On the radial abundance gradients in disks of irregular galaxies

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1 INTRODUCTION

The radial distribution of gas-phase oxygen abundances traced by the Hα regions has been investigated in the disks of many spiral galaxies (Vila-Costas & Edmunds 1992; Zaritsky et al. 1994; van Zee et al. 1998; Pilyugin et al. 2004; Moustakas et al. 2010; Gusev et al. 2012; Pilyugin et al. 2014a; Sánchez et al. 2014). It was found that almost all spiral galaxies show radial abundance gradients in the sense that their inner Hα regions (i.e., those closer to the galactic centers) have higher oxygen abundances than the outer ones.

The radial distribution of abundances across the disks of irregular galaxies is less well studied. Pagel et al. (1978) analyzed spectra of a number of Hα regions in the Small and Large Magellanic Clouds. They determined the abundances in Hα regions through the effective temperature ($T_e$) method using their own measurements together with the spectral measurements by other authors and examined the spatial distributions of abundances in those galaxies. Pagel et al. (1978) concluded that any radial abundance gradient in present-day abundances is small or absent in the Large Magellanic Cloud and is conspicuously absent in the Small Magellanic Cloud. In the Small Magellanic Cloud, also stellar metallicity determinations support the absence of a radial gradient, although there is a large metallicity spread of $\sim 0.6$ dex in [Fe/H] for a given age (Glatt et al. 2008; Cignoni et al. 2013).

Roy et al. (1996) studied the oxygen abundance distributions in the disks of the dwarf irregular galaxy NGC 2366 and the dwarf Seyfert I galaxy NGC 4395 using imaging spectrophotometry with narrow-band filters in the lines of Hα, Hβ, [O III]λ5007 and [N II]λ6584. They used the line ratio [O III]/[N II] as an abundance indicator (O3N2 calibration). They found that there is no global oxygen abundance gradient across the disks of those galaxies.

Hunter (1999) obtained emission-line long-slit spectra of 189 Hα regions in a sample of 65 Im, Sm, and blue compact dwarf galaxies. They estimated the oxygen abundances in Hα regions using the line ratio $O/\alpha$ (O3N2 calibration) and the combination of $R_3 = [OIII]+[OII]$ and $[OIII]/[OII]$ (two-dimensional $R_3$ calibration) when the oxygen line $[OIII]λ3727$ was measured. Hunter (1999) examined the radial abundance distribution in disks of eight Sm and Im galaxies for which they measured at least three Hα regions. They found that the oxygen abundances within a given galaxy generally vary by about 0.2 dex, but they did not detect a trend in oxygen abundances with radius except for the Sm galaxy DDO 204.

Kniazev et al. (2005) measured oxygen abundances with the direct method in three Hα regions in each of the dwarf irregulars Sextans A and Sextans B. While they found Sext A to be chemically homogeneous, one of the three Hα regions in Sex B turned out to be about twice as metal-rich than the other two, and the abundances of other heavy elements suggest an enrichment by a factor of $\sim 2.5$ as compared to the other two Hα regions. Kniazev et al. (2005) attribute this to inhomogeneous chemical enrichment.

van Zee & Haynes (2006) carried out long-slit spectroscopy of 67 Hα regions in 21 dwarf irregular galaxies. Oxygen abundances for 25 Hα regions were derived through the direct $T_e$ method; the abundances in other Hα regions were estimated using strong line calibrations. van Zee & Haynes (2006) considered the oxygen abundances as a function of radius for 12 irregular galaxies with three or more observations and found that the abundances are very similar (within the formal errors) within each galaxy with the
possible exception of the galaxy UGC 12894. [van Zee & Haynes (2000)] noted that the radial trend in oxygen abundances (three points) in the UGC 12894 may be artificial because the abundances of the inner and outer H\n regions were obtained via different methods (through the strong line calibration for two inner H\n regions and through the $T_e$ method for outer H\n region).

Similarly, [Lee et al. (2007)] obtained oxygen abundances for 35 H\n regions in eight dwarf galaxies in the Centaurus A group and in 13 H\n regions in closer dwarfs. Some of their measurements use the direct $T_e$ method, while the majority of the abundance determinations is based on strong-line calibrations. Although the results for individual H\n regions in a given galaxy tend to vary, Lee et al. point out that the variations are within the uncertainties of the strong-line method. In one of the dwarf irregulars of the Cen A group, AM 1318 – 444, one of the H\n regions is considerably more oxygen-rich than the others. Lee et al. argue that the measured line intensity ratios suggest that this emission nebula is a supernova remnant. They also note that radial gradients may exist in some of their targets such as in the Sm NGC 3109 or NGC 5264, but that more and deeper data are needed to establish this.

