Active Galactic Nuclei

- **AGN**: nuclei of galaxies with energetic phenomena that cannot clearly and directly attributed to stars
Active Galactic Nuclei

- Luminous UV emission from compact region in the center
- Doppler-broad emission lines
- High variability of days, months time scales
- Non-thermal emission
- Compact Radio Core
- Extended linear radio structures (jets + hotspots)
- X-ray, $\gamma$-ray and (also) TeV emission
- CR production
History of AGN

- Two main classes of AGN:
  - **Seyfert galaxies**: often spiral with $L \approx L_{\text{gal}}$
  - **Quasars**: often elliptical with $L \gtrsim 100 \, L_{\text{gal}}$
History of AGN

- **1908**: Fath & Slipher detect strong emission lines similar to PN with width of $\sim \text{few } \times 100 \text{km/s}$ in NGC 1068
History of AGN: Seyfert galaxies

- Galaxy centers show broad lines
- High-excitation emission lines
- What is the source of broad lines?
History of AGN: First detection of Optical jets

- **1923**: Curtis detected jets in M87
History of AGN: Hubble discovery

- **1926**: Hubble discovers the expansion of the universe → “nebulae” are indeed extra-galactic objects
- **1943**: Seyfert finds multiple galaxies similar to NGC1068 (hence their name)
- **1955**: Detector of radio emission from NGC1068
- **1959**: First insight on Seyfert galaxies (Woltjer):
  - unresolved nuclei (< 100 pc)
  - nuclear emission last for > 10^8 yr (1/100 of spirals are Seyfert and universe is 10^{10} yr old)
  - nuclear mass is high if broadening is caused by bounded material (\( M \approx \frac{v^2 r}{G} \sim 10^9 \, M_\odot \))
Early radio surveys played a crucial role in discovering quasars

- **3C**: third Cambridge catalogue (1959) at 159 MHz (> 9 Jy) → basis for extra-galactic radio astronomy, cosmology and quasars!
- **PKS**: Parkes (Australia) @408 MHz (> 4 Jy) and @1420 MHz (> 1 Jy)
- **4C**: fourth Cambridge (now 8): deeper/smaller
- **AO**: Aricibo Occultation survey

Mostly normal galaxies (i.e. thermal emission of spirals)

“Stars” with strange broad emission lines
Radio Galaxy Emission

- Typical (“normal”) radio emission from a galaxy is due to:
  - synchrotron radiation: $e^-$ and other c-rays moving in the galactic magnetic field - $S \propto \nu^{-0.7/-0.9}$
  - free-free emission from HII regions - $S \propto \nu^{-0.15}$
  - thermal emission from dust heated by stellar radiation - $S \propto B(T)\nu^{1.5}$
History of AGN: Discovery of Quasars

- **3C273**: the 273 source in the 3C catalogue
- Compact radio sources, star like but for a wisp of light
Radio Properties of Quasars

- Although quasars discovered with radio they always are quite faint at radio wavelengths
- Two main components:
  - **Compact**: $< 1''$ with flat spectrum, optically thick and also have clear optical source
  - **Extended**: usually double lobes with steep spectra and optically thin
Large radio-galaxies with lobes can be divided into two types from Fanaroff-Riley (1974):

- **FRI**: weaker radio sources, bright at the center and fainter toward the edges
- **FRII**: collimated jets with hotspots

Transition @ $L_{1.4 \text{GHz}} = 10^{32} \text{ergs/s/Hz}$
Classes of (extended) Radio-Galaxies

- FRI
- FRII

NRAO/AUI
The Zoo of AGN

- Diagnostic via BPT (Baldwin, Phillips & Telervich) diags.
- Why these lines? In general lines are sensitive to different parameters affecting the ISM ($T$, $\rho$, ionizing field, etc.)
  - $[\text{OIII}]/[\text{OII}]$: is sensitive to ionization parameter (i.e. how the gas is ionized)
  - $[\text{OI}]/H_\alpha$: is sensitive to hardness (energy) of radiation field
The Zoo of AGN: Seyfert

- Seyfert type depends on the width of the optical lines
- **Sy2**: narrow emission lines FWHM $\sim$ few $\times$ 100 km/s
- **Sy1**: broad permitted lines (H$\alpha$,HeII,..) of $\delta v \lesssim 10^4$ km/s from high density $n_e > 10^9$ cm$^{-3}$ and narrow forbidden lines ([OIII],[NII]) from low density $n_e \approx 10^3 - 10^6$ cm$^{-3}$
- **Sy1.x(1.9,1.8,..)**: increase with width of H$\alpha$ and H$\beta$ lines
- **NL Sy1**: subclass of Sy2 with X-ray excess and optical Fell emission
The Zoo of AGN: Quasars and QSO

