On the relation between electron temperatures in the O+ and O++ zones in high-metallicity H II regions

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ABSTRACT

We suggest a new way to establish the relation between the electron temperature \( t_3 \) within the [O III] zone and the electron temperature \( t_2 \) within the [O II] zone in high-metallicity (12+log(O/H) > 8.25) H II regions. The \( t_2 - t_3 \) diagram is constructed by applying our method to a sample of 372 H II regions. We find that the correlation between \( t_2 \) and \( t_3 \) is tight and can be approximated by a linear expression. The new \( t_2 - t_3 \) relation can be used to determine \( t_2 \) and accurate abundances in high-metallicity H II regions with a measured \( t_3 \). It can also be used in conjunction with the ff relation for the determination of \( t_3 \) and \( t_2 \) and oxygen abundances in high-metallicity H II regions where the [OIII]λ4363 auroral line is not detected. The derived \( t_2 - t_3 \) relation is independent of photoionization models of H II regions.

Key words: galaxies: abundances – ISM: abundances – H II regions

1 INTRODUCTION

Accurate abundances in H II regions can be derived via the classic \( T_e \) method, \( T_e \) being the electron temperature of the H II region. In this method, the reliability of the equations for determining the O+++/H+ and O++/H+ ionic oxygen abundances depends to a great part on the reliability of the atomic data (Pagel et al. (1992)) and have found close agreement. Thus, the equations for the determination of the ionic oxygen abundances depend to a great part on the reliability of the atomic data. Pilyugin & Thuan (2005) have compared the ionic oxygen abundances derived with a recent set of equations using the latest atomic data (Izotov et al. (2006)), with those determined from an earlier set of equations (Pagel et al. (1992)) and have found close agreement. Thus, the equations for the determination of the ionic oxygen abundances in H II regions appear to be robust, in the sense that, for a given set of measured electron temperatures \( t_3 \) and \( t_2 \), relations determined by different authors result in close oxygen abundances in H II regions.

The electron temperatures \( t_3 \) within the [O III] zone and \( t_2 \) within the [O II] zone are determined from diagnostic line ratios when they are available. The intensity ratio of the [O II]λ4959 + λ5007 nebular line to the [O II]λ4363 auroral line is used to determine \( t_3 \). As for the intensity ratio of the [O II]λ3727 nebular line to the [O II]λ7320+λ7330 auroral line is used. Based on a sample of H II regions where all the necessary oxygen lines are detected, Kennicutt et al. (2003) found that the \( t_3 \) temperatures show a large scatter and that they are nearly uncorrelated with \( t_3 \) temperatures. They noted that the measurements of the faint [O II]λ7320+λ7330 auroral lines may contain large random errors. Furthermore, Rubin (1986), Tsamis et al. (2003) have pointed out that the [O II]λ5727/[O II]λ7320 + λ7330 ratio may be affected by recombination. Izotov et al. (2006) have derived \( t_2 \) and \( t_3 \) from the above ratios for a sample of H II regions. They concluded that the two temperatures generally follow the \( t_2 - t_3 \) relation obtained from photoionization models (e.g. Stasinska 1982, 1990), but that the scatter of the data points is very large. The large scatter was attributed to large flux errors of the weak [O II]λ7320 + λ7330 emission lines.

The intensity ratio of the [N II]λ6548 + λ6584 nebular line to the [N II]λ5755 auroral line is also used to determine \( t_2 \). It seems to give more reliable values. However, the contribution of recombination to the excitation of the [N II]λ5755 line may affect temperatures derived from the [N II] nebular to auroral line ratios (Rubin 1986, Tsamis et al. 2003). The ([N II]λ6548 + λ6584)/[N II]λ5755 ratio is measured in only a few H II regions with a detected ([O III]λ4959 + λ5007)/[O III]λ4363 line ratio.

When only a single temperature measurement is available, a \( t_2 - t_3 \) relation based on grids of H II region models is usually used. Several versions of such a \( t_2 - t_3 \) relation have been proposed (e.g. Campbell et al. 1986, Pagel et al. 1992, Izotov et al., 1997, Deharveng et al. 2000, Oey & Shields, 2000), but the agreement between them is not very good. The available measurements do not provide an undisputable evidence in favor of any one of suggested relations, i.e. the choice of the relation is in fact arbitrary.
Thus, the $t_2 - t_3$ relation seems to be the weakest link of the classic $T_e$ method. We will address this problem here.

