Interstellar medium for dummies

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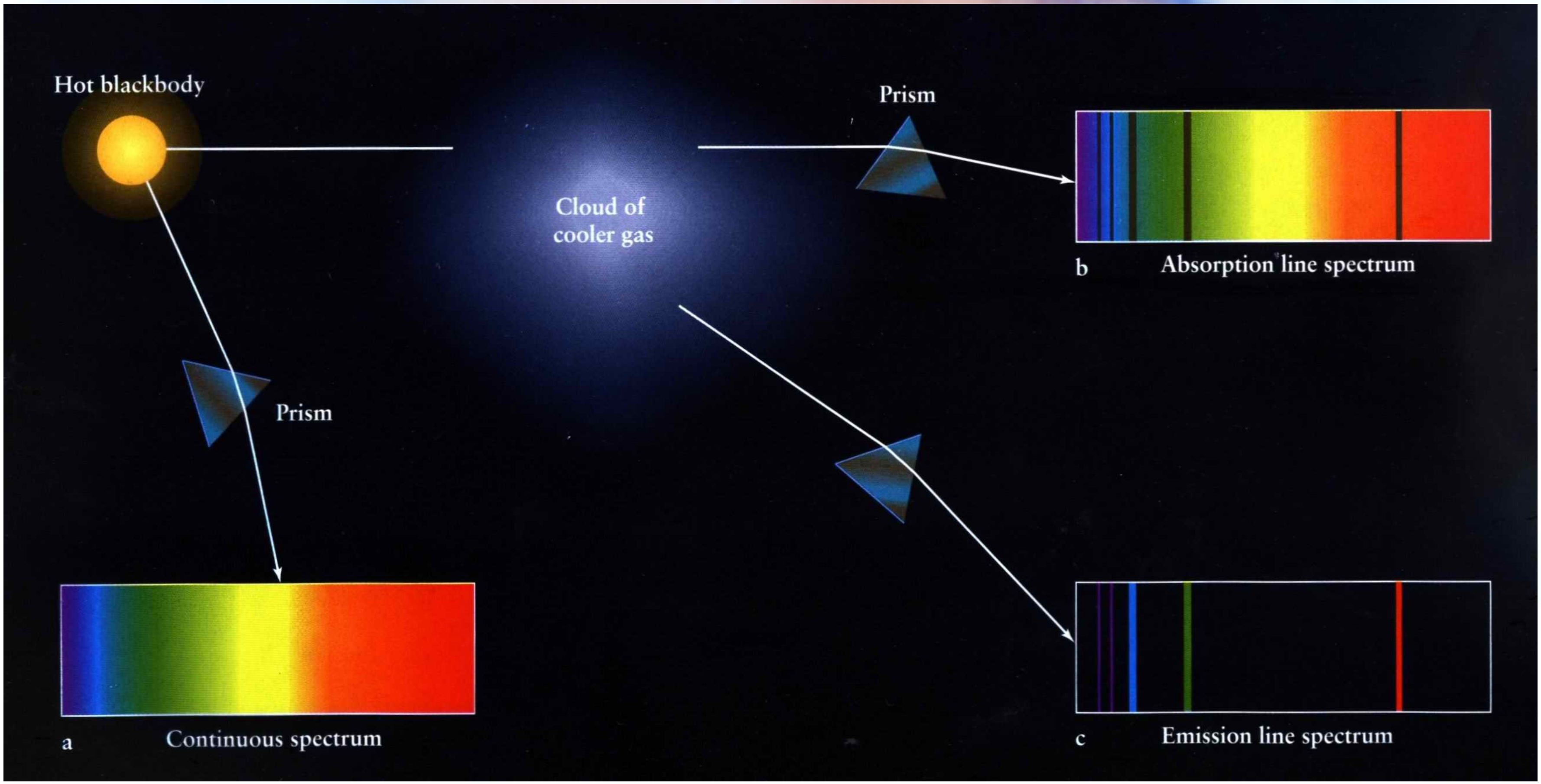
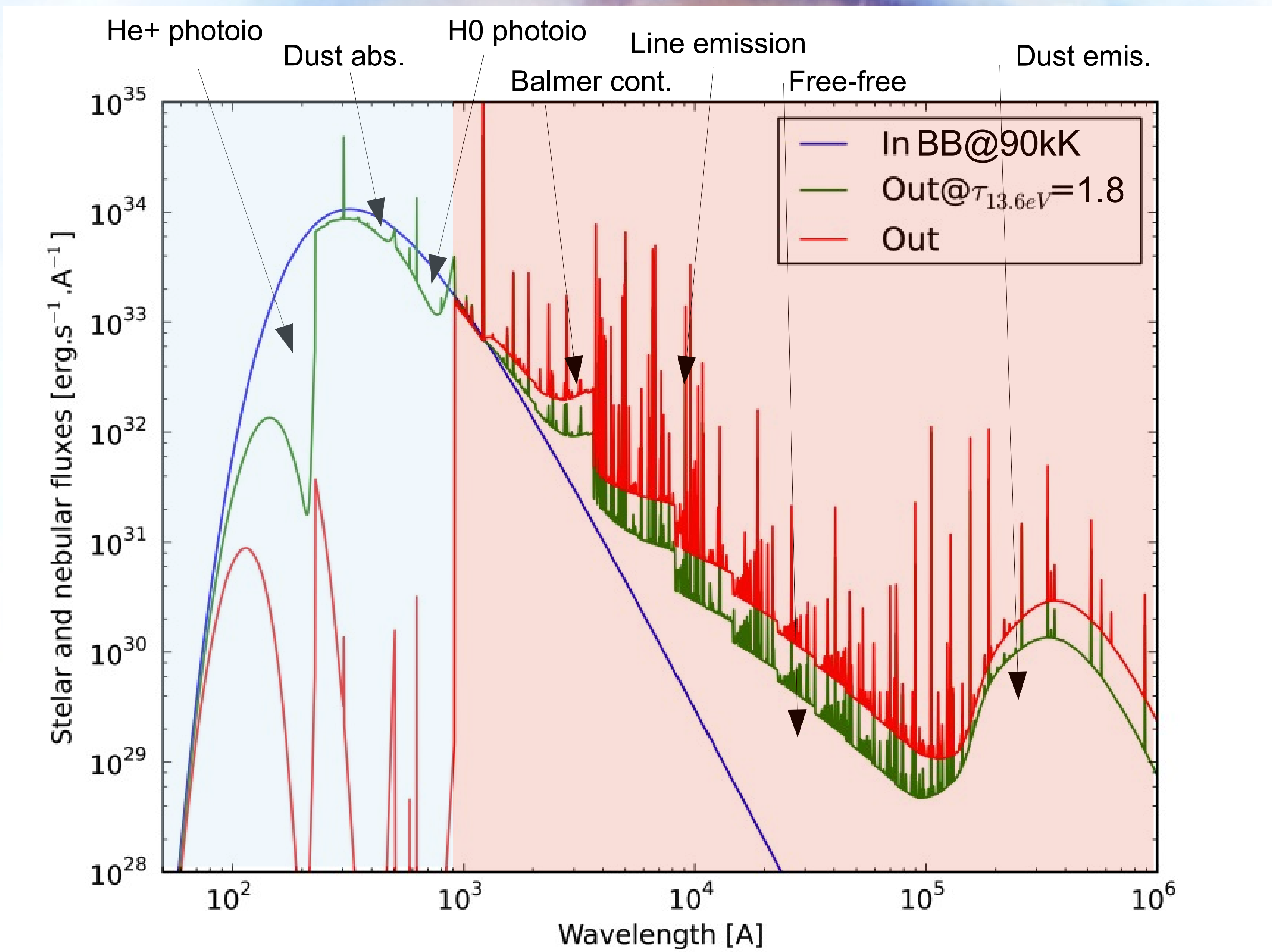
Summary

