Oxygen abundances in the most oxygen-rich spiral galaxies

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Abstract

Oxygen abundances in the spiral galaxies expected to be richest in oxygen are estimated. The new abundance determinations are based on the recently discovered relation between auroral and nebular oxygen line fluxes in high-metallicity H\textsc{ii} regions. We find that the maximum gas-phase oxygen abundance in the central regions of spiral galaxies is $12+\log(O/H) \sim 8.75$. This value is significantly lower (by a factor $\gtrsim 5$) than the previously accepted value. The central oxygen abundance in the Milky Way is similar to that in other large spirals.

Key words: galaxies: abundances – ISM: abundances – H\textsc{ii} regions

1 INTRODUCTION

The oxygen abundance in spiral galaxies has been the subject of much discussion for a long time. Which spiral galaxy is the oxygen-richest one? And how high is the oxygen abundance in the oxygen-richest galaxies? Due to the presence of radial abundance gradients in the disks of spiral galaxies, the maximum oxygen abundance occurs at their centers. The notation $(O/H)_C = 12+\log(O/H)_{R=0}$ will be used thereafter to denote the central oxygen abundance.

The chemical composition of various samples of spiral galaxies has been discussed in a number of papers (e.g., Vila-Costas & Edmunds 1992; Zaritsky et al. 1994; Garnett et al. 1997; van Zee et al. 1998; Garnett et al. 2002). According to those articles, the oxygen-richest galaxies are: NGC 5194 (M 51) with $(O/H)_C = 9.54$ (Vila-Costas & Edmunds 1992), NGC 3351 with $(O/H)_C = 9.41$ (Zaritsky et al. 1994), NGC 3184 with $(O/H)_C = 9.50$ (van Zee et al. 1998), NGC 6744 with $(O/H)_C = 9.64$ (Garnett et al. 1997). Different versions of the one-dimensional empirical method, proposed first by Pagel et al. (1979) a quarter of a century ago, have been used for oxygen abundance determinations in those papers. Pilyugin et al. (2000, 2001, 2003) has shown that the oxygen abundances in galaxies determined with the one-dimensional empirical calibrations are significantly overestimated at the high-metallicity end ($12 + \log O/H > 8.25$). This is because accurate oxygen abundances can be derived via the classical $T_e$ – method. Here we consider anew the problem of the maximum oxygen abundance in spiral galaxies by attempting to derive more accurate oxygen abundances. These can be derived via the classical $T_e$ – method. We will estimate $(O/H)_C$ in the spiral galaxies reported to be the oxygen-richest ones, NGC 3184, NGC 3351, NGC 5194, and NGC 6744. For comparison, we will also include NGC 2903, NGC 2997, NGC 5236 as well as the Milky Way Galaxy.

We describe the method used to determine oxygen abundances in H\textsc{ii} regions in Section 2. The oxygen abundances in the spiral galaxies NGC 3184, NGC 3351, NGC 5194, NGC 6744, NGC 2903, NGC 2997, NGC 5236 and the Milky Way Galaxy are determined in Section 3. We discuss the reliability of the derived abundances and summarize our conclusions in Section 4.

For the line fluxes, we will be using the following notations throughout the paper: $R_2 = I_{\{OIII\}4959 \rightarrow \lambda5007}/I_{H\beta}$, $R_3 = I_{\{OIII\}4363}/I_{H\beta}$. With these definitions, the excitation parameter $P$ can then be expressed as: $P = R_3/(R_2+R_3)$.
2 ABUNDANCE DERIVATION