The main goal of this paper is to derive a $t_2 - t_3$ relation which is model-independent. This allows one to relax the arbitrariness in the choice of the $t_2 - t_3$ relation. The basic idea is the following. Usually, the set of equations used for the determination of the ionic $O^{++}/H^+$ and $O^{+}/H^+$ abundances in H II regions is applied to the whole nebula. If we apply the equation for $O^{++}/H^+$ only to the $O^{++}$ zone, then this would yield, not the ionic $O^{++}/H^+$ abundance, but the total O/H oxygen abundance instead. There is no reason to suspect that the oxygen abundances in the $O^{++}$ and $O^+$ zones differ. We therefore require that the equation for $O^{++}/H^+$ applied to the $O^{++}$ zone and the one for $O^+/H^+$ applied to the $O^+$ zone result in exactly the same value of the oxygen abundance. This condition allows us to derive a relation between $t_2$ and $t_3$. We can apply the equation for $O^{++}/H^+$ to the $O^{++}$ zone alone, only if we know the contribution of the $O^{++}$ zone to the measured $H_β$ flux of the H II region. We will be using the ff relation [Pilyugin 2003, Pilyugin et al. 2006] for this purpose.

The observational sample to be used is described in Section 2. The strategy for determining the $t_2 - t_3$ relation is discussed in Section 3. A model-independent $t_2 - t_3$ relation is derived in Section 4. We discuss the results in Section 5, and summarize our conclusions in Section 6.

We will be using the following notations throughout the paper: $R_2 = I[OII]λ3727+λ3729/H_β$, $R_3 = I[OIII]λ4959+λ5007/H_β$, $R = I[OII]λ3727/λ3729$, $R_{23} = R_2 + R_3$. With these definitions, the excitation parameter $P$ can be expressed as: $P = R_3/(R_2 + R_3)$.

2 OBSERVATIONAL DATA

A large sample of high-precision measurements of H II regions is at the base of the present investigation. We include first the sample of [Pilyugin & Thuan 2003] who have carried out an extensive search of the literature to compile a list of more than 700 individual spectra of H II regions in irregular and spiral galaxies, with the requirement that they all possess a detected [O II] $\lambda4363$ emission line. While we have tried to include as many sources as possible, we do not claim our search to be exhaustive. Since the majority of extragalactic H II regions are in the low-density regime [Zaritsky et al. 1994; Bresolin et al. 2003], only such H II regions will be considered here. Of the objects with the electron density-sensitive ratio $r_o = [S II] \lambda6716/[S II] \lambda6731$ available, those with $r_o < 1.3$ were excluded.

We have also included the sample of [Izotov et al. 2000, 2004, 2006] who have extracted from the Data Release 3 of the Sloan Digital Sky Survey (SDSS) around 4500 spectra of H II regions with an [O II] $\lambda4363$ emission line detected at a level better than 1σ, and carefully measured the line intensities in each spectrum. The SDSS H II regions are also in a low-density regime. Yuri Izotov and Natalia Guseva have kindly provided us with the total list of their measurements, as only part of these have been published [Izotov et al. 2004, 2006]. In total, our sample consists of around 5200 H II region spectra.

Following [Pilyugin & Thuan 2003], we can use the ff relation [Pilyugin et al. 2006] to select out the H II regions with the highest quality measurements. We can define a "discrepancy index", equal to the difference between the logarithm of the observed flux $R_{\text{obs}}$ in the [O II] $\lambda4363$ line and the logarithm of the flux $R_{\text{cal}}$ of that line derived from the strong [O II] $\lambda3727$, [O III] $\lambda4959,5007$ lines using the ff relation:

$$D_H = \log R_{\text{obs}} - \log R_{\text{cal}}.$$  (1)

