Active Galactic Nuclei at the Half-Century Mark

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Brera Lectures

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Topics to be Covered

• **Lecture 1**: AGN properties and taxonomy, fundamental physics of AGNs, AGN structure, AGN luminosity function and its evolution

• **Lecture 2**: The broad-line region, emission-line variability, reverberation mapping principles, practice, and results, AGN outflows and disk-wind models, the radius–luminosity relationship

• **Lecture 3**: Role of black holes, direct/indirect measurement of AGN black hole masses, relationships between BH mass and AGN/host properties, limiting uncertainties and systematics
“Active Galactic Nuclei (AGN)”

• The phrase “active nucleus” was originally used by V.A. Ambartsumian in 1968
  – “the violent motions of gaseous clouds, considerable excess radiation in the ultraviolet, relatively rapid changes in brightness, expulsions of jets and condensations”
    
Ambartsumian 1970

• First use in paper title: Dan Weedman (1974)
  – “nuclei that contain extensive star formation or luminous non-thermal sources” BAAS, 6, 441

• First use in PhD dissertation title: Jean Eilek (1975)
  – “Cosmic Ray Acceleration of Gas in Active Galactic Nuclei” University of British Columbia
“Active Galactic Nuclei (AGN)”

- “Activity” was usually taken to mean “radio source”
- Came to be used to encompass “Seyfert galaxies” and “quasars”
  - “…energetic phenomena in the nuclei, or central regions, of galaxies which cannot be attributed clearly and directly to stars.” Peterson 1997, An Introduction to Active Galactic Nuclei
- Modern definition: “Active nuclei are those that emit radiation that is fundamentally powered by accretion onto supermassive (> $10^6 \, M_\odot$) black holes.”
Properties of AGNs

- Strong X-ray emission
Properties of AGNs

• Strong X-ray emission
• Non-stellar ultraviolet/optical continuum emission
Properties of AGNs

• Strong X-ray emission
• Non-stellar ultraviolet/optical continuum emission
• Relatively strong radio emission
Properties of AGNs

- Strong X-ray emission
- Non-stellar ultraviolet/optical continuum emission
- Relatively strong radio emission
- UV through IR spectrum dominated by strong, broad emission lines.

Not every AGN shares all of these characteristics.
There are three major classes of AGNs:
- Seyfert galaxies
- Quasars
- Radio galaxies

<table>
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<tr>
<th>Luminosity</th>
<th>Quasars</th>
<th>Seyferts</th>
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<td>High</td>
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<td>Accretion rate</td>
<td>High</td>
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LINERs are somewhat problematic in this classification.
Seyfert Galaxies

- Spiral galaxies with high surface brightness cores
  - Spectrum of core shows strong, broad emission lines

NGC 4151

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“Quasar” is short for “quasi-stellar radio source”.
- Discovered in 1960s as radio sources.
- Radio astronomy was an outgrowth of radar technology developed in the Second World War
Radio Galaxies

• Most radio sources were found to be associated with galaxies.
• However, some of the radio sources were high Galactic latitude (out of the Galactic plane) star-like sources.

The radio galaxy Centaurus A
Quasars

• These “radio stars” had a somewhat “fuzzy” appearance.
• Some radio stars had linear features like “jets”.
• These unusual sources were thus “quasi-stellar radio sources”.

The brightest (still!) quasi-stellar source, 3C 273
Optical Studies of Quasi-Stellar Radio Sources

• Optical observations of these sources were made with the Hale 5-m telescope on Mt. Palomar.

• Early spectra were confusing. In 1963, Maarten Schmidt identified features as redshifted emission lines.

Maarten Schmidt (left) and Allan Sandage
First Spectrum of 3C 273

Comparison

4000 Å 5000 Å 6000 Å

3C 273

Hδ  Hγ  Hβ
Quasi-Stellar Sources

• The spectral lines in 3C 273 are highly redshifted:

\[ z = \frac{\Delta \lambda}{\lambda} = 0.158 \]

• This is comparable to the most distant clusters of galaxies known in 1963.

3C 273
The Brightest Objects in the Universe

• For 3C 273, the large redshift implies:
  – $D \approx 680$ Mpc
  – 3C 273 is about 100 times brighter than giant galaxies like the Milky Way or M 31.

The Andromeda Galaxy M 31
And Now Another Surprise...

