Spectral lines and supermassive black hole mass measurements

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12 SCSLSA, SS: AGN VARIABILITY DEVOTED TO A. I. SHAPOVALOVA
• 50 papers, 25 in leading astronomical journals
Monitoring programs - size of the BLR, geometry of the BLR

- Monitoring programs (see e.g. Shapovalova+, Popovic+ 2008–2014)
- reverberation mapping
- based on the assumption that the BLR gas is photoionized by the continuum

Continuum source

Time delay between continuum and line photon.

Continuum and line variability.

Broad Line Region
Alla’s monitoring program - Observations

- 6m + 1m telescopes - SAO RAS (Russia)
- 2.1 m telescope - Guillermo Haro Observatory, Cananea, Sonora, Mexico
- 2.1 m telescope - Observatorio Astronómico Nacional, San Pedro Martir, Baja California, Mexico
Long-term monitoring

• PIs: Alla I. Shapovalova (Russia)

• constantly observing well known AGN:
  – NGC 4151 – 11 years (Shapovalova+ 2008, 2009, 2010a)
  – NGC 7469 -20 years (Shapovalova + 2017)
  – 3C390.3 – 13 years (Shapovalova+ 2010b, Popović+ 2011, Jovanović+ 2010)
  – Arp 102B – 12 years (Shapovalova+2013, Popovic+ 2014 , A&A)
  – Ark 564 – 11 years (Shapovalova+ 2012, ApJS)
  – OSO E1821+643 -24 years (Shapovalvova+2016)
  – NGC 3516 -22 years (Shapovalova + 2019)

• Study of variability: continuum flux, line shapes, line fluxes …
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Measure SMBH masses, why?

AGN – M87

The Event Horizon Telescope project, researchers captured the very first image of a black hole, and it's the beast lurking in the core of galaxy M87.
Black Hole - Bulge Relation

\[ M_{BH} = 0.2 \% M_{\text{bulge}} \]

\[ M_{BH} \propto M_{\text{bulge}}^{1.74} \]
Coevolution of black holes and galaxies

- Galaxy merger
- Galaxy formation and evolution

Hierarchical growth

- Normal galaxy
- AGN feedback
- AGN - quasar

Starburst and AGN starting phase

Gas inflows

Growth of BH
Hierarchical Galaxy Formation

AGN → NG → AGN → NG → AGN

NG
AGN phase is very good for SMBH measurements, why?

What is an AGN?

- $\text{AGN} = \text{central SMBH} + \text{gas}$
AGN model - unification

Accretion of gas

Black hole
Accretion of gas
Spectral lines & SMBH mass measurements

• X-ray, Fe Kα line
• UV/Optical spectral band – a number of broad emission lines which are emitted from broad emission region (BLR)
Measuring the mass of SMBH in AGNs

- Several methods (stellar dynamics, gas dynamics, masers, reverberation): Direct and indirect (see Peterson 2014 SSRev)

- Line shift and width as indicator of gas motion

Macchetto et al. (1997)
To measure the black hole mass – virialization: $M$ vs. $R$, $v$

$$v = \sqrt{\frac{GM_{BH}}{R_{EC}}}$$

$$M_{BH} = \frac{R_{EC}v^2}{G}$$
First ideas from 1970s and 1980s

- Single-epoch measurements (Dibai ideas, see Bochkarev & Gaskell 2009, AstL 35, 287)
- Connect the line width with velocity and find line emitting radius using time lag between continuum and broad line flux variability -reverberation (see Peterson 1993 PASP, 105, 247)
- Present status: Several groups & several telescopes (reverberation in different spectral bands)
Problems: measuring $R_{EC}$ and velocity $v$ => inclination
Broad emission lines (BLR) - reverberation

Very close to the Black hole (BH)

Virialization: $R_{\text{BLR}} \sim c\tau$, $\tau$ – time lag between continuum and line flux

Line widths ~ rotational velocity

$M_{\text{BH}} = f \frac{R_{\text{BLR}}v^2}{G}$

- Calculated from broad line widths
- Dimensions of BLR => reverberation
- Geometry, orientation of BLR
Reverberation

- Find the relation between \( R_{\text{BLR}} \) and \( L_{\text{cont}} \)

