Emission lines of ionized gas in galaxies

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basic parameters

- 1 eV =12394 A=2.41867x10^{14} Hz =11605K=1.6x10^{-12} erg
- Ry: 里德伯能量 13.6eV
- 精细结构常数：α = $\frac{e}{ch} \approx \frac{1}{137}$

Overview of ionized gas

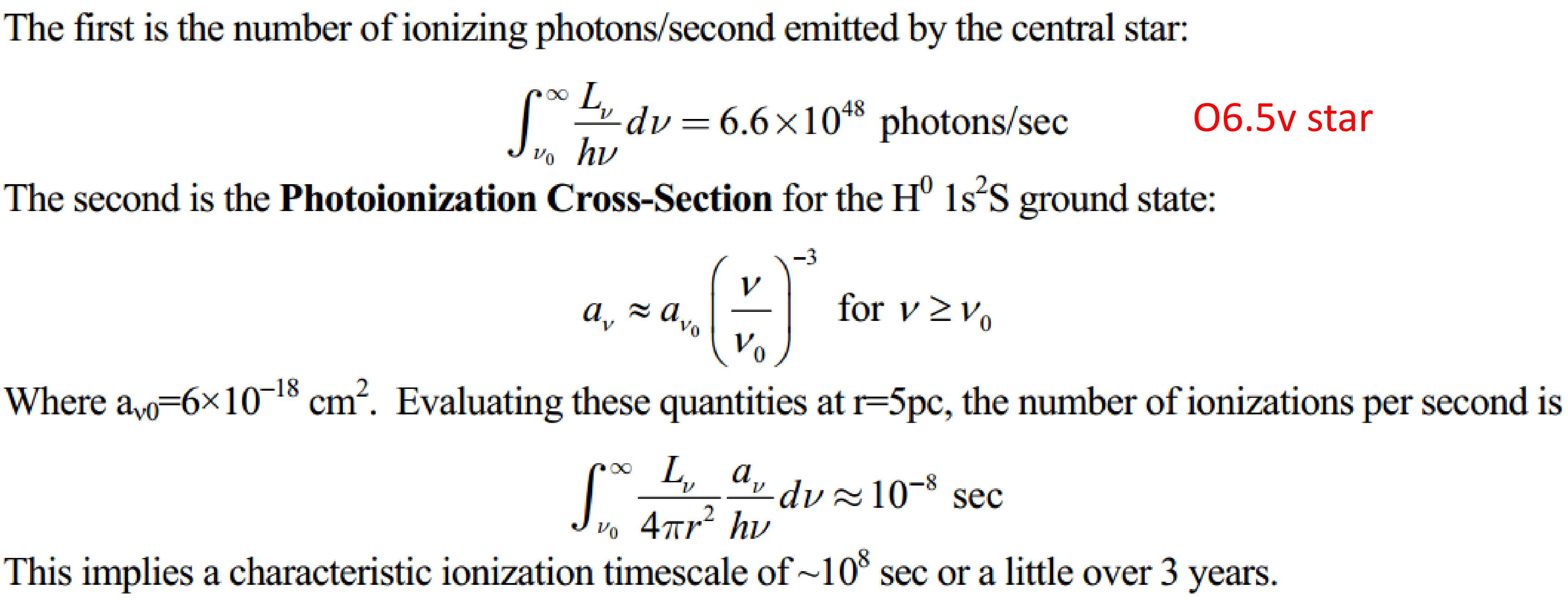
- Together, ionized gas makes up about 23% of the mass of the ISM in our Galaxy.
- Coronal gas
  - $T \sim 10^{5.5}$ K, $n \sim 0.004$ cm^{-3} (the hot ionized medium)
- $T > 10^4$ K, $n \sim 0.3\text{-}10^4$ cm^{-3}
  - discrete H II regions around massive OB stars and planetary nebulae
  - diffuse ionized gas caused by photons leaking from discrete H II regions (the warm ionized medium, WIM)
- Of these, the WIM contains the most mass

Ionization in Predominantly Neutral region

- 光致电离
  - C,O等金属的电离界面远大于H
  - About 99.9% of gas-phase interstellar carbon（100K）is ionized （电离势<13.6eV）
- 宇宙线电离

Strömgren Sphere

- Pure Hydrogen Nebula



The first is the number of ionizing photons/second emitted by the central star:

$$\int_{\nu_0}^{\infty} \frac{L_\nu}{h\nu} d\nu = 6.6 \times 10^{48} \text{ photons/sec}$$

O6.5v star

The second is the **Photoionization Cross-Section** for the H^0 $1s^2S$ ground state:

$$a_\nu \approx a_{\nu_0} \left(\frac{\nu}{\nu_0} \right)^{-3} \text{ for } \nu \geq \nu_0$$

Where $a_{\nu 0}=6\times10^{-18}$ cm^2. Evaluating these quantities at r=5pc, the number of ionizations per second is

$$\int_{\nu_0}^{\infty} \frac{L_\nu}{4\pi r^2} \frac{a_\nu}{h\nu} d\nu \approx 10^{-8} \text{ sec}$$

This implies a characteristic ionization timescale of ~10^8 sec or a little over 3 years.

For typical nebular conditions, the recombination coefficient is:

T~10000K $$\alpha(H^0,T) \approx 4\times10^{-13}\ \text{cm}^3\ \text{s}^{-1}$$

This corresponds to a characteristic **Recombination Time** of

$$t_{rec} = \frac{1}{n_e\alpha(H^0,T)}$$

For $n_e \approx 10\ \text{cm}^{-3}$ (assuming nearly completely ionized H) the recombination time is $\sim 3\times10^{11}$ sec or $\sim 10^4$ years. In such a region, once a neutral Hydrogen atom is photoionized it stays ionized for a long time before recombining, and when it recombines it is relatively quickly photoionized again. This

$$\xi\times(10^{-8}) = (1-\xi)^2 n_H (4\times10^{-13})$$

$$\xi \approx 4\times10^{-4} \ll 1$$

Stromgren Radius: ~5pc, fully ionized, very sharp-edged

The transition between ionized ($\xi \ll 1$) and neutral ($\xi \approx 1$) is very abrupt. The mean-free path of an ionizing photon with $\nu=\nu_0$ is

$$\ell_{\nu_0} = \frac{1}{a_{\nu_0} n_{H^0}}$$

At the location where $\xi=0.5$ (50% neutral), $n_{H^0} = \xi\, n_H = 0.5\times10 = 5\ \text{cm}^{-3}$ and the ionization cross section at the ionization threshold is $a_{\nu_0} \approx 6\times10^{-18}\ \text{cm}^2$. The resulting mean-free path is:

$$\ell_{\nu_0} \approx 3\times10^{16}\ \text{cm} \approx 0.01\ \text{pc}\,.$$

Timescale of for ionizing a Strömgren Sphere

$$t_{ionize} = \frac{\text{\# of ions to create}}{\text{\# of ionizing photons / second}} = \frac{(4\pi/3) r_1^3 n_H}{Q(H^0)}$$

$$t_{ionization} \approx 10^3 n_{100}^{-1} \text{ yr}$$

O型星寿命：1My

$$t_{sound} = \frac{r_1}{c_s}$$

where c_s is the sound speed:

