AGNAGN Seminar Sec4-4.End

Misato Fujii

4.4 Radio-Frequency Continuum and Line Radiation

・”thermal” radio-frequency radiation: extinction of the optical line and continuous spectra

↔radiation in radio-frequency region is somewhat different from the optical region

・in radio-frequency region, $h\nu \ll kT$ and stimulated emission (proportional to $\exp(-h\nu/kT)$) are important

continuous spectrum in radio-frequency region

・continuum is from free-free emission

・emission coefficient is given by (4.22) same as in the optical region

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

・in radio-frequency region, Gaunt factor g_{ff} is($\gamma = 0.577$: Euler's constant)

$$g_{ff}(T, Z, \nu) = \frac{\sqrt{3}}{\pi} \left[\ln \left(\frac{8k^3T^3}{\pi^2 Z^2 e^4 m \nu^2} \right)^{1/2} - \frac{5\gamma}{2} \right], \qquad (4.30)$$

・free-free effective absorption coefficient can be derived Kirchhoff's law

$$\kappa_\nu = n_+ n_e \frac{16\pi^2 Z^2 e^6}{(6\pi m k T)^{3/2} \nu^2 c} g_{ff} \qquad (4.31)$$

・effective absorption coefficient is difference between the true absorption coefficient and the stimulated emission coefficient

・stimulated emission of photon: negative absorption process

・when $h\nu \ll kT$, stimulated emission≃true absorption and correction

・correction for stimulated emission: $[1 - \exp(-h\nu/kT)] \approx h\nu/kT \ll 1$

continuous spectrum in radio-frequency region

→substitute numerical value

$$\tau_\nu = \int \kappa_\nu \, ds$$
$$= 8.24 \times 10^{-2} T^{-1.35} \nu^{-2.1} \int n_+ n_e \, ds$$
$$= 8.24 \times 10^{-2} T^{-1.35} \nu^{-2.1} E_c.$$

(E_c: continuum emission measure)

⇨at sufficiently low frequency, all nebulae become optically thick

・in fact, many nebulae are optically thick at low frequency and optically thin at high frequency

・ for no incident radiation, the solution of equation of radiative transfer

$$I_\nu = \int_0^{\tau_\nu} B_\nu(T) \exp(-\tau_\nu) d\tau_\nu.$$

・in radio-frequency region

$$B_\nu(T) = \frac{2h\nu^3}{c^2} \frac{1}{\exp(h\nu/kT) - 1} \approx \frac{2\nu^2 kT}{c^2}$$

: proportional to T

⇨ $$T_{b\nu} = \int_0^{\tau} T \exp(-\tau_\nu) \, d\tau_\nu,$$

($T_{bn} = c^2 I_\nu 2\nu^2 k$: brightness temperature)

・for isothermal nebula, $T_{b\nu} = T[1 - \exp(\tau_\nu)] \begin{bmatrix} \to T\tau_\nu \ (\tau_\nu \to 0) \\ \to T \ (\tau_\nu \to \infty) \end{bmatrix}$

⇨ $T_{b\nu}$ varies as ν^{-2} at high frequency and is dependent of ν at low frequency

Recombination line spectrum in radio-frequency

・emission coefficient in radio recombination line can be calculated as optical recombination line

・in radio-frequency region, only n_n need to be considered $(n > n_{CL})$

・additional process to those described in Sec4.2(optical region)

・collisional ionization of levels with large n and its inverse process (three-body recombination)

$$H^0(n) + e \Leftrightarrow H^+ + e + e.$$

・rate of collisional ionization from level n: $n_n n_e \overline{u\sigma_{ionization}(n)} = n_n n_e q_{n,i}(T),$

・rate of three-body recombination: $n_p n_e^2 \phi_n(T)$

⇨ $$\phi_n(T) = n^2 \left(\frac{h^2}{2\pi mkT}\right)^{3/2} \exp(X_n/kT) q_{n,i}(T).$$ (from (4.6), (4.18), principle of balance)

Recombination line spectrum in radio-frequency

⇨equilibrium equation at high n:

$$n_p n_e \left[\alpha_n(T) + n_e \phi_n(T)\right] + \sum_{n'>n}^{\infty} n_{n'} A_{n',n} + \sum_{n'=n_0}^{\infty} n_{n'} n_e q_{n',n}$$
$$= n_n \left[\sum_{n'=n_0}^{n-1} A_{n,n'} + \sum_{n'=n_0}^{\infty} n_e q_{n,n'}(T) + n_e q_{n,i}(T) \right],$$

- $A_{n,n'} = \frac{1}{n^2} \sum_{L,L'} (2L+1) A_{nL,n'L'}$: mean transition probability averaged over all the L levels
- can be expressed by coefficient b_n instead of n_n
  - b_n: defined by thermodynamic equilibrium at local T, n_e, n_p
    - $b_n \to 1$ $(n \to \infty)$
  - solution can be found numerically by standard matrix-inversion techniques
  - Figure4.2: calculated values of b_n
    - as n_e increse, the importance of collisional transitions increase and $b_n \approx 1$ at even lower n

