The oxygen abundance deficiency in irregular galaxies

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Abstract. The observed oxygen abundances in a number of irregular galaxies have been compared with predictions of the closed-box model of chemical and photometric evolution of galaxies. Oxygen is found to be deficient with respect to the predicted abundances. This is an indicator in favor of loss of heavy elements via galactic winds or/and of infall of low–abundance gas onto the galaxy.

The oxygen abundance deficiency observed within the optical edge of a galaxy cannot be explained by mixing with the gas envelope observed outside the optical limit. We confirm the widespread idea that a significant part of the heavy elements is ejected by irregular galaxies in the intergalactic medium.

Key words: Galaxies: abundances - Galaxies: evolution - Galaxies: ISM - Galaxies: irregular

1. Introduction

Irregular galaxies gained a central position in extragalactic studies, as the most abundant and least evolved galaxies in the universe. It was soon understood that they are not closed systems, and that galactic winds had to play a relevant role in their chemical evolution.

The hydrodynamic simulations of irregular galaxies lead to conflicting conclusions: de Young & Gallagher (1990), de Young & Heckman (1994) and MacLow & Ferrara (1999) found that irregulars can lose a significant fraction of metals via galactic winds; conversely, Silich & Tenorio-Tagle (1998) concluded that a low-density gaseous halo can inhibit the loss of matter from dwarf galaxies. Models of chemical evolution of irregular galaxies suggested that galactic winds can explain the chemical properties of these objects (Matteucci & Chiosi 1983; Matteucci & Tosi 1985; Pilyugin 1993, 1996; Marconi et al 1994; Bradamante et al 1998, and many others). Outflows of ionized gas have been observed in a number of irregular galaxies (Marlowe et al 1995). Skillman (1997) has summarized the pros and cons for galactic wind–dominated evolution of irregular galaxies and has concluded that neither case is very strong.

In our previous work (Pilyugin & Ferrini 1998), we defined the oxygen abundance deficiency in galaxies as 1 minus the ratio of the observed oxygen abundance to that predicted by the closed-box model for the same gas mass fraction. Variations of the oxygen abundance deficiency from galaxy to galaxy can only be caused by differences in gas exchange between galaxies and their environments. In turn, the oxygen abundance deficiency can be considered as an indicator of mass exchange, in particular by galactic winds. The goal of the present study is to study this problem quantitatively. In Section 2 we present the observational data base. The stellar mass to luminosity ratio in irregular galaxies is derived in Section 3, the values of the oxygen abundance deficiency for a number of irregulars are obtained in Section 4. Section 5 contains discussion and a summary.

2. Observational data

The data base used in this study consists of published B magnitudes of irregular galaxies, B–V colors, distances, oxygen abundances, HI emission fluxes, and radial distributions of HI. The variations in oxygen abundance from region to region in the best studied irregular galaxies are always within the observational errors (Pagel et al 1978, Skillman et al 1989) and there is no detectable radial oxygen abundance gradient. Then, the chemical composition of irregular galaxy can be specified by a single parameter.

Our sample contains 25 irregular galaxies for which we have collected the relevant observational data, given with references in Table 1. The commonly used name(s) are given in columns 1 and 2, the Hubble type (T from de Vaucouleurs et al 1991, RC3) in column 3, the adopted
Table 1. Observational characteristics (with references) for the galaxies included in the present sample