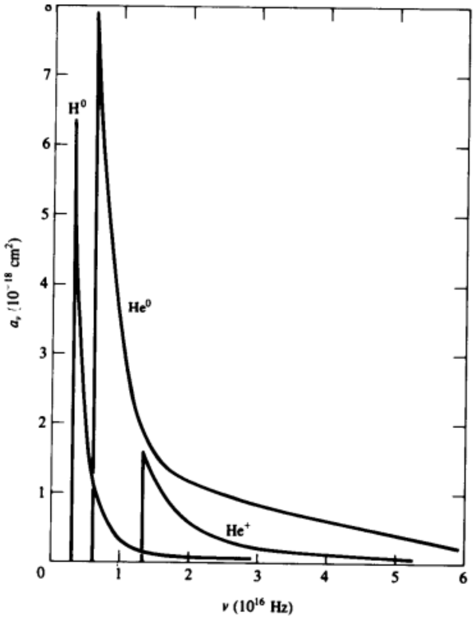
$$c_s = \sqrt{\frac{2kT}{m_H}} \approx 13 T_4^{1/2} \text{ km sec}^{-1}$$

For typical nebular conditions ($T_4=1$, $n_H=100 \text{ cm}^{-3}$),

$$t_{sound} = \frac{\left(3Q(H^0)/4\pi n_H^2 \alpha_B(H^0,T)\right)^{1/3}}{\left(2kT/m_H\right)^{1/2}} \approx 2\times10^5 \frac{Q_{49}^{1/3}}{n_{100}^{2/3}} \text{ yr}$$

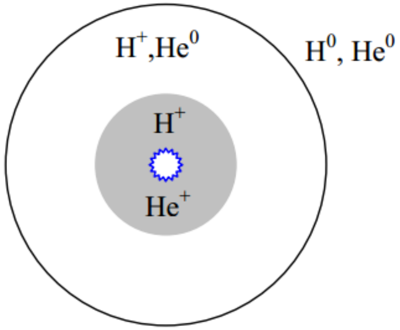
Nebulae with Hydrogen and Helium

- H0→H+ hV1=13.6 eV
- He0→He+ hV2=24.6 eV
- He+→He++ hV3=54.4 eV

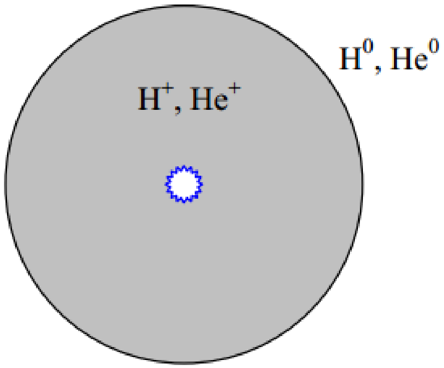


- nHe=0.1nH
  - cross-section for He0 ionization ~10 times larger than H0
  - ionizing photons with hv>hv2 will primarily ionize He0 instead of H0.

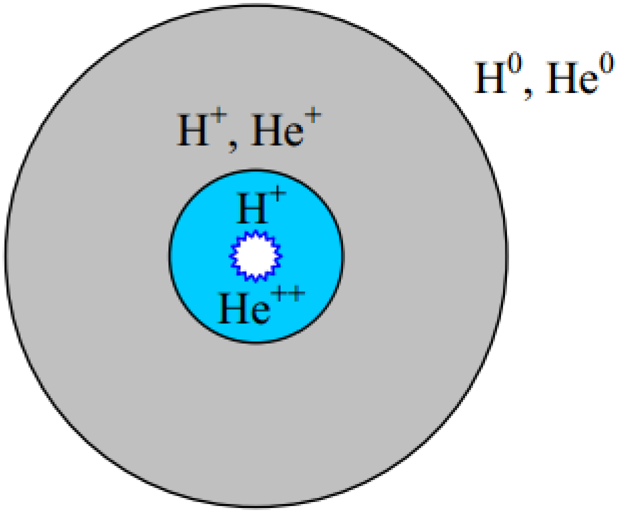
- **"Cool" Stars ($T<40000$ K)** stars later than O6.



- **Hot Stars (T =40,000 – 100,000 K)**:



- **Very Hot Stars (T>10^5 K)**
  - Wolf-Rayet stars， AGN



Metals

- Metals have low abundances relative to Hydrogen and Helium
- so absorption by the different ionization stages of the metals does not significantly modify the radiation field of low density nebulae
- In typical HII regions, therefore, the electron density, ne, is primarily coupled to the H+He, density with negligible contributions from the metals.

$$\begin{aligned} O^0(2p^{4}\,{}^3P) + h\nu &\rightarrow O^+(2p^{3}\,{}^4S) + ks \text{ or } + kd \quad \text{for } h\nu \geq 13.6\,\text{eV} \\ &\rightarrow O^+(2p^{3}\,{}^2D) + ks \text{ or } + kd \quad \text{for } h\nu \geq 16.9\,\text{eV} \\ &\rightarrow O^+(2p^{3}\,{}^2P) + ks \text{ or } + kd \quad \text{for } h\nu \geq 18.6\,\text{eV} \end{aligned}$$