2.1 Adopted equations for the $T_e$ method

A two-zone model for the temperature structure within the H\textsc{ii} region was adopted. Izotov et al. (2005) have recently published a set of equations for the determination of the oxygen abundance in H\textsc{ii} regions for a five-level atom. According to those authors, the electron temperature $t_3$ within the [O\textsc{iii}] zone, in units of $10^4\text{K}$, is given by the following equation

$$t_3 = \frac{1.432}{\log(R_3/H) - \log C_T}$$

where

$$C_T = (8.44 - 1.09 t_3 + 0.5 t_3^2 - 0.08 t_3^3) v$$

and

$$v = 1 + 0.0004 x_3 \frac{1 + 0.044 x_3}{1 + x_3}$$

As for the ionic oxygen abundances, they are derived from the following equations

$$12 + \log(O^{++}/H^+) = \log(I_{\lambda 4959 + \lambda 5007}/I_{\text{H}2}) + 6.200 + \frac{1.251}{t_3} - 0.55 \log t_3 - 0.014 t_3,$$  

$$12 + \log(O^{+}/H^+) = \log(I_{\lambda 3727 + \lambda 3729}/I_{\text{H}2}) + 5.961 + \frac{1.676}{t_2} - 0.40 \log t_2 - 0.034 t_2 + \log(1 + 1.35 x_2).$$

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\textsc{ii}] zone is usually determined from an equation which relates $t_2$ to $t_3$, derived by fitting H\textsc{ii} region models. Several versions of this $t_2 - t_3$ relation have been proposed. A widely used relation has been suggested by Campbell et al. (1986) (see also Garnett (1992)) based on the H\textsc{ii} region models of Stasińska and Straniero (1982). Izotov et al. (2005) has found that the $t_2 - t_3$ relationship can be parameterized as

$$t_2 = 0.7 t_3 + 0.3.$$  

It will be used here.

2.2 The ff – relation

The fluxes $R$ in the auroral lines are necessary to derive the oxygen abundances in H\textsc{ii} regions using the $T_e$ method. But they are faint and often undetectable in spectra of high-metallicity H\textsc{ii} regions. It was shown by Pilyugin (2005) that the flux $R$ in the auroral line is related to the total flux $R_{23}$ in the strong nebular lines through a relation of the type

$$\log R = a + b \times \log R_{23}.$$  

Eq. (10) will be hereinafter referred to as the flux – flux or ff – relation. It was found that this relationship is metallicity-dependent at low metallicities, but becomes independent of metallicity (within the uncertainties of the available data) at metallicities higher than $12 + \log O/H > 8.25$, i.e. there is one-to-one correspondence between the auroral and nebular oxygen line fluxes in spectra of high-metallicity H\textsc{ii} regions. Pilyugin (2005) derived

$$\log R = -4.264 + 3.087 \log R_{23}.$$  

We can now make use of the ff – relation to define a “discrepancy index”, equal to the difference between the logarithm of the observed flux $R_{\text{obs}}$ in the [O\textsc{iii}]$\lambda 4363$ line and that of the flux $R_{\text{cal}}$ of that line derived from the strong [O\textsc{ii}]$\lambda 3727$, [O\textsc{iii}]$\lambda 4959, 5007$ lines using the ff - relation:

$$D_R = \log R_{\text{obs}} - \log R_{\text{cal}}.$$  

Since $R_{23} = R_3/P$, the ff – relation can also be expressed in the form $R = f(R_3/P)$. We will consider an expression of the type

$$\log R = a_1 + a_2 \log P + a_3 \log R_3 + a_4 (\log P)^2.$$  

Using a sample of H\textsc{ii} regions with recent high-precision measurements of oxygen lines fluxes, the values of the coefficients in Eq. (13) can be derived. Such a sample has been compiled by Pilyugin (2005). Bresolin et al. (2004) have recently detected the auroral lines [S\textsc{ii}]$\lambda 6716, 6731$ and/or [N\textsc{ii}]$\lambda 5755$ and determined $T_e$-based abundances in 10 faint H\textsc{ii} regions in the spiral galaxy M 51. Unfortunately they were unable to detect the oxygen auroral line. Using the electron temperature $t_3$ recommended by Bresolin et al. (2004) and the equations given above for the $T_e$-method, we have estimated the value of $R$ which corresponds to the $t_3$ for every H\textsc{ii} region. It has been found by Pilyugin (2005) that the oxygen line fluxes in six faint H\textsc{ii} regions in the spiral galaxy M 51 (CCM 54, CCM 55, CCM 57, CCM 57A, CCM 71A, and CCM 84A) satisfy the ff – relation. These data are included in the present sample to enlarge the ranges in $P$ and $R_3$. Thus, our sample consists of a total of 48 data points.

