Active Galactic Nuclei

In 1908, Edward Fath (1880-1959) observed NGC 1068 with his spectroscope, which displayed odd (and very strong) emission lines. In 1926 Hubble recorded emission lines of this and two other galaxies. In 1943 Carl K. Seyfert (1911-1960) reported that a small fraction of galaxies have very, very bright nuclei that show broad emission lines produced by atoms in high ionization states.

NGC 1068

[Graph showing emission lines]
Today, such objects are Seyfert galaxies.

Seyfert I galaxies have broad emission lines (1000-5000 km/s)

Seyfert II galaxies have narrow lines (<500 km/s)

NGC 1068 is a Seyfert II
Mrk 1243 - Seyfert I (Osterbrock 1984, QJRAS, 25, 1)
Mrk 1157 - Seyfert II (Osterbrock 1984, QJRAS, 25, 1)
To characterize strength of emission lines, use **Equivalent Width**: 

\[ W_\lambda = \int d\lambda \frac{S_c(\lambda) - S_\lambda(\lambda)}{S_c(\lambda)} \approx \frac{F_{\text{line}}}{S_c(\lambda_0)} \]

Where \( S_\lambda \) is the source flux density, \( S_c \) is the flux density of the continuum, and \( F_{\text{line}} \) is the flux of the line.

*Normally*: convention is that \( W < 0 \) are emission lines, \( W > 0 \) are absorption lines.

Also characterize line in terms of the width \( \Delta \lambda \) at full width at half maximum (FWHM). May be specified in Å or km/s: \( \Delta \lambda / \lambda_0 = \Delta v / c \).
Where $S_l$ is the source flux density, $S_c$ is the flux density of the continuum, and $F_{\text{line}}$ is the flux of the line.

Conventionally $W > 0$ are emission lines, $W < 0$ are absorption lines.

Also characterize line in terms of the width $\Delta \lambda$ at full width at half maximum (FWHM). May be specified in Å or km/s: $\Delta \lambda/\lambda_0 = \Delta v / c$.

Seyfert I’s have emission lines with FWHM~1000 km/s.

Seyfert II’s have emission lines of a few x 100 km/s.

Broad-line Quasars have FWHM ~ 10,000 km/s.
Active Galactic Nuclei

In 1959, Lodewijk Woltjer argued that Seyfert cores were $<100$ pc, else they would be resolved on photographic plates. Therefore, if

$$\frac{GM}{r} \approx v^2$$

then based on the observational fact that $v \sim 1000$ km/s, you can estimate the mass:

$$M(r) > 10^{10} \left( \frac{r}{100 \text{ pc}} \right) M_\odot$$

Enormous Mass concentration in small size.

Three images of Seyfert NGC 4151 at increasing exposure times.
Active Galactic Nuclei

“Mrk” means from the catalog of E. B. Markarian (1913-1985) who produced a catalog of Seyfert galaxies in 1965.

Galaxies known to emit strongly in X-rays are Seyferts (type I’s have more X-rays than type II’s).

Other types of Active Galaxies include radio galaxies, quasars, and blazars.

Radio Galaxies

After WWII, science of radio astronomy took off. First discrete source of radio waves (other than the Sun) was Cygnus A. Below is a VLA image.

Redshift of Cygnus A is $z=0.057$, which from Hubble’s Law gives a distance of 240 Mpc. Brightest radio source is well beyond the Milky Way!

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Radio Jets come from nuclei.

Centaurus A, visual and radio emission

~70 kpc
Radio Galaxies

**FR I**: Fanaroff-Riley Type I (FR I): brightest radio emission close to core, surface brightness decreases outwards. Typically have $L(1.4 \text{ GHz}) < 10^{32} \text{ erg s}^{-1} \text{ Hz}^{-1}$.

**FR II**: Surface brightness increases outwards (like jets and lobes). Luminosity is generally higher than FR I, $L(1.4 \text{ GHz}) > 10^{32} \text{ erg s}^{-1} \text{ Hz}^{-1}$.
Bridle & Perley (1984 ARAA, 22, 319)
Active Galactic Nuclei
Quasars

As radio telescopes increased numbers of sources in late 1950s, astronomers began identifying them in optical images.

In 1960 Thomas Matthews and Allan Sandage found a m=16 mag object matching 3C 48 (3C= “Third Cambridge Catalog” of radio sources) with an emission line spectrum that could not be identified.

Sandage said, “The thing was exceedingly weird”.

In 1963, a similar spectrum was seen in 3C 273.

Optically, they looked like point sources (like stars?!) and not like galaxies.

The became known as **quasi-stellar radio sources = Quasars**.

Later astronomers recognized the emission lines as Balmer Hydrogen lines, but redshifted to incredible velocities, z=0.158 for 3C 273, or \( v \sim cz = 47,000 \) km /s !

3C 48 has z=0.367, or a radial velocity of 0.303 c !
The spectral lines of quasar 3C 273 has $z = 0.158$. This is one of the nearest and brightest quasars (as far as apparent magnitude goes).
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Quasars

Composite spectrum of 718 QSOs
Active Galactic Nuclei

**Active Galactic Nuclei**

**Quasars Luminosities**

Calculate the luminosity of 3C 273. The apparent magnitude is $V=12.8$ mag. The modern day distance for its redshift is 620 Mpc.

$$M_V = V - 5 \log_{10}(d / 10 \text{ pc}) = -26.2 \text{ mag.}$$

Using $M_{\text{Sun}} = +4.82$ for the absolute magnitude, we can estimate 3C273’s visual luminosity:

$$L_V = 100^{(M_{\text{sun}} - M_V)/5} \ L_\odot = 2.6 \times 10^{12} \ L_\odot = 10^{39} \ W.$$}

Bolometric luminosities of Quasars range from $10^{38}$ to $10^{39}$ W, this is more than 100 times the output of a galaxy like the Milky Way!
Currently, Quasars have been identified with redshifts \( z > 6 \)!