| Name       | Other name | $T$ type | Distance Mpc | Ref     | $\log L_B$ | $\log M_{HI}$ | B-V | 12+$\log O/H$ | Ref     |
|------------|------------|----------|--------------|---------|------------|---------------|-----|---------------|---------|
| WLM        | DDO 221    | 10       | 0.95 c       | MF, LFM, SC | 7.92       | 7.80          | 0.31 | 7.74          | STM     |
| NGC55      | 9          | 1.45     | G            |         | 9.47       | 8.99          | 0.38 | 8.34          | RM      |
| IC10       | 10         | 0.83 c   | SHKD, WWRSH  |         | 8.76       | 7.96          | 1.06 | 8.18          | LPRSTP  |
| SMC        | 9          | 0.06 c   | F            |         | 8.82       | 8.68          | 0.36 | 8.03          | RM      |
| IC1613     | DDO 8      | 10       | 0.75 c       | MF, LFM  | 8.02       | 7.80          | 0.65 | 7.71          | RM      |
| NGC1156    | 9          | 7.80     | KMG          |         | 9.44       | 9.03          | 0.38 | 8.23          | VSC     |
| NGC1569    | 7 Zw 16    | 10       | 2.01         | KT      | 9.02       | 7.97          | 0.23 | 8.16          | RM      |
| LMC        | 9          | 0.05     | LFM          |         | 9.31       | 8.58          | 0.43 | 8.35          | RM      |
| NGC2366    | DDO 42     | 10       | 3.44 c       | TSHM    | 8.85       | 8.91          | 0.45 | 7.92          | RM      |
| DDO47      | 10         | 4.27     | KT           |         | 8.05       | 8.44          | 0.45 | 7.85          | SKH     |
| HolmbergII | DDO 50     | 10       | 3.05 c       | HSD     | 8.80       | 8.82          | 0.39 | 7.92          | RM      |
| Leo A      | DDO 69     | 10       | 2.20 c       | HSKD    | 7.80       | 7.87          | 0.26 | 7.30          | SKH     |
| Sex B      | DDO 70     | 10       | 1.44 c       | MF      | 7.88       | 7.65          | 0.47 | 8.11          | MAM     |
| NGC3109    | DDO 236    | 9        | 1.36 c       | MPC     | 8.66       | 8.74          |       | 8.06          | RM      |
| Sex A      | DDO 75     | 10       | 1.45 c       | SMF     | 7.82       | 7.94          | 0.35 | 7.49          | SKH     |
| IC2574     | DDO 81     | 9        | 3.40         | KT      | 9.12       | 9.05          | 0.34 | 8.08          | RM      |
| NGC4214    | 10         | 4.10     | Letal        |         | 9.37       | 9.05          | 0.43 | 8.23          | RM      |
| NGC4449    | 10         | 5.40     | HT           |         | 9.69       | 9.47          | 0.37 | 8.32          | SKH     |
| GR8        | DDO 155    | 10       | 2.24 c       | TSHD    | 7.04       | 7.00          | 0.30 | 7.68          | MAM     |
| NGC5253    | 10         | 4.09 c   | Setal        |         | 9.23       | 8.36          | 0.28 | 8.16          | PSTE, RSRWR |
| NGC5408    | Tol 116    | 10       | 3.24         | RM      | 8.54       | 8.21          | 0.42 | 8.01          | RM      |
| IC4662     | 10         | 2.00     | H-MMM        |         | 8.29       | 8.08          | 0.29 | 8.06          | H-MMM   |
| NGC6822    | 10         | 0.51 c   | MF, LFM      |         | 8.25       | 7.84          |       | 8.23          | RM      |
| Pegasus    | 10         | 0.76     | Getal        |         | 6.77       | 6.51          | 0.54 | 7.93          | SBK     |

Note to Table:
The cepheid distances are labeled with letter c.
The B-V value for IC10 is taken from VSC.
HI measurement for DDO53 is taken from vDetal