The values of the coefficients in Eq. (13) are derived by using an iteration procedure. In the first step, the relation is determined from all data using the least-square method. Then, the point with the largest deviation is rejected, and a new relation is derived. The iteration procedure is pursued until two successive relations have all their coefficients differing by less 0.001 and the absolute value of the largest deviation is less than 0.1 dex. The following ff – relation was obtained

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

2.3 Characteristics of the ff – relation

The top panel in Fig. 1 shows the flux $R$ in the oxygen auroral line as a function of the flux $R_3$ in strong nebular [O\textsc{iii}]$\lambda 4959 + \lambda 5007$ lines. The open and filled circles show individual H\textsc{ii} regions with $12 + \log O/H > 8.25$. The relations corresponding to Eq. (14) for different values of the excitation parameter are shown by the solid ($P = 1.0$), long-dashed ($P = 0.7$), short-dashed ($P = 0.3$), and dotted ($P = 0.1$) line.
Figure 1. The ff – relations for H\textsc{ii} regions. Top panel. Flux R in the oxygen auroral line as a function of the flux R\textsubscript{3} in the strong nebular [O\textsc{iii}]\(\lambda 4959 + \lambda 5007\) lines for H\textsc{ii} regions. The circles (open and filled) show H\textsc{ii} regions with 12+logO/H > 8.25. The relations corresponding to Eq.(14) for different values of the excitation parameter are shown by the solid (P = 1.0), long-dashed (P = 0.7), short-dashed (P = 0.3), and dotted (P = 0.1) lines. Only filled circles are used in deriving Eq.(13). Bottom panel. Flux R in the oxygen auroral line as a function of the total flux R\textsubscript{23} in the strong nebular [O\textsc{iii}]\(\lambda 3727 + \lambda 3729\) and [O\textsc{iii}]\(\lambda 4959 + \lambda 5007\) lines. The open and filled circles have the same meaning as in the top panel. The relations corresponding to Eq.(14) for different values of the excitation parameter are shown by the solid (P = 1.0), long-dashed (P = 0.3), short-dashed (P = 0.2), and dotted (P = 0.1) lines. The relation corresponding to Eq.(11) is shown by plus signs.

Figure 2. Deviations from the ff – relation as parameterized by the discrepancy index D\textsubscript{ff} as a function of oxygen abundance (top panel) and of excitation parameter P (bottom panel). The filled circles are H\textsc{ii} regions used in deriving the ff – relation. The open circles are other H\textsc{ii} regions.

0.1) lines. The filled circles show the data used in deriving Eq.(14) (40 out of 48 original data points).

The deviations from the ff – relation given by Eq.(11) as parameterized by the discrepancy index D\textsubscript{ff} are shown in Fig. 2 as a function of oxygen abundance (top panel) and of excitation parameter P (bottom panel). The filled circles are H\textsc{ii} regions used in deriving Eq.(14). The open circles are the other H\textsc{ii} regions. Fig. 3 shows that the deviations do not show a correlation either with metallicity or with the excitation parameter.

Let us compare the two ff - relations given by Eq.(11) and Eq.(14). The bottom panel in Fig. 1 shows that the available measurements for calibrating H\textsc{ii} regions which have a discrep-
ancy index D\textsubscript{ff} smaller absolute values of D\textsubscript{ff} may result in a more precise
fit to the observational data. At the same time, there is an appreciable divergence between those two relations at low values of the excitation parameter, P < 0.3. For definiteness’s sake, we will use the ff – relation given by Eq.(14) for all values of P.

