AGNAGN
Sec.5.4-5.6

25/6/20

5.4 Temperature Determinations from Radio-Continuum Measurements

Nebula: optically thick for low frequency radio
⇒Emergent intensity is the same as **blackbody**(**Planck func.**)
⇒**brightness temperature = temp. within the nebula**

$$T_{b\nu} = T\left[1 - \exp(-\tau_\nu)\right] \to T \quad \text{as } \tau_\nu \to \infty \tag{5.8}$$

(include non-thermal synchrotron radiation/foreground radiation)

$$T_{b\nu} = T_{fg\nu} + T\left[1 - \exp\left(-\tau_\nu\right)\right] + T_{bg\nu} \exp\left(-\tau_\nu\right) \to T_{fg\nu} + T \quad \text{as } \tau_\nu \to \infty \tag{5.9}$$

$$T_{b\nu} = \int_0^{\tau} T \exp(-\tau_\nu)\, d\tau_\nu, \tag{4.37}$$

Measure the optical depth of nebula

Considering the beam size is necessary to derive temperature

- Low frequency→(beam size)>(nebular size)
- Sensitivity is not uniform

Overestimate optical depth

Correction and deriving distribution of optical depth are required

Derive he distribution of optical depth and temperature

How to derive:

① Assume nebular temperature T

② Derive optical depth of high frequency radio(optically thin)

$$T_{b1} = T[1 - \exp(-\tau_1)] \to T\tau_1 \text{ as } \tau_1 \to 0, \quad (5.10)$$

High frequency
=good angular resolution

③ Transform optical depth from high frequency to low frequency

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

④ Derive the brightness temperature

$$T_{b2} = T[1 - \exp(-\tau_2)]. \quad (5.11)$$

⑤ Check the differences between ④ and mean brightness temp.

Table 5.1

Radio and optical temperature determinations in H II regions

Object	Radio continuum (K)	Radio recombination (K)	Optical (K)
M42	$7,875 \pm 360$	8,500	8800
M43	$9,000 \pm 1,700$	6,700	
NGC 2024	$8,400 \pm 1,000$	8,200	
W51	$7,800 \pm 300$	7,500	
W43	$5,410 \pm 300$	5,640	
M17	$7,600 \pm 400$	$9,100 \pm 100$	
NGC 6334	7,000	7,000	
NGC 6357	6,900	7,300	

References for table: Shaver et al. 1983, MNRAS, 204, 53; Subrahmanyan, R., & Goss, W. M. 1996, MNRAS, 281, 239; and papers cited therein.

Planetary nebular:
Smaller than nebular⇒same correction is required
(use Hβ surface brightness)

5.5 Temperature Determinations from Radio and UV Absorption Lines

HI 21cm line:

- **Occurs as an electron spin-flip transition**
- **Possible to measure the excitation temperature T_{ex} (hyperfine structure)**

$$\frac{n_u}{n_l} = \frac{\omega_u}{\omega_l} \exp(-\chi_{ul}/kT_{ex})$$

χ_{ul}: excitation energy of the line
$n_{u,l}$: population of lower/upper level
$\omega_{u,l}$: statistical weights of lower/upper level

- **$T_{ex} = \mathrm{T}$ when collisional excitation is dominant (usually, $T_{ex} \sim \mathrm{T}$ is a good approximation)**

Line optical depth & temperature:

Line optical depth:

L: path length
a: absorption cross section

$$\tau = \kappa L = a(n_l - n_u \omega_l/\omega_u)L \tag{5.13}$$

Opacity $\boldsymbol{\kappa}$:

$$\kappa = a n_l [1 - \exp(-\chi_{ul}/kT_{ex})] \ [\mathrm{cm}^{-1}]$$

$$\kappa_{UV} = a_{UV} n_l.$$

(UV like Ly α)

$$\kappa_{radio} = a_{radio} n_l \frac{\chi_{ul}}{kT_{ex}}$$

(Radio like 21cm line)

$$\frac{\tau_{radio}}{\tau_{UV}} = \frac{n_{l,radio}}{n_{l,UV}} \frac{\kappa_{radio} L}{\kappa_{UV} L} = \frac{n_{l,radio}}{n_{l,UV}} \frac{a_{radio}}{a_{UV}} \frac{\chi_{ul}}{kT_{ex}}.$$

$$\frac{\tau_{21\mathrm{cm}}}{\tau_{\mathrm{L}\alpha}} = \frac{1}{4} \frac{a_{21\mathrm{cm}}}{a_{\mathrm{L}\alpha}} \frac{\chi_{ul}}{kT_{ex}} = \frac{1}{4} \frac{A_{21\mathrm{cm}} \lambda^3_{21\mathrm{cm}}}{A_{\mathrm{L}\alpha} \lambda^3_{\mathrm{L}\alpha}} \frac{\chi_{ul}}{kT_{ex}} = 3.84 \times 10^{-7} T_{ex}^{-1}.$$

5.6 Electron Densities from Emission Lines

How to measure average electron density:

Observe the effects of collisional deexcitation by comparing the intensities of two lines

1. **Of the same ion,**
2. **Emitted by different levels,**
3. **with nearly the same excitation energy**

(Examples: [OII]3729/3726, [SII]6716/6731)

