

(AGN)<sup>2</sup>

## 5. Comparison of Theory with Observations

Week 7

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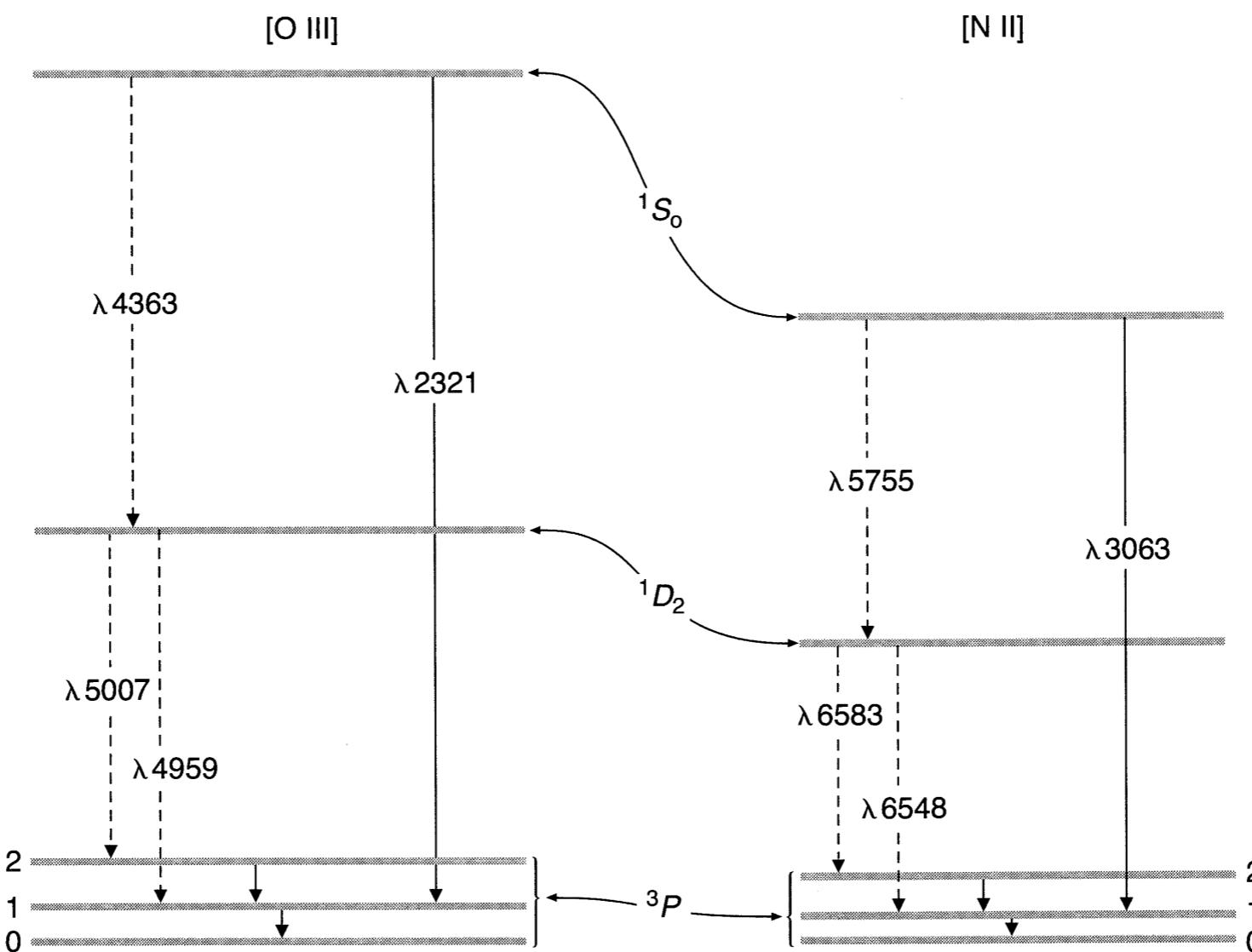
## 5.1 Introduction

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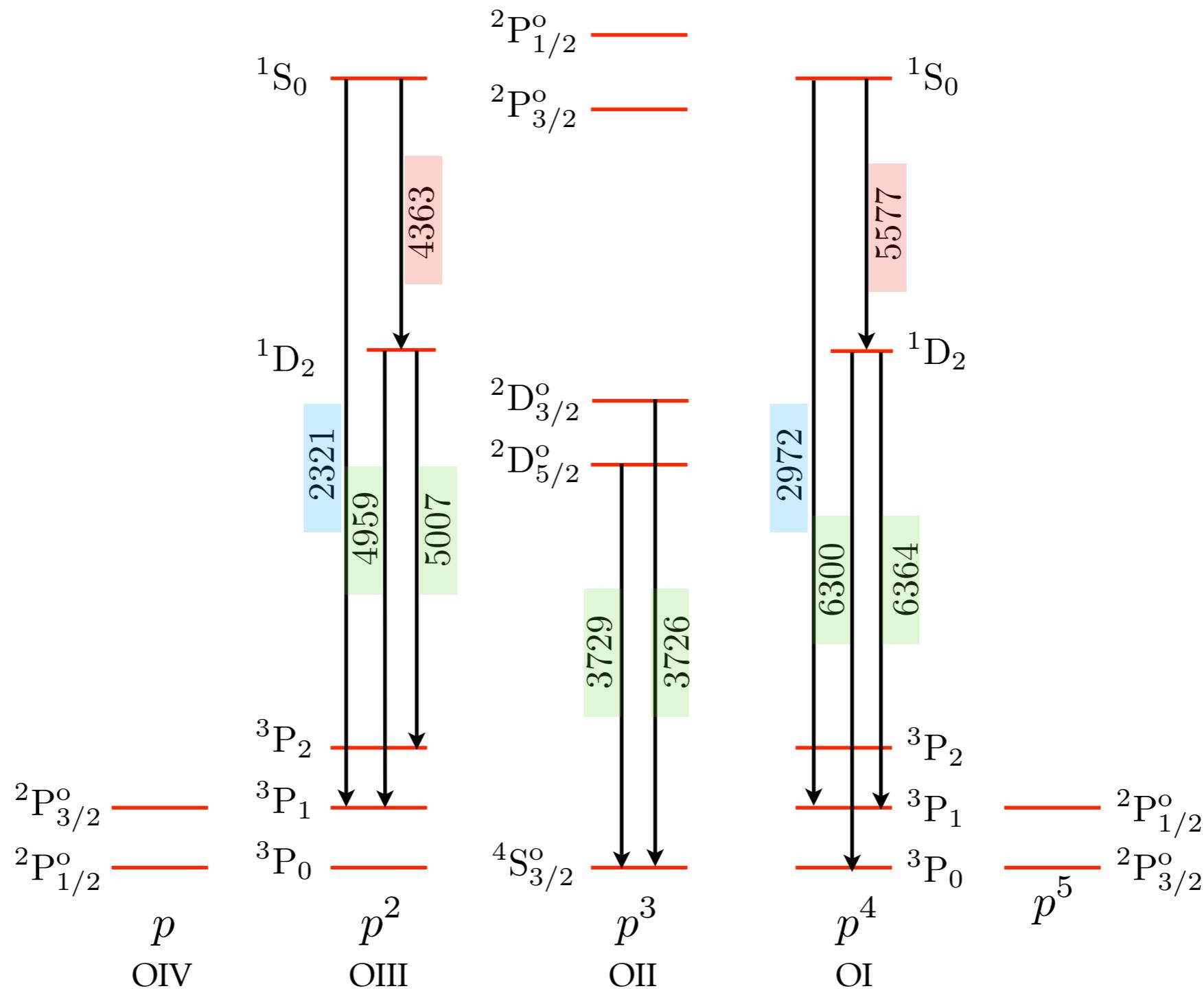
- We are now in a position to compare the theory with the available observations.
- **Temperature**
  - Intensity ratios of pairs of emission line — emitted by a single ion from two levels with considerably different excitation energies.
  - The relative strengths of H recombination lines vary weakly with  $T$ . However, the ratio of the line intensity to the recombination continuum intensity varies more rapidly and can be used to measure  $T$ .
  - Combining long- and short-wavelength continuum, which has large and small optical depths, respectively.
  - Long-wavelength continuum and optical-line observations
- **Electron density**
  - Intensity ratios of other pairs of lines — emitted by a single ion from two levels with nearly the same energy but with different radiative-transition probabilities.
  - Relative strengths of the radio recombination lines (both the density and temperature).
- **Information on the involved stars**
  - If a nebula is optically thick to a particular type of ionizing radiation, then the total number of photons of this type emitted by the star can be determined from its observational properties.
  - FUV ionizing radiation, optical measurements of the stars, a long base-line color index that gives information on the temperature of the stars.
- **Abundance**
  - Once the  $T$  and  $\rho$  are known, the observed strength of a line gives information on the total number of ions, and thus the abundances of the elements.

## 5.2 Temperature Measurements from Emission Lines

- Ions that have two different upper levels with considerable different excitation energies.
  - [O III]  $\lambda 4363$  occurs from the upper  $^1S$ , while [O III]  $\lambda 4959$  and  $\lambda 5007$  occur from the intermediate  $^1D$  level. The relative rates of excitation to the  $^1S$  and  $^1D$  levels depend very strongly on  $T$ .



[Figure 3.1]



- In the low-density limit (no collisional deexcitation):

- $3 \rightarrow 2$  and  $3 \rightarrow 1$  transitions:

$$4\pi j(3 \rightarrow 2) = n_e n_P \left( k_{P3} + k_{P4} \frac{A_{43}}{A_{43} + A_{41}} \right) \frac{A_{32}}{A_{32} + A_{31}} h\nu_{32}$$

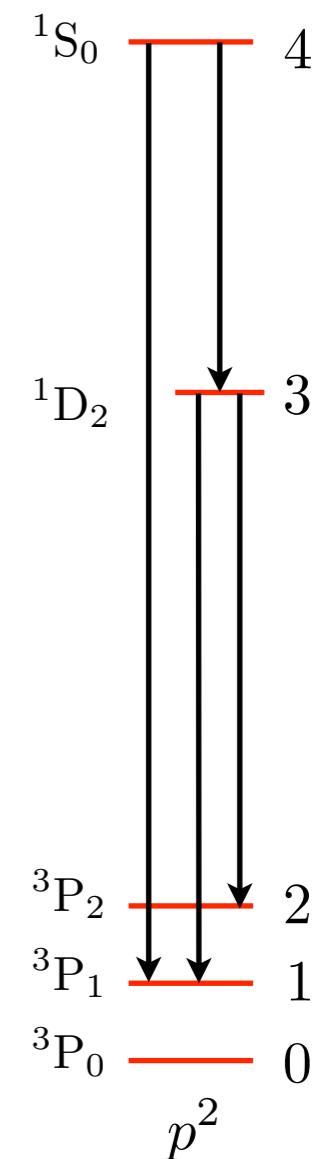
$$4\pi j(3 \rightarrow 1) = n_e n_P \left( k_{P3} + k_{P4} \frac{A_{43}}{A_{43} + A_{41}} \right) \frac{A_{31}}{A_{32} + A_{31}} h\nu_{31}$$

These terms are negligible.

Here,  $P$  indicates  ${}^3P_{0,1,2}$  levels as a whole

- $4 \rightarrow 3$  transition:

$$4\pi j(4 \rightarrow 3) = n_e n_P k_{P4} \frac{A_{43}}{A_{43} + A_{41}} h\nu_{43}$$



Combining these equations, we obtain

$$\frac{j(3 \rightarrow 1) + j(3 \rightarrow 2)}{j(4 \rightarrow 3)} = \frac{\bar{\nu}}{\nu_{43}} \frac{A_{43} + A_{41}}{A_{43}} \frac{k_{P3}}{k_{P4}} \left( 1 + \frac{k_{P4}}{k_{P3}} \frac{A_{43}}{A_{43} + A_{41}} \right) \quad \text{where } \bar{\nu} \equiv \frac{A_{32}\nu_{32} + A_{31}\nu_{31}}{A_{32} + A_{31}}$$

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$k_{0u} = \frac{\beta}{T^{1/2}} \frac{\langle \Omega_{u0} \rangle}{g_0} e^{-E_{u0}/kT_{\text{gas}}}$

$\downarrow$

$$\frac{k_{P3}}{k_{P4}} = \frac{\langle \Omega_{3P} \rangle}{\langle \Omega_{4P} \rangle} \frac{e^{-h\nu_{30}/kT}}{e^{-h\nu_{40}/kT}} = \frac{\langle \Omega_{3P} \rangle}{\langle \Omega_{4P} \rangle} e^{h\nu_{43}/kT} \quad (\text{where } \nu_{43} = \nu_{40} - \nu_{30})$$

$$\begin{aligned} \frac{j(3 \rightarrow 1) + j(3 \rightarrow 2)}{j(4 \rightarrow 3)} &= \frac{\bar{\nu}}{\nu_{43}} \frac{A_{43} + A_{41}}{A_{43}} \frac{\langle \Omega_{30} \rangle}{\langle \Omega_{40} \rangle} e^{h\nu_{43}/kT} \left( 1 + \frac{\langle \Omega_{40} \rangle}{\langle \Omega_{30} \rangle} \frac{A_{43}}{A_{43} + A_{41}} e^{-h\nu_{43}/kT} \right) \\ &\simeq \frac{\bar{\nu}}{\nu_{43}} \frac{A_{43} + A_{41}}{A_{43}} \frac{\langle \Omega_{30} \rangle}{\langle \Omega_{40} \rangle} e^{h\nu_{43}/kT} \end{aligned}$$

Note  $\langle \Omega_{4P} \rangle < \langle \Omega_{3P} \rangle$  and  $e^{-h\nu_{43}/kT} \ll 1$

Thus, the second term inside the parenthesis is negligible.

$$\begin{aligned} \frac{j(3 \rightarrow 1) + j(3 \rightarrow 2)}{j(4 \rightarrow 3)} &= \frac{\bar{\nu}}{\nu_{43}} \frac{A_{43} + A_{41}}{A_{43}} \frac{\langle \Omega_{3P} \rangle}{\langle \Omega_{4P} \rangle} e^{h\nu_{43}/kT} \left( 1 + \frac{\langle \Omega_{4P} \rangle}{\langle \Omega_{3P} \rangle} \frac{A_{43}}{A_{43} + A_{41}} e^{-h\nu_{43}/kT} \right) \\ &\simeq \frac{\bar{\nu}}{\nu_{43}} \frac{A_{43} + A_{41}}{A_{43}} \frac{\langle \Omega_{3P} \rangle}{\langle \Omega_{4P} \rangle} e^{h\nu_{43}/kT} \end{aligned}$$

$$\frac{j(3 \rightarrow 1) + j(3 \rightarrow 2)}{j(4 \rightarrow 3)} \simeq \frac{\bar{\nu}}{\nu_{43}} \frac{A_{43} + A_{41}}{A_{43}} \frac{\langle \Omega_{3P} \rangle}{\langle \Omega_{4P} \rangle} e^{h\nu_{43}/kT}$$

Dependence of collision strength on temperature is very weak.  
So, we will adopt a typical value.

[O III]	$\langle \Omega_{3P} \rangle = 2.29$	$A_{32} = 2.0 \times 10^{-2} \text{ [s}^{-1}\text{]}$
	$\langle \Omega_{4P} \rangle = 0.29$	$A_{31} = 6.8 \times 10^{-3} \text{ [s}^{-1}\text{]}$
	$\langle \Omega_{43} \rangle = 0.58$	$A_{43} = 1.6 \text{ [s}^{-1}\text{]}$
	$E_{40}/k = 61207 \text{ [K]}$	$A_{41} = 2.3 \times 10^{-1} \text{ [s}^{-1}\text{]}$
	$E_{30}/k = 29169 \text{ [K]}$	$g_3 = 5$
	$E_{20}/k = 441 \text{ [K]}$	$g_4 = 1$
	$E_{10}/k = 163 \text{ [K]}$	
[N II]	$\langle \Omega_{3P} \rangle = 2.64$	$A_{32} = 3.0 \times 10^{-3} \text{ [s}^{-1}\text{]}$
	$\langle \Omega_{4P} \rangle = 0.29$	$A_{31} = 9.8 \times 10^{-4} \text{ [s}^{-1}\text{]}$
	$\langle \Omega_{43} \rangle = 0.83$	$A_{43} = 1.0 \text{ [s}^{-1}\text{]}$
	$E_{40}/k = 47033 \text{ [K]}$	$A_{41} = 3.3 \times 10^{-2} \text{ [s}^{-1}\text{]}$
	$E_{30}/k = 22037 \text{ [K]}$	$g_3 = 5$
	$E_{20}/k = 188 \text{ [K]}$	$g_4 = 1$
	$E_{10}/k = 70 \text{ [K]}$	

Table 3.6 Collision Strength

Ion	$^3P, ^1D$	$^3P, ^1S$	$^1D, ^1S$
N <sup>+</sup>	2.64	0.29	0.83
O <sup>+2</sup>	2.29	0.29	0.58

Table 3.12 Transition probabilities

Transition	[N II]		[O III]	
	$A \text{ (s}^{-1}\text{)}$	$\lambda \text{ (\AA)}$	$A \text{ (s}^{-1}\text{)}$	$\lambda \text{ (\AA)}$
$^1D_2 - ^1S_0$	1.0	5754.6	1.6	4363.2
$^3P_2 - ^1S_0$	$1.3 \times 10^{-4}$	3070.8	$6.1 \times 10^{-4}$	2331.4
$^3P_1 - ^1S_0$	$3.3 \times 10^{-2}$	3062.8	$2.3 \times 10^{-1}$	2321.0
$^3P_2 - ^1D_2$	$3.0 \times 10^{-3}$	6583.4	$2.0 \times 10^{-2}$	5006.9
$^3P_1 - ^1D_2$	$9.8 \times 10^{-4}$	6548.0	$6.8 \times 10^{-3}$	4958.9
$^3P_0 - ^1D_2$	$3.6 \times 10^{-7}$	6527.1	$1.7 \times 10^{-6}$	4931.1

We obtain the line ratio as a function of temperature.

$$\frac{[\text{O III}] 4960 + 5008}{[\text{O III}] 4364} = 8.12 e^{3.20 \times 10^4/T}$$

$$\frac{[\text{N II}] 6549 + 6585}{[\text{N II}] 5756} = 8.23 e^{2.50 \times 10^4/T}$$

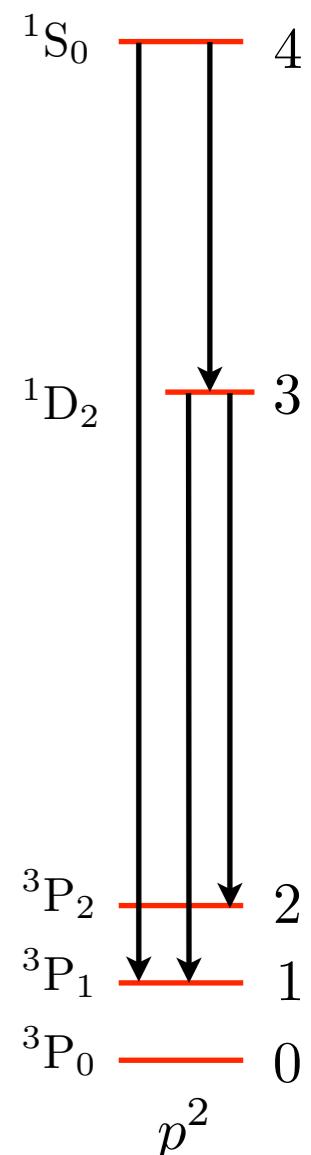
The discrepancy in numerical values within the [O III] formula arise from the differences in the adopted energy level values.