It is well known that the relation between the oxygen abundance and the strong oxygen line intensities is double-valued, with two distinct parts, traditionally known as the upper high-metallicity branch and the lower low-metallicity branch of the $R_{23} - O/H$ diagram. Following [Pilyugin & Thuan 2003], we adopt the value of $12+\log(O/H) = 8.25$ as the boundary between the upper branch and the transition zone. The exact boundary is difficult to establish, but we have chosen that value because we will be using later the ff relation which is applicable at metallicities above $12+\log(O/H) \sim 8.25$. We have extracted from our total sample a subsample of high-metallicity H II regions with an oxygen abundance $12+\log(O/H) > 8.25$. The oxygen abundances have been calculated with the equations [Izotov et al. 2006] for the $T_e$ method, and with the $t_2 - t_3$ relation of [Campbell et al. 1988]. Fig. 1 shows the cumulative number of individual H II region measurements with the absolute value of the discrepancy index $D_H$ less than a certain value. Solid and open circles show data for H II regions with respectively positive and negative values of the discrepancy index. It is seen that the agreement between the cumulative numbers of measurements with positive and negative values of the discrepancy index $D_H$ is good for values of $D_H$ less than 0.5, but gets increasingly worse at higher values. This is the result of a selection effect. Indeed, a large positive value of $D_H$ means that the observed $R_{\text{obs}}$ is significantly overestimated. This leads to a substantial overestimate of the electron temperature and an underestimate of the oxygen abundance, bringing it lower than our metallicity cut-off of $12+\log(O/H) = 8.25$. This effect thus systematically depletes the number of high-metallicity H II regions with a large positive $D_H$. To free ourselves from this systematic effect, we select only measurements with the absolute value of $D_H$ less than 0.05. This sample contains 372 data points and will be referred to as the standard sample. The H II regions in it have line intensity errors that are random.

3 A STRATEGY FOR THE DETERMINATION OF THE $t_2 - t_3$ RELATION

3.1 The usual version of the $T_e$ method

For abundance determination in an H II region, a two-zone model for its temperature structure is usually adopted. [Izotov et al. 2006] have recently published a set of equations for the determination of the oxygen abundance in H II regions in the context of such a two-zone model. According to those authors, the electron temperature $t_3$ within the [O II] zone, in units of $10^4$K, is given by the following equation

$$t_3 = \frac{1.432}{\log(R_3/R) - \log C_T},$$  (2)

The quantity $C_T$ is defined by:
\[
C_T = (8.44 - 1.09 t_3 + 0.5 t_3^2 - 0.08 t_3^3) \nu,
\]
where
\[
v = \frac{1 + 0.0004 x_3}{1 + 0.044 x_3}
\]
and
\[
x_3 = 10^{-4} n_e t_3^{-1/2}.
\]

As for the ionic oxygen abundances, they are given by the following equations:
\[
12 + \log(O^{++}/H^+) = \log(I_{\lambda 4959+\lambda 5007}/I_{\beta}) + 6.200 + \frac{1.251}{t_3} - 0.55 \log t_3 - 0.014 t_3,
\]
and
\[
12 + \log(O^{++}/H^+) = \log(I_{\lambda 4388+\lambda 4922}/I_{\beta}) + 5.961 + \frac{1.676}{t_2} - 0.40 \log t_2 - 0.034 t_2 + \log(1 + 1.35x_2),
\]
where
\[
x_2 = 10^{-4} n_e t_2^{-1/2}.
\]
Here \(n_e\) is the electron density in cm\(^{-3}\).

The total oxygen abundances are then derived from the following equation:
\[
\frac{O}{H} = \frac{O^+}{H^+} + \frac{O^{++}}{H^{++}}.
\]

The electron temperature \(t_2\) of the [O\(\text{II}\)] zone is usually determined from an equation which relates \(t_2\) to \(t_3\), derived by fitting H\(\text{II}\) region models. Several versions of this \(t_2 - t_3\) relation have been proposed. A widely used relation is the one by Campbell et al. (1986) (see also Garnett (1992)) based on the H\(\text{II}\) region models of Stasińska (1982):
\[
t_2 = 0.7 t_3 + 0.3.
\]

Another relation has been proposed by Pagel et al. (1992), also based on H\(\text{II}\) region models of Stasińska (1990):
\[
\frac{1}{t_2} = 0.5 \left( \frac{1}{t_3} + 0.8 \right).
\]