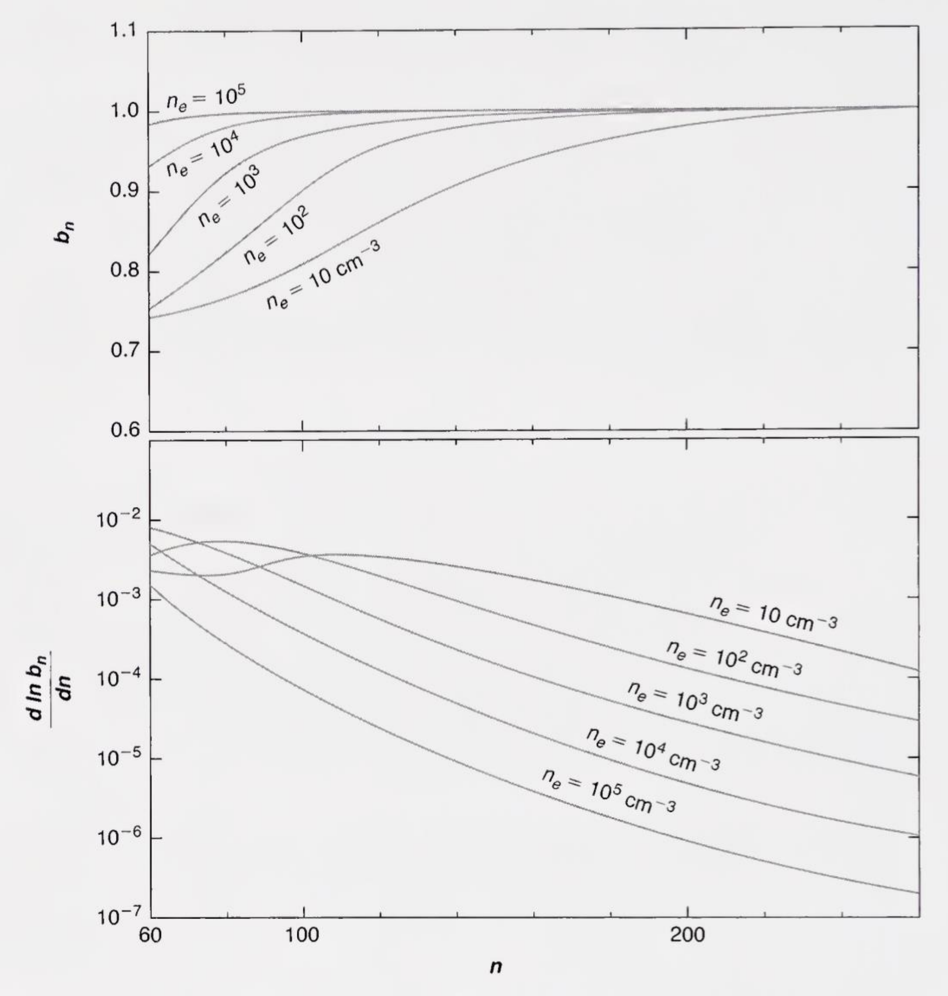

Figure 4.2
Dependence of b_n and $d \ln b_n/dn$ on n at various densities, all at $T = 10{,}000$ K.

Recombination line spectrum in radio-frequency

・to calculate the emission in specific recombination line

・solve the equation of transfer with the effects of stimulated emission

・line-absorption coefficient corrected for stimulated emission:

$$k_{\nu l} = k_{\nu l}\left(1 - \frac{b_m}{b_n}\exp(-h\nu/kT)\right)$$ ($k_{\nu l}$: true line-absorption coefficient)

・from the equation of transfer

・$m = n + \Delta n$: upper level

・net difference between the rates of absorption and emission

→expand in a power series:

$$k_{\nu L} = k_{\nu l}\left(\frac{b_m}{b_n}\frac{h\nu}{kT} - \frac{d\ln(b_n)}{dn}\Delta n\right).$$

・ $b_m/b_n \approx 1$, $h\nu \ll kT$

⇨if $(d\ln b_n)/dn$ become sufficient large, $k_{\nu l}$ become negative (positive maser action)

