AGNAGN seminar
chapter 5. Comparison of Theory with Observations 5.1-5.3

Taiki Kikuchi

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5.1 Introduction

Estimate physical quantities from observations

- Temperature T
  - The strengths of H recombination lines **themselves** vary **extremely weakly** with T.
  - But **the ratio** of a line to recombination continuum varies **more rapidly**.
  - So, we can utilize the ratio for estimating the temperature T.
- Electron density n_e
  - We can estimate n by using the ratios of pair of lines with **close energy** but with **different transition probabilities**.
- abundance
  - Once we estimate T, n_e, then we can obtain the total number of ions.

5.2 Temperature measurements from emission lines

- A few ions have energy-level structures that result in emission lines from **two different upper levels**.
- The relative **rates of excitation** to upper levels **depend very strongly on** T, so the relative strength of the lines emitted by these levels may be used to measure electron temperature.
- We can calculate **exact populations** of the various levels , according to Section 3.5.
- However, it is simpler and more instructive to proceed by direct physical reasoning.

Hereafter, we consider [OIII] lines , which are the best example.

5.2 Energy levels of [OIII]

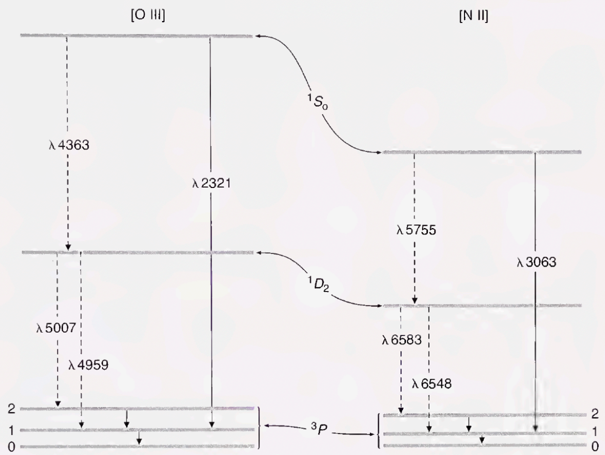


Figure 3.1

5.2 Properties of [OIII]

- ^1D level decays into $^3P_2$ or $^3P_1$ which result in emission of a photon $\lambda5007, \lambda4959$ respectively.
- In the limit $n_e \to 0$, line ratio is calculated by the relative transition probabilities. $(\lambda5007 : \lambda4959 \fallingdotseq 3 : 1)$
- ^1S level decays into ^1D or $^3P_1$ which result in emission of a photon $\lambda4363, \lambda2321$ respectively.
- Cascade decay $^1S \to^1 D \to^3 P$ is possible, but its contribution is relatively small. So, we neglect this here.

5.2 Emission line ratio

The ratio of emission-line strengths in the limit $n_e \to 0$ (collisional deexcitation is negligible)is given simply by

emission line ratio

$$\frac{j_{\lambda 4959} + j_{\lambda 5007}}{j_{\lambda 4363}} = \frac{\Upsilon(^3P, ^1D)}{\Upsilon(^3P, ^1S)} \left[\frac{A(^1S, ^1D) + A(^1S, ^3P)}{A(^1S, ^1D)} \right] \frac{\bar{\nu}(^3P, ^1D)}{\nu(^1D, ^1S)} \exp(\Delta E/kT) \tag{1}$$

where, $h\bar{\nu}$ is transition-probability-averaged energy

$$\bar{\nu}(^3P, ^1D) = \frac{A(^1D_2, ^3P_2)\nu(\lambda 5007) + A(^1D_2, ^3P_1)\nu(\lambda 4959)}{A(^1D_2, ^3P_2) + A(^1D_2, ^3P_1)} \tag{2}$$

and ΔE is the energy difference between the $^1D_2$ and $^1S_0$.

