Radio galaxies: main classes
Large radio galaxies with lobes are divided into two types called Fanaroff-Riley (1974):

FRI: weaker radio sources that are bright in the center and fainter towards edge of lobes.

FRII: Brighter radio sources that are brighter towards the limbs.

Luminosity transition around $L_{1.4\text{GHz}}=10^{25}$ J/s/Hz
Example FRI and FRII morphologies:
Quasar 3C175
YLA 6cm image (c) NRAO 1996
1 kpc
Taylor et al.
Quasar variability

Quasars are variable in every waveband and in emission lines.

The variability time-scale can be days to months, hence the size of the emission region is light-days to light-months.
Key concepts:

Unified scheme
Superluminal motion
Inverse Compton Scattering in AGN

- synchrotron radio emission originates from relativistic electrons that can upscatter photons to high energy
  - some connection between radio and gamma-ray properties is expected!
  - observationally, all gamma-ray AGNs are radio loud, unlike most X-ray QSOs
Background

- the **blazar sequence** was originally devised on the basis of the **radio luminosity**
- See Muecke et al. etc

Donato et al. (2001)
M87

Abdo et al. (2009)
Cen A

Fermi (>200 MeV)  WMAP (20 GHz)  LWA1 (74 MHz)

Summary of AGN classes

- Seyferts
  - Type 1 and 2: broad and narrow emission lines
  - Weak radio emission
  - X-ray emission
  - Spiral host galaxies
  - Variability
Summary of AGN classes

• Seyferts
  – Type 1 and 2: broad and narrow emission lines
  – weak radio emission
  – X-ray emission
  – Spiral host galaxies
  – Variability
- Quasars
  - **Radio loud**
    - broad and narrow emission
    - Strong radio emission
    - Some polarization
    - FRII morphology
    - Variability
  - **Radio quiet**
    - broad and narrow emission
    - weak radio emission
    - weak polarization
    - Variability

![Quasar Spectra](https://via.placeholder.com/150)

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<table>
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<td>4000</td>
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• Radio galaxies
  – BLRG
    • broad and narrow emission lines
    • strong radio emission
    • FRII morphology
    • weak polarization
    • Elliptical host galaxies
    • Variable

  – NLRG
    • narrow emission line only
    • strong radio emission
    • FRI and FRII morphologies
    • no polarization
    • Elliptical host galaxies
    • No variability
• Blazars
  – BL Lacs
    • almost no emission lines
    • strong radio emission
    • strong polarization
    • 90% have elliptical host galaxies
    • Strong variability
  – OVV quasars/ FSRQs
    • broad and narrow emission lines
    • strong radio emission
    • strong polarization
    • Strong variability
    • Much more luminous than BL Lacs
• ULIRGs
  – Possibly dust-enshrouded quasars
  – Alternatively a starburst phenomena

• LINERs
  – Similar to Seyfert 2s (narrow lines)
  – Low-ionization emission lines
  – Alternatively a starburst phenomena or HII region emission.
Distinguishing AGN
Seyferts are separated from HII regions (which also produce emission lines by photoionization by stars) by *line ratios*.

Common criterion for Seyferts:

\[
\frac{[\text{OIII}] 5007}{\text{H} \beta} > 3
\]

This requires a relatively hard, non-stellar ionizing continuum.

Problem: reddening can affect line ratios.
Solution:

a) Use line ratios of lines which are very close in wavelength (same reddening dependence)

b) Use two sets of widely separated lines (line ratio depends on continuum shape)

LINERs have lower ionization levels than Seyferts, but higher than HII regions.
Active Galactic Nuclei - General Summary

• Emission that cannot be attributed to stars

• Occur both in spirals and E/S0s (Sy/Quasars, distinguished mostly in the amount of energy emitted)

• Emit energy comparable, or larger than all the stars in the host galaxy over a wide range of wavelengths, sometimes including the radio

• Can show linear structures (jets/lobes/hotspots) in the radio (and jet in the optical) of the order of ~ Mpc
• AGN show strong broad emission lines. Combined with small emission region this indicates a high concentration of mass.

• AGN come in many shapes and forms, not always with a clear connection.

• Are often highly variable, supporting a small central engine
Why are AGN interesting?

a) For studying black hole physics
b) Studying high energy physics
c) Background sources on cosmological scales
   a) Lyman alpha forest in optical spectra (absorbing gas in walls? IGM information)
   b) Gravitationally lensed by clusters, can get Hubble constant from time delay
c) background radiation to detect absorption lines in host galaxies at large redshifts

d) produce cosmic background radiation, e.g. X-ray wavelengths

d) Use radio cores as cosmic reference points for fixed coordinate systems

e) History of the Milky Way: have all galaxies been an AGN at some point? Are they still?
AGN diagnostic diagram

Baldwin, Phillips & Terlevich 1981: 
*BPT-diagram*

The BPT diagrams are used to distinguish between hard and soft radiation.

