Active Galactic Nuclei

- Many Galaxies, especially younger ones (far away), have extremely bright center (nucleus); can vary over ≈ few days
  - Seyfert Galaxies (typically spiral):
    - Bright nucleus with **emission** lines (instead of absorption as normal)
    - Doppler broadening (Seyfert I), lots of X-rays
    - continuum spectrum (central source) brighter than rest of galaxy
    - (radio loud/quiet - UV, X-ray) from extremely hot center
  - Radio Galaxies:
    - Emission mostly at 10 cm; have jets and “radio lobes”
    - Example: Cygnus A (240 Mpc) brighter in radio spectrum than all but sun and 1 nearby supernova remnant (\(5 \times 10^{37} \text{ W} = 10^{11} \text{ suns!}\))
AGN NGC3079 taken in H\textalpha{} (Balmer series, \(\lambda =656.28\) nm) filter. Picture courtesy Josh Frechem ©
Quasars

- **Quasars (quasi-stellar radio sources)**
  - Detected in the 60’s:
    - Very strongly red-shifted (30-95% c) => far away (?) (100-1000 Mpc)
    - Extremely bright (10^{12-14} suns, up to 10^5 Milky Ways), broad spectra
    - appear star-like in telescope (since nuclei outshine whole galaxy by huge factor)
    - Vary within days/hours - cannot be large (causality argument)
  - initial controversy: Redshift-distance relationship wrong?
  - View now: Early stages of most galaxies, powered by accretion
Engine for all these AGNs: Supermassive Black Holes

• Size:
  – Cannot be much larger than $t_{\text{var}} \times c$ (illuminated sphere) $\Rightarrow$ 1 hr implies 7 AU

• Mass: Eddington limit
  – Energy flux density: $F = \frac{L}{4\pi r^2}$  
    Momentum Flux: $F_p = \frac{L/c}{4\pi r^2}$
  
  – Radiation Force on electrons: $F_{r.p.} = \frac{L}{4\pi r^2 c} \sigma_e$  
    $\kappa = \frac{1}{m_H / \sigma_e}$
  – ...must be < grav. force on proton (attached to e- in plasma): $F_{\text{grav}} = \frac{GMm_p}{r^2}$

  $\Rightarrow$ yields max. Lumi: $L_E = \frac{4\pi GMc}{\bar{K}} = \frac{4\pi GMm_p c}{\sigma_e} = 3.3 - 3.8 \times 10^4 L_{\text{sun}} \frac{M}{M_{\text{sun}}}$
  – $\Rightarrow M > 3 \times 10^8 M_{\text{sun}}$ for $10^{13} L_{\text{sun}}$
  – Schwarzschild radius $9 \times 10^8 \text{ km} = 6 \text{ A.U.} \Rightarrow$ Consistent!
Luminosity via Accretion

• Straight-line infall - mass-energy disappears and simply makes black hole bigger (\(\text{\footnotesize{\textbullet}}\))
• Accretion disk (rotating) - lots of gas, “friction” \(\Rightarrow\) most of gravitational energy change converted into heat \(\Rightarrow\) luminosity
• Non-rotating BH \(\Rightarrow\) smallest orbit = \(3R_S\), expect grav. binding energy = \(1/6 \ mc^2\) but in fact only 5.7% available (= efficiency)
• Rotating BH \(\Rightarrow\) can get up to 42% (some energy rotational)
• Assume efficiency \(\eta = 10\%\) on average
• \(\text{\large{\text{\footnotesize{\textbullet}}}}\) \(L = \eta \ dM/dt \ c^2\)
• \(\Rightarrow\) \(dM/dt = 7 \ M_{\text{sun}}/\text{yr}\) for \(L = 10^{13} \ L_{\text{sun}}\)
  – Compare nuclear: \(\eta = 0.7\%\) \(\Rightarrow\) req. \(10^{11} \ M_{\text{sun}}\) in 1 B years
• Maybe explains history: after a few\(10^9\) yrs, BH creates maximum \(L\); later it runs out of fuel - see later…
Observed Properties of Jets and the Angle to the Line of Sight $\theta$

<table>
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<th>Host Galaxy</th>
<th>AGN</th>
<th>Angle</th>
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AGN NGC 4151
Iron Blowing in Quasar Winds

Brightness vs. Energy (kiloelectron volts)

- NuSTAR
- XMM-Newton

Iron Emission
Iron Absorption
Galactic Evolution

- Looking at far-away galaxies we see young galaxies (as they were a long time ago)
  - Example: Quasar with redshift $z = 6.4$ (meaning $\frac{\lambda_{\text{obs}}}{\lambda_{\text{em}}} = 7.4$) $\Rightarrow$ light we see was emitted when Universe was only 2 Gyr old
    - at that time, quasar was 3.7 Gyr·c away
    - Now it’s 27 Gyr·c away
  - Luminosity requires accretion of 200 $M_{\text{sun}}$/yr
  - Do that for 10 Gyr $\Rightarrow$ $2 \times 10^{12}$ $M_{\text{sun}}$! No black holes that large have ever been seen (plus where should that mass come from?)
  - Back then, 1 in 1000 galaxies was a quasar
  - Today: 1 in $10^6$ galaxies is a quasar
  - Possible reasons:
    - fuel is all gobbled up or blown away, BHs still around but “hibernating”
    - Much more food around in the past: colliding galaxies (higher density)
Galactic Evolution II

- General observation: Oldest stars only a few Gyr younger than Universe, most in galaxies
- Most elliptical galaxies (and bulges) probably were formed after 3 Gyr (did the disks come later?)
  - Possible precursors: “weirdly shaped” irregulars that later merged (see Hubble Deep Sky survey)
- Initially high star forming activity, many giants -> relatively high luminosity, blue color
- Later smaller stars dominate, more reddish color
- Spiral galaxies: continue to make new stars - plenty of gas left
- Elliptic galaxies: May have used up their gas quickly; due to larger initial density fluctuation?
  - or because of wind from central BH? or are they due to collisions
- Summary: Evolution is complicated and not yet fully understood
  - collisions in the early Universe play a big role!