- Collisional effects:
  - The above equations are good approximation up to  $n_e \approx 10^5 \text{ cm}^{-3}$ . At higher densities, collisional deexcitation begins to play a role.
  - The lower  ${}^1D$  term (level 3) has a considerably longer radiative lifetime than the highest  ${}^1S$  term (level 4), so it is collisionally deexcited at lower electron densities than  ${}^1S$  (level 4), thus weakening  $\lambda 4959$  and  $\lambda 5007$ .
  - In addition, collisional excitation of  ${}^1S$  (level 4) from the excited  ${}^1D$  level (level 3) begins to strengthen  $\lambda 4363$ .

$$4\pi j(3 \rightarrow 2) = n_e n_P \left( k_{P3} + k_{P4} \frac{A_{43} + n_e k_{43}}{A_{43} + A_{41} + n_e k_{43} + n_e k_{41}} \right) \frac{A_{32}}{A_{32} + A_{31} + n_e k_{32} + n_e k_{31}} h\nu_{32}$$

$$4\pi j(3 \rightarrow 1) = n_e n_P \left( k_{P3} + k_{P4} \frac{A_{43} + n_e k_{43}}{A_{43} + A_{41} + n_e k_{43} + n_e k_{41}} \right) \frac{A_{31}}{A_{32} + A_{31} + n_e k_{32} + n_e k_{31}} h\nu_{31}$$

$$4\pi j(4 \rightarrow 3) = n_e n_P k_{P4} \frac{A_{43}}{A_{43} + A_{41} + n_e k_{43} + n_e k_{41}} h\nu_{43}$$



$$9 \\$$

$$4\pi j(3 \rightarrow 2) = n_e n_P \left( k_{P3} + k_{P4} \frac{A_{43} + n_e k_{43}}{A_{43} + A_{41} + n_e k_{43} + n_e k_{41}} \right) \frac{A_{32}}{A_{32} + A_{31} + n_e k_{32} + n_e k_{31}} h\nu_{32}$$

$$4\pi j(3 \rightarrow 1) = n_e n_P \left( k_{P3} + k_{P4} \frac{A_{43} + n_e k_{43}}{A_{43} + A_{41} + n_e k_{43} + n_e k_{41}} \right) \frac{A_{31}}{A_{32} + A_{31} + n_e k_{32} + n_e k_{31}} h\nu_{31}$$

$$4\pi j(4 \rightarrow 3) = n_e n_P k_{P4} \frac{A_{43}}{A_{43} + A_{41} + n_e k_{43} + n_e k_{41}} h\nu_{43}$$

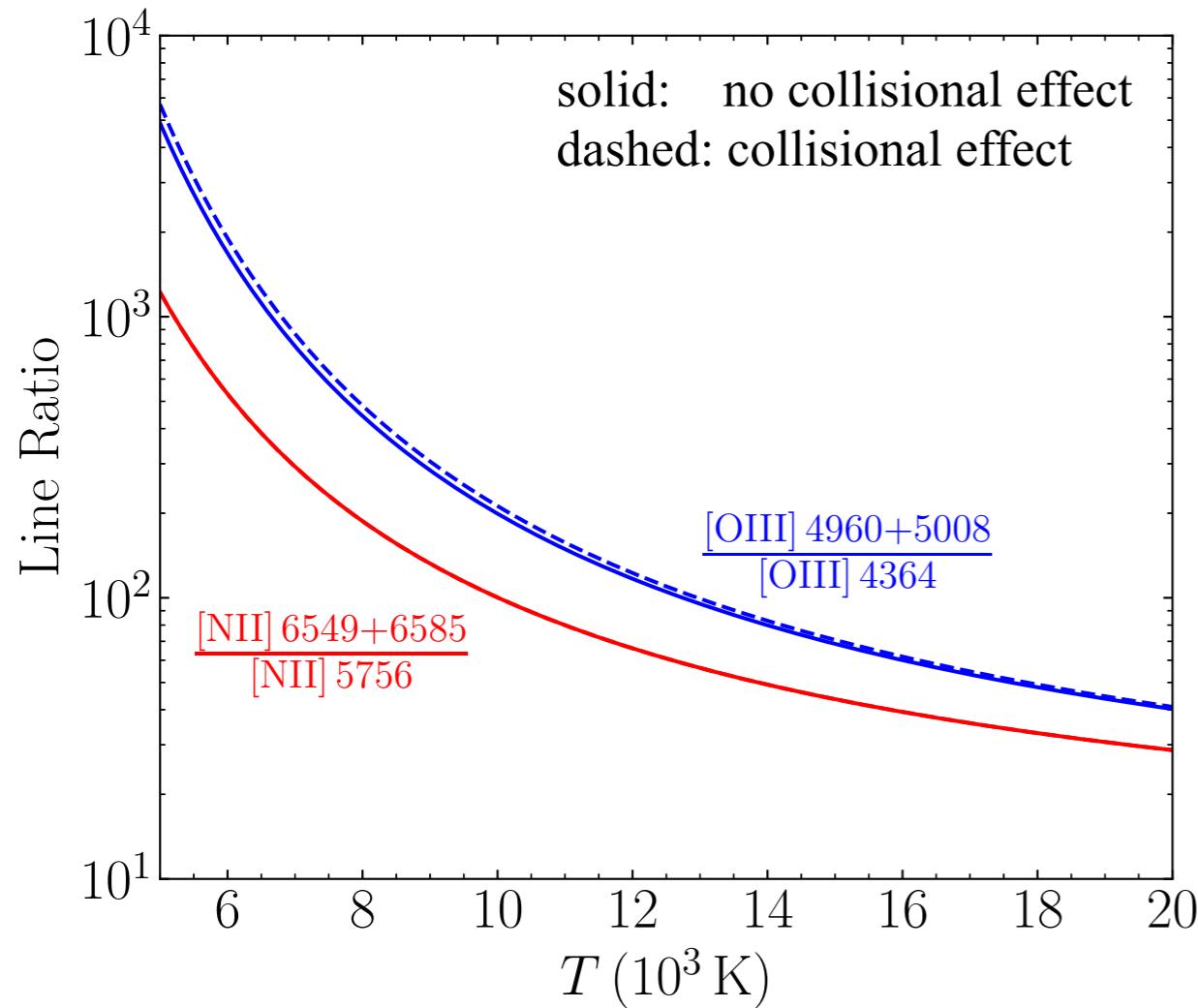
$$\frac{A_{32}}{A_{32} + A_{31} + n_e k_{32} + n_e k_{31}} = \frac{A_{32}}{(A_{32} + A_{31}) \left( 1 + \frac{n_e k_{32} + n_e k_{31}}{A_{32} + A_{31}} \right)}$$

$$\frac{A_{43}}{A_{43} + A_{41} + n_e k_{43} + n_e k_{41}} = \frac{A_{43}}{(A_{43} + A_{41}) \left( 1 + \frac{n_e k_{43} + n_e k_{41}}{A_{43} + A_{41}} \right)}$$

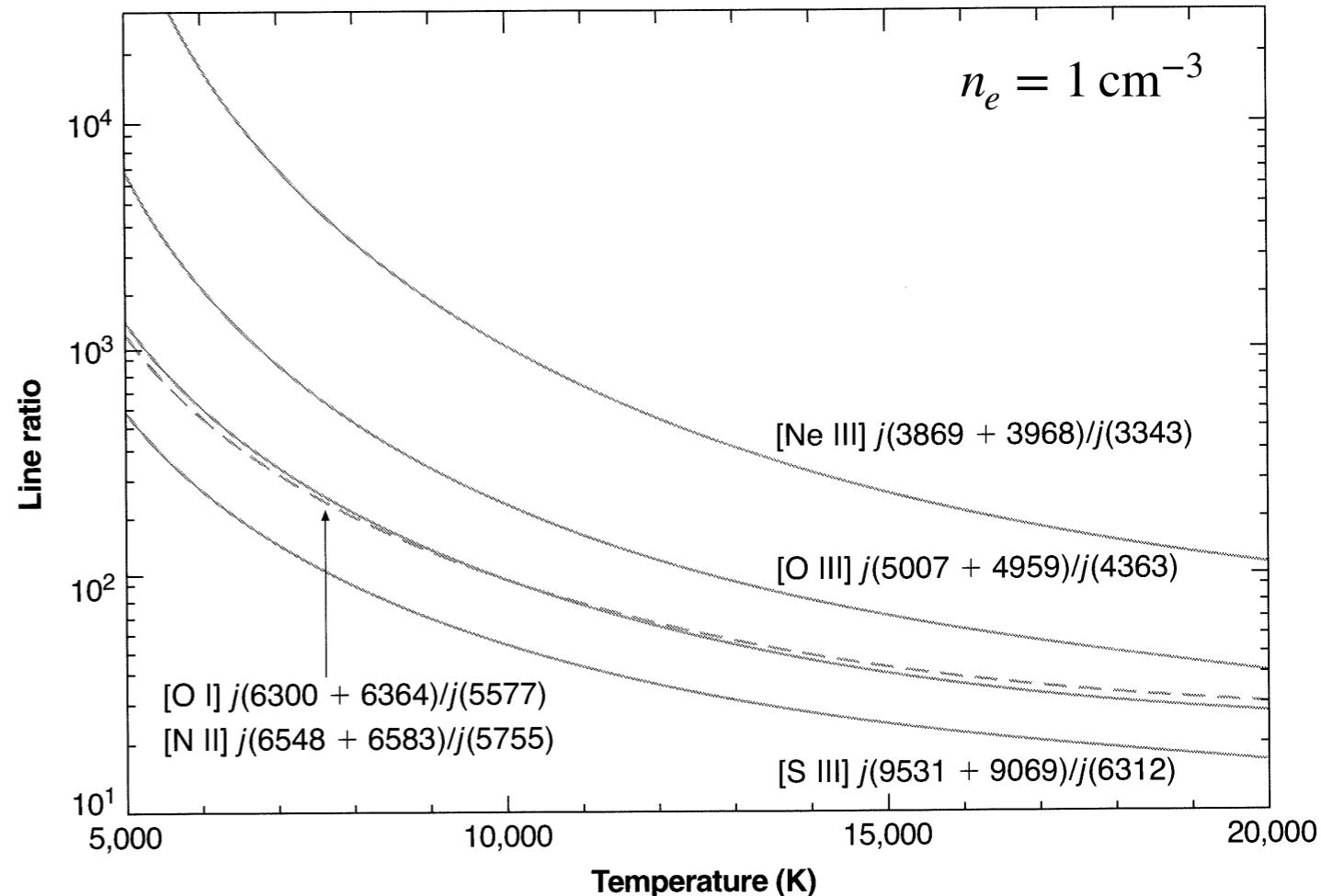
$$\frac{j(3 \rightarrow 1) + j(3 \rightarrow 2)}{j(4 \rightarrow 3)} \simeq \left. \frac{j(3 \rightarrow 1) + j(3 \rightarrow 2)}{j(4 \rightarrow 3)} \right|_0 \frac{1}{f_c} \qquad \qquad k_{ji} = \frac{\beta}{T^{1/2}} \frac{\langle \Omega_{ji} \rangle}{g_j}$$

$$f_c = \frac{1 + \frac{n_e k_{32} + n_e k_{31}}{A_{32} + A_{31}}}{1 + \frac{n_e k_{43} + n_e k_{41}}{A_{43} + A_{41}}} \simeq 1 + n_e \left( \frac{k_{32} + k_{31}}{A_{32} + A_{31}} - \frac{k_{43} + k_{41}}{A_{43} + A_{41}} \right) \qquad \qquad \beta = 8.629 \times 10^{-6}$$

[Figure 5.1]



See Equations (5.4)-(5.7) for a correction factor for the density effect.



$$[\text{O III}] \frac{j_{\lambda 4959} + j_{\lambda 5007}}{j_{\lambda 4363}} = \frac{7.90 \exp(3.29 \times 10^4/T)}{1 + 4.5 \times 10^{-4} n_e / T^{1/2}}$$

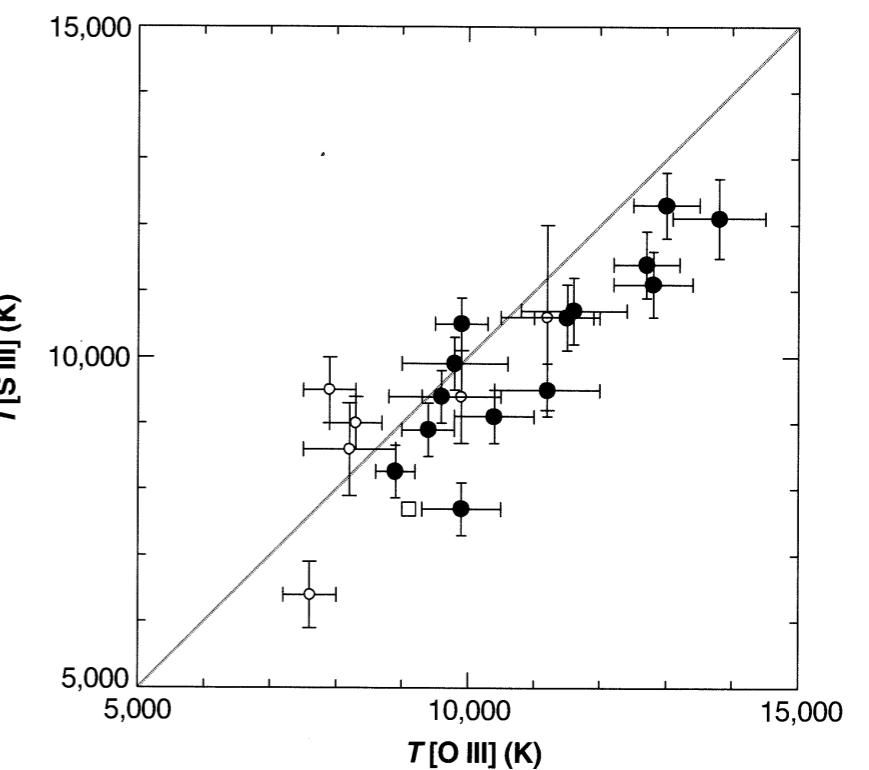
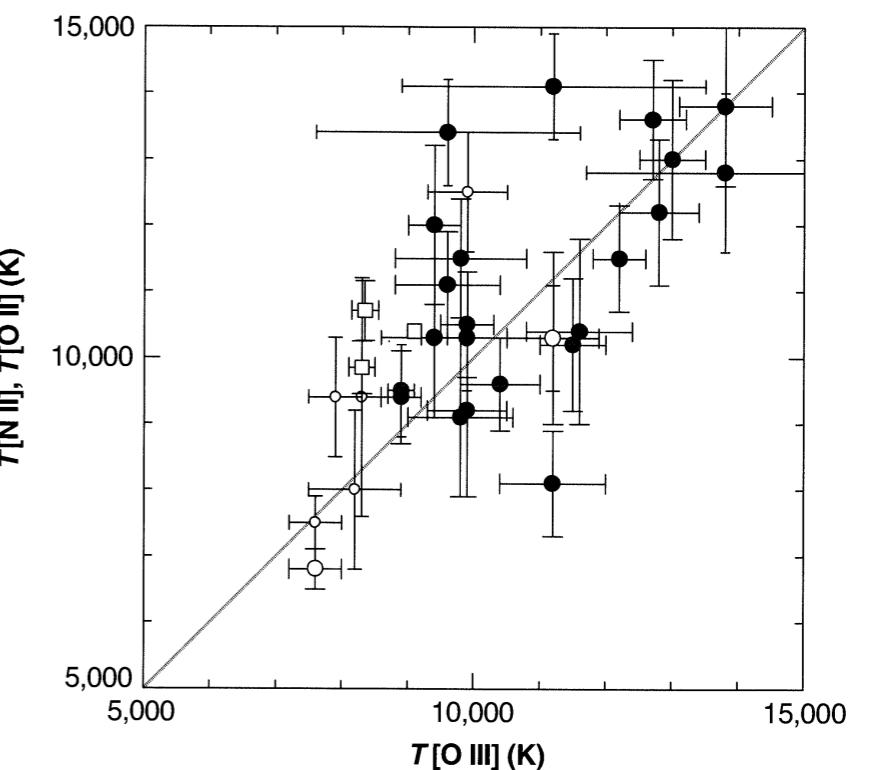
$$[\text{N II}] \frac{j_{\lambda 6548} + j_{\lambda 6583}}{j_{\lambda 5755}} = \frac{8.23 \exp(2.50 \times 10^4/T)}{1 + 4.4 \times 10^{-3} n_e / T^{1/2}}$$

$$[\text{Ne III}] \frac{j_{\lambda 3869} + j_{\lambda 3968}}{j_{\lambda 3343}} = \frac{13.7 \exp(4.30 \times 10^4/T)}{1 + 3.8 \times 10^{-5} n_e / T^{1/2}}$$

$$[\text{S III}] \frac{j_{\lambda 9531} + j_{\lambda 9069}}{j_{\lambda 6312}} = \frac{5.44 \exp(2.28 \times 10^4/T)}{1 + 3.5 \times 10^{-4} n_e / T^{1/2}}$$

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- Comparison with observations
    - Since the forbidden lines are optically thin, the ratio of emergent intensities are the ratio of the integrals of the emission coefficients along a ray through the nebula.
    - The observed strengths of the lines must be corrected for interstellar extinction, but this correction is usually not too large because the temperature-sensitive lines are relatively close in wavelength.
  - $[\text{O III}] (\lambda 4959 + \lambda 5007) / \lambda 4363$ 
    - $\lambda 4959 + \lambda 5007$  are strong lines, but  $\lambda 4363$  is relatively weak, and is close to Hg I  $\lambda 4358$  due to light pollution in the sky.
    - Therefore, the line ratio is quite large and difficult to measure accurately.
    - Early works have been centered on the [O III] lines, because they are in the blue spectral region where detectors are most sensitive, and they are quite bright in typical planetary nebulae.
  - $[\text{N II}]$ 
    - The lines are stronger in the outer parts of H II regions, where the ionization is lower and the O mostly emits [O II] lines.
    - Most recent works have used all of these lines.
  - $^2D^o$  and  $^2P^o$  levels of [O II] and [S II] (see page 4)
    - The two levels can also be used as temperature indicators.
    - They have advantage of lying in spectral regions that are relatively easy to observe, but the lines are widely separated in wavelength so that correction for interstellar dust extinction is larger.

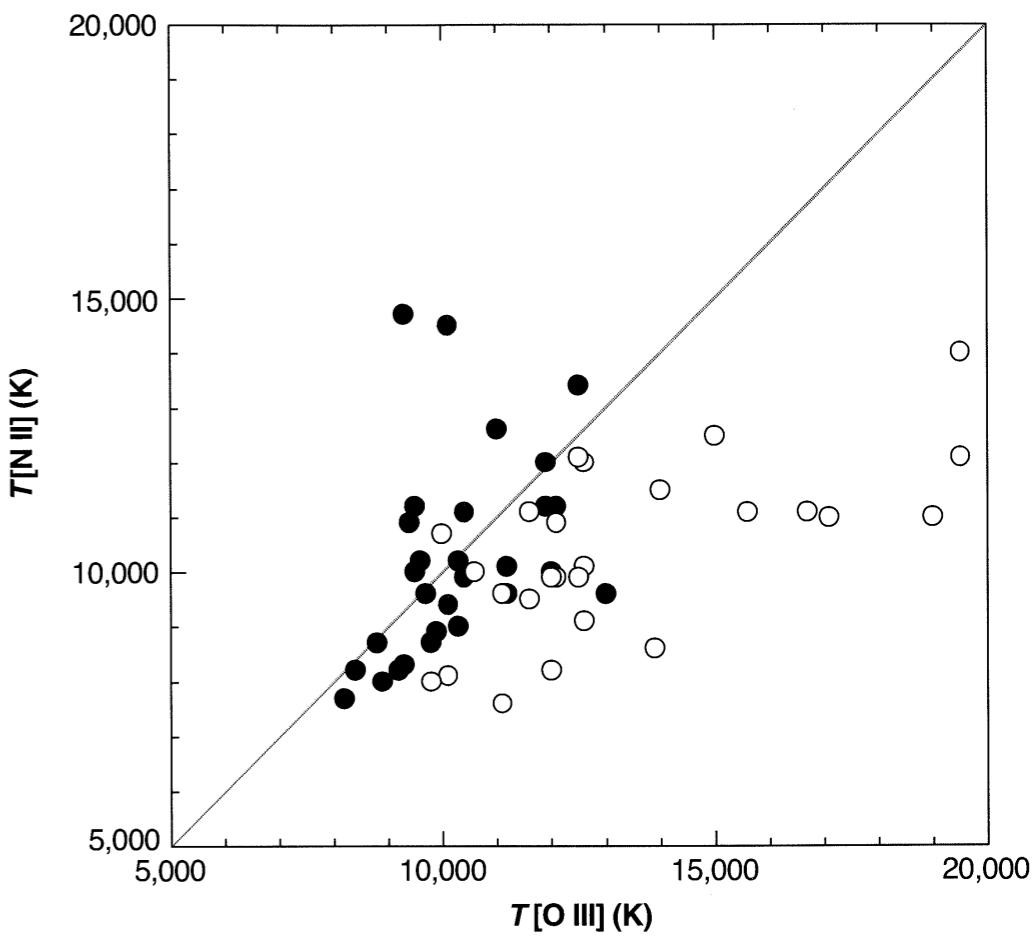
- Temperatures of H II regions
  - The temperatures are in the range 7,000-14,000 K.
  - The abundances of the heavy elements tend to increase inward, resulting in the differences in temperatures.



**Figure 5.2**

A comparison of values of the temperature in H II regions. The closed circles are H II regions in M 101; the open circles, in NGC 2403; and the open squares, different locations in the Orion Nebula.

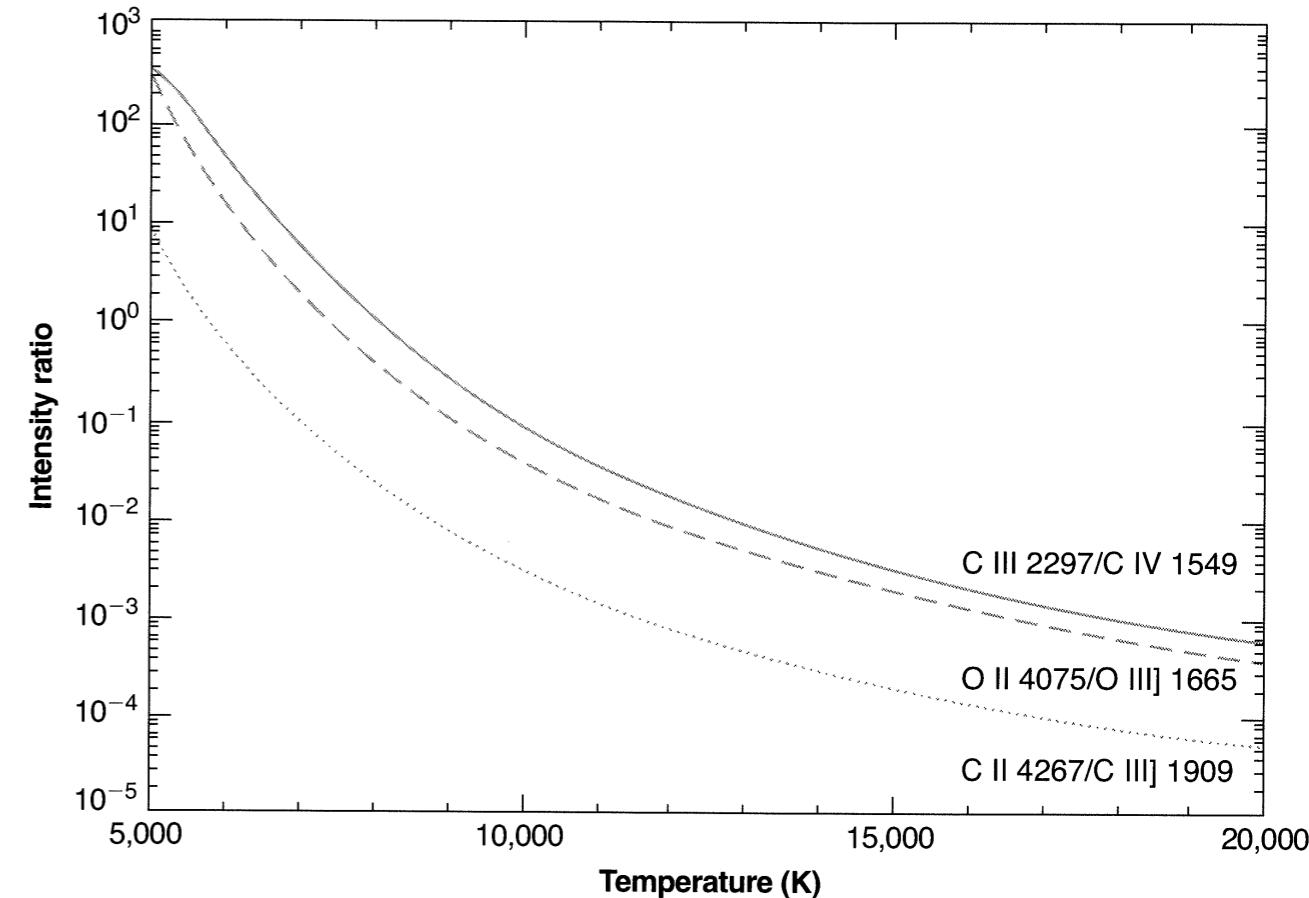
- Temperature of Planetary nebulae
  - PNe have higher surface brightness than H II regions.
  - Temperatures are measured using [O III].
  - [N II] is relatively weak, but measurements of it are also available.
  - The temperatures in the hottest PNe are somewhat higher than in H II regions, as a consequence of higher effective stellar temperatures and the higher electron densities in PNe, resulting in collisional deexcitation and decreased efficiency of radiative cooling.
  - Halo objects with relatively low heavy-element abundance results in somewhat above-average temperatures due to the lower cooling efficiency.
- It is reasonable to adopt  $T \approx 10^4$  K as an order-of-magnitude estimate for any nebula with near-normal abundances.
  - $T \approx 9,000$  K in the brighter parts of an H II region.
  - $T \approx 11,000$  K in a typical bright PN.



