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Abundance determinations in H II regions

Model fitting versus T_e–method

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Abstract. The discrepancy between the oxygen abundances in high-metallicity H II regions determined through the T_e–method (and/or through the corresponding "strong lines – oxygen abundance" calibration) and that determined through the model fitting (and/or through the corresponding "strong lines – oxygen abundance" calibration) is discussed. It is suggested to use the interstellar oxygen abundance in the solar vicinity, derived with very high precision from the high-resolution observations of the weak interstellar OIλ1356 absorption lines towards the stars, as a "Rosetta stone" to verify the validity of the oxygen abundances derived in H II regions with the T_e–method at high abundances. The agreement between the value of the oxygen abundance at the solar galactocentric distance traced by the abundances derived in H II regions through the T_e–method and that derived from the interstellar absorption lines towards the stars is strong evidence in favor of that i) the two-zone model for T_e seems to be a realistic interpretation of the temperature structure within H II regions, and ii) the classic T_e–method provides accurate oxygen abundances in H II regions. It has been concluded that the "strong lines – oxygen abundance" calibrations must be based on the H II regions with the oxygen abundances derived with the T_e–method but not on the existing grids of the models for H II regions.

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

1. Introduction

An investigation of variations of chemical properties among galaxies is very important for the development of the theory of the structure and evolution of galaxies. Accurate abundances are necessary for such investigations. Good spectrophotometry of H II regions is now available for a large number of galaxies, and the realibility of abundances is mainly defined by the method for abundance determination in H II regions.

Abundance in H II regions can be derived from measurements of temperature-sensitive line ratios, such as [OIII]$\lambda\lambda$4959, 5007/[OIII]λ4363. Following Stasinska (2002b), this classical T_e–method will be referred to as the direct empirical method. The abundance in H II regions can be also derived through photoionization model fitting. This method for abundance determination will be referred to as the theoretical (or model) method.

Unfortunately, in oxygen-rich H II regions the temperature-sensitive lines such as [OIII]λ4363 are often too weak to be detected. For such H II regions, abundance indicators based on more readily observable lines were suggested (Pagel et al. 1979; Alloin et al. 1979). The oxygen abundance indicator R_{23} = ([OII]$\lambda\lambda$3727, 3729 + [OIII]$\lambda\lambda$4959, 5007)/H_β, suggested by Pagel et al. (1979), has found widespread acceptance and use for the oxygen abundance determination in H II regions where the temperature-sensitive lines are undetectable. The strategy of this way of abundance determination is very simple: the relation between strong oxygen line intensities and oxygen abundances is established based on the H II regions in which the oxygen abundances are determined through the T_e–method, and then this relation is used for the abundance determination in H II regions in which the temperature-sensitive lines are not available. The relation (between strong oxygen line intensities and oxygen abundances) established on the basis of H II regions in which the oxygen abundances are determined through the T_e–method (direct empirical method) will be referred to as empirical calibration.

The grids of photoionization models are often used to establish the relation between strong oxygen line intensities and oxygen abundances (Edmunds & Pagel 1984; McCall et al. 1985; Dopita & Evans 1986; Kobulnicky et al. 1999; Kewley & Dopita 2002, among others). The relation (between strong oxygen line intensities and oxygen abundances) established on the basis of the grids of the photoionization models for H II regions will be referred to as theoretical or model calibration.