- Shortly after their discovery, quasars were found to be highly variable in brightness.
- Rapid variability implies that the emitting source must be very small.
Source “Coherence”

• A variable source must be smaller than the light-travel time associated with significant variations in brightness.

\[ D = c\Delta t \]
Amplitude of Optical Variability

The mean absolute value at each $\Delta t$ is the "structure function."
Sizes of Quasars

- Variability on time scales as short as one day implies sources that are less than one light day in size.
- A volume the size of our Solar System produces the light of a nearly a trillion \((10^{12})\) stars!
- This ushered in a two-decade controversy about the nature of quasars redshifts.
  - Weedman's premise: this wouldn’t have happened had not the original Seyferts and original quasars been such extreme members of their respective classes
Seyferts and Quasars

- **Modern view:**
  - Seyferts are lower-luminosity AGNs
  - Quasars are higher-luminosity AGNs

- **View in the 1960s:**
  - Seyferts are relatively local spiral galaxies with rather abnormally bright cores
  - Quasars are mostly unresolved, high redshift, highly luminous, variable, non-stellar radio sources

### Observational Data

**NGC 4051**
- $z = 0.00234$
- $\log L_{\text{opt}} = 41.2$

**Mrk 79**
- $z = 0.0222$
- $\log L_{\text{opt}} = 43.7$

**PG 0953+414**
- $z = 0.234$
- $\log L_{\text{opt}} = 45.1$
Finding Quasars

- That quasars are very blue compared to stars was recognized early.

Optical color selection allows us to bypass the difficult radio identification by using “UV excess”.

\[ U - B \]

\[ B - V \]
Quasi-Stellar Objects

• Most of these blue star-like sources are like the radio-selected quasars, but are **radio-quiet**.

• These became generically known as “**quasi-stellar objects**”, or QSOs.

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**Spitzer-era mean SED from Shang et al. (2006)**

**Elvis et al. (1994)**
AGN Taxonomy

- Khachikian and Weedman (1974) found that Seyfert galaxies could be separated into two spectroscopic classes.
  - Type 1 Seyferts have broad and narrow lines
Khachikian and Weedman (1974) found that Seyfert galaxies could be separated into two spectroscopic classes.

- Type 1 Seyferts have broad and narrow lines
- Type 2 Seyferts have only narrow lines
AGN Taxonomy

- Narrow-line Seyfert 1 (NLS1) galaxies are true broad-line objects, but with an especially narrow broad component, FWHM < 2000 km s⁻¹

Osterbrock & Pogge 1985
AGN Taxonomy

- Heckman (1980) identified a class of Low-Ionization Nuclear Emission Region (LINER) galaxies.
  - Lower ionization level lines are stronger than in Sy 2
AGN Taxonomy

- **BL Lac objects** share many quasar properties (blue, variable, radio sources), but have no emission or absorption lines.
  - Appear to be quasars observed along the jet axis
  - Are often subsumed into a larger class called **blazars**.
AGN Paradigm circa 1995

- Black hole plus accretion disk
- Broad-line region
- Narrow-line region
- Dusty “obscuring torus”
- Jets (optional?)

Urry & Padovani 1995
Driving Force in AGNs

• Simple arguments suggest AGNs are powered by supermassive black holes
  – Eddington limit requires $M \geq 10^6 M_\odot$ for moderately luminous Seyfert galaxy with $L \approx 10^{44}$ ergs s$^{-1}$
  – Requirement is that self-gravity exceeds radiation pressure

Key insights: Salpeter 1964; Zel’dovich & Novikov 1964; Lynden-Bell 1969
• Energy flux

\[ F = \frac{L}{4\pi r^2} \]

• Momentum flux

\[ P_{\text{rad}} = \frac{F}{c} = \frac{L}{4\pi r^2 c} \]

• Force due to radiation

\[ F_{\text{rad}} = P_{\text{rad}} \sigma_e = \frac{L\sigma_e}{4\pi r^2 c} \]

\[ \frac{L\sigma_e}{4\pi r^2 c} < \frac{GMm}{r^2} \]

\[ L < \frac{4\pi Gcm}{\sigma_e} M \approx 1.26 \times 10^{38} \left( \frac{M}{M_\odot} \right) \text{ ergs s}^{-1} \]

“The Eddington Limit”
– Potential energy of infalling mass $m$ is converted to radiant energy with some efficiency $\eta$ so $E = \eta mc^2$

– Potential energy is $U = GM_{BH}m/r$

– Energy dissipated at $\sim 10 \ R_g$ where $R_g = GM_{BH}/c^2$ (to be shown)

– Available energy:

$$ U = \frac{GM_{BH}m}{10R_g} = 0.1 \frac{GM_{BH}m}{GM_{BH}/c^2} = 0.1mc^2 $$

– Thus the efficiency of accretion $\eta \approx 0.1$

Compare to hydrogen fusion $4H \rightarrow \text{He}$ with $\eta = 0.007$
Eddington Rate

