Active Galaxies & Emission Line Diagnostics

- Review of Properties Discussed:
  1) Powered by accretion unto a supermassive nuclear black hole
  2) They are the possible precursors to luminous massive galaxies

- Things hinted at:
  1) AGN may be activated by a merger/interaction event.
AGN Nomenclature

AGN come in several flavors. The classes we will discuss are:

- Seyfert Galaxies
- Radio Galaxies
- Quasi Stellar Radio Sources (Quasars or QSRs)
- Quasi Stellar Objects (QSOs)
- Low Ionization Nuclear Emission Regions (LINERs)
Seyfert Galaxies

- Bright, unresolved nuclei
- Typically have blue continuum
- Strong nuclear emission lines
- Moderate radio emission \((L_{\text{rad}} \sim 10^{40} \text{ erg s}^{-1})\)
- Strong X-ray emission \((L_{\chi} \sim 10^{42} \text{ erg s}^{-1})\)
Seyfert Galaxy Classes

1) Type I – **Permitted** emission lines (i.e., recombination lines) are broader than **Forbidden** emission lines (e.g. [O II] \(\lambda 3727\), [O III] \(\lambda \lambda 4959+5007\))

2) Type II – Both Permitted & Forbidden emission lines have the same line width. Type II Seyferts are also weaker X-ray sources
Radio Galaxies

- Luminous, nonthermal radio emission \( (L_{\text{rad}} > 10^{42} \text{ erg s}^{-1}) \)
- Extended (100 kpc – 10 Mpc) radio jets
- Starlight spectra in the case of weak radio emission, & Seyfert-like spectra in the case of strong radio emission
- Radio Galaxies come in two classes:
  1) Broad Line Radio Galaxies (BLRG) \( \approx \) to Seyfert 1
  2) Narrow Line Radio Galaxies (NLRG) \( \approx \) to Seyfert 2
Radio Galaxy Classification via Radio Jet Morphology

• Fanaroff-Riley I (FR I)
  1) Edge-Darkended Lobes
  2) $v_{\text{jet}} \sim v_{\text{sound}}$
  3) $P_{408\text{MHz}} \leq 10^{25.3} \text{ W Hz}^{-1}$ (typically)

• Fanaroff-Riley II (FR II)
  1) Edge-brightened lobes
  2) $V_{\text{jet}} \sim 0.1c$
  3) $P_{408\text{MHz}} \leq 10^{25.3} \text{ W Hz}^{-1}$ (typically)

3C31

Cygnus A = 3C 405
Quasi-Stellar Radio Sources

• Bright & unresolved nuclei. The underlying galaxy is difficult to see

• $L_{\text{rad}}$ & radio morphologies are similar to luminous radio galaxies

• Seyfert 1 – like optical emission line spectra
Quasi-Objects

- Bright & unresolved nuclei. The underlying galaxy is very difficult to see
- Radio-Quiet
- Seyfert 1 – like emission line spectra
Low Ionization Nuclear Emission Regions

- $L_{H\alpha} < 10^{40}$ erg s$^{-1}$
- Low-ionization spectra ($[\text{O III}]$ is a high ionization line)
- No evidence of non-thermal continuum
- About half of all spiral galaxies are LINERs

Table 1. Local Galaxy Space Densities

<table>
<thead>
<tr>
<th>Class</th>
<th>Space Density (Mpc$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field Galaxies</td>
<td>$10^{-1}$</td>
</tr>
<tr>
<td>Luminous Spirals</td>
<td>$10^{-2}$</td>
</tr>
<tr>
<td>Seyfert Galaxies</td>
<td>$10^{-4}$</td>
</tr>
<tr>
<td>Radio Galaxies</td>
<td>$10^{-6}$</td>
</tr>
<tr>
<td>QSOs</td>
<td>$10^{-7}$</td>
</tr>
<tr>
<td>Quasars</td>
<td>$10^{-9}$</td>
</tr>
</tbody>
</table>

From Osterbrock 1989.
General AGN Model

- General Model – Accretion disk surrounding a supermassive black hole.
- $\Delta v_{BLR} \sim 2000$ km s$^{-1}$
- $\Delta v_{NLR} \sim 500-100$ km s$^{-1}$
- Orientation may be what separates one type of AGN from another
Size of the BLR

