Outline

- Go over problems 5-1, 5-2

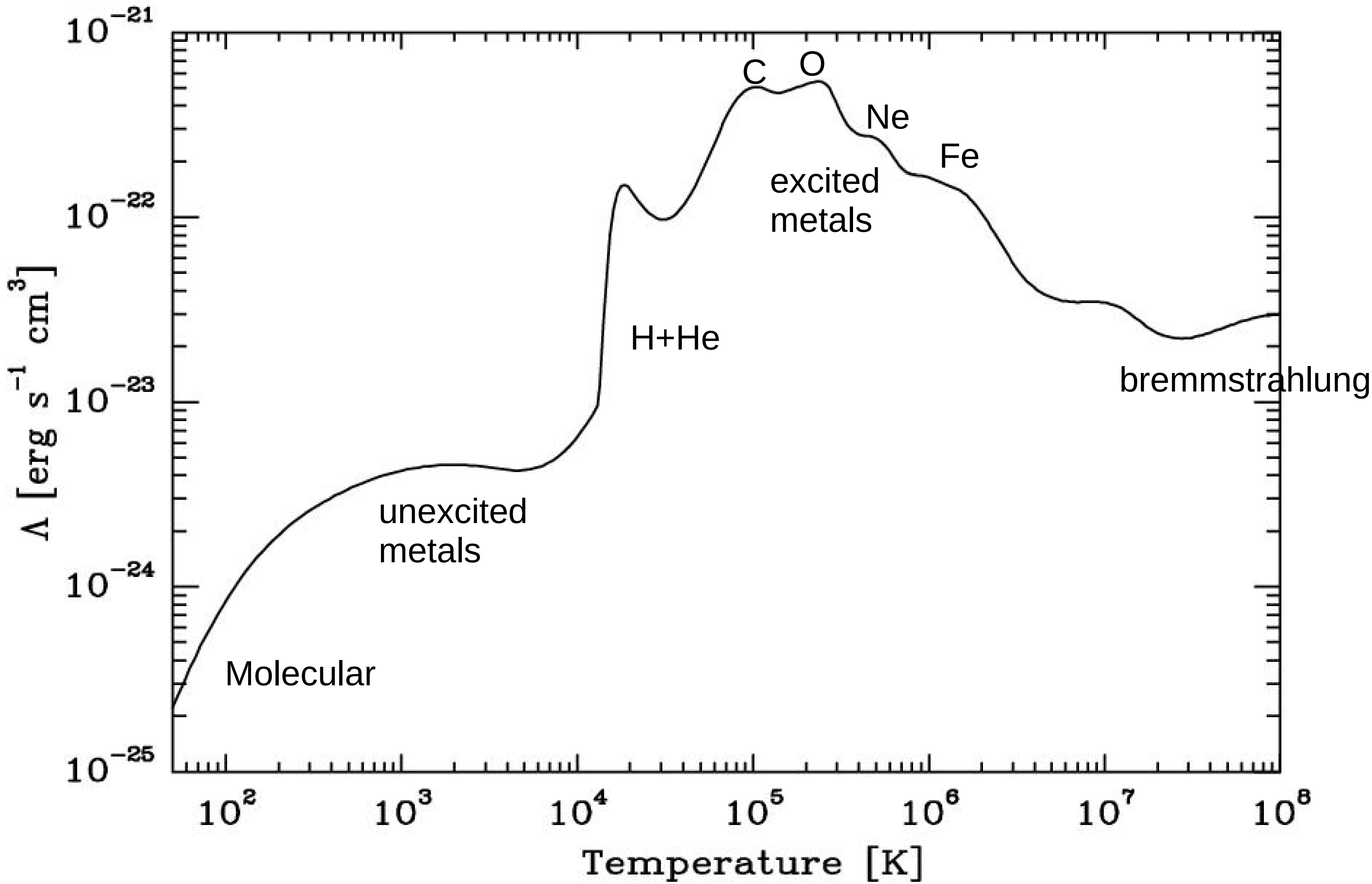
- Gas heating and cooling
- Critical density
- Emission from HII regions
- Measuring temperature with spectral lines

