The Structure of Active Galactic Nuclei on Scales from 100mas to 100µas

Martin Elvis
Harvard-Smithsonian Center for Astrophysics
Quasars – the Quintessential Point Sources

100,000th Hubble Exposure, 1996. credit: STScI, Steidel (Caltech)
Scales in AGNs

Painfully deduced from decades of spectroscopy and variability studies

1 mas \sim 100 \text{ l-day} \sim 3 \times 10^{17} \text{ cm}

\begin{align*}
10^{21} \text{ cm} & \quad 10^{19} \text{ cm} & \quad 10^{16} \text{ cm} & \quad 1 \text{ AU} & \quad 10^7 M_\odot \\
\end{align*}

\begin{itemize}
\item Host
\item Cool Dust
\item Narrow Emission Lines (NLR) bicones
\item Hot Dust
\item Broad Emission Lines
\item Wind
\item SMBH Sphere of influence
\item X-ray Continuum
\item Optical/UV continuum
\end{itemize}

Many structures in common with stars

\begin{align*}
10^9 R_S & \quad 10^6 & \quad 10^5 & \quad 1000 & \quad 10 & \quad 1 \\
\end{align*}

\begin{itemize}
\item \(20 \text{ Mpc}\)
\item \(\text{Seyferts}\)
\end{itemize}

Martin Elvis, Ten Years of VLT-I, ESO, Garching, 24-27 October 2011
Sensitivity is Crucial

1-2 extra mags would open a huge discovery space

Data thanks to Leonard Burtscher
The Quasar Standard Model

- **massive black hole**
  - Lynden-Bell 1969

- **accretion disk**
  - Lynden-Bell 1969, Pringle & Rees 1972,
  - Shakura & Sunyaev 1972

- **relativistic jet**
  - Rees 1967 [PhD],
  - Blandford & Rees 1974

No prediction of:
- Atomic Features: AGN ‘types’
- Maximally Hot dust
- X-rays
- Evolution
The Broad Emission Line Region
Quasar Atomic Features: Broad Emission Lines

Dense, high ionization gas close to black hole

Peterson 1999
Quasar Sizes (& Black Hole Masses)

\[ v^2 r = \text{const} \quad \text{Keplerian} \]
\[ v^2 r = GM \quad \text{Keplerian} \]

\[ R = L^{1/2} \]

\[ R (\text{cm}) \]

Lag (days)

FWHM

\[ R(r_g) \]

~0.3 mas in nearest AGNs

Reverberation Mapping

Peterson et al. 1993, PASP, 105, 247; 2006MmSAI..77..581P

Peterson & Wandel 1999
BEL Polarimetry

Warning: Implies significant electron-scattered light


A Simple Wind Model

The 3 Forms of Radiation Pressure Explain Quasar Structure
Resolving the Broad Emission Line Region

Near-Infrared Broad Emission Lines

IRTF/SPEX YJHK Spectra of AGN

Landt et al. 2008

Martin Elvis, Ten Years of VLT-I, ESO, Garching, 24-27 October 2011
Accretion Disk Winds: the 4th Element
Explains ALL Emission & Absorption Lines

massive black hole
Lynden-Bell 1969

accretion disk
Lynden-Bell 1969, Pringle & Rees 1972,
Shakura & Sunyaev 1972

relativistic jet
Rees 1967 [PhD],
Blandford & Rees 1974

disk winds
Murray et al., 1995
Elvis 2000
Nenkova et al., 2008

Expects: Broad, Narrow Absorption Lines, High Ionization Emission Lines, hot dust

No prediction of:
Maximally Hot dust
X-rays
Evolution
Hot Dust in AGNs
Scales in AGNs

1 mas ~ 100 l-day ~ 3 x 10^{17} cm

- 20 Mpc
- Seyferts

- 10^{21} cm
- 10^{19} cm
- 10^{16} cm
- 1 AU
- 10^7 M_☉

Host

Narrow Emission Lines (NLR) bicones

Cool Dust

Hot Dust

Broad Emission Lines

Low

High

Wind

SMBH Sphere of influence

"Torus"

X-ray Continuum

Optical/UV continuum

Seyferts

10^{19} - 10^{21} cm

10^{16} - 10^{17} cm

10^9 - 10^5 R_s

Martin Elvis, Ten Years of VLT-I, ESO, Garching, 24-27 October 2011
Maximally Hot Dust

Not seen in starburst galaxies

\[ R_{\text{sub}} = 0.13 \times L_{44}^{1/2} \times T_{1500}^{-2.8} = 1.5 \times 10^6 \ldots R_g \]

Barvainis 1987, Lawrence & Elvis 2010

Glickman et al. 2005
The Quasar “Torus” Emission

Dust emission

Accretion disk

Radio

IR

Opt/UV

EUV

X-ray

Well-suited to interferometry

Elvis et al. 1994 ApJS, 95, 1

Martin Elvis, Ten Years of VLT-I, ESO, Garching, 24-27 October 2011
AGN Flattened Obscurers

Polarized flux spectrum


Warning: Implies significant electron-scattered light

Martin Elvis, Ten Years of VLT-I, ESO, Garching, 24-27 October 2011
Dust reprocesses UV, X-rays

Elvis et al. 1994 ApJS, 95, 1
Hot Dust Region Size


MAGNUM Project

Rapid dust formation as AGN luminosity dims (~1yr)
Koshida et al. 2009

Agrees roughly with Prediction ➔ Details tell dust properties

~0.5 mas
The Mid-IR Dust and Narrow Emission Line Regions
Scales in AGNs

- Optical/UV continuum
- Black Hole
- X-ray Continuum
- SMBH Sphere of influence
- "Torus"
- Narrow Emission Lines (NLR) bicones
- Broad Emission Lines
- Hot Dust
- Cool Dust

