AGN at the Crossroads of Astrophysics

J.A. Zensus & A.P. Lobanov
Max-Planck Institut f. Radioastronomie

Exploring the Cosmic Frontier
Astrophysical Instruments for the 21st Century
Berlin, 19 Mai 2004
Active Galactic Nuclei

Nuclear activity

- is ubiquitous: almost every galaxy exhibits some level of activity
- comes in many faces: Quasars, BL Lac, BLRG, LINER, Sy1,2…
- covers the entire range of the electromagnetic spectrum
- spans over 12 orders of magnitude in spatial and temporal domain
- reflects processes and physical conditions in the immediate vicinity of a BH
- can be observed throughout much of the Universe: from the Galactic Center to $z>6$
Fundamental Questions

- Where does the emission come from and how is accretion energy converted to radiation? Energy extraction mechanism?

- Is there a unified model for all of the different types of AGN? Can we draw an evolutionary diagram for AGN?

- What is the relationship between the SMBH and the host galaxy? Which forms first and what causes the excellent correlation between black hole mass and galactic bulge?

Answering any of these questions can only be done by studying AGN in more than one spectral domain — AGN science is synthetic by its virtue.

- How are AGN jets produced and collimated?

- What is the physics of the relativistic outflows on pc to Mpc scales? How do they interact with, and affect, the host galaxy.

- Are multiple SMBH common in AGN, and how do they form and evolve?
AGN and their Studies

<table>
<thead>
<tr>
<th>Properties</th>
<th>Popularity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small angular size</td>
<td>Many</td>
</tr>
<tr>
<td>Galactic (or greater) luminosity</td>
<td>Many</td>
</tr>
<tr>
<td>Broad-band continuum</td>
<td>Most</td>
</tr>
<tr>
<td>Strong emission lines</td>
<td>Most</td>
</tr>
<tr>
<td>Variability</td>
<td>Most</td>
</tr>
<tr>
<td>Weakly polarized</td>
<td>Most</td>
</tr>
<tr>
<td>Radio emission</td>
<td>Many</td>
</tr>
<tr>
<td>Collimated outflows</td>
<td>Many</td>
</tr>
<tr>
<td>Supermassive black holes</td>
<td>Most</td>
</tr>
</tbody>
</table>

Source of energy in AGN
1. colliding galaxies
2. starburst
3. gravitational collapse
4. SN chain explosions
5. annihilation
6. quark interaction
7. compact stellar cluster
8. accretion on a black hole

AGN: basic studies
1. surveys: correlations between different types of AGN
2. multifrequency campaigns: broad-band spectra
3. spectroscopy: narrow-band spectra, X-ray spectra
4. variability: long and short term changes of emission
5. morphology: optical, X-ray and radio structures on scales of up to a few Mpc
6. radio interferometry: structure and evolution of parsec-scale emission
SMBH in a Larger Context

- SMBH are expected to form in the early Universe, in the course of multiple mergers of dark matter halos (hierarchical structure formation). Multiple SMBH may be common in galaxies.

- SMBH are seemingly present in all \textit{(or almost all)} galaxies (Kormendy & Richstone 1995)

- BH masses correlated with velocity dispersion in galactic bulges (Merritt 2001)

- BH masses correlated with radio emission (Ho 2002)

- SMBH are closely related to (just about) every aspect of galactic activity, and may be one of the most significant energy sources in the Universe.

- Activity depends critically on the availability of accreting gas – may be connected to the presence of multiple SMBH in a host galaxy.

- Binary SMBH may be common in the most powerful AGN -- likely source of gravitational radiation on cosmologically significant scales.
Evidence for SMBH

Superluminal motions: apparent speeds $\beta_{\text{app}} \sim 20$, which requires an effective mechanism for energy release

Exceptional stability of jet direction on timescales of $\sim 10^6$ years

Proper motions of stars around SgrA* imply a black hole of $10^5$ solar masses

Observations of accretion disks: Keplerian motions imply densities of $\sim 10^{12}$ $M_{\text{sol}}/\text{pc}^3$

Other evidence: rapid variability, emission line width, gravitational redshift of Fe K line, etc.
• **Line profile argument:** X-rays generated above the accretion disk interact with the disk material and produce Fe fluorescence line emission – observed by XMM

• Line profiles show relativistic velocities, Doppler shifts and gravitational redshift – modelling of the line profiles depends on the disk inclination and spin of the SMBH – can distinguish between rotating and non-rotating BH.