The early calibrations were one-dimensional (Edmunds & Pagel 1984; McCall et al. 1985; Dopita & Evans 1986; Zaritsky et al. 1994), i.e. the relation of the type O/H = $f(R_{23})$ was used. It has been shown (Pilyugin 2000, 2001a,b) that the error in the oxygen abundance derived with the one-dimensional calibrations involves a systematic error. The origin of this systematic error is evident. In a general case, the intensities of oxygen emission lines in spectra of H II region depend not

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only on the oxygen abundance but also on the physical conditions (hardness of the ionizing radiation and geometrical factors). Then in determininig the oxygen abundance from line intensities the physical conditions in the H II region should be taken into account. In the T_e–method this is done via T_e. In one-dimensional calibrations the physical conditions in H II regions are ignored. Starting from the idea of McGaugh (1991) that the strong oxygen lines contain the necessary information to determine accurate abundances in (low-metallicity) H II regions, it has been shown (Pilyugin 2000, 2001a,b) that the physical conditions in H II regions can be estimated and taken into account via the excitation parameter P. A two-dimensional or parametric calibration (P–method) has been suggested. A more general relation of the type O/H = $f(P, R_{23})$ is used in the P–method, compared to the relation of the type O/H = $f(R_{23})$ used in one-dimensional calibrations.

It should be stressed that "strong lines – oxygen abundance" calibrations do not form a uniform family. One should clearly recognize that there are two different types of calibrations. The calibrations of the first type are the empirical calibrations (established on the basis of H II regions in which the oxygen abundances are determined through the T_e–method). Two-dimensional empirical calibrations both at low and at high metallicities were recently derived by Pilyugin (2000, 2001a,c). The calibrations of the second type are the theoretical (or model) calibrations (established on the basis of the grids of the photoionization models of H II regions). The two-dimensional theoretical calibrations were recently suggested by Kobulnicky et al. (1999) and Kewley & Dopita (2002).

Thus, at the present day there actually exist two scales of oxygen abundances in H II regions. The first (empirical) scale corresponds to the oxygen abundances derived with the T_e–method or with empirical calibrations (the P–method). The second (theoretical or model) scale corresponds to the oxygen abundances derived through the model fitting or with theoretical (model) calibrations. The comparison of these scales of oxygen abundances in H II regions and their evaluation are the goals of the present study.

2. Oxygen abundances in H II regions: Model fitting versus T_e–method

Figure 1 shows the two-dimensional empirical calibration obtained by Pilyugin (2000, 2001c) (low-metallicity range) and Pilyugin (2001a) (high-metallicity range). Each O/H – R_{23} relation is labeled with corresponding value of the excitation parameter P which is defined as

$$P = \frac{[\mathrm{OIII}]\lambda\lambda4959, 5007}{[\mathrm{OII}]\lambda3727 + [\mathrm{OIII}]\lambda\lambda4959, 5007}. \quad (1)$$

The points in Fig. 1 are H II regions with oxygen abundances determined through the T_e–method (compilation of data from Pilyugin 2000, 2001a).

Figure 2 shows the two-dimensional theoretical calibration reported by Kobulnicky et al. (1999). This calibration is based on the grid of the models of H II regions after McGaugh (1991). The O/H = $f(R_{23})$ relations after Kobulnicky et al. (1999) are shown in Fig. 2 with lines. Every line is labeled with corresponding value of the excitation parameter P. The ionization parameter y was used in the two-dimensional theoretical calibration reported by Kobulnicky et al. (1999). The ionization parameter y was defined as

$$y = \log \frac{[\mathrm{OIII}]\lambda\lambda4959, 5007}{[\mathrm{OII}]\lambda3727}. \quad (2)$$

As can be seen from Eqs. (1) and (2), the excitation parameter P used in the two-dimensional empirical calibration of Pilyugin (2000, 2001a,c) and the ionization parameter y used in the two-dimensional theoretical calibration reported by Kobulnicky et al. (1999) are connected by a simple relation