- Introduction
- Emission processes
- Line emissivities
- PyNeb
- Atomic data

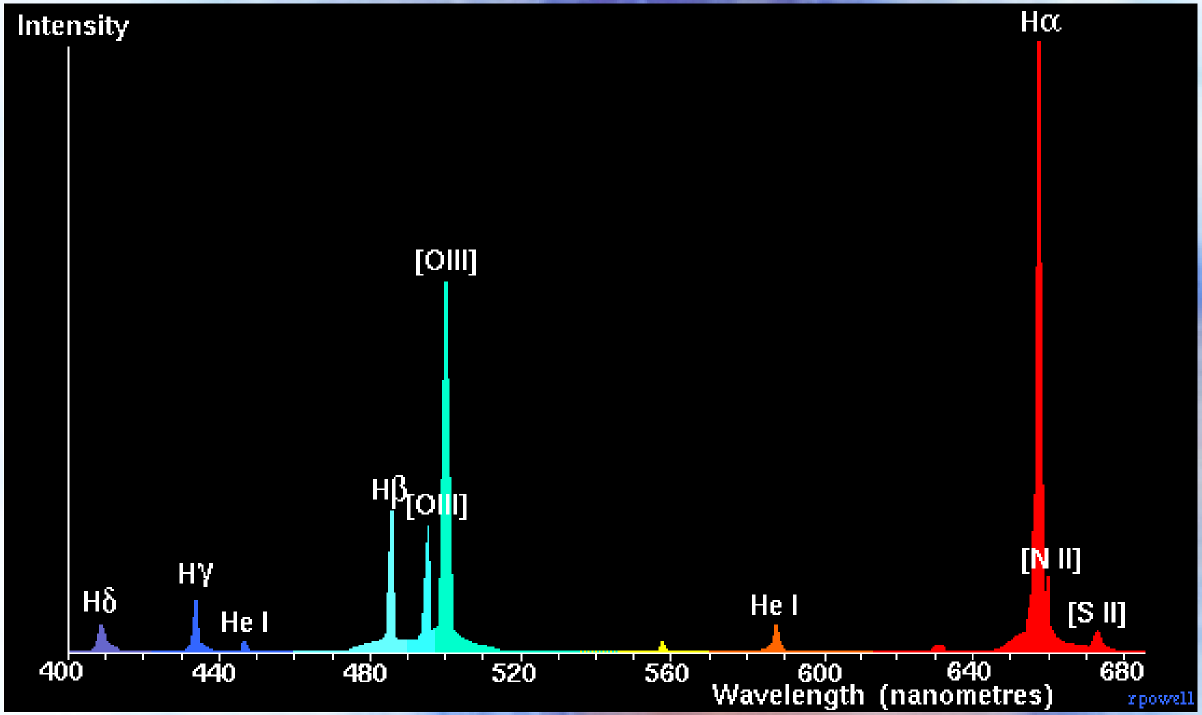
Kirchhoff 1860



Ionized ISM is an active filter to the ionizing photons

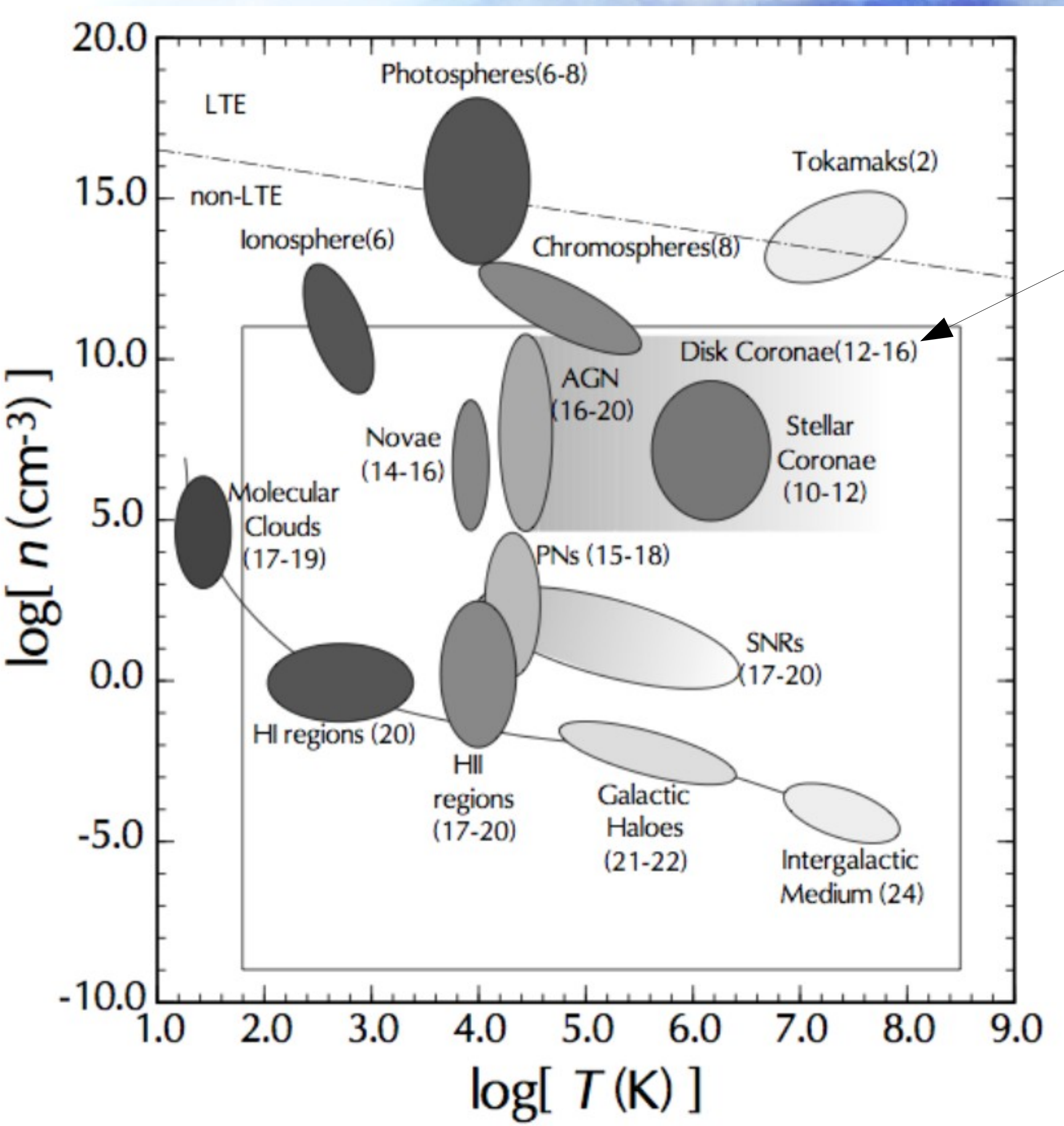


Emission lines



- Easy to detect and measure on a faint continuum. Redshifts
- Trace gas
- Close to ionizing source :
  - Hot stars (Hot == OB == Young, CSPN == Old)
  - AGN
  - (shocks)

Astrophysical plasmas



Log size [cm]

Dopita & Sutherland, 2003

ISM: the two equilibria

- Ionization equilibrium :

ionization <==> recombination

Photoionization	Radiative recombination
Collisions (micro)	Dielectronic recombination
Charge exchange	Charge exchange

- Thermal equilibrium :

heating <==> cooling

Photoionization	Free-free radiation
Collisions (macro)	Free-bound radiation
	Bound-bound radiation

Some formulae

Formulae

Kinetic equilibrium -> electron temperature :

$$E = \frac{1}{2}.m.v^2 = \frac{3}{2}.k_B.T_e$$

$$E(eV) = T_e/7736K$$

Energy [eV] to ionize H^0 into H^+ + e- ?

Corresponding wavelength ?

Corresponding Te ?

Formulae

Kinetic equilibrium -> electron temperature :

$$E = \frac{1}{2}.m.v^2 = \frac{3}{2}.k_B.T_e$$

$$E(eV) = T_e/7736K$$

Energy [eV] to ionize H^0 into H^+ + e- : **13.6 eV**

Corresponding wavelength : **912 A**

Corresponding Te : **105,000 K**

Collisional ionization

Formulae

Planck function

$$B(\lambda, T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda k_B T}} - 1}$$

Peak at T / 3030K (eV)

Te corresponding to peak at 13.6 eV ?

Stellar type ?

Formulae