**Figure 5.3**

A comparison of two temperature indicators for a sample of planetary nebulae.

- Ratio of a collisionally excited line to a recombination line.
  - Another method to determine the temperature is to compare the relative strength of a collisionally excited line, such as C III]  $\lambda 1909$ , with a recombination line of the next lower state of ionization, such as C II  $\lambda 4267$
  - This is because both depend on the product of densities  $n(\text{C}^{++})n_e$ , which therefore cancels out of their ratios.
  - This method has been applied to relatively few objects because the collisionally excited line usually occurs in the vacuum UV.
  - However, this method has the advantage that the observed ratio is a very powerful function of the temperature so that even modest signal-to-noise spectra can determine the temperature quite accurately

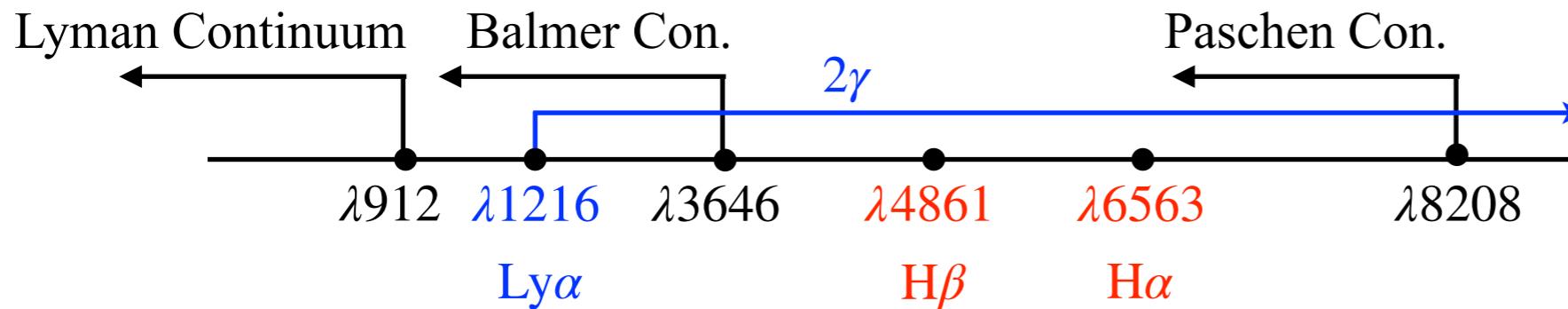


**Figure 5.4**

Several temperature-sensitive line-intensity ratios of dielectronic recombination to collisionally excited lines.

## 5.3 Temperature Determinations from Optical Continuum Measurements

- Is it possible to use the H recombination lines to determine the temperature?
  - No! The relative strengths of the H lines are almost independent of temperature. (Table 4.4) This is because of the following two reasons:
    - All recombination cross sections have approximately the same velocity dependence, so the relative numbers of atoms formed by capture to each level are nearly independent of  $T$ .
    - Furthermore, the cascade matrices depend only on transition probabilities.
- However, the temperature can be determined by measuring **the relative strength of the recombination continuum w.r.t. a recombination line**.
  - This is because the recombination continuum depends on  $T$ .
- Continuum choice:
  - (1) Continuum near  $H\beta \lambda 4861$ , which includes the H I Paschen and higher-series recombination continua and two-photon emission, and He I recombination continuum.
  - (2) Balmer discontinuity (Balmer jump),  $J_\nu(\lambda 3646-) - J_\nu(\lambda 3646+)$ , which includes only the H I recombination continuum due to capture into  $n = 2$ .

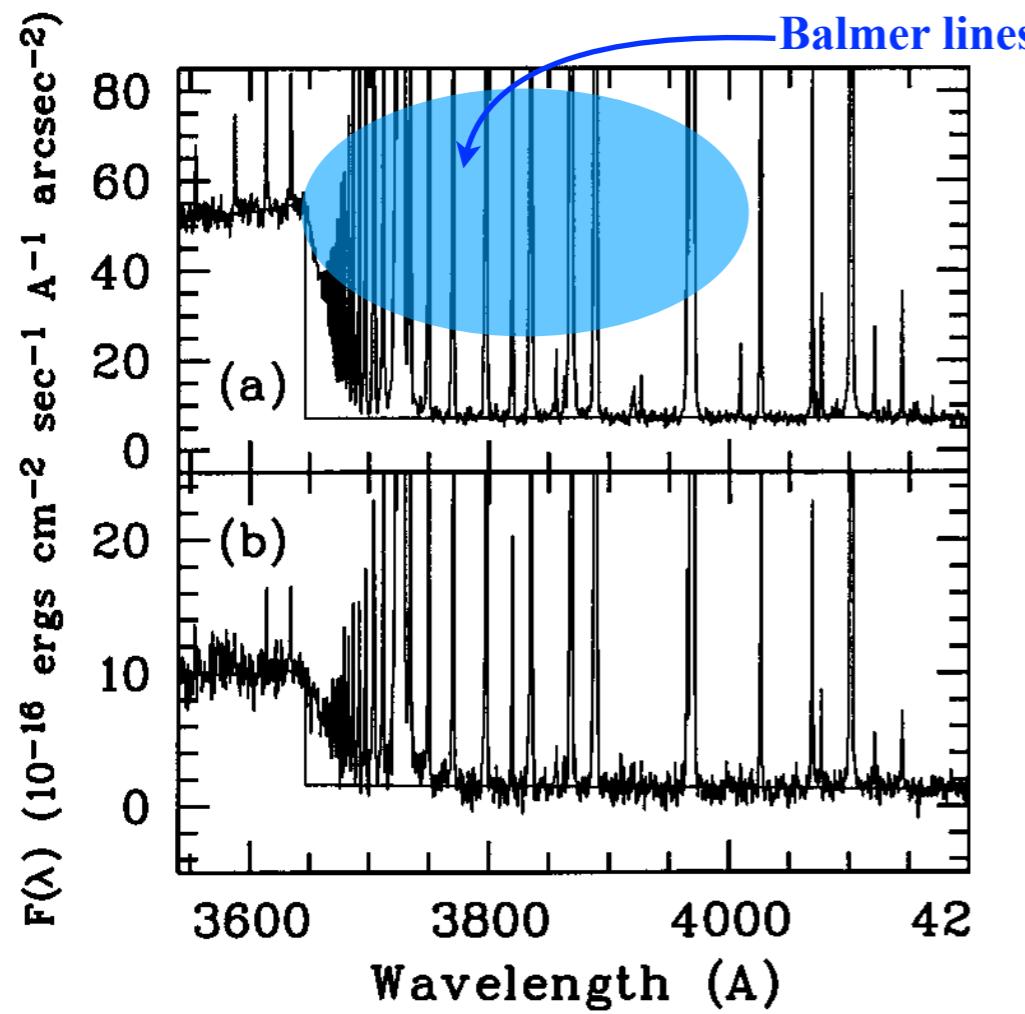


$$\frac{hc}{\lambda_{\text{Lyc}}} \geq \frac{1}{1^2} \text{Ryd}$$

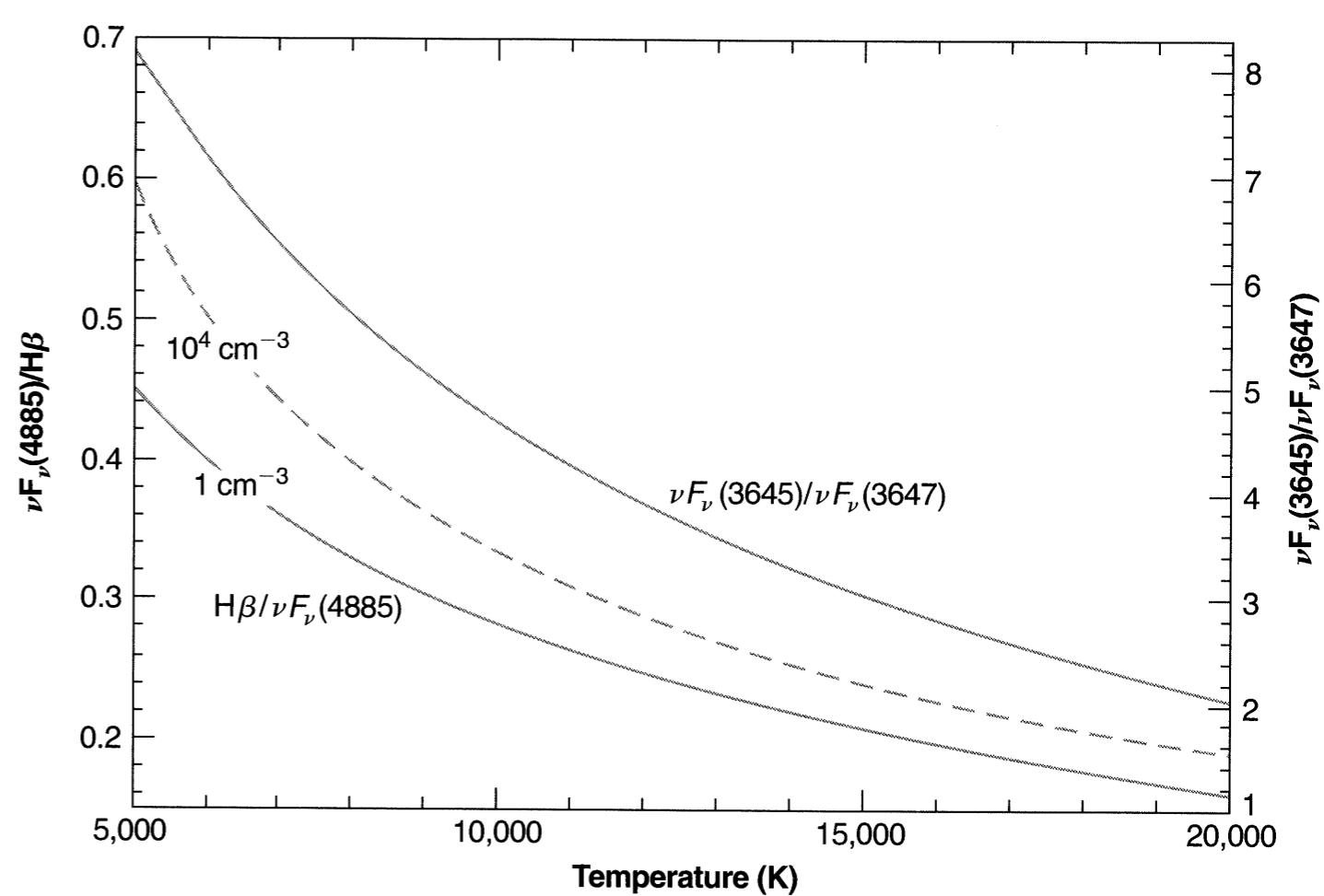
$$\frac{hc}{\lambda_{\text{Hc}}} \geq \frac{1}{2^2} \text{Ryd}$$

$$\frac{hc}{\lambda_{\text{Pac}}} \geq \frac{1}{3^2} \text{Ryd}$$

- $\lambda 4861$  continuum = (1) H I Paschen and higher-series continua, whose sum increases slowly with  $T$ , and (2) the two-photon continuum, whose strength decreases slowly with  $T$ .
  - ▶ Thus, the continuum to  $H\beta$  increases with  $T$ .
  - ▶ Collisional deexcitation of  $2^2S$  decreases the strength of the two photon emission. The ratio depends on density.
- The Balmer continuum decreases as  $\sim T^{-3/2}$ .
  - ▶ Thus, its ratio to  $H\beta$  decreases slowly with  $T$ , and is independent of density.



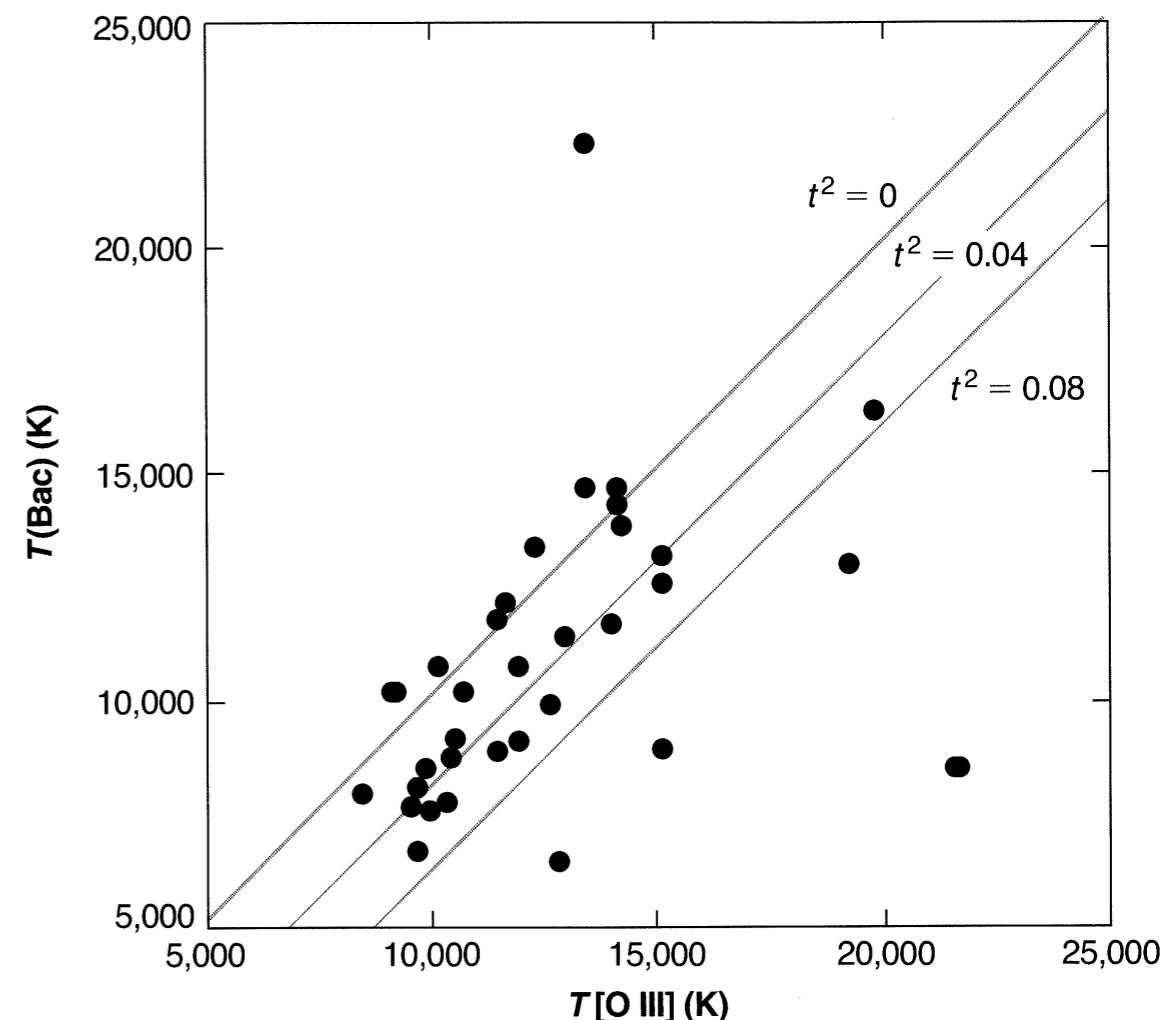
[Figure 3] Spectra of M42 near the Balmer jump region (Liu 1995, ApJL)



[Figure 5.5] continuum-to-recombination line ratio vs. temperature

- The observation of the continuum is difficult because:
  - It is weak and can be seriously affected by weak lines.
  - The second method using the Balmer continuum is the most accurate.
  - However, the higher Balmer lines are crowded just redward of the limit ( $\lambda \geq \lambda_{\text{Hc}}$ ). So the intensity must be measured at longer wavelengths and extrapolated to  $\lambda 3446 +$ .
  - Stellar continuum scattered by interstellar dust may have a considerable Balmer discontinuity (Balmer break).

- Figure 5.6
  - **The temperatures measured by the Balmer continuum method are generally smaller than the temperatures measured from forbidden-line ratios.**
  - This discrepancy is known to be due to temperature fluctuations in the nebulae. (will be discussed in the section 5.11.)



[Figure 5.6] Comparison of temperatures derived using the [O III] and Balmer continuum for planetary nebulae.

## 5.4 Temperature Determinations from Radio-Continuum Measurements

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- Radio continuum observations
  - At sufficiently low frequencies, any nebula becomes optically thick (due to free-free absorption), and therefore, at these frequencies the emergent intensity is the same as that from a blackbody (assuming an isothermal nebula).
  - At low frequencies, the brightness temperature is the gas temperature:

$$T_{b\nu} = T \left[ 1 - \exp(-\tau_\nu) \right] \rightarrow T \text{ as } \tau_\nu \rightarrow \infty$$

If there is (a) background non-thermal synchrotron radiation (behind the nebula) with brightness temperature  $T_{bg\nu}$  and (b) foreground radiation (between the nebula and the observer) with brightness temperature  $T_{fg\nu}$ , the RT equation gives

$$T_{b\nu} = T_{fg\nu} + T \left[ 1 - \exp(-\tau_\nu) \right] + T_{bg\nu} \exp(-\tau_\nu) \rightarrow T_{fg\nu} + T \text{ as } \tau_\nu \rightarrow \infty \text{ and } T_{fg\nu} = 0.$$

**This result suggests that the measurements at low frequencies can be used to obtain the temperature.**

- Difficulties in spatial resolution
  - However, **the beam size (PSF) of antenna pattern is order  $\lambda/d$ , where  $d$  is the diameter of the telescope.**
    - ▶ At sufficiently low frequencies ( $\nu \approx 3 \times 10^8 \text{ Hz}$  or  $\lambda \approx 10^2 \text{ cm}$ ), even the largest radio telescope have beam sizes that are comparable to or larger than the angular size of typical H II regions.
    - ▶ Thus, the antenna pattern tends to broaden the brightness temperature distribution, resulting in the mean brightness temperature.
    - ▶ Moreover, the optical depth decreases decreases continuously but with many fluctuations, from the maximum near the center to zero outside the edge of the nebula.

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- How to resolve the difficulties at low frequencies.
    - This issue may be resolved by combining the low frequency measurement with high frequency measurements.
    - Suppose that  $\nu_1$  = high frequency,  $\nu_2$  = low frequency.
    - Measurements of brightness temperatures:
 
$$T_{b1} = T [1 - \exp(-\tau_1)] \approx T\tau_1 \text{ (because } \tau_1 \approx 0\text{)} \Rightarrow \text{position-dependent optical depth}$$

$$T_{b2} = T [1 - \exp(-\tau_2)] \qquad \qquad \qquad \Rightarrow \text{mean optical depth, independent of location.}$$
    - The free-free absorption coefficient is  $\kappa_\nu = n_+ n_e \frac{16\pi^2 Z^2 e^6}{(6\pi m_e k T)^{3/2} \nu^2 c} g_{ff}$ .
- Therefore, the ratio between the optical depths is obtained as  $\tau_2 = (\nu_1^2 / \nu_2^2) \tau_1$ .
- Procedure for correcting the effects of finite beam size at low frequencies:
    - (1) assume a temperature  $T$  (isothermal, independent of location)
    - (2)  $\tau_1 \approx T_{b1}/T$  as a function of location
    - (3) calculate  $\tau_2 = (\nu_1^2 / \nu_2^2) \tau_1$  as a function of location
    - (4) calculate  $T_{b2}(\mathbf{r})$  as a function of location
    - (5) convolve  $T_{b2}(\mathbf{r})$  with the antenna profile and predict  $\tau_{b2}^{\text{predict}}$ .
    - (6) if the predicted one ( $\tau_{b2}^{\text{predict}}$ ) is different from the measured one  $\tau_{b2}$ , select a different  $T$  and go to step (1) until the prediction matches with the measured one.

- 
- Planetary Nebulae is much smaller than H II regions.
    - The correction for this effect is quite important. Nearly all the PNe are too small for mapping at low frequencies with single-dish radio telescopes.
    - But, it is possible to estimate the relative values of  $\tau_2$  at each point in the nebula using the surface brightness in a H recombination line such as H $\beta$ , since H $\beta$  intensity is proportional to the emission measure:

$$I(\text{H}\beta) \propto \int n_p n_e ds = \text{EM}_p$$

For any assumed optical depth at one point and at one frequency, the optical depths at all other points and at all frequencies can be calculated.

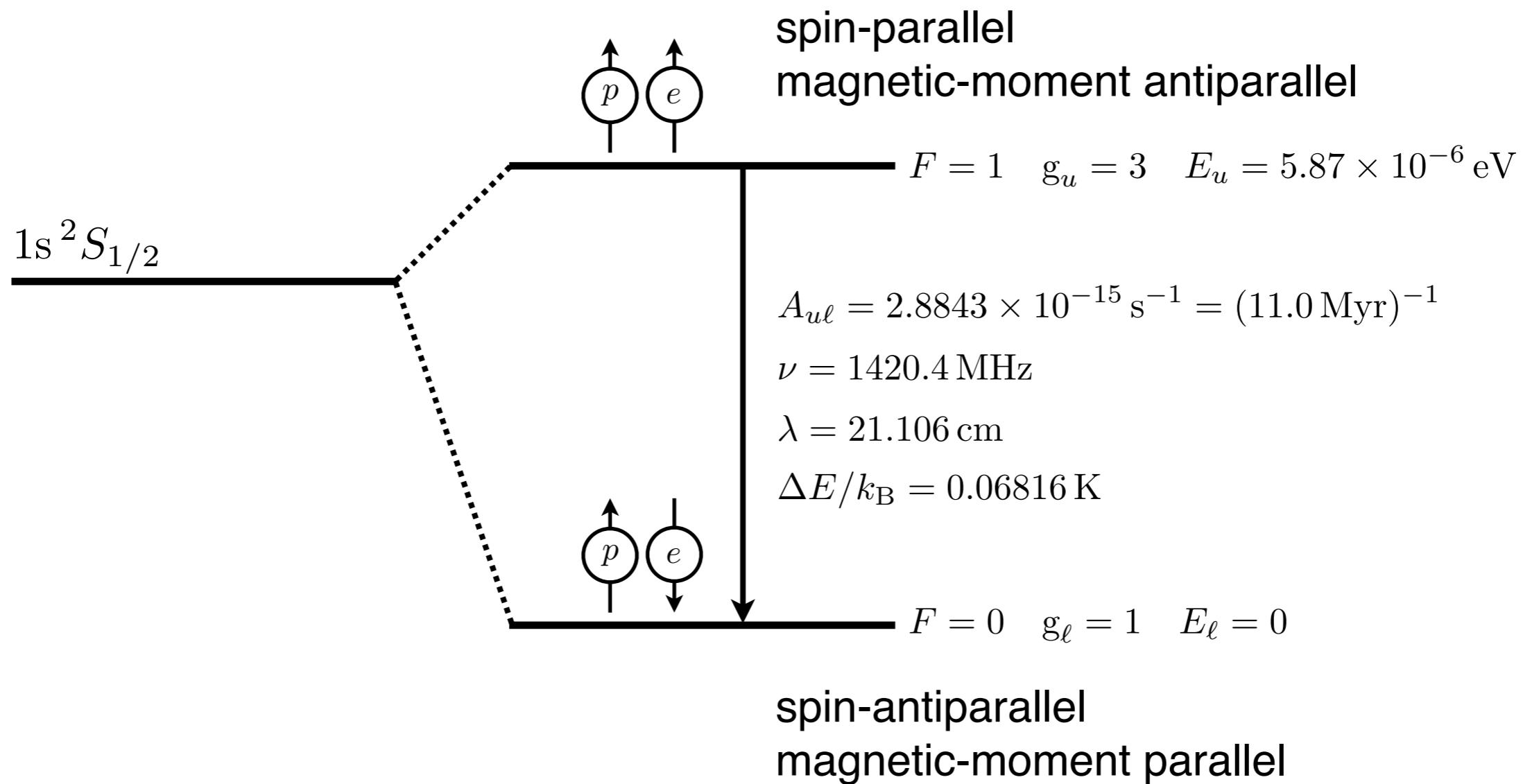
For any assumed temperature, the expected flux at each frequency can thus be calculated and compared with measurements.