・Figure4.2: calculated values of $(d\ln b_n)/dn$

⇨maser effect is quite important

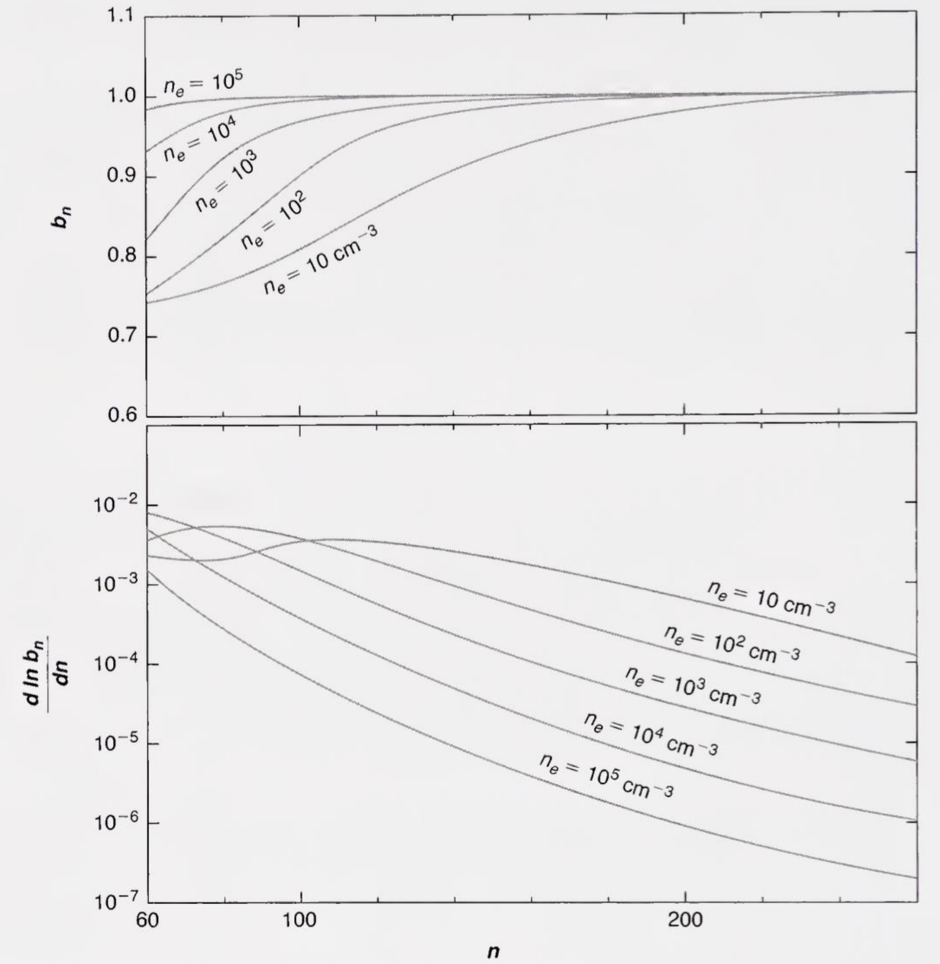

Figure 4.2
Dependence of b_n and $d\ln b_n/dn$ on n at various densities, all at $T = 10{,}000$ K.

4.5. Radiative Transfer Effects in HI

・for most of the emission lines observed in nebulae, there isn't radiative-transfer problem

↔in some lines, the optical depth are appreciable

⇨scattering and absorption must be considered in calculating the expected line strengths

・especially the resonance lines of abundant atoms

・two extreme assumptions (Case A and Case B) do not require a detailed radiative-transfer solution

↔in the intermediate cases, more sophisticated treatment is necessary

・other radiative-transfer problem arise

・HeI triplets

・conversion of HeII Lα and HI Lβ into OIII or OI line radiation by Bowen resonance-fluorescence process

・fluorescence excitation of other lines by stellar continuum radiation

Line absorption coefficient with line-broadening

・in a static nebula, the line-broadening mechanisms are only thermal Doppler broadening and radiative damping

・in the core of the lines, radiative damping can be neglected

⇨line-absorption coefficient has the Doppler form

$$\kappa_{\nu l} = k_{0l} \exp\left[-\left(\Delta\nu/\Delta\nu_D\right)^2\right] = k_{0l} \exp(-x^2) \quad [\mathrm{cm}^2],$$

・ $k_{0l} = \frac{\lambda^2}{8\pi^{3/2}} \frac{\omega_j}{\omega_i} \frac{A_{j,i}}{\Delta\nu_D} = \frac{\sqrt{\pi} e^2 f_{ij}}{mc\Delta\nu_D} \quad [\mathrm{cm}^2]$: line-absorption cross section at the center of the line

・ $\Delta\nu_D = \sqrt{\frac{2kT}{m_H c^2}}\,\nu_0$ [Hz]: thermal Doppler width

・ f_{ij}: absorption oscillator strength between the lower(i) and upper level(j)

・small-scale micro-turbulence can be a further source of broadening of the line-absorption coefficient

・ $\Delta\nu_D^2 = \Delta\nu_{thermal}^2 + \Delta\nu_{turbulent}^2$

・larger scale turbulence and expansion of the nebula

・consider the frequency shift between the emitting and absorbing volumes

Escape probability of photon from the nebula

- photon emitted at a particular point in a particular direction with frequency χ in a static nebula
  - probability of escaping from nebula without further scattering and absorption: $\exp(-\tau_\chi)$
    - τ_χ: optical depth from the point to the edge of the nebula
    - average over the frequency profile of the emission coefficient
      →mean escape probability from the point
  - for the forbidden lines and most of the other lines
    - the optical depths are so small in every direction
    ⇨mean escape probabilities from all points: 1

