Probing gas flows around supermassive black holes with Spectropolarimetry

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Goals: new insights into the structure of AGN

Geometry and kinematics of source + scattering regions are imprinted on the polarization spectrum

Establish general structure of the scattering regions, inside and outside torus

What is the structure of the broad emission line region? Is it part of the accretion disk?

Are there gas outflows from the disk, or torus?

Map accretion flows on sub-torus (sub-pc) scales?
Outline

- A refined AGN scattering geometry
- Evidence for sub-pc accretion flows
  - Mrk509; NGC4151
- Evidence for high velocity outflows
  - Rotating outflow – PG1700+583
- The nature of Narrow Line Seyfert 1’s
  - No preferred orientation
- Gravitational recoil observed in scattered light?
  - E1821+643
Optical spectropolarimetry of \( \approx 90 \) BL AGN to date

- Mostly \( z < 0.3 \)
- Mostly radio quiet
- Seyfert types 1 \( \rightarrow \) 1.9; NLS1
- Weak Seyferts to luminous QSOs
  - \( \sim 4 \) orders of magnitude in luminosity

Interstellar polarization (dichroic absorption by aligned dust grains) arising in our ISM or host galaxy dominates in many objects… But here we are concerned only with polarization by scattering
Seyfert scattering geometries

- The E-vector is perpendicular to scattering plane
  - an important clue to the scattering geometry
- For polar scattering, expect polarization PA to be perpendicular to system axis (traced by radio jet, sometimes...)
  - Usually the case in polarized BL Sy2's

- But Sy1's tend to have pol PA parallel to radio axis ⇒ scattering in equatorial plane of torus

Smith et al. 2002
Brindle et al. 1990
Antonucci 1983

Two scattering routes: compact equatorial scattering region also present
Seyfert 1 polarization properties

Three broad categories

- **Null polarization**
  - $p < 0.3\%$ (detection limit)
- **Equatorial scattering**
  - $p \sim 0.5-1\%$
  - Distinctive variations in $p$, $\theta$ across broad $\text{H}\alpha$ line
- **Polar scattering ($\sim 30\%$ of S1)**
  - $p \sim 1-5\%$
  - Exhibit “Seyfert 2-like” polarization spectra

-Smith et al. 2002; 2004; 2005 & refs therein

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All Seyferts (non-Blazar AGN?) contain
- Polar scattering region (outside torus)
- Compact equatorial scattering region (within torus)

**observed** polarization properties determined by orientation

Young 2000, MNRAS 312, 567

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Unification of Seyfert Polarization Properties

\( i \approx 0^\circ \): null pol Sy1

circular symmetry \( \rightarrow \) cancellation

\( 0 < i < 45^\circ \): most Sy1

equatorial scattering dominates

PA \( \parallel \) radio axis

\( i \approx 45^\circ \): 30\% of Sy1

polar scattering dominates

PA \( \perp \) radio axis; direct l-o-s subject to \( A_V \approx 1 \)

\( i > 45^\circ \): Sy2

polar scattering dominates

PA \( \perp \) radio axis

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What can we learn from spectropolarimetry?

Disk line profiles at different inclinations

- **Polar** $i \approx 0^\circ$
- **Direct** $i \approx 35^\circ$
- **Equatorial** $i \approx 90^\circ$

Outflowing polar scattering region $\rightarrow$ redshifted profile in polarized flux

Two-component (equatorial + polar) scattering geometry

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Signatures of equatorial scattering + rotation

Double PA rotation across broad Hα, Hβ

Peak-trough-peak variation in p

NGC4151
Young et al 2010, in prep

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Explains variations in both $p$ & $\theta$

- Narrower directly viewed profile dilutes polarized profile
- Redshifted & blueshifted rays subtend different angles at scattering element

Emily Down poster

Emission Disk with near-field Equatorial Scattering

rotating broad-line emitting disk

direct (unpolarized) light

scattered (polarized) light

Scattering element co-planar with disk

E-vectors of scattered rays

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Kinematics of the Equatorial Scattering zone

- Bulk radial motions appear as asymmetries in polarization spectrum
  - E.g., inflow produces blue asymmetry

- Blue asymmetries are common in objects with equatorial scattering signatures
Accretion flows in Mrk 509 & NGC4151?