• Accretion rate necessary to attain Eddington luminosity is the maximum possible

\[ \dot{M}_{\text{Edd}} = \frac{L_{\text{Edd}}}{\eta c^2} = 1.47 \times 10^{17} \left( \frac{M_{\text{BH}}}{M_\odot} \right) \text{gm s}^{-1} \]

• Eddington rate is ratio of actual accretion rate to maximum possible

\[ \dot{m} \equiv \lambda = \frac{\dot{M}}{\dot{M}_{\text{Edd}}} \]
Accretion Disks

• Angular momentum of infalling material will lead to formation of an accretion disk.

\[ L = \frac{G M_{BH} \dot{M}}{2r} = 2\pi r^2 \sigma T^4 \]

\[ T(r) = \left( \frac{G M_{BH} \dot{M}}{4\pi \sigma r^3} \right)^{1/4} \]
\[ T(r) \approx 3.7 \times 10^5 \dot{m}^{1/4} \left( \frac{M_{BH}}{10^8 M_\odot} \right)^{-1/4} \left( \frac{r}{R_g} \right)^{-3/4} \text{ K} \]

Assuming that QSO SED peak at 1000 Å represents accretion disk, Wien’s law tells us \( T \approx 5 \times 10^5 \text{ K} \).

For \( M_{BH} = 10^8 M_\odot \), \( R \approx 14 R_g \).
Other Quasar Properties

• Quasars as radio sources
  – High spin, conservation of B field leads to jet formation
  – Jets are common, but apparently not mandatory

• Quasars as X-ray sources
  – All highly accreting objects are X-ray sources
  – Hard X-rays (~ 10 keV) are the surest identifier of an active nucleus
Even Quiescent Galaxies Should Harbor Black Holes

• The comoving space density of quasars was much higher in the past \((z \sim 2 - 3)\); where are they now?

• Integrated flux density of quasars reveals the integrated accretion history of black holes. (Soltan 1982)
Evidence for Supermassive Black Holes

- Milky Way: Stars orbit a black hole of $2.6 \times 10^6 M_\odot$.

- NGC 4258: H$_2$O megamaser radial velocities and proper motions give a mass $4 \times 10^7 M_\odot$. 
Evidence for Supermassive Black Holes

- In the case of AGNs, reverberation mapping of the broad emission lines can be used to measure black hole masses.
  - Later elaboration

\[ M_{\text{BH}} \propto \frac{\Delta V^2 R}{G} \Rightarrow \Delta V \propto R^{-1/2} \]
The Broad-Line Region

- UV, optical, and IR permitted lines have broad components
  - $1000 \leq \text{FWHM} \leq 25,000 \text{ km s}^{-1}$
  - Spectra are typical of photoionized gases at $T \approx 10^4 \text{ K}$
  - Absence of forbidden lines implies high density
    - C III] $\lambda 1909 \Rightarrow n_e < 10^{10} \text{ cm}^{-3}$
Photoionization Equilibrium Modeling

• Tool of long standing in AGNs
  Davidson & Netzer 1979

• Simple photoionization models are characterized by:
  1) Shape of the ionizing continuum
  2) Elemental abundances
  3) Particle density
  4) An ionization parameter $U$ that is proportional to ratio of ionization rate to recombination rate
The (Dimensionless) Ionization Parameter $U$

Rate at which H-ionizing photons are emitted by source.

$$Q_{\text{ion}}(H) = \int_{v_{\text{ion}}}^{\infty} \frac{L_v}{h\nu} \, d\nu$$

Ratio of ionizing photon density at distance $r$ from source to particle density.

$$U = \frac{Q_{\text{ion}}(H)}{4\pi r^2 c n_H}$$

Davidson 1972
A Simple Model

- **Assumptions:**
  - AGN-like continuum
  - Solar abundances
  - Fixed density $10^{11}$ cm$^{-3}$
  - Maximum column density
- **Output product:**
  - Predicted flux ratios as a function of $U$
- **Conclusion:**
  - Best fit to AGN spectrum is $U \approx 10^{-2}$
Photoionization Model of the BLR in NGC 4151

• Limitations:
  – Single-cloud model cannot simultaneously fit low and high-ionization lines.
  – Energy budget problem: line luminosities require more than 100% of the continuum energy

Ferland & Mushotzky 1982
Broad-Line Profiles

• For the most part, broad-line profiles tell us little about kinematics.
Double-Peaked Emission Lines

- A relatively small subset of AGNs have double-peaked profiles that are characteristic of rotation.
  - Tendency to appear in low accretion-rate objects
  - Disks are not simple; non-axisymmetric.
  - Sometimes also seen in difference or rms spectra.