Many of these come from the Sloan Digital Sky Survey (SDSS).

Your book quotes that there are 520 quasars with \( z > 4 \). At \( z = 4 \) the recessional velocity is 0.92 \( c \)!

To determine distances at such large redshifts requires geometrical considerations (more on this when we do cosmology).

Effectively, the fractional change in wavelength due to the redshift is the same as the fraction change in the size of the Universe (recall the Universe is expanding!)

\[
z = \frac{\lambda_{\text{obs}} - \lambda_{\text{rest}}}{\lambda_{\text{rest}}} = \frac{R_{\text{obs}} - R_{\text{emitted}}}{R_{\text{emitted}}}
\]

Where \( R_{\text{obs}} \) is the size of the Universe when the photon is observed and \( R_{\text{emitted}} \) is the size of the Universe when the photon was emitted.
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What powers Quasars and AGN?

Most likely candidate is supermassive blackholes accreting material at a substantial fraction of the Eddington Limit.

Quasars are point sources even in HST images, implying the regions emitting the intense luminosity are < 0.1 kpc.

HST studies of QSOs show that they have host galaxies with tell-tale signs of mergers.
Spectra of Active Galactic Nuclei

When AGN were first studied, it was thought their continua followed a power-law:

\[ F_\nu \propto \nu^{-\alpha} \]

where \( F_\nu \) is the monochromatic flux density and \( \alpha \) is the spectral index.

A “flat” spectrum has \( \alpha=0 \).

Historically, AGN had spectral indexes of \( \alpha \approx 1 \), and means that an equal amount of energy is emitted in every logarithmic frequency interval.

The power (luminosity) received within any frequency interval is

\[ L \propto \int_{\nu_1}^{\nu_2} F_\nu \, d\nu = \int_{\nu_1}^{\nu_2} \nu F_\nu \, \frac{d\nu}{\nu} = \ln 10 \int_{\log \nu_1}^{\log \nu_2} \nu F_\nu \, d\log \nu \]
Generically AGN have Spectral Energy Distributions (SEDs) like this figure.
Radio Emission of Active Galactic Nuclei

Synchrotron Radiation:

Electron has energy $E = \gamma m_e c^2$. The characteristic frequency of the emission is

$$\nu_c = \frac{3\gamma^2 eB}{4\pi m_e c} \sim 4.2 \times 10^6 \gamma^2 \left( \frac{B}{1 \text{ G}} \right)$$

Velocity comes in the Lorentz Factor, $\gamma = (1 - v^2/c^2)^{-1/2}$.
Radio Emission of Active Galactic Nuclei

Synchrotron spectrum, \( F_\nu \sim \nu^{-1/3} \)

Electrons become opaque to their own emission, “synchrotron self-absorption”, \( F_\nu \sim \nu^{-5/2} \)
Radio Emission of Active Galactic Nuclei

Electron has energy $E = \gamma m_e c^2$. The characteristic frequency of the emission is

$$\nu_c = \frac{3 \gamma^2 c B}{4 \pi m_e c} \sim 4.2 \times 10^6 \gamma^2 \left( \frac{B}{1 \text{ G}} \right)$$

Velocity comes in the Lorentz Factor,

$$\gamma = \left(1 - \frac{v^2}{c^2}\right)^{-1/2}.$$  

To produce radio emission (at cm wavelengths) in a weak, $B \sim 10^{-4}$ G, field requires $\gamma \sim 10^5$. 

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If the energy distribution of electrons follows a power-law,

\[ N(E) \, dE \sim E^{-s} \, dE, \]

then the Synchrotron radiation spectrum will also be a power law.
Radio Emission of Active Galactic Nuclei

Observed spectra in radio galaxies is $\alpha = 0.7$. This yields an energy distribution of electrons of $N(E) \sim E^{-2.4}$, very similar to cosmic rays in the Milky Way.
Radio Emission of Active Galactic Nuclei

Cooling Timescale for Synchrotron Radiation

The Power is \( P = -\frac{dE}{dt} = \frac{4e^4 B^2 \gamma^2}{9m_e c^3} \)

The time for cooling is \( t = \frac{E}{P} \):

\[
t_{\text{cool}} = \frac{E}{P} = 2.4 \times 10^5 \left( \frac{\gamma}{10^4} \right)^{-1} \left( \frac{B}{1 \text{ G}} \right)^{-2} \text{ yr}
\]

For low-frequency radio emission, this cooling time is longer than age of radio sources.

For high-frequency radio emission, cooling can be considerably shorter than the lifetime of the radio source. Requires a source of particle acceleration not confined to core of galaxy!
Active Galactic Nuclei

- Blazars
- Radio Loud Quasars
- Narrow Line Region
- Radio Loud
- Radio Quiet
- Jet
- Broad Line Radio Galaxies
- Narrow Line Radio Galaxies
- Black Hole
- Accretion Disk
- Obscuring Torus
- Seyfert Galaxies Type 2
- Seyfert Galaxies Type 1
- Radio Quiet Quasars
- Viewing Angle
Active Galactic Nuclei

Magnetic field lines

Disk

Disk

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Active Galactic Nuclei

Outflow

B

Disk

Black hole

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