- Quasars: Quasi Stellar Radio sources
- QSO: Quasi Stellar Object
- Scaled version of Seyfert where nucleus is very luminous $M_b < -21.5$
- Often star-like
- Spectra similar to Sy 1 but with weaker NL
- Either Radio-Loud QSOs or Radio-Quiet QSOs with transition at $P_{5\text{GHz}} \approx 10^{24.7}\text{W/Hz/sr}$. RL QSOs are only 5-10% of total QSOs
The Zoo of AGN: BL Lac

- **BL Lac**: is the prototype of its class. Star like with very weak emission lines and variable, intense and polarized continuum. Lines appear during quiescent phases

- **Blazars**: Encompass BL Lacs and optically violent-variable (OVV) QSOs. Strong relativistically beamed jet along the los
Unification Scheme?

- Postulate a standard model for the structure of AGN
- Radio galaxies, quasars, QSOs, Seyfert, BL Lacs are indeed the same type of object → what’s the origin of the difference?
- The angle is everything: viewing angle makes the difference
- Centre of a galaxy is a **Black Hole** surrounded by an **accretion disk**, together with **clouds of gas** and a **dusty torus**
- Energy output comes from accretion of material onto the BH
Unification Scheme!
Standard Model of AGN

- **Accretion disk**: $r \sim 10^{-3}\text{pc}$, $n \sim 10^{15}\text{cm}^{-3}$ and $v \sim 0.3c$
- **Broad Line Region**: $r \sim 0.01 - 0.1\text{pc}$, $n \sim 10^{10}\text{cm}^{-3}$ and $v \sim \text{few} \times 10^3\text{km/s}$
- **Torus**: $r \sim 1 - 100\text{pc}$, $n \sim 10^3 - 10^6\text{cm}^{-3}$
- **Narrow Line Region**: $r \sim 100 - 1000\text{pc}$, $n \sim 10^3 - 10^6\text{cm}^{-3}$ and $v \sim \text{few} \times 100\text{km/s}$
Unification of AGNs

All AGN-type are the same but looked at from a different point of view

<table>
<thead>
<tr>
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<th>Face-on</th>
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<tr>
<td>Radio-Quiet</td>
<td>Sy1</td>
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<td>Quasar</td>
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This idea dates back to, at least, Rowan-Robinson (1977), and became popular in the mid-80s (reviews by Lawrence 1987, Antonucci 1993, Urry & Padovani 1997, Goodrich 2001).
Support to Unification

- BLR near nucleus is obscured by torus in Sy2. Hot scattered $e^-$ from BLR can arrive to observer $\rightarrow$ Sy2 is like Sy1 in polarised light
Support to Unification

- Ionization cones: UV emission comes from the accretion disk and light up a cone of gas away from the torus that absorbs part of it.
- All Seyfert galaxies have a NLR with very similar properties.
Support to Unification

- Direct image of torus
Van der Kruit (1971) discovered a correlation in a Seyfert (AGN) galaxy between luminosity at 10$\mu$m and at 1415 MHz

Extended and verified for “normal” galaxies thanks to the IRAS satellite from which

$$\left( \frac{FIR}{Wm^{-2}} \right) = 1.26 \times 10^{-14} \left( \frac{2.58 \ S_{60\mu m} + S_{100\mu m}}{Jy} \right)$$

total flux $40\mu m < \lambda < 120\mu m$

Define

$$q \equiv \log \left( \frac{FIR}{3.75 \times 10^{12} \ Wm^{-2}} \right) - \log \left( \frac{S_{\nu}}{Wm^{-2}Hz^{-1}} \right)$$

$q \log$ version of ratio: $\sigma_q \approx 0.2$ and $\langle q \rangle = 2.3$ at 1.4 GHz
FIR/Radio Correlation
Cygnus A from VLA @ 2cm
Why Study Radio-Loud AGN?