HII区的温度

$$L_R = L_R(H) + L_R(He)$$

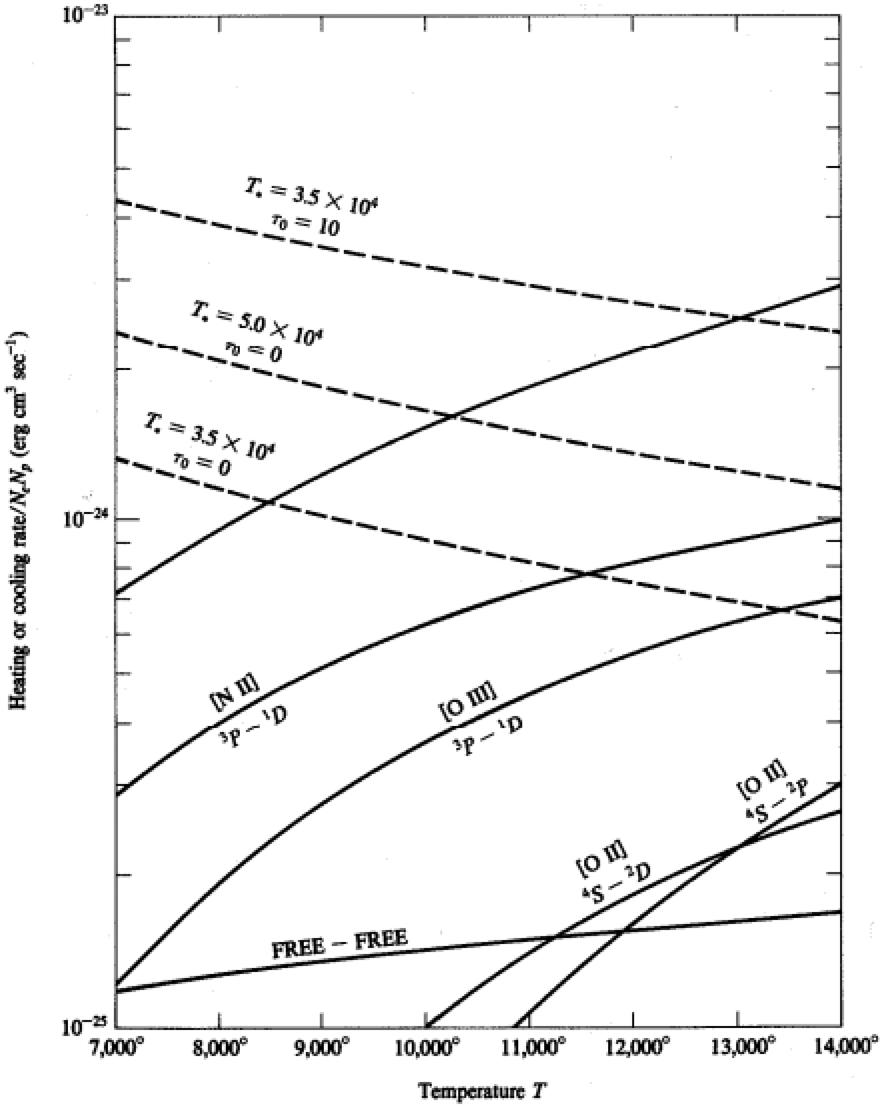
- 复合冷却 $L_R(H) = n_e n_p kT\beta_A(H^0, T)$ $L_R(He) = n_e n_{He^+} kT\beta_A(He^0, T)$
- 自由--自由冷却（韧致辐射）

$$L_{ff}(Z) = 1.42\times10^{-27} Z^2 T^{1/2} g_{ff} n_e n_+$$

温度不敏感
不是很有效

- 碰撞激发线冷却 （禁线）
  - 金属离子 O+ N+ O++ S+
    - 精细能级 ~few eV

$$(G - L_R) = L_{ff} + L_C$$



10^{-23}
10^{-24}
10^{-25}
Heating or cooling rate/N_eN_p (erg cm^3 sec^{-1})
$T_* = 3.5 \times 10^4$
$\tau_0 = 10$
$T_* = 5.0 \times 10^4$
$\tau_0 = 0$
$T_* = 3.5 \times 10^4$
$\tau_0 = 0$
[N II]
$^3P - ^1D$
[O III]
$^3P - ^1D$
[O II]
$^4S - ^2P$
[O II]
$^4S - ^2D$
FREE – FREE
7,000°
8,000°
9,000°
10,000°
11,000°
12,000°
13,000°
14,000°
Temperature T

禁线：Forbidden line

- 碰撞激发到亚稳态，时标长
    - 碰撞激发截面远大于复合截面（3个量级）
- 低密度(避免碰撞退激发）
- 质量大（强度高）
- 可见光部分的强禁线
    - [OIII]5007/4959A （靠近H_beta:4861A）
    - [NII] 6548/6583A (靠近H_alpha:6563A)
    - [SII] 6716A/6731A
    - [OII] 3726A/3729A
- 21cm （跃迁概率$10^{-14.5}$ /s）

Selection Rules

$${}^{2S+1}\mathcal{L}^{p}_{J}\,,$$

L: 总轨道角动量量子数（S,P,D,F）
S：总自旋量子数
J: |L + S| （2S+1)(2L+1）种取值
P: L 的奇偶性

1) Parity must change.
2) $\Delta L = 0, \pm 1$, but $\Delta L = 0 \rightarrow 0$ forbidden. ($\Delta L = 0$ ruled out by rule # 1).
3) $\Delta J = 0, \pm 1$, but $J = 0 \rightarrow 0$ forbidden.
4) Only one single electron wavefunction changes, with $\Delta\ell = \pm 1$. This one took me a while initially to wrap my head around. There are many ways that you could have $\Delta l = 0, \pm 1$ if you allow for multiple electrons to transition. The electron carries away angular momentum, and this angular momentum must come from the atom; thus the rule.
5) $\Delta S = 0$ (Spin does not change). This is another way of saying that the transitions must be between states with the same multiplicity.

碰撞激发　　碰撞退激发　自发辐射

$$n_l n_e q_{lu} = n_u n_e q_{ul} + n_u A_{ul}$$

- 简单模型
  - 低电子密度极限 (n_e→0)
    - 碰撞激发后处于亚稳态（无碰撞退激发），自发辐射

$$4\pi j_{ul} \rightarrow n_l n_e q_{lu} h\nu_{ul} \propto n_e^2$$

  - 高电子密度极限
    - 碰撞退激发主导（无辐射）

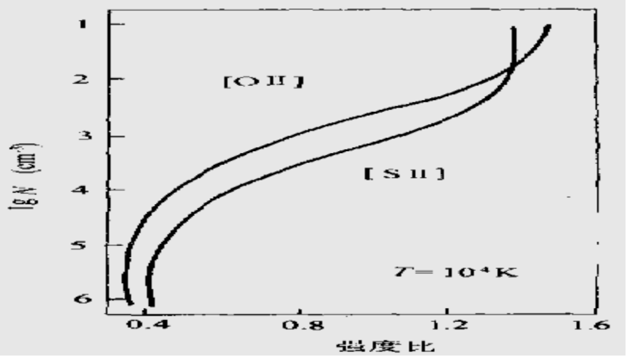
$$4\pi j_{ul} \rightarrow n_u A_{ul} h\nu_{ul} \propto n_e$$