Gas Cooling

- "Cooling" = energy loss from a system.
- Cooling occurs via radiation of photons:
  - $< 10^3$ K → molecular line emission
  - $10^3 – 10^4$ K → optical lines of neutral and low-ionization metals
  - $10^4 – 10^5$ K → H and He recombination
  - $10^5 – 10^6$ K → UV and X-ray lines of high-ionization metals
  - $> 10^7$ K → bremmstrahlung (free-free) emission

- "Cooling" does not necessarily mean a decrease in temperature or the kinetic energy of the gas, since cooling can mainly represent release of energy via recombination.
- Cooling function = rate of energy loss per unit volume as a function of temperature of gas. Depends on metallicity and gas excitation mechanism (collisional versus photoionization).

Cooling Function

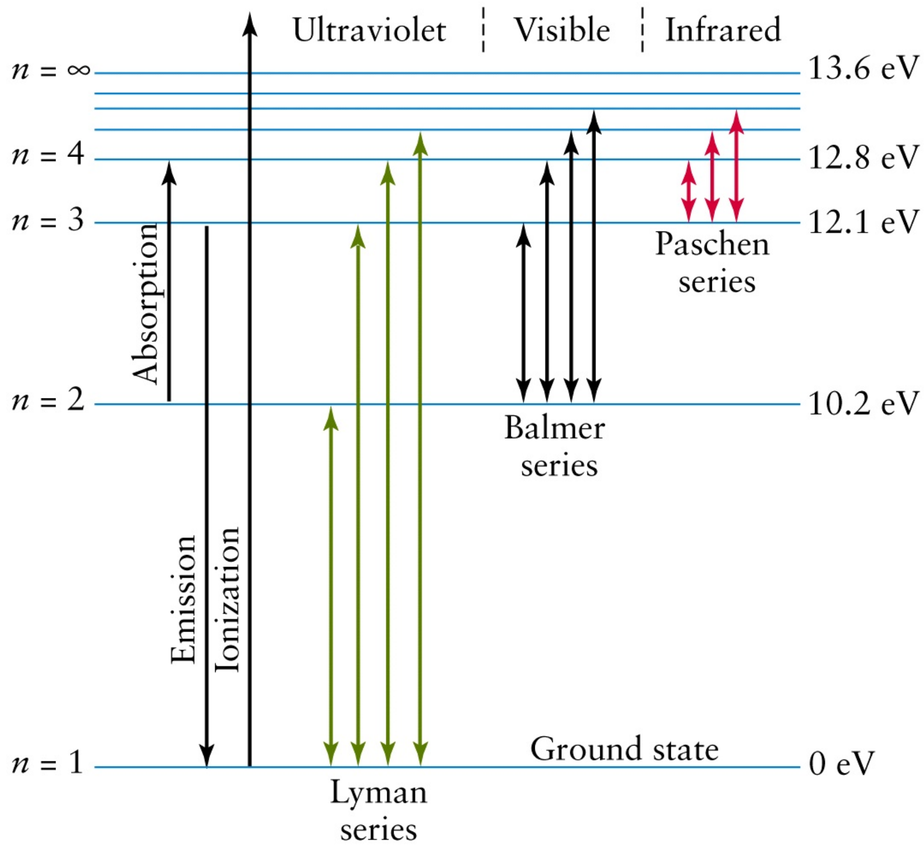


Boltzmann factor

- Consider two energy levels of an atom or ion.
- Number density in level 1 = n_1, in level 2 = n_2. Also called population of a level.
- Statistical weight = g_i = number of distinct quantum states of an energy level, e.g. due to electron spin or orbital angular momentum.
- Boltzmann factor gives ratio of populations:

$$\frac{n_2}{n_1} = \frac{g_2}{g_1} e^{-\Delta E/kT}$$

- To produce photons hν = ΔE, need hν ~ kT
- E.g. for T ~ 20,000 K, kT ~ 2 eV, Balmer emission is strongest