↔for lines of larger optical depth, need to examine the escape probability

Mean escape probability

- idealized spherical homogeneous nebula with optical radius in the center of line (τ_{0l})
  - for $\tau_{0l} < 10^4$, only Doppler core of the line-absorption cross section need to be considered
    - photons are emitted with same Doppler profile
    - mean escape probability must be averaged over this Doppler profile
    - mean escape probability averaged over all directions and volumes
      - $$p(\tau_\chi) = \frac{3}{4\tau_x}\left[1 - \frac{1}{2\tau_x^2} + \left(\frac{1}{\tau_x} + \frac{1}{2\tau_x^2}\right)\exp(-2\tau_x)\right].$$
        - τ_χ: optical radius of the nebula at a particular normalized frequency χ

→average over the Doppler profile

→mean escape probability for photon emitted in the line: $\varepsilon(\tau_{0l}) = \frac{1}{\sqrt{\pi}}\int_{-\infty}^{\infty} p(\tau_x)\exp(-x^2)dx$

- for optical radii ($\tau_{0l} \leq 50$), can be fitted with $\varepsilon(\tau_{0l}) = 1.72/(\tau_{0l} + 1.72)$

Lyman-line spectra from the nebula

・if photons do not escape from the nebula, they are absorbed by another hydrogen atom

・each absorption process represents an excitation of the n^2P^o level of HI

・excited level undergoes a radiative decay very quickly

→・resonance scattering

・resonance fluorescence excitation of another HI line

・photon emitted in a $1^2S - n^2P^o$ transition→process is resonance scattering of Ln photon

・photon emitted in the $2^2S - n^2P^O$ transition→process is conversion of Ln into Hn and excitation of 2^2S

→emission of two photons in the continuum

・photon emitted in the $3^2S - n^2P^O$ transition→process is conversion of Ln into Pn and excitation of 3^2S

→emission of Hα and Lα

・$P_n(Lm)$ $\left(P_n(Hm)\right)$: probabilities that absorption of Ln photon results in emission of Lm(Hm) photon

⇨

$$P_n(\mathrm{L}m) = C_{n1,m1} P_{m1,10}$$

$$P_n(\mathrm{H}m) = C_{n1,m0} P_{m0,21} + C_{n1,m1} P_{m1,20} + C_{n1,m2} P_{m2,21}.$$

(probability matrices $C_{nL,n'L'}$ and $L_{nL,n'L'}$ (Sec4.2))

Lyman line spectra from the nebula

→calculate the Lyman-line spectrum emitted from a model nebula

- J_n: total number of Ln photons emitted in the nebula per unit time
  - $J_n = R_n + \sum_{m=n}^{\infty} A_m P_m(\mathrm{L}n).$
    - R_n: total number of Ln photons generated in the nebula by recombination and subsequent cascading
    - A_n: total number of Ln photons absorbed in the nebular

  →total number of Ln photons escaping the nebula per unit time

  - $E_n = \varepsilon_n J_n = \varepsilon_n \left[R_n + \sum_{m=n}^{\infty} A_m P_m(\mathrm{L}n) \right]$ (ε_n: escape probability of each Ln photon emitted)
- in a steady state, the number of Ln photons emitted = the numbers absorbed and escaping

  → $J_n = A_n + E_n = A_n + \varepsilon_n J_n.$
- eliminate J_n→ $A_n = (1 - \varepsilon_n) \left[R_n + \sum_{m=n}^{\infty} A_m P_m(\mathrm{L}n) \right].$

⇨solve for A_n (R_n, $P_m(Ln)$, ε_n are known)

⇨ E_n can be calculated , giving the emergent Lyman-line spectrum

Balmer-line spectra from the nebula

・suppose that there is no absorption of Balmer-line photons

・S_n: number of Hn photons generated in the nebula by recombination and subsequent cascading

・K_n: total number of Hn photons emitted in the nebula

→ $$K_n = S_n + \sum_{m=n}^{\infty} A_m P_m(\mathrm{H}n).$$

⇨calculate K_n

・S_n, $P_m(Hn)$, A_m are known

⇨obtain the emergent Balmer-line spectrum

・R_n, S_n, J_n, K_n, A_n are proportional to the total number of photons

・equations are linear to these quantities

⇨entire calculation can be normalized to any S_n (S_4: number of Hβ photons)

→can calculate the ratio of Hα/Hβ, Hβ/Hγ

Balmer-line spectra from the nebula

・in most nebulae, the optical depth in the Balmer lines are small

↔in the case that the density $n(H^0, 2^2S)$ is sufficiently high, some self-absorption could occur in Balmer lines

・optical depth in Balmer lines can be calculated from (4.45)

・optical depth is proportional to $n(H^0, 2^2S)$

→radiative-transfer problem is now a function of two variables ($\tau_{0l}(L\alpha)$, $\tau_{0l}(H\alpha)$)

→equation are much more complicated

・same general type of formula as Lyman-line absorption

⇨for here, discuss physically the calculated results (Figure4.3)