List of references to Table: F – Freedman, 1988; G – Graham, 1982; Getal – Gallagher et al, 1998; GKT – Georgiev, Karachentsev, Tikhonov, 1997; H-MMM – Heydari-Malayeri, Melnick, Martin 1990; HSD – Hoessel, Saha, Danielson, 1998; HSKD – Hoessel, Saha, Krist, Danielson, 1994; HT – Hunter, Thronson, 1996; KMG – Karachentsev, Musella, Grimaldi, 1996; KSRWR – Kobulnicky, Skillman, Roy, Walsh, Rosa, 1997; KT – Karachentsev, Tikhonov, 1994; Letal – Leitherer, Vacca, Conti, Filippenko, Robert, Sargent, 1996; LFM – Lee, Freedman, Madore, 1993; LPRSTP – Lequeux, Peimbert, Rayo, serrano, Torres-Peimbert, 1979; MAM – Moles, Aparicio, Masegosa, 1990; HSD – Hoessel, Danielson, 1991; MFC – Musella, Piutto, Capaccioli, 1997; PSTE – Pagel, Simonson, Terlevich, Edmunds, 1992; RM – Richer, McCall, 1995; SC – Sandage, Carlson, 1985; SBK – Skillman, Robert, 1989; TSHD – Tolstoy, Saha, Hoessel, Danielson, 1995; TSHD – Tolstoy, Saha, Hoessel, McQuade, 1995; vDetal – van Driel, Kraan-Korteweg, Binggeli, Huchtmeier, 1998; VSC – Vigroux, Stasinska, Comte, 1987; WWRSH – Wilson, Welch, Reid, Saha, Hoessel, 1996

3. Stellar mass to luminosity ratio

Irregular galaxies can contain a large amount of dark matter (Carignan & Beaulieu 1989, Kumai & Tosa 1992) which might not take part directly to the chemical evolution. The luminous mass (mass of gas, stars, and stellar remnants) should be used rather than the dynamical mass in investigations of the chemical properties of irregular galaxies. The mass of stars $M_s$ including stellar rem-
nants can be derived from the luminosity of the galaxy if the stellar mass to light ratio $\Upsilon = M_s/L_B$ can be determined. It depends on the star formation history (SFH) in the galaxy. For a few nearby irregular galaxies the star formation history can be derived from the color-magnitude diagram of a large number of individual stars. Such determinations exist for the LMC (Butcher 1977, Frogel 1984, Bertelli et al 1992, Elson et al 1994), NGC 6822 (Gallart et al 1996a,b), the Pegasus dwarf (Aparicio et al 1997, Gallagher et al 1998), and Sextans A (Dohm-Palmer et al 1997). Two variants of star formation histories will be used for Pegasus dwarf according to two different estimates of the distance: 0.95 Mpc from Aparicio et al (1997), and 0.76 Mpc from Gallagher et al (1998).

| Galaxy      | (U-B)$O$ | (U-B)$C$ | (B-V)$O$ | (B-V)$C$ | $M_s/L_B$ |
|-------------|---------|---------|--------|--------|---------|
| LMC         | -0.06   | -0.08   | 0.43   | 0.44   | 0.47    |
| NGC6822     | -0.37   | 0.24    | 0.35   | 0.75   | 0.94    |
| Pegasus$^1$ | 0.06    | -0.07   | 0.54   | 0.48   | 0.75    |
| Pegasus$^2$ | 0.06    | 0.02    | 0.54   | 0.59   | 0.94    |
| Sextans A   | -0.36   | -0.38   | 0.26   | 0.24   | 0.29    |

Notes to Table: 1 – SFH from Aparicio et al, 1997; 2 – SFH from Gallagher et al, 1998

Using our model for the chemical and photometric evolution of an one-zone system (Pilyugin & Ferrini 1998), the mass to luminosity ratios $M_s/L_B$ and colors U-B and B-V have been computed for galaxies with known star formation histories. The case S of nucleosynthesis has been adopted (Pilyugin & Ferrini 1998). The computed and observed U-B and B-V colors as well as the computed star mass to luminosity ratios of these galaxies are given in Table 2. The observed colors of galaxies were taken from RC3 for the LMC and the Pegasus dwarf, and from Hunter & Plummer (1996) for Sextans A.

Fig. 1. The positions of galaxies with known star formation history (SFH) (filled circles) in the diagram stellar mass to luminosity ratio $M_s/L_B$ versus B-V. These positions are compared with the results of models with smooth SFHs (crosses) for different values of $\tau$, and of models with gasping (long-dashed line) and bursting (short-dashed line) SFHs for different values of $t_0$. The solid line is the $M_s/L_B - (B-V)$ relationship adopted in this paper.