Critical Density

- Two levels, gas loses energy by line emission
  - Rate = $R_{21,\mathrm{rad}} = n_2\, A_{21}$ where A_{21} = spontaneous Einstein coefficient
  - A_{21} = 1/(mean life time for decay $2 \rightarrow 1$).
- Gas is excited by collisions of electrons with ions
  - Rate = $R_{12,\mathrm{coll}} = n_\mathrm{e}\, n_1\, q_{12}$ where q_{12} = collisional excitation coefficient
  - $q = q(T) = \langle \sigma v \rangle$ is like recombination coefficient $\alpha(T)$, units = cm^3 s^{-1}
  - Note $n = n_1 + n_2$, so $R_{12,\mathrm{coll}} = n_\mathrm{e}\,(n - n_2)\, q_{12}$
- Also have collisional de-excitations
  - Rate = $R_{21,\mathrm{coll}} = n_\mathrm{e}\, n_2\, q_{21}$
- In equilibrium, $R_{12,\mathrm{coll}} = R_{21,\mathrm{coll}} + R_{21,\mathrm{rad}}$

$$n_e(n-n_2)\,q_{12} = n_2\, n_e\, q_{21} + n_2\, A_{21} \;\rightarrow\; n_2 = \frac{n_e\, n\, q_{12}}{n_e(q_{21}+q_{12}) + A_{21}}$$

Critical Density

- Luminosity in the line emission (per unit volume) is
  - $L_{21} = n_2 A_{21} h\nu$

$$L_{21} = \frac{n_e n q_{12} A_{21} h\nu}{n_e(q_{21}+q_{12})+A_{21}} = \frac{n_e n q_{12} h\nu}{(1+q_{12}/q_{21})n_e/n_{crit}+1}$$

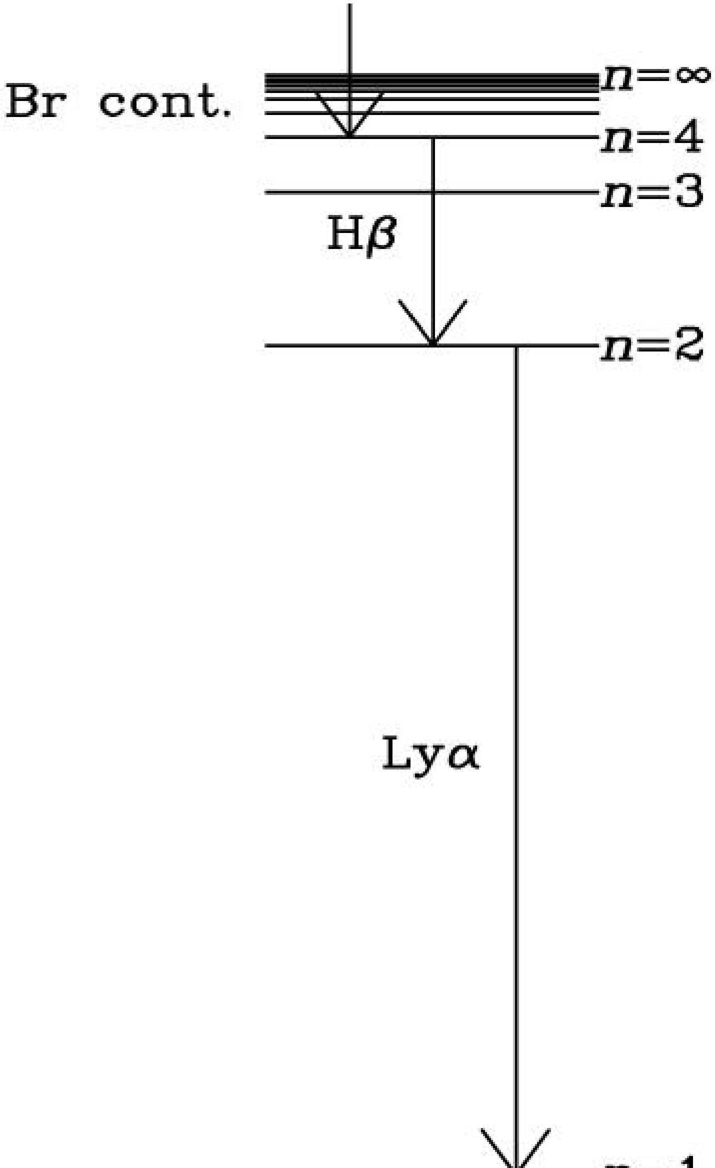
where $n_{\mathrm{crit}} = A_{21}/q_{21}$