5.2 Rough explanation of the emission line ratio

- The emission line strength is proportional to the collision strenghs Υ(refer to my slides of Chapter3).
- $\Upsilon(^3P,^1S) \times [A(^1S,^1D)/(A(^1S,^1D) + A(^1S,^3P)]$ means the collision strength from ^1S to ^1D ($\Upsilon(^1S,^1D)$).
- The energy of a single photon by the transition is $h\nu$, which corresponds to the energy gap of the levels.
- Boltzmann factor $\exp(\Delta E/kT)$ corresponds to the population ratio.

5.2 1st Order Correction by collisional deexcitation

- The emission line ratio (1) is a good approximation up to $n_e \sim 10^5 \mathrm{cm}^{-3}$.
- However, at higher densities **collisional deexcitation** begins to play a role.
- **First order correction** in $n_e, \exp(-\Delta E/kT)$: the RHS of eq(1) is divided by a factor

$$f = \frac{1 + \frac{C(^1D,^3P)C(^1D,^3P)}{C(^1S,^3P)A(^1D,^3P)} + \frac{C(^1D,^3P)}{A(^1D,^3P)}}{1 + \frac{C(^1S,^3P) + C(^1S,^1D)}{A(^1S,^3P) + A(^1S,^1D)}} \tag{3}$$

where

$$C(i,j) = q(i,j)n_e = 8.629 \times 10^{-6} \frac{n_e}{T^{1/2}} \frac{\Upsilon(i,j)}{\omega_i} \tag{4}$$

(In brief, C is deexcitation rate. Refer to my slides of Chapter3)

5.2 Numerical values of the line ratios

By substituting numerical values of the collisional strengths and transition probabilities, we then get

$$\frac{j_{\lambda 4959} + j_{\lambda 5007}}{j_{\lambda 4363}} = \frac{7.9 \exp\left(3.29 \times 10^4/T\right)}{1 + 4.5 \times 10^{-4} n_e/T^{1/2}} \quad (5)$$

In the same way, we can calculate line ratios of [NII], [NeIII], [SIII]

$$[\mathrm{NII}]\frac{j_{\lambda 6548} + j_{\lambda 6583}}{j_{\lambda 5755}} = \frac{8.23 \exp\left(2.5 \times 10^4/T\right)}{1 + 4.4 \times 10^{-3} n_e/T^{1/2}} \quad (6)$$

$$[\mathrm{NeIII}]\frac{j_{\lambda 3869} + j_{\lambda 3968}}{j_{\lambda 3343}} = \frac{13.7 \exp\left(4.3 \times 10^4/T\right)}{1 + 3.8 \times 10^{-5} n_e/T^{1/2}} \quad (7)$$

$$[\mathrm{SIII}]\frac{j_{\lambda 9532} + j_{\lambda 9069}}{j_{\lambda 6312}} = \frac{5.44 \exp\left(2.28 \times 10^4/T\right)}{1 + 3.5 \times 10^{-4} n_e/T^{1/2}} \quad (8)$$

5.2 Examples of line ratio in low density limit

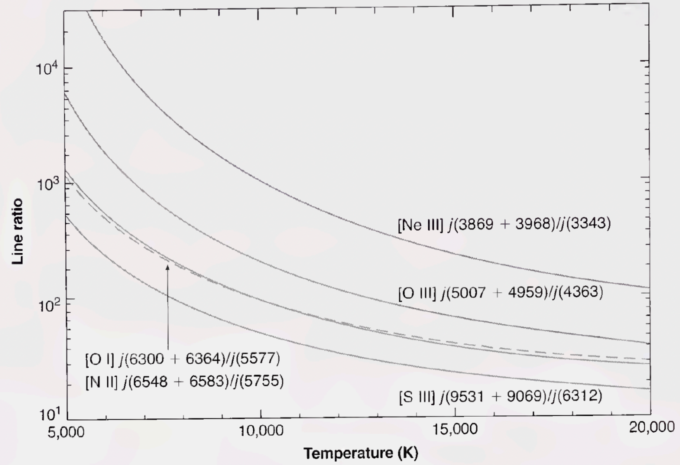


Figure 5.1

$n_e = 1\mathrm{cm}^{-3}$

5.2 Temperature T determination

Since the nebulae are optically thin $(\tau \ll 1)$,

$$\frac{I_{\lambda 4959} + I_{\lambda 5007}}{I_{\lambda 4363}} \simeq \frac{\int (j_{\lambda 4959} + j_{\lambda 5007}) ds}{\int j_{\lambda 4363} ds} \tag{9}$$