It should be noted however that the particular form of the analytical expression adopted for the ff – relation may be questioned. We have chosen a simple form, Eq.(13), but perhaps a more complex expression may give a better fit to the auroral – nebular oxygen line fluxes relationship. Furthermore, the coefficients in the adopted expression are derived using calibrating H\textsc{ii} regions which have a discrepancy index D\textsubscript{ff} as large as 0.1 dex in absolute value. Perhaps smaller absolute values of D\textsubscript{ff} may result in a more precise relation. It can be seen that the calibration curves give a satisfactory fit to the observational data. At the same time, Fig. 1 shows that the available measurements for calibrating faint H\textsc{ii} regions (those with low R\textsubscript{3}) are very few in
number. Furthermore, the $R$ values for the faint $\text{H} \text{\textsc{ii}}$ regions from [Bresolin et al. (2004)] are not measured but estimated from the electron temperatures $T_e$ and, consequently, they are not beyond question. Clearly, high-precision measurements of oxygen lines fluxes in faint $\text{H} \text{\textsc{ii}}$ regions are needed to check the derived $ff$ – relation.

### 2.4 The $(O/H)_f$ abundances

Using the $T_e$ method, both $(O/H)_{T_e}$ abundances based on the measured line fluxes $R^{\text{obs}}$, and $(O/H)_f$ abundances based on the line fluxes $R^{\text{ff}}$ determined from the $ff$ – relation, can be derived for our sample of $\text{H} \text{\textsc{ii}}$ regions. Comparison of their values gives us a check on the $(O/H)_f$ abundances. Fig. 3 shows the difference $\Delta \log(O/H) = \log(O/H)_{T_e} - \log(O/H)_f$ as a function of $\log(O/H)_{T_e}$ (top panel), of excitation parameter $P$ (middle panel), and of discrepancy index $D_{ff}$ (bottom panel). Inspection of Fig. 3 shows that the differences $\Delta \log(O/H)$ do not show an appreciable correlation with metallicity or with excitation parameter. There is however an anticorrelation of $D_{ff}$ with $D_{ff}$. This can be easily understood. The discrepancy index appears to be an indicator of the error in the auroral line $R$ measurements. In that case, positive values of $D_{ff}$ imply overestimated $R$ fluxes, which result in turn in overestimated electron temperatures and underestimated oxygen abundances, i.e. negative $\Delta \log(O/H)$, just the observed trend. In general, the $(O/H)_f$ abundances agree satisfactorily with the $(O/H)_{T_e}$ abundances and do not show any systematic trend.

In summary, the flux in the faint auroral line [O ii]$\lambda$4363 can be estimated reasonably well from the measured fluxes in the strong nebular lines [O ii]$\lambda$3727 + $\lambda$3729 and [O iii]$\lambda$4959 + $\lambda$5007 via the $ff$ – relation. Then, using the derived flux in the auroral line, the oxygen abundance can be found through the classic $T_e$ – method.

### 3 OXYGEN ABUNDANCES IN SPIRAL GALAXIES

Here the derived $ff$ – relation will be applied to derive the oxygen abundances in a number of spiral galaxies. First, M 51 (NGC 5194), the oxygen-richest spiral galaxy ((O/H)$_C = 9.54$) in the sample of [Vila-Costas & Edmunds (1992)] will be considered. The value of $(O/H)_C$ in M 51 was derived recently from determinations of $(O/H)_{T_e}$ abundances in a number of $\text{H} \text{\textsc{ii}}$ regions by [Bresolin et al. (2004)]. Comparison between the radial distributions of $(O/H)_{T_e}$ and $(O/H)_f$ abundances in the disk of M 51 shows another possibility to test the reliability of the latter. Second, $(O/H)_f$ abundances in NGC 3184, NGC 3351, and NGC 6744 which have been reported to be the most oxygen-rich spirals, will be determined. Third, we will consider three well-observed spiral galaxies NGC 2903, NGC 2997, and NGC 5236 for comparison. Fourth, the $ff$ – relation will be applied to Galactic $\text{H} \text{\textsc{ii}}$ regions to select high-precision measurements.