A grid of models with smooth star formation history for different values of $\tau$ from 1 Gyr (a strongly increasing star formation rate) to 500 Gyr (an almost constant star formation rate) have been computed. The star formation history with $\tau=13$ Gyr is shown in the Fig. by a long-dashed line. The positions of these models in the $M_s/L_B$ versus B-V diagram are shown in the Fig. by crosses. The agreement between these models and the representative points of galaxies is not good. In particular, the values of B-V larger than $\sim 0.4$ observed in some irregulars cannot be reproduced. The predictions of these models together with positions of galaxies from Table are shown on Fig. in the U-B, B-V diagram. It is clear that models with smooth star formation histories cannot reproduce the observed positions of irregular galaxies in this diagram.

This disagreement is a consequence of the hypothesis that the SFH is smooth. Actually star formation in irregular galaxies is not smooth: active periods alternate with quiet periods. In order to take this into account, models with non–smooth star formation histories have been computed. We describe it by the expression

$$\psi(t) \propto \begin{cases} A(t) \exp(t/\tau) & \text{if } A(t) > 0, \\ 0 & \text{if } A(t) \leq 0, \end{cases}$$

$$A(t) = \cos(t/\tau_p + t_0) + c.$$
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Fig. 2. Continuous (long-dashed line), bursting (solid line), and gasping (short-dashed line) star formation histories (SFH).

The parameter $\tau_P$, which indicates the number of cycles of star formation during the lifetime of a galaxy $t_{gal}$ (that we adopted to be $t_{gal} = 13\text{Gyr}$), is defined as

$$t_{gal}/\tau_P = 2n\pi.$$  \hspace{1cm} (4)

Each cycle consists of an epoch with active star formation and an epoch without star formation. Their relative duration is governed by the parameter $c$. The case $c = 0$ corresponds to a periodic star formation history, in which the durations are equal. The values $-1 < c < 0$ corresponds to shorter epochs with active star formation. This case will be referred to as a “bursting” star formation history. The case with $c = -0.75$, $\tau = 13\text{ Gyr}$, $t_0 = 0$, and $n = 7$ is shown in Fig. 2. The values $0 < c < 1$ corresponds to the opposite case. Following Tosi (1993), this case will be referred to as a “gasing” star formation history. The case with $c = 0.75$, $\tau = 13\text{ Gyr}$, $t_0 = 0$, and $n = 7$ is shown in Fig. 2. The point in the cycle of star formation at the present time is governed by the choice of $t_0$ (Fig. 2). As it can be seen in Fig. 2, the B-V color and stellar mass to luminosity ratio $M_s/L_B$ are strongly dependent on $t_0$ (Fig. 2 shows the evolutionary change of B-V and $M_s/L_B$ during the last cycle of star formation). The values of B-V and $M_s/L_B$ have a maximum at the point just before the beginning of the star formation phase. The values B-V and $M_s/L_B$ decrease with increasing of star formation rate, pass through a minimum at the maximum star formation rate, and then increase.

A grid of models with gasping star formation history has been computed. The positions of these models in the $M_s/L_B$ versus (B-V) diagram for various values of $t_0$ and for fixed values of other parameters ($\tau$=13 Gyr, $n=7$, $c=0.75$) are shown in Fig. 3. A similar grid of models with bursting star formation history has also be computed with $\tau$=13 Gyr, $n=7$, $c=-0.75$ (Fig. 3). The fit with observations is now good. It is also good in the U-B versus B-V diagram. Some remaining discrepancies might be explained by the contribution of the ionized gas emission to the radiation of galaxy, which is not taken into account in the present models. Fig. 1 and 3 suggest that the mass to luminosity ratio for and irregular galaxy with unknown star formation history can be estimated from its measured B-V color and relationship between stellar mass to luminosity ratio and B-V color.