Planck function

$$B(\lambda, T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda k_B T}} - 1}$$

Peak at T / 3030K (eV)

Te corresponding to peak at 13.6 eV : **45,000 K**

Stellar type : **O2**

Formulae

Planck function

$$B(\lambda, T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda k_B T}} - 1}$$

Any star with Teff > 24,000 K (B2) emits more than 10 % of its radiation with λ < 912 Å.

Some formulae

Relation of the ionizing photons emitting rate and the volume of ionized gas :

$$Q_H = \int_V n_H^2 . \alpha_B(H) . dv$$

In the case of constant density filled sphere of Strömgren radius R_S:

$$Q_H = ff . \frac{4}{3} . \pi . R_S^3 . n_H^2 . \alpha_B(H)$$

In the case of decreasing density $n_H(r) = \bar{n}_H . r^{-a}$

$$Q_H = ff . 4./(3-2a) . \pi . [R_{rec}^{(3-2a)} - R_{in}^{(3-2a)}] . \bar{n}_H^2 . \alpha_B(H)$$

Some formulae

Hß luminosity of a nebula :

$$L_{H\beta} = n_H^2.ff.V.\epsilon(H\beta)$$

Absorption of ionizing photons :

$$Q_{H,abs} = n_H^2.ff.V.\alpha_b(H)$$

Ionization-bounded case :

$$Q_{H,abs} = Q_H \rightarrow L_{H\beta} = Q_H.\epsilon(H\beta)/\alpha_B(H)$$

Density-bounded case :

$$L_{H\beta} = n_H.M_{neb}.\epsilon(H\beta)/m_H$$

Some formulae

$$U(r) = \frac{Q_H}{4.\pi.r^2.n_H.c}$$

For a Strömgren sphere :

$$Q_H = 4/3.\pi.R_S^3.n_H^2.ff.\alpha_B$$

$$U(R_S) = \frac{Q_H}{4.\pi.R_S^2.n_H.c} = \frac{\Phi_H}{n_H.c}$$

$$< U >= \int_V U dv = \frac{3.Q_H}{4.\pi.R_S^2.n_H.c}$$

$$< U >= A.(Q_H.n_H.ff^2)^{1/3}$$

$$where A = \left[\frac{3.\alpha_B^2}{4.\pi.c^2}\right]^{1/3}$$

Some formulae

Surface brightness :

