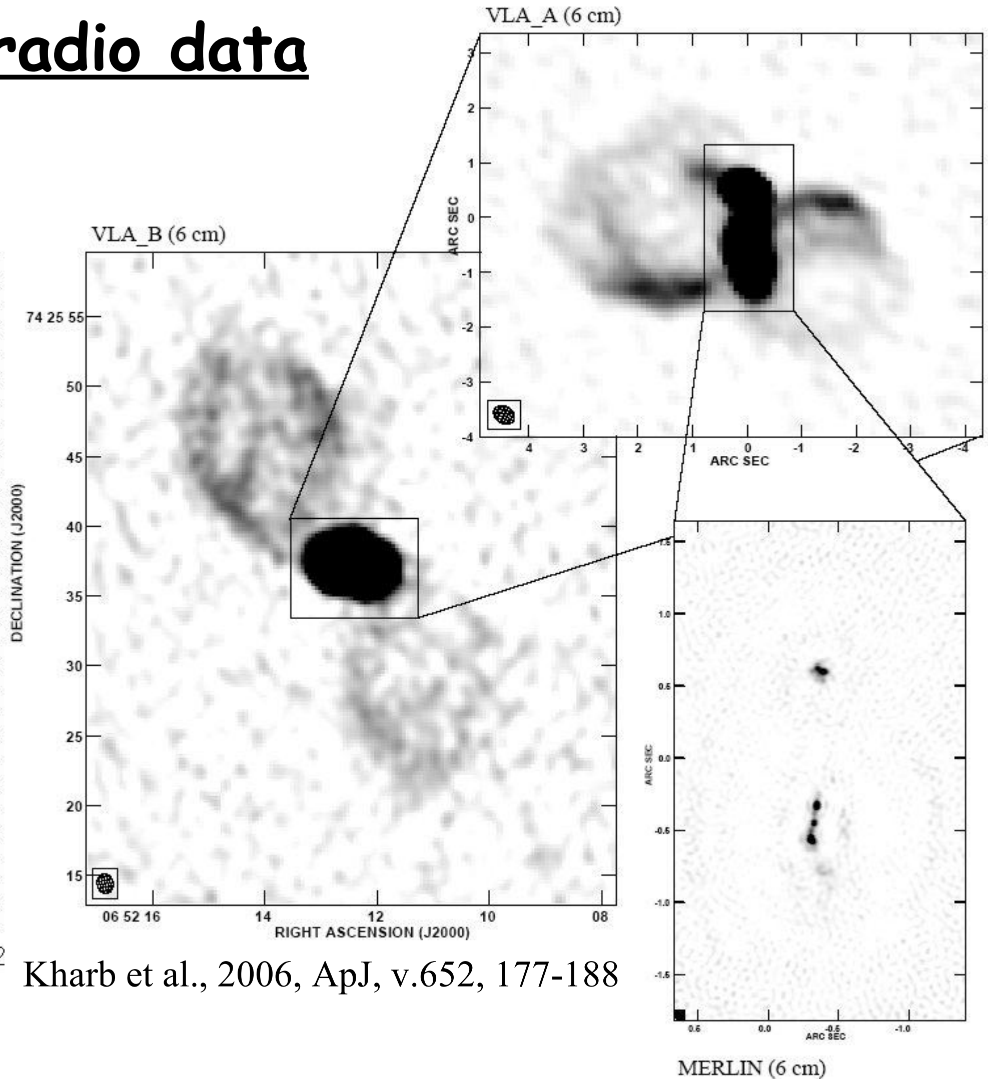
| Date observation | Julian date | Exposure, sec | Q(6000), % | U(6000), % | P(6000), % | PA(6000), degrees |
|---|---|---|---|---|---|---|
| 1997.02.08(*) | 50488 | 4000 | -0.08 ± 0.07 | -0.90 ± 0.07 | 0.90 ± 0.13 | 132.4 ± 1.1 |
| 1998.10.02(*) | 51089 | 2400 | 0.61 ± 0.06 | -0.66 ± 0.06 | 0.90 ± 0.12 | 156.5 ± 0.8 |
| 2010.11.05 | 55505 | 2400 | 0.19 ± 0.12 | -0.55 ± 0.10 | 0.60 ± 0.18 | 144.4 ± 6.2 |
| 2011.08.27 | 55800 | 3360 | 0.50 ± 0.18 | -0.65 ± 0.16 | 0.85 ± 0.21 | 152.8 ± 4.5 |
| 2011.11.21 | 55886 | 2400 | 0.63 ± 0.16 | -0.48 ± 0.21 | 0.83 ± 0.15 | 161.6 ± 6.1 |
| 2012.02.14 | 55971 | 3600 | 1.03 ± 0.14 | -0.32 ± 0.16 | 1.10 ± 0.16 | 170.2 ± 4.2 |
| 2012.04.21 | 56038 | 2880 | 0.46 ± 0.10 | -0.20 ± 0.08 | 0.051 ± 0.09 | 169.4 ± 36 |