Up to here we have only considered models with a fixed present oxygen abundance $12+\log (O/H)=8.2$ ($O/H \approx 1/5(O/H)_\odot$). The mass to luminosity ratio depends not only on the star formation history but also on the metallicity. To examine the dependence of the mass to luminosity ratio on the metallicity, models with bursting star formation history and with present oxygen abundances $12+\log (O/H)=7.9$ ($O/H \approx 1/10(O/H)_\odot$) and $12+\log (O/H)=8.4$ ($O/H \approx 1/3(O/H)_\odot$) have been computed. For the range of observed B-V (0.3 to 0.5) the differences in $M_s/L_B$ predicted by models with $12+\log O/H=7.9$ and $12+\log O/H=8.4$ with those predicted by models with $12+\log O/H=8.2$ are smaller than 15 per cent (Fig. 4). On the other hand, Fig. 5 shows that there is no correlation between B-V and the present-day oxygen abundance. This shows that B-V is mainly determined by the star formation history in the recent past. Therefore the relationship between stellar mass to luminosity ratio $M_s/L_B$ and B-V color can be considered as independent on the present oxygen abundance.
We adopt as a first approximation a linear relationship between mass to luminosity ratio $M_s/L_B$ and B-V color (Fig.1)

$$\Upsilon_s = -0.10 \pm 0.15 + 1.60 (B - V).$$

The error on the intercept includes the range of models.

4. Oxygen abundance deficiency in irregular galaxies

4.1. Hydrogen content in irregular galaxies

The size of irregular galaxies in HI is larger than their optical size (Salpeter & Hoffman 1996, and references therein). As we have seen, the variations of oxygen abundance from region to region in the best studied irregular galaxies are within observational errors, a strong evidence that irregular galaxies are well mixed system inside the optical diameter. If the zone of the mixing extends to the outer HI then the gas outside the optical diameter can contain a significant part of the heavy elements produced by the stars and, therefore, can play an important role in the chemical evolution of the galaxy. Hunter & Gallagher (1985) have found that the presence or absence of extended HI envelopes does not appear to be reflected in the properties of the optical components of irregular galaxies. They concluded that only the gas within the optical limit plays an important role in the life of a galaxy.

The mass of atomic hydrogen in the irregular galaxies listed in Table 1 is the total mass. For a number of irregular galaxies from our sample there are measurements of radial distribution of surface mass density of atomic hydrogen that allows to determine the fraction of HI mass within the optical diameter $f_{opt}$. Table 1 gives the fraction $f_{opt}$ and the ratio of the hydrogen radius $R_H$ (radius at face-on surface mass density of atomic hydrogen of $1 M_\odot pc^{-2}$) to the optical radius $R_{25}$ (from RC3). Table 1 shows the fraction of HI mass within the optical diameter of a galaxy varies widely from $f_{opt} = 0.36$ for GR 8 to $f_{opt} = 0.92$ for NGC 55.

4.2. Oxygen abundance deficiency in irregular galaxies

The gas mass fraction $\mu$ is defined as

$$\mu = M_g/(M_g + M_s),$$

where $M_g$ is the mass of gas within the optical radius $R_{25}$ of the galaxy. The mass of stars is derived from the blue luminosity and the mass to luminosity ratio $\Upsilon_s$

$$M_s = \Upsilon_s \times L_B.$$
The values of Υ_s computed using relation (8) are listed in column 2 of Table 3. The mass of gas within the optical edge of a galaxy is taken as

\[ M_{\text{gas}} = f_{\text{opt}} \times (1.4 \times (1 + r_{H_2}) \times M_{HI}) \]  

(8)

where the factors \( r_{H_2} \) and 1.4 are introduced to take the contributions of molecular hydrogen and helium to gas mass into account, respectively. \( f_{\text{opt}} \) comes from Table 3. The correction for the presence of molecular hydrogen is uncertain since the \( H_2 \) content has been determined from CO line observations in a few irregular galaxies only. Fortunately, the average global \( H_2 \) to HI mass ratio \( r_{H_2} = H_2/\text{HI} \) is not large for these galaxies, \( r_{H_2} = 0.2 \pm 0.04 \), (Israel 1997). Here we adopt \( r_{H_2} = 0.2 \) for all the galaxies. The values of \( \mu \) are given in column 3 of Table 3.

