16.1 Quasars and Active Galactic Nuclei: General Properties and Surveys
Quasars and AGN

• They are highly energetic manifestations in the nuclei of galaxies, believed to be powered by accretion onto massive black holes

• Empirical classification schemes and various types have been developed, on the basis of the spectra; but recently, various unification schemes have been developed to explain AGN as different appearances of the same underlying phenomenon

• Quasars/AGN are observed to evolve strongly in time, with the comoving densities of luminous ones increasing by $\sim 10^3$ from $z \sim 0$ to $z \sim 2$

• At $z \sim 0$, at least 30% of all galaxies show some sign of a nuclear activity (mostly low level); $\sim 1\%$ can be classified as Seyferts (moderately luminous), and $\sim 10^{-6}$ contain luminous quasars

• However, we think that most or all non-dwarf galaxies contain SMBHs, and thus probably underwent at least one AGN phase.
AGN, an artist’s view

- Central black hole
- Relativistic jet / illumination cone
- Accretion disk
- Obscuring dusty torus
Observable Properties of AGN

- Energy emission over a broad range of frequencies, from radio to gamma rays
  - Nonthermal radio or X-ray emission is a good way to find AGN
  - Generally bluer spectra than stars: “UV excess”
  - Colors unlike those of stars, especially when modified by the intergalactic absorption
- Presence of strong, usually broad emission lines in their spectra
- Can reach large luminosities, up to $\sim 10^{15} L_\odot$
- Strong variability at all time scales
  - Implies small physical size of the emission region
- Central engines unresolved
- Zero proper motions due to a large distances

All of these have been used to devise methods to discover AGN, and each method has its own limitations and selection effects
Broad-Band Spectra of Quasars

Radio Loud

Radio Quiet

4C 34.47 (radio loud)

Mkn 586 (radio quiet)

mm-break

Inflection

XUV excess

Hard X component

UV Bump

Gap
UV-Optical Spectra of Quasars

Strong, broad emission lines:

- Balmer lines of hydrogen

Prominent lines of abundant ions
Quasar Surveys

• In order to study QSOs (and other AGN), we first have to find them, in large numbers, and hopefully in a systematic fashion
  – This is especially important for studies of their evolution
• Recall that *each discovery method has its own biases*
• Nowadays the most popular technique is to use colors to separate QSOs from normal stars
  – In optical, one can also use slitless spectroscopy, variability, and zero proper motions
• Soft X-ray (up to a few keV) and optical selection find the same types of relatively unobscured objects; hard X-ray selection and FIR/sub-mm detect more obscured populations; radio finds both
• Next: multi-wavelength, survey cross-matching in the Virtual Observatory framework - will help with the selection effects
Quasar Surveys and Catalogs

• To date, there are > 350,000 spectroscopically confirmed QSOs
  – And > 1,000,000 additional QSO candidates selected from colors, still awaiting spectroscopy
  – Most come from large systematic surveys, e.g., SDSS and 2QZ
  – Many smaller surveys in the past were done at Palomar, e.g., Palomar Green (PG), Palomar CCD (PC), Palomar Sky Survey (PSS), etc.
  – There were also many searches for emission line objects (some are AGN, some starformers), e.g., Mrk, UM, CSO, KISS, etc.
  – Older heterogeneous catalogs include Hewitt & Burbidge, and Veron & Veron-Cetty compilations

• There are now also > $10^5$ X-ray sources catalogued (most are probably powered by AGN)

• There is also probably close to ~ $10^6$ radio sources in various catalogs, and many (most?) of them are powered by AGN
  – Major radio surveys include: Parkes (PKS), Green Bank (GB), NRAO VLA Sky Survey (NVSS), Faint Images of Radio Sky at Twenty cm (FIRST), etc. etc.
Quasar Counts