  - 临界密度

$$n_{crit} = \frac{A_{ul}}{q_{ul}}$$

双线

- [OIII]4959/5007,[NII]6548/6583能级差比较大，对电子温度敏感
  - 电子服从麦克斯韦分布（库仑作用强）
- [OII],[SII]线强比敏感于电子密度
  - 在n→0 时，无碰撞退激发 [OII]3726/[OII]3728=[SII]6716/[SII6731]=1.5
  - 在n → ∞ 碰撞退激发
    - [OII]3726/[OII]3728=[SII]6716/[SII6731]=0.3



dust

- Absorption UV photons
  - re-radiate in Far-IR bands
- Photo-evaporate
  - Element Depletion
    - Reduce the

The Spectra of Ionized Hydrogen Regions

- HI复合线
  - Case A： nebula is optically thin in all of the HI resonance lines arising from the 1s ground state (Lyα, Ly β etc.)
    - High T region （>10⁶K）
  - Case B： nebula is optically thick to UV Lyman resonance line absorption, each Lyman photon absorbed is quickly re-emitted
    - 1s→3p, 88% 3p→1s; 12% 3p-2s(Hα) then 2-photon continuum (forbidden 2s-1s transition) → 1s
    - Case B 的Hα比较强

$$\tau_{Ly\alpha} \approx 10^4 \tau_{912}$$

$$\tau_{Ly\beta} \approx 10^3 \tau_{912}$$

$$\alpha_B(T_e) = \begin{cases} 2.90 \times 10^{-10}\, T_e^{-0.77}, & T_e \le 2.6 \times 10^4 \text{ K} \\ 1.31 \times 10^{-8}\, T_e^{-1.13}, & T_e > 2.6 \times 10^4 \text{ K} \end{cases} \text{cm}^3\ \text{s}^{-1}$$

Temperature	5000	10,000		20,000	
N_e (cm^{-3})	10^4	10^2	10^6	10^2	10^4
$\alpha^{\text{eff}}_{\text{H}\beta}$	5.44	3.02	3.07	1.61	1.61
$I(\text{H}\alpha)/I(\text{H}\beta)$	3.00	2.86	2.81	2.75	2.74
$I(\text{H}\gamma)/I(\text{H}\beta)$	0.460	0.468	0.471	0.475	0.476
$I(\text{H}\epsilon)/I(\text{H}\beta)$	0.155	0.159	0.163	0.163	0.163

Ferland, G. J., 1980, PASP

Other possibilities

- High densities (Ne=$10^{8\text{-}12}$ cm^{-3}), 碰撞激发
- 光学深度
  - Balmer线是光深的（AGN的宽线区）
  - Lyman光子leak
- Lyman光子被其它元素共振吸收
  - Dust
  - 趋向Case A

$$O^0(^3P) + H^+ \leftrightarrow O^+(^4S) + H^0(^2S)$$

HeII 4686Å emission

- PN T~20,000 K （Z=2）

$$\alpha_{nL}(Z,T) = Z\alpha_{nL}(H^0, T/Z)$$

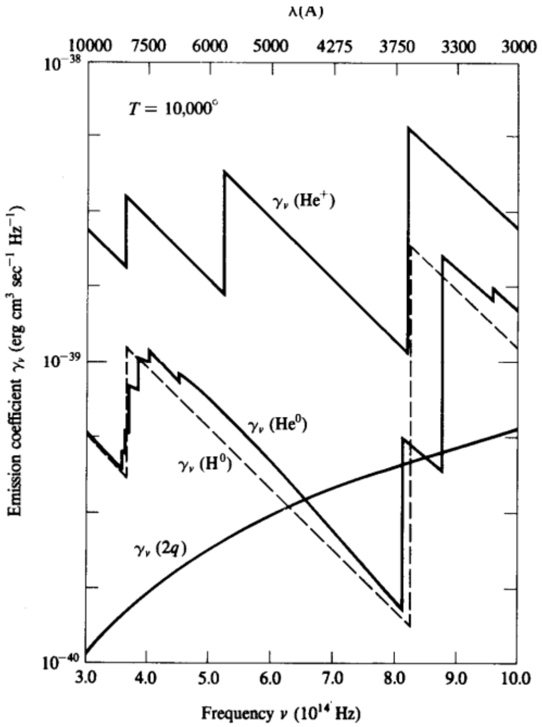
$$h\nu_{nn'}(Z) = Z^2 h\nu_{nn'}(H^0)$$

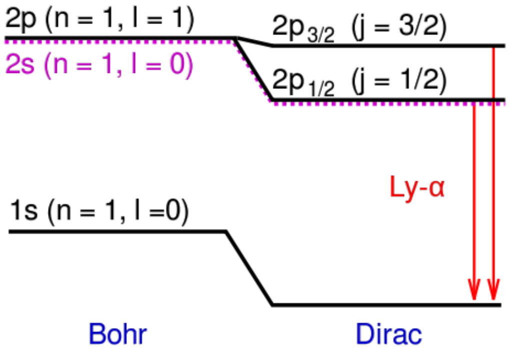
$$j_{nn'}(Z,T) = Z^3 j_{nn'}(H^0, T/Z^2)$$

$$A_{nn'}(Z) = Z^4 A_{nn'}(H^0)$$

Nebular Continuum

- Free-bound
  - >13.6 eV 的电子被复合
- Free-Free
  - 电子散射（韧致辐射）
- 2光子 HI (case B recombination)
  - 2s → 1s
  - 2p→ 1s (Lyman α)