- The radio measurements must be available for at least two frequencies, because we are assuming two independent variables ( $\tau$  at one point and temperature  $T$ ).

The two parameters must be varied to get the best fit between calculations and measurements.

- Angular resolution of the VLA (Very Large Array) radio interferometer is  $\sim 0.05''$  at high frequency ( $\lambda = 1.3$  cm). Therefore, ideal for these measurements. Measurements determined in this way for PNe are:
  - ▶  $T = 8,300$  K for NGC 6543,  $T = 18,500$  K for IC 418, and  $T = 14,000$  K for NGC 7027.

## Hyperfine splitting of the 1s ground state of atomic H



Note that the magnetic moment is proportional to the charge, so the electron and proton have opposite directions of the magnetic moments.

- 
- H I 21-cm line
    - an electron spin-flip transition, with a transition probability of  $A = 2.85 \times 10^{-15} \text{ s}^{-1}$ .
    - spin temperature  $\frac{n_u}{n_l} = \frac{g_u}{g_l} \exp(-\chi_{ul}/kT_{\text{ex}})$ , where  $u$  and  $l$  indicate the upper and lower levels, and  $\chi_{ul}$  is the excitation energy of the line.
    - $T_{\text{ex}}(21 \text{ cm}) = T$  in most conditions
      - ▶  $T_{\text{ex}}$  becomes equal to the gas kinetic temperature if the level populations are determined by collisions with electrons and H atoms (or Ly $\alpha$  pumping; Wouthuysen-Field effect, Seon & Kim 2020, ApJS).
      - ▶ This is usually the case when the electron or H density is higher than the critical density of the 21 cm transition, and the radiation density at 21 cm is low.
      - ▶ The critical electron density is  $3.6 \times 10^{-7} \text{ cm}^{-3}$ , so the populations are collisionally determined for most conditions.
      - ▶ Scattering by Ly $\alpha$  photons is also important in most ISM conditions.
  - Line optical depth  $\tau$  of any transition
    - $$\tau = \kappa L = \sigma \left( n_l - \frac{g_l}{g_u} n_u \right) L$$
    - Here,  $\kappa$  = line opacity,  $L$  = path length,  $\sigma$  = atomic absorption cross section ( $\text{cm}^2$ ).
    - The first term represents the pure absorption and the second term corrects for stimulated emission.

- Using the definition of  $T_{\text{ex}}$ , the opacity  $\kappa$  can be written as

$$\begin{aligned}\kappa &= \sigma n_l [1 - \exp(-\chi_{ul}/kT_{\text{ex}})] \\ &= \sigma n_l \quad \text{if } \chi_{ul} \gg kT_{\text{ex}} \approx kT \quad (\text{for Ly}\alpha \text{ at } T \sim 10^4 \text{ K}) \\ &= \sigma n_l \frac{\chi_{nl}}{T_{\text{ex}}} \quad \text{if } \chi_{ul} \ll kT_{\text{ex}} \approx kT \quad (\text{for HI 21 cm})\end{aligned}$$

- Therefore, the optical depth between the radio and UV lines is given by
- **The ratio of the optical depths of the HI 21 cm and Ly $\alpha$  lines can be combined to measure the excitation temperature, which is in practice the same as the gas temperature.**

$$\frac{\tau_{\text{radio}}}{\tau_{\text{UV}}} = \frac{n_{l,\text{radio}}}{n_{l,\text{UV}}} \frac{\kappa_{\text{radio}} L}{\kappa_{\text{UV}} L} = \frac{n_{l,\text{radio}}}{n_{l,\text{UV}}} \frac{\sigma_{\text{radio}}}{\sigma_{\text{UV}}} \frac{\chi_{ul,\text{UV}}}{kT_{\text{ex}}} \quad \begin{aligned}A_{21\text{ cm}} &= 2.85 \times 10^{-15} \text{ s}^{-1} \\ A_{\text{Ly}\alpha} &= 6.265 \times 10^8 \text{ s}^{-1}\end{aligned}$$

$$\boxed{\frac{\tau_{21\text{ cm}}}{\tau_{\text{Ly}\alpha}} = \frac{1}{4} \frac{\sigma_{21\text{ cm}}}{\sigma_{\text{Ly}\alpha}} \frac{\chi_{ul}}{kT_{\text{ex}}} = \frac{1}{4} \frac{A_{21\text{ cm}} \lambda_{21\text{ cm}}^3}{A_{\text{Ly}\alpha} \lambda_{\text{Ly}\alpha}^3} \frac{\chi_{ul,\text{Ly}\alpha}}{kT_{\text{ex}}} = 3.84 \times 10^{-7} T_{\text{ex}}^{-1}}$$

Here, we note that

$$n_{l,\text{Ly}\alpha} = n_{n=1}$$

$$n_{l,21\text{ cm}} = \frac{g_{F=0}}{g_{F=0} + g_{F=1}} n_{n=1} = \frac{1}{4} n_{n=1} \quad \Leftarrow \quad \frac{n_{l,21\text{ cm}}}{n_{u,21\text{ cm}}} = \frac{g_{F=0}}{g_{F=1}} \exp\left(-\frac{h\nu_{21\text{ cm}}}{kT_{\text{ex}}}\right) \approx \frac{1}{3}$$

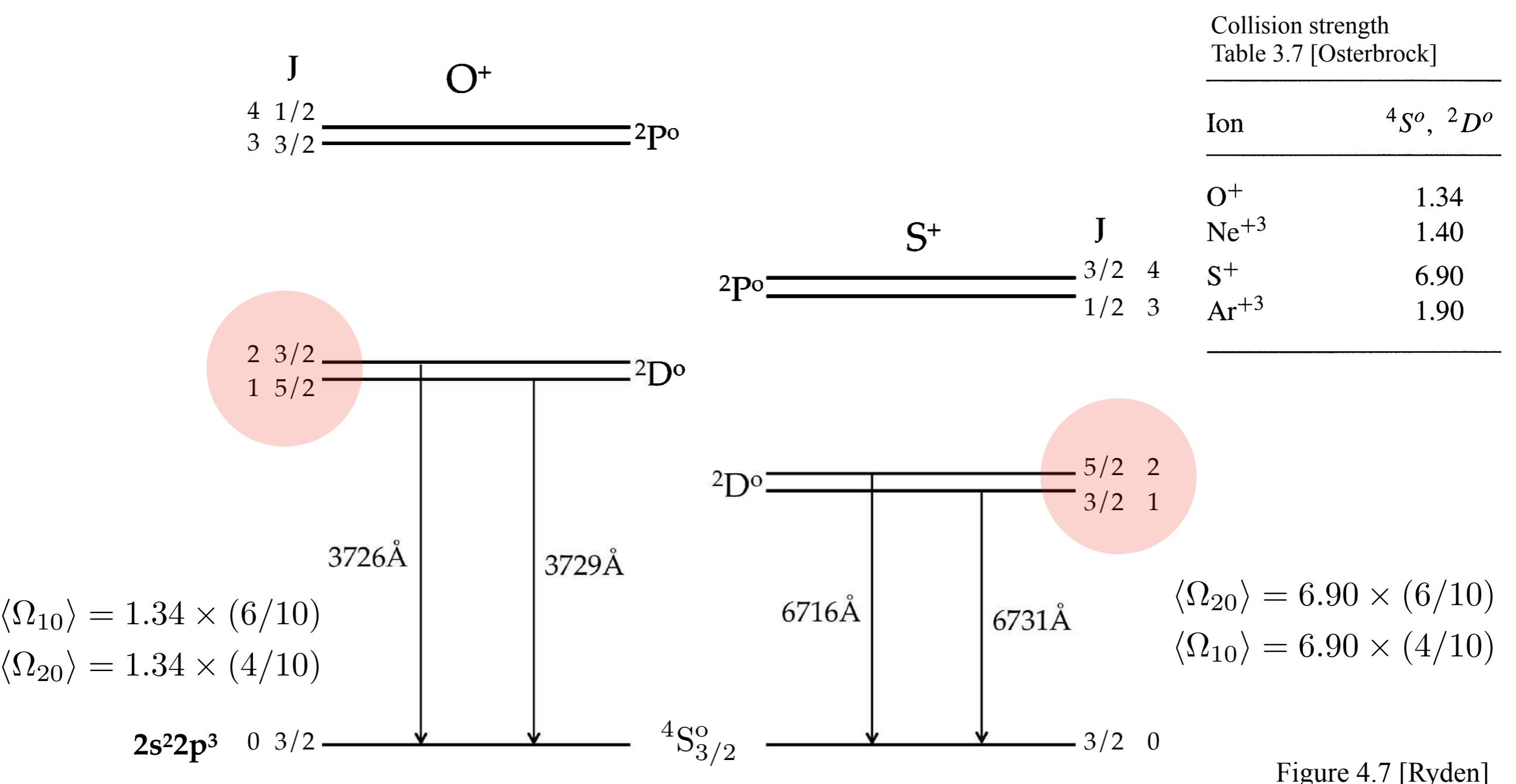
## 5.6 Electron Densities from Emission Lines

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- Density diagnostics
  - The average electron density may be measured by observing the effects of collisional deexcitation.
  - This can be done by comparing the intensities of two lines of the same ion, emitted by different levels with nearly the same excitation energy so that the relative excitation rates to the two levels depend only on the ratio of collision strengths.
  - If the two levels have different radiative transition probabilities or different collisional deexcitation rates, their relative populations will depend on the density and the ratio of intensities will likewise depend on the density.
  - The best examples are  $[\text{O III}] \lambda 3729/\lambda 3726$  and  $[\text{S II}] \lambda 6716/\lambda 6731$ .
- Ions with 7 or 15 electrons have  $2s^22p^3$  and  $3s^23p^3$  configurations, with energy level structures that make them suitable for use as density diagnostics.

Density-sensitive nebular lines (Å).

$p^3$ Ions	[O II]	[S II]	[Ne IV]	[Ar IV]
$^2\text{D}_{3/2} \rightarrow ^4\text{S}_{3/2}$	3726	6731	2423	4740
$^2\text{D}_{5/2} \rightarrow ^4\text{S}_{3/2}$	3729	6716	2426	4711
	$2s^22p^2$	$3s^23p^2$	$2s^22p^2$	$3s^23p^2$
	Z = 8	Z = 16	Z = 10	Z = 18



Notice that energy ordering of the fine-structure levels are different between  $O^+$  and  $S^+$ . The  $p^3$  configuration for the two ions are half-filled, and thus **Hund's rule for the energy ordering is not applicable**.

- Here, we will ignore the transition between 2 and 1 because the transition is very slow.
  - $1 \rightarrow 0$  transition:
    - The emissivity of the  $1 \rightarrow 0$  transition, integrated over the entire line width, is

$$4\pi j(1 \rightarrow 0) = n_1 A_{10} h\nu_{10}$$

- In statistical equilibrium, the rate of collisional excitation from the ground state will be balanced by radiative and collisional de-excitation:

Then,  $n_e n_0 k_{01} = n_1 (A_{10} + n_e k_{10})$

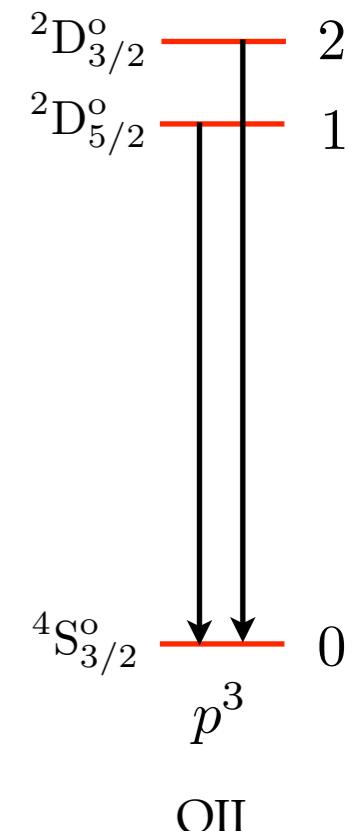
$$\Rightarrow n_1$$

$$\begin{aligned} 4\pi j(1 \rightarrow 0) &= n_e n_0 \frac{k_{01}}{A_{10} + n_e k_{10}} A_{10} h\nu_{10} \\ &= n_e n_0 \frac{k_{01}}{1 + n_e/n_{\text{crit},1}} h\nu_{10} \quad \text{where } n_{\text{crit},1} \equiv A_{10}/k_{10} \end{aligned}$$

- $2 \rightarrow 0$  transition:

- Similarly, we obtain

$$4\pi j(2 \rightarrow 0) = n_e n_0 \frac{k_{02}}{1 + n_e/n_{\text{crit},2}} h\nu_{20} \quad \text{where } n_{\text{crit},2} \equiv A_{20}/k_{20}$$



- The ratio of the strength of the two lines in the doublet is

$$\begin{aligned}\frac{j(2 \rightarrow 0)}{j(1 \rightarrow 0)} &= \frac{\nu_{20}}{\nu_{10}} \frac{k_{02}}{k_{01}} \frac{1 + n_e/n_{\text{crit},1}}{1 + n_e/n_{\text{crit},2}} \\ &= \frac{\nu_{20}}{\nu_{10}} \frac{\langle \Omega_{20} \rangle}{\langle \Omega_{10} \rangle} e^{-h\nu_{21}/kT} \frac{1 + n_e/n_{\text{crit},1}}{1 + n_e/n_{\text{crit},2}}\end{aligned}$$

$$k_{0u} = \left( \frac{\beta}{T^{1/2}} \frac{1}{g_0} \right) \langle \Omega_{u0} \rangle e^{-h\nu_{u0}/kT}$$

$$\beta = 8.62942 \times 10^{-6}$$

- Thus, we can write the line ratio as

$$\frac{j(2 \rightarrow 0)}{j(1 \rightarrow 0)} \simeq \frac{\langle \Omega_{20} \rangle}{\langle \Omega_{10} \rangle} \frac{1 + n_e/n_{\text{crit},1}}{1 + n_e/n_{\text{crit},2}}$$

$h\nu_{20} \simeq h\nu_{10}$  Levels 1 and 2 are very close in energy.

$h\nu_{21} \equiv h\nu_{20} - h\nu_{10} \ll kT$

$h\nu_{21} \approx 2 \text{ meV}$  for O II ions

- In the low-density limit ( $n_e \ll n_{\text{crit},1}, n_{\text{crit},2}$ ),

$$\frac{j(2 \rightarrow 0)}{j(1 \rightarrow 0)} \simeq \frac{\langle \Omega_{20} \rangle}{\langle \Omega_{10} \rangle} = \frac{g_2}{g_1}$$

$$\Omega_{(\text{SLJ}, \text{S'L'J}')} = \frac{(2J' + 1)}{(2S' + 1)(2L' + 1)} \Omega_{(\text{SL}, \text{S'L'})}$$

Recall the sum rule for the collision strength for the fine-structure transitions.

[However, it is not clear that the sum rule is valid even beyond the LS-coupling scheme. Recent QM calculations show that the proportionality relation is only an approximation.]

- In high-density limit ( $n_e \gg n_{\text{crit},2}, n_{\text{crit},1}$ ),

$$\frac{j(2 \rightarrow 0)}{j(1 \rightarrow 0)} \simeq \frac{\langle \Omega_{20} \rangle}{\langle \Omega_{10} \rangle} \frac{n_{\text{crit},2}}{n_{\text{crit},1}} = \frac{\langle \Omega_{20} \rangle}{\langle \Omega_{10} \rangle} \frac{A_{20}/k_{20}}{A_{10}/k_{10}} = \frac{g_2}{g_1} \frac{A_{20}}{A_{10}}$$

$$k_{u0} = \frac{\beta}{T^{1/2}} \frac{\langle \Omega_{u0} \rangle}{g_u}$$

► For O II ion,

$$n_e \ll n_{\text{crit}} \rightarrow \frac{j(1 \rightarrow 0)}{j(2 \rightarrow 0)} \simeq \frac{g_1}{g_2}$$

$$n_e \gg n_{\text{crit}} \rightarrow \frac{j(1 \rightarrow 0)}{j(2 \rightarrow 0)} \simeq \frac{g_1}{g_2} \frac{A_{10}}{A_{20}}$$

$$\frac{j([\text{O II}] 3728.8)}{j([\text{O II}] 3726.1)} = 1.5$$

$$\frac{j([\text{O II}] 3728.8)}{j([\text{O II}] 3726.1)} = 0.3$$

$$\frac{j(3729)}{j(3726)} = 1.5 \frac{1 + (n_e / 1.55 \times 10^4 \text{ cm}^{-3}) T_4^{-1/2}}{1 + (n_e / 3.11 \times 10^3 \text{ cm}^{-3}) T_4^{-1/2}}$$

$$g_1 = 6, \quad A_{10} = 3.59 \times 10^{-5} \text{ s}^{-1}$$

$$g_2 = 4, \quad A_{20} = 1.79 \times 10^{-4} \text{ s}^{-1}$$

$$\langle \Omega_{10} \rangle = 1.34 \times (6/10)$$

$$\langle \Omega_{20} \rangle = 1.34 \times (4/10)$$

► For S II ion,

$$n_e \ll n_{\text{crit}} \rightarrow \frac{j(2 \rightarrow 0)}{j(1 \rightarrow 0)} \simeq \frac{g_2}{g_1}$$

$$n_e \gg n_{\text{crit}} \rightarrow \frac{j(2 \rightarrow 0)}{j(1 \rightarrow 0)} \simeq \frac{g_2}{g_1} \frac{A_{20}}{A_{10}}$$

$$\frac{j([\text{S II}] 6716)}{j([\text{S II}] 6731)} = 1.5$$

$$\frac{j([\text{S II}] 6716)}{j([\text{S II}] 6731)} = 0.44$$

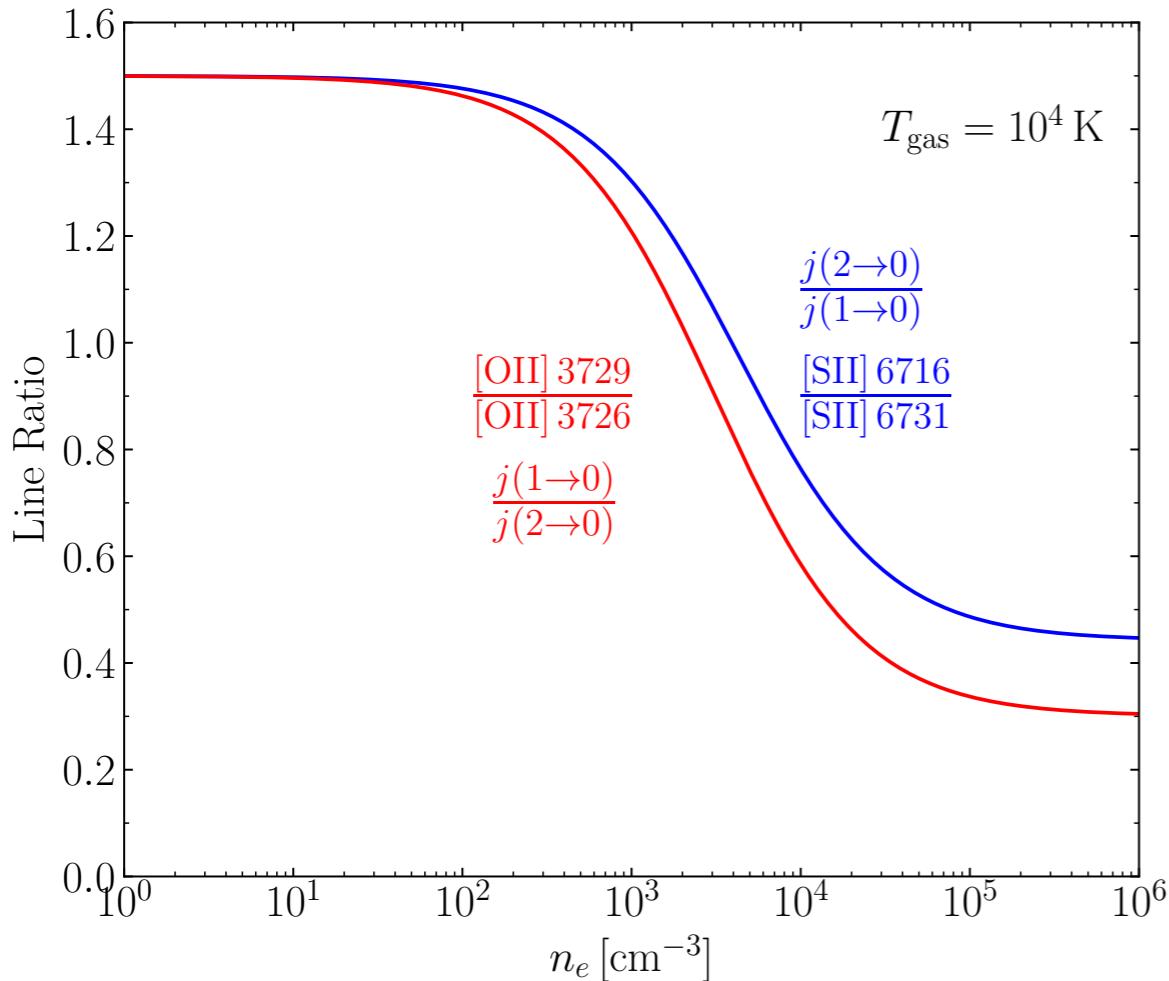
$$g_2 = 6, \quad A_{20} = 2.60 \times 10^{-4} \text{ s}^{-1}$$

