Temperature Fluctuations in Ionized Nebulae and their Effect on the Oxygen Abundance Determination

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Temperature Fluctuations in Ionized Nebulae and their Effect on the Oxygen Abundance Determination

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Temperature Fluctuations or Temperature Inhomogeneities?

- Temperature Fluctuations or Temperature Inhomogeneities are the same:
- They are just departures from a homogeneous temperature.
- They are characterized by the normalized standard deviation from the average temperature.

$$t^2 = \left\langle \frac{[T(r) - T_0]^2}{T_0^2} \right\rangle \qquad T_0 = \langle T(r) \rangle$$

- Where the average is done over the observed volume and weighted by n_e and n_{ion}*.

Outline

1) What are the temperature inhomogeneities?
2) Qualitatively: What is their effect in abundance determinations?
3) How do we know they are there?
4) What is the amplitude of the inhomogeneities?
5) Quantitatively: What is their effect in abundance determinations?
6) Statistically: What should be done to improve the abundance determinations?
7) Conclusions

What are the Temperature Inhomogeneities?

- The standard study of photoionzed regions is based on the hypothesis that to derive reliable abundances it is enough to do an analysis assuming homogeneous temperature and density.

- For many objects, it is possible to determine one (or a few) temperature and one (or a few) density using Colisionally Excited Line (CEL) ratios.

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- There is an additional assumption that, if there are some small variations in the temperature, the temperature one determines will be an average and when determining abundances the effects of this single temperature will average out.
- Small things that are usually included are:
  - 2 zone analysis.
  - Photoionization models produce t^2 values of about 0.004.

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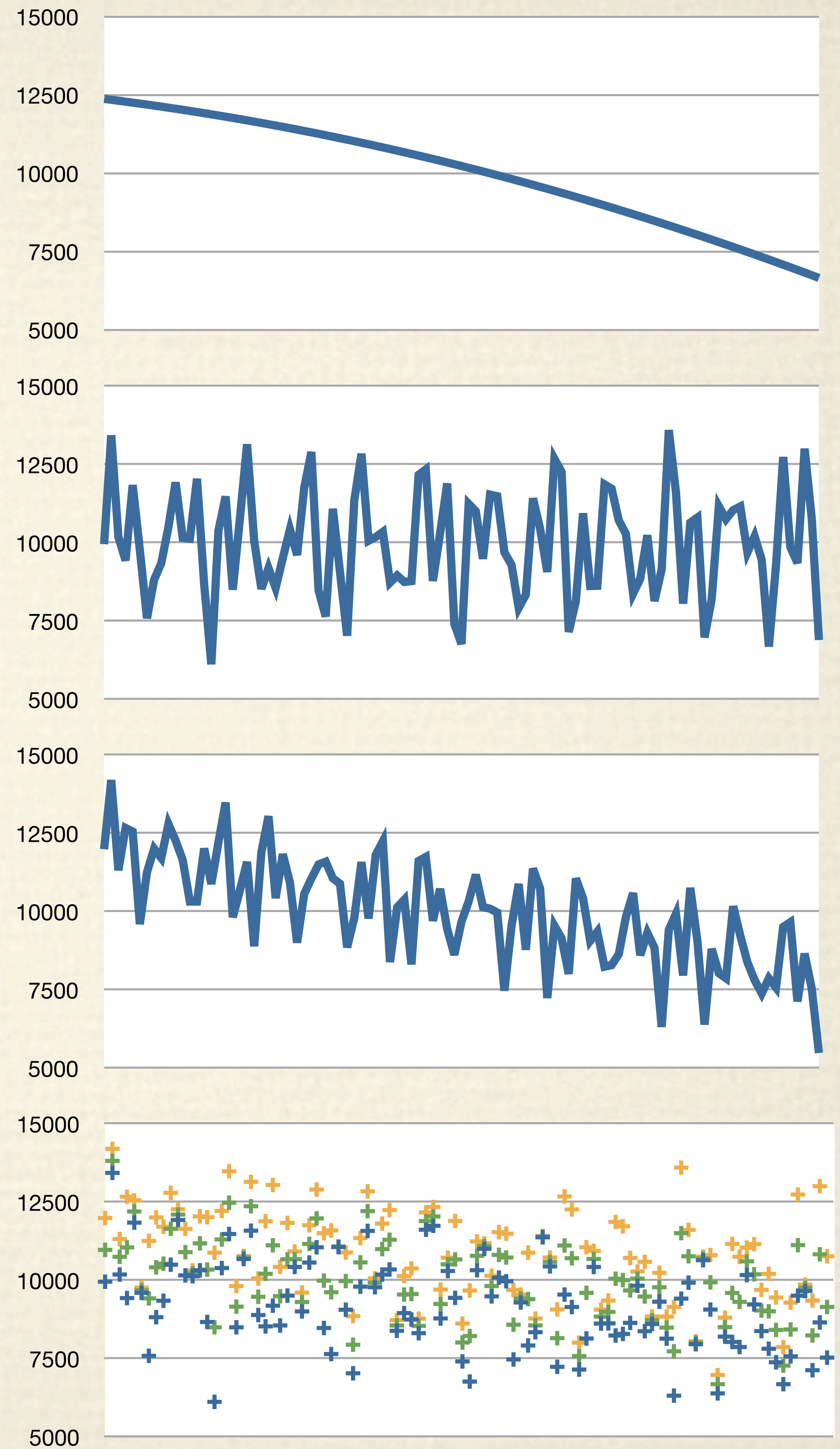
- The specific intensity of the emission lines depends on the velocity distribution of the electrons on the observed region of space.
- And the conclusions can be deeply skewed if one assumes a single temperature (Maxwellian distribution*) in a region where several temperatures (Maxwellian distributions*) are present.
- It doesn’t matter whether the inhomogeneities come from a steep gradient, small scale fluctuations or even coexisting Maxwellians within the same microscopic volume*.



Qualitatively: What is the effect of the Temperature Inhomogeneities?

- In the presence of thermal inhomogeneities, Optical (and UV) CELs are brighter in the hotter regions while RLs are brighter in the cooler regions.
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  - The temperature determined from Optical CELs is higher than the average.
  - The CELs from the hotter regions would be considered adequately, while the CELs from the cooler regions would be much fainter than expected.
  - The RLs from the hotter regions would be considered adequately, while RLs from the cooler regions would be brighter than expected.
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- Therefore the abundances would be underestimated.
- This effect can easily explain the observed ADFs of H II regions and of most PNe.
- Caveats:
  - Some PNe (maybe 10%) do have H poor clumps.
  - If a significant amount of the emission comes form regions with densities over 10^5, the density inhomogeneities would mimic the effects of temperature inhomogeneities.
    - For IR lines it breaks down when there is a significant amount of emission from regions with densities over 10^3.

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- Temperatures determined from different ions give different results.
- Temperatures determined using RLs are always lower than those determined from Optical CELs.
- There are ADFs in most (if not all) H II regions and PNe.
- We know there are shockwaves, shadowed regions, ionization fronts, x-rays and cosmic rays.
- Some people insist that photoionization dominates the energetics of these regions but, the presence of filling factors, $\epsilon << 1.00$, indicates this is not the case.

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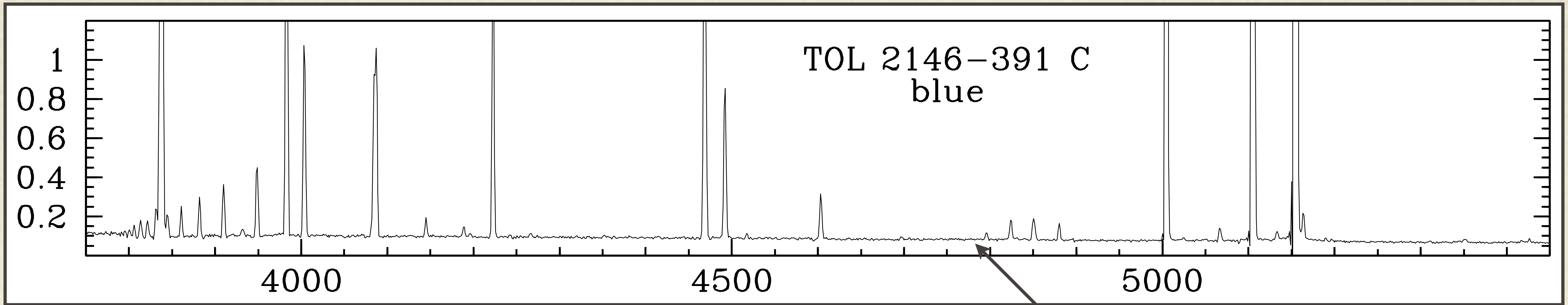
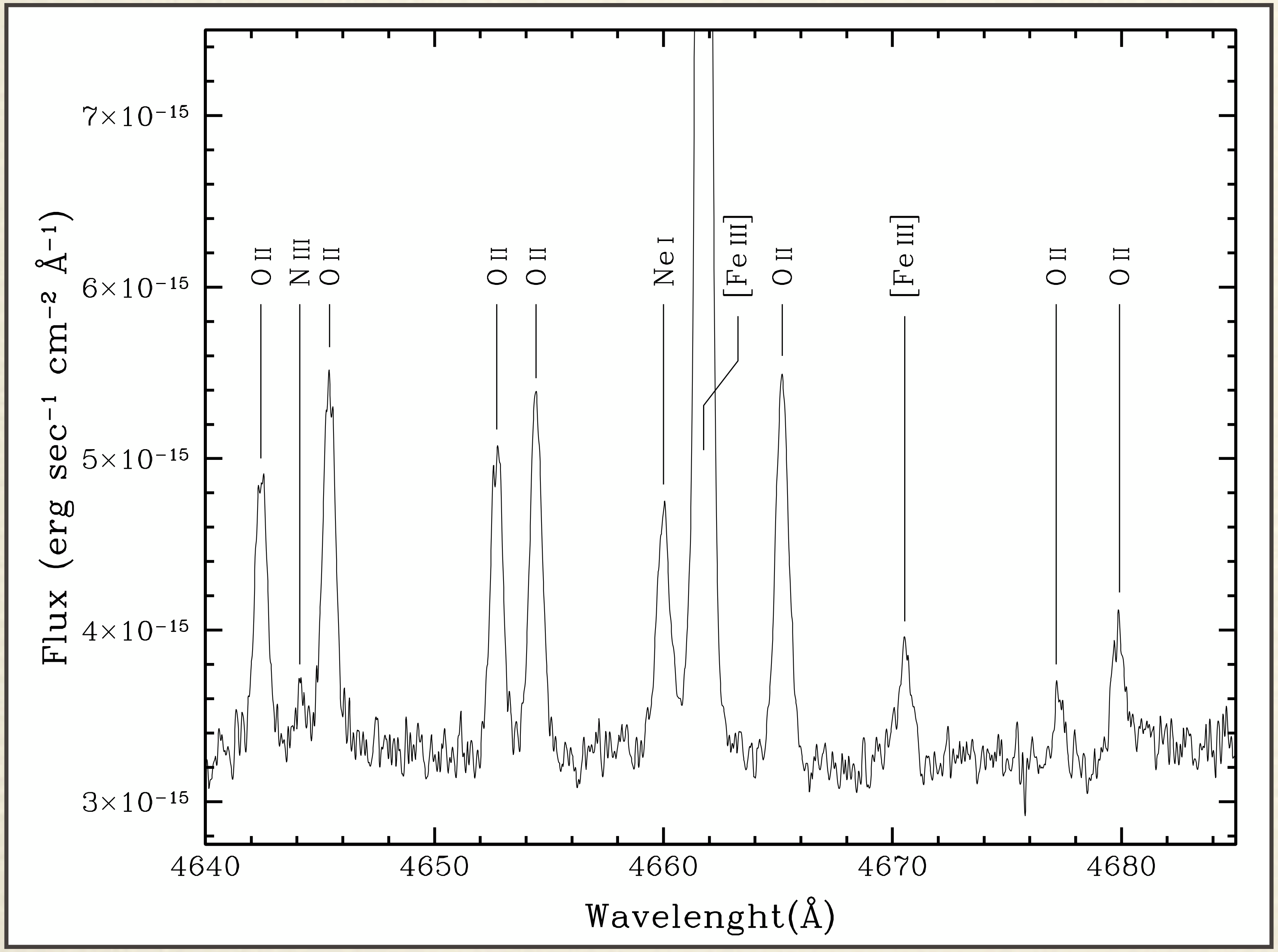
- A different question is whether these inhomogeneities occur in a chemically homogeneous region or not.
  - We have used several different methods to determine the magnitude of these thermal inhomogeneities.
    - Comparing: Balmer with Oxygen CEL temperatures.
    - Comparing O^{++} CEL with O^{++} RL abundances.
    - Comparing C^{++} CEL with C^{++} RL abundances.
    - Comparing Oxygen CEL with He^{+} RL temperatures.
  - These magnitudes agree with each other showing that H, He , C, and O well mixed.