where, s is the distance along the ray.
If the temperature T and the electron density n_e are uniform, then the ratio of the intensities becomes simple.

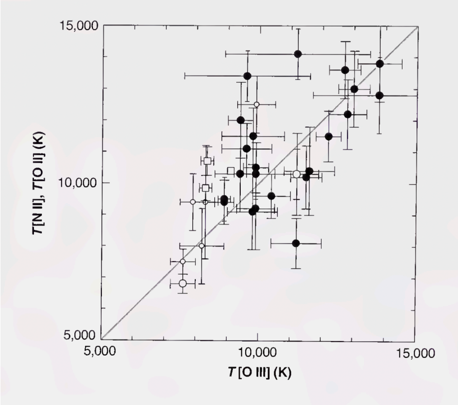
$$\frac{I_{\lambda 4959} + I_{\lambda 5007}}{I_{\lambda 4363}} = \frac{(j_{\lambda 4959} + j_{\lambda 5007}) s}{j_{\lambda 4363} \times s} = \frac{j_{\lambda 4959} + j_{\lambda 5007}}{j_{\lambda 4363} \times} \tag{10}$$

Therefore, in this case, we can estimate T by observing the intensity ratio and by using Fig 5.1.

5.2 Details

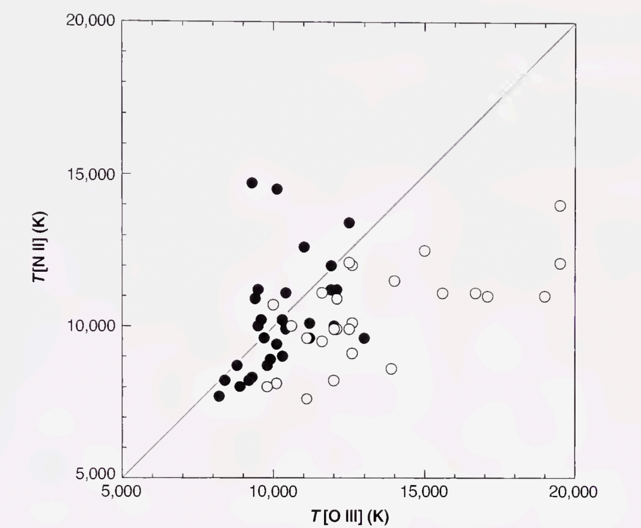
- In the case of **smaller nebulae**, no information need be known on the distance of the nebula, the amount of O++ because they **cancel out**.
- If collisional deexcitation is**not negligible**, even a rough estimate of n_e provides **a good value of** T.
- The effect of the **dust correction is not too large** because the line wavelengths are relatively close .
- The [OIII] line ratio is **quite large** and is therefore rather **difficult to measure accurately**.
- In recent years, light pollution of Hg Iλ4358 have been increasing, so it becomes harder to measure [OIII]λ4363.

5.2 Observation of HII region



All temperatures of these H II regions are in the range $7,000 - 14,000$K.
Large part of the dispersion is due to physical differences between H II regions.

5.2 Observation of Planetary nebulae



5.2 Characteristics of Planetary Nebulae

- Planetary nebulae have higher surface brightness than H II region, so there is a good deal observations.
- The typical temperature of planetary nebulae is somewhat higher than that of HII region. This is because
  - higher temperature of the central star and it leads to a higher energy input
  - higher electron density leads to collisional deexcitations and it then suppress the cooling by emission lines.