---

**XMM on MSG 6-30-15**

*Fabian et al. 2002*
• **Enclosed mass argument:** Optical spectroscopy reveals the Doppler shift caused by the fast rotation of material in the accretion disk – implying masses of $1 \times 10^9 \, M_{\text{sol}}$ in M84 and $2.5 \times 10^9 \, M_{\text{sol}}$ in M87.
**Radio Studies of AGN**

- **Monitoring programs:** jet kinematic and spectral evolution: 3C345, 3C273, etc.; detailed physical modelling of individual objects (3C345, 3C273, 0836+710, etc.).

- **Variability:** long-term: dynamics of nuclear regions; short-term & IDV: compact structures.

- **Surveys and statistics:** modelling the distributions of $\theta_{\text{app}}$, $\beta_{\text{app}}$, $T_b \Rightarrow$ jet composition.

- **Polarization:** B-field distribution, circular polarization (jet composition).

- **Advanced imaging:** mapping the $S_m$, $\nu_m$ and $B$ distributions; plasma diagnostics in jets.

- **Internal structure of jets:** diagnostics of jet plasma.

- **Physics of nuclear region:** opacity effects in the nucleus, synchrotron self-absorption and external absorption, magnetic field and rotation measures, H$_2$O and OH maser emission.
Activity in a Seyfert Galaxy

High resolution phase referencing
VLBI Studies of Seyfert Galaxies –

**NGC 3079** a different picture

Middelberg et al. (2003)

Kondratko et al. (2003)

- **1.7 GHz**
- **2.3 GHz**
- **5.0 GHz**
- **15 GHz**
Free-free Absorption in 3C84

NGC1275 (3C84) Free-free Absorption


3C84 GEOMETRY
Symmetric Jets / Absorbing Disk Model

VIEW FROM SIDE
VIEW FROM EARTH

22.2 GHz  15.3 GHz  8.4 GHz  5.0 GHz

Right Ascension Offset (mas)
Declination Offset (mas)
Study of motion in two-sided jets allows one to determine the intrinsic jet speed and – in principle – the distance of the source (Hubble constant).

The determination of the (frequency dependent) jet-to-counter jet ratio gives insight on the absorbing accretion disk.

The distance between base of jet and counter-jet yields important size limits of the region where the jet is made and accelerated.

Towards millimeter wavelengths the foreground absorption becomes optically thin, facilitating a more direct view into the nucleus.
Outflow Physics: 3C345
New upper limit for the size of the jet base in M87:

\[234 \times 59 \, \mu\text{as} = 23 \times 6 \, \text{light days} = 67 \times 17 \, R_s\]

transverse width of jet at 1mas: \(~230 \, R_s\)

\(\Rightarrow\) see posters by Agudo, Krichbaum
3C84 = NGC1275 = Per A
25 light days resolution in the innermost jet at 86 GHz

T. Krichbaum et al.
Accelerated motions: 3C84

NGC 1275

GROUND VIEW
HUBBLE SPACE TELESCOPE VIEW (WFPC)

43 GHz: acceleration from 0.05 to 0.2c

Dhawan et al.
Accelerated motions: Cygnus A
Relativistic shocks: 3C120

- Standing components associated with the recollimation shocks
- New stretched region with increased emission
- Associated peak brightness motion reflects changes in the internal distribution

Upstream motions during moving/standing components interaction

Relativistic, hydrodynamic simulations by Gomez et al. 2000, 2001
VSOP Space VLBI observations provided a resolution improvement sufficient for studying the interior of most prominent jets.

\[ \lambda_{H_5} = 18.0, \lambda_{E_5} = 12.0, \lambda_{E_1} = 4.0, \lambda_{E_2} = 1.9 \]

\[ G_j = 2.1, M_j = 3.5, \tilde{\nu} = 0.02, a_j = 0.53, v_w = 0.21 \]

Lobanov & Zensus 2001
K-H Instability: M87

Compare the analytical K-H model image to the structure observed in M87

Lobanov, Hardee & Eilek 2003
Binary Black Hole: 3C345

\[
M_1 = 1 \times 10^9 M_\odot, \quad M_2 = 5 \times 10^8 M_\odot
\]

\[
a_{\text{maj}} = 0.63 \text{pc (0.13 mas)}, \quad e = 0.1
\]

\[
P_{\text{orb}} \approx 170 \text{years},
\]

\[
P_{\text{prec}} \approx 2500 \text{years}
\]
Extragalactic jets are no longer the sovereign domain of radio astronomy.