#### 3.1 Oxygen abundances in M 51

The compilation of published spectra of $\text{H} \text{\textsc{ii}}$ regions in M 51 is taken from [Pilyugin et al. (2004)]. The $\text{H} \text{\textsc{ii}}$ regions with measured $R_3$ and $R_2$ fluxes from [Bresolin et al. (2004)] (their Tables 1 and 6) have been added. We determine $(O/H)_f$ abundances for every $\text{H} \text{\textsc{ii}}$ region using the derived $ff$ – relation. The $(O/H)_f$ abundances in the $\text{H} \text{\textsc{ii}}$ regions of M 51 are shown as a function of galactocentric distance in Fig. 4.

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**Figure 3.** The difference $\Delta \log(O/H) = \log(O/H)_{T_e} - \log(O/H)_f$ as a function of $\log(O/H)_{T_e}$ (top panel), of excitation parameter $P$ (middle panel), and of discrepancy index $D_{ff}$ (bottom panel).

**Figure 4.** Radial distribution of oxygen abundances in the disk of the spiral galaxy M 51 (NGC 5194). The open circles denote $(O/H)_f$ abundances. The solid line is the linear least-square best fit to those data. The filled circles show $(O/H)_{T_e}$ abundances from [Bresolin et al. (2004)]. The dashed line is their linear regression fit.
by open circles. The solid line is the linear least-square best fit to those data:

\[
12 + \log(O/H) = 8.74 (\pm 0.03) - 0.025 (\pm 0.004) \times R. \tag{15}
\]

The distance of M 51 (\(d = 7.64\) Mpc) and the isophotal radius (\(R_{25} = 5.61\) arcmin) were taken from Pilyugin et al. (2004). The filled circles are \((O/H)_{\text{II}}\) abundances determined by Bresolin et al. (2004). The dashed line is their linear regression:

\[
12 + \log(O/H) = 8.72 (\pm 0.09) - 0.02 (\pm 0.01) \times R. \tag{16}
\]

Fig. 4 shows that the radial distribution of \((O/H)_{\text{II}}\) abundances agrees well with that of \((O/H)_{\text{II}}\) abundances (compare also Eqs.(15,17,18,19)). This is a strong argument in favor of the reliability of the \((O/H)_{\text{II}}\) abundances.

Some H\textsc{ii} regions show large deviations from the general radial trend in oxygen abundances. Some of these deviations can be real, but some are probably caused by uncertainties in the oxygen abundance determinations. It should be emphasized that the uncertainties in the \((O/H)_{\text{II}}\) abundances are not necessarily caused by uncertainties in the line flux measurements. It has been noted (Pilyugin 2005) that the ff – relation gives reliable results only if two conditions are satisfied; i) the measured fluxes reflect their relative contributions to the radiation of the whole nebula, and ii) the H\textsc{ii} region is ionization-bounded. If these two conditions are not met, then the derived \((O/H)_{\text{II}}\) abundances may be significantly in error.

### 3.2 Oxygen abundances in the most oxygen-rich spiral galaxies

The compilation of published spectra of H\textsc{ii} regions in the spiral galaxies NGC 3184, NGC 3351, and NGC 6744 was taken from Pilyugin et al. (2004). The \((O/H)_{\text{II}}\) abundances in the H\textsc{ii} regions of NGC 3184 is shown as a function of galactocentric distance in the top panel of Fig. 5. The solid line is the linear least-square best fit to those data:

\[
12 + \log(O/H) = 8.73 (\pm 0.03) - 0.035 (\pm 0.004) \times R. \tag{17}
\]

The same data are shown for the H\textsc{ii} regions of NGC 3351 in the middle panel of Fig. 5. The solid line is the linear least-square best fit to those data:

\[
12 + \log(O/H) = 8.74 (\pm 0.02) - 0.023 (\pm 0.004) \times R. \tag{18}
\]

Similarly, the data for the H\textsc{ii} regions of NGC 6744 are shown in the bottom panel of Fig. 5. The linear least-square best fit to those data is given by:

\[
12 + \log(O/H) = 8.75 (\pm 0.04) - 0.022 (\pm 0.003) \times R. \tag{19}
\]

The distances of the galaxies and the galactocentric distances of the H\textsc{ii} regions were taken from Pilyugin et al. (2004).

