ON THE EFFECTIVE OXYGEN YIELD IN THE DISKS OF SPIRAL GALAXIES

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ABSTRACT

The factors that influence the chemical evolution of galaxies are poorly understood. Both gas inflow and gas outflow reduce the gas-phase abundance of heavy elements (metallicity), whereas ongoing star formation contributes to it. To exclude the stellar nucleosynthesis from consideration, we analyze for a sample of 14 spiral galaxies the radial distribution of the effective yield of oxygen \( \gamma_{\text{eff}} \), which would be identical to the true stellar yield \( \gamma \), if the evolution followed the closed-box model. The obtained data for gas-phase abundances, we used the O/H radial profiles from Fontanot et al., based on two different calibrations (the PT2005 and KK2004 methods). In most of the galaxies with the PT2005 calibration, which we consider the preferred one, the yield \( \gamma_{\text{eff}} \) in the main disk \( (R > 0.2 R_{25}) \), where \( R_{25} \) is the optical radius) increases with radius, whereas it remains constant or decreases with radius for the other galaxies. This may indicate the infall of less-enriched gas predominantly to the inner disk regions, which reduces \( \gamma_{\text{eff}} \). We show that the maximal values of the effective yield in the main disks of galaxies, \( \gamma_{\text{eff,max}} \), anticorrelate with the total mass of galaxies and with the mass of their dark halos enclosed within \( R_{25} \). It allows us to propose the greater role of gas accretion for galaxies with massive halos. We also found that the radial gradient of oxygen abundance normalized to \( R_{25} \) has a tendency to be shallower in the systems with lower dark halo to stellar mass ratio within the optical radius, which, if confirmed, gives evidence of the effective radial mixing of gas in galaxies with a relatively light dark matter halo.

Key words: galaxies: ISM – galaxies: spiral

1. INTRODUCTION

Gas-phase metal abundance (gas metallicity) in the disks of galaxies depends on their star-formation history and generally grows with time as the result of the enrichment of interstellar gas by the products of stellar nucleosynthesis. The observed relations between gas metallicity and stellar disk properties, such as the stellar mass–metallicity relation (Pilyugin et al. 2013; Zahid et al. 2014) or the local metallicity versus local disk surface density relation (Moran et al. 2012; Rosales-Ortega et al. 2012; Sánchez et al. 2013; Pilyugin et al. 2014b) give evidence that the chemical evolution is mostly a product of internal processes rather than the environment, although the gas exchange between disk and halo or intergalactic medium also plays a significant role, especially at the early stage of evolution.

Following Ascasibar et al. (2015), we proceed from the assumption that there are two parameters directly obtained from observations, which describe the evolutionary stage of a star-forming galaxy: a gas mass fraction \( \mu = M_g/(M_g + M_b) \), where the g and b indices are related to the gas and stellar population masses, respectively, and gas metallicity, usually presented by the oxygen abundance \( 12 + \log(O/H) \), which is a product of short-lived stars. In the general case, both parameters vary along the galactocentric radius \( R \) and change over time. Continuous star formation leads to the monotonic decrease of \( \mu \) over the timescale of several gigayears, accompanied by the corresponding growth of \( O/H \), but the situation becomes more complex in the presence of gas accretion or gas losses.

The existence of gas accreting onto galaxies, which dilutes the interstellar gas, and gas outflow from the disks of galaxies are supported by much observational evidence (see, for example, the review by Sánchez Almeida et al. 2014). The efficiency of gas inflow/outflow processes and their role in chemical evolution have been discussed and modeled in many papers (see, for example, Dalcanton 2007; Pilyugin et al. 2007; Spitoni et al. 2010; Zahid et al. 2014; Ascasibar et al. 2015; Kudritzki et al. 2015; Lu et al. 2015). However, the results are still contradictory and model dependent. In particular, there remains a degeneracy between the influence of gas inflow and the outflow of enriched gas onto chemical evolution because both of them tend to decrease the gas-phase metallicity. Note, however, that the accretion and wind can in principle be disentangled (see Kudritzki et al. 2015). Although the results remain model dependent, they demonstrate that the role of gas inflow/outflow may be different for different spiral galaxies.