It is the current belief that irregular galaxies generally do not show radial abundance gradients in their young populations and are chemically homogeneous. This implies that there is a “spiral versus irregular dichotomy” in the sense that there is a sudden change from spiral (radial abundance gradients are usually present) to irregular galaxies (typically no gradients). However, other properties (e.g., gas fraction, global metallicity) vary smoothly in transition from spirals to irregulars [Zaritsky et al. 1994; Pilyugin & Ferrini 2004; Garnett 2002; Pilyugin et al. 2004, among others].

The measurements of the abundance gradients in the disks of irregular galaxies often encounter the following difficulty. Reliable oxygen abundances in a number of H\n regions in the disk of a galaxy should be determined in order to evaluate the existence of an abundance gradient. Abundance determinations using the direct $T_e$ method require high-precision spectroscopy including the weak auroral lines [O\n\n]\lambda 4363\,\AA\ and [N\n\n]\lambda 5755. Unfortunately, these weak auroral lines are usually only detected in the spectra of a few (if any) of the brightest H\n regions in a given irregular galaxy. The oxygen abundances in the other H\n regions are then estimated using the strong-line method pioneered by [Pagel et al. 1979] and [Alloin et al. 1979]. The principal idea of the strong-line method is to establish the relation between the (oxygen) abundance in an H\n region and some combination of the intensities of strong emission lines in its spectrum (such a relation is usually called a “calibration”). Different calibrations were suggested. A prominent characteristic of the calibrations is that they are not applicable across the whole range of metallicities of H\n regions but only within a limited interval (usually only at high or at low metallicities). The oxygen abundances of irregular galaxies typically lie within or near the transition zone in the $R_{23} – O/H$ diagram (from $R_{23} + \log(O/H) \sim 7.9$ to $\sim 8.3$) where calibrations cannot be used or where they provide abundances with large uncertainties.

We recently suggested a new method (the “C method”) for abundance determinations in H\n regions, which can be used over the whole range of metallicities of H\n regions and which provides oxygen and nitrogen abundances on the same metallicity scale as the classic $T_e$ method [Pilyugin et al. 2012, 2013]. Using this method, we examined the abundance gradients in the disks of 130 late-type galaxies including several irregular galaxies [Pilyugin et al. 2014a]. In that study, radial abundance gradients were found in irregular galaxies. Here we will focus on the investigation of the abundance gradients in a sample of irregular galaxies (Sm and Im, morphological $T$ types 9 and 10). Since there is a relation between oxygen abundance and disk surface brightness in spiral galaxies (e.g., [Pilyugin et al. 2014b]), we will also examine the relation between radial abundance distributions and surface brightness profiles of the disks of irregular galaxies.

The paper is structured as follows. The spectral and photometric data are reported in Section 2. The radial abundance gradients are determined in Section 3. The discussion and conclusions are given in Section 4, followed by a summary (Section 5).

2 THE DATA

2.1 Our sample

We have selected a sample of irregular Sm and Im galaxies with morphological $T$ types of 9 and 10 according to the RC3 catalogue [de Vaucouleurs et al. 1991]. It should be noted that the morphological classification of some galaxies is not robust. The morphological $T$ types in different sources can differ by up to 1. We only consider irregular galaxies with available spectra for four and more H\n regions. The validity of the radial abundance is defined not only by the quantity and quality of the spectra but also by the distribution of the measured H\n regions along the galactic radius. We reject galaxies where the measured H\n regions cover less than $\sim 1/3$ of the optical radius of a galaxy. For example, for this reason we rejected the galaxy UGC 5666 (a.k.a. IC 2574 or DDO 81). More than ten spectra are available for this galaxy [Miller & Hodge 1996; Croxall et al. 2009], but the measured H\n regions cover only a small fraction of the optical radius of the galaxy, which prevents a reliable investigation of a radial abundance gradient.