Figs. 4 and 5 (see also Eqs. (15,17,18,19)) show that the values of \((O/H)_{\text{C}}\) in these spiral galaxies are \(\sim 8.75\).

### 3.3 Oxygen abundances in other spiral galaxies

We will consider here three well-observed spiral galaxies for comparison. The compilation of the published spectra of H\textsc{ii} regions in the spiral galaxies NGC 2903, NGC 2997, and NGC 5236 was taken from Pilyugin et al. (2004). Recent measurements from Bresolin et al. (2005) have been added. Oxygen abundances were calculated for every H\textsc{ii} region using the derived ff – relation.

The \((O/H)_{\text{II}}\) abundances in the H\textsc{ii} regions of NGC 2903 are shown as a function of galactocentric distance in the top panel of Fig. 5. The solid line is the linear least-square best fit to those data:

\[
12 + \log(O/H) = 8.68 (\pm 0.02) - 0.026 (\pm 0.003) \times R. \tag{20}
\]

The middle panel of Fig. 5 shows the same for NGC 2997. The linear least-square fit to those data is:

\[
12 + \log(O/H) = 8.59 (\pm 0.05) - 0.021 (\pm 0.007) \times R. \tag{21}
\]

The data for NGC 5236 are shown in the bottom panel of Fig. 5. The linear least-square fit to those data is:

\[
12 + \log(O/H) = 8.62 (\pm 0.01) - 0.022 (\pm 0.005) \times R. \tag{22}
\]

The distances of the galaxies were taken from Pilyugin et al. (2004).

Fig. 5 (see also Eqs. (20,21,22)) shows that the \((O/H)_{\text{C}}\)
abundances in NGC 2903, NGC 2997, and NGC 5236 are smaller than 8.70, i.e. lower than in NGC 3184, NGC 3351, NGC 5194, and NGC 6744.

Thus, the maximum gas-phase oxygen abundance in the oxygen-richest spiral galaxies is $12 + \log(O/H) \sim 8.75$. This value is significantly lower (by a factor of 5 or more) than the previous value based on the one-dimensional empirical calibrations (e.g. Vila-Costas & Edmunds 1992; Zaritsky et al. 1994; van Zee et al. 1998; Garnett 2002).

### 3.4 Oxygen abundances in the Milky Way Galaxy

We now consider the Milky Way Galaxy. A compilation of published spectra of Galactic H\textsc{ii} regions with an auroral [O\textsc{ii}]$\lambda$3727 line has been carried out by Pilyugin et al. (2003). That list contains 69 individual measurements of 13 H\textsc{ii} regions in the range of galactocentric distances from 6.6 to 14.8 kpc. Recent measurements of six Galactic H\textsc{ii} regions by Esteban et al. (2003) were added to that list, resulting in a total of 75 measurements. The T\textsubscript{e}\textsuperscript{-} based oxygen abundances were estimated using the equations above.

The derived $(O/H)_{T_e}$ abundances are shown as a function of galactocentric distance by the open circles in the top panel of Fig. 7. The linear least-square best fit to those data (with two points with a deviation more than 0.2 dex rejected)

$$12 + \log(O/H) = 8.79 (\pm 0.05) - 0.034 (\pm 0.005) \times R \quad (23)$$

is shown by the solid line in the top panel of Fig. 7.