1 mas $\sim 100$ l-day $\sim 3 \times 10^{17}$ cm

$10^{21}$ cm $\rightarrow 10^{19}$ cm $\rightarrow 10^{16}$ cm $\rightarrow 1$ AU $\rightarrow 10^7 M_\odot$

$\leftarrow 20$ Mpc

$\leftrightarrow$ Seyferts

$10^9 \rightarrow 10^6 \rightarrow 10^5 \rightarrow 1000 \rightarrow 10 \rightarrow 1$

Martin Elvis, Ten Years of VLT-I, ESO, Garching, 24-27 October 2011
Gap between 100 pc and sub-100 pc mid-IR emission

Well-defined IR ‘core’

Martin Elvis, Ten Years of VLT-I, ESO, Garching, 24-27 October 2011
Quasar Atomic Features: Narrow Forbidden Emission Lines

Low density, high ionization gas far from the black hole

Peterson 1999

Martin Elvis, Ten Years of VLT-I, ESO, Garching, 24-27 October 2011
Narrow Line Bi-cones in AGNs

Tadhunter & Tsvetanov 1989 Nature 341, 422
NGC4151:
• Bicones show feedback
• ‘Spiral’ inflow shows feeding
• Need to follow structure well within black hole sphere of influence <10pc, <100 mas
NGC4151:
- Bicones show feedback
- ‘Spiral’ inflow shows feeding
- Need to follow structure well within black hole sphere of influence <10pc, <100 mas

Storchi-Bergman et al.; Wang J. et al. (2011a)
Near-Infrared Narrow Emission Lines

Mostly weak

Landt et al. 2008

Ark 564 (z=0.025)

rest wavelength [Å]

Landt et al. 2008
Warped Disk Obscurers

Observed warps:
- Maser disks
- CO disks

Produced by isotropic accretion molecular clouds or minor mergers

Volonteri et al. 2007
Warped Mid-IR Disk Obscurers

Predicts:
• correct Type1:Type2 ratio*
• Jet-obscurer axis misalignments

Observable with VLT-I MIDI?

High Redshift Quasars
Angular dia. vs. z

Cosmology: Angular dia. vs. Linear dia. = metric

Magdelena Ridge Observatory Interferometer

True imaging with many baselines: ~1mas ~0.1pc = Hot dust region

Sensitive enough to detect many AGNs: Needs ~US$50M

NEEDS ~ US$50M
Magdelena Ridge Observatory Interferometer

True imaging with many baselines: $\sim1\text{mas} \sim 0.1\text{pc} = \text{Hot dust region}$

Sensitive enough to detect many AGNs:
Needs $\sim\text{US\$50M}$
AGN Interferometer Wish List

1. K ~0.1mas
2. N~1mas
3. 1-2 mag. more sensitivity: K>11
4. Emission line centroiding to <0.1mas
5. US$50M for MRO-I
Broader Interferometry Considerations
Movies, not Snapshots

Astronomy suffers from a ‘static illusion’
What we can image changes on timescales longer than our lifetimes

At sub-arcsec resolution we start to see changing structures
At mas resolution everything moves
Qualitatively new view of universe

A partial list: (please send additions)

- Galactic Center stars (AO)
- HH-30 expanding jets (HST)
- Rotating pinwheel around WR104
- XZ Tau expanding jet (HST)
- Mizar A binary orbit
- V1663Aql - Nova expansion
- SN 1987A expansion/rings (speckle, HST)
- Crab nebula wisps (Chandra)
- Vela SN jet (Chandra)
- Superluminal radio jets (VLBA)

http://hea-www.harvard.edu/~elvis/motion.html
Imaging Quasars

What we really want is to look at quasar structure

**Imaging reverberation mapping** of Broad Emission Line Region:

6-D: 3 space, 3 velocity

Also hot dust region
Imaging Quasars

What we really want is to look at quasar structure

**Imaging reverberation mapping** of Broad Emission Line Region:

6-D: 3 space, 3 velocity
Also hot dust region

![Graph showing BLR angular diameter vs. redshift](image)

**Ideal:**
- 5 km-10 km IR 2μm interferometer at Antarctica Dome A or C, Greenland ice peak
- ½-1 km UV space interferometer
A Sociological Note

Extragalactic astronomers don’t ask for high angular resolution because what they do doesn’t need it.

What they do doesn’t need high angular resolution because they can’t do it.

I.e. They never thought about it. Need to proselytise.
Angular Sizes of Astronomical Objects

Are we missing classes of objects?

- Image Sn1a to get Baade-Wesselink distances?
- axion constraints from stellar diameters/pulsations? [Physics Today]
Figure 17. Fringes created with the double reflection interferometer have been achieved in the laboratory. The above fringes are from Cash et al. (2000).

Figure 18. A two mirror periscope. $h$ is the separation between the mirrors. $h \sin \theta$ is the delay in path length.
X-ray Telephoto Interferometer

Willingale, Butcher & Stevenson, 2005 SPIE, 5900, 432

Nesting of parallel systems. Slatted mirror M2

~1 meter
~0.1 mas
@ 1 keV

3 large flat mirrors M1, M3, M4

fringes
Gamma-ray Interferometry

~0.1 μarcsec,
~100,000 km focal length

Fresnel/Laue Imagers
In Gamma-rays
Skinner G., 2004
Applied Optics, 43, 4845