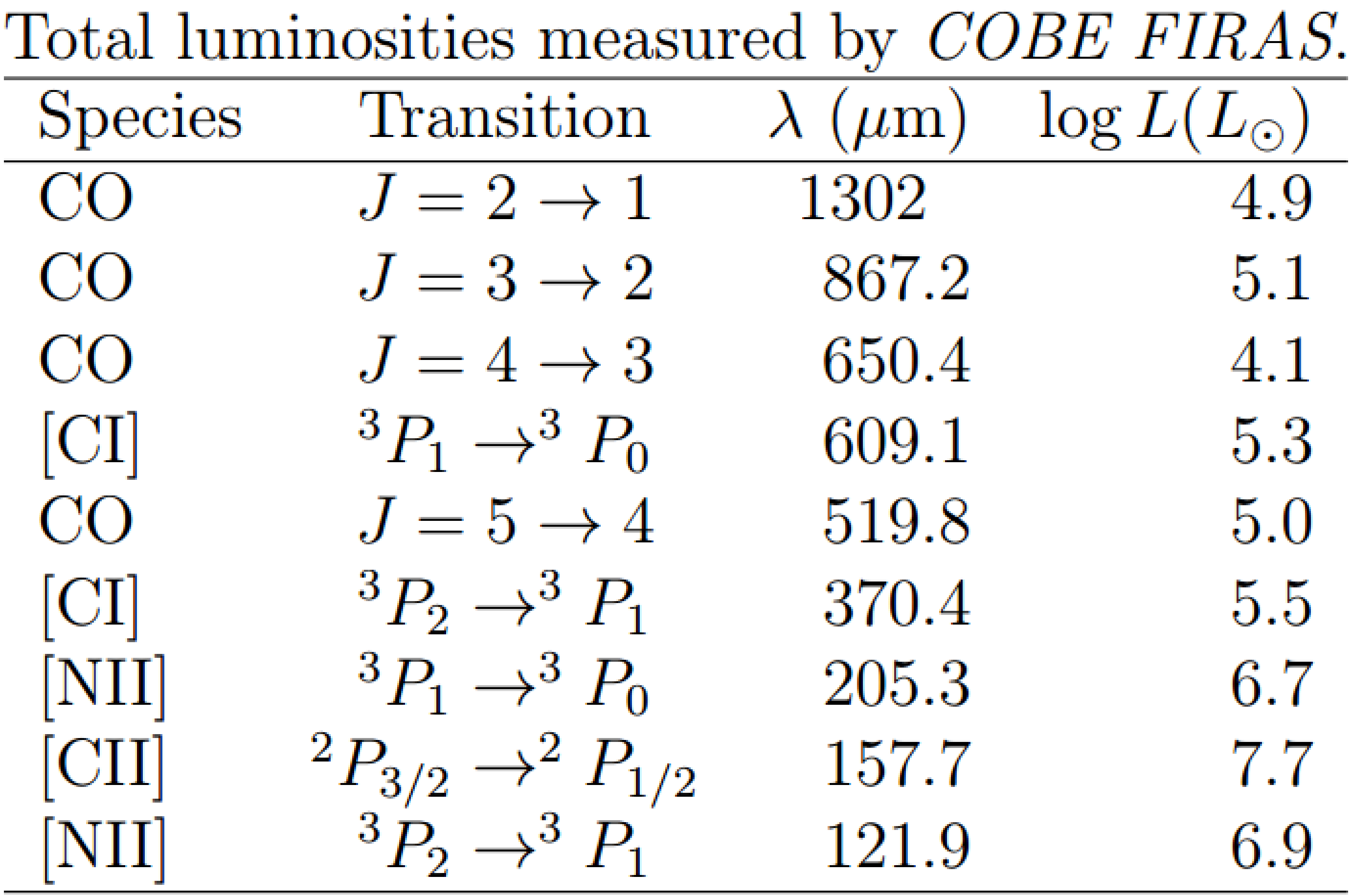


$$A_{2^2S,1^2S} = 8.23\,\mathrm{s}^{-1}$$

mitted must add up to the Lyα phot

$$h\nu' + h\nu'' = h\nu_{12} \approx 10.2\,\mathrm{eV}$$

红外波段的显著发射线



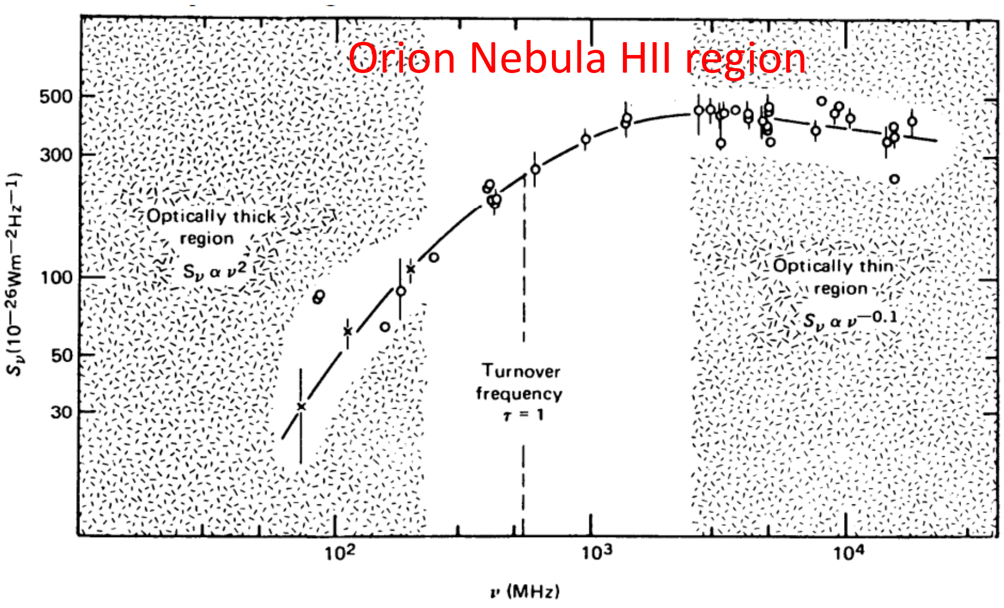
Total luminosities measured by *COBE FIRAS*.

Species	Transition	λ (μm)	$\log L(L_\odot)$
CO	$J = 2 \rightarrow 1$	1302	4.9
CO	$J = 3 \rightarrow 2$	867.2	5.1
CO	$J = 4 \rightarrow 3$	650.4	4.1
[CI]	$^3P_1 \rightarrow^3 P_0$	609.1	5.3
CO	$J = 5 \rightarrow 4$	519.8	5.0
[CI]	$^3P_2 \rightarrow^3 P_1$	370.4	5.5
[NII]	$^3P_1 \rightarrow^3 P_0$	205.3	6.7
[CII]	$^2P_{3/2} \rightarrow^2 P_{1/2}$	157.7	7.7
[NII]	$^3P_2 \rightarrow^3 P_1$	121.9	6.9

[CII] line is the most efficient cooling line of the ISM!