$$g_1 = 4, \quad A_{10} = 8.82 \times 10^{-4} \text{ s}^{-1}$$

$$\langle \Omega_{20} \rangle = 6.90 \times (6/10)$$

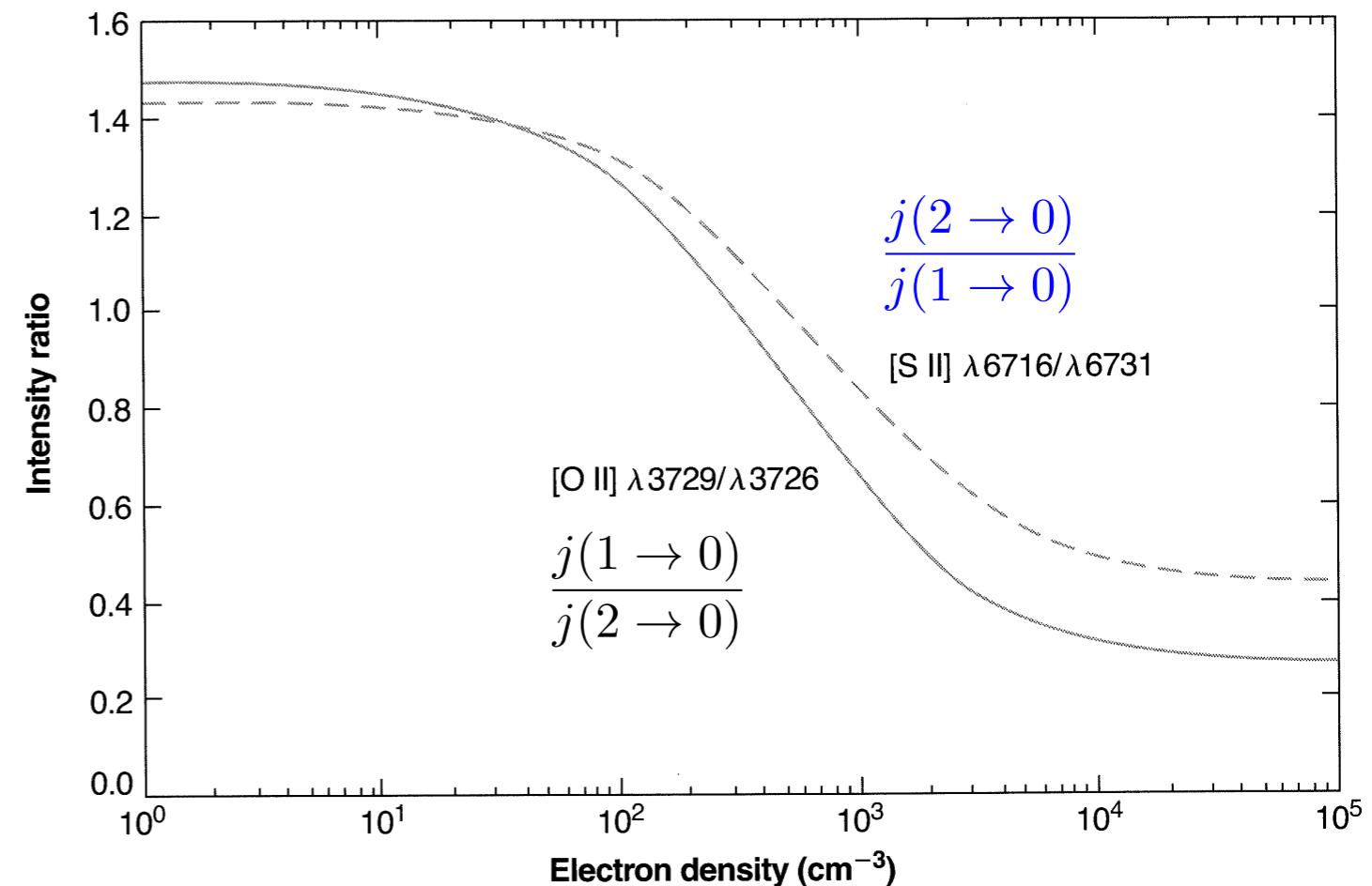
$$\langle \Omega_{10} \rangle = 6.90 \times (4/10)$$

$$\frac{j(6716)}{j(6731)} = 1.5 \frac{1 + (n_e / 1.48 \times 10^4 \text{ cm}^{-3}) T_4^{-1/2}}{1 + (n_e / 4.37 \times 10^3 \text{ cm}^{-3}) T_4^{-1/2}}$$



Obtained using the approximate equations in this lecture note.

***Notice differences between two figures.***



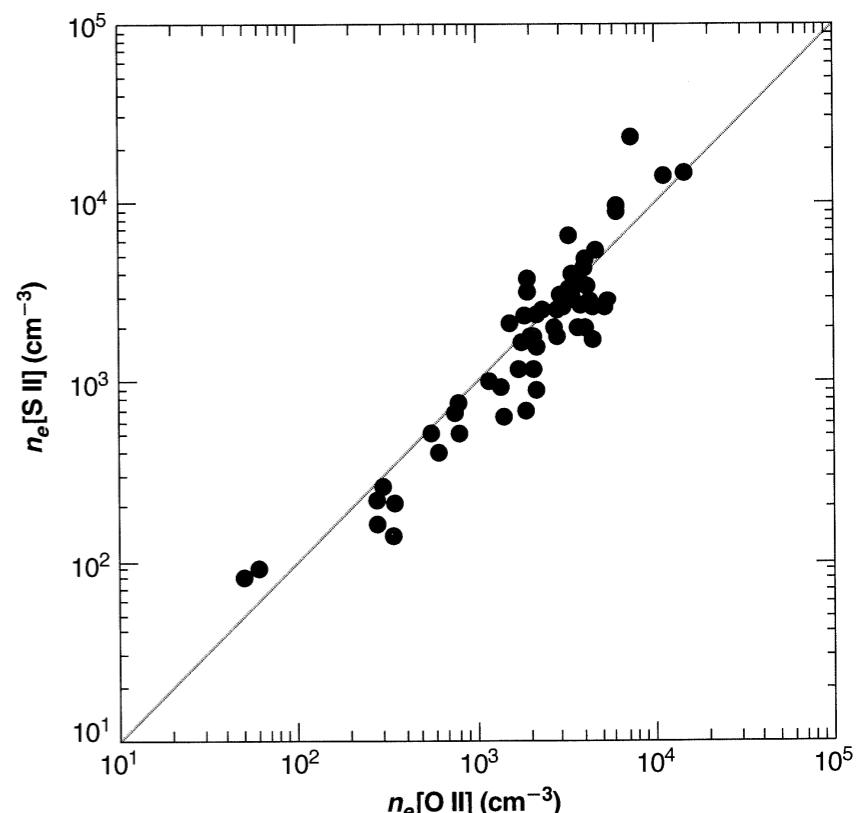
[Figure 5.8] The full solution of the equilibrium equations, which also takes into account all transitions, including excitation to the  ${}^2\text{P}^o$  levels with subsequent cascading downward.

- 
- Observations
    - From the observational point of view, it is unfortunate that the [O II]  $\lambda\lambda 3726, 3729$  are so close in wavelength; a high spectral resolution spectrograph (or spectrometer) must be used to separate the lines.
    - NGC 1976
      - ▶ Observations of [O II] ratio in NGC 1976 show that the mean electron density is higher near the center of the nebula and decreases relatively smoothly outward in all directions.
      - ▶ The intensity observed at the center results from emission accumulated along the line of sight, so the actual central density must be higher than the observed value.
      - ▶ A theoretical model reproduced all the [O II] ratios in NGC 1976; this model has  $n_e \approx 1.7 \times 10^4 \text{ cm}^{-3}$  at the center and decreases to  $n_e \approx 10^2 \text{ cm}^{-3}$  in the outer parts.
      - ▶ [S II] lines give the similar densities as those estimated from the [O II] lines.
    - M 8
      - ▶ In M 8, the density falls off outward from the Hourglass (a small condensation where  $n_e \approx 1 \times 10^3 \text{ cm}^{-3}$ ).

[Table 5.2] Electron densities in H II regions

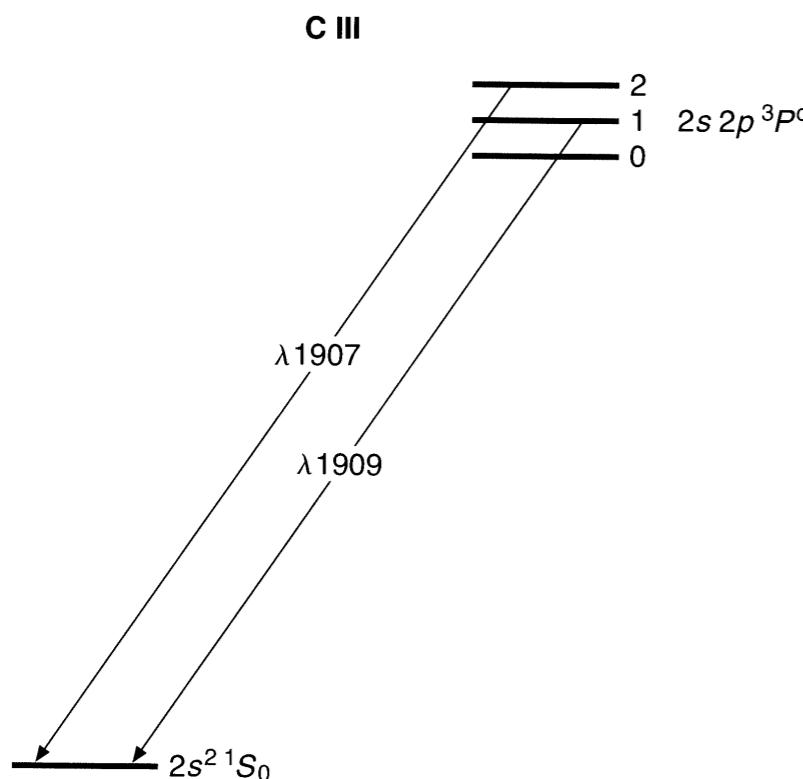
Object	$I(\lambda 3729)/I(\lambda 3726)$	$n_e (\text{cm}^{-3})$
NGC 1976 A	0.5	$3.0 \times 10^3$
NGC 1976 M	1.26	$1.4 \times 10^2$
M 8 Hourglass	0.67	$1.6 \times 10^3$
M 8 Outer	1.26	$1.5 \times 10^2$
MGC 281	1.37	70
NGC 7000	1.38	60

- In PNe,
  - The densities derived from these two ions are mostly within a factor of two of each other.
  - In most PNe, the degree of ionization is high. Therefore, most of the [O II] and [S II] lines arise either in the outermost parts or in the densest parts, where the ionization degree is low. Therefore, the densities derived from these ions may not be representative of the entire nebula.
  - The higher stages of ionization, [Ar IV], [K V], are more representative, but their lines are weaker.
    - ▶ For instance, for NGC 7662, [Ar IV] lines give  $n_e \approx 1.0 \times 10^4 \text{ cm}^{-3}$  and [Ne IV]  $\lambda\lambda 2422, 2424$  give  $n_e \approx 9.6 \times 10^3 \text{ cm}^{-3}$  at an assumed  $T = 10^4 \text{ K}$ .
- Temperature + Density
  - The electron densities derived from these line ratios may be used to correct the results of temperature-sensitive lines of [O III] and [N II] for the slight collisional deexcitation effect.
  - However, the emitting region of [O III] lines would be different from the regions where most [O II] lines originate. But, the density effect is small.

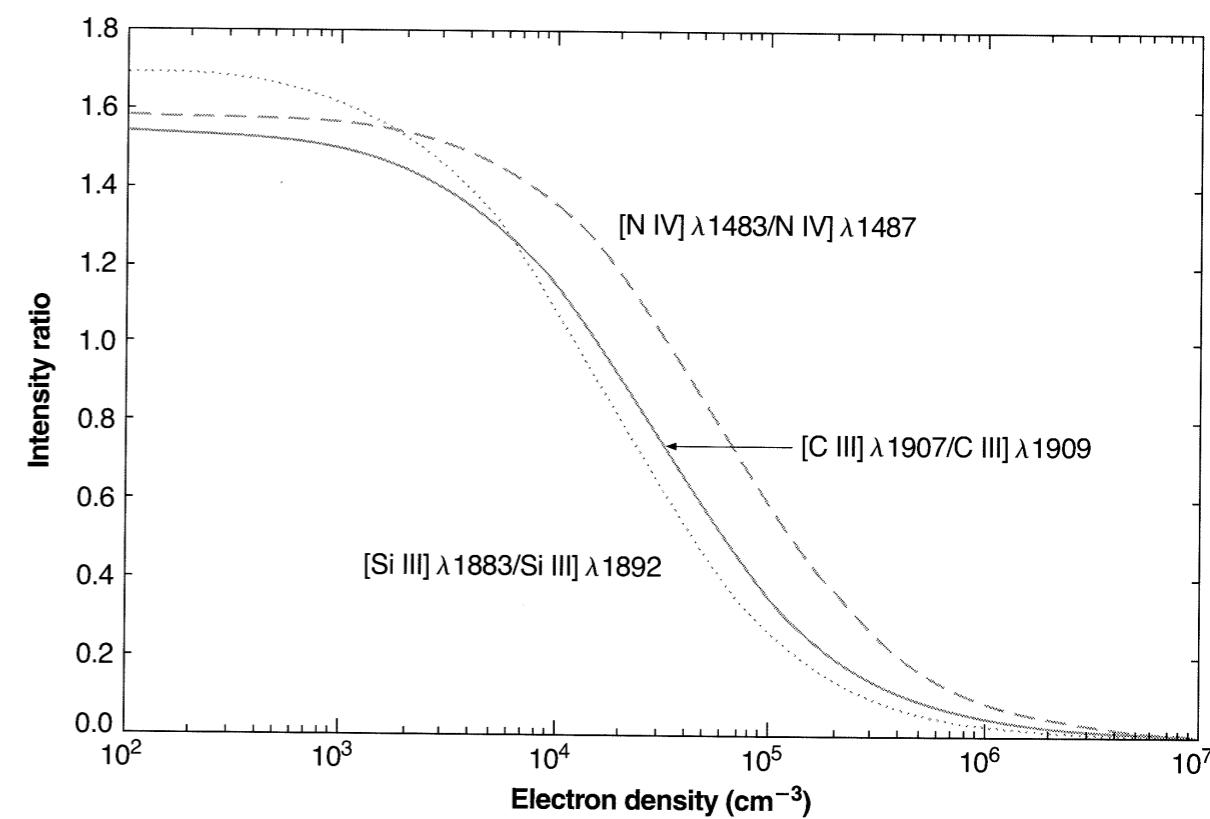


[Figure 5.9] Densities of PNe calculated from the [O II] and [S II] line ratios.

- In densest PNe, collisional deexcitation of [O III]  $^1D_2$  is strong enough so that the line ratio is significantly affected.
- IC 4997
  - ▶  $\lambda 3729/\lambda 3726 = 0.34$ , corresponding to  $n_e$  poorly determined but  $n_e > 10^5 \text{ cm}^{-3}$ .
  - ▶  $(\lambda 4959 + \lambda 5007)/\lambda 4363 \approx 22$ , corresponding to  $T \approx 4 \times 10^4 \text{ K}$  if there is no collisional effect. This temperature is far too large to be understood from the known heating and cooling mechanisms. The ratio indicates undoubtedly strongly affected by collisions.
  - ▶ If  $T \approx 12,000 \text{ K}$  is assumed, the [O III] ratio implies  $n_e \approx 10^6 \text{ cm}^{-3}$
- In Denser environments,
  - Transitions with higher critical densities can be used.



[Figure 5.10] Energy levels of lowest terms of C<sup>++</sup>.



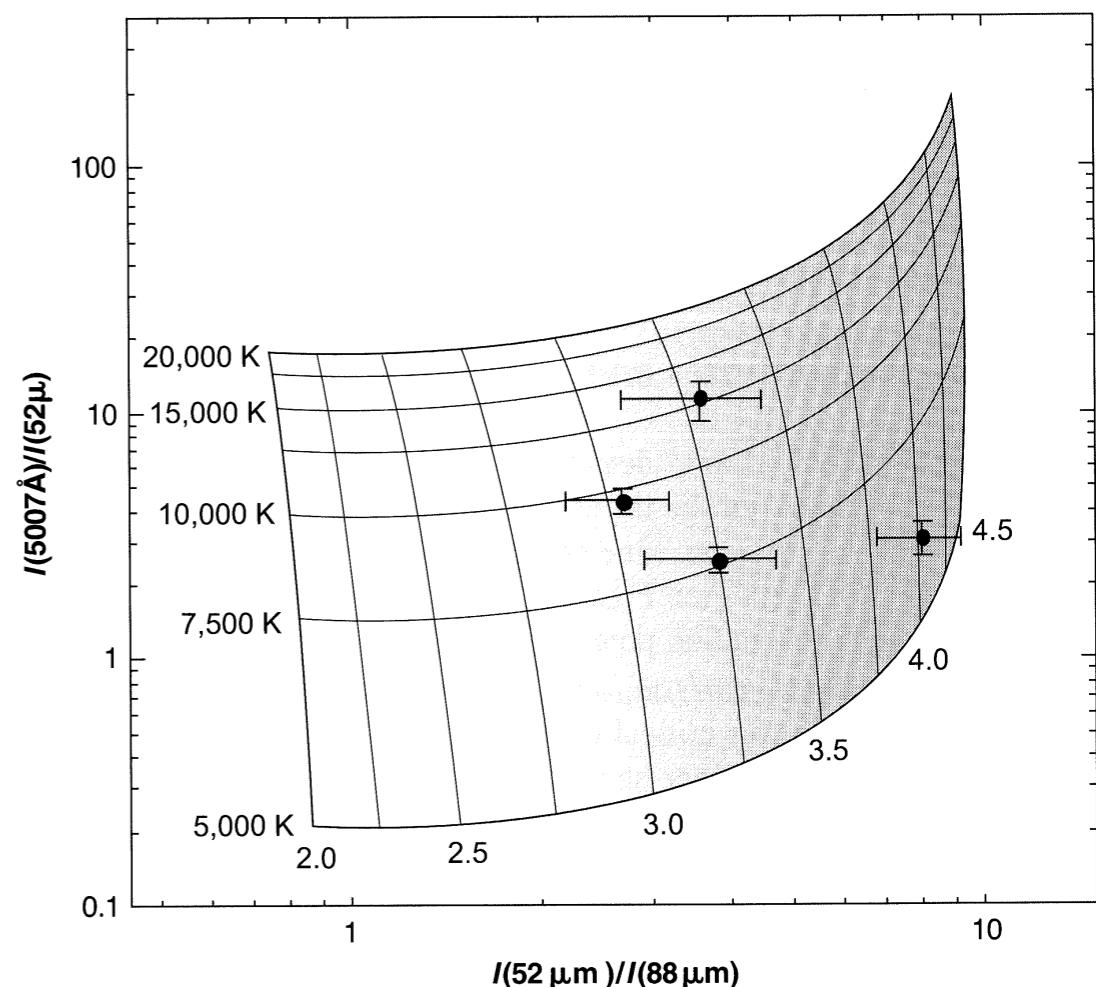
[Figure 5.11] Line ratios for the high-density environments

## 5.7 Electron Temperatures and Densities from Infrared Emission Lines

- Sensitive IR detectors have made it possible to measure “fine-structure” lines such as [O III]  $^3P_0 - ^3P_1 \lambda 88 \mu\text{m}$  and  $^3P_1 - ^3P_2 \lambda 52 \mu\text{m}$ .
  - These FIR lines have much smaller excitation potentials than the optical lines such as [O III]  $^3P_2 - ^1D_2 \lambda 5007$ .
  - $\lambda 5007/\lambda 88 \mu\text{m}$  depends strongly on temperature, but, since the  $^3P_2$  level has a much lower critical density than  $^1D_2$  does, the ratio depends on density also.
  - $\lambda 52 \mu\text{m}/\lambda 88 \mu\text{m}$  hardly depends on temperature at all (since both excitation potentials are so low in comparison with typical nebular temperatures), but does depend strongly on density (since the two upper levels have different critical densities).
  - Hence, by measuring the two ratios, we can determine both the parameters  $T$  and  $n_e$ .

Figure 5.12 shows the curves of the  $T$  and  $n_e$  values predicted from the two [O III] intensity ratios. The figure also shows the observed values for several PNe.

The predicted values for PNe agree reasonably well with those determined independently from optical lines.

