AGN - Summary

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This summary is based on the book Chapter 28 from Carroll, Bradley W., and Dale A. Ostlie. An Introduction to Modern Astrophysics

1 Active Galaxy (AGN) classification

- **Seyferts:** spiral galaxies with unusually bright emission lines from their cores. Several indications of galaxy interactions which may cause the activity.
  - Type I - very broad emission lines → Doppler broadening → high velocities
  - Type II - narrow emission lines
- **Quasars** - Quasi stellar radio Objects → very far away (high redshift) and very bright → 10^5 times more energetic than a normal galaxy like our own Milky Way.
  - radio loud - more energetic than the radio quite version
  - radio quite - sometimes also called QSO - quasi stellar object. typically less energetic as the radio loud versions
- **radio galaxies** - typically elliptical galaxies at large distances. → several million times more radio energy than is produced by a normal galaxy. Components: core, jets, radio lobes, radio halo. Often associated with galaxy clusters → interactions and mergers. Often also bright in the X-ray, e.g. X-ray halos and jets.
  - BLRG - broad-line radio galaxies
  - NLRG - narrow-line radio galaxies
- **Blazars** - very bright compact objects that occur when the jet is pointing directly towards us, rapid variability and a high degree of linear polarization at visible wavelengths
  - BL Lacs - spectrum shows only a featureless continuum with very weak emission and absorption lines.
  - OVV quasars - optically violently variable quasars, similar to the BL Lacs except that they are typically much more luminous, and their spectra may display broad emission lines
- **ULIRGs** - ultraluminous infrared galaxies → very bright in the infrared → most likely due to a large amount of dust + possible contribution of star formation → indicates galaxy mergers as the origin
- **LINERs** - Low Ionization Nuclear Emission-line Regions, low luminosities in their nuclei, but with strong emission lines of low-ionization species,

1.1 The spectra

The spectral energy distribution (SED) is bright over 10 orders of magnitude in frequency. This wide spectrum is markedly different from the thermal (blackbody) spectrum. Common features: infrared bump → from warm dust, big blue bump → from the accretion disk

spectral index: describes the slope of the low frequency end (radio) of the spectra.

a **synchrotron spectrum** is produced by the combined radiation emitted by individual electrons as they spiral around magnetic field lines. At a transition frequency, the spectrum turns over because the plasma of spiralling electrons becomes opaque to its own synchrotron radiation, known as **synchrotron self-absorption**.

Synchrotron radiation is the electromagnetic radiation emitted when relativistic charged particles are subject to an acceleration perpendicular to their velocity.

1.2 Evidence for AGN evolution

Bright quasars were more common at earlier epochs than they are now. Both the total number of quasars and their luminosities may have been different. A well-defined relationship exists between the mass of a supermassive black hole and the velocity dispersion of the spheroid of a galaxy, suggesting that as the mass of the galaxy grows and the velocity dispersion of its spheroid increases, so does the mass of the central supermassive black hole.

There is evidence, including interactions in observed quasars, suggesting that an individual quasar "event" lasts only for a galactic dynamical timescale → indicates short periods of AGN activity → these are most likely triggered by mergers and interaction.

Short time scale variation → small physical size of the source of the radiation.

2 The Unified model of AGN

Active galactic nuclei are all powered by the same general engine, **accretion onto central supermassive black holes**. Accordingly, the observational differences are due to the different orientations of the objects as viewed from Earth and to the different rates of accretion and masses of the central black holes.

Evidence:
- the H_α luminosity is proportional to the continuum luminsoity → photoionization of hydrogen atoms by the continuum radiation and subsequent recombination
- within some Seyfert 2s are Seyfert 1 nuclei that are hidden from the direct view of Earth by some optically thick material. → orientation of the AGN relative to the line of sight
- upper limit to the luminosity of any spherically symmetric object that is in equilibrium must be less than the **Eddington limit**
- the small timescale of AGN variability → a large amount of mass in a small space is clear evidence for a supermassive black hole