- $L_{\text{bol}} \sim \text{several} \times 10^{12} \, L_{\text{sun}}$
- $M_{\text{BH}} \sim 10^8 \, M_{\text{sun}}$
- $\Delta v_{\text{BLR}} \sim 2000\, \text{km} \, \text{s}^{-1}$

$$r = \frac{GM (<r)}{\Delta v_{\text{FWHM}}^2} = 0.035\, \text{pc}$$

BLR has a full extent of about 0.1 pc.
Evidence of Dust Torus

Orientation Models

- NLRG(FR-II) → BLRG(FR-II) → QSR
- NLRG(FR-I) → BLRG(FR-I) → QSO

- The apparent length of QSR jets are smaller than those of radio galaxies, also supporting the orientation model (Barthel 1989, ApJ, 336, 606)
Narrow Lines Visible, Broad Lines Obscured

(Osterbrock 1989)
Broad Lines Visible, Narrow Lines Visible

(Osterbrock 1989)
Obscuration is also supported by observations of NIR BLR in Optical Seyfert 1

Permitted Lines

n=4
γ
β
Paα

n=3
β
Hα
Paschen

n=2

Balmer

Ly α

n=1
Lyman
Permitted vs. Forbidden Lines

Permitted Line emission is seen from both the BLR & NLR, whereas forbidden line emission is seen only from the NLR.

• The permitted recombination lines result from free electrons recombining with nuclei & cascading down to the ground state
• The forbidden lines have extremely low transition probabilities
  
  1) $A_{ij} \approx 10^{-2} \text{ s}^{-1}$ for forbidden lines
  2) $A_{ij} \approx 10^{8} \text{ s}^{-1}$ for permitted lines

• Thus, forbidden line emission is typically excited by collisions in the NLR
For an atom with two levels 1 & 2,

\[
\text{Collision radiative collisional} \\
\text{excitation} = \text{de-excitation} + \text{de-excitation}
\]

which can be written as,

\[
n_1 n_e (v \sigma_{12}) = n_2 A_{21} + n_2 n_e (v \sigma_{21}),
\]

where \( n_1, n_2, \) and \( n_e \) are the level 1, 2, and free electron number densities, respectively, \( v \) is the velocity of the free electrons, & the \( \sigma \)'s are the collisional cross sections.

The critical \( n_e \) for collisional de-excitation is thus,

\[
n_c = \frac{A_{21}}{v \sigma_{21}}.
\]

Thus, if \( n_e < n_c \), collisions do not dominate the de-excitation & there is forbidden line emission.
One can use the critical densities of different species to determine the NLR & BLR densities:

- For the BLR, $n_e = 10^9$ cm$^{-3}$. This is because
  - 1) There is no [O III] $\lambda\lambda 4959+5007$ emission in BLR, which means that $n_e > 10^8$ cm$^{-3}$
  - 2) There is C III] $\lambda 1909$ emission in the BLR, which means that $n_e < 10^{10}$ cm$^{-3}$.

- For the NLR, where both permitted & forbidden lines are seen, $n_e = 10^5$ cm$^{-3}$.
The Host Galaxies of AGN (i.e., QSOs and Radio Galaxies)

- SEDs
- Host Galaxies
- Black Hole Masses
- Molecular Gas
SED of QSOs

- Radio – Non-Thermal
- Infrared – Thermal Emission from dust
- $T_{\text{dust}} = 20 - 120$ K

(Müller, Chini, Haas et al. 2001)
“Typical” QSO Spectrum

- $\nu f_\nu = \text{total energy output at } \nu$
- $20 - 40\%$ of $L_{\text{bol}}$ is thermal emission from dust.

(Sanders et al. 1989)
For Radio Galaxies…

- Radio – Non-Thermal
- Infrared – Thermal Emission from dust
- $T_{\text{dust}} = 30 – 80$ K

(Müller, Chini, Haas et al. 2001)
Note: optical to near-infrared emission from radio galaxies is primarily stellar in nature. Moreso for NLRGs than BLRGs.

I.e., obscuration of AGN is a major factor.

(Evans 1996)
Hosts: Galaxy Type
Focus: QSOs

• **Main problem:** The bright QSO nucleus makes it difficult to observe the underlying host galaxy.