Izotov et al. (1997), fitting also the H\(\text{II}\) region models of Stasińska (1990), have proposed the following expression
\[
t_2 = 0.243 + 1.031 t_3 - 0.184 t_3^2.
\]
Based on H\(\text{II}\) region model calculations by Stasińska & Schaerer (1997), Deharveng et al. (2000) have suggested the following relation
\[
t_2 = 0.775 t_3 + 0.281.
\]
Oey & Shields (2000) have found that the Campbell et al. relation is reasonable for \(t_2 > 1.0\). However at lower temperatures, the models are more consistent with an isothermal nebula. They consequently adopted the formulation,
\[
t_2 = \begin{cases} 0.7 t_3 + 0.3, & t_3 > 1.0 \vspace{1mm} \\
0.3 t_3 + 0.2, & t_3 < 1.0. \end{cases}
\]

Using the system of equations Eqs. (12 - 18), and one of the \(t_2 - t_3\) relations chosen among Eqs. (10 - 14), the oxygen abundance \((O/H)_{T_e}\) in an H\(\text{II}\) region can then be determined.

### 3.2 An alternative version of the \(T_e\) method

Examination of Eq. (3) shows that the fluxes used to calculate \(R_3\) in and the H\(\beta\) line originate from different volumes of the nebula. The H\(\beta\) flux comes from the whole H\(\text{II}\) region while the \(R_3\) fluxes come from the volume where the oxygen is in the O\(^{++}\) stage. If Eq. (3) is applied to the O\(^{++}\) zone only, then it gives the total \(\frac{O}{H}\) instead of the ionic \(\frac{O^{++}}{H^{++}}\) oxygen abundance as in the traditional approach. In that case, Eq. (13) takes the form
\[
12 + \log(O/H) = \log(I_{\lambda 4959+\lambda 5007}/(w \times I_{\beta})) + 6.200 + \frac{1.251}{t_3} - 0.55 \log t_3 - 0.014 t_3,
\]
where \(w\) is the fraction of the H\(\beta\) flux in the O\(^{++}\) zone. With the adopted notations, Eq. (15) can be rewritten as
\[
12 + \log(O/H) = \log(R_3/w) + 6.200 + \frac{1.251}{t_3} - 0.55 \log t_3 - 0.014 t_3.
\]

Similarly, Eq. (17) can be rewritten as
\[
12 + \log(O/H) = \log(I_{\lambda 4388+\lambda 4922}/[(1 - w) \times I_{\beta}]) + 5.961 + \frac{1.676}{t_2} - 0.40 \log t_2 - 0.034 t_2 + \log(1 + 1.35x_2).
\]

or
\[
12 + \log(O/H) = \log(R_2/(1 - w)) + 5.961 + \frac{1.676}{t_2} - 0.40 \log t_2 - 0.034 t_2 + \log(1 + 1.35x_2).
\]

There is no reason to expect the oxygen abundance in the O\(^{++}\) zone to differ from that in the O\(^{+}\) zone within the same H\(\text{II}\) region. In other words, the oxygen abundance derived from Eq. (15) must be equal to the one derived from Eq. (18).

Equating the right-hand sides of these two equations result in
\[
\log(R_3/w) + 6.200 + \frac{1.251}{t_3} - 0.55 \log t_3 - 0.014 t_3 = \log(R_2/(1 - w)) + 5.961 + \frac{1.676}{t_2} - 0.40 \log t_2 - 0.034 t_2 + \log(1 + 1.35x_2).
\]
Figure 2. The $R$ vs. $R_3$ diagram. The circles show individual H II region measurements from the standard sample. The relation corresponding to Eq. (20) for the value of the excitation parameter $P = 1.0$ is shown by the solid line. The dotted lines show from right to left the relations corresponding to that equation for $P = 0.8, 0.6, 0.4$ and 0.2. The dashed lines show from top to bottom the positions of H II regions with a given value of the electron temperature $t_3 = 1.2, 1.1, 1.0, 0.9, 0.8$ and 0.7, in units of $10^4$ K.

Eq. (19) can be solved for $t_2$ if the values of $t_3$, $n_e$, and $w$ are known. The majority of extragalactic H II regions are in the low-density regime (Zaritsky et al. 1994; Bresolin et al. 2004). Therefore we adopt an electron density $n_e = 100$ cm$^{-3}$ for all the H II regions in our sample. Thus, Eq. (19) allows to derive the electron temperature $t_2$ within the [O III] zone in a H II region if the electron temperature $t_3$ within the [O III] zone and the fraction $w$ of H$\beta$ flux in the O$^{++}$ zone are known.