Discussion of Figure4.3

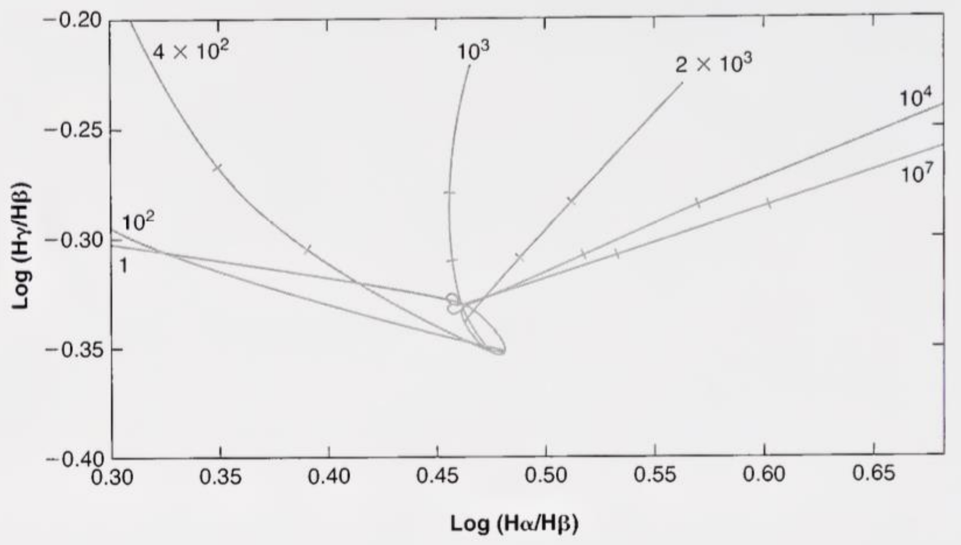

Figure 4.3

Radiative transfer effects caused by finite optical depths in Lyman and Balmer lines. Ratios of total emitted fluxes Hα/Hβ are shown for homogeneous static isothermal model nebulae at $T = 10{,}000$ K. Each line connects a series of models with the τ_{0l}(Lα), given at the end of the line; along it τ_{0l}(Hα) = 5 and 10 at the two points along each line indicated by bars for τ_{0l}(Lα) ≥ 400.

- for $\tau_{0l}(H\alpha) = 0$
  - as $\tau_{0l}(L\alpha)$ increase, Lβ is converted into Hα and two-photon continuum

  →Hα/Hβ ratio of the escaping photon increase

  →move of the point to the right in Figure4.3
- for slightly large $\tau_{0l}(L\alpha)$, Lγ is converted mainly Hβ

  →move of the point to downward and to the left in Figure4.3
- for still larger $\tau_{0l}(L\alpha)$, higher Ln photons are converted

  →Hγ is strengthened

→taking into all effects,

- representative point describes the small loop as the conditions change from Case A to Case B

- for large $\tau_{0l}(L\alpha)$, as $\tau_{0l}(H\alpha)$ increase, Hα is merely scattered (formed Lβ photons are quickly absorbed and converted back to Hα), and Hβ is absorbed and converted to Hα and Pα

  →Hα/Hβ increase and Hβ/Hγ decrease as in Figure4.3

4.6. Radiative Transfer Effects in HeI

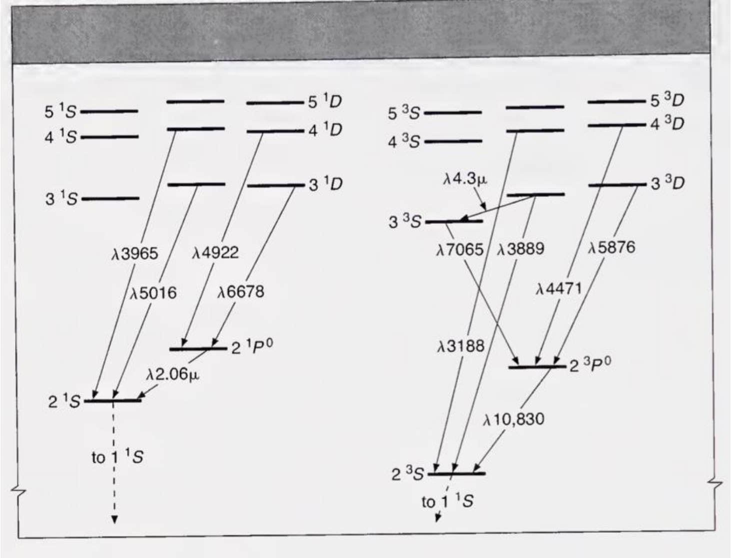

Figure 4.4
Partial energy-level diagram of He I, showing strongest optical lines observed in nebulae. Note that $1\,^2S$ has been omitted, and terms with $n \geq 6$ or $L \geq 3$ have been omitted for the sake of space and clarity.