- Comparison between radio-load AGN and optical AGN samples → origin of radio-loudness
- Some radio and soft X-ray AGN show little or no line emission → include AGN missed from emission-line selection
- Radio activity is an efficient mean of feeding AGN energy directly back into environment (e.g. sound waves) → role of AGN feedback on environment
- Radio galaxies and Radio-loud quasars are the most powerfull radio sources → but radio is a small fraction of the total amount of energy $\sim 10^{-4}$ of optical output
AGN Spectral Energy Distribution

![AGN Spectral Energy Distribution](image)

- Radio
- MIR-NIR
- Optical-UV
- Soft X-ray
- Hard X-ray
- Gamma
- Sub-mm/FIR
- cm/mm
- CM

Log_{10} F_{\nu} (relative)

Log_{10} \nu (Hz)

Accretion disc
Hot corona
Reflection
"Soft excess"
Dusty torus
Non thermal radio

Variable AGN cont.
Radio Loud
Starburst SED
Largely unobservable
Derive SED from radio surveys

- There are several mechanisms acting to contribute to the SED: relativistic $e^{-}$ can lose energy by adiabatic expansion, synch., inverse Compton, etc.
- We already know that $N(E)$ varies with time both for adiabatic expansion (decrease in $L$ but spectrum unchanged) and by radiation.

\[ E = \frac{1.7 \times 10^8}{B^2 t_{1/2}} \rightarrow \nu_{\text{break}} \approx B^{-3} t_{\text{yr}}^{-2} \]

- For $\nu < \nu_{\text{break}}$ spectra index is unchanged.
- For $\nu > \nu_{\text{break}}$ $\rightarrow \alpha = \alpha_0 - 1/2$
Derive SED from radio surveys

- Energy lost affects mainly large scale structures (e.g. lobes)
- Typical $\alpha = 0.7$ for radio lobes

$$t_{1/2} = 1.6 \times 10^3 \left(\frac{B}{\mu G}\right)^{-3/2} \left(\frac{\nu}{\text{GHz}}\right)^{-1/2} \sim 20 - 50 \text{Myr}$$
Self-absorption in the relativistic $e^-$ gas

- **Optically thick case**: consider internal absorption of $e^- \rightarrow T_b$ is close to the kinetics temperature of $e^-$

- Opacity larger at lower $\nu \rightarrow$ plasma opaque at low-$\nu$ and transparent at high

\[ \tau \gg 1 \quad S(\nu) \propto \nu^{-5/2} B^{-1/2} d\Omega \]

- Strong inverted spectrum at low-frequency. Find the frequency at which $\tau \approx 1$

\[ \nu_{\text{max}} \approx S_{\text{max}}^{2/5} \theta^{-4/5} B^{1/5} (1 + z)^{1/5} \]

- Mainly in the central compact region or very small radio sources

- Higher turnover frequency $\rightarrow$ smaller size of emitting region
Self-absorption in the relativistic $e^-$ gas
Polarization

- Synchrotron emission is highly polarized
- For an uniform $B$, the polarization of an ensemble of $e^-$ is linear, normal to $B$ and with fraction

\[
p = \frac{3\alpha + 3}{3\alpha + 7}
\]

- Expected around 70-80% with $2 < \alpha < 4$ but observed up to 20% $\rightarrow$ tangled $B$
Morphology of radio galaxies could be different for several reasons:

- **radio power** probably related to AGN power
- **orientation** of the radio emission
- **intrinsic** differences in the (nuclear regions of) **host galaxy**
- **environment**
Different types of Radio Galaxies
Different types of Radio Galaxies

- Morphology does not depend on size
Different type of Radio Galaxies

- Interaction with environment
Fanaroff-Riley Type I and II

- **FRII**:  
  - high radio power with very bright edges (hot-spots)  
  - collimated jets, $B \parallel$ to jets, high Mach number (supersonic jet)  
  - backflow  
  - steep spectral index from hot-spot to nucleus

- **FRI**:  
  - low radio power  
  - large opening angle jet, $B \perp$ to jets, low Mach number  
  - faint lobes  
  - spectral index steep away from nucleus
Fanaroff-Riley Type I and II

- Reasons for differences are not totally clear; likely related to nuclear region
- Different seen also in other wavebands
- Possible impact from environment: low-power radio galaxies are usually in clusters
- Not only morphological but also physical: strong separation in $M_b - F_{1400}$ plane

![Graph](image)
Source of AGN power

- Main source is accretion onto the central BH
- Before entering matter is heated by friction to high temperatures (X-ray emission)
- BH radius is
  \[ R_S = \frac{2GM_{BH}}{c^2} = \text{few light hours} \]
- Energy available for a mass \( m \) at distance \( R_S \)?
  \[ E_{\text{max}} = \frac{GM_{BH} m}{R_S} = \frac{1}{2} mc^2 \]
- Half the rest energy of the infalling mass is converted into kinetic energy
- If mass is decelerated by friction \( \rightarrow \) KE into thermal energy with efficiency \( \eta \lesssim 0.5 \) (usually \( \eta = 0.1 \))
Source of AGN power