### 3.3 Estimation of the parameter $w$

The fraction $w$ of H$\beta$ flux in the O$^{++}$ zone can be estimated in the following way. We have investigated recently the relationship between the observed auroral and nebular oxygen line fluxes in spectra of H II regions (Pilyugin 2002; Pilyugin et al. 2004). We have found a relation (called the II relation) that is metallicity-dependent at low metallicities, but independent of metallicity above $12 + \log O/H \sim 8.25$, i.e. there is one-to-one correspondence between the auroral and nebular oxygen line fluxes in spectra of high-metallicity H II regions. Using a compilation of recent high-precision measurements of oxygen lines fluxes in high-metallicity H II regions, the following II relation was derived (Pilyugin et al. 2004):

$$
\log R = -4.151 - 3.118 \log P + 2.958 \log R_3 - 0.680 (\log P)^2.
$$

Fig. 2 shows the relation corresponding to Eq. (20) in the $R$–$R_3$ diagram for various values of the excitation parameter $P$. The solid line, called hereafter as the basic line, corresponds to $P = 1.0$, while the dotted lines correspond, from right to left, to $P = 0.8, 0.6, 0.4, 0.2$. The dashed lines show the loci of H II regions for several values of the electron temperature $t_3$. From top to bottom, $t_3 = 1.2, 1.1, 1.0, 0.9, 0.8, 0.7$ in units of $10^4$ K. The circles show individual measurements of H II regions from the present sample.

Let us consider a sequence of H II regions with the same value of $t_3$. The fraction of radiation of the H II region in the O$^{++}$ zone increases along this sequence from low to high values of $P$, and reaches its maximum value, $w = 1$, at $P = 1$, i.e. at the intersection point of a dashed line with a given electron temperature with the basic solid line. Then, the fraction of radiation in the O$^{++}$ zone can be estimated as

$$
w = \frac{R_3^{\text{obs}}}{R_3^{P=1}}.
$$

(21)

Such an estimate is not airtight since not only $w$ can change along a sequence of H II regions with a fixed value of $t_3$, but other characteristics of H II regions, such as, for example, their oxygen abundance, can do so as well. Therefore, the value of $t_2^*$ derived from Eq. (19) and Eq. (21) may carry some systematic error $E_t$. That error should be small for high-excitation H II regions (they are located close to the basic line) but increase with decreasing $P$. In the following, we discuss how to estimate that error and correct $t_2^*$ for it.

### 4 THE $t_2$–$t_3$ RELATION

The top panel in Fig. 3 shows the value of $t_2^*$ as derived from Eq. (19) and Eq. (21) for the objects in our standard subsample of high-metallicity H II regions. As noted above, $t_2^*$ has a systematic error $E_t$ that depends on the value of the excitation parameter $P$. To illustrate the point, we show in the bottom panel of Fig. 3 high quality data (those with $|D_H| < 0.01$) for H II regions with $0.9 > P > 0.8$ (filled circles) and for those with $0.5 > P > 0.4$ (open circles). Inspection of the bottom panel in Fig. 3 shows that indeed the $t_2$–$t_3$ relations are slightly different for H II regions with different values of $P$: at a given value of $t_3$, $t_2^* = t_2 + E_t$ is slightly smaller, on average, for low than for high excitation H II regions. The true $t_2$–$t_3$ relation can be found by extrapolation of the $t_2^*$–$t_3$ relation to $P = 1$.

The bottom panel in Fig. 3 shows that the systematic error $E_t$ is small. Therefore, we will approximate it by a linear expression, i.e. the true $t_2$ and the derived $t_2^*$ values are related by

$$
t_2 = t_2^* - E_t = t_2^* - c (1 - P).
$$

(22)

Examination of Fig. 3 shows also that the $t_2$–$t_3$ relation can be parametrized as

$$
t_2 = a t_3 + b.
$$

(23)

The coefficients $a$ and $b$ in Eq. (23) and the coefficient $c$ in Eq. (22) can be found simultaneously by fitting the data in the top panel of Fig. 3 by an expression of the type

$$
t_2^* = a t_3 + b + c (1 - P).
$$

(24)