2.1 Accretion

- release of gravitational potential energy through mass accretion → as matter spirals in toward a black hole through an accretion disk, a substantial fraction of the rest energy can be released as viscosity converts kinetic energy into heat and radiation.
- nonrotating black hole → about 7% of the rest-mass energy can be released
- rotating black hole → about 42% of the rest-mass energy can be released
- to produce the brightness of the AGN → an accretion disk around a supermassive black hole is an essential
- Schwarzschild radius increases with increasing mass → disk temperature decreases as the mass of the black hole increases. $T_{disk} \propto M^{-1/4}$
- the temperature peak usually corresponds to radiation in the extreme ultra violet → corresponds to the big blue bump in the spectrum → the accretion disk alone cannot account for the wide continuum emission
- accretion disk spectrum may be sufficient to account for the soft (low-energy) X-rays
- inverse Compton scattering may produce the gamma rays
- Luminous quasars must be fed at a rate of around 1 to 10 $M_\odot yr^{-1}$
- the high luminosities from the accretion disk must have a significant effect on the disk's structure → some models suggest a puffed up inner disk, thinner outer disk, flared edge of the disk

2.2 Relativistic outflows

- ionized disk material is highly conducting → magnetic field that is generated by the accretion disk → accelerating charged particles to relativistic speeds
- the rotation of a black hole in a magnetic field will produce a potential difference between its poles and its equator.
- Blandford-Znajek mechanism
- Up to 9.2% of the rest energy of a maximally rotating black hole may be extracted in this manner.
- Relativisticly accelerated electrons in the magnetic field → Syncrotron radiation

2.3 Broad-line emission

- broad-line region that is relatively close to the centre.
- when the intensity of the continuum radiation varied, most of the broad emission lines responded very quickly
- temperature in the broad-line region is $\sim 10^4 K$
- broad-line region must be clumpy
- optically thick torus of gas and dust surrounds the clouds of the broad-line region → visibility depends on the orientation with the line of sight
- Overall, the light received directly from the central nucleus makes Seyfert 1 galaxies generally brighter than Seyfert 2s.

2.4 Narrow-line emission

- density of electrons in the narrow-line region is comparable to the values found in planetary nebulae and dense H II regions. → can be treated as a clumpy H II region
- temperature of approximately 10^4 K
- clumpy distribution → clouds occupy roughly 2% of the volume of the narrow-line region.
- probably composed of a more or less spherical distribution of clouds.
- The clouds are far enough above or below the plane of the obscuring torus → can be illuminated and photoionized by the continuum radiation from the centre.
- extended blue wings in the spectral lines → perhaps associated with an outflow → could be driven by a combination of radiation pressure and a wind coming from the accretion disk or could be associated with the material in radio jets.
- jets move through the interstellar material, the gas is ionized at a temperature of $\sim 10^7$ K. The overheated gas expands outward away from the jets

2.5 Unified model

- Its central engine is an accretion disk orbiting a rotating, supermassive black hole.
- The AGN is powered by the conversion of gravitational potential energy into synchrotron radiation, although the rotational kinetic energy of the black hole may also serve as an important energy source.
- The structure of the accretion disk depends on the ratio of the accretion luminosity to the Eddington limit. To supply the observed luminosities, the most energetic AGNs must accrete between about 1 and $10_{\odot} yr^{-1}$.
- The perspective of the observer, together with the mass accretion rate and mass of the black hole, largely determines whether the AGN is called a Seyfert 1, a Seyfert 2, a BLRG, a NLRG, or a radio-loud or radio-quiet quasar.
- The unified model does appear to provide an important framework for describing many of the general characteristics of active galaxies.

3 Radio galaxies

3.1 Radio jets

Radio loud AGN typically have: radio core, one or two detectable jets, and two dominant radio lobes. They are also often bright in X-rays.

Radio-quiet sources are less luminous at radio wavelengths by a factor of $10^3 to 10^4$

- radio lobes are produced by jets of charged particles ejected from the central nucleus of the AGN at relativistic speeds.
- powered by the energy of accretion and/or by the extraction of rotational kinetic energy from the black hole via the Blandford-Znajek mechanism.
- The jet must be electrically neutral overall, but it is not clear whether the ejected material consists of electrons and ions or an electron-positron plasma.
- narrowness and straightness of some jets means that a collimating process must be at work very near the central engine powering the jet.
- Two effects that can contribute to the collimation:
  - "centrifugal barrier" there may be a relatively empty cavity that can act as a nozzle, directing the accreting gases outward along the walls of the cavity.
  - magnetohydrodynamic (MHD) effects could play an important role
- The direction of the jet ejection is determined either by the angular momentum axis of the accretion disc or the spin axis of the black hole.
- they radiate in all wavebands from the radio through to the gamma-ray range via the synchrotron and the inverse-Compton scattering process

3.2 Radio lobes

- As a jet of material travels outward, its energy is primarily kinetic energy of the particles.
- As the jet encounters resistance as it moves trough the interstellar medium within the host galaxy and the intergalactic medium → The material is slowed, and a shock front forms