- Note $\mathrm{R}_{21,\mathrm{rad}} = n_2 A_{21}$ and $\mathrm{R}_{21,\mathrm{coll}} = n_\mathrm{e}\, n_2\, q_{21}$,
  - so $\mathrm{R}_{21,\mathrm{rad}} / \mathrm{R}_{21,\mathrm{coll}} = n_2 A_{21} / n_\mathrm{e}\, n_2\, q_{21} = A_{21} / n_\mathrm{e}\, q_{21}$
  - set $\mathrm{R}_{21,\mathrm{rad}} / \mathrm{R}_{21,\mathrm{coll}} = 1$ and find $n_\mathrm{e} = n_\mathrm{crit} = A_{21} / q_{21}$
  - density where radiative and collisional deexcitation have same rate

Critical Density

- Look at q_{12} / q_{21} , consider case with no radiative decay
- In equilibrium $R_{21,coll} = n_e\, n_2\, q_{21} = R_{12,coll} = n_e\, n_1\, q_{12}$, so $q_{12} / q_{21} = n_2 / n_1$
- use Boltzmann factor $$\frac{q_{12}}{q_{21}} = \frac{n_2}{n_1} = \frac{g_2}{g_1} e^{-\Delta E/kT} \lesssim 1$$
- Back to line luminosity $$L_{21} = \frac{n_e n q_{12} h\nu}{(1+q_{12}/q_{21}) n_e/n_{crit}+1}$$
- For $n_e << n_{crit}$ find $L_{21} \propto n_e\, n \propto n^2$
- For $n_e >> n_{crit}$ find $L_{21} \propto n$
- For hydrogen recombination and bremsstrahlung, $L \propto n^2$
- Thus hydrogen recombination and bremsstrahlung dominate at high n.