Our final list includes fourteen irregular galaxies with optical radii of $R_{25} \geq 2$ kpc. Table 1 lists the general characteristics of each galaxy. The column 1 contains the order number. The columns 2 – 4 give the galaxy’s name. We list the number of a galaxy according to the New General Catalogue (NGC, column 2), the Uppsala General Catalog of Galaxies (UGC, column 3), and one other widely used name (column 4). The morphological type of the galaxy (morphological type code $T$) from the RC3 is reported in column 5. The right ascension (R.A.) and declination (Dec.) (J2000.0) of each galaxy are given in columns 6 and 7. The right ascension and declination are obtained from our photometry (see Section 2.3) or taken from the NASA/IPAC Extragalactic Database (nED). The position angle (P.A.), axis ratio ($b/a$), and inclination are listed in columns 8 – 10. The isophotal radius $R_{25}$ in arcmin and in kpc of each galaxy is reported in columns 11 and 12, respectively. The adopted distance $d$ taken from [Karachentsev et al. 2013] or from the nED is reported in column 13. The nED distances use flow corrections for Virgo, the Great Attractor, and Shapley Supercluster infall. The references to sources for geometrical parameters (first reference) and for distances (second reference) are given in column 14.

2.2 Emission line intensities in the H$n$ region spectra

We use the emission line intensities in published spectra of H$n$ regions from different works for abundance determinations. We have searched for spectra of H$n$ regions with measured H$\alpha$, H$\beta$, etc., 000–000
Table 1. The adopted properties of our galaxies.

| n | NGC | Name                      | T type | R.A.      | Dec.      | P.A. | b/a | Inclination degree | R_{25} arcmin | R_{25} kpc | d Mpc | Reference               |
|---|-----|---------------------------|--------|-----------|-----------|------|-----|-------------------|---------------|------------|-------|------------------------|
| 1 | 2023| DDO 25                    | 10     | 02:33:18.20 | 33:29:28.0 | 1.00 | 0   | 0.83             | 2.24          | 9.30       | RC3; K13              |
| 6 | 3738| DDO 50                    | 10     | 08:19:04.98 | 70:43:12.1 | 15   | 0.79| 3.97             | 3.92          | 3.39       | RC3; K13              |
| 7 | 6980|                           | 10     | 11:35:48.81 | 54:31:25.8 | 167  | 0.66| 1.43             | 2.04          | 4.90       | Here; K13             |
| 8 | 4214|                           | 10     | 12:15:39.19 | 36:19:36.6 | 126  | 0.89| 3.18             | 2.72          | 2.94       | Here; K13             |
| 9 | 4395|                           | 9      | 12:25:48.88 | 33:32:48.7 | 135  | 0.64| 3.07             | 1.98          | 1.39       | Here; K13             |
| 10| 7557|                           | 9      | 12:27:11.24 | 07:15:47.1 | 148  | 0.80| 1.14             | 4.54          | 13.70      | Here; NED             |
| 11| 4449|                           | 10     | 12:28:11.01 | 44:05:38.1 | 48   | 0.56| 3.07             | 1.36          | 4.21       | Here; K13             |
| 12| 7592|                           | 10     | 12:58:52.80 | 13:09:08.8 | 172  | 0.60| 0.49             | 1.98          | 13.90      | Here; NED             |
| 13| 9614|                           | 10     | 14:56:47.70 | 09:30:33.4 | 10   | 0.77| 0.50             | 7.23          | 49.70      | Here; NED             |
| 14| 12709|                          | 9      | 23:37:24.05 | 00:23:30.7 | 150  | 0.73| 0.73             | 7.86          | 37.00      | Here; NED             |

* K13 – Karachentsev et al. (2013)

![Image of comparison between measured surface brightness profiles in the SDSS r band (line) and R band (open circles) from Swaters & Balcells (2002). The arrow marks the optical isophotal radius R_{25}.](image1)

![Image of radial profiles in the SDSS r band (solid line) and R-band profiles (open circles) from Swaters & Balcells (2003).](image2)

2.3 Surface brightness profiles

We constructed radial surface brightness profiles in the infrared W1 band (with an isophotal wavelength of 3.4 μm) using the publicly available photometric maps obtained in the framework of the Wide-field Infrared Survey Explorer (WISE) project (Wright et al. 2010). The conversion of the photometric map into the surface brightness profile is discussed in Pilyugin et al. (2014a). Parameters such as the galaxy center, the position angle of the major axis, and the axis ratio are obtained through fitting of the isophotes by ellipses. We also constructed radial surface brightness profiles in the SDSS g and r bands using the photometric maps of SDSS data release 9 (Ahn et al. 2012). To estimate the optical isophotal radius R_{25} of a galaxy, the surface brightnesses in the SDSS filters g and r were converted to B-band brightnesses, and the AB magnitudes were reduced to the Vega photometric system using the conversion relations and solar magnitudes of Blanton & Roweis (2007).