• **A note on nomenclature:** QSO and QSR refer to the AGN itself, not to the whole galaxy. Also, people commonly use “QSO” or “Quasar” to refer to both radio-loud & radio-quiet objects.
Models

1) Subtract PSF

2) Match model QSO+galaxy to real data

Degrade Resolution to Match Resolution of Imaging Data.
PSF Subtraction

Before... After. (Bahcall et al. 1997)
Results to Date

• Almost all of the Brightest Quasars are in Elliptical Galaxies
• The Fainter Quasars are in Spiral Galaxies, Elliptical Galaxies, & Galaxy Mergers

(Dunlop et al. 2001)
Radio Galaxies

Radio Loud Quasars

Radio-Quiet Quasars

$M_v \sim -23.5$

Figure 1. Histograms of the best-fit values of $\beta$, where host-galaxy surface brightness is proportional to \( \exp(-(r)^\beta) \), shown for the radio-galaxy, radio-loud quasar and radio-quiet quasar sub-samples imaged with the HST by Dunlop et al. (2001). The dotted line at $\beta = 0.25$ indicates a perfect de Vaucouleurs law, and all of the radio-loud hosts are consistent with this within the errors. Two of the three RQQs with hosts for which $\beta > 0.4$ transpire to be the two least luminous nuclei in the sample, and should really be reclassified as Seyferts. $\beta = 0.25$

(de Vaucouleurs law)

(Dunlop 2001)
Figure: Bahcall et al. 1997
Figure: Hamilton et al. 2001
$L_{\text{bulge}} / L_{\text{host}}$ vs. $M_v$ (nucleus)

- Disk-Dominated host galaxies become rare with increasing nuclear power.

Figure 2. The relative contribution of the spheroidal component to the total luminosity of the host galaxy plotted against absolute V-band luminosity of the nuclear component. The plot shows the results for our own HST sample (RLQs as open circles, RQQs as filled circles) along with the results from Schade et al. (2000) for a larger sample of X-ray selected AGN spanning a wider but lower range of optical luminosities (asterisks). This plot illustrates very clearly how disc-dominated host galaxies become increasingly rare with increasing nuclear power, as is expected if more luminous AGN are powered by more massive black holes which, in turn, are housed in more massive spheroids.

(Dunlop 2001)
The Kormendy Relation

- Slope = 2.95 for inactive elliptical galaxies

- Slope = 2.90 ± 0.2

- $r_{1/2}$ (RLQ) = 12 kpc
- $r_{1/2}$ (RQQ) = 8 kpc
- $r_{1/2}$ (RG) = 11 kpc
- $r_{1/2}$ (BCG) = 13 kpc

(Dunlop 2001)
M_{BH} Based on $\Delta v_{H\beta}$ + Reverberation Method

- The H\beta data…

(McClure & Dunlop 2001)
The Results...

\[ \langle M_{\text{BH}} \ (\text{RLQ}) \rangle = 1 \times 10^9 \ M_{\odot} \]

\[ \langle M_{\text{BH}} \ (\text{RQQ}) \rangle = 5 \times 10^8 \ M_{\odot} \]

*Figure 5.* A comparison between the black-hole masses of quasars as predicted from host-galaxy spheroidal luminosity by Dunlop et al. (2001), and the corresponding values determined from \( H\beta \) line-width by McLure & Dunlop (2001). The shaded area is shown to demonstrate that there is a region in which both approaches agree that \( M_{\text{bh}} \gtrsim 10^9 M_{\odot} \), and that this region contains all except one of the RLQs (open circles), but excludes all except 2 of the RQQs (filled circles).

(Dunlop 2001)
An Infrared Excess Sample

- Palomar-Green Quasar Survey
- $L_{\text{IR}} / L_{\text{bbb}} (0.1-1.0 \, \mu\text{m}) > 0.36$
- Redshift, $z < 0.17$
- $M_B < -22.0$

- 17 QSOs match this description

(Surace, Sanders & Evans 2001
Evans et al. 2001)
Molecular Gas: The Fuel for AGN activity?

- Detected in 8 of the 17 IR-excess QSOs to date
- $M(H_2) \sim 10^9 - 10^{10} \, M_{\text{sun}}$ of gas ($\alpha = L'_{\text{CO}} / M(H_2) = 4$)

(Evans et al 2001)
Evidence of Molecular Gas Associated with AGN

(Evans et al. 2000; 2002)
Imaging Data: Diverse Morphologies
(B & I-band Data)

Half are in spiral galaxies.

And half of those are barred.

(Surace, Sanders & Evans 2001)
Diverse Morphologies

A quarter are in major merger systems as evidenced by tidal tails 20-80 kpc in length.