Carrying out a standard least-squares fit to the data, we obtain the following values of the coefficients: $a = 0.716 \pm 0.012$, $b = 0.264 \pm 0.013$, $c = -0.042 \pm 0.007$. Then, the true $t_2$–$t_3$ relation is

$$
t_2 = 0.716(\pm0.012) t_3 + 0.264(\pm0.013).
$$

(25)

The value of $w$ given by Eq. (21) is the fraction of radiation in the O$^{++}$ zone if the condition $t_2^* = t_3$ holds. This
We found the differences between the $t_2^*$ expressions adopted for the $t_2^*$ relation. We have recomputed the values of $t_2^*$ between the value of $t_2^*$ justified. The top panel of Fig. 4 shows the difference $\Delta t_2^*$ of excitation parameter $P$. The points are individual measurements and the one derived from Eq.(24) as a function of the excitation parameter $P$. The points are individual measurements of H II regions from our standard sample, and the line is the linear best fit to those data obtained through the least-squares method. The middle panel in Fig. 4 shows the same difference $\Delta t_2^*$ as a function of the electron temperature $t_3$. Examination of the top and middle panels of Fig. 4 shows that $\Delta t_2^*$ does not correlate either with $P$ or $t_3$, justifying our adoption of linear forms for the $t_2 - t_3$ and $t_2^* - t_2$ relations.

The bottom panel in Fig. 4 shows $\Delta t_2^*$ as a function of the discrepancy index $D_{ff}$. There is an anticorrelation of the two quantities. Since the discrepancy index appears to be an indicator of the error in the auroral line R measurements, this suggests that the $t_2 - t_3$ correlation is rather tight, and that any scatter in this correlation is caused mainly by uncertainties in the measurements.

Examination of the top and middle panels of Fig. 4 shows that $\Delta t_2^*$ is dependent on the electron temperature (Aller 1984). $E_{4,2}$, is dependent on the electron temperature $t_3$.

$$E_{4,2}^* = 1.387 t^{0.983} 10^{-0.0424/t},$$

then the contribution $w_c$ of the [OIII] zone to the total flux of the nebula in the H$\beta$ line is given by the following expression

$$w_c = \frac{E_{4,2}^*(t_3)}{E_{4,2}^*(t_3) + E_{4,2}^*(t_2) (1 - w)}.$$  

We now check whether the linear forms of the analytical expressions adopted for the $t_2 - t_3$ and $t_2^* - t_2$ relations are justified. The top panel of Fig. 4 shows the difference $\Delta t_2^*$ between the value of $t_2^*$ derived from Eq.(24) and Eq.(24) and the one derived from Eq.(24) as a function of the excitation parameter $P$. The points are individual measurements of H II regions from our standard sample, and the line is the linear best fit to those data obtained through the least-squares method. The middle panel in Fig. 4 shows the same difference $\Delta t_2^*$ as a function of the electron temperature $t_3$. Examination of the top and middle panels of Fig. 4 shows that $\Delta t_2^*$ does not correlate either with $P$ or $t_3$, justifying our adoption of linear forms for the $t_2 - t_3$ and $t_2^* - t_2$ relations.

The bottom panel in Fig. 4 shows $\Delta t_2^*$ as a function of the discrepancy index $D_{ff}$. There is an anticorrelation of the two quantities. Since the discrepancy index appears to be an indicator of the error in the auroral line R measurements, this suggests that the $t_2 - t_3$ correlation is rather tight, and that any scatter in this correlation is caused mainly by uncertainties in the measurements.

Examination of the top and middle panels of Fig. 4 shows that $\Delta t_2^*$ is dependent on the electron temperature (Aller 1984). $E_{4,2}$, is dependent on the electron temperature $t_3$.
This relation is shown by the solid line in the top panel of Fig. 4. For comparison, the bottom panel of Fig. 4 shows the $t_2^* - t_3$ diagram and the $t_2 - t_3$ relation for the whole standard sample.

Fig. 5 shows the differences $\Delta t_2^*$ between the values of $t_2^*$ derived from Eq. (19) and Eq. (21) and the one derived from Eq. (25) as a function of $P$ (top panel), $t_3$ (middle panel) and discrepancy index $D_{ff}$ (bottom panel). The points are individual H II regions with $0.01 > D_{ff} > -0.01$, the lines are linear least-square fits to those data. Comparison of Fig. 4 and Fig. 5 shows clearly that the scatter in $t_2$ at a fixed value of $t_3$ decreases in the subsample of H II regions with more precise measurements. This confirms our conclusion that the $t_2 - t_3$ correlation is rather tight, and that the scatter in it is caused mainly by measurement uncertainties.