Scattering models → equatorial scattering region has bulk inward radial velocity ~ 900 km s\(^{-1}\)

Scattering electrons part of accretion flow?
Mass inflow through ESR exceeds accretion rate in both objects

- Most of mass accreted through ESR gets “blown out” again by disk wind
- NGC4151: mass outflow rate through NLR ~ 0.2 $M_\odot$ yr$^{-1}$ (Crenshaw & Kraemer 2007)

 mass inflow rates

~ 0.7 $M_\odot$ yr$^{-1}$ for Mrk 509

~ 0.2 $M_\odot$ yr$^{-1}$ for NGC 4151

$\dot{m}_{acc} \sim \frac{L_{Bol}}{\eta c^2}$
Winds launched from accretion disk thought to be key components of AGN

Physics
- Carry away disk angular momentum?
- Significant mechanical luminosity?
- Feedback to host ISM?

Phenomenology
- Broad absorption lines (BAL’s)
- Narrow (UV) absorption lines
- X-ray “warm absorbers”
- High ionization broad emission lines?
- Torus?

e.g. Elvis 2000, 2003
Low redshift \((z=0.292)\), so \(\text{H} \alpha\) accessible in optical

Polarization PA exhibits behavior similar to that seen in Seyfert 1 galaxies in which equatorial scattering dominates polarization.

However, scattered line profile, seen in polarized flux, redshifted by \(~4000\ \text{km s}^{-1}\) relative to its total flux counterpart.

Implication: velocity field of scattering medium includes both rotational and outflow components ⇒ outflow from a rotating disk — a disk wind.
First detection of a quasar disk-wind

- Polarization spectrum shows signatures of both outflow and rotation at speeds expected for gas orbiting a $10^9 M_\odot$ black hole at the inferred wind launch radius

$\nu_{W,z} \sim \nu_{W,\phi} \sim \nu_K \sim 4000 \text{ km s}^{-1}$

Mass outflow rate (scattering region only)

$\dot{m}_W \sim 10 \ M_\odot/\text{yr}$

Accretion rate

$\dot{m}(L_{Bol}) \sim 7 \ M_\odot/\text{yr}$

- First direct observational evidence that quasar winds are launched from the accretion disk

The rotating wind of the quasar PG 1700+518
S. Young$^{1,2}$, D. J. Axon$^{1,2}$, A. Robinson$^{1,2}$, J. H. Hough$^2$ & J. E. Smith$^2$

*Nature, Sept 2007*
Narrow Line Seyfert 1’s (NLS1)

- Hα, Hβ FWHM < 2000 km/s
- Strong FeII emission
- Relatively weak narrow lines ([OIII]/Hβ < 5)
- Steep soft X-ray spectra
  - Often with blueshifted “warm absorbers” ⇒ gas outflowing at speeds ~1000 km/s

Small FWHM but “normal” luminosity suggests NLS1 are physically defined by:
- Low black hole mass (factor ~10 lower than BLS1)
- \( L_{\text{AGN}}/L_{\text{E}} \rightarrow 1 \)
  ⇒ rapid SMBH growth & radiation pressure driven winds
Or are NLS1 merely viewed “face on”?

- What if BLR has a disk geometry?
- Are NLS1 simply “normal” Sy 1’s viewed close to the disk axis?

If so, observed FWHM underestimates BH mass

- Anomalous NLS1 SMBH masses & Eddington ratios can be explained if average inclination is ~ 15°
  - Decarli et al. 2008

Mrk 478 – intrinsically unpolarized

- Low measured polarization
  Consistent with zero intrinsic polarization

⇒ Viewed close to system axis
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NGC4051 — equatorial scattering

If equatorial scattering, viewed at intermediate angle

PA parallel to arcsec radio jet

Hα broader in polarized flux

Line of sight
Cont. pol. increases to blue; local peaks at broad lines

4/16 NLS1 show polar scattering characteristics, same fraction as in general Sy 1 sample

Viewed at large inclination to torus axis

Line of sight

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E1821+643: gravitational recoil candidate, SMBH binary or superwind?