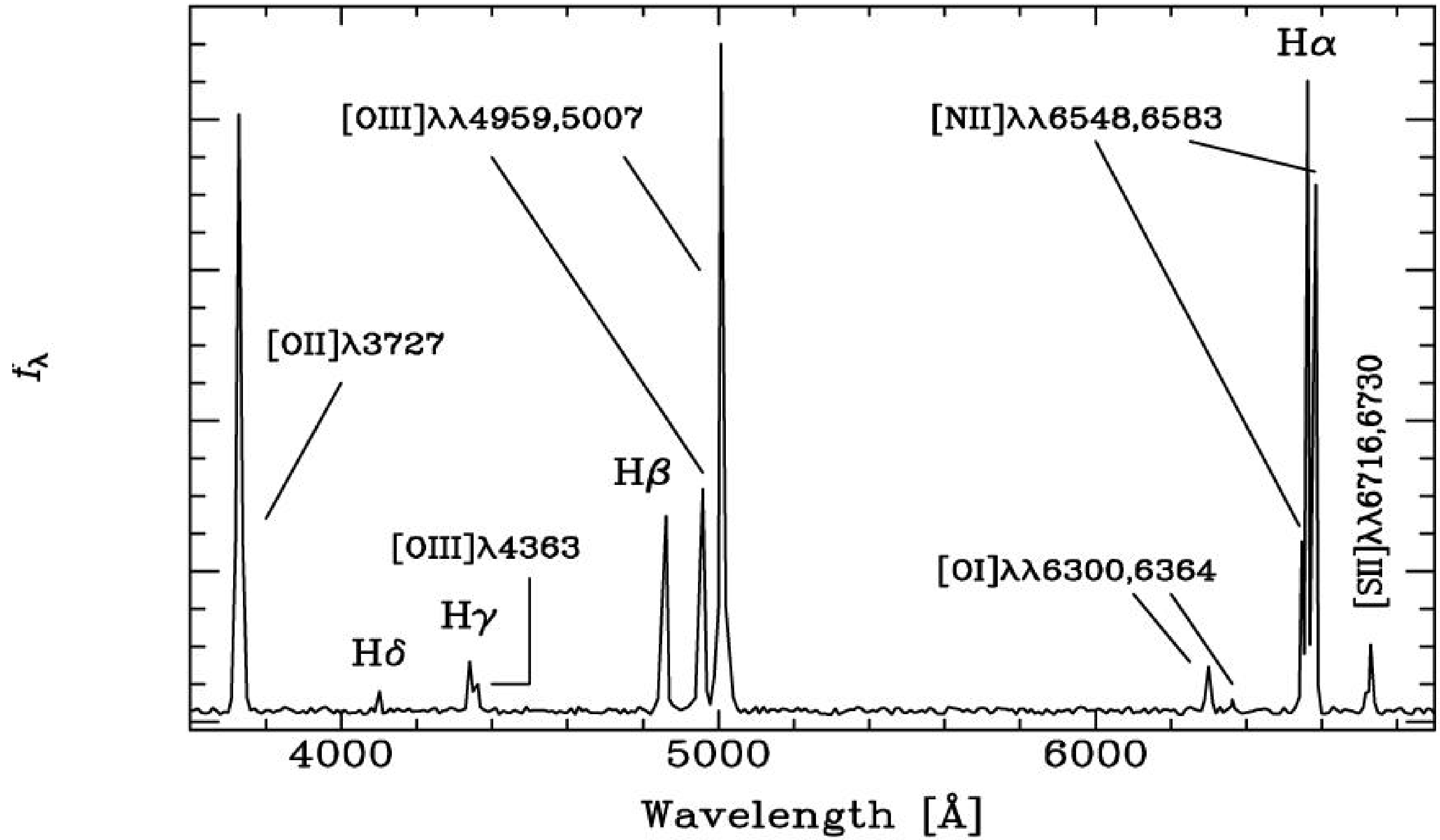
H II regions



- Photons $E > 13.6$ eV can ionize H
  - ionization σ is high, $\sigma \sim 6.3\times10^{-18}$ cm^2
  - photons are absorbed $r < r_{strom}$
- Photons $E < 13.6$ eV cannot ionize H
  - interact with free electrons (Thomson)
  - $\sigma = 6.7\times10^{-25}$ cm^2 is low
  - mean free path $l \sim 1/n\sigma \sim$ 50 pc $> r_{strom}$
- Emitted spectrum is *not* blackbody
  - high *E* photons absorbed, then re-emitted in cascade ending with Lyman α
  - low E photons escape
  - Lyman α random walks to edge of region
  - photons from metals also escape
- Gas inside *is* in thermal equilibrium with itself, but not with radiation.

Oxygen Line Emission

- For [O III], critical density ~ 10^6 cm^{-3}.
- Density is sufficiently low that [O III] lines had never been seen in a laboratory before they were found astronomically, initial conclusion was existence of a new element "nebulium".
- At low densities, [O III] is a dominant cooling mechanism.