NGC 1097
Storchi-Bergmann et al. 2003
Luminosity Effects

• Average line spectra of AGNs are amazingly similar over a wide range of luminosity.

• Exception: Baldwin Effect
  – Relative to continuum, C IV $\lambda 1549$ is weaker in more luminous objects
  – Origin unknown

SDSS composites, by luminosity
Vandenberg Berk et al. (2004)
Dust Reverberation

- Near-IR continuum variations follow those of the UV/optical with a time-delay:
  - Time delays are longer than broad-lines
  - Time delays consistent with dust sublimation radius:

\[ r_{sub} = 1.3 \left( \frac{L_{UV}}{10^{46} \text{ ergs s}^{-1}} \right)^{1/2} \left( \frac{T_{sub}}{1500 \text{ K}} \right)^{-2.8} \text{ pc} \]

Suganuma et al. 2006
Dust Reverberation

- IR continuum is due to reprocessed UV/optical emission at the closest point to the AGN that dust can survive.
- This probably occurs at the inner edge of the obscuring torus.
- All emission lines are inside $r_{\text{sub}}$: the BLR ends where dust first appears.

Suganuma et al. 2006
The Narrow-Line Region

- $200 < \text{FWHM} < 1000 \text{ km s}^{-1}$
- Partially resolvable in nearby AGNs
- In form of “ionization cones”

Falcke, Wilson, & Simpson 1998
NLR Spectra characterized by very high ionization lines
Photoionization Modeling

• Advantages relative to BLR:
  – Kinematics less ambiguous
  – Can use forbidden-line temperature and density diagnostics
  – Forbidden lines are not self-absorbed

• Disadvantage relative to BLR:
  – Dust!
Measuring Density

- Low density: radiative de-excitation, emissivity $\propto n_e^2$
- High density: collisional de-excitation competes, so emissivity $\propto n_e$
- Cross-over point occurs at critical density $n_{\text{crit}}$ where radiation de-excitation rate = collisional de-excitation rate
  - $n_{\text{crit}}([\text{S II} \ \lambda 6716]) = 1.5 \times 10^3 \ \text{cm}^{-3}$
  - $n_{\text{crit}}([\text{S II} \ \lambda 6731]) = 3.9 \times 10^3 \ \text{cm}^{-3}$
Measuring Temperature

• As temperature increases, [O III] λ4363 increases in strength relative to [O III] λλ4959, 5007 because of increasing collisional excitation of \(^1S_0\) level.
Narrow-Line Profiles

- Typically blueward asymmetric, indicating outflow and obscuration of far (redward) side.
Narrow Line Widths

- Correlate with:
  - Critical density
    - Gas near $n_{\text{crit}}$ emits most efficiently
  - Excitation potential
- Interpretation:
  - Consistent with higher densities and higher excitation closer to accretion disk, in deeper gravitational potential
Size of the Narrow-Line Region

\[ j(H\beta) = n_e^2 \alpha_{eff}(H\beta) \frac{h \nu}{4\pi} \text{ ergs s}^{-1} \text{cm}^{-3} \text{ster}^{-1} \]

For \( N_c \) clouds, total emitting volume is \( N_c \times 4\pi r^{3/3} \)

Define filling factor \( \varepsilon \) such that \( \varepsilon 4\pi R^3/3 = N_c 4\pi r^3/3 \)

\[ L(H\beta) = \iiint j(H\beta) \, d\Omega \, dV = \frac{4\pi \varepsilon n_e^2}{3} 1.24 \times 10^{-25} R^3 \text{ ergs s}^{-1} \]

For \( L(H\beta) = 10^{41} \text{ ergs s}^{-1}, n_e = 10^3 \text{ cm}^{-3} \), we get \( R = 20 \varepsilon^{1/3} \text{ pc} \). Typically, \( R \approx 100 \text{ pc} \), so \( \varepsilon \approx 0.01. \)
Mass of the Narrow-Line Region

\[ M_{\text{NLR}} = \frac{4\pi}{3} \varepsilon R^3 n_e m_p \approx 10^6 M_\odot \]
The “Obscuring Torus”

- The answer to the question: “why don’t Seyfert 2s have broad lines?”
- Osterbrock (1978) suggested this since a simple absorbing medium would:
  - Redden the continuum
  - Completely obscure the continuum as well as the BLR
The “Obscuring Torus”

- The key to making this work is scattering by material in the throat of the torus.
  - Prediction: scattering introduces polarization, with E vector perpendicular to axis.
Spectropolarimetry of Seyfert 2 Galaxies

