The Physical Properties of Active Galactic Nuclei

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- Ground-Based image of the barred spiral galaxy NGC 4151 (from the Mt. Lemmon Sky Center 32” Schulman Telescope (courtesy of Adam Block)
- Spiral arms can be seen extending from the inner bar.
- Note the bright, compact nucleus.
• Composite Hubble Space Telescope/Wide Field Camera 3 image of the central ~ 10 kpc of NGC 4151. (courtesy of Judy Schmidt).

• Red – UVIS/F814W

• Blue – UVIS/F555W
Composite X-ray, *Chandra* (blue), optical, 1-m Jacobus Kapteyn/La Palma (yellow), radio/HI, NSF/VLA (red), image of NGC 4151
• AGN, specifically Seyfert galaxies, were initially identified on the basis of their optical spectra – emission lines from various elements (H, He, C, N, O etc).

• **But** – there are many other emission line sources in the Universe.

• **NOTE** – it was not certain before the 1920s whether these “nebula” were part of our Milky Way galaxy, or were some other “island universes”?

• Some examples of emission line objects that are **NOT** AGN: planetary nebulae, HII regions, and, on a larger (a galactic) scale, Starburst galaxies.
Planetary nebulae are shells of gas resulting from the loss of the outer layers of post-main sequence stars. The gas is often highly ionized by the exposed stellar core, which radiates like a black body of $T \sim 10^5$ K.

At left is an HST/WFPC2 composite narrow-band image of NGC 2392.

Red – [N II]  
Green – Hβ  
Blue – [O III]  
Violet - He II
High-resolution, ground-based spectra of NGC 2392, revealing a myriad of narrow emission lines (Zhang et al. 2012)

Note: the presence of strong He II 4686 – requires photons with energies > 54.4 eV
HST/WFPC 2 composite image of the H II region N180B in the LMC.

Hα – red
[O II] - blue
As with the Planetary Nebula, there are numerous narrow emission lines present. Also, the presence of the H Paschen series reveals the hydrogen recombination cascade. These lines are detected on a galaxy-wide scales in Starburst Galaxies, like NGC 3310. In that case, there is extensive formation of young stars.
• At right is an HST/WFPC2 composite image of NGC 3310
• Note the bright blue-white emission in the spiral arms.
• The red/yellow emission in the nucleus traces the older stellar population
Early spectroscopic studies identified some "spiral nebulae" with strong emission lines [most galaxy spectra are dominated by stellar continua and stellar absorption features]

NOTES

N.G.C. 221. Spiral with very sharp nucleus. The accuracy of the measurements for this nebula cannot be estimated less than for an average fixed star. The four values of the effective wave-length obtained here for different intensities of image confirm our conclusion that the photographic Purkinje-effect is of quite subordinate importance for relatively "red" objects.

N.G.C. 224. The great nebula in Andromeda. By reason of the sharp nucleus tolerably distinct grating spectra were obtained, and consequently the value of λc is valid for the center of the nebula.

N.G.C. 598. On the plate of 11. 9. 17, exposure 180”, there are very weak spectra of the most luminous part of the nebula (Yerkes Publ., 2, Plate XXV, X = +34°, Y = -28°), but the measurements are very uncertain and have not been adopted in Table III. The plate of 15. 11. 17, exposure 480”, has a strong veil; the spectra are exceedingly faint.

N.G.C. 628. Though this nebula has a sharp nucleus, the time of exposure, 181”, did not suffice to give a measurable image.

N.G.C. 650-651. We have not obtained measurable images with an exposure of 243”.

N.G.C. 1068. According to Fath the spectrum of this nebula shows bright emission lines. The relatively low value of λc obtained here may possibly be explained by the assumption that the center of intensity in the photographic spectrum is displaced toward the value 413 μ, the mean value of λc for the planetary nebulae measured here. In the same way the low wave-lengths obtained for N.G.C. 2903 and 3627 may perhaps be caused by an appearance of bright lines in their spectra.

N.G.C. 1514. This nebula is a very remarkable object. It was classified by Herschel as a planetary, but on Mr. Isaac Roberts’ photographs³ it has been found to have spiral structure. The value of λc shows that very probably we have to do with a planetary nebula.