For the unobscured, Type 1 QSOs; they may be outnumbered by the obscured ones. Down to \( \sim 22^{\text{th}} \) mag, there are \( \sim 100 \, \text{deg}^{-2} \); down to \( \sim 29^{\text{th}} \) mag, probably a few hundred more \( \rightarrow \) a total of a few \( \times 10^7 \) over the entire sky, or \( \sim 1 \) per 1000 faint galaxies.
Ratios of fluxes in different survey filters (=colors) are in general different for QSOs and for stars - even though both look “stellar” on the images. The colors will change with redshift as different features (emission lines, continuum breaks) shift from one filter to another. For each redshift range, a different filter combination would be the optimal one for QSO selection.
SDSS Quasar Survey

Examples of color selection of QSOs, as outliers away from the stellar locus
Where the QSOs (colored dots) are as a function of redshift in each color space

Black dots: stars and galaxies
2QZ Quasar Survey

Uses 2dF spectrograph at the AAT

UV color selection (limits redshifts to $z < 2.3$)

23,424 QSOs

http://www.2dfquasar.org/
Redshift-sorted spectra. Strong emission lines (bright ridges) shift to the red as the redshift increases.
16.2 Active Galactic Nuclei: Classification

1. Geospiza magnirostris.
2. Geospiza fortis.
AGN Classification

- According to radio emission:
  - Radio loud: radio galaxies (RGs) and quasars; F-R types I and II
  - Radio quiet (but perhaps not entirely radio silent)

- According to optical spectrum:
  - Narrow-line RGs, Seyfert 2’s; Liners
  - Broad line RGs, Seyfert 1’s, quasars

- According to optical luminosity:
  - Seyfert to quasar sequence, range of radio powers, etc.

- Special types:
  - Blazars (aka BL Lac’s) and optically violently variable (OVV) objects

- These classifications are largely parallel

- Some distinction may reflect real, internal physical differences, and some may be simply orientation effects
  - This is the central thesis of the AGN unification models
Active Galactic Nuclei: Seyferts

• Seyferts are the low luminosity counterparts of quasars
• First noted by Fath at Lick Observatory in 1908 (!), who was taking spectra of the nuclei of “spiral nebulae” and noted that NGC 1068 had strong emission lines
• Slipher obtained a higher quality spectrum at Lowell in 1917, noted the lines were similar to planetary nebulae
• In 1926, Hubble noted 3 galaxies with strong emission lines: NGC 1068, NGC 4051, NGC 4151
• In 1943 (~30 years later!), Carl Seyfert recognized that there was a class of galaxies (now known as Seyfert galaxies), with strong, broad high-ionization emission lines and bright nuclei
  – Why this was not remembered when the first spectra of quasars were taken in 1960’s, is a mystery …
Active Galactic Nuclei: Seyferts

- Seyfert nuclei are found in spiral galaxies; up to ~10% of Sa and Sb’s are Seyferts; but at a lower level of activity, there are more.
- Seyferts have only moderate radio emission (~$10^{40}$ erg/s) but strong x-ray emission (> $10^{42}$ erg/s).

NGC 5548

NGC 3277
Quasar Images

Even with HST imaging, difficult to detect the light of the host galaxy due to the high luminosity of the nucleus.

Spiral host - somewhat unusual

Elliptical host - more common

In general, QSO hosts tend to show signs of tidal interactions or mergers - suggesting a triggering / fueling mechanism.
Types of Seyfert Galaxies

Type 1 Seyfert galaxies have in their spectra:
- Narrow emission lines, with a width of several hundred km/s
- Broad emission lines, with widths up to $10^4$ km/s

They also have brighter and bluer nuclei
Type 2 Seyfert galaxies have only the narrow line component:

Both types have high ionization, forbidden lines (= transitions not easily observed in the lab)
Spectroscopic Diagnostics

Intensity ratios of various emission lines depend on the spectrum of the ionizing continuum radiation: to get lines from high energy levels (e.g., ionizing potentials of tens of eV), one needs “hard” spectra with lots of high energy (UV / soft X-ray) photons.