Swaters & Balcells (2002) reported surface brightness profiles in the R band for a large number of galaxies. Figure 1 shows the comparison between our measured surface brightness profiles in the SDSS r band (solid line) and R-band profiles (open circles) from Swaters & Balcells (2003). Our surface brightness profiles within the optical isophotal radius R_{25} agree satisfactorily well with those of Swaters & Balcells (2002).

All surface brightness measurements were corrected for Galactic foreground extinction using the A_V values from the recalibration of the maps of Schlegel et al. (1998) by Schlafly & Finkbeiner (2011) and the extinction curve of Cardelli et al. (1989), assuming a ratio of total to selective extinction of R_V = A_V/E(R-V) = 3.1. The A_V values given in the NASA Extragalactic Database (NED) were adopted. To transform the surface brightness measurements to solar units, we used the magnitude of the Sun in the W1 band, which we obtained from its magnitude in the V band and from its color (V - W1) = 1.608 taken from Casagrande et al. (2012).

The radial profiles in the SDSS g and r bands were used to estimate the isophotal R_{25} radius of each galaxy. The obtained radial profiles were reduced to a face-on galaxy orientation. Note that the inclination correction is purely geometrical, and it does not include any correction for inclination-dependent internal obscuration. The values of the optical radius R_{25} determined here are listed in Table 1. There are no SDSS photometric maps for several galaxies of our sample. The optical radii R_{25} (as well as the position angle of the major axis and the inclination angle) for those galaxies were taken from the RC3 (de Vaucouleurs et al. 1991).

The observed surface brightness profile of an irregular galaxy can be fitted by an exponential (Swaters & Balcells 2002; Herrmann et al. 2013). There are bulges, bars, or nuclear star clusters at the centres of some irregular galaxies. A bulge or a nuclear star cluster can be fitted with a general Sérsic profile. A profile showing a increase of (optical) surface brightness in the central part...
of a galaxy (with or without bulge-like component) will be referred to as a steep inner profile below. Irregular galaxies with a steep inner profile are presented in Fig. 2.

It is known that the surface brightnesses in some irregular galaxies are flat or even increase out to a region of slope change where they tend to fall off (Swaters & Balcells 2002; Taylor et al. 2005; Hermann et al. 2013). Such surface brightness profiles can be formally fitted by an exponential disk with a bulge-like component of negative brightness. Such profiles will be referred to as flat inner profiles below. Irregular galaxies with flat inner profiles are presented in Fig. 3.

To define the type of surface brightness profile we use our surface brightness profiles in the SDSS r band or R-band profiles from Swaters & Balcells (2002). It should be noted that the shapes of the surface brightness profiles of the same galaxy in the different photometric bands do not necessarily coincide with each other.

3 ABUNDANCES

3.1 Abundance determination

We determine the $T_{e}$-based oxygen ($\text{O}/\text{H}_{T_{e}}$) and nitrogen ($\text{N}/\text{H}_{T_{e}}$) abundances in $\text{H}\alpha$ regions where the auroral line [O iii]4363 is detected using the equations of the $T_{e}$-method from Pilyugin et al. (2013, 2012).

A new method (called the “C method”) for oxygen and nitrogen abundance determinations from strong emission lines has recently been suggested (Pilyugin et al. 2013, 2014). Here, the strong lines $R_{1} = [\text{[O iii]4959,5007}]$, $R_{2} = [\text{[N ii]6548,6584}]$ and $S_{1} = [\text{[S ii]6717,6731}]$ are used in the determinations of the oxygen ($\text{O}/\text{H})_{\text{NS}}$ and nitrogen ($\text{N}/\text{H})_{\text{NS}}$ abundances in individual $\text{H}\alpha$ regions of our target galaxies.