4 O II lines

Added together they are 7 times fainter than the Fe line

and 150 times fainter than 4363

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- We need to model a distribution of temperatures.
- Since we don't know the temperature at each point of the nebula we have to.....
- We can try to make a model with a very large number of gas parcels.
    - It would be a very artificial distribution without much astrophysical meaning.
- We can simplify the problem assuming small deviations.
    - Much work has been done using a Taylor expansion.

t^2 formalism: Taylor expansion

$$I(\lambda, n_e, n_{ion}, T) \equiv I_\lambda(T) \times n_e \times n_{ion}$$

$$I_\lambda(T) = I_\lambda(T_0) + I'_\lambda(T_0)(T - T_0) + \frac{1}{2!} I''_\lambda(T_0)(T - T_0)^2 + \frac{1}{3!} I'''_\lambda(T_0)(T - T_0)^3 + ...$$

$$\begin{aligned} \langle I_\lambda(T(r)) \rangle = I_\lambda(T_0) \quad &+ \quad I'_\lambda(T_0) \langle [T(r) - T_0] \rangle \\ &+ \quad I''_\lambda(T_0) \frac{1}{2!} \left\langle [T(r) - T_0]^2 \right\rangle \\ &+ \quad I'''_\lambda(T_0) \frac{1}{3!} \left\langle [T(r) - T_0]^3 \right\rangle + ... \end{aligned}$$

$$t_k = \left\langle \frac{[T(r) - T_0]^k}{T_0^k} \right\rangle$$

$$\langle I_\lambda(T(r)) \rangle = I_\lambda(T_0) + I'_\lambda(T_0) T_0 t_1 + I''_\lambda(T_0) T_0^2 \frac{t_2}{2!} + I'''_\lambda(T_0) T_0^3 \frac{t_3}{3!} + ...$$

t^2 formalism: second order approximation

$$\langle I_\lambda(T(r))\rangle = I_\lambda(T_0) + I'_\lambda(T_0)T_0t_1 + I''_\lambda(T_0)T_0^2\frac{t_2}{2!} + I'''_\lambda(T_0)T_0^3\frac{t_3}{3!} + ...$$

$$T_0 = \langle T(r)\rangle$$

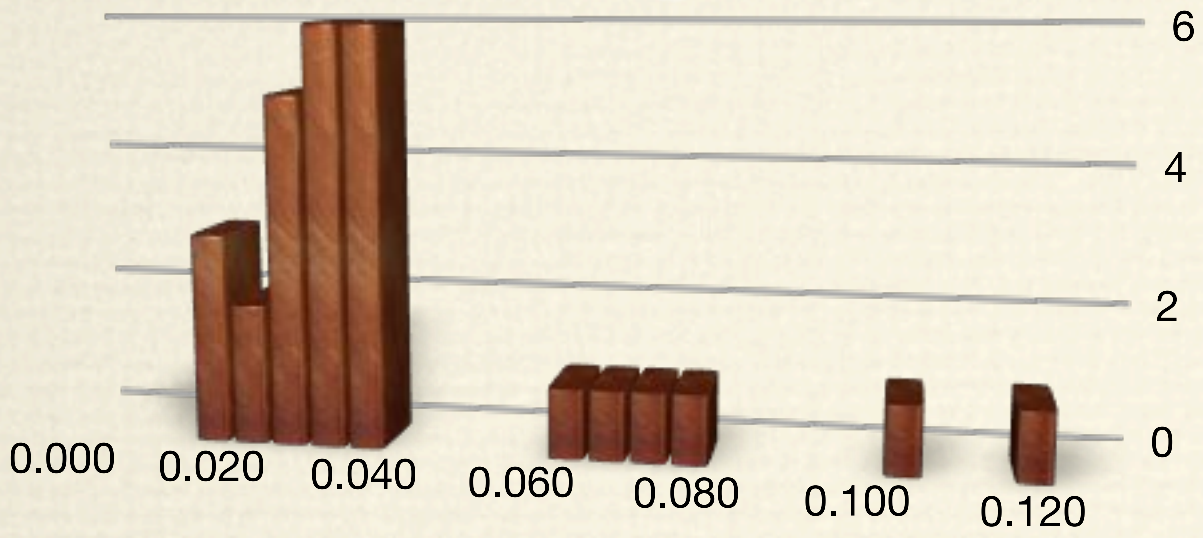
$$\langle I_\lambda(T(r))\rangle = I_\lambda(T_0) + I''_\lambda(T_0)T_0^2\frac{t_2}{2!} + I'''_\lambda(T_0)T_0^3\frac{t_3}{3!} + ...$$

$$\langle I_\lambda(T(r))\rangle = I_\lambda(T_0) + I''_\lambda(T_0)T_0^2\frac{t_2}{2!} + ...$$

$$t^2 = t_2 = \left\langle \frac{[T(r) - T_0]^2}{T_0^2} \right\rangle$$

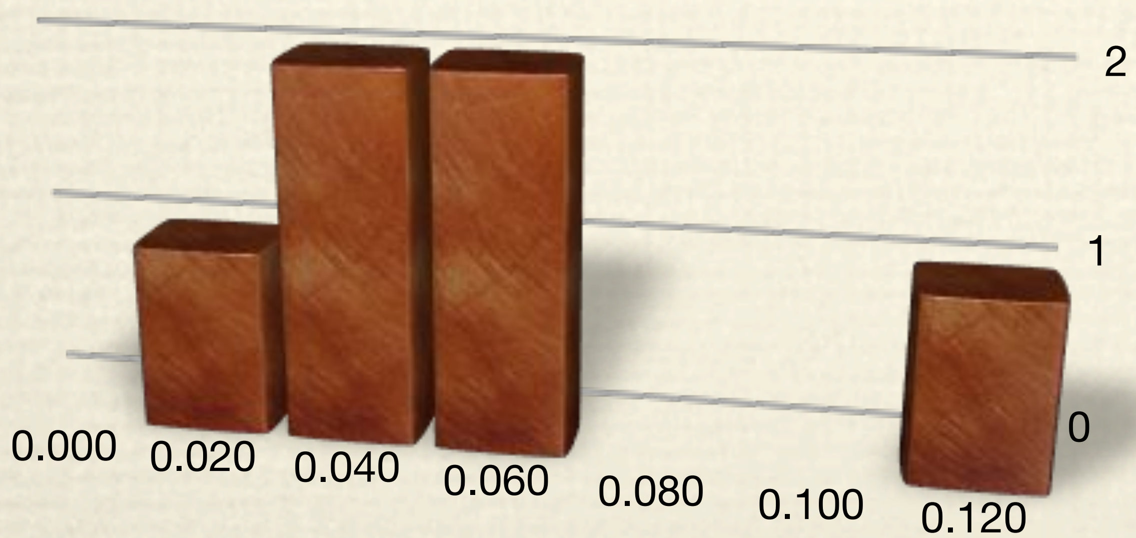
What are the values of t^2?