Accretion disks can provide those in AGN, while objects powered by star formation have much “softer” spectra.
Energy stored in radio lobes can reach $\sim 10^{60} - 10^{61}$ erg. If jet lifetime is $\sim 10^8$ yrs, the implied mechanical luminosities are $\sim 10^{12} - 10^{13} \, L_\odot$. 

Radio Galaxies: Typical Examples

Radio overlayed on optical images

Centaurus A

Fornax A
Cygnus A: A Modern VLA Radio Map

For more good radio images, see the VLA image gallery at http://www.nrao.edu/imagegallery/php/level1.php
Radio Source Classification

Fanaroff-Riley Type I (FR I): Separation between the points of peak intensity in the lobes < 1/2 the largest size of the source
  Edge darkened radio jets, slower jet speeds, lower radio power

Fanaroff-Riley Type II (FR II): Separation between the points of peak intensity in the lobes > 1/2 the largest size of the source
  Edge brightened radio jets, speeds ~0.1c, higher radio power

FR I: 3C272.1  FR II: 3C47
BL Lacs (Blazars)

Named after the prototype BL Lacertae. They have strong, blue, variable continua, and lack strong emission or absorption lines in their spectra:

- They are radio-loud quasars, viewed along the relativistic jet.
- Relativistic beaming amplifies any variations in intensity.
Optically Violent Variables (OVVs)

Related class to blazars are optically violent variables (OVV).

All AGN are variable, but OVVs show large variations (> 0.1 mag) in optical flux on short timescales (< day), and much stronger at longer time scales.

Variability can be due to accretion to the central engine (black hole), or the instabilities in the jet. It may or may not be correlated between different wavelengths.
AGN: A Physical Classification

... but in addition, there will be some dependence on the viewing orientation.
16.3 AGN Unification Models
Unification Models for AGN

- The basic idea is that in a given radio-loudness category, all AGN are really the same type of objects, viewed from different angles.

- The key feature is a presence of an obscuring dusty torus.

- There may be some real variation in the physical properties at any given orientation.
AGN Unification Models

They seek to explain different classes of AGN as being due to different orientations of intrinsically similar systems to the observer’s line of sight.

**Seyfert 1 and Seyfert 2 galaxies:** Probably the most secure unification. Basic idea: an obscuring torus prevents us seeing the broad line region in Seyfert 2’s:

*NB: This cartoon not even remotely to scale!*
Why do we still see the continuum in Seyfert 2 galaxies?

Continuum radiation comes from the disk at smaller radii than the broad lines - why doesn’t the torus block that too?

Assume that a scattering medium (e.g. free electrons) scatters some of this radiation into our line of sight…
Support for this picture: in some Seyfert 2 galaxies the *polarized emission* (e.g., reflected from dust grains) shows broad lines:

![Graph showing flux vs wavelength for Mrk 348 and PxF (4500 to 7000) wavelengths.]

This is consistent with the unification, since scattering produces polarization. Conclude:

- At least some Seyfert 2’s are intrinsically similar to Seyfert 1’s
- If this applies to all Seyferts, statistics mean that the torus must block about 3/4 of the sky as seen from the nucleus
**Ionization Cones**

In addition to the spectro-polarimetry, evidence for anisotropy in AGN comes from images of resolved narrow-line emission region:

The gas seems ionized in cones bracketing the nucleus, which are also aligned with the radio jets (if present).

This is as expected if the rest of the gas does not see the nucleus, due to a toroidal obscuration.
AGN Unification

It is now easonably secure to also fit quasars and blazars, and the radio loud equivalents, into this unified scheme:

- Obscured
  - Seyfert 2
  - Type 2 QSO or radio galaxy

- Unobscured
  - Seyfert 1
  - Type 1 QSO or radio quasar

- Viewed directly down the jet
  - Blazars
  - Accretion rate

Type 2 or highly obscured luminous AGN are also needed to make up the hard X-ray background. Populations of such objects have been found recently both in the optical and X-ray surveys.