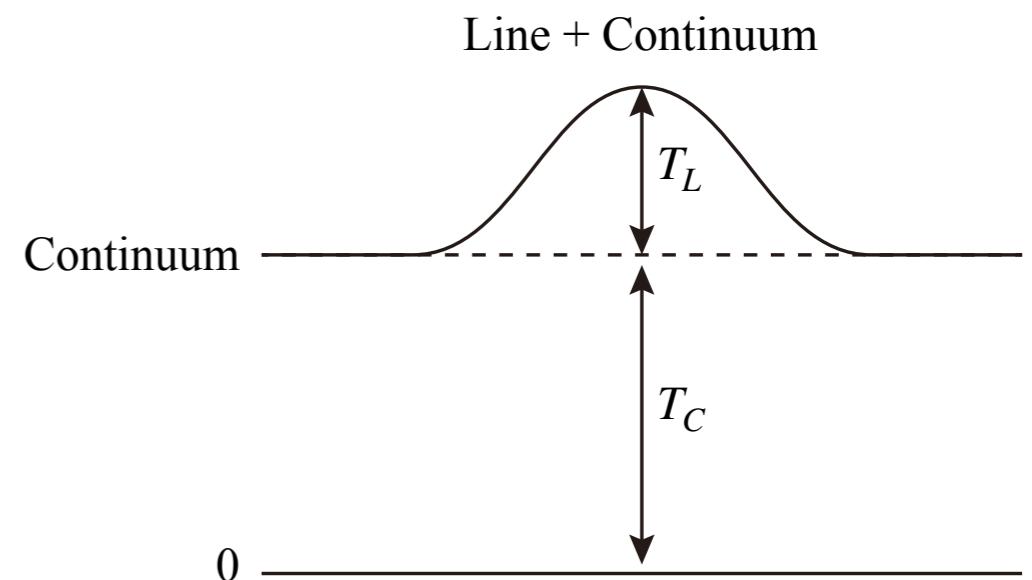


## 5.8 Electron Temperatures and Densities from Radio Recombination Lines

- Radio recombination lines gives  $n_e$ ,  $T$ , and EM.
  - H II regions have considerably larger fluxes of radio recombination lines than PNe and hence can be more readily observed.
  - The populations of the high levels of H depend on  $T$  and  $n_e$ . Therefore, the line strengths emitted by the levels relative to the continuum and to one another depend on  $T$ ,  $n_e$  and the free-free optical depth, which is expressed in terms of the continuum emission measure  $EM_c$ .

free-free optical depth:  $\tau_\nu = 8.24 \times 10^{-2} T^{-1.35} \nu^{-2.1} \int n_+ n_e ds$

- The RT equation must be solved because
  - the maser effect is often important, and
  - the continuum radiation is not weak in comparison with the line radiation.
  - The observations are generally reported in terms of brightness temperature.
    - ▶  $T_C$  = brightness temperature in the continuum near the line
    - ▶  $T_L + T_C$  = brightness temperature at the peak of the line
    - ▶  $T_L$  = excess brightness temperature due to the line



- 
- Optical depth
    - Optical depth in the line center:  $\tau_{cL} = \tau_L + \tau_C$  = sum of the optical depths in the continuum  $\tau_C$  and the contribution from the line  $\tau_L$
    - Consider a transition between a lower level  $n$  and an upper level  $m = n + \Delta n$ . Then, the optical depth for the line

$$d\tau_L = \kappa_L ds = n_n \sigma_{0nm} ds$$

- The central line-absorption cross section, corrected for stimulated emission is

$$\kappa_{0nm} = \chi_0 \left[ 1 - \frac{b_m}{b_n} \exp(-h\nu_{nm}/kT) \right] \Leftarrow \chi_0 \left[ 1 - \frac{n_m/g_m}{n_n/g_n} \right]$$

where  $\chi_0 = f_{nm} \frac{\pi e^2}{m_e c} \frac{1}{\Delta\nu_D} \frac{1}{\sqrt{\pi}} = \frac{g_m}{g_n} \frac{\lambda_{nm}^2}{8\pi^{3/2} \Delta\nu_D} A_{mn}$   $\Rightarrow f_{nm} \frac{\pi e^2}{m_e c} \frac{2\sqrt{\ln 2}}{\Delta\nu_L} \frac{1}{\sqrt{\pi}} = \frac{g_m}{g_n} \frac{\lambda_{nm}^2 (\ln 2)^2}{4\pi^{3/2} \Delta\nu_L} A_{mn}$

$$\left( f_{nm} \frac{\pi e^2}{m_e c} = \frac{h\nu_{nm}}{4\pi} B_{nm} = \frac{h\nu_{mn}}{4\pi} \frac{g_m}{g_n} \frac{c^2}{2h\nu_{mn}^3} A_{mn} \right)$$

$\Delta\nu_D = \nu_{nm}(v_{\text{th}}/c)$  = the Doppler width (the half width at  $e^{-1}$  of maximum)

$\Delta\nu_L = 2\sqrt{\ln 2} \Delta\nu_D$  = the full-width at half-maximum, the conventional quantity used in radio astronomy.

- For the special case of LTE ( $b_n = b_m = 1$ ) and  $\exp(X_n/kT) \approx 1$  to a good approximation for radio recombination lines.

$$\kappa_{0nm} = \chi_0 \left[ 1 - \frac{b_m}{b_n} \exp(-h\nu_{nm}/kT) \right] \approx \chi_0 \frac{b_m}{b_n} \frac{h\nu_{nm}}{kT} = f_{nm} \frac{\pi e^2}{m_e c} \frac{2\sqrt{\ln 2}}{\Delta\nu_L} \frac{1}{\sqrt{\pi}} \frac{b_m}{b_n} \frac{h\nu_{nm}}{kT}$$

$$\Leftarrow 1 - \frac{b_m}{b_n} \exp(-h\nu_{nm}/kT) \approx \frac{b_m}{b_n} \frac{h\nu}{kT} \Leftarrow \text{if } b_m \approx b_n \approx 1$$

- Combining the above equation with  $n_n = b_n n^2 \left( \frac{h^2}{2\pi m k T} \right)^{3/2} \exp(X_n/kT) n_p n_e$ , which is associated with

$$n_{nL} = b_{nL} (2L + 1) \left( \frac{h^2}{2\pi m k T} \right)^{3/2} \exp(-X_n/kT) n_p n_e$$

- The line-center optical depth in LTE is

$$\begin{aligned} \tau_L^* &= n_n \int \kappa_{0nm} ds = b_n n^2 \left( \frac{h^2}{2\pi m_e k T} \right)^{3/2} f_{nm} \frac{\pi e^2}{m_e c} \frac{2\sqrt{\ln 2}}{\Delta\nu_L} \frac{1}{\sqrt{\pi}} \frac{b_m}{b_n} \frac{h\nu_{nm}}{kT} \int n_p n_e ds \\ &= \left( \frac{h^2}{2m_e} \right)^{3/2} \frac{\pi e^2}{m_e c} \frac{2\sqrt{\ln 2}}{\pi} \frac{n^2 f_{nm} h\nu_{nm}}{\Delta\nu_L (kT)^{5/2}} \int n_p n_e ds \end{aligned}$$

Hence,

$$\tau_L^* = 1.53 \times 10^{-9} \frac{n^2 f_{nm} \nu_{nm}}{\Delta\nu_L T^{5/2}} \text{EM}_p = 1.01 \times 10^7 \frac{\Delta n f_{nm}}{n \Delta\nu_L T^{5/2}} \text{EM}_p$$

←

$$\nu_{nm} = \frac{\nu_0}{n^2} - \frac{\nu_0}{m^2} \approx \frac{2\nu_0 \Delta n}{n^3}$$

- In general non-LTE cases,

- the line optical depth is

$$\tau_L = \tau_L^* b_n \frac{1 - (b_m/b_n) \exp(-h\nu_{nm}/kT)}{1 - \exp(-h\nu_{nm}/kT)}$$

$$\approx \tau_L^* b_m \left( 1 - \frac{kT}{h\nu_{nm}} \frac{d \ln b_n}{dn} \Delta n \right)$$

- However, the continuum optical depth is the same as in LTE, because the free electrons have a Maxwellian distribution.

- The ratio of brightness temperatures  $r = T_L/T_C$

- In the case of LTE,

$$\begin{aligned} r^* &= \frac{T_L}{T_C} = \frac{T_L + T_C}{T_C} - 1 = \frac{T [1 - \exp(-\tau_{CL})]}{T [1 - \exp(-\tau_C)]} - 1 \\ &= \frac{1 - \exp[-(\tau_L^* + \tau_C)]}{1 - \exp(-\tau_C)} - 1 \end{aligned}$$

$$r^* = \frac{\tau_L^*}{\tau_C} \quad \xleftarrow{\hspace{1cm}}$$

if  $\tau_L^* \ll 1$  (a good approximation in all line observed to date), and  
 if  $\tau_C \ll 1$  (generally but not always a good approximation)

- In LTE, the ratio of brightness temperature in line and continuum is the same as the ratio of optical depths.

- The ratio can give  $T$ :

$$r_* = \frac{T_L}{T_C} = \frac{\tau_L^*}{\tau_C} \propto T^{-1.15} \frac{\text{EM}_p}{\text{EM}_C}$$



$$\tau_C = 8.24 \times 10^{-2} T^{-1.35} \nu^{-2.1} \text{EM}_c \quad (\text{EM}_c = \int n_+ n_e ds)$$

$$\tau_L^* = 1.01 \times 10^7 \frac{\Delta n f_{nm}}{n \Delta \nu_L T^{5/2}} \text{EM}_p \quad (\text{EM}_p = \int n_p n_e ds)$$

The ratio between the continuum EM (involving all positive ions) and the proton EM (involving only H<sup>+</sup>) depends weakly on the helium abundance.

This scheme was used in the early days to determine the temperature in H II regions. However, it is not correct because the deviation from LTE are significant in a nebula. Measurements of different lines in the same nebula give different temperatures.

- In the non-LTE conditions,

- The brightness temperature in the continuum is given by

$$T_C = T \left[ 1 - \exp(-\tau_C) \right] \quad \text{the same as in the case of LTE}$$

- However, both the line-emission and line-absorption coefficients differ from their LTE values.

Line-emission coefficient is proportional to the population of the upper level ( $m$ ).

$$j_L = j_L^* b_m \quad \text{because} \quad n_m = b_m n_m^*$$

Line-absorption coefficient is

$$\kappa_L = \kappa_L^* b_m \beta \quad \text{where} \quad \beta = 1 - \frac{hT}{h\nu_{nm}} \frac{d \ln b_n}{db} \Delta n \quad \text{from the previous page.}$$

- 
- The equation of RT, in intensity terms, is

$$\frac{dI_\nu}{d\tau_{CL}} = -I_\nu + S_\nu$$

Kirchhoff's law  $j/\kappa = B$

$$S_\nu = \frac{j_L + j_C}{\kappa_L + \kappa_C} = \frac{j_L^* b_m + j_C}{\kappa_L^* b_m \beta + \kappa_C} = \frac{\kappa_L^* b_m + \kappa_C}{\kappa_L^* b_m \beta + \kappa_C} B_\nu(T)$$

Therefore, the brightness temperature at the line center is given by

$$T_L + T_C = \left[ \frac{\kappa_L^* b_m + \kappa_C}{\kappa_L^* b_m \beta + \kappa_C} \right] T \left\{ 1 - \exp \left[ - \left( b_m \beta \tau_L^* + \tau_C \right) \right] \right\}$$

Finally, the ratio of the brightness temperatures is

$$r = \frac{T_L}{T_C} = \left[ \frac{\kappa_L^* b_m + \kappa_C}{\kappa_L^* b_m \beta + \kappa_C} \right] T \left\{ 1 - \exp \left[ - \left( b_m \beta \tau_L^* + \tau_C \right) \right] \right\} - 1$$

This equation depends on (1) the continuum optical depth  $\tau_C$ , (2) the ratio of optical depths  $\tau_L^*/\tau_C = \kappa_L^*/\kappa_C$ , and (3) the  $b_n$  factor. Here, the ratio of optical depths is a function of  $T$ ,  $\text{EM}_c$ , and  $\text{EM}_p$ , and the  $b_n$  depends on  $n_e$  and  $T$ .

**Hence,  $r$  depends not only on  $T$ , but also on  $n_e$  and EMs. Therefore, observations of several different lines in the same nebula are necessary to determine these parameters.**

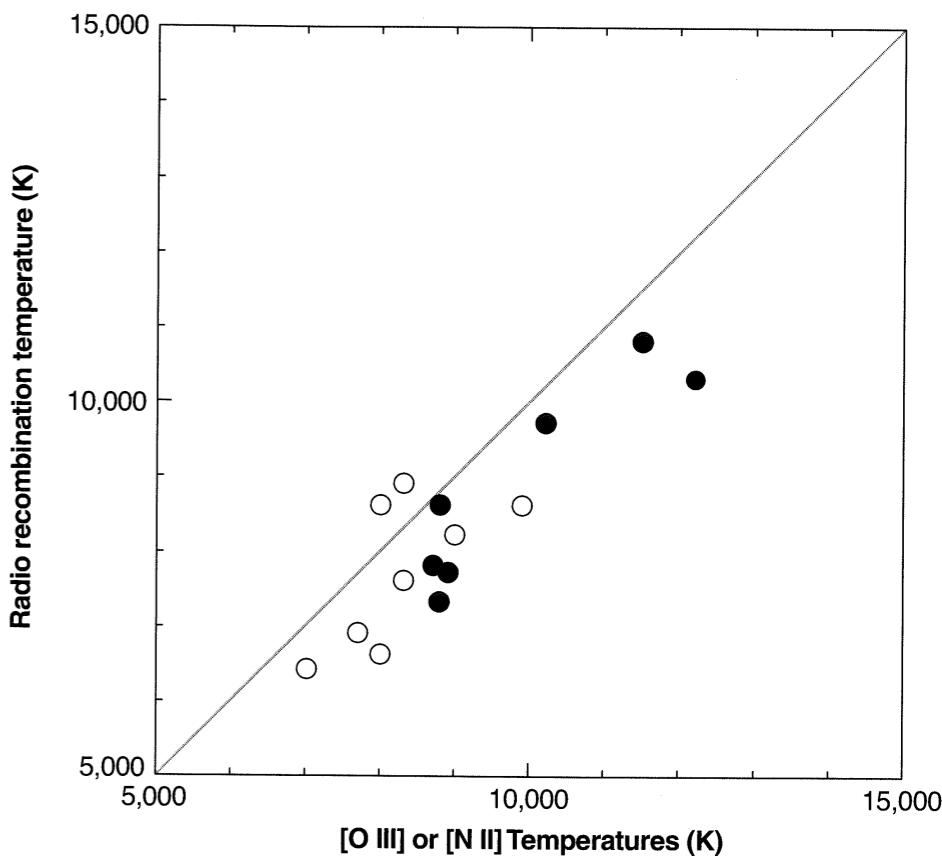
- 
- Observations
    - Method
      - ▶ Find the best match between the all line measurements and theoretical calculations for a given  $T$ ,  $n_e$ , and EM, using  $b_n(T, n_e)$  described in Chapter 4.
      - ▶ Measurements of lines with  $\Delta n = 1$  at frequencies 10 GHz (e.g.,  $109\alpha$  at 5.009 GHz) are only slightly affected by maser effects and less deviated from LTE.
    - Difficulties
      - ▶ The radio recombination lines come from levels with large  $n$  and thus large atomic radii, suffer significant impact broadening even at low densities. This causes the wings of the line difficult to define observationally except with very high SNR data.
      - ▶ Measurements are made at different frequencies and with different radio telescopes, so the antenna beam patterns are different for all lines.
    - Advantages
      - ▶ Radio techniques have the advantage that nebulae can be detected at large distances within the galactic plane, where interstellar extinction prevents optical spectroscopy.
      - ▶ **The measured temperatures show an increase with increasing distance from the center, which is consistent with the decrease in heavy-element abundance outward from the center.**

[Figure 5.14]

## Systematic underestimation of temperature

Figure 5.14 compares the temperatures determined by the recombination line measurements with those determined from collisionally excited lines.

**The temperatures determined from the radio recombination lines tend to be lower than those determined from collisionally excited lines, as was also found with the Balmer jump and radio continuum.**



- Electron densities can also be found from the radio recombination lines
  - The best method is to compare lines of two different frequencies, such as  $85\alpha$  and  $109\alpha$ , or  $66\alpha$  and  $85\alpha$ .
  - It is important to match the antenna beam widths as closely as possible.
  - Very high  $n$  lines cannot be used, because impact (Stark) broadening becomes important, make the wings difficult to measure accurately.
  - H II regions:  $n_e = 2.4 \times 10^3 \text{ cm}^{-3}$  in the Orion Nebula (NGC 1976), comparable with that obtained using the [O II] determinations.
  - PNe:  $n_e = 8.5 \times 10^3 \text{ cm}^{-3}$  in NGC 6543,  $n_e = 1.6 \times 10^5 \text{ cm}^{-3}$  in NGC 7027.

## 5.9 Filling and Covering Factors

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- Density Fluctuations
  - Nearly all PNe and H II regions show chaotic structure to some degree.
  - Large hollow central regions in some nebulae, resulting from highly ionized, low-density, high-velocity “wind,” flowing out from the central star or stars.
  - Departures from spherical symmetry, with significant regions being relatively free of matter.
- They can be detected quantitatively.
  - If the densities derived from [O II] line ratios, for a well resolved nebula (e.g., NGC 1976), are used to predict the high-frequency radio continuum brightness temperature by combining the following equations and assuming the spherical symmetry.

$$\tau_\nu = 8.24 \times 10^{-2} T^{-1.35} \nu^{-2.1} \text{EM}_c \quad \text{and} \quad T_{b\nu} = \int_0^{\tau_\nu} T \exp(-\tau'_\nu) d\tau'_\nu$$

- This gives a good approximation of the brightness temperature for high-frequency observations, where  $\tau_\nu \ll 1$ . The resulting brightness temperature depends only very weakly on the nebular temperature.

$$T_{b\nu} = T(1 - e^{-\tau_\nu}) \approx T\tau_\nu = 8.24 \times 10^{-2} T^{-0.35} \nu^{-2.1} \text{EM}_c$$

- **The measured  $T_{b\nu}$  is always smaller than this value predicted using [O II], typically by a factor of order ten.**
- This can be understood (1) if the nebula is thinner along the line of sight than perpendicular to it (this is the case for the Orion nebula), or (2) in terms of density fluctuations.
- The line-ratio density measurements are heavily weighted toward the regions of strongest emission — of highest density. These measured densities deviate greatly from the average density along a typical path through the nebula.

$$\text{EM} = \int \varepsilon n^2 ds \Rightarrow \langle n \rangle_{\text{EM}} = \sqrt{\varepsilon n} \longrightarrow \boxed{\langle n \rangle_{\text{EM}} = \sqrt{\varepsilon n} > \langle n \rangle_{\text{path}} = \varepsilon n}$$

- 
- Two phase medium - the simplest assumption
    - Assume that gas contains small clumps or condensations with electron density  $n_e$  and zero-density regions between them.
    - **The filling factor  $\varepsilon$**  is the fraction of the total volume occupied by the clumps.
      - ▶ For simplicity, the filling factor may be assumed to be constant throughout a nebula or allowed to vary with position.
      - ▶ The comparison of density and radio-continuum measurements gives  $\varepsilon = 0.03$ , ranging from 0.01 to 0.5 in H II regions and PNe.
    - **The covering factor  $\Omega/4\pi$**  is the fraction of  $4\pi$  sr that is covered by gas clumps, as viewed from the location of the central star.
    - The intensity of an emission and the luminosity, integrated over the volume, are

$$I_l = \int j_l ds = \int \varepsilon n_i n_e k_l(T) ds \text{ and } L_l = \frac{\Omega}{4\pi} \int \varepsilon n_i n_e k_l(T) dV, \text{ where } k_l(T) \text{ is the collisional excitation rate coefficient.}$$

- The number of recombinations is

$$Q(\text{H}^0) = \frac{\Omega}{4\pi} \int_0^{r_1} \varepsilon n_p n_e \alpha_B(\text{H}^0) dV = \frac{\Omega}{4\pi} \frac{4\pi}{3} r_1^3 \varepsilon n_p n_e \alpha_B(\text{H}^0)$$

- The total mass of H in the nebula is

$$M_{\text{H}} = m_{\text{H}} \frac{\Omega}{4\pi} \int_0^{r_1} \varepsilon n_p dV$$

- The radial optical depth becomes

$$\tau_\nu(r) = \int_0^r \varepsilon n(\text{H}^0, r') \sigma_\nu dr'$$

## 5.10 Ionizing Radiation from Stars

- **Number of LyC photons:**

- **Observations of ionized nebulae may be used to find the number of ionizing (LyC) photons emitted by a star.**
- If the gas around the star is optically thick in the LyC, it will absorb all the ionizing photons from the star.
- Total number of ionization per unit time = total number of ionizing photons emitted per unit time = total number of recombination per unit time (in photoionization equilibrium)

$$\int_{\nu_0}^{\infty} \frac{L_{\nu}}{h\nu} d\nu = Q(H^0) = \int_0^{r_1} n_p n_e \alpha_B(H^0, T) dV$$

- The luminosity of the entire nebula in a particular emission line (say H $\beta$ ) also depends on recombination

$$L(H\beta) = \int_0^{r_1} 4\pi j_{H\beta} dV = h\nu_{H\beta} \int_0^{r_1} n_p n_e \alpha_{H\beta}^{\text{eff}}(H^0, T) dV$$

Thus,

$$\frac{\frac{L(H\beta)}{h\nu_{H\beta}}}{\int_{\nu_0}^{\infty} \frac{L_{\nu}}{h\nu} d\nu} \approx \frac{\alpha_{H\beta}^{\text{eff}}(H^0, T)}{\alpha_B(H^0, T)}.$$

number of LyC photons =  $\frac{\alpha_B}{\alpha_{H\beta}} \times$  number of H $\beta$  photons

- The number of LyC photons emitted in a specific recombination line is directly proportional to the number of LyC photons emitted by the star. This proportionality is a good approximation because  $\alpha_{H\beta}^{\text{eff}}/\alpha_B$  depends only weakly on  $T$ , and also does not depend on any assumption about constant density.
- **Therefore, the number of LyC photons can be obtained from the number of H $\beta$  photons, together with  $\alpha_{H\beta}^{\text{eff}}/\alpha_B$ .**
- Furthermore, (1) any other emission line could have been used instead of H $\beta$ , or (2) alternatively the radio continuum emission at any frequency, which is optically thin, could be used, except that the ratio of nebular photons emitted to LyC photons would involve the ratio of the number of protons to the total number of positive ions, which depends weakly on the He abundance.

- The ratio between the number of LyC photons and the stellar luminosity at a particular frequency  $\nu_f$  is

$$\frac{L_{\nu_f}}{\int_{\nu_0}^{\infty} \frac{L_{\nu}}{h\nu} d\nu} = \frac{L_{\nu_f}}{\frac{L(\text{H}\beta)}{h\nu_{\text{H}\beta}}} \frac{\frac{L(\text{H}\beta)}{h\nu_{\text{H}\beta}}}{\int_{\nu_0}^{\infty} \frac{L_{\nu}}{h\nu} d\nu} = h\nu_{\text{H}\beta} \frac{\alpha_{\text{H}\beta}^{\text{eff}}(\text{H}^0, T)}{\alpha_{\text{B}}(\text{H}^0, T)} \frac{\pi F_{\nu_f}}{\pi F_{\text{H}\beta}}$$

This ratio is independent of the distance, and is in addition independent of the interstellar extinction if the nebula and the star are observed at the same effective wavelength ( $\nu_f = \nu_{\text{H}\beta}$ ).

Therefore, **this equation gives the number of LyC photons from the measurements at H $\beta$  and  $\nu_f$ .**

- It is often convenient to measure the luminosities with a wide filter (e.g, UBV filters), and we can write a similar equation in terms of

$$L_V = \int_0^{\infty} s_{\nu}(V) L_{\nu} d\nu \quad \text{and} \quad \pi F_V = \int_0^{\infty} s_{\nu}(V) \pi F_{\nu} d\nu,$$

where  $s_{\nu}(V)$  is the sensitivity function of the filter. It is advantageous to use a narrower-band filter that isolates a spectral region in the continuum between the nebular emission lines, to minimize the correction for the “sky” background.