- H II Regions



- range 0.020-0.120
- median ~ 0.035
- average ~ 0.044

- Planetary Nebulae

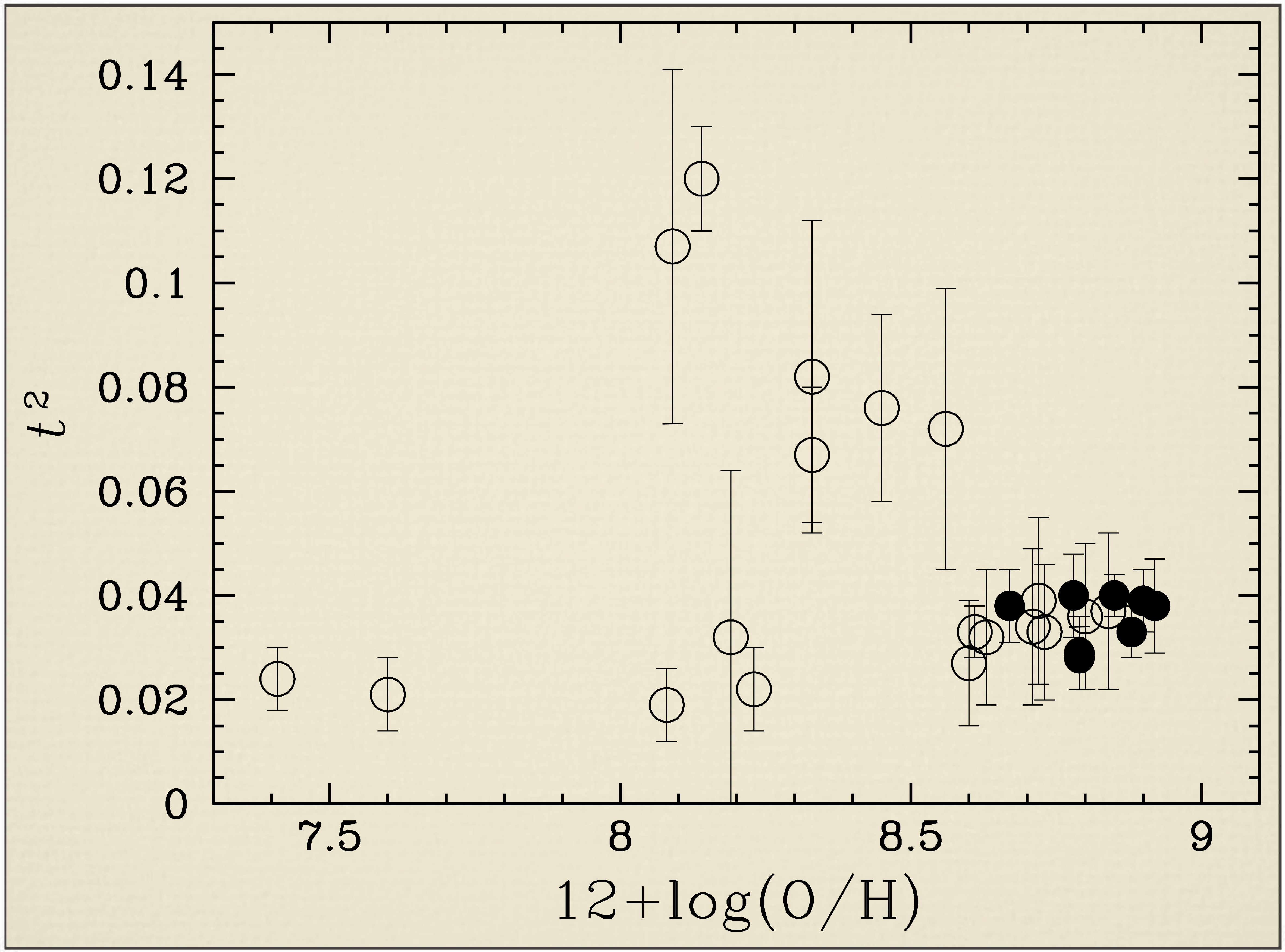


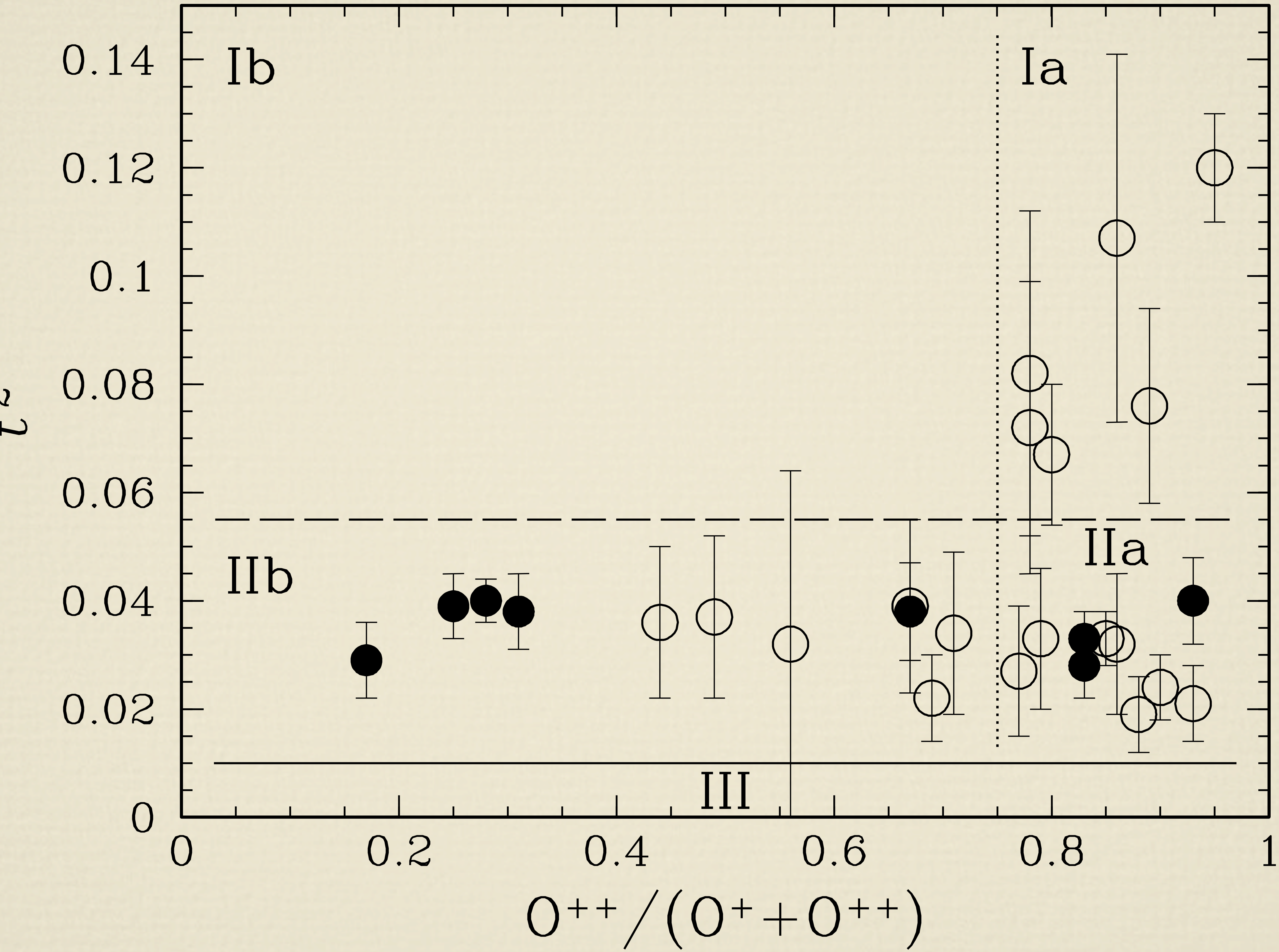
- range 0.028-0.120
- median ~ 0.050
- average ~ 0.055

Table 11 — Average t^2 for Wide Metallicity Range H II regions (WMR)

Object	Location[a]	O/H[b]	O/H[c]	t^2	$\frac{O^{++}}{O^{+}+O^{++}}$	T_e[O III]	n_e[O II]	References	Type[d]
NGC 3576	G	8.56	8.92	0.038±0.009	0.67	8500±50	2300±200	1	IIb
M16	G	8.50	8.90	0.039±0.006	0.25	7650±250	1050±250	2	IIb
M17	G	8.52	8.88	0.033±0.005	0.83	8950±380	480 ±150	3	IIa
M8	G	8.51	8.85	0.040±0.004	0.28	8090±140	1800±800	3	IIb
H1013	X	8.45	8.84	0.037	0.49	7370±630	280 ±60	4	IIb
NGC 595	X	8.45	8.80	0.036	0.44	7450±330	260 ±30	4	IIb
M20	G	8.53	8.79	0.029±0.007	0.17	7800±300	240 ±70	2	IIb
Orion	G	8.51	8.79	0.028±0.006	0.83	8300±40	2400±300	5, 6	IIa
NGC 3603	G	8.46	8.78	0.040±0.008	0.93	9060±200	2300±750	2	IIa
K932	X	8.41	8.73	0.033	0.79	8360±150	470 ±40	4	IIa
NGC 2403	X	8.36	8.72	0.039	0.67	8270±210	370 ±40	4	IIb
NGC 604	X	8.38	8.71	0.034±0.015	0.71	8150±160	270 ±30	4	IIb
S 311	G	8.39	8.67	0.038±0.007	0.31	9000±200	260 ±110	7	IIb
NGC 5447	X	8.35	8.63	0.032	0.86	9280±180	280^{+690}_{-280}	4	IIa
30 Doradus	X	8.33	8.61	0.033±0.005	0.85	9950±60	279 ±16	8	IIa
NGC 5461	X	8.41	8.60	0.027±0.012	0.77	8470±200	540 ±110[e]	4, 9	IIa
NGC 5253	X	8.18	8.56	0.072±0.027	0.78	11960±290	660 ±140	10	Ia
NGC 6822	X	8.08	8.45	0.076±0.018	0.89	13000±1000	190 ±30	11	Ia
NGC 5471	X	8.03	8.33	0.082±0.030	0.78	14100±300	220 ±70[f]	9	Ia
NGC 456	X	7.99	8.33	0.067±0.013	0.80	12165±200	130 ±30	12	Ia
NGC 346	X	8.07	8.23	0.022±0.008	0.69	13070±50	144^{+44}_{-38} [g]	13, 14	IIb
NGC 460	X	7.96	8.19	0.032±0.032	0.56	12400±450	170 ±20	12	IIb
NGC 2363	X	7.76	8.14	0.120±0.010	0.95	16200±300	550 ±100	4	Ia
TOL 2146 − 391	X	7.79	8.09	0.107±0.034	0.86	15800±170	280 ±30	15	Ia
TOL 0357 − 3915	X	7.90	8.12	0.029±0.064	0.87	14870±230	340 ±50	15	Ia
Haro 29	X	7.87	8.05	0.019±0.007	0.88	16050±100	235 ±85[g]	13, 16	IIa
SBS 0335−052	X	7.35	7.60	0.021±0.007	0.93	20500±200	297 ±85[g]	13, 17	IIa
I Zw 18	X	7.22	7.41	0.024±0.006	0.90	19060±610	87^{+65}_{-56} [g]	13, 17	IIa
$<t^2$(WMR)$>$=0.044									