3.2 Radial abundance gradients

The deprojected radii of the $\text{H}\alpha$ regions were computed using their coordinates and geometrical parameters (position angle of the major axis and galaxy inclination) listed in Table 1.

The radial oxygen abundance distribution within the isophotal radius in every galaxy was fitted by the following equation:

\[ 12 + \log(\text{O}/\text{H}) = 12 + \log(\text{O}/\text{H})_{R_{0}} + C_{O/H} \times (R/R_{25}), \]

where $12 + \log(\text{O}/\text{H})_{R_{0}}$ is the oxygen abundance at $R_{0} = 0$, i.e., the extrapolated central oxygen abundance. $C_{O/H}$ is the slope of the oxygen abundance gradient expressed in terms of dex $R_{25}^{−1}$, and $R/R_{25}$ is the fractional radius (the galactocentric distance normalized to the disk’s isophotal radius $R_{25}$). The derived parameters of the oxygen abundance distributions are presented in Table 2. The name of the galaxy is listed in column 1. The optical isophotal radius $R_{25}$ in kpc is reported in column 2. The extrapolated central $12 + \log(\text{O}/\text{H})_{R_{0}}$ oxygen abundance and the gradient expressed in terms of dex $R_{25}^{−1}$ are listed in columns 3 and 4 (the bootstrapped error of the gradient is given in parenthesis). The scatter of oxygen abundances around the general radial oxygen abundance trend is reported in column 5. The references to sources for spectroscopic data are given in column 9. The radial distributions of the oxygen abundances in irregular galaxies are shown in Figs. 2 and 3 together with the surface brightness profiles.

The statistical error of the gradient listed in column 4 comes from the best fitting procedure. We also estimate the bootstrapped error of the gradient in the following way. The measured $\text{H}\alpha$ regions in a galaxy are numbered from 1 to $n$. We then produce $n$ random integer numbers using a random number generator, and form a bootstrapped subsample of $\text{H}\alpha$ regions choosing the corresponding $\text{H}\alpha$ regions from the original sample of $\text{H}\alpha$ regions. The amount of $\text{H}\alpha$ regions in the bootstrapped subsample is adopted to be equal to the amount of the $\text{H}\alpha$ regions in the original sample. Thus, some $\text{H}\alpha$ regions from the original sample can be repeatedly included in the bootstrapped subsample while other $\text{H}\alpha$ regions from the original sample will not at all be included in the bootstrapped subsample. If a bootstrapped subsample involves less than three different $\text{H}\alpha$ regions then this subsample is rejected.

The abundance gradient for the bootstrapped subsample is determined through the best fit, and the error of the original gradient, i.e., the difference between the values of the gradients for the bootstrapped subsample and for the original sample of $\text{H}\alpha$ regions is obtained. We considered $k = 10^{5}$ bootstrapped subsamples and determined the bootstrapped error of the gradient as $\left((\sum \mid \text{gradient difference}\mid/k\right)^{(1/2)}$. This bootstrapped error of the oxygen abundance gradient is given in Table 3, column 4 in parenthesis.

The statistical and bootstrapped errors of the oxygen abundance gradients are close to each other except in the case of the galaxy UGC 2216 where the bootstrapped error exceeds dramatically the statistical error. This is caused by the following. The radial abundance gradient in the UGC 2216 is strongly biased by an $\text{H}\alpha$ region at a galactocentric distance of 4.43 kpc. When the bootstrapped subsample does not contain this point then the value of the radial abundance gradient is very uncertain since in this case the gradient is determined from measurements at close galactocentric distances. As a result, the bootstrapped error of the radial abundance gradient for this galaxy is quite large.

As in the case of the oxygen abundance, the radial nitrogen abundance distribution in every galaxy was fitted by the following equation:

\[ 12 + \log(\text{N}/\text{H}) = 12 + \log(\text{N}/\text{H})_{R_{0}} + C_{N/H} \times (R/R_{25}). \]

The derived parameters of the nitrogen abundance distributions are presented in Table 2. The extrapolated central $12 + \log(\text{N}/\text{H})_{R_{0}}$ nitrogen abundance and the gradient in terms of dex $R_{25}^{−1}$ are listed in columns 6 and 7. The scatter of oxygen abundances around the general radial oxygen abundance trend is reported in column 8. The value in the parenthesis in column 7 is the bootstrapped error of the nitrogen abundance gradient obtained in the same way as for the oxygen abundance gradient.