- Spectropolarimetry of the nuclei of Type 2 Seyferts shows Type 1 spectra in polarized light, as predicted.
Distinguishing Seyfert 2s from Other Emission-Line Galaxies

- Ionizing photon source can be distinguished from relative strength of emission
  - Best diagnostics are often weak lines
  - Fortunately, some ratios of strong lines can be used also

BPT (Baldwin, Phillips, & Terlevich 1981) diagram for SDSS emission-line galaxies in SDSS. From Groves et al. (2006).
Distinguishing Seyfert 2s from Other Emission-Line Galaxies

• BPT diagram plots pairs of flux ratios for strong lines
  – Lines closely spaced in wavelength to make insensitive to reddening

BPT (Baldwin, Phillips, & Terlevich 1981) diagram for SDSS emission-line galaxies in SDSS. From Groves et al. (2006).
Green points: ionized by hot stars. Sequence from left to right is one of metallicity: $[\text{O III}]/\text{H}\beta$ increases with decreasing metallicity because the $[\text{O III}]$ lines increase in importance as a coolant. $[\text{N II}]/\text{H}\alpha$ is less complicated, just depends on abundance of nitrogen relative to hydrogen.
• Blue points: ionized by a harder spectrum and high ionization parameter.
• Red points: hard spectrum, but low ionization parameter
Unification Issues and the NLR

• Problems with the torus:
  – Theoretical size much larger than IR cores of nearby AGN
  – Models are unstable
Unification Issues and the NLR

- Solution: replace “doughnut” with system of small, dusty clouds
  - Increase emitting area
  - Better reproduces spectrum
  - Increases emitting area, smaller system
  - Can explain changes of AGN type

Elitzur 2006
Unification Issues and the NLR

A naïve expectation is that the narrow-line spectra of Sy 1 and Sy 2 are the same.

Type 1 objects have stronger high-ionization lines.

These are probably formed in the “throat” of the torus.

Elitzur 2006
Unification Issues and the NLR

- At low luminosity, Type 2 AGNs outnumber Type 1 AGNs by 3:1
- High luminosity Type 2s ("Type 2 quasars") are exceedingly rare.
- Can be explained by a "receding torus".
  - Model below can explain apparent difference in how the projected size of the NLR scales differently in Type 1 and Type 2 objects.

Type 1: \( r \propto L^{0.44} \)

Type 2: \( r \propto L^{0.29} \)

Bennert et al. 2006
Cosmic Evolution of AGNs

- Very luminous AGNs were much more common in the past.
- The “quasar era” occurred when the Universe was 10-20% its current age.
Modern Surveys

- Recent surveys are detecting luminous AGNs at very high redshift and large numbers of quasars at intermediate redshift.

SDSS quasars with $z > 5.7$
Fan 2006
Largest Known Redshifts

![Diagram showing redshift over time with data points for optical and radio selected quasars and galaxies.](image-url)
**High-z Quasars**

- Current highest quasar redshift $z \approx 6.4$
  - Supermassive black holes appeared within a few hundred million years of the Big Bang
  - Metals in their spectra indicate processing in stars already occurred.

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Fan et al. 2001

Vestergaard & Osmer 2009
Evolution of the QSO Luminosity Function

- **Density evolution:** quasars “turn off” and luminosity function translates downward.
- Several problems, most importantly that local density of very luminous quasars is overpredicted.

![Density evolution graph](image-url)
Evolution of the QSO Luminosity Function

- **Luminosity evolution**: quasars just become fainter with time.
- Does not agree with observation that most quasars are emitting near the Eddington limit: the typical nearby quasar is about 50 times fainter than it would have been at $z \approx 2$. 
Evolution of the AGN Luminosity Function

- Because we can now observe lower-luminosity AGNs at high-z, our view of evolution of the luminosity function is changing.
- Preferred scenario is now “luminosity-dependent density evolution” (LDDE) or “cosmic downsizing.”

Comoving density of 2dF+SDSS quasars at different luminosities. Croom et al. 2009
Cosmic Downsizing

- The space density of lower-luminosity AGNs peaks later in time than that of luminous AGNs.
Evolution of the AGN Luminosity Function

- Luminosity-dependent density evolution is most clearly seen in the X-rays
  - Low-luminosity systems are accessible at high z in X-rays

X-ray luminosity function
Brandt & Hasinger 2005
Summary of Key Points

• Apparently all massive galaxies have supermassive black holes at their centers.
• Black holes accreting mass are “active galactic nuclei”.
• A broad range of AGN phenomena are attributable to differences in inclination, luminosity, and Eddington accretion rate.
• High-luminosity AGNs were common in the past. Their remnants are quiescent black holes in massive galaxies.