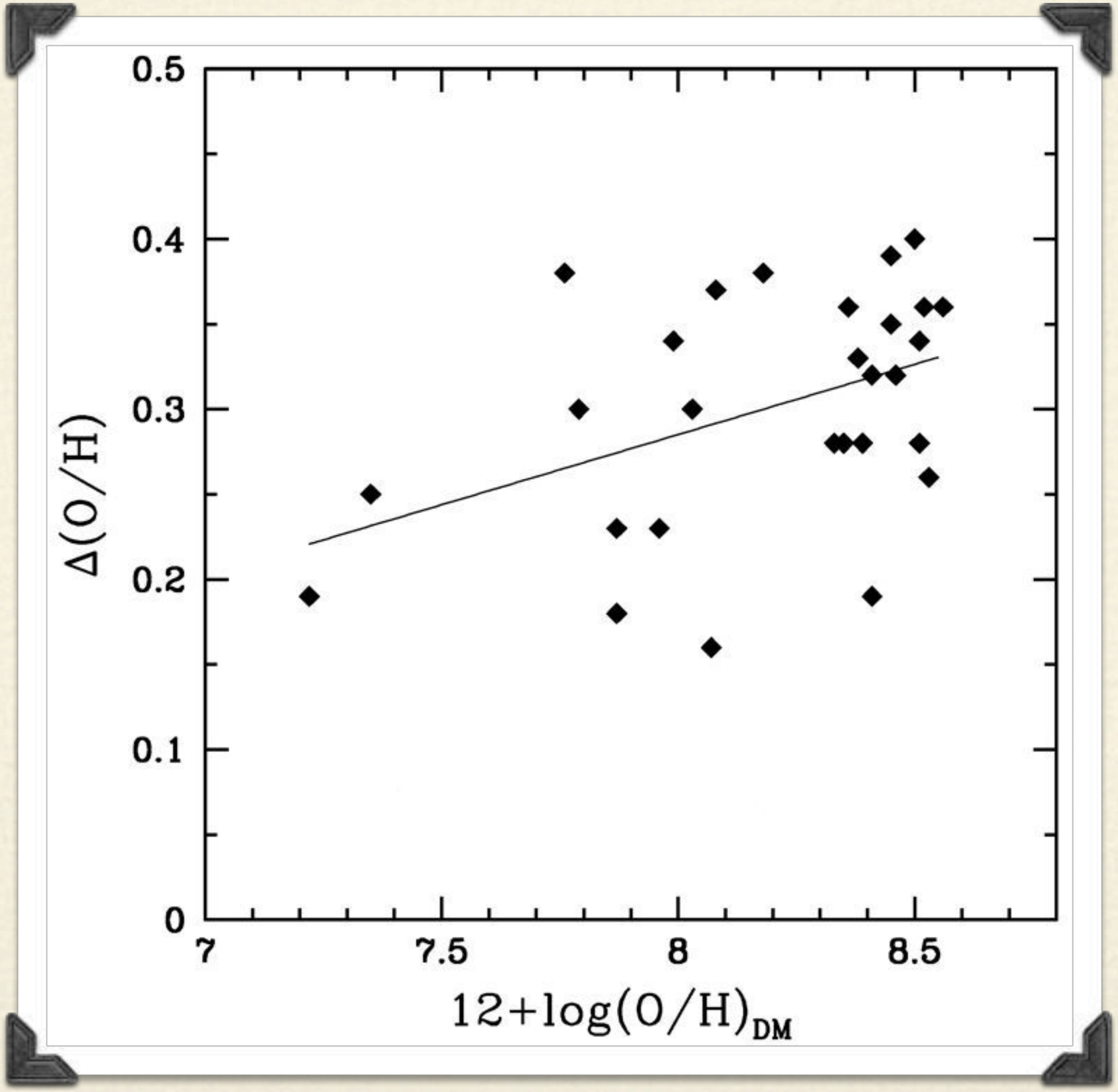
- 8 meter class telescope
- 19 echelle
- 9 long slit


0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
t^2
7.5
8
8.5
9
12+log(O/H)

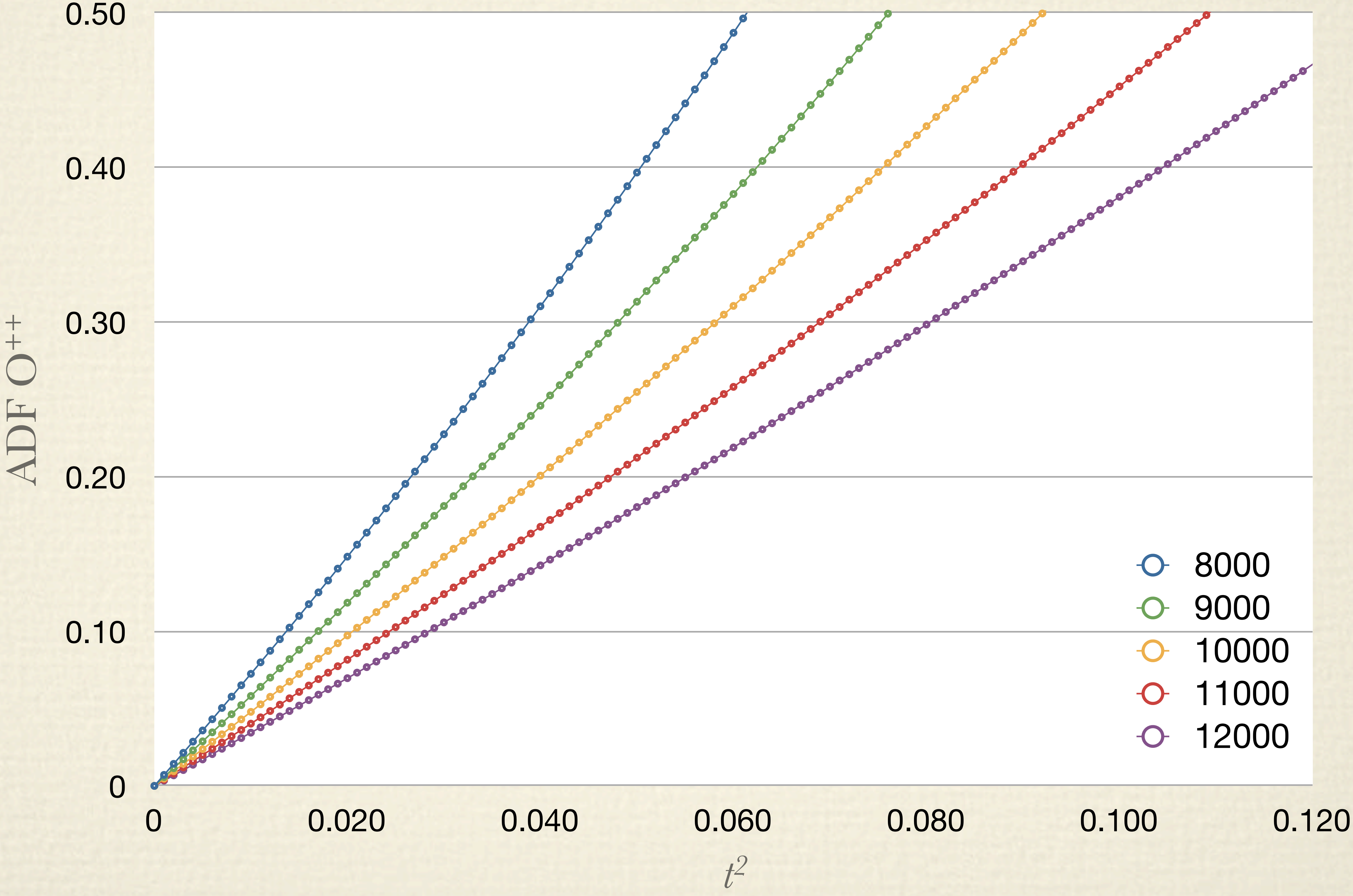


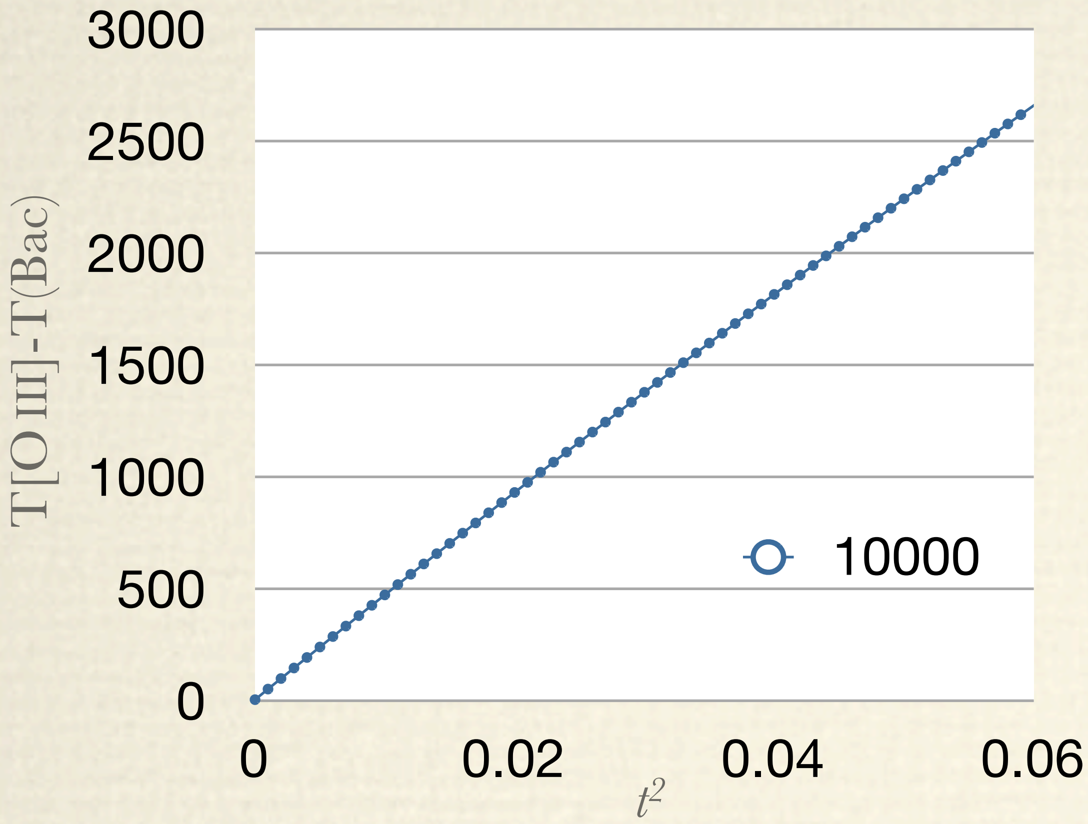
Ib
Ia
IIb
IIa
III
t^2
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0
0.2
0.4
0.6
0.8
1
$O^{++}/(O^{+}+O^{++})$