- One of most luminous AGN in local universe
- Large CD galaxy at center of large X-ray cluster (Schneider et al 1992, Hall 1997, Russell et al 2010)
- “Radio-Quiet” but with ~250 kpc FR I source (Blundell & Rawlings 2001)
- Jet bends through ~90° on ~arcsec scales (Blundell et al 1996)
  - Precession in binary SMBH?
  - Re-orientation of spin axis following SMBH coalescence? (Merritt & Ekers 2002)

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SPECTROPOLARIMETRIC EVIDENCE FOR A KICKED SUPERMASSIVE BLACK HOLE IN THE QUASAR E1821+643

z = 0.297 1 arcsec = 4.3 kpc
Spectropolarimetry of E1821+643

- Broad H$\alpha$, H$\beta$ redshifted & red asymmetric in total flux
- Broad H$\alpha$ blueshifted & blue asymmetric in polarized flux
- Average pol PA $\sim$ perpendicular to 1" jet
E1821-643: H\(\alpha\) in total & polarized flux

- Blueshifted & blue asymmetric in pol. flux
- Redshifted & red asymmetric in total flux (median velocity +1170 km/s)

- Total flux profile described by 2 Gaussian components:
  - R1: low velocity, low velocity dispersion
  - R2: high velocity; high velocity dispersion
- “Mirroring” of these components explains polarized flux profile

R1: \(v = +470\) km/s FWHM \(\approx 3600\) km/s
R2: \(v = +2100\) km/s FWHM 7800 km/s
E1821+643: scattering model

Both BLR components move
- away from observer ⇒ redshifts in direct light
- towards scattering region ⇒ blueshifts in scattered (polarized) light

Shift & asymmetry reversal

This requires bulk motion of BLR relative to host galaxy
- R1: 480 - 1400 km/s
- R2: 2100 - 6100 km/s (depending on inclination)
Coalescence of progenitor binary SMBH → gravitational recoil of merged BH
- Asymmetric radiation of gravitational waves
- Numerical relativity \( \Rightarrow v_{\text{recoil}} > 10^3 \text{ km/s} \) possible

- If change in jet direction due to “spin flip”
  - Time elapsed since coalescence \( \sim 10^4 - 10^5 \text{ yr} \)
  - SMBH has moved 20 - 200 pc (but almost along line of sight)

[e.g., Baker+ 06,07,08, Campanelli+ 06, 07a,b, Dain+08, Gonzales+ 06, 07a,b, Herrman+ 07a,b, Koppitz+ 07, Pretorius 05, 07,, Schnittman+ 07, 08,Healy+08 ...]
Summary

Spectropolarimetry of broad-line AGN provides a unique probe of the kinematics of circum-nuclear gas flows, even inside the torus.

- Observations indicate 2 major scattering regions
  - Extended polar region
  - Compact (within torus) equatorial region
- Direct evidence that BLR has a rotating disk-like component
- Blue shifted Doppler ghosts in polarized light yield direct measure of accretion on sub-pc (torus→BLR) scales
- NLS1 are not viewed at preferred orientation (ie pole-on)
  - favours low BH mass systems radiating near Eddington limit
- Rotating outflow detected in low-z BAL QSO — direct observational evidence for winds launched from accretion disks
- Evidence for gravitational recoil of SMBH in QSO E1821+643
What polarimetry tells us about AGN

In powerful AGN (quasars) the accretion disk launches a spiralling wind, which dumps mechanical energy in the host galaxy.

The line-emitting disk is surrounded by a coplanar scattering region.

Broad Balmer lines come from a rotating disk – the accretion disk.

The scattering material may form part of a fueling gas flow between the torus and the accretion disk.