To find \( f \) coefficient, then from single epoch observation we can estimate SMBH! Only to measure \( L_{\text{cont}} \) and FWHM of broad lines, see e.g. Bentz et al. 2009

\[
\log(R_{\text{BLR}}) = K + \alpha \log(\lambda L_\lambda (5100 \text{ Å}))
\]

Loli Martínez-Aldama et al. 2019, cosmological application
Reverberation in different lines – different dimensions, different problems

E.g. broad Fe Kα spectral line (e.g. Mizumoto et al. 2019, MNRAS)

Short timescale lags around $\sim 5 \, \text{Rg}/c$
Broad Fe Kα spectral line - reverberation


Short lags are likely to be produced by a fast (0.2c) outflowing, highly ionised wind at 50 – 100 Rg (see, Mizumoto et al. 2019).

VIRIALIZATION?

WHAT IS WITH THE UV LINES?
The UV broad lines

- Lyα, CIV (see e.g. Michael & Fromerth 2000)
Lyα and CIV

• Line profiles, disk-wind model (see e.g. Chiang & Murray 1996), wind has very important influence on line shape-intensity (variability)

• E.q. CIV, Mejía-Restrepo et al. 2016, connecting Mg II with CIV! Correction for the wind contribution!
The UV and optical broad lines

- Ly$\alpha$, CIV, CIII], Mg II, H$\beta$, H$\alpha$
- Wind & disk, or high- and low-ionization lines (see e.g. Marziani 2019)
- Usually, H$\beta$ Reverberation Measurements and then calibrating Mg II–based SMBH mass measurement (see Bahk et al. 2019)
- Then calibrating CIV, CIII] using Mg II line (see e.g. Mejía-Restrepo et al. 2016)
The UV and optical broad lines

- $\text{Ly}\alpha$, CIV, CIII], $\text{Mg II, H}\beta, \text{H}\alpha$
- $\text{H}\alpha$ – probability for forming line is high, and the shape and variability may be affected by different effects
- $\text{H}\beta$ is promising => $\text{H}\beta$ can be used for calibration (see e.g. Popovic et al. 2019)
- Mg II?
Very important

- Measure SMBHs on different cosmological scales, e.g. in optical different lines (SDSS) at different redshift (Pol1 & Wadadekar 2017, MNRAS)
Difference between Mg II and Hβ, shift and width

- Jonic et al. 2016, z vs. FWHM
Mg II and Hβ

- A sample of 285 type 1 AGN, covering both lines
Seems to be good, but...

- Virialization in MgII and Hβ broad lines – line profiles (Popovic et al. 2019)

Same width-shape-geometry?
Virialization in whole Mg II is a problem (Popovic et al. 2019), fountain-like region contribution to the Mg II wings, vertical motion see Czerny & Hryniewicz 2011, Kollatschny & Zetzl 2013, Czerny et al. 2017
• Mg II very broad (Popovic et al. 2019) contribution of the ‘fountain-like’ region, see Leon-Tavares 2013. Be careful with huge FWHM, and without Lorentz-like profile (bumps in the Mg II wings)
Some problems

- $\text{H}\beta$ seems to be virialized (not so big vertical motion, NL Sy1?), but several problems:
  
- complex BLR and accretion rate (Bozhana, Paola)
Problem with broad Hβ line, as e.g. Difference between Pop A and Popb B (Sulentic, Marziani), i.e. with High Accretion Rates in AGN. Size–Luminosity Scaling Relation for the BLR, see Du et al. 2016 ApJ 825 126 6
Continuum vs. line variability (e.g. NGC4151, Shapovalova et al. 2008)

- Variability and changing look AGN (Gisella, Andjelka, Paola, Marco ...
- Response the line to the continuum variability
- Binary (Pu, Sasha, Edi, Wolfram)
E1821+643 – SMBBHs, Shapovalova et al. 2016
Polarization in the broad lines Equatorial scattering (Afanasiev & Popovic 2015, Afanasiev, Popovic, Shapovalova 2019)—more in talk of Elena & Victor

\[ v_i = \sqrt{\frac{GM_{BH}}{R_{SC} \tan(\varphi)}} \]

\[ \log(v_i) = a - b \log(\tan(\varphi)) \]

\[ a = f\left(\frac{M_{BH}}{R_{SC}}\right) \]

\[ b = 0.5 \]
Conclusions

1. Lines for SMBH measurements
2. Fe K and UV lines?
3. Optical Hβ seems to be the best one

Thank you for your attention