- **Zanstra Temperature:**

- The method of using the nebular observations to measure the stellar UV radiation was first proposed by Zanstra.
- It is assumed that the flux from a star could be approximated by the Planck function  $B_{\nu}(T_*)$ , so that

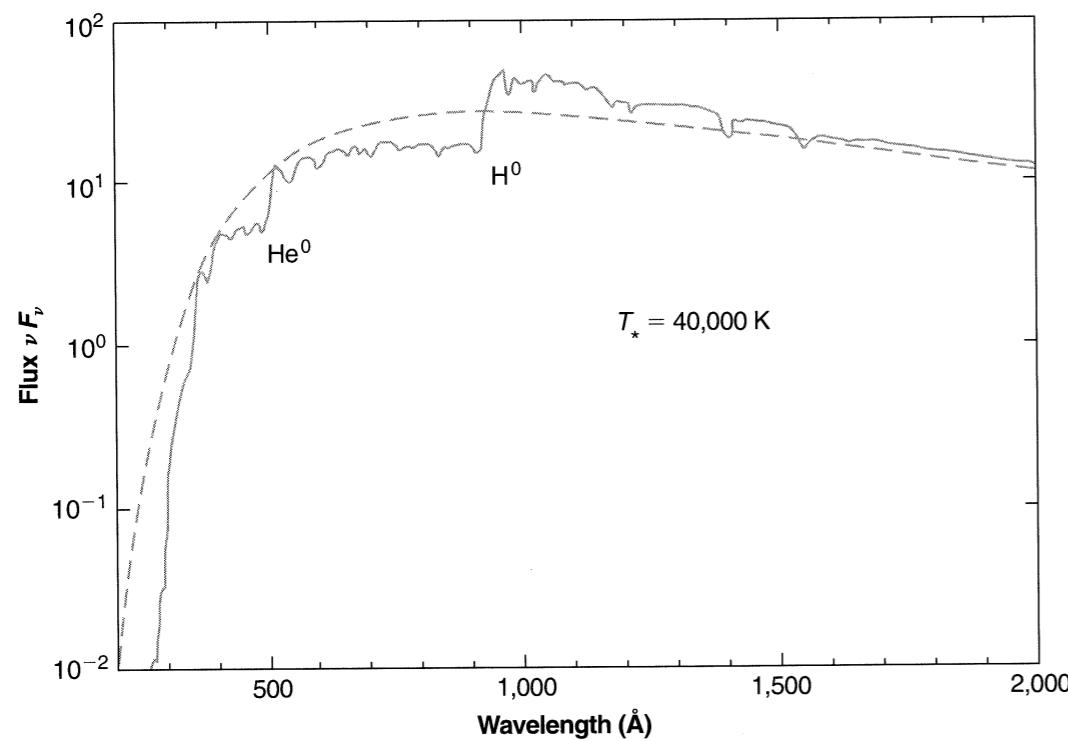
$$\frac{L_{\nu_f}}{\int_{\nu_0}^{\infty} \frac{L_{\nu}}{h\nu} d\nu} = \frac{B_{\nu_f}(T_*)}{\int_{\nu_0}^{\infty} \frac{B_{\nu}(T_*)}{h\nu} d\nu}$$

This allows to estimate the stellar temperature from the measurement of the number of LyC photons, which is called the Zanstra temperature.

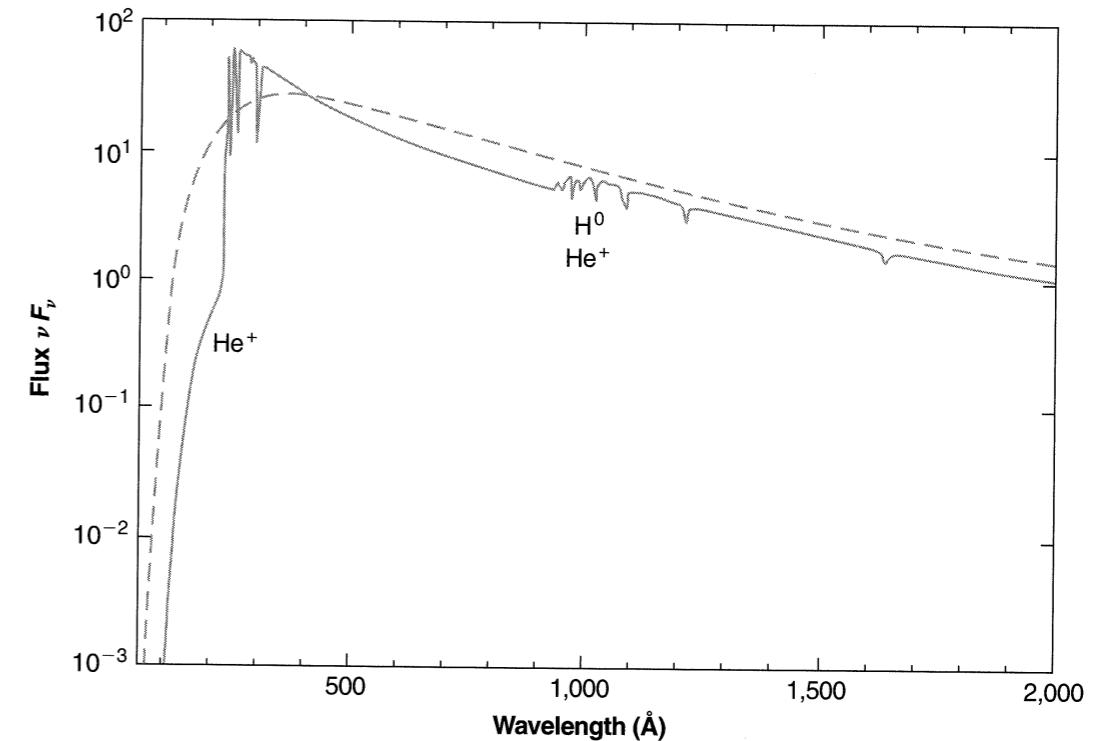
- However, stellar spectra shows significant deviations from Planck function, particularly in the frequency regions where there are large changes in opacity, such as at the Lyman limit and other limits.
- Therefore, the ratios should be determined from the model stellar atmospheres:

$$\frac{L_{\nu_f}}{\int_{\nu_0}^{\infty} \frac{L_{\nu}}{h\nu} d\nu} = \frac{\pi F_{\nu_f}(T_*, g)}{\int_{\nu_0}^{\infty} \frac{\pi F_{\nu}(T_*, g)}{h\nu} d\nu} = y(T_*),$$

where  $g$  is the surface gravity of the star.



[Figure 5.15] The stellar spectrum of O6 star with  $T_* = 40,000$  K,  $\log g = 4$ , compared with blackbody spectrum for the same effective temperature. The ionization edges of H and He are marked.



[Figure 5.16] A model stellar spectrum for a planetary-nebula star with  $T_* = 100,000$  K,  $\log g = 6$ , compared with blackbody spectrum for the same effective temperature. The ionization edges of H and  $\text{He}^+$  are marked.

- 
- H II regions
    - A large fraction of H II regions contain several O stars and thus complicate the determination of the effective temperature of individual stars.
    - The best cases are clearly nebulas with only a single hot star, and the ionization-bounded cases.
    - However, absorption of LyC photons by dust can still cause serious errors in the results.
  - Planetary nebulae or Giant H II regions: He<sup>+</sup>-ionizing photons
    - The number of ionizing photons shortward of the He<sup>+</sup> limit can be measured from  $\lambda 4686$  (the strongest He II recombination line).
      - ▶ This line is in general not present or very weak, and has only been observed in some giant extragalactic H II regions.
      - ▶ This indicates that the flux of He<sup>+</sup>-ionizing photons is small in all main-sequence O stars.
    - The number of He<sup>+</sup>-ionizing photons ( $h\nu > 4h\nu_0 = 54.4$  eV) can be estimated from the He II observations:

$$\frac{L_{\nu_f}}{\int_{4\nu_0}^{\infty} \frac{L_\nu}{h\nu} d\nu} = h\nu_{\lambda 4686} \frac{\alpha_{\lambda 4686}^{\text{eff}}(\text{He}^+, T) \pi F_{\nu_f}}{\alpha_B(\text{He}^+, T) \pi F_{\lambda 4686}}$$

- **From the measured H I and He II recombination line fluxes, together with the measured stellar flux at some frequency, two independent determinations of  $T_*$  can be made by the Zanstra method.**
- **In some nebulae, these two temperatures agree, but in other nebulae they disagree.** For instance, in NGC 7662,  $T_* = 70,000$  K from the H I measurement, while  $T_* = 113,000$  K from He II measurement.

- This discrepancy can be understood as resulting from the fact that the nebula is not optically thick to the LyC photons, but LyC is density-bounded. In this case,

$$\frac{L_{\nu_f}}{\int_{\nu_0}^{\infty} \frac{L_{\nu}}{h\nu} d\nu} = \eta_H h \nu_{H\beta} \frac{\alpha_{H\beta}^{\text{eff}}(H^0, T)}{\alpha_B(H^0, T)} \frac{\pi F_{\nu_f}}{\pi F_{H\beta}}$$

Here,  $\eta_H$  represents the fraction of the H-ionizing photons that are absorbed in the nebula.

- It would be possible to imagine that all the He<sup>+</sup>-ionizing photons are not absorbed within the nebula.
  - ▶ However, this does not seem to occur in most of the PNe because they show He I lines, indicating the existence of an outer He<sup>+</sup> zone, which is optically thick to He<sup>+</sup> ionizing photons.
  - ▶ Similarly, the detection of [O I] lines indicates the presence of O<sup>0</sup>, and therefore also of H<sup>0</sup>, which has the same ionization potential as O<sup>0</sup>, and thus indicates that the nebula is optically thick to H-ionizing radiation.
- **Number of the He<sup>0</sup>-ionizing photons**

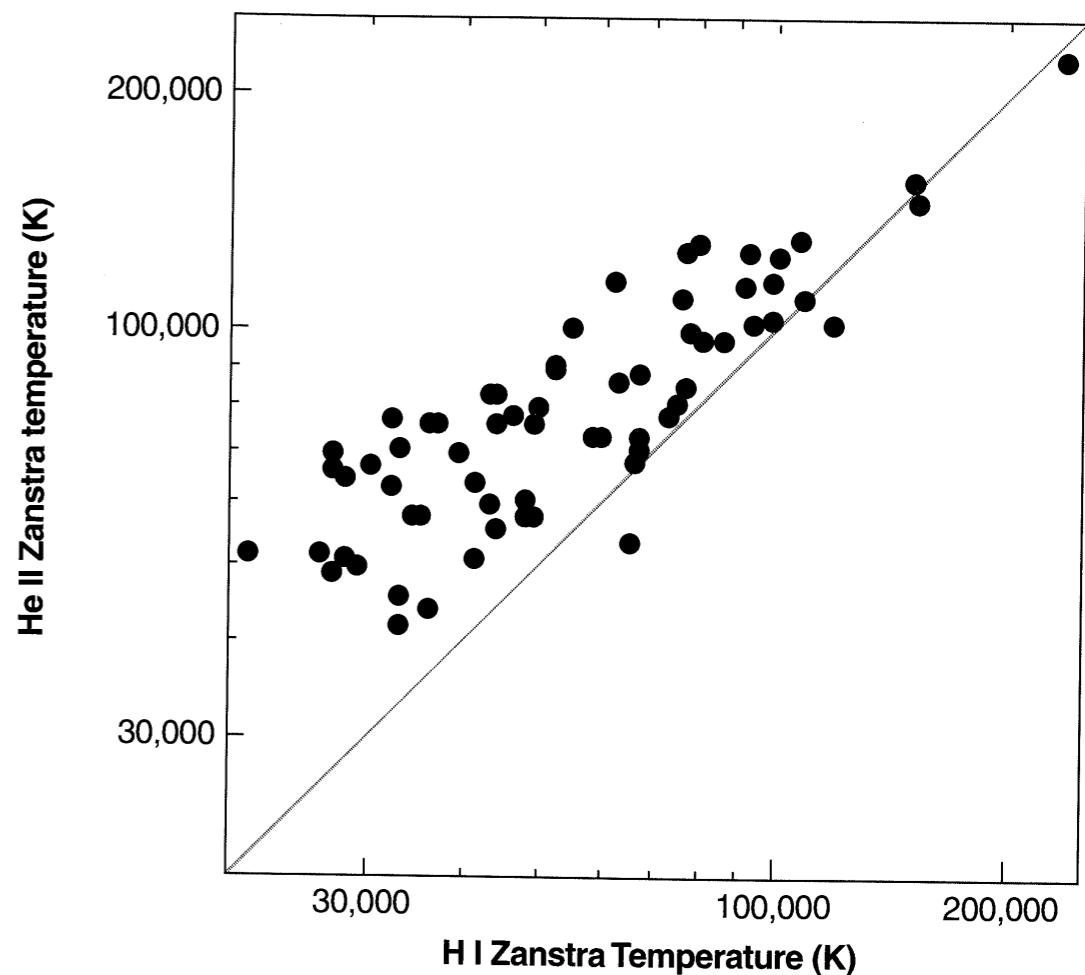
- The number of He<sup>0</sup>-ionizing photons can be obtained from measurements of the He I recombination lines (e.g.,  $\lambda 4471$  or  $\lambda 5876$ ), as follows:

$$\frac{L_{\nu_f}}{\int_{\nu_2}^{\infty} \frac{L_{\nu}}{h\nu} d\nu} = \eta_{He} h \nu_{\lambda 5876} \frac{\alpha_{\lambda 5876}^{\text{eff}}(He^0, T) \pi F_{\nu_f}}{\alpha_B(He^0, T) \pi F_{\lambda 5876}}$$

- ▶ If the nebula is known to be optically thick to the He-ionizing photons (either because the He<sup>+</sup> zone is observed to be smaller than the H<sup>+</sup> zone, or because the abundance ratio  $n(He^+)/n_p \leq 0.1$ , indicating the He<sup>+</sup> zone is smaller than the H<sup>+</sup> zone.), then  $\eta_{He} = 1$ .

- Correctness of the equations
  - Although the integrals giving the number of photons that can ionize  $\text{He}^+$ ,  $\text{He}^0$ , and  $\text{H}^0$  overlap, the equations are essentially correct,
  - because nearly every recombination of a  $\text{He}^{++}$  ion leads to emission of a photon that can ionize  $\text{He}^0$  or  $\text{H}^0$ , and nearly every recombination of a  $\text{He}^+$  ion leads to emission of a photon that can ionize  $\text{H}^0$ .
- Comparison of the two temperatures
  - Figure 5.17 compares Zanstra temperatures obtained from H I and He II recombination lines.
  - The He II Zanstra temperature often exceed the H I temperature.
  - This is generally ascribed to the nebulae being partially transparent to hydrogen-ionizing radiation, suggesting that **the He II temperature is more accurate**.

[Figure 5.17]



- **Energy balance or Stoy's method** - another method to derive the stellar temperature

- Recall the following conditions in the photoionization equilibrium
  - ▶ Number of recombinations = Number of photoionizations
  - ▶ Energy input to the nebula = Energy radiated by the nebula (sum of all emission line fluxes and the continuum, from UV to IR)
- Note that

$$L(\text{H}\beta) = h\nu_{\text{H}\beta} \frac{\alpha_{\text{H}\beta}^{\text{eff}}(\text{H}^0)}{\alpha_{\text{B}}(\text{H}^0)} \int_{\nu_0}^{\infty} \frac{L_\nu}{h\nu} d\nu$$

$$\# \text{ of recombination} = n_p n_e \alpha_{\text{B}}(\text{H}^0, T) \Delta V = \frac{\alpha_{\text{B}}}{\alpha_{\text{H}\beta}^{\text{eff}}} \frac{L(\text{H}\beta)}{h\nu_{\text{H}\beta}} \quad \Leftarrow L(\text{H}\beta) = h\nu_{\text{H}\beta} n_p n_e \alpha_{\text{H}\beta}^{\text{eff}}(\text{H}^0, T) \Delta V$$

$$\text{Heating (energy input)} = \int_{\nu_0}^{\infty} \frac{L_\nu}{h\nu} h(\nu - \nu_0) \sigma_\nu^{\text{p.i.}} d\nu$$

$$\frac{\text{total cooling}}{\# \text{ of recombination}} = \frac{\text{total heating}}{\# \text{ of recombination}} = \frac{\alpha_{\text{H}\beta}^{\text{eff}}}{\alpha_{\text{B}}} \frac{h\nu_{\text{H}\beta}}{L(\text{H}\beta)} \int_{\nu_0}^{\infty} \frac{L_\nu}{h\nu} h(\nu - \nu_0) \sigma_\nu^{\text{p.i.}} d\nu$$

- Therefore, “(total cooling)/ $L(\text{H}\beta)$ ” represents the total heating per the number of photoionization:

$$\frac{\text{total cooling}}{L(\text{H}\beta)} = \frac{\alpha_{\text{B}}}{h\nu_{\text{H}\beta} \alpha_{\text{H}\beta}^{\text{eff}}} \frac{\int_{\nu_0}^{\infty} \frac{L_\nu}{h\nu} h(\nu - \nu_0) \sigma_\nu^{\text{p.i.}} d\nu}{\int_{\nu_0}^{\infty} \frac{L_\nu}{h\nu} d\nu}$$

number of photoionization =  $\int_{\nu_0}^{\infty} \frac{L_\nu}{h\nu} d\nu$

- ▶ Now, we can determine the effective stellar temperature by substituting the stellar synthesis model on the right hand side and compare it with the observation on the left hand side.

## 5.11 Abundances of the Elements in Nebulae

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- Abundances can be derived from measurements of the relative strengths of their emission lines
  - All nebula lines are optically thin. No curve-of-growth effects that complicate stellar atmosphere abundance determinations occur.
  - H, He, N, O, and Ne are observable in the optical spectra.
  - But, C can be observed in the vacuum UV spectral region.
  - Moreover, all stages of ionization of an element are generally not observable in the optical spectral region.
    - ▶ For instance, [O II] and [O III] are strong in diffuse nebulae, but O IV and O V are not.
    - ▶ However, an [O IV] line is available in the FIR, and O IV] and O V lines are in the vacuum UV.
- Collisionally Excited Lines vs. Recombination Lines
  - **Collisionally excited lines can be quite bright, but their strengths depend strongly on temperature, complicating the determination of relative abundance.** The intensity  $I_l$  of an emission line is given by  $I_l = \int j_l ds = \int n_i n_e k_l(T) ds$
  - Intensities of recombination lines are given as, for instance,  $I_{H\beta} = \frac{1}{4\pi} \int h\nu_{H\beta} n_p n_e \alpha_{H\beta}^{\text{eff}}(H^0, T) ds$ .  
**The recombination rate coefficients are not particularly temperature sensitive and the abundances derived from them do not depend strongly on  $T$ .** However, **recombination lines of elements heavier than He are faint and hard to observe.**

- 
- Recombination lines from heavy elements
    - C II, O IV, and O V have weak permitted emission lines as observed in PNe, which are attributed to resulting from recombination. However, some of these lines may be excited by resonance fluorescence, and their emission coefficients depend not only on temperature and density but also the local radiation field. It is not easy to utilize them.
    - C II  $3^2D - 4^2F \lambda 4267$  line cannot be excited by resonance fluorescence, and are suitable for abundance determinations.
  - Discrepancy between the temperatures derived from collisionally excited lines and recombination lines has been found in several nebulae.
  - He<sup>+</sup> abundance in H II regions
    - can be obtained from relative strengths of the radio recombination lines of H I and He I.
    - **At a very high  $n$  (radio region)**, both H and He are nearly identical on-electron systems except for their masses.
    - Hence, **their relative strengths are directly proportional to their abundances** (as long as they are optically thin, and the nebula is a complete H<sup>+</sup> plus He<sup>+</sup> region, without no H<sup>+</sup> plus He<sup>0</sup> region).
  - Abundances of heavy elements
    - For this purpose, strong collisionally excited lines are available. However, the temperature must be determined from observational data because the lines depends sensitively on the temperature.

$$I_\nu = \frac{1}{4\pi} \int h\nu_{12} n_2 n_e q_{12}(T) ds \quad \text{where the collisional excitation rate coefficient } q_{12} = \frac{8.63 \times 10^{-6}}{T^{1/2}} \frac{\Omega_{21}}{g_1} e^{-\chi/kT}.$$

# (Abundance Determination)

- Helium abundance
  - The abundance of He is determined from **comparison of the strengths of radiative recombination lines of H and He** in regions ionized by stars that are sufficiently hot ( $T \gtrsim 3.9 \times 10^4$  K) so that He is ionized throughout the H II regions.
- Heavy elements
  - The abundance of heavy elements can be inferred by **comparing the strengths of collisionally excited lines with recombination lines of H.**

**Oxygen:**

$$\left( \lambda_{\text{H}\beta} = 4861.35 \text{\AA} \right)$$

$$4\pi j([\text{OIII}] 5008) = n_e n(\text{O}^{+2}) k_{03} \frac{A_{32}}{A_{31} + A_{32}} E_{32}$$

$$4\pi j(\text{H}\beta) = n_e n(\text{H}^+) \alpha_{\text{eff}, \text{H}\beta} E_{\text{H}\beta}$$

where

$$\alpha_{\text{eff}, \text{H}\beta} \approx 3.03 \times 10^{-14} T_4^{-0.874 - 0.058 \ln T_4} \text{ cm}^3 \text{ s}^{-1}$$

$$k_{03} = 8.62942 \times 10^{-8} T_4^{-1/2} \frac{\Omega_{30}}{g_0} e^{-E_{30}/kT} \text{ cm}^3 \text{ s}^{-1} \quad (g_0 = 1)$$

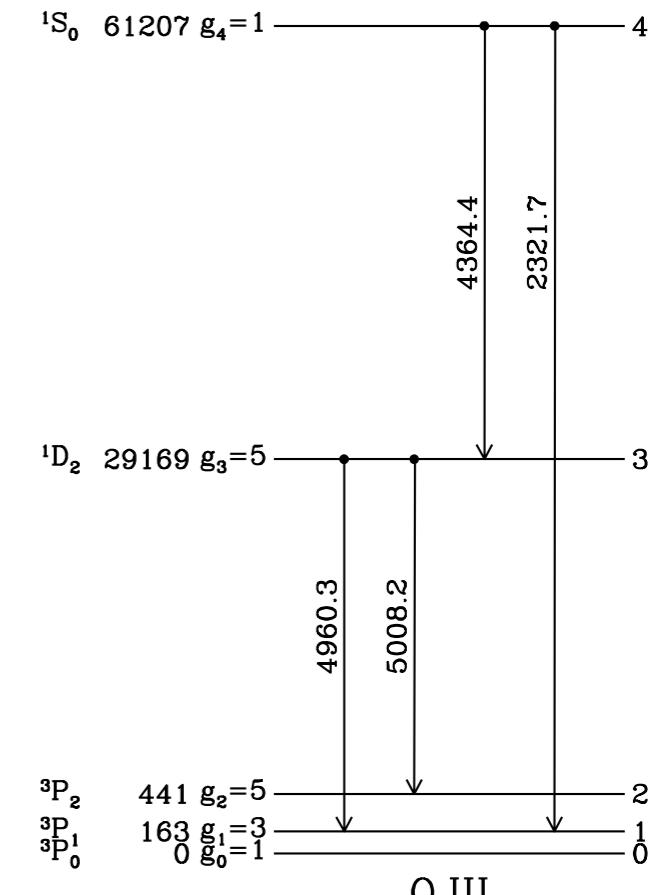
$$E_{32}/k = 29169 \text{ K}, \quad E_{\text{H}\beta}/k = 29588.5 \text{ K}$$

$$\Omega_{30} = 0.243 T_4^{0.120 + 0.031 \ln T_4}$$

$$A_{32} = 2.0 \times 10^{-2} [\text{s}^{-1}]$$

$$A_{31} = 6.8 \times 10^{-3} [\text{s}^{-1}]$$

$$\frac{[\text{OIII}] 5008}{\text{H}\beta} = 5.091 \times 10^5 T_4^{0.494 + 0.089 \ln T_4} e^{-2.917/T_4} \frac{n(\text{O}^{+2})}{n(\text{H}^+)}$$