・recombination radiation of HeI singlets is similar to HI

・Case B is a good approximation for HeI Lyman lines

↔ $He^0, 2^3S$ is more metastable than $H^0, 2^2S$

⇨self-absorption effects are important

・2^3S is the lowest triplet in He and recaptures to triplets tend to cascade down to 2^3S

・depopulation from 2^3S occurs only by

・photoionization especially by HI Lα

・collisional transitions to 2^1S and 2^1P^o

・strongly forbidden $2^3S - 1^1S$ radiative transition

⇨$n(2^3S)$ is large and optical depth in lower $2^3S - n^3P^o$ lines significant

・$2^3S - 2^3P^o(\lambda 10830)$ photons are simply scattered

・absorption of $2^3S - 3^3P^o(\lambda 3889)$ photons can lead conversion to $3^3S - 3^3P^o(\lambda 4.3\mu m)$, $2^3P - 3^3S(\lambda 7065)$, $2^3S - 2^3P^o(\lambda 10830)$

・at larger $\tau_{0l}(\lambda 10830)$, higher numbers of $2^3S - n^3P^o$ are converted into longer wavelength photons

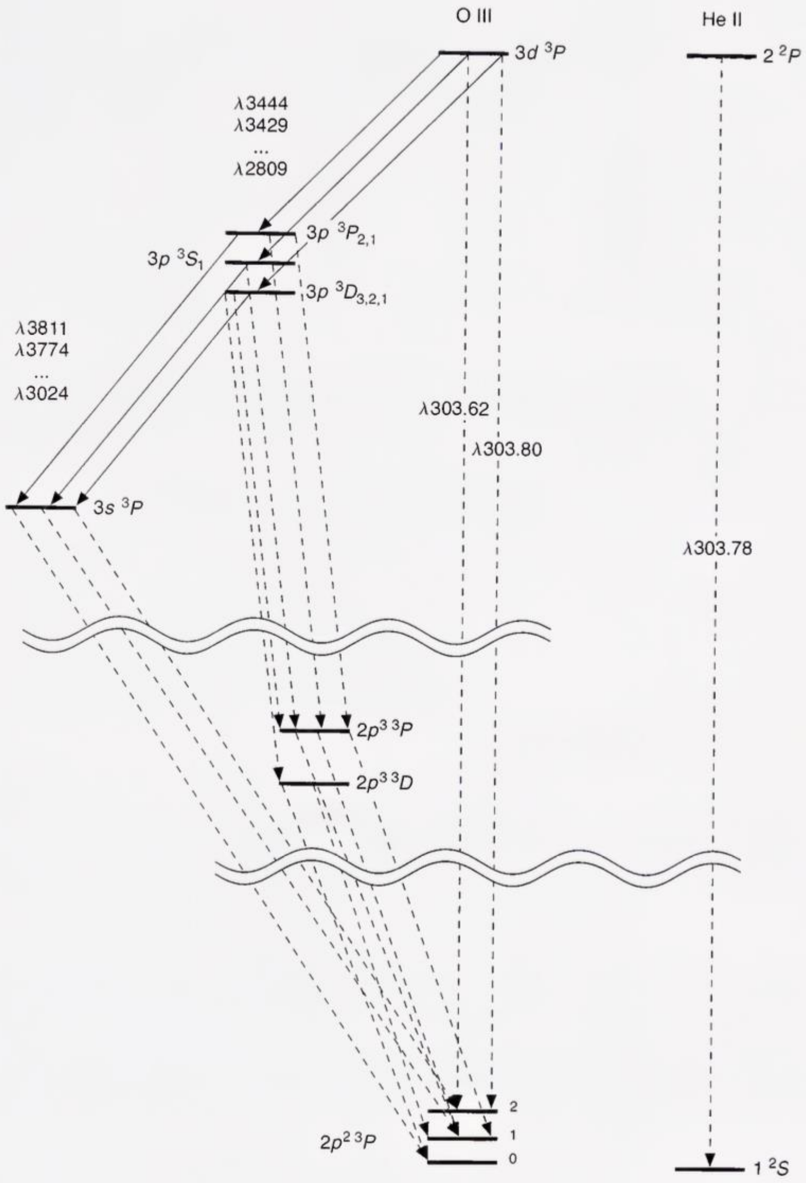

Figure 4.6

Schematized partial energy-level diagrams of [O III] and He II showing coincidence of He II Lα and [O III] $2p^2\,{}^3P_2$–$3d\,{}^3P\,\lambda 303.80$. The Bowen resonance fluorescence lines in the optical and near-ultraviolet are indicated by solid lines, and the far-ultraviolet lines that lead to excitation or decay are indicated by dashed lines. There are six observable lines in all leading down from $3d\,{}^3P_2^o$, and 14 from $3p\,{}^3P_{2,1}$, $3p\,{}^3S_1$, and $3p\,{}^3D_{3,2,1}$, and with relative strengths that can be calculated just from the ratios of transition probabilities.