The accretion rate, as well as the intensity of galactic wind or radial gas migration in the disk plane, depends on the deepness of the potential well provided by the extended dark halo. In particular, the baryonic mass growth of a disk due to accretion may be less efficient both for low-mass halos and for very massive halos \( M_{\text{halo}} \geq 10^{12} M_{\odot} \) (Bouché et al. 2010). The latter is caused by the shock heating of cool gas flows penetrating into a massive halo from the intergalactic space so that it requires a long time for the hot halo gas to cool and to fall onto a disk (see the discussion in Sánchez Almeida et al. 2014 and van de Voort et al. 2011). In turn, the massive halo reduces or prevents the gas losses of a galaxy, so the enriched gas that leaves a disk as the result of stellar feedback may replenish the gas in the halo and return back to the disk much later. The greater the mass of a halo, the hotter and thinner its gas, and the less efficiently it cools before settling down onto a disk. However, the relation between \( M_{\text{halo}} \) and the efficiency of gas accretion and gas losses depends on many factors and remains poorly understood, although some restrictions may be done for the net accretion rate and the net mass outflow rate based on a comparison of the observational
There are big uncertainties in the modeling of the mixing of metals with the medium, so the results given by different models of chemical evolution, even being compatible with observational data, remain model dependent and rather contradictory concerning the role of gas accretion and galactic winds in concrete galaxies. In addition, the true yield of metals in stellar nucleosynthesis is also poorly known. Moreover, there is no agreement between the different methods of evaluation of gas-phase metallicity, so the estimates, based on the radiation balance equation of HII regions, are systematically higher than gas-phase metallicity, so the estimates, based on the radiation balance equation of HII regions, are systematically higher than those obtained by semiempirical methods: the difference may be as high as a factor of five between the O/H ratio estimates (Kewley & Ellison 2008).

In this work we aim to study the properties of the gas-phase evolution of metal content in different spiral galaxies, avoiding the use of sophisticated evolution models. To exclude from consideration a history of gas consumption in the formation of stars, we consider the effective yield of oxygen $\gamma_{\text{eff}}$, which by definition is equal to the true stellar yield of oxygen $y_o$ per stellar generation if the model of closed-box evolution is valid. In this simple model, the gas-phase metallicity is governed by star formation without the inflow or outflow of gas, gas enrichment is instantaneous, and the gas is well mixed. The oxygen yield $y_o$ may be calculated from theoretical models of stellar evolution (see, for example, Vincenzo et al. 2015) or found by empirical means (Pilyugin et al. 2007). In the closed-box model, the oxygen mass fraction $Z \approx 12(O/H)$ is linked with the gas to stellar mass ratio (or, locally, gas surface density fraction $\mu$) by a simple relation (Searle & Sargent 1972; Edmunds 1990; Belfiore et al. 2015):

$$Z = \frac{y_o}{1 - r} \cdot \ln(1/\mu)$$

where $r$ is the total mass fraction (including both processed and unprocessed material) returned back into the interstellar medium as the result of stellar evolution. Actually, the closed-box model is too primitive to describe the evolution of stellar-gaseous disks of galaxies.

The effective yield is defined as

$$\gamma_{\text{eff}} = \frac{Z}{\ln(1/\mu)}.$$  

Its value does not depend on star-formation efficiency or the history of star formation, differing from the true stellar yield $y_o$ by the nominator $(1 - r)$ in the closed-box model. In the general case, $\gamma_{\text{eff}}$ may strongly differ from $y_o$. A comparison of these two yields may give valuable information for concrete galaxies about the factors influencing the chemical evolution of gas besides stellar nucleosynthesis. For example, Kudritzki et al. (2015) showed with their model that the high effective yield of galaxies may be explained by relatively low rates of accretion and winds. In the general case, $\gamma_{\text{eff}}$ may change drastically along the radius. In this paper we focus on the radial trend of the effective yield.

2. RADIAL PROFILES OF THE EFFECTIVE OXYGEN YIELD

Both the inflow of low-metal gas and the outflow of enriched gas from the disk result in the reduction of $\gamma_{\text{eff}}$ (Dalcanton 2007). It is only the weak mixing of the enriched and nonenriched gas or radial migration of the enriched gas from the inner regions outward that can lead to an increase of $\gamma_{\text{eff}}$ in the disk periphery. The latter manifests itself as the flattening of the $(O/H)$ gradient at large radial distances $R$, mostly observed in galaxies that experience or have experienced a strong interaction (Werk et al. 2011; Zasov et al. 2015).

A comparison of $\gamma_{\text{eff}}$ and $y_o$ has been used by different authors to clarify the degree of difference of evolution from the closed-box model and to specify the processes that are responsible for the metal abundance besides star formation and gas consumption (see, for example, Zahid et al. 2014; Ascasibar et al. 2015; Kudritzki et al. 2015).

