AGNAGN semi
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Section 4.3 Optical Continuum Radiation

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[1]. What is the 'Continuum radiation' ?

There are two kinds in spectrum

1. line radiation

- Strong emission at specific wavelengths
- as electrons transition between energy levels

2. continuum radiation

- over a wide range of wavelengths rather than from specific energy levels.

[2]. Sources of Continuous Radiation

continuous radiation: arises during recombination processes.

- Recombination: a free electron recombines with an ion
- produced through free-bound and free-free transitions

Free-bound transition:

- a free electron becomes **bound** to an atom.
- electron recombine into many different energy levels -> appearing as continuum emission

Free-free transition (= bremsstrahlung):

- interacts with an ion, changes its velocity, and emits a photon in the process
- not tied to discrete energy levels.
- strong in the infrared and radio wavelength ranges.

[3]. Types of Recombination Continuum Radiation

1. H I (neutral hydrogen) continuum radiation
   - most abundant element -> **strongest** continuum radiation.
   - Occurs when a proton and an electron recombine to form a neutral hydrogen atom
2. He II (doubly ionized helium) continuum radiation
   - helium is doubly ionized (He^{2+}) -> recombination continuum is also significant
3. He I (singly ionized helium) continuum radiation
   - relatively weaker signal compared to hydrogen

[4]. Differences by Wavelength Range

1. Optical region (visible light):
   - free electrons are captured into atomic energy levels
2. Infrared (IR) and radio wavelengths:
   - occurs when free electrons interact with ions while remaining unbound

[5]. Two-photon decay

A special process involving the 2^2S energy level of the hydrogen atom.

- two photons are emitted simultaneously
- often populated after recombination, making the process particularly important.

Equation (4.19): $$h\nu = \frac{1}{2}u^2 + \chi_n$$

$h\nu$: energy of photon
u: velocity of free electron
$\frac{1}{2}u^2$: The kinetic energy of the free electron (per unit mass)
χ_n: The ionization energy of the atomic level n the electron is captured into
→ energy required to remove an electron from that level

Why is the mass m missing?
This is due to the choice of unit system.
commonly used in astrophysics and quantum mechanics, the following physical constants are normalized to 1

$$h\nu \geq X_{n_1} = \frac{h\nu_0}{n_1^2}, \tag{4.20}$$

$h\nu$: energy of photon
χ_{n1}: ionization energy of the energy level with principal quantum number n1
ν_0: reference frequency corresponding to the ionization energy of hydrogen's ground state (n=1)

Physical interpretation:
the energy of the photon **must be greater** than the ionization energy χ_{n1} of that level.

What are H I Recombination Lines?

- H I refers to neutral hydrogen
  - a proton (p^+) and an electron (e^-) recombine -> hydrogen atom undergoes a cascade of transitions

More specifically:
- recombines with a proton and enters a high energy level ($n \gg 1$) of the hydrogen atom
- electron gradually transitions to lower levels (e.g., $n = 10 \to 9 \to 8 \to \cdots$), emitting photons in the process.

The light emitted at these specific wavelengths forms the H I recombination lines.

Examples of H I recombination line series:
- Lyman series: $n > 1 \to n = 1$ (ultraviolet region)
- Balmer series: $n > 2 \to n = 2$ (visible region, e.g., Hα = 6563 Å)
- Paschen, Brackett, Pfund series, etc.: infrared region

Importance of H I Recombination Lines:
- strongly in hot, low-density nebulae and are widely used to diagnose **<u>electron density and temperature</u>**

Transition of *n*	3→2	4→2	5→2	6→2	7→2	8→2	9→2	∞→2
Name	H-α / Ba-α	H-β / Ba-β	H-γ / Ba-γ	H-δ / Ba-δ	H-ε / Ba-ε	H-ζ / Ba-ζ	H-η / Ba-η	Balmer break
Wavelength (nm, air)	656.279[2]	486.135[2]	434.0472[2]	410.1734[2]	397.0075[2]	388.9064[2]	383.5397[2]	364.5
Energy difference (eV)	1.89	2.55	2.86	3.03	3.13	3.19	3.23	3.40
Color	Red	Cyan	Blue	Violet	(Ultraviolet)	(Ultraviolet)	(Ultraviolet)	(Ultraviolet)

What are H II Recombination Lines?
: emission lines produced when ionized hydrogen (H^+) in an H II region recombines
electron enters an atomic orbit -> releases energy in multiple steps

Conditions for Occurrence:
only produced in ionized regions (H II regions) → H II Recombination Lines are characteristic features of H II regions.