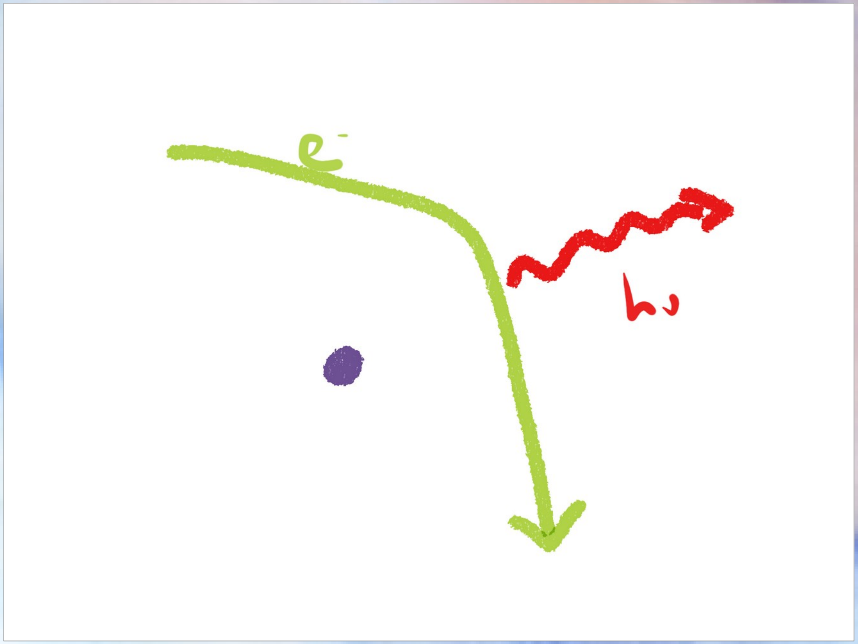
$$S(H\beta) = F(H\beta)/\Theta^2 = L(H\beta)/(4.\pi.d^2.\Theta^2) = L(H\beta)/(4.\pi.R_S^2)$$

For a radiation-bounded nebula :