Below we present the radial profiles of the effective oxygen yield $\gamma_{\text{eff}}$ for 14 spiral galaxies (see Table 1 for the names of the galaxies, the adopted distances in Mpc, morphological types, and B-band absolute magnitudes) obtained for the closed-box model:

$$\gamma_{\text{eff}} \approx \frac{12(O/H)}{\ln(1/\mu)}$$

The radial profiles of the surface densities of gas ($\sigma_{\text{H}_2+\text{He}}$ and $\sigma_{\text{H}_2+\text{He}+\text{H}}$) and stars ($\sigma_s$) were taken from Leroy et al. (2008). We took into account the bulge contribution to the total stellar surface-density profiles. To do it we first decomposed the profiles into the components of an exponential disk, $\sigma_d(R) = \sigma_{\text{bd}} e^{-R/R_d}$ (here $\sigma_{\text{bd}}$ is the central surface density of the disk and $R_d$ is the disk exponential scale length), and Sérsic bulge, $\sigma_b(R) = \sigma_{\text{bS}} 10^{-b_0(R/R_c)^{1/n}}$ ($\sigma_{\text{bS}}$ is the central surface density of the bulge, $R_c$ is the effective radius, and $b_0$ is defined through the bulge shape parameter $n$). After decomposition we subtracted the bulge contributions from the surface-density profiles and used the resulting stellar mass profile in our analysis.

The radial distribution of oxygen abundance, taken from Moustakas et al. (2010), is as follows:

$$12 + \log \left( \frac{O}{H} \right) = 12 + \log \left( \frac{O}{H} \right)_0 + C_{O/H} \cdot \frac{R}{R_{25}},$$

where $R_{25}$ is the optical radius confined by the B-isophote 25th per arcsec². The term $12 + \log \left( \frac{O}{H} \right)_0$ is the intercept and $C_{O/H}$ is the gradient of the relationship. These authors evaluated the

| Galaxy   | Distance, Mpc | Type | $M_B$ |
|----------|---------------|------|-------|
| NGC 0628 | 7.3           | Sc   | -20   |
| NGC 0925 | 9.2           | Scd  | -20   |
| NGC 2403 | 3.2           | SABc | -19.4 |
| NGC 2841 | 14.1          | Sc   | -20.2 |
| NGC 3184 | 11.1          | SABe | -19.9 |
| NGC 3198 | 13.8          | Sc   | -20.8 |
| NGC 3351 | 10.1          | Sc   | -19.9 |
| NGC 3521 | 10.7          | SABb | -20.9 |
| NGC 4736 | 4.7           | Sab  | -19.8 |
| NGC 5055 | 10.1          | Sbc  | -21.1 |
| NGC 5194 | 8             | Sbc  | -21.2 |
| NGC 6946 | 5.9           | SABc | -20.6 |
| NGC 7331 | 14.7          | Sbc  | -21.7 |
| NGC 7793 | 3.9           | Scd  | -18.8 |

Table 1 Galaxy Sample
oxygen abundances using two strong line calibrations: the theoretical calibration of Kobulnicky & Kewley (2004, hereafter KK2004) and the empirical calibration of Pilyugin & Thuan (2005, hereafter PT2005). Note that more recent work by Pilyugin et al. (2014) contains more galaxies with measured O/H than in the Moustakas et al. (2010) paper, although the latter authors used a single empirical method for O/H determination without resorting to the emission lines of C or N.

The difference between theoretical (KK2004) and empirical (PT2005) calibrations cannot be reduced to a constant factor. Although both calibrations have their own weaknesses (see, for example, Kewley & Ellison 2008), we prefer the empirical one. This choice is based on the excellent concordance (within 0.1 dex) between the O/H estimates obtained by the empirical method and by the direct (T_e) method for both metal-rich and metal-poor gas (Pilyugin 2003), as well as the agreement of gas-phase O/H estimates for the solar circle with the metallicity of young stars (Kudritzki et al. 2015) and with the independent valuation of O/H from the interstellar absorption line of neutral oxygen (Pilyugin 2003).

In Figure 1 we show the obtained radial profiles of the effective oxygen yield. As one can expect, the estimations of the effective yield are sensitive to the method of determination of the oxygen abundance. The (O/H) ratios based on the PT2005 calibration are significantly lower than those obtained by the KK2004 method. The mean ratio of the two yields for our sample galaxies is 4.2 ± 0.96, and the mean ratio of the gradients is 1.6 ± 1.1. Despite the systematics, a general shape of radial profiles of y_eff has a common behavior in most of the galaxies. The ratio of the two yields is roughly constant with radius in a majority of objects from our sample, except NGC 3521 and NGC 7331, which also have the biggest difference between the oxygen gradients obtained by two calibrations.