N.G.C. 2245, 2261, 2245 resembles a star and shows nebulos rays. 2261
In 1943, Carl Seyfert observed several spiral galaxies (including NGC 1068 and NGC 4151), noting their unusually broad emission lines.
• Although one path to identifying AGN is via their optical emission – e.g., Seyfert, AGN were also detected by radio observations
• The first major effort was at Cambridge in the 1950s – CR catalogs – using the Cambridge Interferometer

• 3CR sources: 3C48 and 3C273 – QUASARS

• Optical counterparts found in early 1960s (Sandage & Matthews)

Marten Schmidt – identified emission lines in the optical spectrum of 3C 273 as hydrogen recombination lines with wavelengths shifted by ~15% - set of a long controversy – e.g, Arp, Burbidge, about the “cosmological” nature of the shifts.
• Another form of AGN is Radio Galaxies.
• Faranoff & Riley 1974 – $R_{FR} < 0.5$ FRI, $> 0.5$ FRII
• Jets – 80% of FR Is
• FR IIs, more luminous, cores of jets brighter
• Less clustering around FR IIs

X-ray (Marshall et al., radio (Zhou et al.) and optical (Perlman et al.) imaging of the jet in the nearby FRI radio galaxy M87
Luminous AGN (Quasars) can be powerful radio sources. At right are VLA maps of the luminous quasar 3C273 (Perley & Meisenheimer 2017)
• Other radio-identified AGN are BLAZARS – include BL Lacs (low power) and OVVs (high power) – e.g., Urry (1998).

• "red" BL Lacs – radio selected, "blue" BL Lacs, X-ray selected. Vary most at frequencies higher than where their continua (Spectral Energy Distribution) peaks.

• Exhibit super-luminal motion and jets directed along our line-of-sight
AGN can be divided into " Radio Loud" or " Radio Quiet".  
- $R = f(4440\text{Å})/f(6\text{ cm}) > 10$, for "Loud" (Kellerman et al. 1979)  
- Radio Loud 1000 times more luminous than Quiet  
- ~90% of AGN are radio quiet (e.g. Panessa et al. 2019)
A related phenomenon – luminous Infrared Galaxies (Soifer et al. 1984)

- LIRGS – IR luminosity $10^{11} L_\odot$
- ULIRGS – $10^{12} L_\odot$
- HyLIRGS – $10^{13} L_\odot$

Connection with starbursts (Sanders et al. 2009)
Major mergers of gas-rich spirals – *may* harbor an AGN

HST composite image of II Zw 96

HST/WFPC2 I-band images of LIRGs
Before proceeding, a few physical parameters

- The Luminosity (or power output) of an AGN, integrated over all energies/frequencies/wavelengths is the **Bolometric Luminosity** (we’ll get back to that later).

- The emitted energy spectrum, which can have different physical origins at different energies is a continuum. Generally referred to as the **Spectral Energy Distribution**, or SED.

- Of particular importance are the photons with energies > 13.6 eV. Integrating the Luminosity starting this energy yields the ionizing Luminosity (this can be calculated as photon/sec or ergs/sec)

\[
L = \int_{\nu_0}^{\infty} L_\nu d\nu
\]
As we will discuss, AGN are powered by mass accretion onto a supermassive black hole.

One way to quantify this process is to look at the conversion of mass into energy:

\[ L_{\text{rel}} = \eta \dot{M} c^2 \]

This can be compared to the conversion of gravitational potential energy to radiation:

\[ L_{\text{grav}} = \frac{G M_{\text{bh}} \dot{M}}{r} \]

Generally, \( \eta \approx 0.1 \), which corresponds to an infall radius of several times the Schwarzschild radius.
The emission-line spectra (in AGN or any emission-line sources) include lines from the recombination cascade of H (as shown here) or He.