Optical depth for HeI

- radiative transfer problem is similar to Lyman lines
  - handled by the same kind of formalism

- thermal Doppler width of HeI lines is smaller than HI lines

⇨turbulent or expansion velocity in nebula is important in broadening the HeI lines
  - simplest example: model spherical nebula expanding with a velocity

  → $U_{\text{exp}}(r) = \omega r;\ 0 \le r \le R;$

  →relative radial velocity between any two points in the nebula(r_1, r_2): $u(r_1, r_2) = \omega s,$
    - s: distance between the points
    - ω: constant velocity gradient

  →photons emitted at r_1 have a line profile centered on the line frequency ν_L where r_1 is at rest
    - at r_2, encounter material absorbing with a profile centered on the frequency

    → $\nu'(r_1, r_2) = \nu_L \left(1 + \frac{\omega s}{c}\right),$

Optical depth for HeI

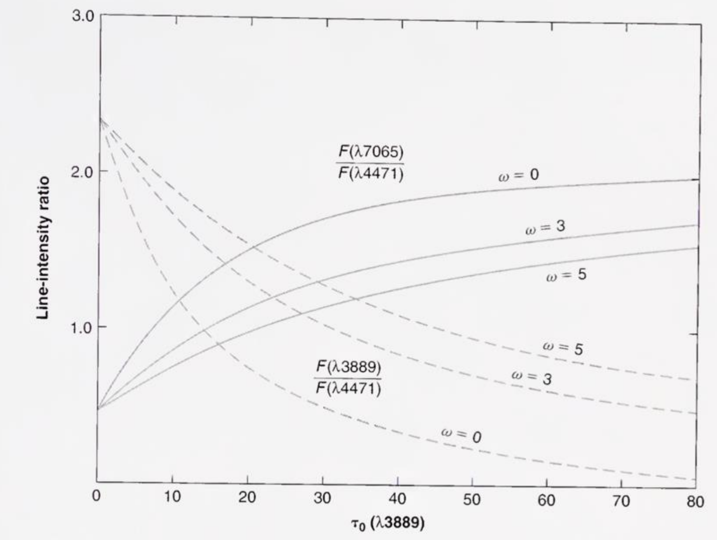

Figure 4.5
Radiative transfer effects due to finite optical depths in He I λ3889 $2\,^3S$–$3\,^3P^o$. Ratios of emergent fluxes of λ7065 and λ3889 to the flux in λ4471 are as a function of optical radius $\tau_0(\lambda 3889)$ of homogeneous static ($\omega = 0$) and expanding ($\omega \neq 0$) isothermal nebulae at $T = 10{,}000$ K.

→optical depth in a particular direction to the boundary of the nebula for a photon emitted at r_1 with frequency ν:

$$\tau_\nu(r_1) = \int_0^{r_2=R} n(2\,^3S)k_{0l} \exp\left\{-\left[\frac{\nu - \nu'(r_1, r_2)}{\Delta\nu_D}\right]^2\right\} ds.$$

⇨at a fixed density $n(2^3S)$, as velocity of expansion increase, optical depth decreases, and self-absorption effects decrease

・Figure4.5:

・ratio of intensities of $\lambda 3889$ (weakened by self-absorption) and $\lambda 7065$(strengthened by resonance fluorescence) to the intensity $\lambda 4471(2^3P^o - 4^3D$, only slightly affected by absorption)

・ratio of the expansion velocity $u_{exp}(R) = \omega R$ to the thermal velocity $u_{th} = (2kT/m_{He})^{1/2}$ (ω=0,3,5)

・as functions of $\tau_{0l}(\lambda 3889) = n(2^3S)\kappa_{0l}(\lambda 3889)R$(optical radius)

→for large u_{exp}/u_{th} and τ_0, calculated intensity ratios are quite similar to those for smaller u_{exp}/u_{th} and τ_0

4.7 The Bowen Resonance-Fluorescence Mechanisms for OIII and OI

・wavelength coincide between HeII Lα line at $\lambda 303.78$ and OIII $2p^2\ {}^3P_2 - 3d\ {}^3P_2^o$ line at $\lambda 303.80$
・some residual H^+ in the H^{++} zone of a nebula
→HeII Lα photons emitted by recombination are scattered many times
→high density of HeII Lα photons
→since O^{++} is also present, some of the HeII Lα photons are absorbed by O^{++} and excite $3d\ {}^3P_2^o$ level of OIII
→quickly decays by a radiative transition
・by resonance scattering in the $2p^2\ {}^3P_2 - 3d\ {}^3P_2^o$ line by emitting photon (most frequent)
・by emission of $\lambda 303.62\ 2p^2\ {}^3P_1 - 3d\ {}^3P_2^o$
・may then escape or be reabsorbed by another O^{++} ion, again populating $3d\ {}^3P_2^o$
・by emitting one of six longer wavelength photons $3p\ {}^3L_J - 3d\ {}^3P_2^o$
・level $3p\ {}^3L_J$ then decay to $3s$ and ultimately back to $2p^2\ {}^3P$ or decay to $2p^3$ and then back to $2p^2\ {}^3P$