There is a relative large number of measurements of abundances in the Milky Way Galaxy. They show a large scatter since the quality of the data obtained over a period of more than thirty years is necessarily heterogeneous. Some measurements have a low accuracy. The ff – relation provides a way to select out the H\textsc{ii} regions with high quality measurements (Pilyugin & Thuan 2005). The bottom panel of Fig. 7 shows the $(O/H)_{T_e}$ abundances as a function of galactocentric distance for objects with an absolute value of the discrepancy index $D_{ff}$ less than 0.05 dex. The linear least-square best fit to those data

$$12 + \log(O/H) = 8.70 (\pm 0.04) - 0.022 (\pm 0.004) \times R \quad (24)$$

is shown by the solid line in the bottom panel of Fig. 7. The open square is the oxygen abundance of the interstellar gas at the solar galactocentric distance (see below).

The central oxygen abundance in the Milky Way obtained here, $(O/H)_{C} \sim 8.70$, is significantly lower than the widely used $(O/H)_{C} = 9.38$ of Shaver et al. (1983). Our oxygen abundance radial gradient is in agreement with that of Daflon & Cunha (2004). They derived the relation

$$12 + \log(O/H) = 8.762 (\pm 0.105) - 0.031 (\pm 0.012) \times R \quad (25)$$
from abundance determinations in young OB stars.

We note that the central oxygen abundance obtained here for the Milky Way is close to that in other large spirals.

4 DISCUSSION AND CONCLUSIONS

The (O/H)$_T$ abundances determined here rely on the validity of the classical $T_e$ - method. This has been questioned for the high-metallicity regime in a number of investigations by comparison with H II region photoionization models. One should keep in mind however that the existing numerical models of H II regions are far from being perfect (Stasińska 2004), and, hence, the statement that H II region models provide more realistic abundances as compared to the $T_e$ - method should not be taken for granted (Pilyugin 2003).

Recently Stasińska (2005) has examined the biases involved in $T_e$-based abundance determinations at high metallicities. She has found that, as long as the metallicity is low, the derived (O/H)$_{T_e}$ value is very close to the real one. Discrepancies appear around 12+log(O/H) = 8.6 - 8.7, and may become very large as the metallicity increases (Fig. 1a in Stasińska 2004). The derived (O/H)$_{T_e}$ values are smaller than the real ones, sometimes by enormous factors. This means that, if such metal-rich H II regions exist, the classic $T_e$ - method will always lead to systematically lower derived oxygen abundances.

Can the effect discussed by Stasińska be responsible for the low (O/H)$_{T_e}$ abundances obtained here? Let us assume that it is the case, and that the true central oxygen abundances in the spiral galaxies are higher than 12 + log(O/H) = 9.0. What radial distributions of (O/H)$_{T_e}$ abundances in the disk of spiral galaxies would one expect in this case? Starting from the periphery of a galaxy, the (O/H)$_{T_e}$ abundances would increase with decreasing galactocentric distance (following the true abundances) until the (O/H)$_{T_e}$ abundance reaches the value of 12+log(O/H) ~ 8.7. After that the (O/H)$_{T_e}$ abundances would decrease with decreasing galactocentric distance because of the Stasińska (Fig. 1a in Stasińska 2002) effect, although the true abundances continue to increase with decreasing galactocentric distance. Thus, the radial distribution of (O/H)$_{T_e}$ abundances should show a bow-shaped curve with a maximum value of 12+log(O/H) ~ 8.7 at some galactocentric distance.

Do the actual data (Fig. 5-7) show such a behavior? The derived radial distributions of (O/H)$_{T_e}$ abundances in the disks of spiral galaxies do not show an appreciable curvature, and the (O/H)$_{T_e}$ abundances increase more or less monotonically with decreasing galactocentric distance. Only the H II regions in the very central parts of the spiral galaxies NGC 3351 (the middle panel of Fig. 5) and NGC 2997 (the middle panel of Fig. 6) may show (O/H)$_{T_e}$ abundances which are slightly lower than expected from the general radial abundance trends, but the effect is very slight and may not be real if errors of 0.1 dex (Fig. 3) in the calibration and in the line intensity measurements are taken into account.

To settle the question of whether the abundances in the metal-richest H II regions are affected by the Stasińska’s effect, many more accurate measurements of H II regions (including those in the very central parts) in the most oxygen-rich spiral galaxies are necessary.