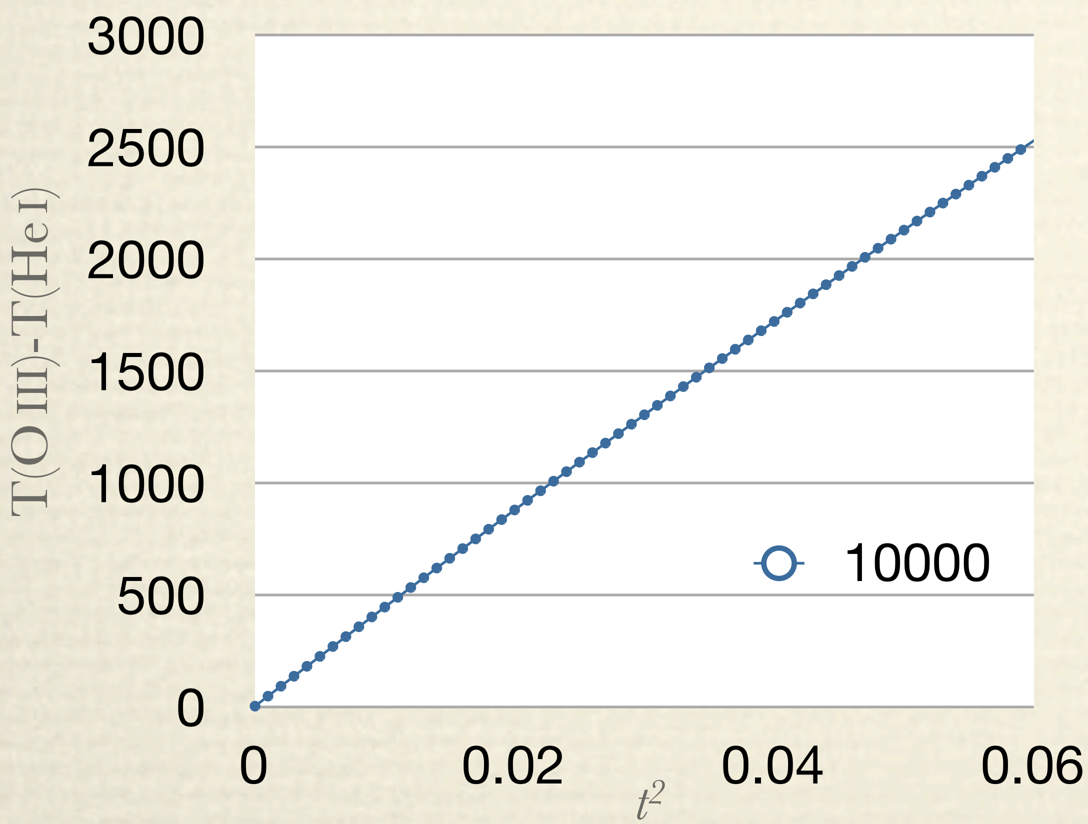
Quantitatively: What is their effect in abundance determinations?



It is possible to determine the ADF as a function of t^2 and T_e[O III]

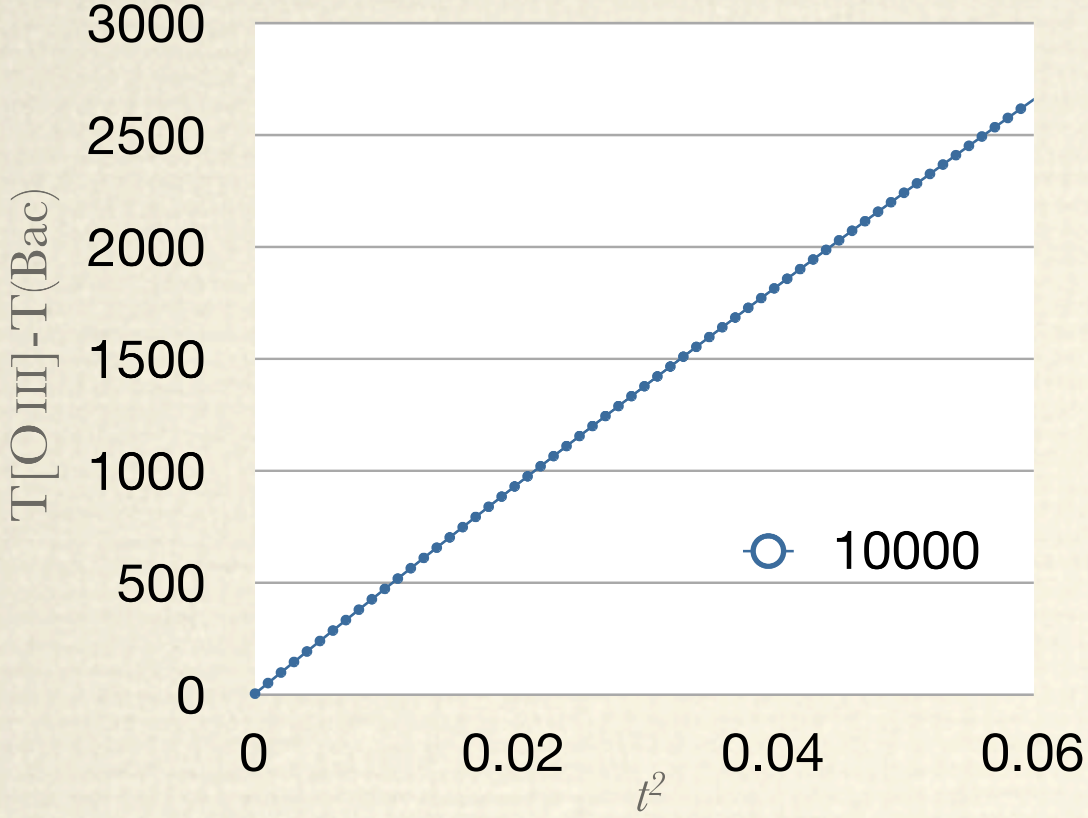


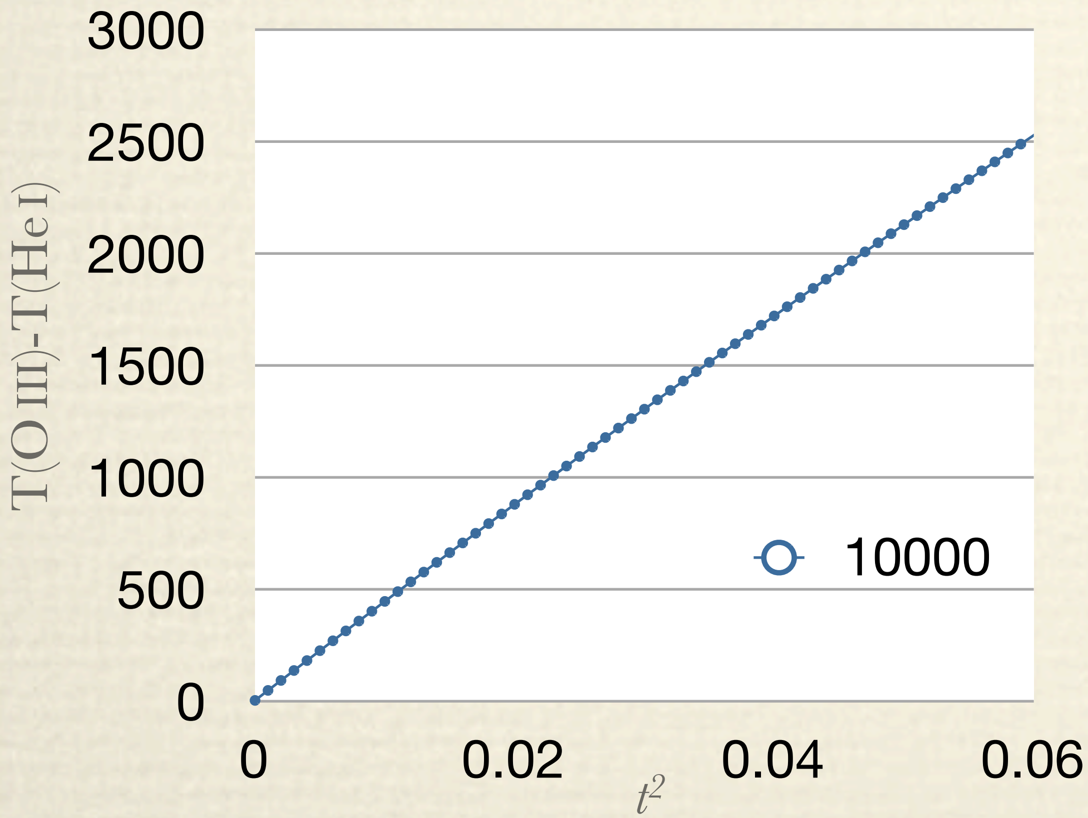


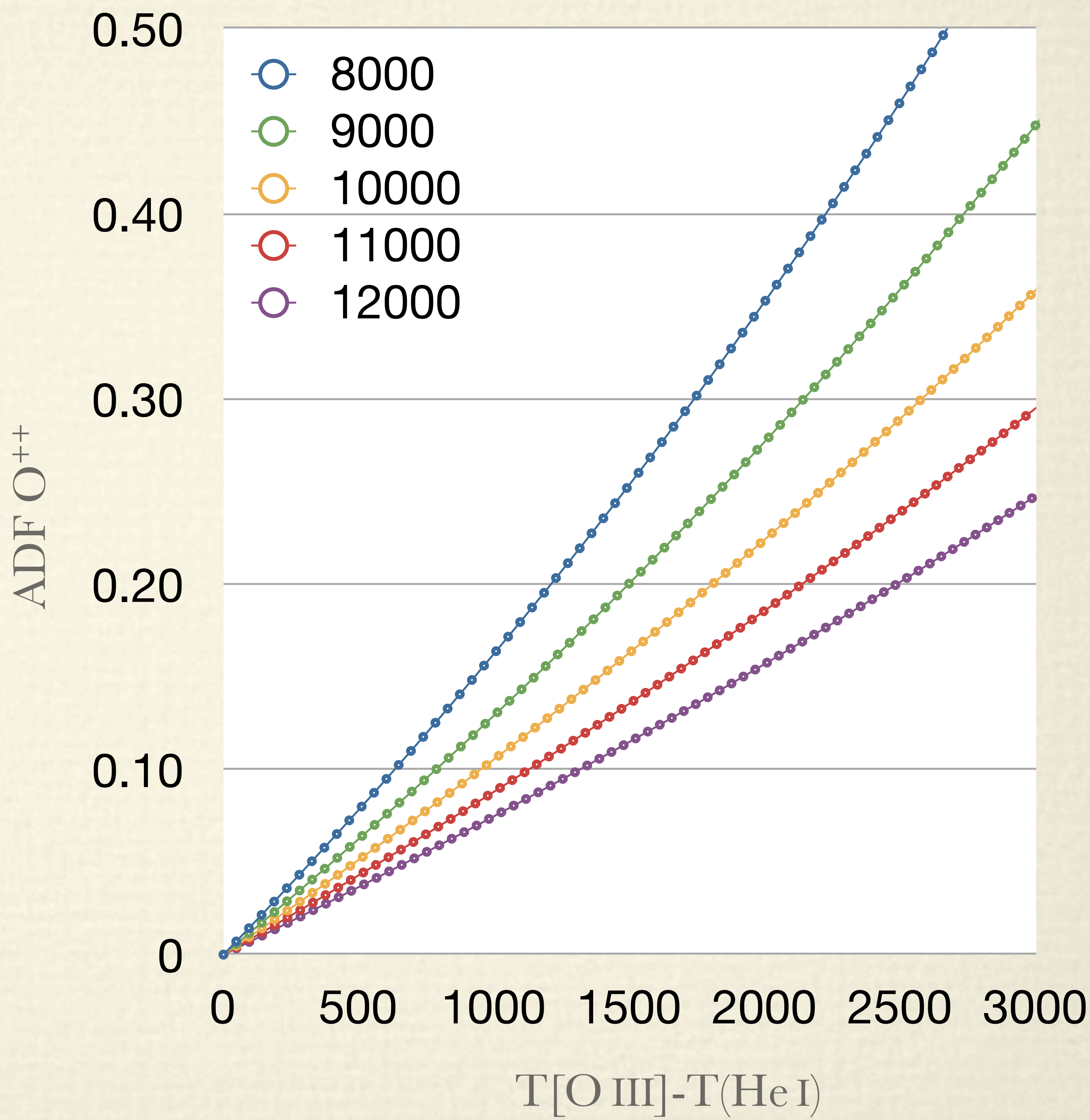


- When comparing temperatures from different ions it is important to make sure you are considering the same volumes
    - ...or at least similar volumes.
- e.g. objects with high fraction of He^{++} are not very good.