It is essential that the PT2005 calibration gives the effective oxygen yield that increases along the radial distance in most of the galaxies of our sample, although in some cases the growth is very mild, so y_eff can be interpreted as approximately constant. Taking into account that both gas inflow and outflow reduce y_eff, one may conclude that these processes should be especially effective for the inner parts of most of the galaxies considered. As is shown in Figure 1, there is a peak of y_eff in the innermost region of galaxies, followed by a local minimum of the radial profile. If real, the central maximum may reflect a special way of chemical evolution of the bulge-dominated region, where a stellar population of a bulge contributes to the metal enrichment of a gas. Note that the instantaneous enrichment approximation is not valid in this case even in the absence of gas inflow/outflow from a galaxy.

Belfiore et al. (2015) analyzed the profile of y_eff for NGC 0628, one of the galaxies from our sample. They used photometry in different bands to obtain a reliable estimate of the stellar mass surface density by performing full spectral energy distribution (SED) fitting and different metallicity calibrations, and they came to a qualitatively similar result, that y_eff increases to the peripheral disk region.

There are three galaxies in our sample (NGC 2841, NGC 5055, and NGC 5194) where the effective yield behaves in a different way, being lower for the disk periphery for both PT2005 and KK2004 measurements of O/H. The KK2004 calibration adds three more galaxies that have a decreasing radial profile of y_eff: NGC 3521, NGC 6946, and NGC 7331, demonstrating that the radial behavior of y_eff depends on the calibration used. All of these six galaxies have a high total luminosity and velocity of rotation. We did not find any connection between the presence of a bar or a ring or the galaxy environment and the shape of the radial profile of y_eff.

These galaxies do not stand out also by their dark halo masses inside the optical borders presented in Saburova & Del Popolo (2014): their dark halo to stellar mass ratios are quite typical, being in a range 0.9–2.4. It is worth noting that the mean central metallicity of three galaxies with the decrease of effective yield for both PT2005 and KK2004 calibrations is 12 + log(O/H)_0 ≈ 8.50 (PT2005) and ≈9.2 (KK2004), which are slightly higher than for the rest of the galaxies of our sample: 12 + log(O/H)_0 ≈ 8.37 ± 0.1 (PT2005) and ≈8.98 ± 0.13 (KK2004). It is natural to propose that the mechanisms reducing y_eff along the radius in these galaxies, unlike the other ones, more effectively influence the gas-phase metallicity at large radial distances than in the central parts, reflecting some peculiarities of their evolution (say, due to minor merging, accretion, or outflow of enriched gas).

Insofar as the largest observed values of y_eff should be restricted by the level of true nucleosynthetic yield y_o, the saturation level of y_eff for different galaxies may be used to estimate y_o empirically. By this method it was found that y_o = 0.003–0.004 (Dalcanton 2007; Pilyugin et al. 2007). A similar value was obtained for the Milky Way disk by Kudritzki et al. (2015) in their analytical chemical evolution model with constant ratios of galactic mass loss and mass gain to the star-formation rate (SFR). Taken as the upper limit, its value agrees pretty well with the y_o found for the galaxies considered here by the PT2005 method of oxygen abundance estimation, but it is much lower than the values from the KK2004 estimates (see Figure 1). It is essential that irrespective of where y_eff is maximal—in the central parts or at large radial distances—their values based on the PT2005 calibration nowhere exceed the estimates of y_o mentioned above.

It is worth noting that the recent paper by Vincenzo et al. (2015), which considers stellar evolution models for not-too-low metallicity Z/Z_☉ ≥ 10^{-3}, gave much higher values y_o = 0.01–0.04 depending on the adopted stellar initial mass function (IMF). The differences between these large values of y_o and the estimates of y_eff for the PT2005 data are too big to be compatible with each other: either the true yield theoretically found by Vincenzo et al. (2015) is strongly overestimated, or the semiempirical method of measurements of the oxygen abundance strongly underestimates (O/H) and y_eff. One should have in mind, however, that the stellar evolution–based estimates of y_o still remain not too reliable. Note also that even the KK2004 values of y_eff are in most cases lower than 0.01.

There are not many known mechanisms that may significantly reduce y_eff in comparison with the expected stellar yield y_o. These are

i. the low upper-limit mass of IMF,
ii. the bottom-heavy stellar IMF,
iii. accretion onto a disk of low abundant gas from the intergalactic medium (cold flows) or from a halo (hot accretion mode of cooling gas or the recycled galactic

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5 It should be noted, however that one of these galaxies—NGC 5194—is a strongly interacting galaxy, which may have an effect on the chemical evolution of its disk.
Figure 1. Radial profiles of the effective oxygen yield. Top and bottom curves are based on KK2004 and PT2005 methods, respectively (see text).
wind; see Oppenheimer et al. 2010) or a gain of nonenveloped gas as the result of minor merging, and iv. outflows of the enriched gas induced by star formation from a disk to halo or into the intergalactic space.