But there are some low-\(L\), unobscured AGN, with no broad lines…
Radio Loud vs. Radio Quiet

More ambitious unification schemes aim to explain why some AGN are radio loud, others radio quiet. *Possible* physical difference is the spin of the SMBH:

<table>
<thead>
<tr>
<th>Radio loud</th>
<th>Radio quiet</th>
</tr>
</thead>
<tbody>
<tr>
<td>High spin holes with $a \sim 1$</td>
<td>Low spin holes, $a &lt;&lt; 1$</td>
</tr>
<tr>
<td>Produce jets, which are the origin of radio emission (note: blazars are radio loud)</td>
<td>No jets</td>
</tr>
<tr>
<td>Jets powered by spin energy extracted from black hole</td>
<td>Spectrum produced by the accretion disk (blackbody + nonthermal em.)</td>
</tr>
<tr>
<td>Also have accretion disks</td>
<td></td>
</tr>
</tbody>
</table>

$a$ is the spin parameter: $a = \frac{cJ}{GM^2}$
Radio Loud vs. Radio Quiet

Where do the SMBHs get their angular momentum? It is very hard to do via accretion, since the infalling material must come in on nearly radial orbits in order to hit the small target BH. A plausible source is mergers, where the orbital angular momentum of two merging BHs is converted to an internal angular momentum of the product.

Black hole mergers may produce gravitational wave signals, that may be detectable by LISA or pulsar timing (but not LIGO).

This scenario would also help explain why powerful radio sources seem to favor giant ellipticals as hosts, and cluster environments (that’s where most large E’s are) - and ellipticals are more likely to be products of large mergers.

It all must depend on the details of the growth processes of SMBHs in the early universe, and that is still not well understood.
16.4 AGN Central Engine:

Supermassive Black Holes

and Eddington Limit
Massive Black Holes in Galactic Nuclei

- They are **ubiquitous**, even though only a small fraction are active today; but these SMBHs are just **dormant quasars**, which were once active - this is where their mass comes from!
- They are detected through central velocity dispersion or rotation cusps near the center, or kinematics of emission line gas.
Black Hole in NGC4258

Observe the positions and velocities of water masers in a thin gas disk orbiting the black hole; their Keplerian motions provide a measurement of the central point mass.
Dynamical Evidence for a Supermassive Black Hole at the Galactic Center

Note: \( R_S (M_\bullet = 2.6 \times 10^6 M_\odot) = 7.8 \times 10^8 \text{ cm} = 6.5 \times 10^{-8} \text{ arcsec} \)

\( \rightarrow \) Unresolvable by any technology we have now
Where Does the Energy Come From?

• Accretion onto the central supermassive black holes provides the only known viable answer

• The fuel comes from ~ kpc scales (or larger) and ends near the Schwarzschild radius, \( R_s = \frac{2GM}{c^2} \) (actually, the relevant radius is the smallest stable orbit, at a few \( R_s \)). For a \( M_\bullet \sim 10^8 M_\odot \), \( R_s \sim 3 \times 10^8 \text{ km} \sim 10^{-5} \text{ pc} \)

• The binding energy for a mass element \( m \) is: \( E_b(R) = G m M_\bullet / R \)

• In order for it to be accreted over many orders of magnitude in radius, it has to release the amount of energy comparable to \( E_b \) namely \( G m M_\bullet / R_{\text{min}} = m c^2 / 2 \), where \( R_{\text{min}} \sim \) a few \( R_s \)

⇒ Accretion to black holes can result in the energy release comparable to the rest mass energy! Usually a \( \sim 10\% \) net efficiency is assumed, still much larger than the 0.1% energy conversion efficiency of thermonuclear reactions.
The Black Hole Paradigm for AGN

Black holes are completely specified by their mass $M$, angular momentum $J$, and charge $Q$ (likely $\sim 0$): the no-hair theorem

Schwarzschild black hole: $Q = 0, J = 0$

Spherically symmetric. Solution has two important radii:

- An **event horizon** at Schwarzschild radius: $R_s = \frac{2GM}{c^2}$

- The last stable circular orbit radius: $R_{ms} = \frac{6GM}{c^2}$

Outside $R_{ms}$ test particles can orbit indefinitely in stable circular orbits, inside $R_{ms}$ they spiral rapidly past the event horizon into the BH. This defines the inner edge of the gas disk in AGN and sets a minimum orbital period, $\sim$ hours for the $M_\bullet \sim 10^7 - 10^8 M_{\odot}$
Evidence for SMBHs From X-Ray Spectroscopy

Measuring of the spectral line profiles in the inner parts of the accretion disk, close to the SMBH, offers another test for the presence of SMBHs in AGN

Fe lines in the X-rays come from the innermost parts of the disk, and are used for this test

**Newtonian case:** \[
\frac{\Delta \nu}{\nu} = \frac{v_{\text{obs}}}{c}
\]

Characteristic “double-horned” profile from a Doppler shift will only work for a Newtonian disk

But in a relativistic case, several new effects appear …
Newtonian profile from single annulus

Transverse doppler effect: “moving clocks appear to run slow”. Observed frequency is reduced compared to rest frame value by factor \((1 - v^2 / c^2)^{-1/2}\)

Beaming: Boosts blue wing of the line, attenuates red wing

Gravitational redshift

Further shifts profile to lower energies

Integrate over all disk radii and predict: Broad, asymmetric line profile with a sharp cutoff at high \(E\)
Fe line profile is found to be often extremely broad, and the detailed modeling of the line shape favors a rapidly spinning BH.

Possibly the best proof to date of presence of BHs in AGN.
**Spinning Black Holes**

**Kerr black hole:** $Q = 0$, $J$ and $M$ arbitrary

Axisymmetric solution - hole has a preferred rotation axis. Define the amount of angular momentum via a dimensionless **spin parameter**: $a = \frac{cJ}{GM^2}$

Maximum angular momentum of a Kerr BH corresponds $a = 1$

Gas can spiral deeper into the potential well before reaching $R_{ms}$ around a Kerr black hole: **more energy can be extracted**

A Kerr black hole has an **irreducible mass**, given by: $M_{ir} = \frac{M}{2} \left[ \left( 1 + \sqrt{1 - a^2} \right)^2 + a^2 \right]^{1/2}$

For $a = 1$, $M_{ir} = 0.707 \, M$

$(M - M_{ir})$ represents *rotational energy of the BH* which can in principle be extracted, possibly by threading the hole with a large scale magnetic field (the Blandford-Znajek process)
For an AGN with an observed bolometric luminosity $L$, we can estimate the *minimum* mass of the black hole involved:

Suppose the gas around the BH is spherically symmetric, and fully ionized hydrogen. At distance $r$, energy flux is:

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

The corresponding momentum flux, which would produce the radiation pressure, is:

$$P_{\text{rad}} = \frac{L}{4\pi r^2 c}$$

Force exerted on the gas depends upon the opacity, but the *minimum* force is due to the absorption by free electrons, given by the Thomson cross-section:

$$\sigma_e = \frac{8\pi}{3} \left( \frac{e^2}{m_e c^2} \right)^2 = 6.65 \times 10^{-25} \text{ cm}^2$$

The resulting *outward* radiation pressure force on a single electron is:

$$F_{\text{rad}} = \frac{L \sigma_e}{4\pi r^2 c}$$
Eddington Limit, cont.

This has to be balanced by the inward force due to gravity of a central point mass $M$:

$$F_{\text{grav}} = \frac{GM(m_p + m_e)}{r^2} \approx \frac{GMm_p}{r^2}$$

We include the proton mass since electrons and protons are coupled electrostatically.

Setting $F_{\text{rad}} = F_{\text{grav}}$, and solving for $L$:

$$L = \frac{4\pi G cm}{\sigma_e} M$$

This is the maximum luminosity which an isotropically emitting source with a mass $M$ could have.

Invert the formula:

$$M_E = 8 \times 10^5 \left( \frac{L}{10^{44} \text{ erg s}^{-1}} \right) M_{\text{sun}}$$

The Eddington Luminosity.