$$y = \log \frac{P}{1 - P}. \quad (3)$$

McGaugh (1991) has concluded that his grid of H II region models agrees with existing oxygen abundances determined through the T_e–method at low metallicities (his Fig. 14), the rms of the residuals between his abundances and published abundances based on temperature-sensitive line ratios is 0.05 dex with no zero-point offset. Inspection of Fig. 2 confirms that the theoretical calibration of Kobulnicky et al. (1999), based on McGaugh's grid of H II region models, agrees quantitatively with the recent oxygen abundances derived through the direct empirical method (the T_e–method) at low metallicities. A comparison of Fig. 1 with Fig. 2 shows that the discrepancy between the theoretical calibration of Kobulnicky et al. and the empirical calibration of Pilyugin is negligible small for the very low-metallicity (12+log O/H around 7.3), high-excitation (P around 0.95) H II regions, but the discrepancy increases with increasing metallicity and with decreasing excitation parameter, reaching the value of Δlog O/H around 0.15 dex for H II regions with 12+log O/H around 7.9. The agreement between the theoretical calibration of Kobulnicky et al. and the empirical calibration of Pilyugin disappears for H II regions that lie on the upper branch of the O/H – R_{23} diagram.

It should be noted that the agreement (at least quantitative) between the theoretical calibrations and the empirical calibrations at low metallicities is not a general rule. For example, there is a significant discrepancy between two-dimensional theoretical calibration of Kewley & Dopita (2002) and the empirical calibration of Pilyugin at high and at low metallicities. The theoretical calibration of Kewley & Dopita is also in conflict with the theoretical calibration of Kobulnicky et al.

Thus, the theoretical calibration of Kobulnicky et al. (1999) agrees quantitatively with the empirical calibrations of Pilyugin (2000, 2001a,b) at low metallicities and these calibrations are in conflict at high metallicities.

3. Verification of the validity of the T_e–method at high metallicities

The validity of the T_e–method at high metallicities has been questioned in a number of investigations. According to Stasinska (2002a,b), at high metallicities large temperature gradients are expected in ionized nebulae. Therefore, the T_e–method based on [OIII]λ4363/5007 will underestimate the

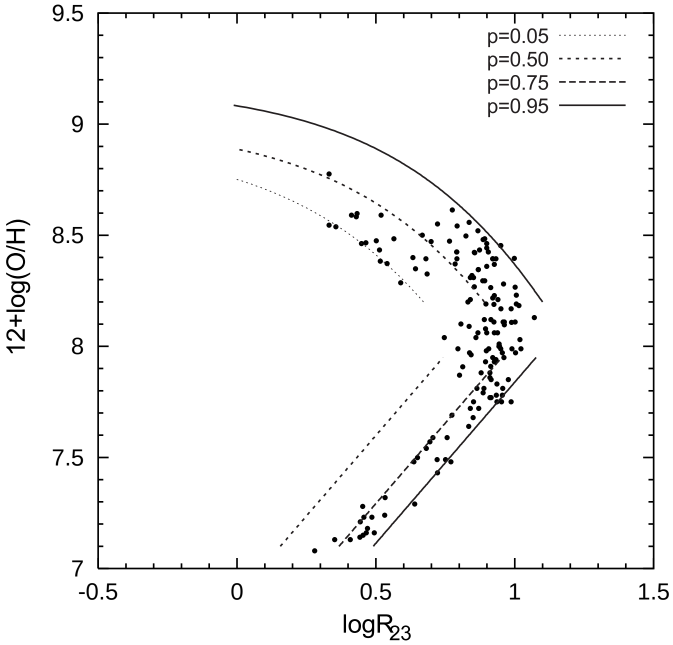

Fig. 1. The two-dimensional empirical calibration obtained by Pilyugin (2000, 2001c) (low-metallicity range) and Pilyugin (2001a) (high-metallicity range). Each O/H – R_{23} relation is labeled with corresponding value of the excitation parameter P. The points are H II regions with oxygen abundances determined through the T_e–method (compilation of data from Pilyugin 2000, 2001a).