The radial oxygen abundance gradients in irregular galaxies obtained here are based mainly (or only) on oxygen abundances ($\text{O}/\text{H})_{\text{NS}}$ estimated through strong emission lines using the $C_{\text{NS}}$ method. Figs. 2 and 3 show that the scatter in the ($\text{O}/\text{H})_{\text{NS}}$ abundances around the general radial trend is often lower than the scatter in the ($\text{O}/\text{H}_{T_{e}}$) abundances. Five galaxies from our present sample are in the list of galaxies considered in our previous study (Pilyugin et al. 2014). The values of gradients obtained here are slightly different from those reported in our previous study for the following reasons. First, in our current work we obtain and use new parameters for our target galaxies such as inclination, position angle of the major axis, and optical isophotal radius. Furthermore, in Pilyugin et al. (2014) the oxygen and nitrogen abundances were estimated via the $C_{\text{ON}}$ method for $\text{H}\alpha$ regions with available measurements of the [O ii]λλ3727,3729 emission line, and with the $C_{\text{NS}}$ method for the other $\text{H}\alpha$ regions. In our current study, the oxygen and nitrogen abundances were estimated through the $C_{\text{NS}}$ method for all $\text{H}\alpha$ regions, and $T_{e}$-based abundances are added.
Abundance gradients in irregulars

4 DISCUSSION AND CONCLUSIONS

Fig. 2 shows the surface brightness profiles and radial distributions of oxygen abundances for irregular galaxies with steep inner profiles. Each galaxy is presented in two panels. Each upper panel Na shows the surface brightness profiles in the SDSS g band as a light-grey (blue) solid line, in the SDSS r band as a dark (black) long-dashed line, and in the WISE W1 band as a dark-grey (red) short-dashed line. Each lower panel Nb shows the oxygen abundance in individual H ii regions as a function of radius. The dark (black) open circles show (O/H)$_{CNS}$ abundances and the grey (red) filled circles indicate the (O/H)$_{Te}$ abundances. The solid line represents the inferred linear abundance gradient. (A color version of this figure is available in the on-line edition.)

Fig. 3 shows the surface brightness profiles and radial distributions of the oxygen abundances for irregular galaxies with flat inner profiles. Inspection of Fig. 3 shows that the irregular galaxies with steep inner profiles have appreciable radial abundance gradients.

Fig. 3 shows the surface brightness profiles and radial distributions of the oxygen abundances for irregular galaxies with flat inner profiles. Inspection of Fig. 3 shows that the radial abundance gra-
Figure 3. The same as Fig. 2 but for irregular galaxies with flat inner profiles. For galaxies without SDSS photometric maps, the surface brightness profile in the R band from Waters & Balcells (2002) is indicated with dark (black) plus signs. (A color version of this figure is available in the online edition.)

dients in the irregular galaxies with flat inner profiles are shallower than the gradients in irregular galaxies with steep inner profiles.

Thus, our data suggest that there is a relation between the radial abundance gradient in an irregular galaxy and its surface brightness profile. Panel a of Fig. 4 shows the radial oxygen abundance gradient as a function of optical radius $R_{25}$ for our sample of irregular galaxies. The dark (black) open circles mark irregular galaxies with steep inner photometric profiles. The dark-grey (red) open squares denote galaxies with flat inner profiles. The dark (black) dotted line is the arithmetic mean of the gradients for galaxies with steep inner photometric profiles, whereas the dark-grey (red) dashed line is the mean for galaxies with flat inner photometric profiles. The light-grey (green) solid line is the arithmetic mean of the gradients for all our galaxies (both those with steep and those with flat inner profiles). Since the numbers of galaxies in our sample are small even one deviant galaxy may appreciably change the arithmetic mean for the sample. Indeed the arithmetic mean of the gradients for galaxies with steep inner photometric profiles is changed by $\sim 0.05$ dex $R_{25}^{-1}$ when the deviating galaxy NGC 4214
Table 2. The derived parameters of the radial oxygen and nitrogen abundance distributions in our target galaxies.