This is ascribed to non-stellar or stellar activity, respectively.
How can we bring all AGN types into a single framework?

• We will "postulate" a standard model for the structure of AGN

• Different types result from different viewing angles
  – and perhaps some different physical conditions
  – we need to remove the aspect-dependency to determine this!

• We call this unification.
  – What are the evidence for unification?
The Unified Model for AGN

- Radio galaxies, quasars, QSOs, Seyferts, Blazars etc are *the same type* of objects viewed from different angles.

- The center of the galaxy is a supermassive black hole surrounded by an accretion disk, clouds of gas and a dusty torus.

- The energy output is ascribed to accretion of material onto the black hole.
The Standard Model of AGN

Components:

• Accretion disk
  – $r \sim 10^{-3}$ pc, $n \sim 10^{15}$ cm$^{-3}$, $v \sim 0.3c$

• Broad Line Region (BLR)
  – $r \sim 0.01$-0.1 pc, $n \sim 10^{10}$ cm$^{-3}$, $v \sim$ a few $10^3$ km/s

• Narrow Line Region (NLR)
  – $r \sim 10$-1000 pc, $n \sim 10^3$-$10^6$ cm$^{-3}$, $v \sim$ a few 100 km/s

• Torus (Thick Obscuring Region required by Unification Systems)
  – $r \sim 1$-100 pc, $n \sim 10^3$-$10^6$ cm$^{-3}$
Model for the central region: SMBH, surrounded by accretion disk containing infalling material. If conditions are right, the AGN may possess a magnetically confined jet (the source of radio emission).
Effects of orientation

Central engine (BH+accretion disk)

BLR

Torus

Photoionised cone

NLR

Radio Jet

Seyfert 1 Quasar

Seyfert 2
Proposed by Rowan-Robinson in 1977, and became a popular model in the mid-80s.
Support for unification

1. Hidden emission lines: Some Sy2s show broad lines in polarized light.
Electrons scatter photons from the BLR near the nucleus toward the observer.

The dusty torus shields the direct line-of-sight to the nucleus.

Thus, an Sy2 looks like an Sy1 in polarized emission!

Some NLRGs also behave as Sy2s, showing hidden broad lines.
Support for unification:

2. Ionization cones: The UV emission arises in the accretion disk, illuminating gas in the galaxy. Emission can only escape in a cone, shaped by the torus.
Support for unification

3. IR and $N_H$ excess: The column of neutral H absorbing soft X-rays emitted by the nucleus is associated with dust in the torus. This provides an estimate of the dust content, and the corresponding attenuation.

Sy2s have the largest absorbing column densities: X-rays suppressed below 10 keV.

Sy2s also have colder IR colors than Sy1s: Explained if the torus is partially thick at mid-IR wavelengths.

Risaliti et al 1999
Support for unification:

4. Quasar host galaxies: RLQs have same hosts as FRII radio galaxies.

5. Number counts: a simple relationship is expected between number of RLQs and FRIIs based on the obscuring angle of the torus.

6. Environments: RLQs and FRIIs occupy similar environments: poor cluster/groups.

Blazars and FRIs appear to have the same host galaxies
Free-free absorption in 1946+708

Peck & Taylor (2001)
Spectral index map from 1.3/5 GHz VLBI observations
HI absorption in 1946+708

Peck & Taylor (2001)

“Global” VLBI observations

core:

$M \sim 10^8 \, M_\odot$
Hydra A

Taylor (1996)

core:

$M \sim 2 \times 10^7$ $M_{\odot}$
NGC 4258

- Considered best evidence of a supermassive black hole
- Can estimate central mass
- Can estimate distance to host galaxy

image courtesy Lincoln Greenhill (see Miyoshi et al 1995 Herrnstein et al 1999)
Support for unification:

7. Direct imaging of torus
VLBA Images
At 5 GHz

30 pc
Superluminal motion

constant expansion observed at
rate = Δθ/year = 0.76 ± 0.04 mas/year
z = 0.158 so D = 940 Mpc
assuming \( H_0 = 50 \text{ km sec}^{-1} \text{ Mpc}^{-1} \).
1 mas = 10^{-3} \text{ arcsec} = 4.85 \times 10^{-9} \text{ radians}
d = DΔθ so the apparent transverse velocity, or rate = d/year
= 10 \text{ lt-years/year}
= 10 c \ [!!]
Evidence for limb brightened jet morphology on the parsec scale is present in some FR I radio galaxies: 1144+35, Mkn 501, 3C 264, M87, 0331+39, .......

Velocity Structures
Next time:

Clusters, magnetic fields, and AGN Feedback
Bondi Accretion