It is also possible to determine the ADF as a function of ΔT and T_e[O III]







Statistically: What should be done to improve the Abundance Determinations?

- For most objects it is not possible to determine t^2.

- When determining abundances using the direct method the abundances are underestimated by a factor of about 2.
- For H II regions we propose the Corrected Auroral Line Method (t^2 + dust; in units of 12+log O/H):

$$\boxed{(\mathrm{O/H})_{\mathrm{CALM}} = 1.0825 \times (\mathrm{O/H})_{\mathrm{DM}} - 0.375}$$

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  - Using only 6 points I recommend (only t^2 correction):

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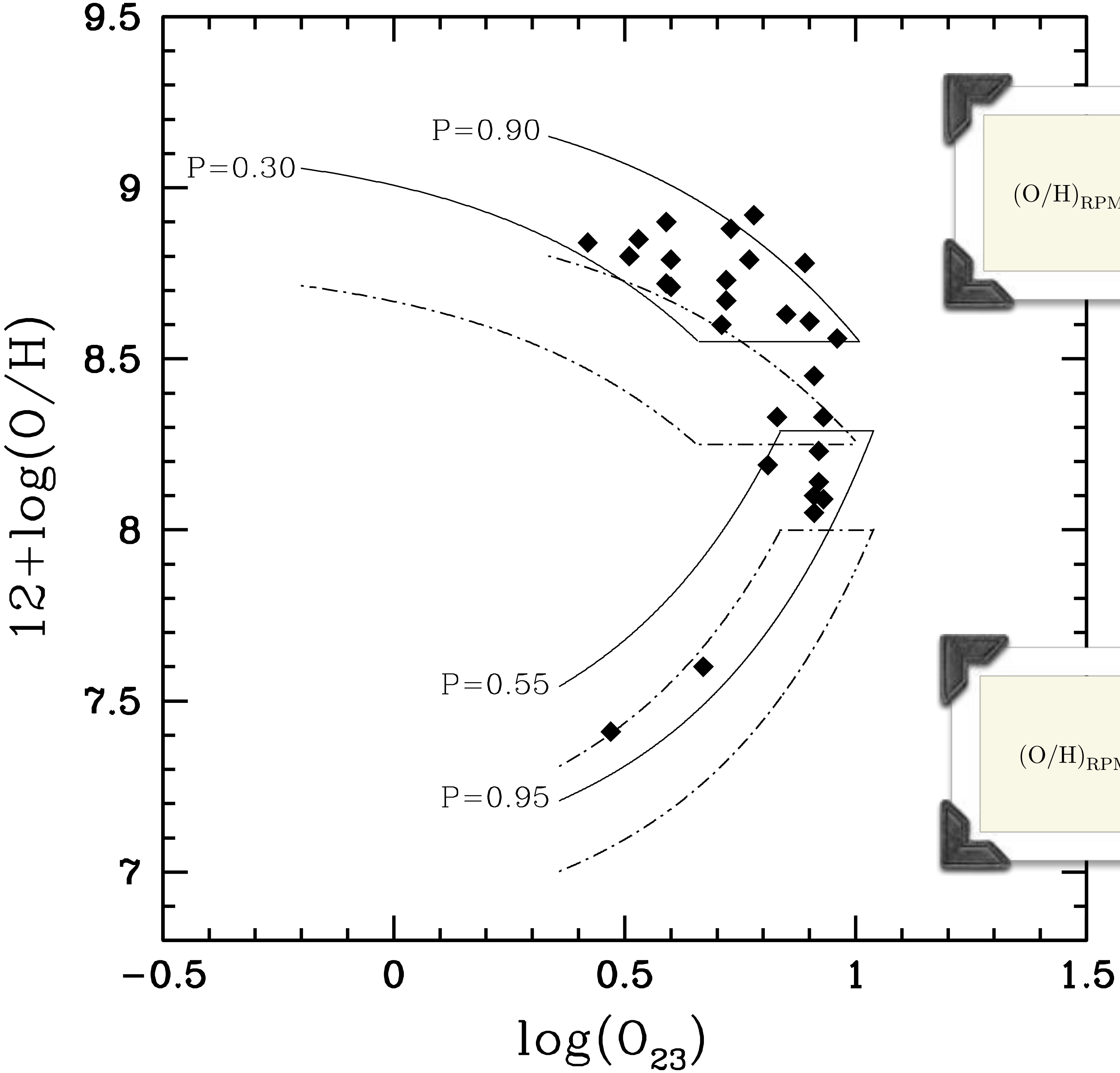
- When doing numerical models an average t^2 should be forced into the model.
  - I would suggest making:
    - 1/4 of the cells slightly cooler.
    - 1/4 of the cells as they are.
    - 1/4 of the cells slightly hotter.
    - and 1/4 of the cells even hotter.
  - The objective would be to obtain:
    - t^2=0.035 for H II regions of low degree of ionization
    - t^2=0.051 for H II regions of high degree of ionization
    - t^2=0.055 for PNe.

- For objects that are even fainter.
    - Using ideas from:
        - Peimbert, M. 1967
        - Pagel, B. E. J. et al. 1979
        - Pilyugin, L. S. et al. 2005
        - Peimbert, A. et al. 2010
        - Peña-Guerrero, M. A. et al. 2012
    - One can Recalibrate Pagel's strong line Method:

$$(\mathrm{O/H})_{\mathrm{RPM}} = \frac{\mathrm{O}_{23} + 1837 + 2146\mathrm{P} - 850\mathrm{P}^2}{209.5 + 201.7\mathrm{P} + 107.2\mathrm{P}^2 - 4.37\mathrm{O}_{23}}$$

$$(\mathrm{O/H})_{\mathrm{RPM}} = \frac{\mathrm{O}_{23} + 90.73 + 94.58\mathrm{P} - 5.26\mathrm{P}^2}{14.81 + 5.52\mathrm{P} + 5.81\mathrm{P}^2 - 0.252\mathrm{O}_{23}}$$



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- If ignored, these Inhomogeneites will lead to systematic underestimations of the O/H ratio.
- Most H II regions and PNe are chemically homogeneous.
- When available, RLs are better to determine abundances since they have the same dependence on T_e and n_e than Hβ.
- In H II regions the effect is in the 0.15 - 0.45 dex range (where 0.10 is due to the oxygen trapped in dust).
- In PNe the effect is in the 0.15 - 0.70 dex range.

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- In H II regions the effect is in the 0.15 - 0.45 dex range (where 0.10 is due to the oxygen trapped in dust).
- In PNe the effect is in the 0.15 - 0.70 dex range.
- For H II regions, it is possible to (statistically) correct the abundances obtained from the direct method.

$$\boxed{(\mathrm{O/H})_{\mathrm{CALM}} = 1.0825 \times (\mathrm{O/H})_{\mathrm{DM}} - 0.375}$$

- This correction should also be used the strong line methods (when calibrated using CELs).

$$(\mathrm{O/H})_{\mathrm{RPM}} = \frac{\mathrm{O}_{23} + 1837 + 2146\mathrm{P} - 850\mathrm{P}^2}{209.5 + 201.7\mathrm{P} + 107.2\mathrm{P}^2 - 4.37\mathrm{O}_{23}}$$

$$(\mathrm{O/H})_{\mathrm{RPM}} = \frac{\mathrm{O}_{23} + 90.73 + 94.58\mathrm{P} - 5.26\mathrm{P}^2}{14.81 + 5.52\mathrm{P} + 5.81\mathrm{P}^2 - 0.252\mathrm{O}_{23}}$$

- PNe need more work.... as of now

$$\boxed{(\mathrm{O/H})_{\mathrm{PNe}} = (\mathrm{O/H})_{\mathrm{DM}} + 0.35}$$

Conclusions

- Temperature Inhomogeneities are real and are higher than predicted by photoionization models.
- To fully understand photoionized regions, it is necessary to understand and model their source; but, to determine abundances it is only necessary to know their magnitude.
- If ignored, these inhomogeneites will lead to systematic underestimations of the O/H ratio.
- Most H II regions and PNe are chemically homogeneous.
- When available, RLs are better to determine abundances since they have the same dependence on T_e and n_e than Hβ.
- In H II regions the effect is in the 0.15 - 0.45 dex range (where 0.10 is due to the oxygen trapped in dust).
- In PNe the effect is in the 0.15 - 0.70 dex range.
- For H II regions, it is possible to (statistically) correct the abundances obtained from the direct method.

$$(\mathrm{O/H})_{\mathrm{CALM}} = 1.0825 \times (\mathrm{O/H})_{\mathrm{DM}} - 0.375$$

- This correction should also be used the strong line methods (when calibrated using CELs).

$$(\mathrm{O/H})_{\mathrm{RPM}} = \frac{\mathrm{O}_{23} + 1837 + 2146\mathrm{P} - 850\mathrm{P}^2}{209.5 + 201.7\mathrm{P} + 107.2\mathrm{P}^2 - 4.37\mathrm{O}_{23}}$$

$$(\mathrm{O/H})_{\mathrm{RPM}} = \frac{\mathrm{O}_{23} + 90.73 + 94.58\mathrm{P} - 5.26\mathrm{P}^2}{14.81 + 5.52\mathrm{P} + 5.81\mathrm{P}^2 - 0.252\mathrm{O}_{23}}$$

- PNe need more work.... as of now

$$(\mathrm{O/H})_{\mathrm{PNe}} = (\mathrm{O/H})_{\mathrm{DM}} + 0.35$$

- Numerical models can be altered to mimic higher t^2.
- When comparing numerical models to observed objects, it is better to fit nebular lines than to fit auroral lines or temperatures.