The global oxygen abundance deficiency is defined as

\[ \eta = 1 - Z_{\text{O, obs}}/Z_{\text{O, CB}}. \]

The values of \( \eta \) are given in column 4 of Table 4. The positions of irregular galaxies in the \( \mu - O/\text{H} \) diagram shown on Fig. 4 by circles. The curve defined by the one-zone closed-box models with different gas mass fraction (this curve will be referred to as standard curve) is shown on Fig. 4 as a solid line. For comparison we show the positions for various regions of the two spiral galaxies NGC 5457 (dashed line with crosses) and NGC 2403 (dashed line with lozenges) (data from Pilyugin & Ferrini 1998). NGC 5457 has no oxygen abundance deficiency, and NGC 2403 has the largest global oxygen abundance deficiency (\( \eta = 0.57 \)) among the spiral galaxies considered by Pilyugin and Ferrini (1998). As it can be seen in Fig. 4, all the irregular galaxies are significantly displaced from the standard curve. Their values of oxygen abundance deficiency are also in excess of that in the dwarf spiral galaxy NGC 2403. The values of oxygen abundance deficiency range from \( \sim 0.5 \) to \( \sim 0.9 \). The relationships between the value of oxygen abundance deficiency and global parameters will be given in one of the next papers of this series.

Since irregular galaxies are gas-rich systems (as it can be seen from Table 3) the mass of gas component exceeds the mass of the stellar component in the galaxy) the total luminous mass to luminosity ratio \( \Upsilon_t = M_t/L_B = (M_s + M_{\text{gas}})/L_B \) is significantly larger than the value of star mass to luminosity ratio \( \Upsilon_s \) (compare the data from columns 2 and 5 of Table 4).

Can the oxygen abundance deficiency within optical edge of irregular galaxy be explained by the mixing of interstellar matter with gas outside the optical edge? To study this possibility, the oxygen abundance deficiency have been re-computed under the assumption that all the gas associated with a galaxy is well mixed. In this case the mass of gas in the galaxy is

\[ M_{\text{gas}} = 1.4 \times (1 + r_{H_2}) \times M_{HI}. \]

(9)
All the other values are derived in the same way as in the previous case. The values of $\mu$, $\eta$, and $M_\ell/L_B$ are listed in columns 6-8 of Table 4.

The positions of irregular galaxies in the $\mu$ vs. O/H diagram in the present case are shown on Fig. 7: significant displacements of irregular galaxies relative to the standard curve remain. The inclusion of extended HI envelope outside the optical radius only slightly decreases the displacement of irregular galaxies relative to the standard curve.

5. Conclusions

We have found that all the irregular galaxies considered here have a significant oxygen abundance deficiency. This is a strong argument in favor of an important role of mass exchange with the environment in the chemical evolution of these galaxies. These conclusions remain even if one takes into consideration the gas envelope observed outside the optical edge. This confirm the widespread idea that a significant part of the heavy elements is ejected by irregular galaxies in the intergalactic medium.

We emphasize that the relation between oxygen abundance vs. gas mass fraction in the closed box model used in present study was constructed so that the positions of the most metal-rich giant spiral galaxies (including NGC 5457) in the $\mu$ - O/H diagram are fitted by this relation (Pilyugin & Ferrini 1998). Therefore the oxygen abundance deficiency of irregular galaxies can also be considered as relative to the giant spiral galaxy NGC 5457. It has been found by Pilyugin & Ferrini (1998) that the precise choice of the oxygen production by individual stars and of the parameters of the initial mass function are not critical in this differential comparison.

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