However, the physical state of the gas, e.g., $T$, depends on the emission from heavy elements, including forbidden transitions, as shown here for [O III].
Seyfert Galaxies

- Relatively nearby \((z < 0.1)\), moderate luminosity \((L_{\text{bol}} \sim 10^{43} - 10^{45} \text{ ergs/sec})\) active galaxies
- Approximately 2\% of Spiral galaxies are Seyfert galaxies – they harbor an “active galactic nucleus”
- Optical and UV Spectra – broad emission-lines, featureless continuum
- Strong X-ray sources (power-law continua)
- Radio “quiet” compared to other AGN, but often show jet-like structure
- IR often dominated by thermal emission from dust
Two classes of Seyfert galaxies:

**Type 1**: broad permitted lines (FWHM ~ several 1000 km/sec); narrower forbidden lines (FWHM < 1000 km/sec); non-stellar continuum

**Type 2**: narrow permitted and forbidden lines; continuum dominated by host galaxy

Optical Spectra of the nearest bright Seyfert 1, NGC 4151, and Seyfert 2, NGC 1068.

Note the broad Hβ 4861 in NGC 4151. The [O III] 4959,5007 is a bit broader in NGC 1068, than NGC 4151.
NGC 4151 in a "low state" (Crenshaw & Kraemer 2007)

The broad line emission is relatively weak, revealing a myriad of narrow lines.

Data are from HST/STIS and span a range from 1200Å to 10000Å
X-ray spectra (of Type 1s) reveal a power law continuum, often absorbed by intervening gas. Both the continuum flux and the absorption can vary on short timescales. Also note the Fe Kα line at ~6.4 keV.
At right, XMM/RGS spectrum of the Seyfert 2 galaxy, NGC 1068

Spitzer IR spectra of several Seyfert 1s
At right is a diagram of the central region of an AGN (according to the Unified model). The central continuum source (c), surrounded by emission-line gas (b), and the dense molecular torus.

Diagram of an AGN (Urry & Padovani 1998), based on the Unified Model.
Before we jump too far into Unified Model classification – one thing missing: **EVOLUTION**

How do AGN get activated?

HST image of merging pair Arp 194

Evidence of minor merger in Seyfert 1 Mrk 509
What powers AGN?

The nucleus (continuum source) is unresolved at spatial resolution of 0.05” - < 1 lyr

Continuum varies on very short timescales (~ hrs)

Only way to efficiently generate radiation is such a small region – mass accretion onto a super massive black hole

Up to 40% of gravitational potential energy can be converted into radiation by an accretion disk around a black hole.
Angular momentum of accreted material causes it to form a disk.

The gravitational potential energy is converted to thermal energy in the disk – thermal radiation.

There is a hot corona above the disk. Mildly relativistic corona electron upscatter disk photons (inverse Compton) producing the X-ray continuum.
Zooming in on NGC 1068
NGC 1068 – HST/WFPC2 Image

blue - stars
red - $\text{H}\alpha$
green - $[\text{O III}]$ (NLR)
NGC 1068: NLR – [O III] Image

continuum “hot spot”

4.0” (290 pc)
NGC 1068: STIS Long-Slit Spectrum (Hβ, [O III])
A bit more about fueling the AGN

Deo et al. 2009: HST images of the inner regions of Seyfert galaxies – bars and stellar rings

Pogge & Martini 2002: HST images revealing dust structure in inner regions of Seyferts
Figure 16. Cartoon interpretation of the AGN feedback process occurring in Mrk 573. Host disk gas initially rotates in the galaxy plane. After the AGN turns on, gas in spiral arms enters the NLR and is ionized. Gas located at small radii (<750 pc) is radiatively accelerated away from the nucleus as outflows. Gas located at larger radii is ionized but not driven away from the nucleus and remains in rotation.
Evidence for large scale mergers, coalescence of Black Holes

Combined HST, SDSS image of the QSO SDSS J0849+1114 (Pfeifle et al. 2019)

Chandra image of the same
The defining physical parameters for AGN activity are Black Hole mass and the mass accretion rate.
Summary Points

- AGN emit strongly across the electromagnetic spectrum
- They are powered by mass accretion onto a supermassive black hole
- There are several possibilities for fueling. Merger, major or minor, or gravitational disturbances within the host galaxy
- The must be some type of evolutionary sequence for AGN activity

We will revisit some of the physics of AGN in the next lectures.