射电波段

- 连续谱 （free-free）

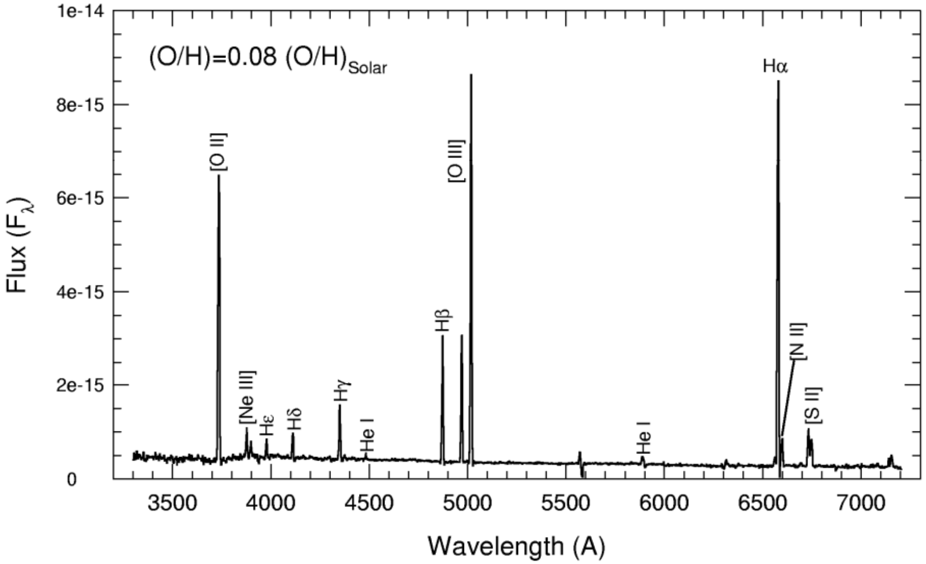

Orion Nebula HII region

- 复合线 （主量子数很大的时候） very faint
  - 最大量子数 n~740 in typical nebular

$$\left(\frac{I_\ell}{I_C}\right) \propto \nu^{2.1} T_e^{-1.15}$$

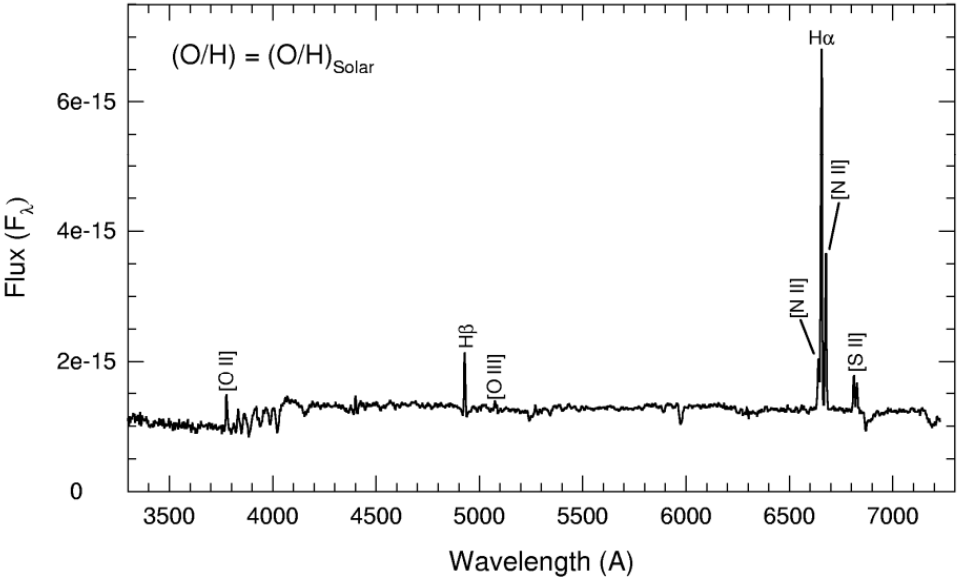
可以推算电子温度

The Spectra of Ionized Nebulae: star forming galaxies



Lower metallicity, hotter nebular, Stronger [OIII]