$$L(H\beta) \propto Q_H$$

$$< U > \propto S(H\beta)/n_H$$

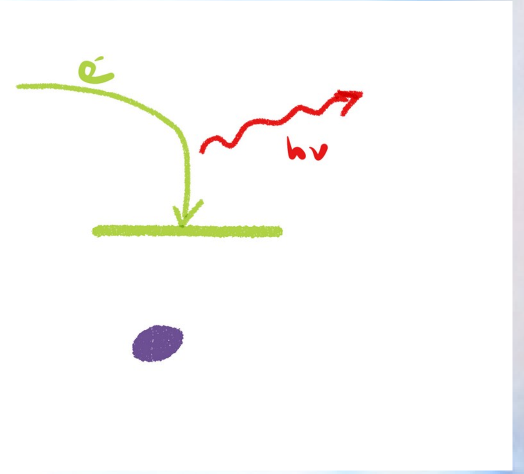
Emission processes



Bremstrallung = free-free

continuous emission

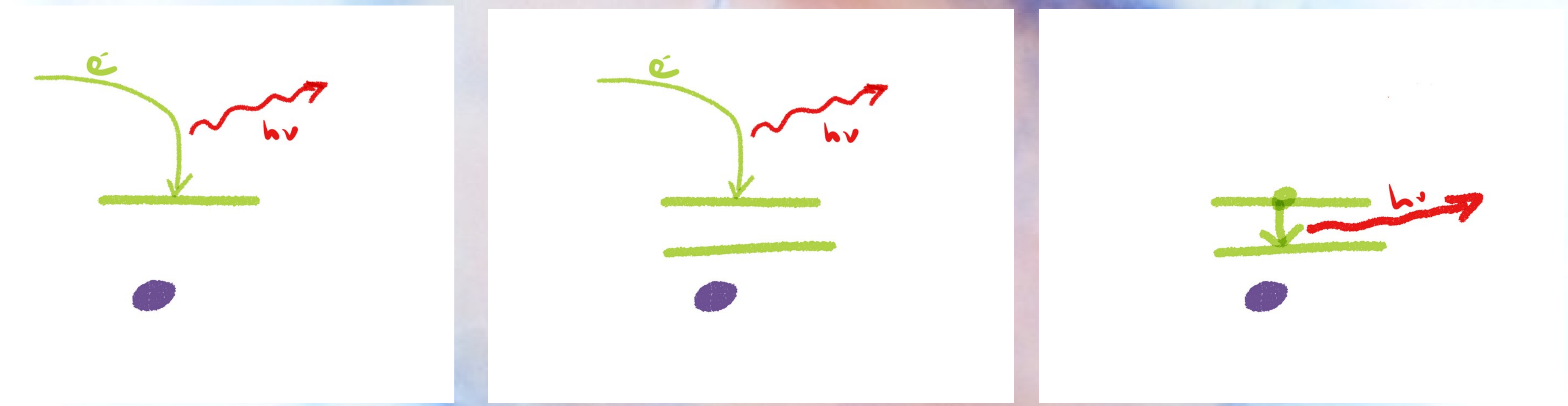
Emission processes



Recombination of an electron to ion :

continuous emission

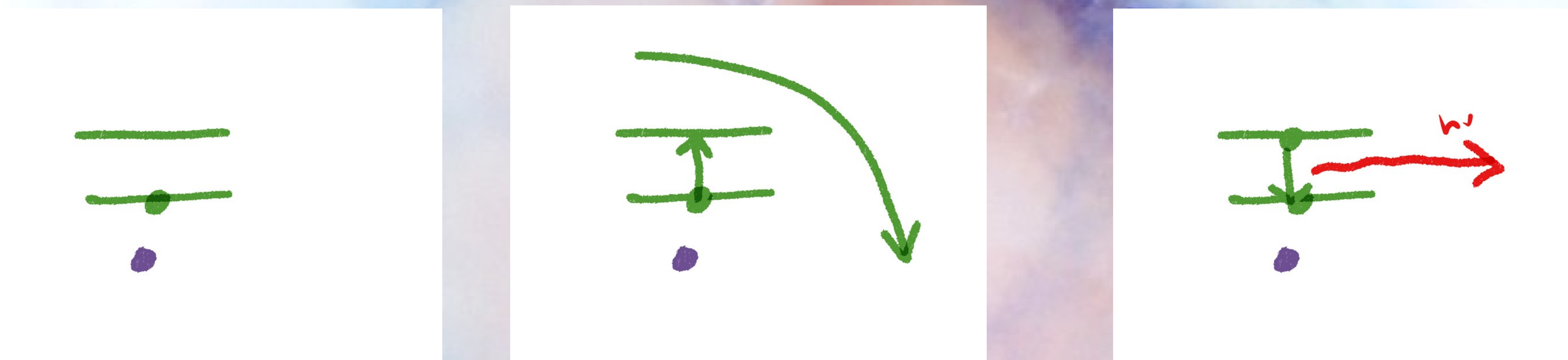
Emission processes



Recombination followed by transition between 2 levels :