What is an H II Region?
H II region is a zone of ionized hydrogen that forms around hot, young stars
- "H" stands for hydrogen.
- "II" indicates the first ionized state (H^+).
- In astronomical notation:
    - I = neutral atom
    - II = singly ionized
    - III = doubly ionized, and so on.
    - -> **H II** refers to hydrogen in the form of free protons.

How does it form?
- Hot stars emit strong ultraviolet (UV) radiation
- splits the hydrogen into electrons (e^-) and protons (p^+), creating H II region.

Section 4.3 Optical Continuum Radiation

Equation 4.21: emission coefficient of **free-bound** radiation

$$j_\nu = \frac{1}{4\pi} n_p n_e \sum_{n=n_1}^{\infty} \sum_{L=0}^{n-1} u \sigma_{nL}(H^0, u) f(u)\, h\nu \frac{du}{d\nu}. \qquad (4.21)$$

jν: Emission coefficient at a specific frequency ν → Units: energy / (time × volume × frequency × solid angle)
np, ne: Proton number density, electron number density
σ_{nL} (H^0, u) : Recombination cost section
f(u): Electron velocity distribution (Maxwell-Boltzmann distribution)
hν: Energy of the emitted photon
➔ calculate the intensity of light emitted during the recombination
➔ consider: number of electrons, number of ions, velocity, emitted energy

Equation 4.22: emission coefficient of **free-free** radiation

$$j_\nu = \frac{1}{4\pi} n_+ n_e \frac{32 Z^2 e^4 h}{3 m^2 c^3} \left(\frac{\pi h \nu_0}{3kT}\right)^{1/2} \exp(-h\nu/kT)\, g_{ff}(T, Z, \nu), \qquad (4.22)$$

Z: Charge of the ion (e.g., 1 for hydrogen, 2 for helium)
T: Temperature of the electrons
$e^{-(h\nu/kT)}$: The probability of emission decreases for higher-energy photons (Boltzmann factor)
g_{ff}: Gaunt factor – a quantum mechanical correction factor
➔ calculate the amount of radiation (light) emitted when electrons pass near ions and their paths are bent
➔ describes phenomenon where electrons emit light as they decelerate near positive charges

Equation 4.23: emission coefficient for the H I recombination continuum, **including both** bound-free and free-free contributions

$$j_\nu(\mathrm{H\ I}) = \frac{1}{4\pi} n_p n_e \gamma_\nu(\mathrm{H}^0, T). \tag{4.23}$$

So far, H I
In a similar way, '**He (Helium)**' also releases a continuum as it recombines:

Equation 4.24: emission coefficient for the He I & He II recombination continuum

$$\begin{aligned} j_\nu(\mathrm{He\ I}) &= \frac{1}{4\pi} n(\mathrm{He}^+) n_e \gamma_\nu(\mathrm{He}^0, T), \\ j_\nu(\mathrm{He\ II}) &= \frac{1}{4\pi} n(\mathrm{He}^{++}) n_e \gamma_\nu(\mathrm{He}^{++}, T), \end{aligned} \tag{4.24}$$

continuum contribution from He II : comparable to that of H I.
continuum contribution from He I : only about 10% of the H I.

Additional important source of continuum emission in nebulae: **two-photon decay** of the 2 ^2S level of H I

Two-photon emission:
- cannot directly decay to the ground state (1s)
- Instead, it decays to the ground state by simultaneously emitting two photons
- Radiative characteristics:
    - combined energy of the two photons equals Lyman-α transition (i.e., $h\nu' + h\nu'' = h\nu(L\alpha) = (3/4)h\nu_0$)
    - emission is continuous ->centered around a frequency of $(1/2)\nu_{12}$

emission coefficient in this two-photon continuum:

$$j_\nu(2q) = \frac{1}{4\pi} n_{2\,^2S} A_{2\,^2S,1\,^2S} 2hyP(y), \qquad (4.25)$$

P(y)dy: normalized probability per decay

$$n_p n_e \alpha^{eff}_{2^2S}(\mathrm{H}^0, T) = n_{2\,^2S} A_{2\,^2S,1\,^2S}$$

$\alpha^{eff}_{2^2S}$: effective recombination coefficient for populating 2^2S

Equilibrium population of the 2^2S level

Paths to the 2^2S state:

1. Direct recombination
2. Cascade from higher energy levels (stepwise transitions)

Collisions: can convert the 2s state into the 2p state, thereby suppressing two-photon emission.