| Galaxy   | $R_{25}$ kpc | $12+\log(O/H)_{K_0}$ | O/H gradient $\sigma$ dex $R_{25}^{-1}$ | $12+\log(N/H)_{K_0}$ | N/H gradient $\sigma$ dex $R_{25}^{-1}$ | References |
|----------|--------------|-----------------------|-----------------------------------------|----------------------|----------------------------------------|------------|
| UGC 02023| 2.24         | 8.08 ± 0.07           | -0.082 ± 0.128 (0.150)                  | 0.052                | -0.137 ± 0.208 (0.252)                  | 0.085      |
| UGC 02216| 4.25         | 8.07 ± 0.02           | -0.040 ± 0.043 (0.300)                  | 0.026                | -0.056 ± 0.091 (0.560)                  | 0.054      |
| NGC 1156 | 3.76         | 8.16 ± 0.04           | -0.124 ± 0.112 (0.138)                  | 0.080                | -0.232 ± 0.202 (0.260)                  | 0.145      |
| NGC 2537 | 3.80         | 8.35 ± 0.01           | -0.071 ± 0.034 (0.031)                  | 0.014                | -0.237 ± 0.113 (0.124)                  | 0.046      |
| UGC 04305| 3.92         | 7.83 ± 0.04           | -0.140 ± 0.078 (0.085)                  | 0.101                | -0.182 ± 0.090 (0.108)                  | 0.116      |
| NGC 3738 | 2.04         | 8.10 ± 0.02           | -0.110 ± 0.103 (0.128)                  | 0.028                | -0.144 ± 0.173 (0.201)                  | 0.046      |
| UGC 06980| 3.55         | 8.06 ± 0.07           | -0.150 ± 0.112 (0.124)                  | 0.056                | -0.145 ± 0.077 (0.089)                  | 0.038      |
| NGC 4214 | 2.72         | 8.20 ± 0.05           | -0.049 ± 0.124 (0.122)                  | 0.090                | 0.057 ± 0.148 (0.189)                   | 0.108      |
| NGC 4395 | 5.47         | 8.32 ± 0.04           | -0.343 ± 0.072 (0.066)                  | 0.064                | -0.629 ± 0.119 (0.085)                  | 0.104      |
| UGC 07557| 4.54         | 8.32 ± 0.06           | -0.176 ± 0.118 (0.176)                  | 0.057                | -0.361 ± 0.280 (0.413)                  | 0.135      |
| NGC 4449 | 3.76         | 8.26 ± 0.01           | -0.207 ± 0.034 (0.063)                  | 0.028                | -0.369 ± 0.053 (0.122)                  | 0.051      |
| CG071-090| 1.98         | 8.19 ± 0.02           | -0.344 ± 0.060 (0.074)                  | 0.026                | -0.525 ± 0.074 (0.104)                  | 0.032      |
| UGC 09614| 7.23         | 8.18 ± 0.09           | -0.218 ± 0.128 (0.198)                  | 0.063                | -0.389 ± 0.195 (0.262)                  | 0.096      |
| UGC 12709| 7.86         | 8.48 ± 0.08           | -0.358 ± 0.113 (0.136)                  | 0.084                | -0.546 ± 0.210 (0.217)                  | 0.156      |

References: Berg et al. (2012), Böker et al. (2001), Croxall et al. (2009), Egorov et al. (2013), Esteban et al. (2009), Gil de Paz et al. (2000), Haubble et al. (1983), Ho et al. (1997), Hunter et al. (1982), Hunter & Hoffmam (1999), Kobulnicky & Skillman (1996), Lequeux et al. (1979), Mould, & Kennicutt (1984), Moustakas & Kennicutt (2004), Romanishin et al. (1983), SDSS York et al. (2000), van Zee et al. (1998), Van Zee & Haynes (2006).
metallicities in irregular galaxies are typically lower than the ones in spiral galaxies since irregular galaxies are less massive and less evolved. The simple model for the chemical evolution of galaxies predicts that the oxygen abundance $\mathrm{O/H}$ varies with gas mass fraction $\mu$ more strongly at low metallicity. Thus a similar change of $\mu$ along the radial direction would result in a larger change of $\mathrm{O/H}$ in irregular galaxies than in spiral galaxies.