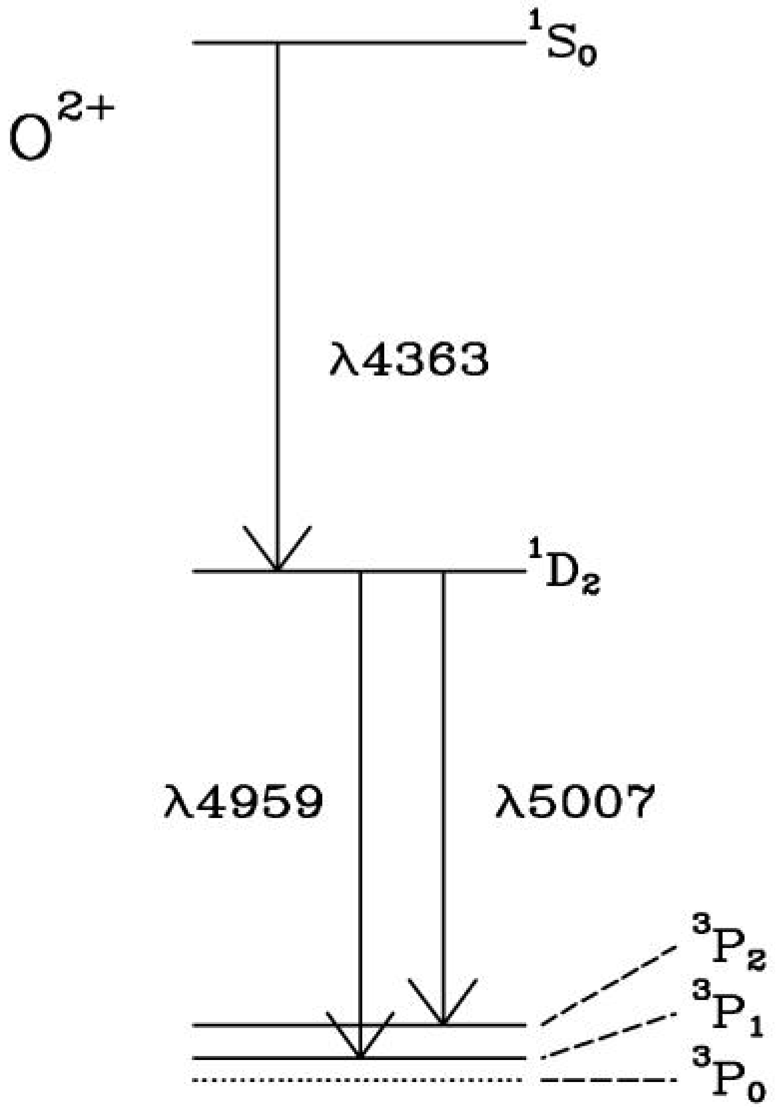
Measuring the Temperature

- Luminosity in λ4363 line $\propto n(^1S_0)$
- $L(\lambda4959)+L(\lambda5007) \propto n(^1D_2)$
- Boltzmann factor