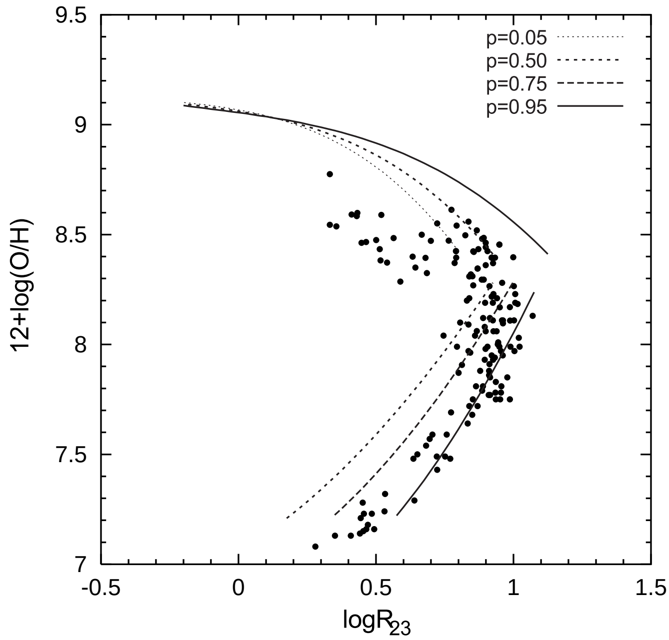

Fig. 2. The two-dimensional theoretical calibration reported by Kobulnicky et al. (1999). The lines are the O/H – R_{23} relations for different values of the excitation parameter P. Every line is labeled with corresponding value of the excitation parameter P. The points are the same data as in Fig. 1.

abundances of heavy elements, since the [OIII]λ4363 line will be essentially emitted in the high temperature zones, inducing a strong overestimate of the average electron temperature. Therefore, although with very large telescopes it will now be possible to measure [OIII]λ4363 even in high metallicity giant H II regions, one should refrain from interpreting this line in the usual way. Doing this, one would necessary find sub-solar oxygen abundances, even for giant H II regions with metallicities well above solar.

Thus, the validity of the T_e–method has been verified by comparison with the H II region models. As it can be seen in the previous section, the recent H II region models are not indisputable even at low metallicities. Why should one expect that H II region models provide more realistic abundances compared to the T_e–method at high metallicities? Indeed, according to Stasinska (2002b) this would be true if the constraints were sufficiently numerous (not only on emission line ratios, but also on the stellar content and on the nebular gas distribution) and if the model fit were perfect (with a photoionization code treating correctly all the relevant physical processes and using accurate atomic data). These conditions are never met in practice. Abundances are not necessary better determined from model fitting.

Then, the validity of the T_e–method at high metallicities cannot be indisputably confirmed or rejected by comparison with the recent H II region models. Fortunately, there is another way to verify the validity of the T_e–method at high metallicities.

High-resolution observations of the weak interstellar OIλ1356 absorption lines towards the stars allow one to determine interstellar oxygen abundance in the solar vicinity with very high precision. It should be noted that this method is in fact model-independent. These observations yield a mean interstellar oxygen abundance of 319 O atoms per 10^6 H atoms (or 12+log (O/H) = 8.50) (Meyer et al. 1998; Sofia & Meyer 2001). There are no statistically significant variations in the measured oxygen abundances from line of sight to line of sight; the rms scatter value for these oxygen abundances is low, ±0.05 dex. Out to 1.5 kpc, the oxygen abundances are stable in diffuse clouds with different physical conditions as measured by the fraction of H in the form of H_2.

Caplan et al. (2000) and Deharveng et al. (2000) have analysed Galactic H II regions and have obtained the slope –0.0395 dex/kpc with central oxygen abundance 12+log (O/H) = 8.82 and 12+log (O/H) = 8.48 at the solar galactocentric distance. All the available spectra of Galactic H II regions with measured [OIII]λ4363 lines were compiled by Pilyugin et al. (2003), and oxygen abundances in Galactic H II regions were recomputed in the same way, using the T_e–method. These data result in oxygen abundance 12+log (O/H) = 8.50 at the solar galactocentric distance although the dispersion in derived abundances is relatively large. Thus, the value of the oxygen abundance at the solar galactocentric distance derived from consideration of the H II regions is in agreement with that derived with high precision from the interstellar absorption lines towards the stars. The agreement between the value of the oxygen abundance at the solar galactocentric distance traced by the abundances derived in