A few are extended but don’t look like anything. They have no resolvable structure, and could be ellipticals or unresolved spirals. Radial profiles do not produce very meaningful results due to convolution effects with PSF.

(Surace et al. 2001)
In some cases there is resolvable small scale structure similar to the star-forming knots found in ULIRG nuclear regions and tidal structure. In most cases the ages of these knots are probably under 100 Myrs based on 4-color analysis and spectral synthesis models.

(Surace et al. 2001)
Optical Imaging of IR-excess QSOs

- IR-Excess QSOs Have Spiral, Merger, and “Elliptical” Galaxy Hosts
- 25% - Ongoing Major Mergers

(Surace et al. 2001)
Can the QSOs Account for most/all of the Bolometric Luminosity?

<table>
<thead>
<tr>
<th>PG QSO</th>
<th>M.</th>
<th>$L_{\text{bol}}/L_{\text{eddington}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>PG 1226+023</td>
<td>$5 \times 10^8$</td>
<td>0.12</td>
</tr>
<tr>
<td>PG 1351+640</td>
<td>$5 \times 10^7$</td>
<td>0.16</td>
</tr>
<tr>
<td>PG 1411+442</td>
<td>$8 \times 10^7$</td>
<td>0.04</td>
</tr>
<tr>
<td>PG 1613+658</td>
<td>$2 \times 10^8$</td>
<td>0.02</td>
</tr>
<tr>
<td>PG 2130+099</td>
<td>$1 \times 10^8$</td>
<td>0.02</td>
</tr>
</tbody>
</table>

From Reverberation Mapping (Kaspi et al. 2000)

Answer: Yes. We’ll return to this later…
Beaming & Superluminal Motion

- Many AGN radio jets have been observed to be moving at superluminal velocities. To understand how this physically impossible property comes about, consider an observer at a distance $r_0$ from an AGN.

- The AGN emits a blob of relativistic material traveling at velocity $v$ & angle $\theta$ to the line of sight of the AGN to the observer.
• At time $t_1$, the light emitted from the blob at the nucleus of the AGN reaches the observer. Thus,

$$t_1 = \frac{r_0}{c}.$$ 

• At time $t_0$, the blob has moved a distance $vt_0$ (in the blob’s frame). The distance the blob has moved projected unto the axis perpendicular to the observer’s line of sight is,

$$\Delta y = vt_0 \sin \theta,$$
• The distance the blob has traveled projected unto the observer line of sight axis is

\[ \Delta x = vt_0 \cos \theta. \]

• At \( t_2 \), the observer see the blob at \( \Delta y \). However, the radiation that the observer sees was emitted from the blob at time \( t_0 \). Thus,

\[ t_2 = t_0 + \frac{(r_0 - vt_0 \cos \theta)}{c}. \]

• Thus, the elapse time for the observer is,

\[ \Delta t = t_2 - t_1 = t_0 + \frac{(r_0 - vt_0 \cos \theta)}{c} - \frac{r_0}{c}; \]

\[ \Delta t = t_0 \left(1 - \frac{\nu}{c} \cos \theta \right) = t_0 (1 - \beta \cos \theta), \]

where \( \beta = \nu / c \).
• The y-axis velocity will be defined as,

\[ v_y = \frac{\Delta y}{\Delta t}. \]

Thus,

\[ v_y = \frac{\Delta y}{\Delta t} = \frac{vt_0 \sin \theta}{t_0(1 - \beta \cos \theta)} = \frac{v \sin \theta}{1 - \beta \cos \theta}. \]

If,

\[ \beta_\perp = \frac{v_y}{c}, \]

then,

\[ \beta_\perp = \frac{\beta \sin \theta}{1 - \beta \cos \theta}. \]
• Given the above expression, relativistic expansion requires that \( v \approx c \) & \( \cos \theta \approx 1 \).
• For a fixed value of \( \beta \), what \( \theta \) maximizes \( \beta_\perp \)?
• Differentiating with respect to \( \theta \),

\[
\frac{d\beta_\perp}{d\theta} = \beta \sin \theta \frac{d(1 - \beta \cos \theta)}{d\theta} + \frac{1}{1 - \beta \cos \theta} \beta \frac{d\sin \theta}{d\theta},
\]

\[0 = \beta \sin \theta (-1) \frac{1}{(1 - \beta \cos \theta)^2} (-\beta \sin \theta) + \frac{\beta \cos \theta}{1 - \beta \cos \theta};\]

\[-\beta^2 \sin^2 \theta \frac{1}{(1 - \beta \cos \theta)^2} = \frac{\beta \cos \theta}{1 - \beta \cos \theta};\]

\[
\frac{\beta \sin^2 \theta}{(1 - \beta \cos \theta)} = \cos \theta;
\]
• It follows that,

\[ \beta(1 - \cos^2 \theta) = \cos \theta - \beta \cos^2 \theta; \]

\[ \beta = \cos \theta. \]

\[ \sin \theta = (1 - \beta^2)^{1/2}. \]