Relativistic outflows are prominent in the optical and in X-ray regimes (and possibly in others).

Nuclear X-ray activity and radio emission from jets are connected – see poster by Kadler.
Radio vs. Other Domains
Radio vs. Other Domains

development of angular resolution in optical/IR astronomy

- Palomar
- speckle interferometry
- Hubble
- AO at VLT/Keck
- IR interferometry at VLT/LBTI
- optical interferometry with VLTI and in space

development of sensitivity in radio astronomy

- Jansky
- Grote Reber
- Cambridge
- VLA
- 100 m
- EVLA
- SKA

log (flux density (Jy)) vs. year

Jy
Outlook to the Future

**Major problem of the present high-resolution radio observations:**
Most of information inferred from the data remains essentially one-dimensional (flux variations, spectra, trajectories, profiles of brightness, spectral index or degree of polarization, etc…) which limits severely the cross-section between data and theory. In the future, this will also limit the possibilities for comparison between radio observations and observations in other spectral domains.
Information from images

- **Observations:** 1D (routinely), 2D (SoA)
- **Models (relativistic).**
  - **Analytical:** 2D (routinely), 3D(t) (SoA)
  - **Numerical:** 3D (routinely), 3D(t) (SoA)
- **Problems:** connecting predictions ($p, v, \rho$) to observables ($S_\nu, \alpha, \beta_{app}$). Elusive $B$, $\Gamma_j$ and $M_j$
- **Solution:** find a way to extract reliable 2D information from images! High-fidelity images and novel reduction and analysis techniques are much needed!

(Hughes et al. 1994)
• Future advances in all aspects of high resolution studies will require “pixel-based” interpretation of data as opposed to the “blob-based” interpretation most commonly used at present.

• Need high-resolution interferometric imaging with reliable pixels down to SNR~5 (in current VLBI images one can trust pixels with SNR>20).

see poster by Lobanov
Synthetic view of AGN

**SMBH**: all bands, interferometry, spectroscopy

**Outflow**: radio, optical, X-ray – high fidelity imaging

**Accretion disk**: optical, high-energy – structure and evolution of AD

**Galaxy**: all bands – galaxy – SMBH connection; formation and co-evolution of galaxies and SMBH

**BLR/NLR**: optical, UV, high-energy – extent, morphology, matter composition

**IGM**: all bands – energy transport into IGM

**Torus**: IR, optical, UV, radio – physics of molecular material

**Evolution**: all bands – surveys, BH census and
Fundamental Questions

- Where does the emission come from and how is accretion energy converted to radiation? Energy extraction mechanism?
- Is there a unified model for all of the different types of AGN? Can we draw an evolutionary diagram for AGN?
- What is the relationship between the SMBH and the host galaxy? Which forms first and what causes the excellent correlation between black hole mass and bulge velocity dispersion.
- Do all galaxies have SMBH? What causes the activity phase in a galaxy?
- Is general relativity correct in the vicinity of a SMBH? The strong gravity limit.
- How are AGN jets produced and collimated?
- What is the physics of the relativistic outflows on pc to Mpc scales? How do they interact with, and affect, the host galaxy.
- Are multiple SMBH common in AGN, and how do they form and evolve?
• Enormous progress in the field of AGN studies

• AGN and jets are far more common than it was expected even only a decade ago

• Jets can be used for a multitude of studies related to physics of relativistic flows and, as well, to more general questions about AGN

• There is a variety of processes governing the dynamics and emission from AGN, but the underlying physics may be simpler (and more fundamental!) than that which we are currently employing.

• Future advances in high-resolution studies of AGN (and many other objects) will depend on our ability to obtain a high-fidelity, two-dimensional information about structures observed on submilliarcsecond scales.