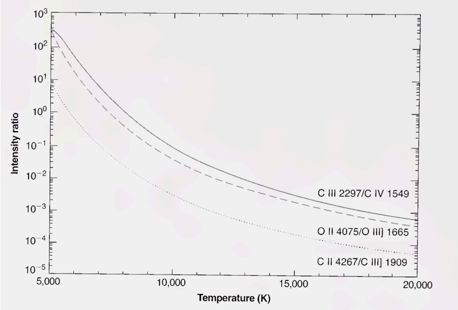
5.2 Another way to estimate the temperature T

Another method

$$\frac{\text{(collisionally excited line)}}{\text{(recombination line of the next lower state of ionization)}} \quad (11)$$

This is because both strengths are proportional to $n(\mathrm{C}^{++})n_e$ and therefore cancel out of their ratio. So, the ratio is the function of T and does not depend on $n(\mathrm{C}^{++})n_e$.

example: collisionally excited line CIII λ1909, recombination line CII λ4267.



5.3 Temperature Determinations from Optical Continuum Measurements

- We can't use H lines as indicators of the temperature T.
- All the recombination cross sections σ_{nL} are proportional to $1/u^2$(same velocity dependence)
- So, relative numbers of captured electrons are nearly independent of T .
- Then, the cascade matrices depend only on transition probabilities A.

However, T can be determined by measuring the relative strength of the recombination continuum with respect to a recombination line.

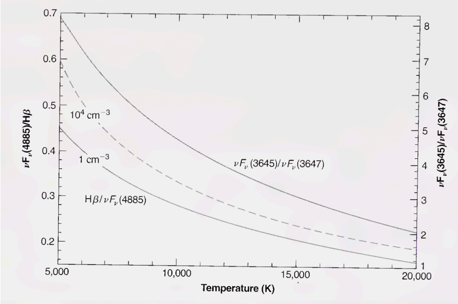
5.3 Temperature Determinations from Optical Continuum Measurement

Rough explanation of why temperature can be determined by measuring the relative strength of the recombination continuum.

- The emission in the continuum depends on velocity-distribution function(Maxwell-Boltzman distribution).

5.3 Two choices of continuum

Substitute numerical values from Table 4.4 to 4.12,



In figure 5.5, we consider Hβ as the recombination line and two choices of continuum.

- λ 4885 (near Hβ)
- Balmer discontinuity $\lambda 3646\pm$.

5.3 Ratio H$\beta/\nu F_\nu(\lambda 4885)$

Continuum $\nu F_\nu(\lambda 4885)$ consists of HI recombination and $2^2S \to 1^2S$ two-photon decay.

- HI recombination: Slowly increase with T.
- two-photon decay : Slowly decrease with T.

Therefore, the total continuum $\nu F_\nu(\lambda 4885)$ is nearly independent of T.
Thus, the dependency of the ratio H$\beta/\nu F_\nu(\lambda 4885)$ is the same as Hβ.
It is known that intensity of Hβ recombination line is proportional to $T^{-0.84}$.

5.3 Ratio of Balmer discontinuity and Hβ

- It is known that the strength of the Balmer continuum at the series limit decreases approximately as $T^{-3/2}$. So, its ratio to Hβ is

$$\frac{\nu F_\nu(3646-) - \nu F_\nu(3646+)}{H\beta} \propto \frac{T^{-1.5}}{T^{-0.84}} = T^{-0.66} \tag{12}$$

  Thus, the ratio slowly decreases with T.
- In the above way, we can determine the temperature by using the ratios of some emission lines and continuum. But,
- It's difficult to observe continuum and Balmer discontinuity because it is also produced by the radiation from the star or by dust scattering.
- It's very difficult to separate Balmer discontinuity by recombination in nebula from that by stellar radiation or dust scattering.