The assumption of the lower upper limit of mass of forming stars or the use of the IMF with a shallower slope in the high-mass end will certainly reduce $\gamma_{\text{eff}}$ (see the numerical estimates by Vincenzo et al. 2015). As was demonstrated by Martín-Navarro et al. (2014), the IMF may vary along the galactocentric distance, but this question requires further investigation. If, on the other hand, to assume that the IMF is more bottom-heavy than is usually accepted it will not change $\gamma_{\text{eff}}$ significantly, but it should decrease the intrinsic stellar yield $\gamma_0$ as the result of decreasing the mass ratio of massive to less-massive stars. In this case, one can expect that the mass-to-light ratios of the stellar population of disks will reveal a tendency to be lower in the inner regions, where $\gamma_{\text{eff}}$ is usually the lowest. However, this version seems to be unlikely, being in conflict with the estimations of mass and mass-to-light ratio of stellar disks at different radii obtained by the decomposition of rotation curves (Martinsson et al. 2013).

The outflow of gas enriched by supernovae and the accretion of nonenriched gas have similar effects on the metal abundance, wherein their roles may be different in the inner and outer disk regions. Gas outflow reduces the radial O/H distribution more effectively than the accretion if the relative gas content $\mu$ is close to unity (Dalcanton 2007), and hence it may be most essential in the peripheral gas-rich regions, where the relative mass of a gas is higher.

Accretion evidently plays a significant role in the chemical evolution of galaxies, but it can hardly explain the $\gamma_{\text{eff}}$ that is several times lower than the true yield if the gas fall is just a recent episode: in this case, even under the most favorable conditions, when the accreted nonenriched gas does not participate in star formation, the total amount of the accreted gas should by several times exceed the initial mass of gas (Dalcanton 2007). In a more realistic case, when the accretion is the long-lasting process, with the rate, say, proportional to the SFR, the effect of accretion may be significant, especially if the gas to stellar disk mass ratio $\mu$ is low. The model developed by Kudritzki et al. (2015) shows that for the accretion rate twice as low as SFR and for $\mu = 0.02$–0.4, which is typical for our galaxies, the abundance of oxygen should be 2–4 times lower than that expected for a closed-box model (see Figure 1 in Kudritzki et al. 2015). $\mu$, usually steadily grows to the disk periphery of galaxies because the gas (mostly H\textsubscript{i}) surface density decreases along the radius more slowly than does the stellar disk surface density. Hence, the accretion rather than the outflow may be responsible for the observed fall of $\gamma_{\text{eff}}$ in the central regions of galaxies, where the gas mass fraction $\mu$ is relatively low. In this case, the metal abundance is expected to be close to that for the closed-box model (Kudritzki et al. 2015). This result is not sensitive to the choice of model parameters of the evolution (see also Ascasibar et al. 2015).

The other way the gas infall may reduce a metal abundance and hence $\gamma_{\text{eff}}$ in the inner disk regions is the hot-mode accretion of the cooling nonenriched halo gas, induced by the galactic fountains that inject gas into the halo as a feedback of star formation (see Fraternali & Binney 2006). Indeed, the SFR is usually the most intense in the inner galaxy, so one may expect that the accretion may be more essential there.

A decrease of gas-phase metallicity in the central disk regions with respect to what is expected for the closed-box model should lead to the flattening of the abundance gradient. A reduction of metallicity due to accretion may also be responsible for the local decline of $\text{grad} (\text{O/H})$ in the central region, directly measured in some galaxies (Sánchez et al. 2014; Belfiore et al. 2015).

3. ON THE RELATION BETWEEN MAXIMAL OXYGEN YIELD AND DARK HALO AND TOTAL MASSES WITHIN THE OPTICAL RADIUS

A dark matter halo plays an important role in the evolution of the disks, affecting both the accretion rate and gas losses and hence influencing the gas-phase metal abundance. Numerical simulations show that for low redshifts the mechanism of accretion is different for galaxies with massive and less-massive dark halos (see discussion in Bouček et al. 2010; Oppenheimer et al. 2010; Sánchez Almeida et al. 2014). For galaxies with a massive dark halo, falling gas is shocked and virialized, so the accretion comes from hot halo gas after it is cooled or from material that was previously thrown out of a galaxy into a halo. For massive halos, the temperature of the halo gas is higher, and gas condensation is regulated by the thermal cooling rate, so it needs billions of years for gas to cool, while for less-massive galaxies the cooling flows of partially ionized gas may directly reach the disk, being the principal mode of accretion. This does not mean that massive halos are guaranteed to provide a low accretion rate because they may contain a huge mass of gas with a cooling time comparable to or lower than the age of the galaxies, especially if one takes into account the galactic fountains inspiring a gas cooling (see Fraternali & Binney 2006).