- Since \( L \) is \( dE/dt \) for an AGN we have
  \[
  L = \eta \frac{dm}{dt} c^2
  \]
- The MW has a luminosity of \( 1000L_\odot \rightarrow dm/dt \approx 10^{-9} M_\odot/\text{yr} \)
- If with \( \eta = 0.1 \) we assume \( 1M_\odot \) per year we will have
  \[
  L = \eta \frac{dm}{dt} c^2 = 0.1 \times \frac{2 \times 10^{33}}{3.15 \times 10^7} (3 \times 10^{10})^2 = 1.6 \times 10^{12} L_\odot
  \]
- 100 times brighter than the entire MW
The Eddington limit

- This is the maximum $L$ for a given BH mass
- Two forces in balance:
  - outward flow of photons
  - gravitational force from infall material

$$\frac{du}{dt} = -\frac{\nabla p}{\rho} - \nabla \Phi = 0$$

- If pressure is dominated by radiation with flux $F$

$$-\frac{\nabla p}{\rho} = \frac{k}{c} F$$

where $k = \sigma_T m_p$ is the opacity (for hydrogen)
- If opacity is constant, with Gauss Theorem and Poisson eq.

$$L = \frac{c}{k} \int_S \nabla \Phi \cdot dS = \frac{c}{k} \int_V \nabla^2 \Phi dV = \frac{4\pi Gc}{k} \int_V \rho dV = \frac{4\pi G M c}{k}$$
The Eddington limit

- Subs. the expression for $k$ we obtain

$$L_{Edd} = \frac{4\pi GMm_p c}{\sigma_T} = 3.2 \times 10^4 \left( \frac{M}{M_\odot} \right) L_\odot$$

- Evidence of SMBH found in most galaxies
- Relation between BH $M$ and $M_b$ and $\sigma_e$
Event Horizon Telescope - Location
Event Horizon Telescope - Visibility Function
M87 - GRMHD sims

GRMHD models

SANE, $a_* = -0.94$, $R_{\text{high}} = 80$

SANE, $a_* = 0$, $R_{\text{high}} = 10$

MAD, $a_* = 0.94$, $R_{\text{high}} = 10$

Simulated EHT observations
M87 - Observations

M87* April 11, 2017

50 μas

April 5 April 6 April 10

Brightness Temperature (10^9 K)
Superluminal motion

- Some radio-galaxies, BL Lac and Quasars show evidence of jets (or part of them) apparently moving faster than light.
- Observed in 1970 and was used to move Quasar from cosmological distance: optical illusions plausible within SR.
- They are indeed optical illusions but Quasars are at cosmological distances!
Superluminal motion

- What is important here is the angle between jet and line-of-sight
- The jet is moving with $v \approx c$ along $AB$. At time $t_1$ a ray from the jet starts in $A$ while at $t_2$ another ray starts at $B$. Observing times are $t'_1$ and $t'_2$
- Elapsed time is $\delta t$ so $AB = v\delta t$ and we can find $AC$ and $BC$
- $t'_2 = t_2 + D_L/c$, $t'_1 = t_1 + D_L/c + v\delta t\cos\theta/c$
- $\delta t' = \delta t + v\delta t\cos\theta/c = \delta t (1 - \beta\cos\theta)$
The apparent jet motion is \( BC = D_L \sin \phi \approx D_L \phi \)

But \( D_L \phi = v \delta t \sin \theta \) and the apparent transverse velocity \( v_T \) along \( BC \) is

\[
v_T = \frac{\phi D_L}{\delta t'} = \frac{v \sin \theta}{1 - \beta \cos \theta} \Rightarrow \beta_T = \frac{v_T}{c} = \frac{\beta \sin \theta}{1 - \beta \cos \theta}
\]
Superluminal motion

- Find angle $\theta$ for maximum $\beta_T$

\[
\frac{\partial \beta_T}{\partial \theta} = 0 \Rightarrow \cos \theta_{\text{max}} = \beta \quad \sin \theta_{\text{max}} = \sqrt{1 - \beta^2} = \frac{1}{\gamma} \Rightarrow \beta_{T_{\text{max}}} = \beta \gamma
\]

- Therefore for $\gamma \gg 1$ - the jet is moving with $v \approx c$ - even if $\beta < 1$ one can get $\beta_{T_{\text{max}}} > 1$ and hence superluminal motion since $v_T$ is the only velocity we can measure.