NGC 1819 - SB0/a Nuclear Ring

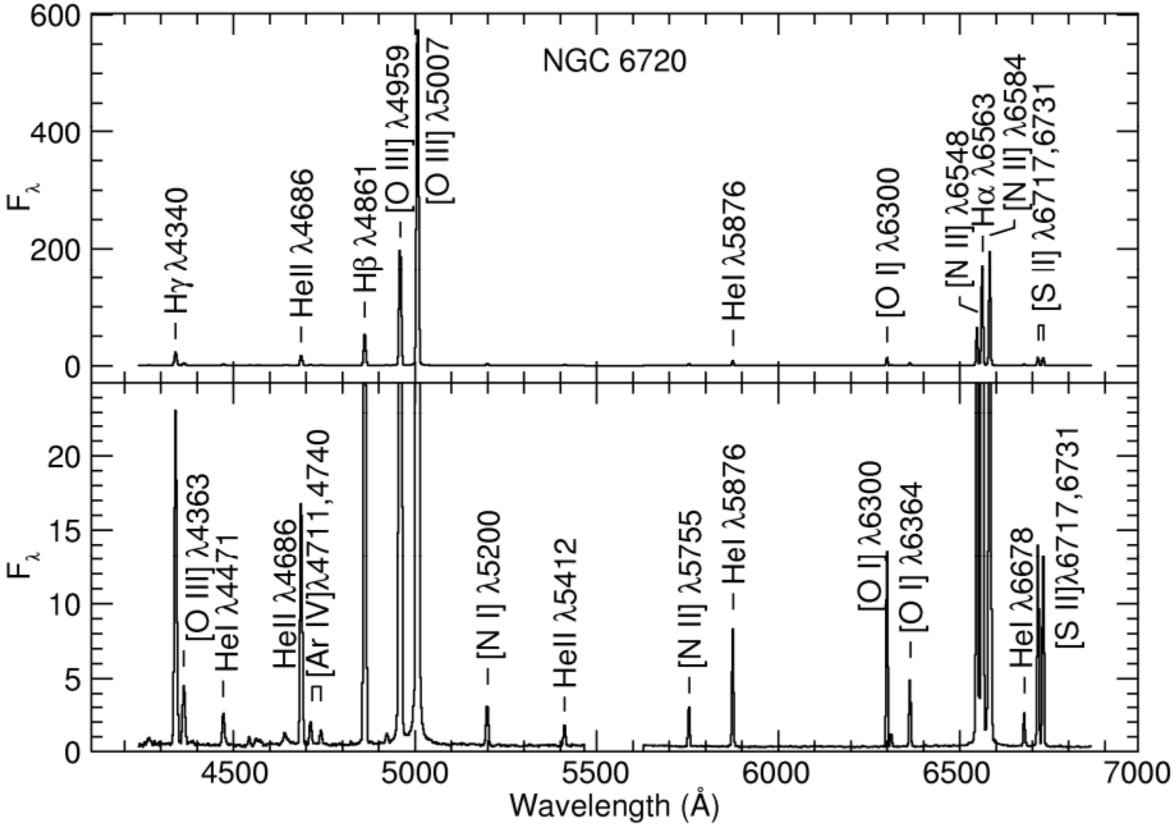


Cooling by far-IR fine structure lines of O and N

PN

Higher T 50,000K-120,000

He++ high level metal lines

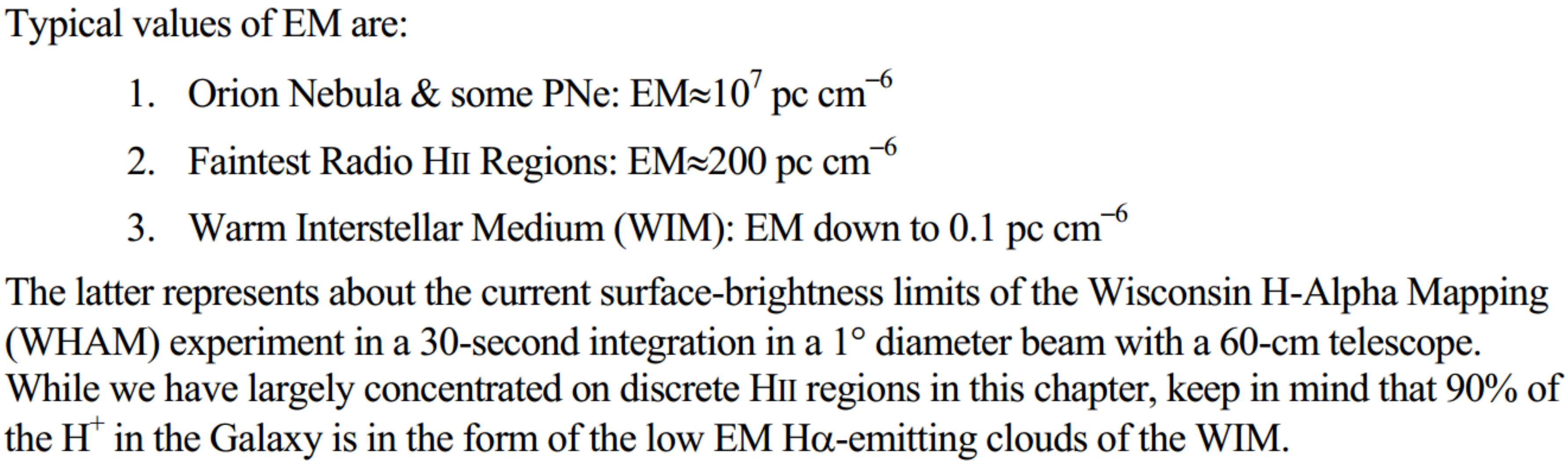


Emission Measure(EM)

$$EM \equiv \int_{los} n_e n_p ds \approx \langle n_e^2 \rangle L$$

$$I(H\beta) = \frac{h\nu_{H\beta}\alpha_{H\beta}^{eff}(H,\langle T\rangle)}{4\pi}\int_{los} n_e n_p ds$$

$$= \frac{h\nu_{H\beta}\alpha_{H\beta}^{eff}(H,\langle T\rangle)}{4\pi} \times EM$$



Typical values of EM are:

1. Orion Nebula & some PNe: EM≈10^7 pc cm^{-6}
2. Faintest Radio HII Regions: EM≈200 pc cm^{-6}
3. Warm Interstellar Medium (WIM): EM down to 0.1 pc cm^{-6}

The latter represents about the current surface-brightness limits of the Wisconsin H-Alpha Mapping (WHAM) experiment in a 30-second integration in a 1° diameter beam with a 60-cm telescope. While we have largely concentrated on discrete HII regions in this chapter, keep in mind that 90% of the H^+ in the Galaxy is in the form of the low EM Hα-emitting clouds of the WIM.

Lyman Continuum

$$Q(H^0)=\int_{\nu_0}^{\infty}\frac{L_\nu}{h\nu}d\nu=\int_0^{r_1}4\pi n_e n_p \alpha_B(H^0,T)r^2dr$$

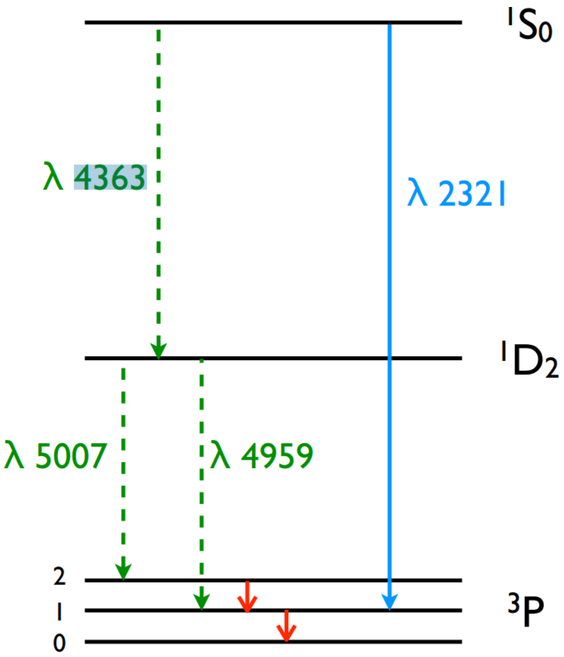
- Hα Hβ lines
  - Hv>13.6 eV的光子无法逃离
  - 来自OB型星， 寿命1My→ SFR

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

- Br α(4.05um) and Br β (2.16um): highly obscured HII regions
- Free-Free continuum at radio wavelenghths
- Drawbacks
  - Lower limit (Lyman Photons escape)
  - Dust reprocession

Nebular Temperatures

- p2 ions, like O++ and N+, all of the levels above the lowest ground state are populated by electron-ion impact excitations.



[OIII] Lines (Measures T_e in O^{++} Zone):

$$R_{[OIII]} = \frac{I(4959)+I(5007)}{I(4363)} \approx \frac{7.73e^{32900/T_e}}{1+4.5\times10^{-4}(n_e/T_e^{1/2})}$$

[NII] Lines (Measures T_e in N^+ Zone):

$$R_{[NII]} = \frac{I(6548)+I(6583)}{I(5755)} \approx \frac{6.91e^{25000/T_e}}{1+2.5\times10^{-3}(n_e/T_e^{1/2})}$$