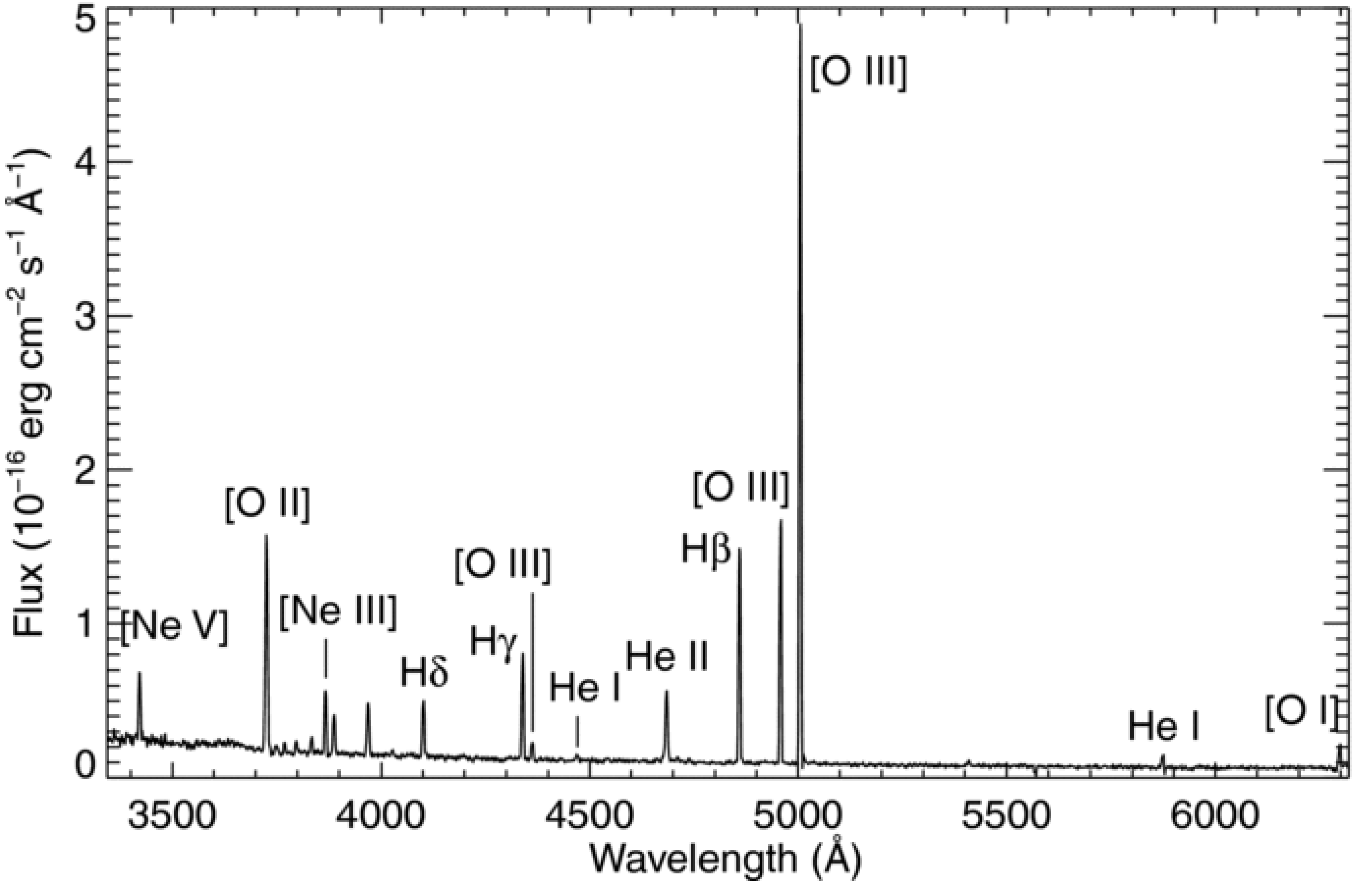
$$\frac{n_S}{n_D} = \frac{g_S}{g_D} e^{-\Delta E/kT}$$

- Can determine $n(^1S_0)$ and $n(^1D_2)$ from L(λ4363) and L(λ4959)+L(λ5007) with corrections for Einstein coefficients and statistical weights. In low *n* limit, find

$$\frac{L_{\lambda 4959}+L_{\lambda 5007}}{L_{\lambda 4363}} = \frac{7.90\exp\left(3.29\times10^4\,T\right)}{1+4.5\times10^{-4}\,n_e/T^{1/2}}$$



Measuring the Temperature



$$\frac{L_{\lambda\,4959}+L_{\lambda\,5007}}{L_{\lambda\,4363}} = 53 \pm 7 \;\rightarrow\; T \approx 17{,}000\,\mathrm{K}$$

- Spectrum of HeIII region surrounding an X-ray binary in the galaxy NGC 5408 (Kaaret & Corbel 2009).

Homework

- For next class:
  - Problem 5-3