Radial mixing of gas flattens the abundance gradient in the disk of a galaxy. Radial mixing of gas can be caused by interacting or merging galaxies (e.g., Rupke et al. 2010a,b) and by galactic fountains (galactic winds and subsequent gas infall). The arguments pro and contra galactic wind-dominated evolution of irregular galaxies are discussed in many studies devoted to the chemical evolution of galaxies (Skillman 1997; Cavilán et al. 2013, among many others). A galactic wind can be caused by the injection of energy by multiple, spatially and temporally clustered supernovae in a galaxy undergoing a starburst (De Young & Gallagher 1990; Mac Low & Ferrara 1999). The efficiency of the galactic winds depends on the number of massive stars that are progenitors of supernovae in a star formation event. Lee et al. (2009) found that continuous, steady star formation dominates in the present epoch in dwarf galaxies. Only $\sim 6\%$ of low-mass galaxies experience strong star formation bursts. The fraction of stars formed in starbursts is $\sim 23\%$. However, it is not clear whether a strong star formation burst can occur with equal probability in every galaxy or whether a starburst happens only in a particular subset of galaxies.

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Figure 4. The panel a shows the oxygen abundance gradient as a function of optical radius $R_{25}$. The dark (black) open circles mark irregular galaxies with steep inner photometric profiles. The dark-grey (red) open squares denote galaxies with flat inner photometric profiles. The dark (black) dotted line is the arithmetic mean of the gradients for galaxies with steep inner profiles, the dark-grey (red) dashed line for galaxies with flat inner profiles, and the light-grey (green) solid line the total sample. Panel b shows the same as panel a but for the nitrogen abundance gradients. Panel c shows the oxygen abundance gradients with bootstrapped errors. On the right side of the panel, the mean values of the gradients for the sample of galaxies with steep inner photometric profiles (the filled dark (black) circle) for the sample of galaxies with flat inner photometric profiles (the filled dark-grey (red) square), and for total sample (the ligh-grey (green) asterisk) and their 95% and 68% confidence intervals are shown. Panel d shows the same as panel c but for the nitrogen abundance gradients. (A color version of this figure is available in the on-line edition.)
Thus, we can interpret our results in the following manner. Irregular galaxies with steep inner profiles do not seem to undergo strong radial mixing of gas at the present epoch and show considerable radial abundance gradients. The radial mixing of gas (through radial flows or galactic fountains) took place in irregular galaxies with flat inner profiles, resulting in shallower (if any) gradients as compared to the galaxies with steep inner profiles. It should be noted that the physical reason for different radial profile types is still a mystery. It is not even clear why there is an exponential drop-off of the brightness profile [Herrmann et al. 2013].

5 SUMMARY

We determined the abundance distributions traced by H\text{II} regions and compare their shape with the surface brightness profiles of the disks of fourteen irregular Sm and Im galaxies (morphological T types of T = 9 and T = 10). We used the emission line intensities in published spectra of H\text{II} regions from different studies to infer the abundances. The oxygen (O/H)\text{r}, and nitrogen (N/H)\text{r}, abundances in the H\text{II} regions with the detected auroral line [O \text{III}]4363 were determined using the equations of the classic T\text{r}-method. In the other H\text{II} regions, oxygen (O/H)\text{NS} and nitrogen (N/H)\text{NS} abundances were obtained through the C method. We then quantified the values of the gradients of the radial abundance profiles.

Moreover, we constructed radial surface brightness profiles in the infrared W1 WISE band and in the SDSS g and r bands using the publicly available photometric maps. The irregular galaxies of our sample can be divided into two types according to the shapes of their surface brightness profiles: those with steep inner profiles, and those with flat inner profiles.

We find that there is a correspondence between the radial abundance gradient in an irregular galaxy and its surface brightness profile with a probability higher than 90%. Irregular galaxies with steep inner profiles usually show a considerable radial abundance gradient. Irregular galaxies with flat inner surface brightness profiles have shallower gradients (if any) as compared to galaxies with steep inner profiles.

Thus, irregular galaxies with steep inner profiles show unusually pronounced radial abundance gradient that resembles that of spiral galaxies. In that sense, those irregular galaxies seem to extend the Hubble sequence of spiral galaxies. In other words, our data suggest that there is no “spiral versus irregular dichotomy” in terms of radial abundance gradients existing only in spiral galaxies, but not in irregulars. While irregulars have long been believed to be chemically homogeneous, our study shows that given enough measurements of nebular abundances of H\text{II} regions across a wide range of galactocentric radii, irregulars may well exhibit radial abundance gradients. This tendency is particularly conspicuous in irregulars with steep surface brightness profiles in their inner regions.

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