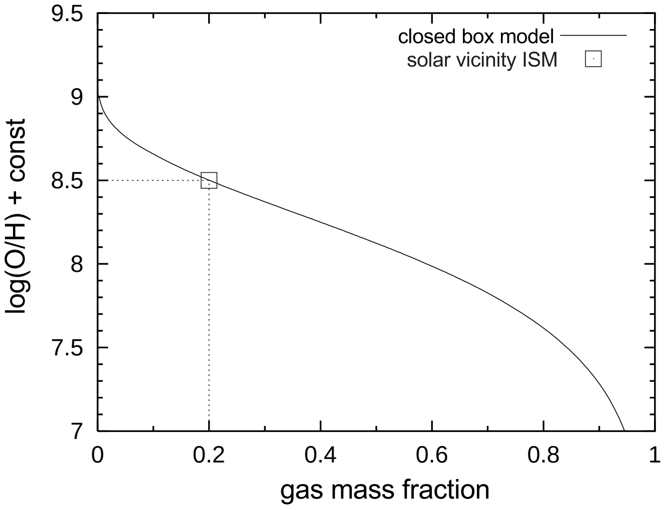

Fig. 3. The oxygen abundance versus gas mass fraction diagram. The constant was chosen in such a way that the value of the gas mass fraction μ = 0.2 corresponds to the oxygen abundance as large as 12+log O/H = 8.5. This comes from the data for the solar vicinity interstellar medium (see text).

H II regions through the T_e–method and that derived from the interstellar absorption lines towards the stars is strong evidence in favor of that *i)* the two-zone model for T_e seems to be a realistic interpretation of the temperature structure within H II regions, and *ii)* the classic T_e–method provides accurate oxygen abundances in H II regions up to oxygen abundances as large as 12 + log (O/H) = 8.60 ÷ 8.70. Thus, one can concluded that the H II regions with T_e–abundances provide a more reliable basis for calibration than the H II region models.

Unfortunately, there are no H II regions with measured [OIII]λ4363 lines at highest metallicities (or at lowest log R_{23}, Fig. 1). There are only two high-metallicity, 12+log (O/H) ∼ 8.9, H II regions with measured temperature-sensitive lines, see Kinkel & Rosa (1994), Castellanos et al. (2002). Therefore, we have to use an extrapolation of the calibration to derive the abundances in H II regions with lowest value of log R_{23}. The oxygen abundances in those H II regions predicted by the empirical calibration are significantly lower compared to abundances predicted by theoretical (model) calibrations. There is hovewer indirect way to test the reality of these predictions. The present-day oxygen abundance in the solar vicinity is 12 + log (O/H) = 8.50, and for the present-day gas mass fraction, 0.15 ÷ 0.20 appears to be a reasonable value (Malinie et al. 1993). Figure 3 shows the O/H–μ diagram, where μ is the gas mass fraction. The prediction of the closed-box model for the chemical evolution of galaxies is presented by the solid line in Fig. 3. The constant for O/H values was chosen in such manner that the value of the gas mass fraction μ = 0.2 corresponds to the oxygen abundance as large as 12 + log O/H = 8.5 as in the solar vicinity (square in Fig. 3). Inspection of Fig. 3 shows that there is no possibility of large central (intersect) oxygen abundances (as large as 12 + log O/H ∼ 9.50 and higher) derived with theoretical (model) calibrations (Zaritsky et al. 1994; Garnett et al. 1997). On the contrary, the low central oxygen abundances predicted by the empirical calibration (Pilyugin et al. 2002) fit this picture well.