It is worth comparing the observed $\gamma_{\text{eff}}$ of galaxies with the masses of dark halos for concrete galaxies. Note that two definitions of a halo mass are in use. A total, or virial, dark halo mass is the mass within the virial radius, which is well outside of the optical radius. This mass comes from cosmological scenarios of the formation of galaxies and is tightly linked with the circular velocity at the virial radius, which does not differ much from the maximal velocity of rotation $V$ of a disk, being slightly lower than the latter (see, for example, Reyes et al. 2012). Unlike the virial mass, a directly measured halo mass is usually restricted by the radius of the observed disk. To be specific, it is convenient to define a halo mass inside $R_{25}$ that is an order of magnitude lower than the virial mass of the halo.

It is well known that the gas abundance is higher in massive and fast-rotating galaxies that are in those with massive halos. However, this trend may be a result of a different history of star formation, so its connection with $\gamma_{\text{eff}}$ is not evident. Dalcanton (2007) found a positive correlation between $V$ and $\gamma_{\text{eff}}$ at $R = 0.4R_{25}$, using the data from Pilyugin et al. (2004), but this correlation is clearly seen only for dwarf galaxies with $V < 100 \text{ km s}^{-1}$, where the effects of gas outflow may be essential (see, however, Gavilán et al. 2013, who found a yield $\gamma_{\text{eff}} \sim 0.006$ with high dispersion for gas-rich dIrr galaxies).

The galaxies we consider here rotate much faster. For them we do not find any significant link between $V$ and $\gamma_{\text{eff}}$ taken either at $R = 0$ or at $R = 0.4R_{25}$ (the correlation coefficients are less than 0.5).

Curiously, a correlation appears for fast-rotating galaxies if we take $\gamma_{\text{eff,max}}$ instead of $\gamma_{\text{eff}}(0)$, where $\gamma_{\text{eff,max}}$ is the maximal value of $\gamma_{\text{eff}}$ for a given galaxy. (We did not take into account
the central peak of $\gamma_{\text{eff}}$ in the bulge-dominated regions at $R < 0.2R_25$, where the accretion regime is dictated by bulge contribution.) In other words, $\gamma_{\text{eff, max}}$ is the effective yield at the radial distance of the main disk where one can expect the weakest influence of accretion or gas outflow on the gas-phase metallicity. In most, but not in all, cases, $\gamma_{\text{eff}}$ reaches its maximum in the outer disk (some exceptions were discussed in Section 2). Figure 2 demonstrates that for the spiral galaxies considered here, where, unlike dwarf galaxies, the effect of gas outflow is expected to be relatively low, there is a tendency to have lower values of $\gamma_{\text{eff, max}}$ for the most rapidly rotating galaxies, possessing massive virial dark halos. The numerical information for all correlations is given in Table 2. In the chi-square reducing procedure we assigned the statistical weights $w_i = 1/x_i^2$ where $x_i$ is the error bar of a given point. We performed the reducing procedure both with and without weighting (solid and dashed lines correspondingly). Insofar as a massive halo tends to reduce galactic winds, it allows us to conclude that it is the accretion that plays a major role in the more massive fast-rotating galaxies containing a large reservoir of slowly cooling gas.

In this and other diagrams for $\gamma_{\text{eff, max}}$ values, we used the oxygen abundance measurements by PT2005. The results for the KK2004 calibration, which we do not reproduce here, give qualitatively similar relationships, although with a larger spread of points on the diagrams.

Dalcanton (2007) found an anticorrelation between the gas mass fraction and $\gamma_{\text{eff}}$, but it is evident only after the inclusion of dwarf irregular galaxies. For the spiral galaxies we consider here, such a correlation is absent. Instead we found a positive trend (although with a large point spread) between the maximal effective yield and the total gas mass fraction $\mu$ (see Figure 3). This relation indicates that the deviation of the effective yield from the real stellar yield is stronger for galaxies with lower gas content: in this case the chemical evolution of gas is more sensitive to the accreting gas flow.