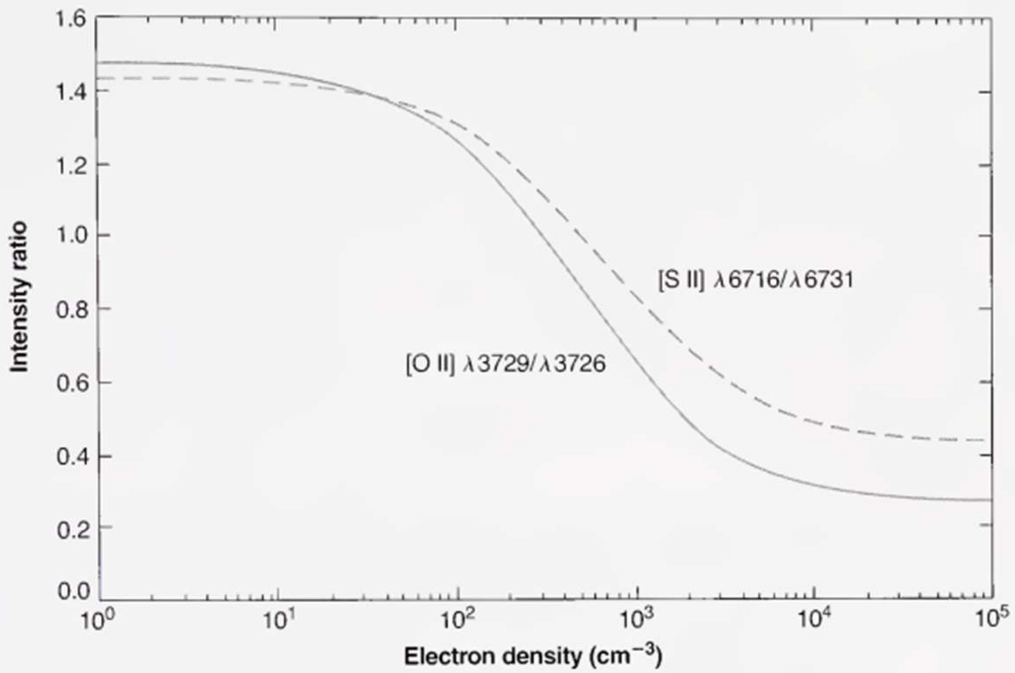

Figure 5.8

Calculated variation of [O II] (*solid line*) and [S II] (*dashed line*) intensity ratios as functions of n_e at T = 10,000 K. At other temperatures the plotted curves are very nearly correct if the horizontal scale is taken to be $n_e(10^4/T)^{1/2}$.

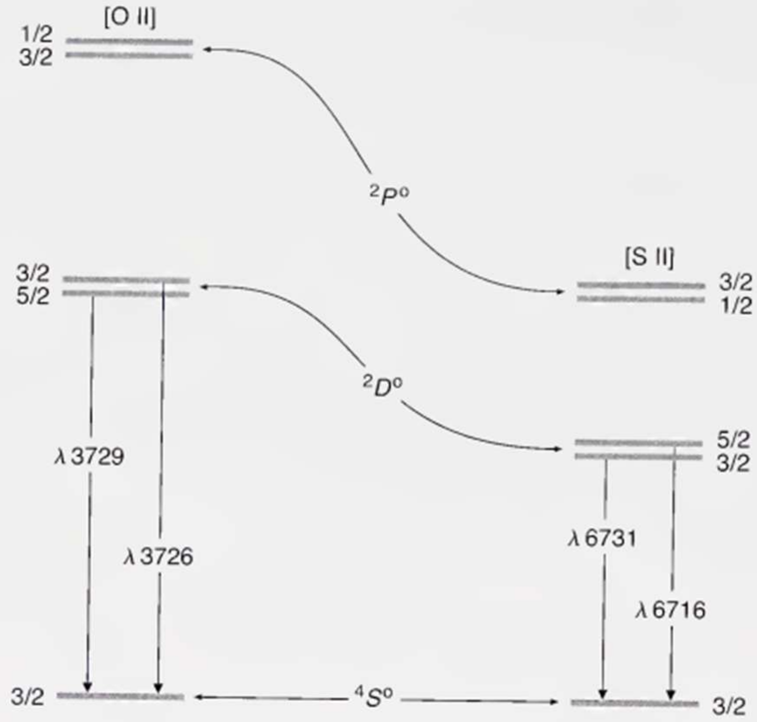

Figure 5.7

Energy-level diagrams of the $2p^3$ ground configuration of [O II] and $3p^3$ ground configuration of [S II].

※[OII] 2 lines are so close in wavelength

Table 5.2
Electron densities in H II regions

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

Purpose of deriving electron density

Correction of [OIII] and [NII] for collisional deexcitation ⇒important to derive electron temperature

$$\frac{j_{\lambda 4959} + j_{\lambda 5007}}{j_{\lambda 4363}} = \frac{7.90 \exp(3.29 \times 10^4/T)}{1 + 4.5 \times 10^{-4} n_e / T^{1/2}}. \qquad (5.4)$$

$$[\mathrm{N\ II}] \frac{j_{\lambda 6548} + j_{\lambda 6583}}{j_{\lambda 5755}} = \frac{8.23 \exp(2.50 \times 10^4/T)}{1 + 4.4 \times 10^{-3} n_e / T^{1/2}} \qquad (5.5)$$

Planetary nebular radiates other lines([CIII], CIII])