It has been known for a long time that permitted lines in H II regions indicate higher oxygen abundances than forbidden lines. Peimbert (1967) suggested that the presence of spatial temperature fluctuations in gaseous nebulae can significantly influence the oxygen abundance in H II regions derived from forbidden lines. In contrast, permitted lines are almost independent of such variations and, in principle, they should be more precise indicators of the true chemical abundances. Esteban et al. (1998) found oxygen abundances for two positions in the Orion nebula from permitted and forbidden lines. The oxygen abundances derived from forbidden lines are coincident for both positions in the Orion nebula (12 + log O/H = 8.47) and agree well with the interstellar oxygen abundance in the solar vicinity derived from interstellar absorption lines towards the stars (12 + log O/H = 8.50). They found from permitted lines the oxygen abundance 12 + log O/H = 8.61 for position 1 and 12 + log O/H = 8.68 for position 2, although the abundances obtained from the different multiplets observed show significant dispersion. The gas-phase oxygen abundance 12 + log O/H = 8.64 and the total (gas+dust) oxygen abundance as large as 12 + log O/H = 8.72 were proposed by Esteban et al. (1998) for the Orion nebula. If permitted lines indicate the true oxygen abundance in the Orion nebula, then the uncertainty around 0.1 dex in the oxygen abundances derived from forbidden lines cannot be excluded. However, the origin of the discrepancy between abundances derived from permitted and forbidden lines is not indisputable (see discussion in Stasinska 2002b). If the total (gas+dust) oxygen abundance in the Orion nebula coincides with the total oxygen abundance in the interstellar medium in the solar vicinity, and if permitted lines provide true gas-phase oxygen abundance in the Orion nebula, then the difference between gas-phase oxygen abundance in the Orion nebula and in the interstellar gas suggests that the depletion of oxygen into dust grains in the interstellar medium is around 0.1 dex higher than in the Orion nebula (and absolute depletion of oxygen in the interstellar medium is around 0.2 dex). It can be verified, in principle, by measurement of the abundance of the same noble gas in the interstellar medium and in the Orion nebula. Unfortunately, measurements of the abundance of only the noble gas krypton in the interstellar medium are available (Cardelli & Meyer 1997), but there is no data on the krypton abundance in the Orion nebula.

Thus it appears that the classic T_e–method provides more accurate oxygen abundances in H II regions at high metallicities as compared to the model fitting, although the uncertainty around 0.1 dex cannot be excluded. As a consequence, the empirical calibration appears to be more justified than the theoretical (model) calibration.

4. Conclusions

The oxygen abundances in H II regions determined through the direct empirical method (the classic T_e–method) and/or through the corresponding empirical "strong lines – oxygen abundance" calibration are compared with abundances determined through the model fitting and/or through the corresponding theoretical (model) "strong lines – oxygen abundance" calibration. It was shown that the theoretical calibration of Kobulnicky et al. (1999) agrees quantitatively with the empirical calibrations of Pilyugin (2000, 2001a,b) at low metallicities and these calibrations are in conflict at high emetallicities.

It is suggested to use the interstellar oxygen abundance in the solar vicinity, derived with very high precision from the high-resolution observations of the weak interstellar OIλ1356 absorption line towards the stars, as a "Rosetta stone" to verify the validity of the oxygen abundances derived in high-metallicity H II regions with the T_e–method. The agreement between the value of the oxygen abundance at the solar galactocentric distance traced by the abundances derived in H II regions through the T_e–method and that derived from the interstellar absorption lines towards the stars is strong evidence in favor of that i) the two-zone model for T_e seems to be a realistic interpretation of the temperature structure within H II regions, and ii) the classic T_e–method provides accurate oxygen abundances in H II regions, although the uncertainty around 0.1 dex cannot be excluded.

It has been concluded that at high metallicities the "strong lines – oxygen abundance" calibrations must be based on the H II regions with the oxygen abundances derived through the T_e–method but not on the existing grids of the models for H II regions.

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