Since the behavior of $\gamma_{\text{eff}}$ beyond the optical borders is not known, it is worth trying to compare $\gamma_{\text{eff, max}}$ with the dark halo mass $M_{\text{halo}}$ inside the optical radius $R_{25}$, using the estimates of $M_{\text{halo}}$ compiled in Saburova & Del Popolo (2014). The results are given in Figure 4. They demonstrate the anticorrelation between the halo mass and $\gamma_{\text{eff, max}}$, which is in agreement with the proposed growing role of accretion along the halo mass sequence. The black open circle in Figure 4 marks the position of M33 according to Saburova & Zasov (2012) for the O/H ratio determined using the $T_e$ method. It agrees with the general tendency to have a higher $\gamma_{\text{eff, max}}$ for less-massive spiral galaxies.

The correlation with $\gamma_{\text{eff, max}}$ becomes tighter if instead of a dark halo mass we take the total mass of a galaxy within $R_{25}$: $M_{\text{tot}} = R_{25}^2V/G$ (see Figure 5). The outlier in the diagrams is NGC 4736. This galaxy possesses the lowest mass of dark halo among all the galaxies we consider (its rotation curve falls to the disk periphery), and hence it has a shallow potential well, so the effective gas outflow could be responsible for the low value of the effective yield. The position of this galaxy on the diagram agrees with that of low-mass dfr galaxies, which occupy a very wide range of $\gamma_{\text{eff}}$, revealing a positive correlation with the velocity of rotation (Dalcanton 2007), as expected in leaky-box models (see, however, the discussion in Gavilan et al. 2013). It seems that the spiral galaxies have a different mechanism regulating the gas inflow/outflow than do the dwarf ones.

We came to the conclusion that the maximal values of the effective yield are systematically lower for more massive dark halos or more massive spiral galaxies. A low maximal value of the effective yield $\gamma_{\text{eff, max}}$ means that the gas-phase abundance in a given galaxy is significantly reduced in comparison with the closed-box model all over a disk. Insofar as the gas outflow is less effective for more massive galaxies, it is natural to propose that the accretion of metal-poor gas, apparently via a cooling of hot halo gas, plays the most important role in galaxies that possess a high total mass or dark halo. This agrees with the models of formation and a subsequent evolution of galaxies that predict a growth of the efficiency of accretion with a halo mass. It is worth mentioning the model of formation of disk galaxies in the preheated media developed by Lu et al. (2015), which enables one to reproduce remarkably well a number of observational scaling relations. In this model the intergalactic circumhalo gas is assumed to be preheated up to a certain entropy level before it is accreted into dark matter halos (the preventative feedback model). Such an approach strongly reduces the baryon fraction that can collapse into the low-mass halos. In agreement with our data, the model predicts a monotonous increase of gas accretion efficiency along the dark halo mass sequence for present-day galaxies (see Figure 10 in Lu et al. 2015).

### 3.1. Relation between Dark Halo Mass Fraction and O/H Radial Gradient

Since the halo mass influences the chemical evolution of gas in a disk, we checked whether there is a connection between the dark halo mass fraction and the radial distribution of metallicity. For this purpose we use larger statistics than we used above, taking the sample of galaxies with available measurements of metallicity gradients from Pilyugin et al. (2014a) and the dark halo masses from Saburova & Del Popolo (2014). Note that the metallicity gradient is less sensitive to the calibration uncertainty than are the values of O/H.

In Figure 6 a mass of dark halo within the optical border, normalized to the stellar mass of a galaxy $M_*$, is compared with the O/H radial gradient expressed in terms of dex $R_{25}$. The stellar masses were calculated from the B-band luminosities and $(B - V)_0$ color indices through the Bell & de Jong
M/L-color model relation. For comparison, with open triangles we also show the gradients taken from the PT2005 calibration that we used above. The statistics are too poor for them to reveal any correlation, but the more representative Pilyugin et al. (2014a) data reveal a shallower gradient for low-halo galaxies. Three outliers with low gradients are NGC 3521, NGC 2841, and NGC 5457, which also have the higher central values of O/H than the average of the sample. Two of these galaxies have decreasing radial profiles of the effective yield (see Section 2), so their high gradient of O/H could be the result of the overabundance of oxygen in their inner parts. It is remarkable that, if we consider the central value of O/H instead of the gradient, the correlation vanishes, so it is not of a local nature. Although the link between the halo mass and the (O/H) gradient is not so tight, one should have in mind that typical errors of estimations are comparable with the dispersion of points on the diagram.