• Thus, if \( \beta = 0.99 \), then \( \theta = 8^\circ \). If \( \beta = 0.999 \), then \( \theta = 2.6^\circ \).

I.e., the radiation becomes beamed – the faster the object moves, the narrower the doppler boosting cone.

• Note also that,

\[ \beta_{\perp} (\text{max}) = \frac{\beta}{(1 - \beta^2)^{1/2}}, \]

• And thus if \( \beta = 0.99 \), \( \beta_{\perp} (\text{max}) = 7 \); the object will appear to the observer to be moving at \( 7c \).
Emission Line Diagnostics

- Seyfert 2s, starburst galaxies, & LINER have narrow emission lines.
- How does one tell the difference between them?
- **Importance**: Tells you what is ionizing the ISM, & potentially tells you the dominant source of ionization in the galaxy.
- This is a very active area of research, especially for galaxies at high redshift.
Photoionization Cross Section

- In order to understand the differences, consider the photoionization cross section, $a_\nu$.
- The mean free path (mfp) is expressed as,

$$\frac{1}{N_{H0}a_\nu},$$

Neutral H number density

- **Punch line**: Low energy photons have have short mfp’s, & the mfp increases with increasing photon energy.
• Most low energy photons are absorbed very close to AGN. The region of ionized gas near the AGN is called the ionized region.

• High energy photons, with their longer mfp’s, escape the ionized region & transfer ionization energy & momentum to the semi-ionized region. Forbidden lines are made here.

• Because AGN make a higher fraction of high energy photons than stars, their semi-ionized region is more extended.
A word of caution

- Shocks likely produce extended semi-ionized regions.
- Shocks can be produced by either weak power-law AGN or supernovae.
- Shocks likely create LINER-like spectra.
- Keep in mind than 30% of all emission line galaxies are LINERs. We will return to this point later.
Emission Line Diagnostic Diagrams

- Low/high ionization to recombination line ratio
- Ratios are of lines with similar wavelengths, thus minimizing extinction effects

(Veilleux et al. 1995)
Dividing Lines: Partly Empirical

Fig. 5—The relationship between the $(\lambda 5007/\lambda 4861)$ and $(\lambda 6584/\lambda 6563)$ intensity ratios. The symbols have the same meanings as in Figures 1 and 2.
Diagnostics at Optical Wavelengths can then be Related to Diagnostic Developed at Longer Wavelengths.

Destroyed by AGN radiation field

(Genzel et al. 1998)
Electron Densities

- \([\text{O II}]\) & \([\text{S II}]\) Doublets
- Levels Collisionally Populated
- De-excitation Forbidden (comparable radiative & collisional de-excitation rates – i.e., \(A_{ul} = C_{ul}\))

**FIGURE 5.2**
Energy-level diagrams of the 2\(p^3\) ground configuration of \([\text{O II}]\) and 3\(p^3\) ground configuration of \([\text{S II}]\).
Electron Densities, cont.

- Low density limit \((N_e \to 0)\)
  De-excitation is radiative

- High density limit \((N_e \to \infty)\)
  Collisional excitation & de-excitation important

\[
\frac{I_{31}}{I_{21}} = \frac{n_3 h\nu_{31}}{n_2 h\nu_{21}} = \frac{g_3}{g_2}.
\]

\[
\frac{I_{31}}{I_{21}} = \frac{g_3 h\nu_{31} A_{31}}{g_2 h\nu_{21} A_{21}}.
\]
Temperatures

- Levels with different excitation energies required
- [O III] & [N II] Transitions thus useful
Temperatures, cont.

\[
\frac{I_{32}}{I_{21}} \propto \exp \left( -\frac{h(v_{32} - v_{21})}{kT} \right)
\]

- But this is only useful up to \( N_e \approx 10^5 \text{ cm}^{-3} \)
- I.e., before Collisional De-excitation becomes important