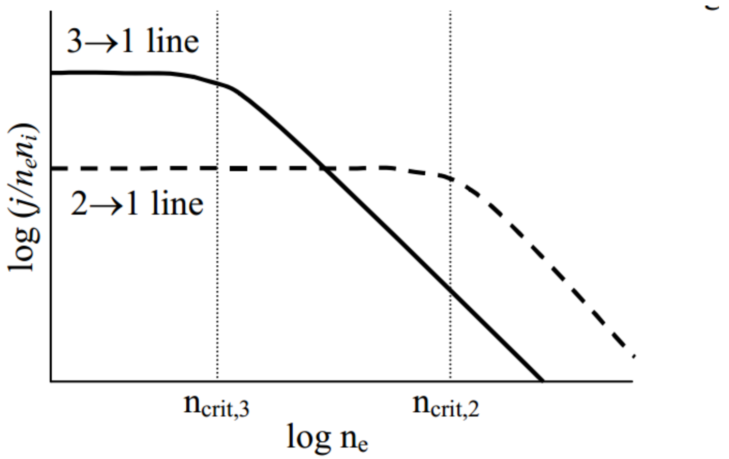
Faint lines

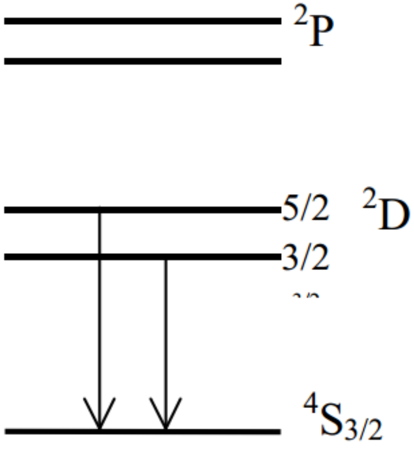
为什么不能直接从双线测量？

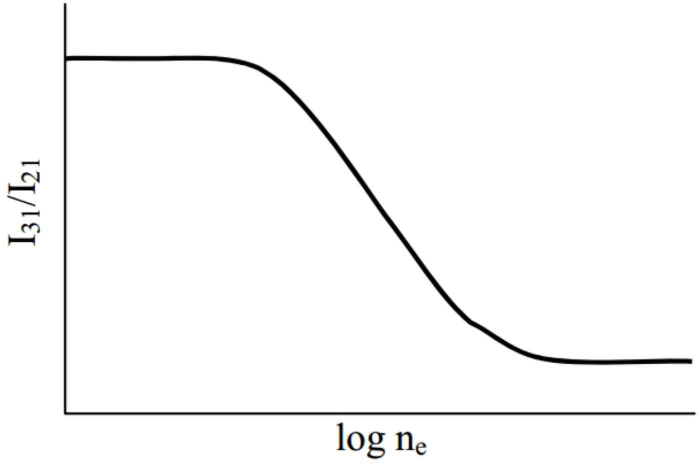
Nebular Densities

$$I_{21} = n_2 A_{21} h\nu_{21}$$
$$\rightarrow n_e^2 \text{ as } n_e \rightarrow 0$$
$$\rightarrow n_e \text{ for } n_e \gg n_{crit,2}$$

- P3 ions S+,   O+
  - [SII] 6716A/6731A
  - [OII] 3726A/3729A

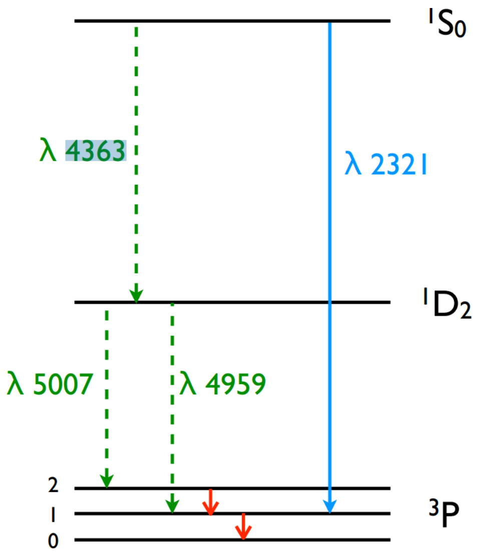






Infrared Fine Structure Lines

- O++ Get Te and n from the same ionic state
  - By measuring two line ratios: I(5007Å)/I(52um) and I(52um)/I(88u m） (Dinerstein, Lester, & Werner 1985, ApJ, 291, 561)



[OIII] $^3P_0 \rightarrow {}^3P_1$ at λ=88.4μm
[OIII] $^3P_1 \rightarrow {}^3P_2$ at λ=51.8μm

Abundance

- **Ionic Abundances:** e.g. O+/H+
- **Total (Elemental) Abundances:** e.g. O/H

Ionic Abundances

the intensity of Hβ is

$$I(H\beta) = \frac{1}{4\pi}\int_{los} n_e n_p h\nu_{H\beta}\alpha^{eff}_{H\beta}(T_e)ds$$

Collisionally excited lines, like [OIII]λ5007Å, are expressed in terms of the collision strengths. In the low-density limit, this is given by:

$$I_{ul} = \frac{1}{4\pi}\int_{los} n_e n_i h\nu_{ul} q_{ul}(T_e) b_{ul} ds$$

Here b_{ul} is the fraction of excitations into the upper excited state that gives rise to the line (it is *not* a

$$\frac{I_{ul}}{I_{H\beta}} = \frac{\int n_e n_i \varepsilon_{ul}(T_e)ds}{\int n_e n_p \varepsilon_{H\beta}(T_e)ds}$$

$$\frac{n_i}{n_p} = \frac{I_{ul}}{I_{H\beta}} \times \frac{\varepsilon_{H\beta}(T_e, n_e)}{\varepsilon_{ul}(T_e, n_e)}$$

For a recombination line, like Hβ:

$$\varepsilon_{H\beta}(T_e) = \frac{4\pi j_{H\beta}}{n_e n_p} = h\nu_{H\beta}\alpha^{eff}_{H\beta}(T_e)$$

For a collisionally-excited line:

$$\varepsilon_{ul}(T_e) = \frac{8.63\times10^{-6}}{T_e^{1/2}}\frac{\gamma_{lu}}{g_u}e^{-h\nu_{ul}/kT}b_{ul}h\nu_{ul}$$

$$\varepsilon_{H\beta} \propto T_e^{-0.9}$$

$$\varepsilon_{ul} \propto T_e^{-0.5}e^{-h\nu_{ul}/kT_e}$$

Inhomogeneous temperature

$$T_0 = \frac{\int n_e n_i T ds}{\int n_e n_i ds}$$

$$t^2 = \frac{\int n_e n_i (T - T_0)^2 ds}{\int n_e n_i ds}$$

Observational work in the visible and Far-IR has produced values

$t^2 \approx 0.035$ for Orion to $t^2 \approx 0.02$ for PNe,

$$T_e(H\beta) \approx T_0[1 - 0.92t^2]$$

Forbidden line

$$T_e \approx T_0 \left[1 + \left(\frac{\chi_1 + \chi_2}{kT_0} - 3 \right) \frac{t^2}{2} \right]$$

Total (Elemental) Abundances

$$\frac{O}{H} = \left(\frac{O^{+} + O^{++}}{H^{+}}\right) \times ICF \approx \left(\frac{O^{+} + O^{++}}{H^{+}}\right) \times \left(\frac{He^{+} + He^{++}}{He^{+}}\right)$$

- Ionization Correction Factor (ICF)

He^{+} (IP=54.4eV) and O^{++} (IP=54.9eV), which differ by 0.5eV

To be continued (next next week)

参考文献：

http://www.astronomy.ohio-state.edu/~pogge/Ast871/