A possible explanation for the correlation is the most efficient radial gas mixing in galaxies with a low relative mass of dark halo as the result of a strong interaction experienced by

### Table 2

Linear Regression Equations

| Equation | A | B | r | Weighting |
|----------|---|---|---|-----------|
| $x_{\text{eff max}} = A + B \log(M_{\text{halo}}/R_{25})$ | 17 ± 6 | −1.4 ± 0.5 | 0.62 | yes |
| $x_{\text{eff max}} = A + B \log(M_{eb}/R_{25})$ | 20 ± 6.0 | −1.7 ± 0.6 | 0.68 | yes |
| $x_{\text{eff max}} = A + B \log(M_{eb}/R_{25})$ | 25 ± 4.8 | −2.0 ± 0.4 | 0.82 | yes |
| $x_{\text{eff max}} = A + B \log(M_{eb}/R_{25})$ | 23 ± 4.95 | −1.8 ± 0.4 | 0.80 | yes |
| $x_{\text{eff max}} = A + BV$ | 3.5 ± 0.6 | −0.007 ± 0.002 | 0.65 | yes |
| $x_{\text{eff max}} = A + BV$ | 4.7 ± 0.6 | −0.01 ± 0.003 | 0.74 | yes |
| $x_{\text{eff max}} = A + B\mu$ | 0.9 ± 0.4 | 4.6 ± 1.7 | 0.61 | yes |
| $x_{\text{eff max}} = A + B\mu$ | 1.6 ± 0.4 | 3.4 ± 1.6 | 0.53 | yes |

grad(O/H) = A + B* log(M_{halo}/M_{*})

Note. (1) Linear regression equation, (2) intercept, (3) slope, (4) correlation coefficient, (5) note on taking into account the error bars (yes for usage of weighting in the estimation of the regression, no for no weighting used).
found values of the effective yield $y_{\text{eff}}$ of galaxies based on the PT2005 data anticorrelate with the masses of galaxies within the optical radius and with their rotation velocities, being systematically lower for massive galaxies with higher dark halo masses. It demonstrates that the evolution of massive spiral galaxies possessing massive halos is especially different from that expected for a closed-box scenario. These results agree with the evolutionary models where the accretion of metal-poor halo gas most effectively reduces the oxygen abundance in the rapidly rotating galaxies with massive halos. We also found that galaxies with higher dark halo to stellar mass ratios have a tendency to possess a more shallow abundance gradient, although this result requires further verification.

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Figure 6. The radial gradient of the oxygen abundance taken from Pilyugin et al. (2014a) (filled circles) and PT2005 (open triangles) compared to the dark halo to stellar mass ratio within the optical borders (Saburova & Del Popolo 2014). The line denotes the linear regression. Three outliers with low gradients are NGC 3521, NGC 2841, and NGC 5457.

these galaxies in the past. The interaction or merging of galaxies leads not only to flattening of the abundance gradient (Werk et al. 2011) but also to the partial destruction of their halos (see the simulation results of Libeskind et al. 2011). In addition, a gas mixing leading to a shallow abundance gradient may also be caused by the turbulent viscosity or accretion of slowly rotating gas (see discussion in Elmegreen et al. 2014), although it is not evident that these processes are more active for low-mass halos.

4. CONCLUSIONS

We considered the radial profiles of the effective oxygen yield $y_{\text{eff}}$, which corresponds to the true stellar yield $y_\odot$, for the closed-box model. In real galaxies it may be lower than $y_\odot$ in the case of accretion or gas outflow from a disk. As the initial data for gas-phase abundance we used the O/H radial profiles for 14 spiral galaxies taken from Moustakas et al. (2010), which are based on different calibrations (the PT2005, Pilyugin & Thuan 2005 and KK2004, Kobulnicky & Kewley 2004 methods). The absolute values and shapes of the radial profiles $y_{\text{eff}}(R)$ of the effective yield are found to be very different for galaxies even of similar types, reflecting their different history of evolution. The yield $y_{\text{eff}}$ varies with galactocentric distance $R$ within a factor of 2–3. For galaxies with prominent bulges, both calibrations reveal a local maximum $y_{\text{eff}}(0)$ that may be interpreted as the result of the enriched gas inflow from bulge onto a disk in the bulge-dominating regions. In most galaxies, $y_{\text{eff}}(R)$ increases or remains roughly constant along the radius for the PT2005 version of O/H (which we consider the preferable one), remaining significantly lower than the existing estimates of the true stellar $y_\odot$. For the KK2004 data the situation is more ambiguous: the effective yield $y_{\text{eff}}(R)$ grows in eight out of 14 galaxies. We argue that the relatively low effective yield is evidence for the accretion of metal-poor gas, and, as the radial profiles of $y_{\text{eff}}$ show, in many cases a gas inflow is most effective for the inner parts of disks. A positive correlation between the $y_{\text{eff}}$ and gas mass fraction indicates that the accretion more significantly decreases the effective yield in galaxies with lower gas content. It is essential that the maximal