Thank you

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POR MI RAZA HABLARA EL ESPIRITU

$$T_0(N_i,N_e) = \frac{\int T(\boldsymbol{r})\,N_i(\boldsymbol{r})\,N_e(\boldsymbol{r})\,d\Omega dl}{\int N_i(\boldsymbol{r})\,N_e(\boldsymbol{r})\,d\Omega dl}, \tag{9}$$

$$t^2 = \left\langle\left[\frac{T(\boldsymbol{r}) - T_0}{T_0}\right]^2\right\rangle = \frac{\int T^2(\boldsymbol{r})\,N_e(\boldsymbol{r})\,N_i(\boldsymbol{r})\,d\Omega dl - T_0{}^2\int N_e(\boldsymbol{r})\,N_i(\boldsymbol{r})\,d\Omega dl}{T_0{}^2\int N_e(\boldsymbol{r})\,N_i(\boldsymbol{r})\,d\Omega dl}. \tag{12}$$

$$I(\lambda, n_e, n_{ion}, T) \equiv I_\lambda(T) \times n_e \times n_{ion}$$

$$I_\lambda(T) = I_\lambda(T_0) + I'_\lambda(T_0)(T-T_0) + \frac{1}{2!}I''_\lambda(T_0)(T-T_0)^2 + \frac{1}{3!}I'''_\lambda(T_0)(T-T_0)^3 + \frac{1}{4!}I''''_\lambda(T_0)(T-T_0)^4 + ...$$

$$\begin{aligned}
\frac{\int_V I_\lambda(T(r))n_e(r)n_{ion}(r)dV}{\int_V n_e(r)n_{ion}(r)dV} &= \frac{\int_V I_\lambda(T_0)n_e(r)n_{ion}(r)dV}{\int_V n_e(r)n_{ion}(r)dV} \\
&+ \frac{\int_V I'_\lambda(T_0)(T(r)-T_0)n_e(r)n_{ion}(r)dV}{\int_V n_e(r)n_{ion}(r)dV} \\
&+ \frac{1}{2!}\frac{\int_V I''_\lambda(T_0)(T(r)-T_0)^2 n_e(r)n_{ion}(r)dV}{\int_V n_e(r)n_{ion}(r)dV} \\
&+ \frac{1}{3!}\frac{\int_V I'''_\lambda(T_0)(T(r)-T_0)^3 n_e(r)n_{ion}(r)dV}{\int_V n_e(r)n_{ion}(r)dV} \\
&+ \frac{1}{4!}\frac{\int_V I''''_\lambda(T_0)(T(r)-T_0)^4 n_e(r)n_{ion}(r)dV}{\int_V n_e(r)n_{ion}(r)dV} + ...
\end{aligned}$$

$$\begin{aligned}
\frac{\int_V I_\lambda(T(r))n_e(r)n_{ion}(r)dV}{\int_V n_e(r)n_{ion}(r)dV} &= I_\lambda(T_0)\frac{\int_V n_e(r)n_{ion}(r)dV}{\int_V n_e(r)n_{ion}(r)dV} \\
&+ I'_\lambda(T_0)\frac{\int_V (T(r)-T_0)n_e(r)n_{ion}(r)dV}{\int_V n_e(r)n_{ion}(r)dV} \\
&+ I''_\lambda(T_0)\frac{1}{2!}\frac{\int_V (T(r)-T_0)^2 n_e(r)n_{ion}(r)dV}{\int_V n_e(r)n_{ion}(r)dV} \\
&+ I'''_\lambda(T_0)\frac{1}{3!}\frac{\int_V (T(r)-T_0)^3 n_e(r)n_{ion}(r)dV}{\int_V n_e(r)n_{ion}(r)dV} \\
&+ I''''_\lambda(T_0)\frac{1}{4!}\frac{\int_V (T(r)-T_0)^4 n_e(r)n_{ion}(r)dV}{\int_V n_e(r)n_{ion}(r)dV} + ...
\end{aligned}$$

$$\begin{aligned}
\frac{\int_V I_\lambda(T(r))n_e(r)n_{ion}(r)dV}{\int_V n_e(r)n_{ion}(r)dV} &= I_\lambda(T_0) \\
&+ I'_\lambda(T_0)T_0 t_1 \\
&+ I''_\lambda(T_0)T_0^2\frac{t_2}{2!} \\
&+ I'''_\lambda(T_0)T_0^3\frac{t_3}{3!} \\
&+ I''''_\lambda(T_0)T_0^4\frac{t_4}{4!} + ...
\end{aligned}$$

$$T_0 = \frac{\int_V T(r)n_e(r)n_{ion}(r)dV}{\int_V n_e(r)n_{ion}(r)dV} \qquad t_k = \frac{\int_V (T(r)-T_0)^k n_e(r)n_{ion}(r)dV}{T_0^k \int_V n_e(r)n_{ion}(r)dV}$$

$$\frac{\int_V I_\lambda(T(r))n_e(r)n_{ion}(r)dV}{\int_V n_e(r)n_{ion}(r)dV} = I_\lambda(T_0) + I'_\lambda(T_0)T_0 t_1 + I''_\lambda(T_0)T_0^2\frac{t_2}{2!} + I'''_\lambda(T_0)T_0^3\frac{t_3}{3!} + I''''_\lambda(T_0)T_0^4\frac{t_4}{4!} + ...$$

$$t^2 = \frac{\int_V [T(r)-T_0]^2 n_e(r)n_{ion}(r)dV}{T_0^2\int_V n_e(r)n_{ion}(r)dV} \qquad t^2 = t_2 = \frac{\int_V [T(r)-T_0]^2 n_e(r)n_{ion}(r)dV}{T_0^2\int_V n_e(r)n_{ion}(r)dV}$$

$$\begin{aligned}
\langle I_\lambda(T(r))\rangle = \langle I_\lambda(T_0)\rangle &+ \left\langle I'_\lambda(T_0)\,[T(r)-T_0]\right\rangle \\
&+ \frac{1}{2!}\left\langle I''_\lambda(T_0)\,[T(r)-T_0]^2\right\rangle \\
&+ \frac{1}{3!}\left\langle I'''_\lambda(T_0)\,[T(r)-T_0]^3\right\rangle \\
&+ \frac{1}{4!}\left\langle I''''_\lambda(T_0)\,[T(r)-T_0]^4\right\rangle + ...
\end{aligned}$$

$$\begin{aligned}
\langle I_\lambda(T(r))\rangle = I_\lambda(T_0) &+ I'_\lambda(T_0)\left\langle [T(r)-T_0]\right\rangle \\
&+ I''_\lambda(T_0)\frac{1}{2!}\left\langle [T(r)-T_0]^2\right\rangle \\
&+ I'''_\lambda(T_0)\frac{1}{3!}\left\langle [T(r)-T_0]^3\right\rangle \\
&+ I''''_\lambda(T_0)\frac{1}{4!}\left\langle [T(r)-T_0]^4\right\rangle + ...
\end{aligned}$$

$$\langle I_\lambda(T(r))\rangle = I_\lambda(T_0) + I'_\lambda(T_0)T_0 t_1 + I''_\lambda(T_0)T_0^2\frac{t_2}{2!} + I'''_\lambda(T_0)T_0^3\frac{t_3}{3!} + I''''_\lambda(T_0)T_0^4\frac{t_4}{4!} + ...$$

$$T_0 = \langle T(r)\rangle \qquad t_k = \left\langle \frac{[T(r)-T_0]^k}{T_0^k}\right\rangle$$

$$\begin{aligned}
\langle I_\lambda(T(r))\rangle &= I_\lambda(T_0) \\
&+ I'_\lambda(T_0)T_0 t_1 \\
&+ I''_\lambda(T_0)T_0^2\frac{t_2}{2!} \\
&+ I'''_\lambda(T_0)T_0^3\frac{t_3}{3!} \\
&+ I''''_\lambda(T_0)T_0^4\frac{t_4}{4!} + ...
\end{aligned}$$

$$t^2 = \left\langle \frac{[T(r)-T_0]^2}{T_0^2}\right\rangle$$

$$t^2 = t_2 = \left\langle \frac{[T(r)-T_0]^2}{T_0^2}\right\rangle$$

$$T_0(ion) = \frac{\int T_e(\mathbf{r}) N_e(\mathbf{r}) N_{ion}(\mathbf{r}) dV}{\int N_e(\mathbf{r}) N_{ion}(\mathbf{r}) dV},$$

$$t^2(ion) \equiv \frac{\int (T_e - T_0)^2 N_e(\mathbf{r}) N_{ion}(\mathbf{r}) dV}{T_0^2 \int N_e(\mathbf{r}) N_{ion}(\mathbf{r}) dV},$$

$$(\mathrm{O/H})_{\mathrm{CALM}} = 1.0825 \times (\mathrm{O/H})_{\mathrm{DM}} - 0.375$$

$$12 + \log(\mathrm{O/H})$$

$$(\mathrm{O/H})_{\mathrm{RPM}} = \frac{\mathrm{O}_{23} + 1837 + 2146\mathrm{P} - 850\mathrm{P}^2}{209.5 + 201.7\mathrm{P} + 107.2\mathrm{P}^2 - 4.37\mathrm{O}_{23}}$$

$$(\mathrm{O/H})_{\mathrm{RPM}} = \frac{\mathrm{O}_{23} + 90.73 + 94.58\mathrm{P} - 5.26\mathrm{P}^2}{14.81 + 5.52\mathrm{P} + 5.81\mathrm{P}^2 - 0.252\mathrm{O}_{23}}$$

$$(\mathrm{O/H}) \geq 8.55$$

$$(\mathrm{O/H}) \leq 8.29$$

$$(\mathrm{O/H})_{\mathrm{CALM}} = (\mathrm{O/H})_{\mathrm{DM}} + f(\mathrm{P}, \mathrm{O/H}),$$