Examination of Eq. (25) and Eq. (29) shows that the $t_2 - t_3$ relations derived from the two different samples of H II regions are very similar and agree within the formal uncertainties. Thus the derived $t_2 - t_3$ relation is rather robust. In the following, we will adopt as the $t_2 - t_3$ relation

$$t_2 = 0.72 t_3 + 0.26$$

(30)

We note that it has been generally accepted that there is a one-to-one correspondence between $t_2$ and $t_3$, i.e. that the $t_2 - t_3$ relation does not depend on an additional parameter. If there is a dependence of the $t_2 - t_3$ relation on the excitation parameter (from general considerations, this cannot be excluded), that dependence cannot be revealed by our approach and can influence the derived relation.

In summary, there is a tight correlation between the electron temperature $t_2$ within the [O III] zone and the electron temperature $t_2$ within the [O II] zone in high-metallicity H II regions. This correlation can be well approximated by a linear expression and its form is rather robust.

5 DISCUSSION

We now compare the $t_2 - t_3$ relation obtained here with those obtained by other authors. Fig. 6 shows our $t_2 - t_3$ relation together with those from Campbell et al. (1986); Izotov et al. (1997); Deharveng et al. (2000); Oey & Shields (2000). Since our $t_2 - t_3$ relation is derived for cool high-metallicity H II regions then the high-temperature low-metallicity part of relation is not considered here. Fig. 6 shows that our $t_2 - t_3$ relation is most similar to the one by Campbell et al. (1986).

We consider next how the obtained $t_2 - t_3$ relation may affect the derived oxygen abundances in H II regions. Since the $t_2 - t_3$ relation of Campbell et al. (1986) has found wide acceptance and use in abundance determinations in H II regions, we will compare oxygen abundances derived with the Campbell et al. (1986) relation and ours. For this purpose, we use the data for H II regions in the spiral galaxy NGC 4254 obtained by McCall et al. (1985); Shields et al. (1991); Henry et al. (1994). Since the auroral [O III] λ4363
$12 + \log(O/H) = 8.86 (\pm 0.03) - 0.045 (\pm 0.004) \times R_g$.  \hfill (32)

Fig. 8 shows that the abundances derived with our $t_2 - t_3$ relation are slightly higher (up to $\sim 0.1$ dex) than those derived with the relation by Campbell et al. [1986]. Comparison of Eq. (31) and Eq. (32) leads to the same conclusion.

6 CONCLUSIONS

We suggest a new way to establish the relation between the electron temperature $t_3$ within the [O III] zone and the electron temperature $t_2$ within the [O II] zone in high-metallicity (12 + log(O/H) > 8.25) H II regions. The basic idea is the following. If we apply the equation used to calculate the ionic abundance $O^{++}/H^+$ not to the entire H II region but only to the O$^{++}$ zone, then this would yield, not the ionic $O^{++}/H^+$ abundance but the total O/H oxygen abundance instead. We require that the equation for $O^{++}/H^+$ applied to the O$^{++}$ zone and the one for $O^+/H^+$ applied to the O$^+$ zone result in exactly the same value of the oxygen abundance. This condition allows us to derive a relation between $t_2$ and $t_3$. We have applied this method to a sample of 372 H II regions selected to have high-quality measurements by using the ff relation \cite{Pilyugin2000}. We find that the correlation between $t_2$ and $t_3$ is tight and can be approximated by a linear expression. The so derived $t_2 - t_3$ relation is independent of photoionization models of H II regions.

The derived relation can be used to determine $t_2$ and accurate abundances in high-metallicity H II regions with a measured $t_3$ temperature. It can also be used in conjunction with the ff relation \cite{Pilyugin2000} for the determination of the $t_3$ and $t_2$ temperatures and oxygen abundances in high-metallicity H II regions where the [O III] $\lambda 4363$ auroral line is not detected.

Our $t_2 - t_3$ relation is close to the widely used relation of Campbell et al. [1986]. However, the abundances derived with our $t_2 - t_3$ relation are slightly higher (up to $\sim 0.1$ dex) than those derived with the Campbell et al. [1986] relation.

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