(*) Smith et al., 2002, MNRAS, v.335, 773

# Polarization variability of  Mkn 6 in continuum

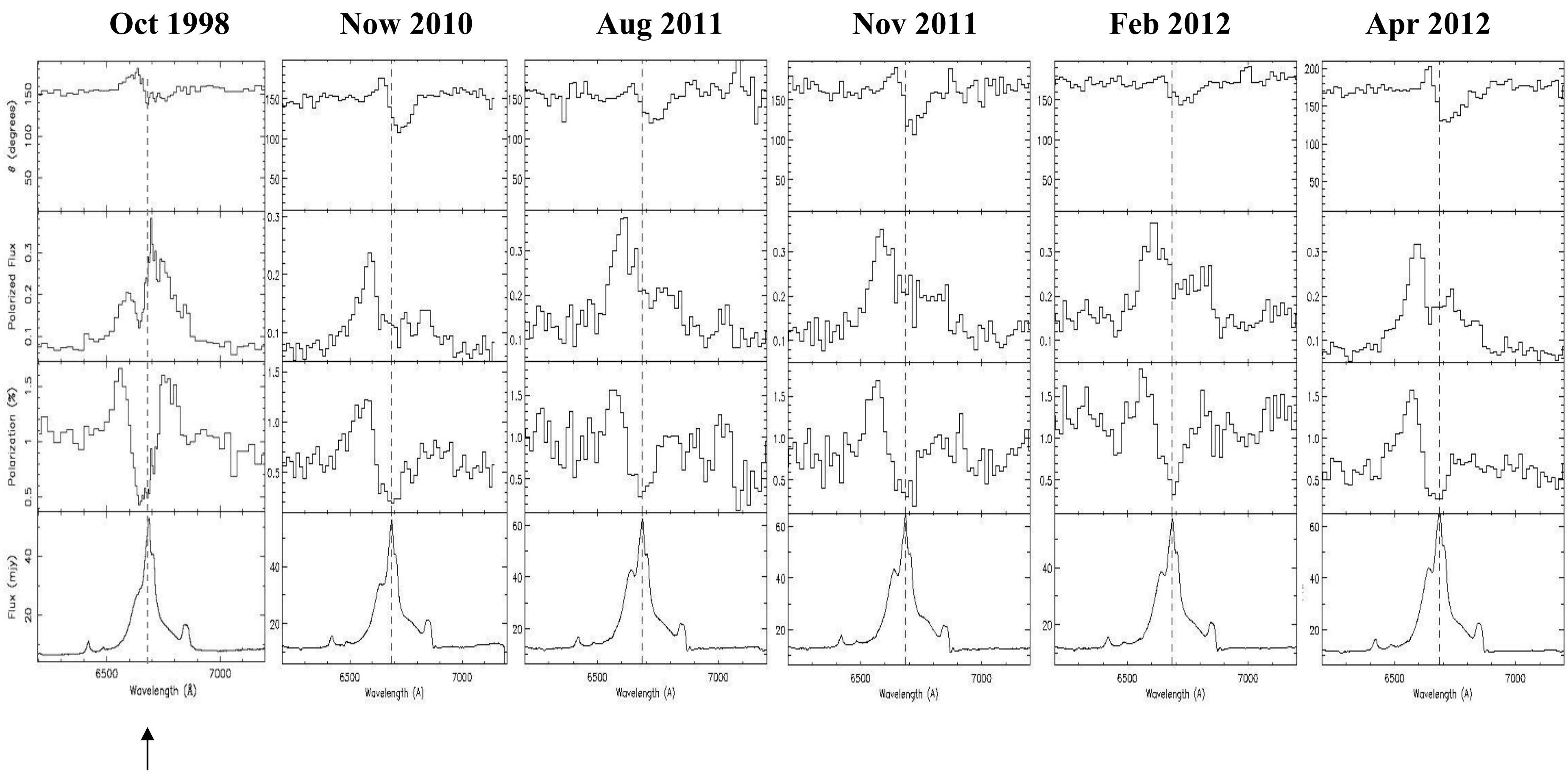
## Comparing optical and radio data



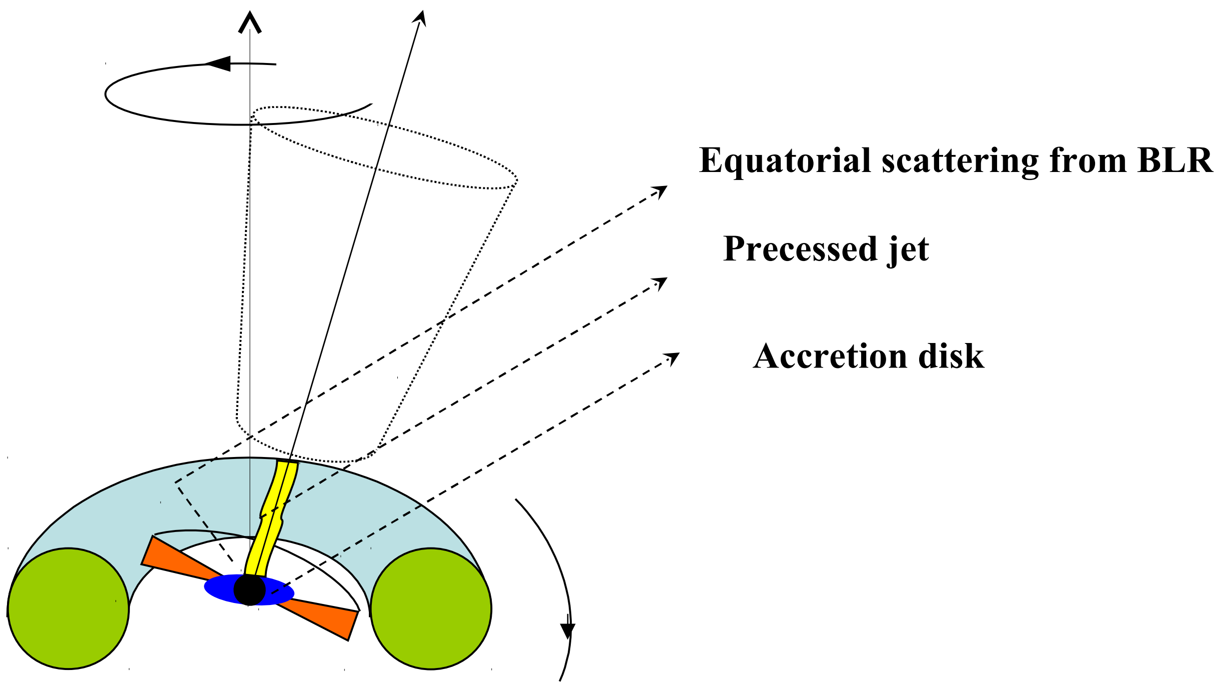

Kharb et al., 2006, ApJ, v.652, 177-188

# Polarization variability in BLR of Mkn 6




Smith et al., 2002

# The fantasy on the polarization in Mrk 6




***Different angular velocity of rotation and spin direction at three regions: accretion disk, BLR-disk and dusty torus***


Thank you !
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АСТРОФИЗИЧЕСКАЯ
ОБСЕРВАТОРИЯ