emission line

Emission processes

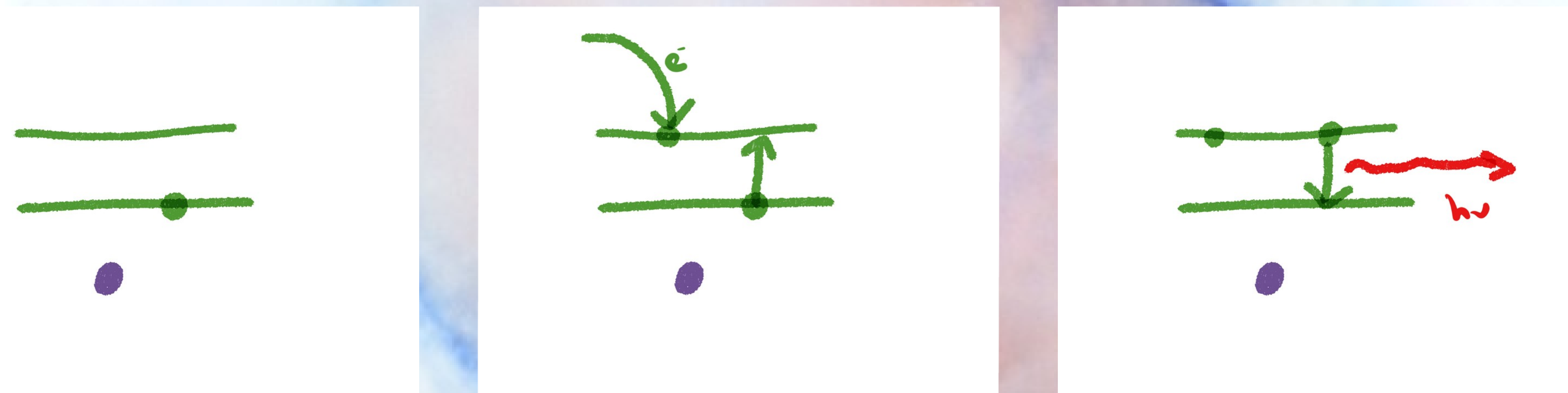


Collisional excitation (an electron gives part of its kinetic energy)

followed by transition :

emission line

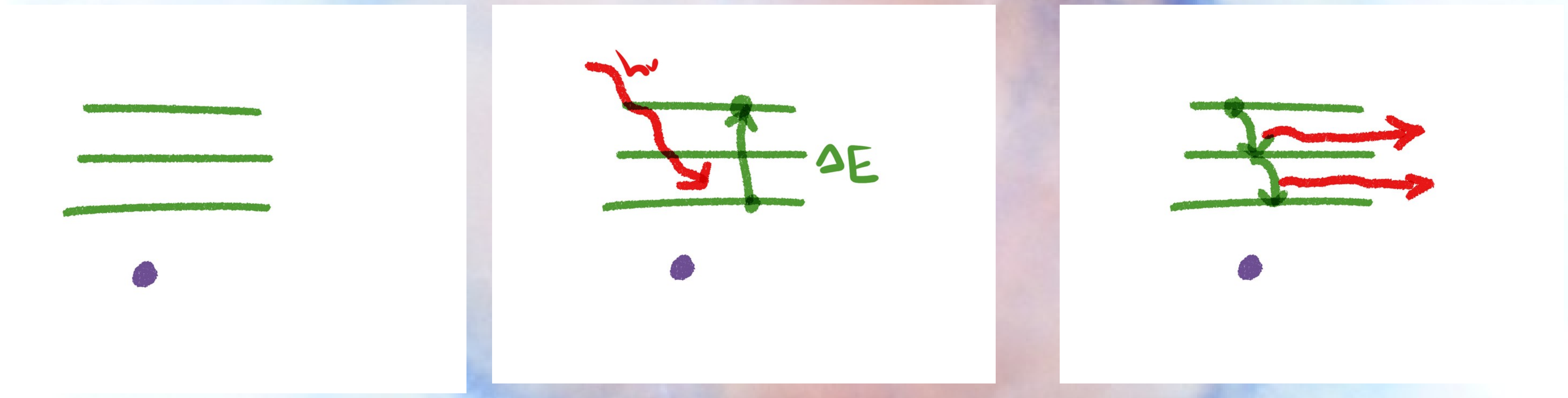
Emission processes



Dielectronic recombination : recombining electron excites inner electron.

emission line

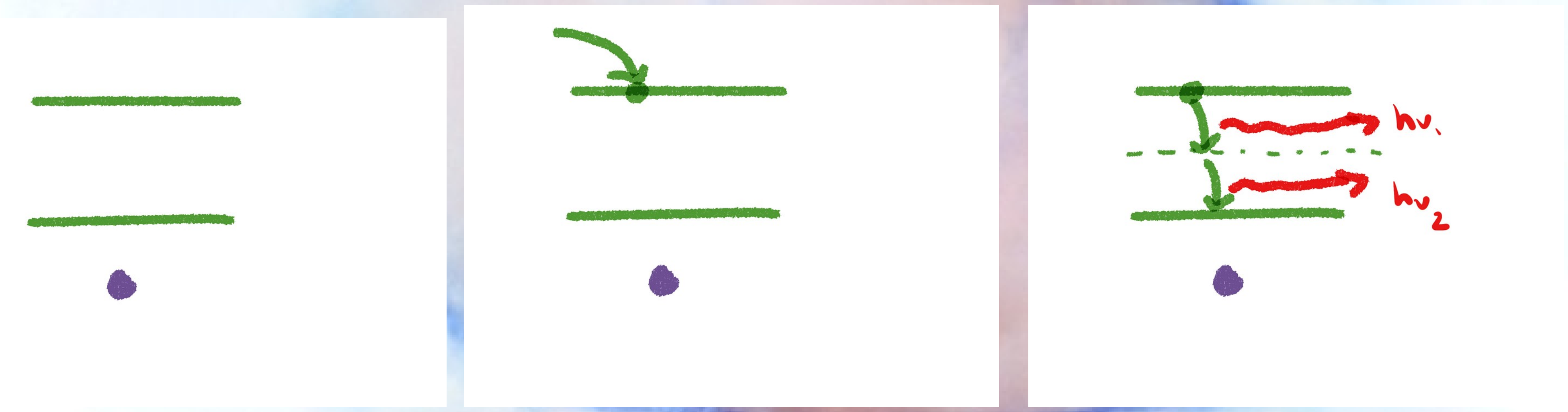
Emission processes



Fluorescence : a photon is absorbed, followed by one or more decay(s)

emission line(s)