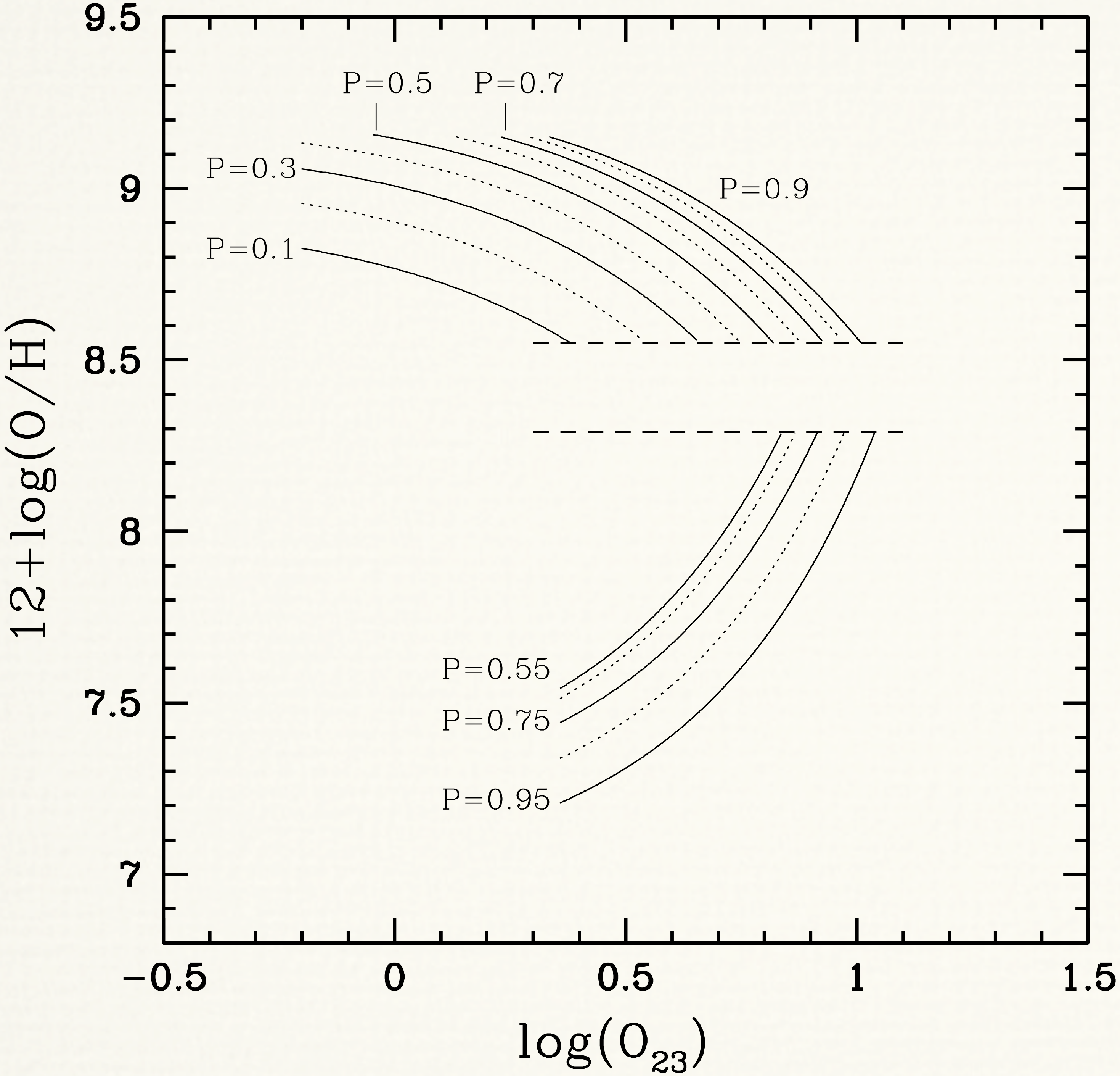
$$f(\mathrm{P}, \mathrm{O/H}) = \mathrm{C}_1 + \mathrm{C}_2 \times \mathrm{P} + \mathrm{C}_3 \times (\mathrm{O/H})_{\mathrm{DM}} + \mathrm{C}_4 \times \mathrm{P} \times (\mathrm{O/H})_{\mathrm{DM}},$$

$$f(\mathrm{P}, \mathrm{O/H}) = f(\mathrm{O/H}) = 0.0825(\mathrm{O/H})_{\mathrm{DM}} - 0.375;$$

$$(\mathrm{O/H})_{\mathrm{CALM}} = 1.0825(\mathrm{O/H})_{\mathrm{DM}} - 0.375.$$

$$\begin{aligned} (\mathrm{O/H})_{\mathrm{RPM}} &= \left(\frac{\mathrm{O}_{23} + 726.1 + 8.42\mathrm{P} + 327.5\mathrm{P}^2}{85.96 + 82.76\mathrm{P} + 43.98\mathrm{P}^2 + 1.793\mathrm{O}_{23}} \right) 1.0825 - 0 \\ &= \frac{\mathrm{O}_{23} + 1837 + 2146\mathrm{P} + 850\mathrm{P}^2}{209.5 + 201.7\mathrm{P} + 107.2\mathrm{P}^2 + 4.37\mathrm{O}_{23}}, \end{aligned}$$

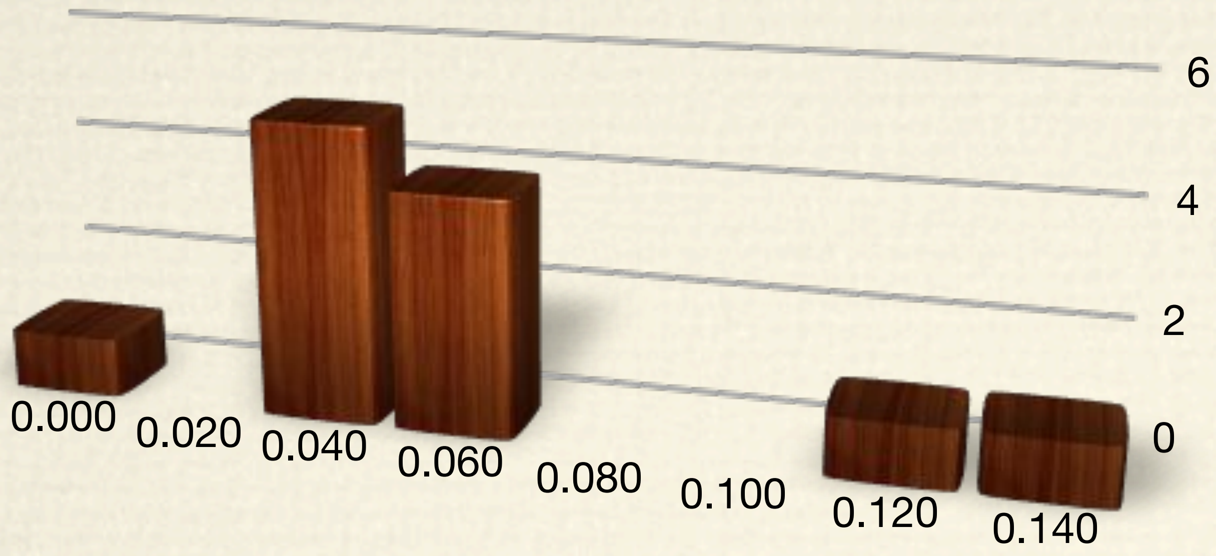
$$\begin{aligned} (\mathrm{O/H})_{\mathrm{RPM}} &= \left(\frac{\mathrm{O}_{23} + 106.4 + 106.8\mathrm{P} - 3.40\mathrm{P}^2}{17.72 + 6.60\mathrm{P} + 6.95\mathrm{P}^2 - 0.302\mathrm{O}_{23}} \right) 1.0825 - 0.375 \\ &= \frac{\mathrm{O}_{23} + 90.73 + 94.58\mathrm{P} - 5.26\mathrm{P}^2}{14.81 + 5.52\mathrm{P} + 5.81\mathrm{P}^2 - 0.252\mathrm{O}_{23}}. \end{aligned}$$



P=0.5
P=0.7
P=0.3
P=0.9
P=0.1
P=0.55
P=0.75
P=0.95
9.5
9
8.5
8
7.5
7
−0.5
0
0.5
1
1.5
12+log(O/H)
log(O23)

Table 1. H II region data

Object	Type[a]	T_e[O III]	t^2	log(O_{23})	P	$\frac{O^{++}}{O^{+}+O^{++}}$	O/H[b]	O/H[c]	References
Upper branch									
NGC 3576	GR	8500±50	0.038±0.009	0.78	0.78	0.67	8.56	8.92	1
M16	GR	7650±250	0.039±0.006	0.59	0.28	0.25	8.50	8.90	2
M17	GR	8950±380	0.033±0.005	0.73	0.83	0.83	8.52	8.88	3
M8	GR	8090±140	0.040±0.004	0.53	0.38	0.28	8.51	8.85	3
H1013	XR	7370±630	0.037	0.42	0.49	0.49	8.45	8.84	4
NGC 595	XR	7450±330	0.036	0.51	0.37	0.44	8.45	8.80	4
M20	GR	7800±300	0.029±0.007	0.60	0.20	0.17	8.53	8.79	2
Orion	GR	8300±40	0.028±0.006	0.77	0.86	0.83	8.51	8.79	5, 6
NGC 3603	GR	9060±200	0.040±0.008	0.89	0.92	0.93	8.46	8.78	2
K932	XR	8360±150	0.033	0.72	0.72	0.79	8.41	8.73	4
NGC 2403	XR	8270±210	0.039	0.59	0.66	0.67	8.36	8.72	4
NGC 604	XR	8150±160	0.034±0.015	0.60	0.71	0.71	8.38	8.71	4
S 311	GR	9000±200	0.038±0.007	0.72	0.32	0.31	8.39	8.67	7
NGC 5447	XR	9280±180	0.032	0.85	0.78	0.86	8.35	8.63	4
30 Doradus	XR	9950±60	0.033±0.005	0.90	0.85	0.85	8.33	8.61	8
NGC 5461	XR	8470±200	0.027±0.012	0.71	0.80	0.77	8.41	8.60	4, 9
NGC 5253	HIIG	11960±290	0.072±0.027	0.96	0.85	0.78	8.18	8.56	10
Transition zone									
NGC 6822-V	XR	13000±1000	0.076±0.018	0.91	0.88	0.89	8.08	8.45	11
NGC 5471	XR	14100±300	0.082±0.030	0.93	0.75	0.78	8.03	8.33	9
NGC 456	XR	12165±200	0.067±0.013	0.83	0.78	0.80	7.99	8.33	12
Lower branch									
NGC 346	XR	13070±50	0.022±0.008	0.92	0.88	0.69	8.07	8.23	13, 14
NGC 460	XR	12400±450	0.032±0.032	0.81	0.62	0.56	7.96	8.19	12
NGC 2363	XR	16200±300	0.120±0.010	0.92	0.97	0.97	7.76	8.14	4
TOL 2146 − 391	HIIG	15800±170	0.107±0.034	0.91	0.92	0.86	7.79	8.09	15
TOL 0357 − 9315	HIIG	14870±230	0.029±0.064	0.93	0.93	0.87	7.90	8.12	15
Haro 29	HIIG	16050±100	0.019±0.007	0.91	0.91	0.88	7.87	8.05	13, 16
SBS 0335−052	HIIG	20500±200	0.021±0.007	0.67	0.93	0.93	7.35	7.60	13, 17
I Zw 18	HIIG	19060±610	0.024±0.006	0.47	0.86	0.90	7.22	7.41	13, 17



Liu & Danziger 2001