Thus, while our results do not rule out the possible existence of the Stasińska’s effect, they suggest that the great majority of H II regions in galaxies are in a metallicity range where this effect is not important. Indeed, the Stasińska’s effect becomes important only at oxygen abundances higher than 12 + log(O/H) ~ 8.7. We have found that this “critical” value is reached only in the central part of the most oxygen-rich galaxies. We conclude that, in the light of our present results, H II regions with 12+log(O/H) > 8.7 are rare, if they exist at all. It should be noted that Stasińska also questioned the existence of such metal-rich H II regions (Section 2.2 in Stasińska 2003).

Another factor that can affect $T_e$-based abundance determinations is the temperature fluctuations inside H II regions (Reimbert 1967). If they are important, the (O/H)$_{T_e}$ abundance would be a lower limit. In most cases the effect appears to be small, probably under 0.1 dex (Pace 2003). Fortunately, there is a way to verify the validity of the $T_e$ – method at high metallicities (Pilyugin 2003). High-resolution observations of the weak interstellar O Iλ1356 absorption lines towards stars allow one to determine the interstellar oxygen abundance in the solar vicinity with a very high precision. It should be noted that this method is model-independent. These observations yield a mean interstellar oxygen abundance of 284 – 390 O atoms per 10$^6$ H atoms (or 12+log(O/H) = 8.45 – 8.59) (Meyer et al. 1998; Sofia & Meyer 2001; Cartledge et al. 2004). Oliveira et al. (2003) have determined a mean O/H ratio of 345 ±19 O atoms per 10$^6$ H atoms (or 12+log(O/H) = 8.50) for the local bubble. Thus, an oxygen abundance 12+log(O/H) = 8.50 in the interstellar gas at the solar galactocentric distance seems to be a reasonable value. The value of the oxygen abundance at the solar galactocentric distance traced by (O/H)$_{T_e}$ abundances in H II regions is then in good agreement with the oxygen abundance derived with high precision from the interstellar absorption lines towards stars (open square in the bottom panel of Fig. 7). This is strong evidence that the classic $T_e$ - method provides accurate oxygen abundances in high-metallicity H II regions.

The measured oxygen abundance in the solar vicinity provides an indirect way to check our derived central oxygen abundances. The oxygen abundance in the solar vicinity is 12+log(O/H) = 8.50, and a gas mass fraction $\mu \sim 0.20$ seems appropriate. The simple model of chemical evolution of galaxies predicts that a decrease of $\mu$ by 0.1 results in a increase of the oxygen abundance by $\sim 0.12$ dex in the range of $\mu$ from $\sim 0.75$ to $\sim 0.05$. When all the gas in the solar vicinity will be converted into stars, the oxygen abundance will increase by $0.2 - 0.25$ dex and will reach a value around 12+log(O/H) = 8.70 – 8.75. This value is in excellent agreement with the central oxygen abundances obtained above for the Milky Way and other galaxies. There is no room for central oxygen abundances as large as 12+logO/H = 9.00 or greater.

The present study suggests that there is an upper limit to the oxygen abundances in spiral galaxies. If true, the existing luminosity – metallicity relation should be revisited. One can expect the metallicity to increase with luminosity up to 12+(O/H) ~ 8.75, but to remain approximately constant for higher metallicities, resulting in a flattening of the luminosity – metallicity relation. This suggestion will be investigated in a future paper.

The maximum gas-phase oxygen abundance in spiral
galaxies is $12 + \log(O/H) \sim 8.75$. The central oxygen abundance in the Milky Way is similar to that in other large spirals. Some fraction of the oxygen is locked into dust grains in H II regions. Esteban et al. (1998) found that the fraction of the dust-phase oxygen abundance in the Orion nebula is about 0.08 dex. Then, the true gas+dust maximum value of the oxygen abundance in H II regions of spiral galaxies is $12 + \log(O/H) \sim 8.85$. This value can increase up to $\sim 8.90 \sim 8.95$ if temperature fluctuations inside H II regions are important.

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