Galaxy formation and evolution
PAP 318, 5 op, autumn 2020

on Zoom

Lecture 13: Formation of active galaxies – Additional notes, 04/12/2020

Lecture 13 additional notes I

- Page 8: Eddington luminosity:
- Radiation pressure force acting on the electrons:

$$F_{\rm rad} = \sigma_T P_{\rm rad}(r) n_e(r) = \frac{L\sigma_T n_e}{4\pi r^2 c}$$

- Gravitational force acting primarily on the protons:

$$F_{\rm grav} = \frac{GM_{\rm BH}\rho(r)}{r^2} = \frac{GM_{\rm BH} m_p n_e}{r^2}$$

- Eddington luminosity: $F_{\rm rad} = F_{\rm grav} \Rightarrow \frac{L\sigma_T n_e}{4\pi r^2 c} = \frac{GM_{\rm BH} m_p n_e}{r^2}$

$$L_{\rm edd} = \frac{4\pi G c m_p}{\sigma_T} M_{\rm BH} \approx 1.28 \times 10^{46} \left(\frac{M_{\rm BH}}{10^8 M_\odot}\right) \ {\rm ergs}^{-1}$$

Lecture 13 additional notes II

- Page 9: The central engine: The efficiency ε is defined as the fraction of the rest-mass energy that can be converted to energy (i.e. by definition ε<1). For normal Hydrogen to helium fusion in stars ε=0.007, whereas the maximum for accreting black holes is ε=0.42 (maximally rotating black hole and the material accreted with opposite angular momentum). The mean efficiency for black hole accretion is ε=0.1, which is still two orders of magnitude higher than fusion in stars.

- Page 10: Accretion discs: The topic of accretion discs is quite complex and an entire course could be devoted to this topic. Here the aim is to just understand the basic reason for why we have accretion discs (conservation of angular momentum in cooling gas) and the temperature structure (highest temperatures closest to the black hole).

Lecture 13 additional notes III

- Page 11: Continuum emission: The brightness temperature can be used as a proxy for what the temperature of the emitting source would be if it was in thermal equilibrium, i.e. emitting as a Black-body. The extremely high brightness temperatures ($T_b \sim 10^{11}$ K) of AGNs and the lack of strong gamma-ray radiation (expected for a Black-body at this temperature) clearly indicates that the emission mechanism is **non-thermal**.

- Page 12: Synchrotron emission: Highly relativistic electrons in strong magnetic fields emit synchrotron emission, which is often the main emission mechanism for AGNs (more details on the High Energy Astrophysics course, Spring 2021).

Lecture 13 additional notes IV

- Page 13: Inverse-Compton emission: The power of inverse-Compton emission exceeds that of synchrotron emission if $T_b > 10^{12}$ K. When this occurs, the cooling of the electrons by radiation is catastrophic, because the inverse-Compton photons can themselves be scattered by the relativistic electrons, enhancing the inverse-Compton emission power even further. Thus, the brightness temperature of the synchrotron emission must in general be below 10^{12} K in order for the electrons to remain relativistic.

- Page 14: Emission lines: Permitted lines have large transition probabilities, i.e. large A_{21}.Forbidden lines have very small transition probabilities, i.e. small A_{21}.

Lecture 13 additional notes V

- Page 14: Emission lines: Produced by spontaneous emission:

$$\mathcal{L}_c = n_2 A_{21} h_P \nu_{12} = \frac{n_e n_1 P_{12} h_P \nu_{12}}{1 + n_e P_{21}/A_{21}}$$

$$\mathcal{L}_\mathrm{c} = \begin{cases} n_\mathrm{e} n_1 P_{12} h_\mathrm{P} \nu_{12} & (\text{if } A_{21} \gg n_\mathrm{e} P_{21}) \\ n_1 \left(P_{12}/P_{21} \right) A_{21} h_\mathrm{P} \nu_{12} & (\text{if } A_{21} \ll n_\mathrm{e} P_{21}). \end{cases}$$

- Page 14: In low density regions where $n_e << A_{21}/P_{21}$, L_c is independent of A_{21} and so both the forbidden and permitted lines can be produced with significant strengths. On the other hand, in high density regions where $n_e >> A_{21}/P_{21}$ for the forbidden line but not for the permitted line, the strength of the forbidden line is reduced by a factor of $A_{21}/(n_e P_{21})$.

Lecture 13 additional notes VI

- Page 16: Emission line regions: Broad-line regions:

$$\frac{GM}{R^2} = \frac{V^2}{R}, \Rightarrow R \sim \frac{GM}{V^2}, \Rightarrow R \sim \frac{GM}{\sigma_v^2}$$

- Page 19: Formation of AGNs:

$$\dot{M}_{\rm BH} = \frac{L}{\epsilon_r c^2} = \left(\frac{L}{L_{\rm edd}}\right)\frac{M_{\rm BH}}{\epsilon_r t_{\rm edd}} \quad t_{\rm Edd} = \frac{\sigma_T c}{4\pi G m_p} \approx 4.4\times 10^8\ {\rm yr}$$

$$L_{\rm edd} = \frac{4\pi G M_{\rm BH} m_p}{\sigma_T}$$

$$t_{\rm BH} = (L/L_{\rm edd})^{-1}\epsilon_r t_{\rm edd} \approx 4.4\times 10^7(\epsilon_r/0.1)(L/L_{\rm edd})^{-1}\ {\rm yr}$$

- Page 19: If L/L_{edd} and ε_r are independent of time:

$$\frac{dM_{\rm BH}}{M_{\rm BH}} = \left(\frac{L}{L_{\rm edd}}\right)\frac{dt}{\epsilon_r t_{\rm edd}} \quad \Rightarrow M_{\rm BH}(t) = M_{\rm BH,0}\,e^{t/t_{\rm BH}}$$

Lecture 13 additional notes VII

- Page 23: AGN and galaxy formation:

$$\frac{dE}{dt} = \epsilon \dot{M}_{\rm BH} c^2, \quad E = \bar{\epsilon} M_{\rm BH} c^2$$

- Page 23: Virial equilibrium: W=-2T, i.e. the potential energy=2xkinetic energy:

$$\frac{E}{|W|} \sim \frac{\bar{\epsilon} M_{\rm BH}}{M_{\rm gal}} \left(\frac{c}{\sigma}\right)^2$$