- The accumulation and deceleration of particles at the shock front → particles "splash back" to form a large lobe in which the energy may be shared equally by the kinetic and magnetic energy.
- numerical simulations are required to model the process.
- the lifetime of the radio emission from radio lobes ranges from 10^7 to more than 10^8 years.
- The presence of power-law spectra and a high degree of linear polarization strongly suggest that the energy emitted by the lobes and jets comes from synchrotron radiation.
- loss of energy by synchrotron radiation is unavoidable→ the relativistic electrons in jets will radiate away their energy after just 10^4 years → implies that there must be some mechanism for accelerating particles in the jets and radio lobes.
- shock waves may accelerate charged particles by magnetically squeezing them and radiation pressure may also play a role
- superluminar velocities → projection effect → can be used to estimate the line of sight angle and the velocity of the jet → relativistic motion of the jet

Doppler boosting → an effect of special relativity when the jet is propagating at relativistic speeds at relatively small angles compared to the line of sight towards our direction → one sided jets

Fanaroff-Riley Luminosity classes:
- Class I: distance between the brightest spots of radio emission on either side of the centre (excluding the central source) to the full extent of the radio source is less than 0.5; "core brightened" the inner bit of the jet is the brightest, often curved jets
- Class II: have a ratio greater than 0.5. "edge brightened" with hot spots and straight jets, the overall luminsoty tends to be brighter compared to the class Is

3.3 AGN fuel source

- Seyferts (at least 90%) are spiral galaxies, and many have close neighbours with whom they may be interacting.
- gravitational torques on the gas in a Seyfert galaxy, drastically reducing its angular momentum and sending the gas plunging into the galactic center → feed the black hole + central star formation
- merger with a galactic companion → depending on the mass ratio an elliptical galaxy could be formed → young radio galaxy
- low-redshift quasars show evidence of past interactions
- galaxies are believed to have contained more gas when they were young
- mergers probably resulted in the coalescing of supermassive black holes, producing even larger central engines
- the diminishing fuel supply of an energetic object could lead to its transformation into a less luminous form
- a lesser luminosity could also be explained by a less massive black hole
- low-level galactic activity may be a common occurrence → galaxies could have periodic AGN activity depending on interactions and mergers
- number of luminous AGNs decreases toward the present-day

4 Related phenomena

4.1 Gravitational lensing

- direct consequence of SR
- a gravitational lens could be any object with mass: galaxies, galaxy clusters, stars and planets (micro lensing)
- using a gravitational lens to focus starlight → distant objects appear brighter
- light passing through the curved spacetime surrounding a massive object could produce multiple images of the source.
- gravitational lenses can magnify and increase an object's brightness → the spectrum of the object stays the same
- the outcome of the lensing depends on the geometry of the systems involved and the mass distribution of the lens
  - generally two images will be formed by the gravitational lens.

  - If a quasar or other bright source lies exactly along the line of sight to the lensing mass, then it will be imaged as an **Einstein ring**
  - if the lensing object is an isothermal ellipsoid → can produce either three or five images → **Einstein cross**
  - arcs are produced by light passing through a cluster of galaxies
- gravitational lensing by galaxy clusters indicates a mass-to-light ratio for the cluster of at least 1000 $M_\odot/L_\odot$, indicating the presence of large amounts of dark matter.
- time delay between the brightening of the lensed images. A time delay of about 1.4-1.5 yr has been measured → the time delay is inversely proportional to the Hubble constant → measure the Hubble constant

4.2 Lyman-alpha forrest

In astronomical spectroscopy, the Lyman-alpha forest is a series of absorption lines in the spectra of distant galaxies and quasars arising from the Lyman-alpha electron transition of the neutral hydrogen atom. As the light travels through multiple gas clouds with different redshifts, multiple absorption lines are formed.

Sources of absorption lines in the spectrum of quasars
- Absorption lines from the host galaxy of the quasar.
- The Lyman-α forest is a dense thicket of hydrogen absorption lines. These lines are believed to be formed in intergalactic clouds and display a variety of redshifts. Absorption by primordial ionized helium (He II) has also been detected.
- Lines are also formed by ionized metals, primarily carbon (C IV) and magnesium (Mg II), together with silicon, iron, aluminum, nitrogen, and oxygen. These lines are thought to be formed in the extended halos or disks of galaxies found along the line of sight to the quasar.

Doppler effect can shift ultraviolet lines to visible wavelengths, where the atmosphere is transparent. For this reason, these absorption lines are seen from the ground only in the spectra of highly redshifted quasars.