Density Conditions	**Explanation**
Low density ($n_p < 10^4$ cm^{-3})	Only two-photon emission needs to be considered
High density	Collisional de-excitation must also be taken into account

Note: Symmetry

- Two-photon emission is symmetric in frequency
- However:
    - not symmetric in wavelength
    - not symmetric in energy

➔ the shape of the spectrum can appear different depending on the units used

This figure is just a simple case.
This figure is only for coefficient, and This figure not mean the strength of contribution to continuum line

Figure 4.1:
how the emission coefficient varies with frequency

① **$\gamma_\nu(H^0)$** – thick solid line
- from neutral hydrogen (H I) as it recombines with free electrons
- Includes both bound-free (b–f) and free-free (f–f) emission
- dominant contribution

② **$\gamma_\nu(He^0)$** – thin solid line
- from neutral helium (He I)
- Weaker than H I, but contributes significantly at certain frequencies

③ **$\gamma_\nu(He^+)$** – dashed line
- from singly ionized helium (He II)
- similar to H I
- If helium is mostly doubly ionized (He^{2+}) -> this can be comparable to H I

④ **$\gamma_\nu(2\gamma)$** – smooth solid line
- Spectrum of two-photon emission
- Occurs when the 2s level of H I decays to the ground state by emitting two photons simultaneously
- forms a continuous spectrum, peaking near a frequency of $\nu_{12}/2$

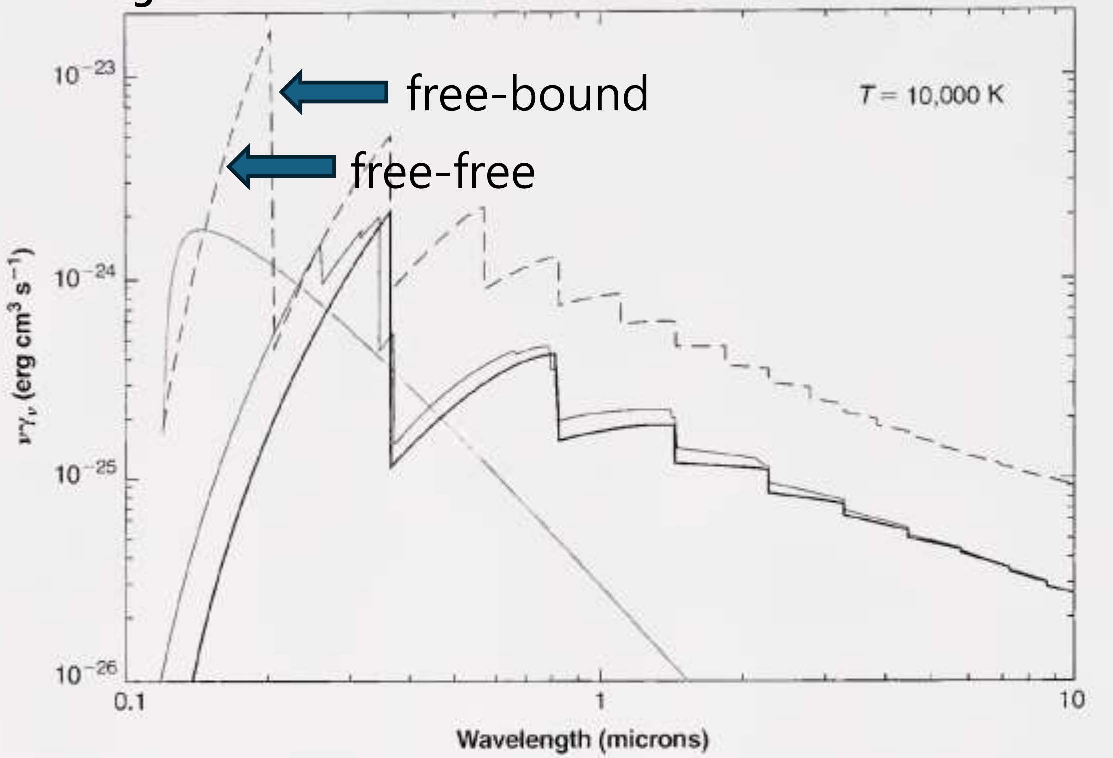

Figure 4.1
Frequency variation of continuous-emission coefficient $\gamma_\nu(H^0$, solid line), γ_ν (He^0, thin solid line), γ_ν (He^+, dashed line), and γ_ν ($2h\nu$, smooth solid line) in the low-density limit $n_e \to 0$, all at $T = 10{,}000$ K.

Characteristics:
- He II: comparable to or even stronger than H I if helium is highly ionized
- discontinuities in the spectrum, which are caused by sudden changes at frequencies corresponding to ionization energies.
  - Examples) Balmer edge (3646 Å), the Lyman edge (912 Å).