Emission processes



2 photons recombination (H)

continuous emission

Emission processes

- Free-free, bound-free and bound-bound processes.
- Recombination works better at low temperature.
- Collision excitation needs enough energetic electrons (high Te if high energy level).

Emission processes

- Forbidden transition : not allowed (!)
- In earth laboratory, not in ISM → 5007 is not emitted by Nebulium

THE ORIGIN OF THE CHIEF NEBULAR LINES

By I. S. Bowen

Several of the strongest lines in the spectra of the gaseous nebulae have not been observed in terrestrial sources. Since the spectra of the light elements, which are thought to form the chief constituents of nebulae, have been thoroughly studied, this leads to the conclusion that some cause, such as low density, must be operating in the nebulae to bring out lines in addition to those found in laboratory sources.

Emission processes

- **Permitted lines vs. forbidden lines** : a matter of transition probability of the upper level. Einstein coefficients As.
- If another collision occurs while the electron is in the upper level : **collisional desexcitation, no emission.**
- The criterium to determine which desexcitation (radiative or collisional) dominates is the density (critical density).

Emission processes

- **Forbidden vs. permitted lines** : related to the decay (upper level lifetime).
- **Collisionally excited or recombination** : related to the upper level population process.
- Not systematically related : there is a contribution from recombination to forbidden lines, and there is collisional excitation of permitted lines.

Atomic data

- Line emissivities are computed using atomic data. They can strongly influence the result.
- Energy emitted by a line from level 2 to level 1 :

$$I_{2,1} = n_2.A_{2,1}.h.\nu_{2,1}$$

- Statistical equilibrium :

$$n_1.n_e.q_{1,2} = n_2.n_e.q_{2,1} + n_2.A_{2,1}$$

$A_{i,j}$: Einstein coefficient
= transition probability
= s^{-1}

q : (de)excitation coefficient
= collision rates
= $cm^{-3}.s^{-1}$

Atomic data

- Effective collision strengths :

$$\Upsilon_{2,1}(T) = \int_0^\infty \Omega_{2,1}(E).e^{-\frac{E}{k.T}}.d\frac{E}{k.T}$$

- Collision coefficients :

$$q_{2,1} = \frac{8.629.10^{-6}}{T^{1/2}}\frac{\Upsilon_{2,1}(T)}{g_2}$$

$$q_{1,2} = \frac{g_2}{g_1}.q_{2,1}.e^{-\frac{h.\nu_{2,1}}{k.T}}$$

Atomic data

General 2-levels emission :

$$I_{2,1} = \frac{n_1 . \frac{g_2}{g_1} . e^{\frac{-h.\nu_{2,1}}{k.T}} . A_{2,1} . h . \nu_{2,1}}{1 + \frac{A_{2,1}}{n_e . q_{2,1}}}$$

Low density limit :

$$I_{2,1} = n_1 . n_2 . q_{1,2} . h . \nu_{2,1} \propto n^2$$

High density limit :

$$I_{2,1} = n_2 . A_{2,1} . h . \nu_{2,1} \propto n$$

Atomic data

- Recombination lines : needs for effective radiative recombination coefficients
- H, He+ and He++
- But also for metals, hard to compute : ADF problem...

Atomic data

- As a summary, the emissivities of recombination lines go like :

$$\epsilon \propto \frac{1}{T_e}$$

- While the emissivities of collisionally excited lines go like :

$$\epsilon \propto \frac{e^{-\frac{h.\nu}{k.Te}}}{\sqrt{Te}}$$

pyStuff

- PyNeb :
  - Luridiana, Morisset, Shaw 2012
  - Python « modern » version of FIVEL and *nebular* packages. Now extends to much more facilities:
    - More levels, recombination lines, continuum, Balmer decrement, plotting facilities.
  - Easy manage atomic data
  - Easy install : pip install pyneb
  - Github : https://github.com/Morisset/PyNeb_devel
  - Google discussion group : https://groups.google.com/forum/#!forum/pyneb