⇨Bowen resonance-fluorescence mechanism
・conversion of HeII Lα to lines that arise from $3d\ {}^3P_2^o$ or from the levels excited by its decay
・for interpretation, require the solution of the problem of scattering, escape, and destruction of HeII Lα with O^{++} scattering and resonance fluorescence

Bowen Resonance-Fluorescence Mechanisms for OI

・wavelength coincide between HI Lβ at $\lambda 1025.72$Å and OI $2p^4\ ^3P_2 - 2p^3 3d\ ^3D_3^o$ line at $\lambda 1025.76$Å
・some atomic oxygen exists in the H^{++} zone
  ・similar to the situation for OIII and HeII Lα
・excitation of $2p^3 3d\ ^3D_3^o$
 →this level decays by producing
    ・$2p^3 3p\ ^3P_2 - 2p^3 3d\ ^3D_3^o\ \lambda 11286.9$Å
    ・$2p^3 3s\ ^3S_1^o - 2p^3 3p\ ^3P_2\ \lambda 8446.36$Å
    ・three lines of the multiplet $2p^4\ ^3P_{2,1,0} - 2p^3 3s\ ^3S_1^o\ \lambda\lambda 1302.17, 1304.86, 1306.03$Å
  ・in simple case, each excitation produces a cascade through the first two of these lines, followed by one of the last three
    →relative intensities of the first two lines = the sum of the intensities of the multiplet
      ・in photon unit
    →predicted relative intensities in energy units are inversely proportional to their wavelength

Table 4.13

Collision strengths Υ for collisions from $He^0(2\,^3S)$

T (K)	$2\,^3S, 2\,^3P^o$	$2\,^3S, 3\,^3S$	$2\,^3S, 3\,^3P^o$	$2\,^3S, 3\,^3D$	$2\,^3S, 3\,^1D$
6,000	16.3	2.40	1.61	1.46	0.249
10,000	25.8	2.29	1.61	1.95	0.259
15,000	37.1	2.25	1.59	2.52	0.257
20,000	46.5	2.26	1.57	2.99	0.252
25,000	55.3	2.31	1.56	3.43	0.245

4.8 Collisional Excitation in HeI

・collisional excitation of H is negligible compared with recombination

↔in He^0, 2^3S level is highly metastable and collisional excitation from it can be important

・consider a nebula sufficiently dense($n_e \gg n_c$)

・main mechanism for depopulating 2^3S is collisional transitions to 2^1S and 2^1P^o

・equilibrium population in 2^3S: $n_e n(\mathrm{He}^+)\alpha_B(\mathrm{He}^0, n^3L) = n_e n(2\,^3S)\left[q_{2\,^3S,2\,^1S} + q_{2\,^3S,2\,^1P^o}\right]$ ·

→rate of collisional population of 2^3P^o: $n_e n(2\,^3S) q_{2\,^3S,2\,^3P^o} = \frac{n_e n(\mathrm{He}^+) q_{2\,^3S,2\,^3P^o}}{\left[q_{2\,^3S,2\,^1S} + q_{2\,^3S,2\,^1P^o}\right]}\alpha_B(\mathrm{He}^0, n^3L)$

→relative importance of collisional to recombination excitation of $\lambda10830$:

$$\frac{n_e n(2\,^3S) q_{2\,^3S,2\,^3P^o}}{n_e n(\mathrm{He}^+)\alpha^{eff}_{\lambda 10830}} = \frac{q_{2\,^3S,2\,^3P^o}}{\left[q_{2\,^3S,2\,^1S} + q_{2\,^3S,2\,^1P^o}\right]} \frac{\alpha_B(\mathrm{He}^0, n\,^3L)}{\alpha^{eff}_{\lambda 10830}}$$

・compute $q_{2^3S,2^3P^o}$ from the collision strengths Υ

・at T=10, 000K, ratio of collisional to recombination excitation ~8

→・collisional excitation from 2^3S completely dominates the emission of $\lambda10830$

・the factor by which it dominates depends weakly on T, and can easily decrease with $n_e < n_c$

Importance of Collisional excitation in HeI for 2^1S and 2^1P^o

・collisional transition rates from 2^3S to 2^1S and 2^1P^o are smaller than to 2^3P^o

・recombination rates of population of 2^1S and 2^1P^o are also smaller

⇨collisions are important in the population of 2^1S and 2^1P^o

・cross section for collisions to the higher singlets and triplets are not negligible

・collisional population of 3^3P^o is significant and somewhat affects the strength of $\lambda3889$

・atomic data indicates that there is a non-negligible collisionally excited component in the observed strength of $\lambda5876$ in planetary nebula

・similar collisional-excitation effects occur from the metastable $\mathrm{He}^0\ 2^1S$ and $\mathrm{H}^0\ 2^2S$ levels

↔decay more rapidly than $\mathrm{He}^0\ 2^3S$

⇨population are much smaller and resulting excitation rates are negligible