- **Nitrogen:**

$$\left( \lambda_{\text{H}\alpha} = 6562.79 \text{\AA} \right)$$

$$4\pi j(\text{[NII]} 6585) = n_e n(\text{N}^+) k_{03} \frac{A_{32}}{A_{31} + A_{32}} E_{32}$$

$$4\pi j(\text{H}\alpha) = n_e n(\text{H}^+) \alpha_{\text{eff}, \text{H}\alpha} E_{\text{H}\alpha}$$

where

$$\alpha_{\text{eff}, \text{H}\alpha} \approx 1.17 \times 10^{-13} T_4^{-0.942 - 0.031 \ln T_4} \text{ cm}^3 \text{ s}^{-1}$$

$$k_{03} = 8.62942 \times 10^{-8} T_4^{-1/2} \frac{\Omega_{30}}{g_0} e^{-E_{30}/kT} \text{ cm}^3 \text{ s}^{-1} \quad (g_0 = 1)$$

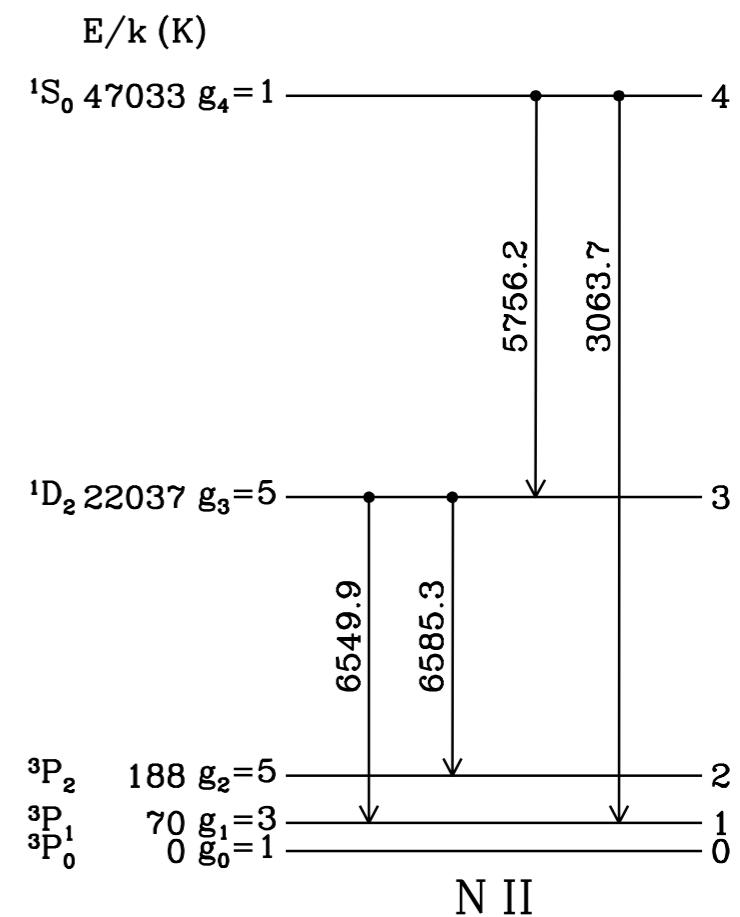
$$E_{32}/k = 21849 \text{ K}, \quad E_{\text{H}\alpha}/k = 21916.9 \text{ K}$$

$$\Omega_{30} = 0.303 T_4^{0.053 + 0.009 \ln T_4}$$

$$A_{32} = 3.0 \times 10^{-3} \text{ [s}^{-1}\text{]}$$

$$A_{31} = 9.8 \times 10^{-4} \text{ [s}^{-1}\text{]}$$

$$\frac{[\text{NII}]}{\text{H}\alpha} = 1.679 \times 10^5 T_4^{0.495 + 0.040 \ln T_4} e^{-2.185/T_4} \frac{n(\text{N}^+)}{n(\text{H}^+)}$$



- Therefore, if the temperature  $T$  is known, the relative abundance of the ion can be obtained from the measured line ratio.
- The total elemental abundances are then obtained by applying **ionization correction factors (ICFs)**, which correct for abundances of unobserved ions.

- 
- One-layer model
    - The abundances can be determined on the basis of a model of the structure of the nebula.
    - The simplest model treats the nebula as homogeneous with constant  $T$  and  $n_e$ , which may be called a one-layer model.
    - Discrepancies in  $n_e$  and  $T$  determined from different line ratios indicate that this model is too simplified, though **the abundances determined from it are generally correct to within a factor of order two or three.**
  - Discrepancies
    - Recall that **the temperatures determined from hydrogen recombination lines, the Balmer jump, and free-free brightness temperatures are lower than the temperature determined from collisionally excited (forbidden) line ratios.**
    - The probable explanation of this discrepancy is that the temperature is not constant throughout the nebula, but rather varies from point to point due to variations in the local heating and cooling rates.
    - A complex model approach, as will be discussed in section 5.12, would be required to know the entire temperature structure.
    - However, the discrepancies can easily be understood in a relatively easy way.

- 
- Origin of the discrepancies
    - The emission line ratios determine the temperature of the region where the lines are predominantly originate from.
    - The emission coefficient of collisionally excited lines increases strongly with increasing temperature, and thus the temperature is strongly weighted toward high-temperature regions.
    - However, the recombination and free-free emission coefficients decrease with increasing temperature, and thus the resulting temperature is weighted toward low-temperature regions.
    - We thus expect that the collisionally excited lines indicate a higher temperature than do the Balmer jump or radio-frequency measurements.
  - A somewhat more sophisticated scheme to understand the discrepancies
    - The emission rate coefficient is expand in a power series of temperature:

$$\varepsilon_l(T) = \varepsilon_l(T_0) + (T - T_0) \left( \frac{d\varepsilon_l}{dT} \right)_0 + \frac{1}{2}(T - T_0)^2 \left( \frac{d^2\varepsilon_l}{dT^2} \right)_0$$

- $\varepsilon_l(T) = c_1 T^{-m}$  ( $m \approx 1$ ) for recombination lines (the recombination rate coefficient)
- $\varepsilon_l(T) = \frac{c_2 \exp(-\chi/kT)}{T^{1/2}}$  for recombination lines

- The emissivity is given by integrating along the line of sight:

$$\int n_i n_e \epsilon_l(T) ds = \epsilon_l(T_0) \int n_i n_e ds + \frac{1}{2} \left( \frac{d^2 \epsilon_l}{dT^2} \right)_0 \int n_i n_e (T - T_0)^2 ds$$

Here, the first order term of  $T - T_0$  vanishes if we choose  $T_0$  as the mean temperature,

$$T_0 = \frac{\int n_i n_e T ds}{\int n_i n_e ds} \Rightarrow \text{mean temperature}$$

and we define  $t^2 = \frac{\int n_i n_e (T - T_0)^2 ds}{T_0^2 \int n_i n_e ds}$ , representing the variance of temperature.

- If all ions had the same space distribution  $n_i(s)$ , then both  $T_0$  and  $t^2$  could be determined by combining two line ratios (for instance [O III]  $(\lambda 4959 + \lambda 5007)/\lambda 4363$  and [N II]  $(\lambda 6543 + \lambda 6583)/\lambda 5755$ )
- Then,  $T_0$  and  $t^2$  could be used to determine the abundances of all the ions with measured lines.

However, all ions do not have the same spatial distribution. For instance, O<sup>++</sup> is more strongly concentrated to the source of ionizing radiation than N<sup>+</sup>.

The most sophisticated method of all to determine the abundances from the observations is to calculate a complete model of the nebula in an attempt to reproduce all its observed properties, as will be discussed in section 5.12.

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- **Notes:**

- [O III] and [N II] collisional excitation lines trace the abundance of O<sup>++</sup> and N<sup>+</sup>, respectively.
- The He I recombination line provides the abundance of He<sup>+</sup>, whereas the He II recombination line traces that of He<sup>++</sup>.
- Because there is no “observable” He I collisional excitation line, **there is no way to determine the He<sup>0</sup> abundance directly.**

- Observational results

- He/H abundance ratio
  - ▶  $n(\text{He}^+)/n_p = 0.06 - 0.09$  in Orion Nebula, suggesting that the varying amounts of He<sup>0</sup> are present.
  - ▶  $n(\text{He}^+)/n_p = 0.009$  in NGC 1982, indicating that the observation was performed in an H<sup>+</sup> plus He<sup>0</sup> zone, where He is predominantly neutral. The exciting star of NGC 1982 is a B1 V star, so the He-ionizing radiation is very weak or absent.

- **Ionization Correction Factor (ICF)**

- ▶ The above observations indicate that some correction is necessary to estimate the abundance of He, specifically to compensate for the amount of unobserved He<sup>0</sup>. An ion of another element can be used its proxy.
- ▶ Empirically, the correction can be based on [S II] $\lambda\lambda 6717, 6731$ , because S<sup>+</sup> has an ionization potential of 23.4 eV, similar to that of He<sup>0</sup> (24.6 eV). Therefore, to a first approximation

$$\frac{n(\text{He}^0)}{n(\text{He}^+)} = \frac{n(S^+)}{n(S^{++})} \quad \Rightarrow \quad n(\text{He}^0) \approx n(\text{He}^+) \frac{n(S^+)}{n(S^{++})}$$

**Such ratios are called ICFs, since they correct for unobserved stages of ionization.**

- 
- Radio measurements of  $\text{He}^+/\text{H}^+$  abundance ratios are available for many diffuse nebulae.
    - ▶ Radio observations have the advantage that they can be done at large distances in the galactic plane.
    - ▶ However, there no known way in which the correction for  $\text{He}^0$  can be obtained from radio measurements.
    - ▶ NGC 2024 and NGC 1982 are observed to have  $n(\text{He}^+)/n_p \approx 0$ . Radio measurements of H II regions very near the galactic center give quite low  $n(\text{He}^+)/n_p$  ratios.
    - ▶ These low ratios are due to their ionizing stars being predominantly cool, rather than suggesting low helium abundance. These indicates corrections are certainly required.
  - PNe
    - ▶ Many PNe show the presence of both  $\text{He}^{++}$  and  $\text{He}^+$ , though some PNe have only He I lines.
    - ▶ Nearly all PNe have central stars that are so hot that they have no outer  $\text{He}^+$ ,  $\text{He}^0$  zones. Therefore, no correction is necessary for unobserved  $\text{He}^0$  in most PNe.
    - ▶ Most of PNe have  $n(\text{He})/n(\text{H}) \approx 0.11$ , slightly higher than those of H II regions. Some PNe show twice larger abundances.
    - ▶ These differences are real, and the He abundance can help distinguish between different populations of PNe.

- 
- Abundance of the heavy elements in H II regions and PNe
    - ▶ They are determined by a combination of collisionally excited lines and hydrogen recombination lines. The line ratio depends mainly on the shape of the stellar continuum from the following relation.

$$\frac{\text{total cooling}}{L(\text{H}\beta)} \approx \frac{\text{cooling by collisional excitation lines}}{L(\text{H}\beta)} \propto \frac{\int_{\nu_0}^{\infty} \frac{L_\nu}{h\nu} h(\nu - \nu_0) \sigma_\nu^{\text{p.i.}} d\nu}{\int_{\nu_0}^{\infty} \frac{L_\nu}{h\nu} d\nu}$$

Note also that the strength of collisionally excited lines depends strongly on temperature, which is determined by the shape of the stellar continuum. On the other hand, the recombination lines are not very sensitive to the gas temperature.

- ▶ The gas is hotter in lower-metallicity nebulae.
- ▶ Disadvantages: (1) Collisional excitation lines can be converted into abundances only when the gas temperature is well measured. (2) Additionally, large and rather uncertain corrections may be required for unobserved ion stages.
- ▶ The abundances of a PN are affected by nuclear processing in the central star, whereas those in H II regions reflect the composition of the interstellar medium.
- Recombination lines of the heavy elements
  - ▶ Large telescopes and CCD detectors have made it possible to detect faint recombination lines of the heavy elements in several H II regions and PNe.
  - ▶ Abundances measured with these methods should be far more robust than those inferred from collision excitation lines, as they have similar dependencies on temperature to hydrogen recombination lines.
  - ▶ This method would not be affected by temperature fluctuations.
  - ▶ However, the lines are faint, and the recombination process is complicated by strong dielectronic recombination.

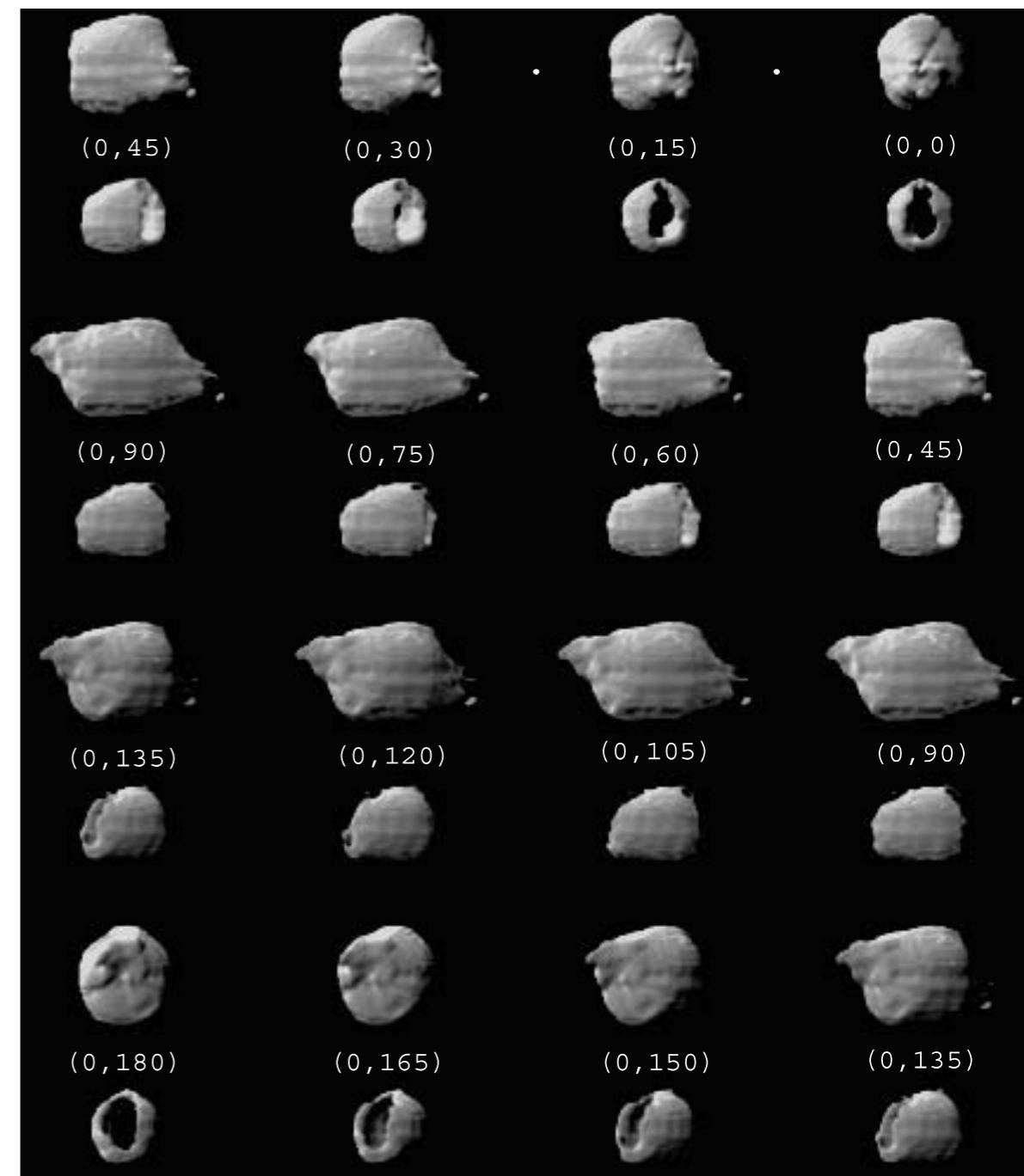
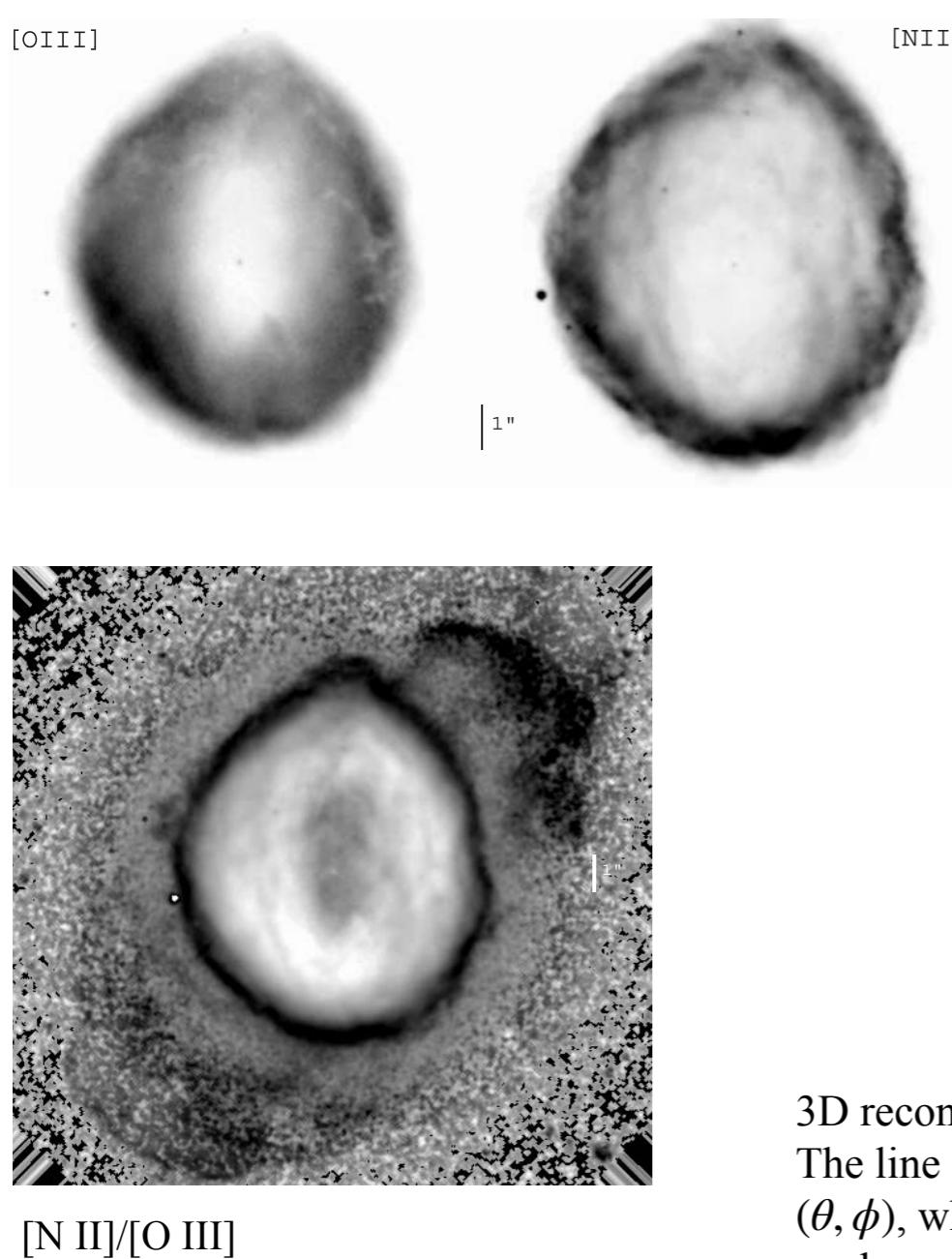
- Discrepancies in H II regions
  - ▶ In H II regions, **the recombination-line abundances tend to be slightly higher than the forbidden-line abundances**, which is attributed to the temperature fluctuations.
  - ▶ If this is the case, the correct gas-phase abundances are about 50%-100% higher than  $t^2 \approx 0.02 - 0.04$
- PNe
  - ▶ Recent works found differences between collisional and recombination abundances that are larger than a factor of ten, too large to be caused by temperature fluctuations.
  - ▶ This suggests that another, presently unknown, process may be affecting one (or both) of the abundance measures.
  - ▶ The fact that the discrepancy varies from object to object, indicates that it is not a simple matter of incorrect atomic data. This difference might be related to physical conditions within PNe. If this is the case, then the higher recombination abundances are more likely to be correct.

## 5.12 Calculation of the Structure of Model Nebulae

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- The basic idea of a calculation of a model H II region (or PN) is quite straightforward.
  - Make reasonable assumptions about the physical parameters of (1) the ionizing star, (2) the density distribution, (3) the relative abundances of the elements in the nebula, and (4) its size, geometrical structure, and so on.
  - Calculate the physical structure (1) the ionization, (2) temperature, (3) emission coefficients (emissivity) as functions of position
  - Calculate the expected emergent radiation at each point in each emission line.
  - Compare this predicted model with the observed properties to check whether the initial assumptions are consistent with the observations.
  - If they are not, then the assumptions must be varied until a match with the observational data is obtained.
- In principle vs. In practice
  - In principle, if all the emission lines were accurately measured at every point in the nebula, and if the central star's radiation were measured at each observable frequency, it might be possible to specify accurately all the properties of the star and of the nebula.
  - In practice, the observations are not sufficiently complete and accurate, and do not have sufficiently high angular resolution to enable us carry out this ambitious program, but nevertheless, quite import information is derived from the model-nebula calculation.

- 3-D ionization structure of the planetary nebula NGC 6565 (Tomography)
  - Turatto et al. 2002, A&A, 384, 1062
  - The PN is an expanding plasma. Thus the position, thickness and density of each elementary volume can be derived from the radial velocity, width and flux of the corresponding emission.



3D reconstructed geometry  
The line of view is given by  $(\theta, \phi)$ , where  $\theta$  is the zenith angle and  $\phi$  the azimuthal angle.