On the origin of the luminosity-metallicity relation for late-type galaxies

Spirals to irregulars transition

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Abstract. We consider the roles of two widely invoked mechanisms for the metallicity-luminosity correlation among late-type galaxies: higher astration level and decreasing efficiency of heavy-element loss with increasing luminosity. We find that both mechanisms contribute about equally to the range in oxygen abundance between low ($logL_B \sim 8$) and high ($logL_B \sim 10.5$) luminosity galaxies.

We also consider the transition from spirals to irregulars, finding that both the oxygen abundance deficiency (indicating the degree of mass exchange between a galaxy and its environment) and the gas fraction vary smoothly along the sequence. Thus we find no "irregular versus spiral dichotomy".

Key words: galaxies: abundances – galaxies: evolution – galaxies: ISM

1. Introduction

Twenty years ago Lequeux et al. (1979) have revealed that the oxygen abundance correlates with total galaxy mass for irregular galaxies. Since the galaxy mass is a poorly known parameter, the luminosity-metallicity relation instead of the mass - metallicity relation is usually considered (Skillman et al. 1989; Richer & McCall 1995). It has been found that the characteristic gas-phase abundances (the oxygen abundance at a predetermined galactocentric distance) and luminosities of spiral galaxies are also correlated (Garnett & Shields 1987; Vila-Costas & Edmunds 1992; Zaritsky et al. 1994; Garnett et al. 1997), and this relationship maps almost directly on to the luminosity-metallicity relationship of irregular galaxies (Zaritsky et al. 1994; Garnett et al. 1997).

It is widely suggested that the luminosity-metallicity relation for irregular galaxies is caused by galactic winds of different efficiencies. In other words, the luminosity-metallicity relation represents the ability of a given galaxy to keep the products of its own evolution rather than their ability to produce metals (Larson 1974). On the other hand, it has been found that the astration level is higher in massive irregular galaxies than in dwarf

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ones (Lequeux et al. 1979; Vigroux et al. 1987). The systematic increase of the astration level with luminosity can also play a role in the origin of the luminosity-metallicity relationship.

The elucidation of mechanisms which are responsible for a luminosity-metallicity relation for spirals and irregulars, the clarification of irregulars versus spirals dichotomy or the justification of the lack of this dichotomy is very important for the understanding of the galaxy formation and evolution. The values of gas mass fraction μ and oxygen abundance deficiency (which is a good indicator of efficiency of mass exchange between a galaxy and its environments) have been derived for a number of spiral (Pilyugin & Ferrini 1998) and irregular (Pilyugin & Ferrini 2000) galaxies. Using these data, the roles of two mechanisms – astration level increasing with luminosity and efficiency of heavy elements loss decreasing – as causes of the metallicity - luminosity correlation among later-type spiral and irregular galaxies will be examined in the present study, along with the transition from spirals to irregulars.

2. The luminosity-metallicity relation for late-type galaxies

The L_B versus O/H diagram for late-type galaxies is presented in Fig. 1. The positions of late-type spiral galaxies from Garnett et al. (1997) are shown by crosses. The representative oxygen abundance is the characteristic mean abundance at one disk scale length from the nucleus. The circles are late-type spiral galaxies for which the values of global oxygen abundance deficiency η and global gas mass fraction μ were derived by Pilyugin & Ferrini (1998). The positions of irregular galaxies from Richer & McCall (1995) are shown with pluses. The triangles are irregular galaxies for which the values of oxygen abundance deficiency and gas mass fraction have been derived by Pilyugin & Ferrini (2000). As can be seen in Fig. 1, the positions of irregular galaxies from our sample are systematically shifted towards high luminosities as compared to the data of Richer and McCall. This small shift is caused by the fact that in the work of Richer & McCall (1995) the absolute B magnitudes are based on the apparent B magnitudes given in RC3 whereas in ours they are based on the B_T^0 (total face-on magnitude corrected for galactic and internal absorption) given in RC3. The solid line
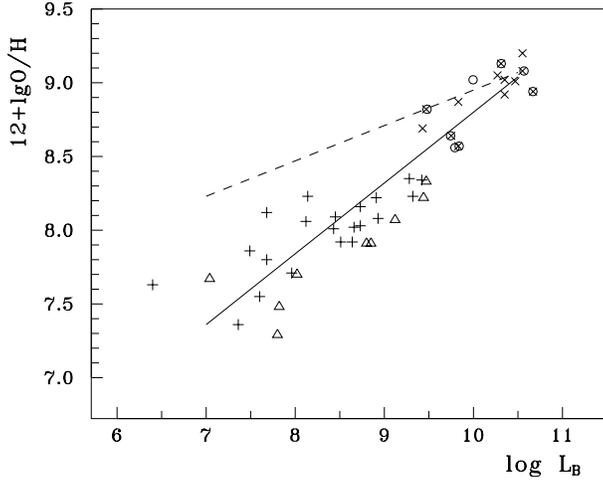
Fig. 1. L_B versus O/H diagram for late-type galaxies. The crosses are late-type spirals from Garnett et al. (1997). The circles are late-type spirals from Pilyugin & Ferrini (1998). The pluses are irregulars from Richer & McCall (1995). The triangles are irregulars from Pilyugin & Ferrini (2000). The solid line is the adopted relationship between oxygen abundance and luminosity. The variation in oxygen abundance with luminosity due to the systematic increase of the astration level with luminosity is shown by the dashed line (see text).

in Fig. 1 is the adopted relationship between oxygen abundance and luminosity. The corresponding equation is

$$12 + \log O/H = 4.0 + 0.48 \times \log L_B. \tag{1}$$

The L_B versus μ diagram and the L_B versus η diagram for late-type galaxies are presented in Fig. 2 and Fig. 3, respectively. The circles are spiral galaxies from Pilyugin & Ferrini (1998), the triangles are irregular galaxies from Pilyugin & Ferrini (2000). Inspection of Fig. 2 shows that there is a correlation between the gas mass fraction μ and the galaxy's luminosity, decreasing from $\mu \sim 0.8$ at $\log L_B = 7$ to $\mu \sim 0.2$ at $\log L_B = 10.5$. At the same time, as can be seen in Fig. 3, the oxygen abundance deficiency (which is an indicator of efficiency of galactic winds or/and the present-day gas infall) increases with decreasing luminosity over the large interval of luminosity. Then, one can expect that both mechanisms contribute to the effect. The available data allow to distinguish the contribution of the decrease of gas mass fraction with luminosity and the contribution of the decrease of galactic wind efficiency with luminosity to the difference in oxygen abundances of low- and high-luminosity galaxies.

We discuss first the contribution of the gas mass fraction. The relationship between it and galaxy luminosity can be approximated by the linear expression shown in Fig. 2 by the dashed line. The corresponding equation is

$$\mu = 2.0 - 0.17 \times \log L_B. \tag{2}$$

The oxygen abundance as a function of present-day gas fraction has been computed for closed-box model galaxies using the model of chemical and photometric evolution of galaxies by Pilyugin & Ferrini (1998). Abundances as a function of present-day gas fraction (standard curve from Pilyugin & Ferrini 1998,
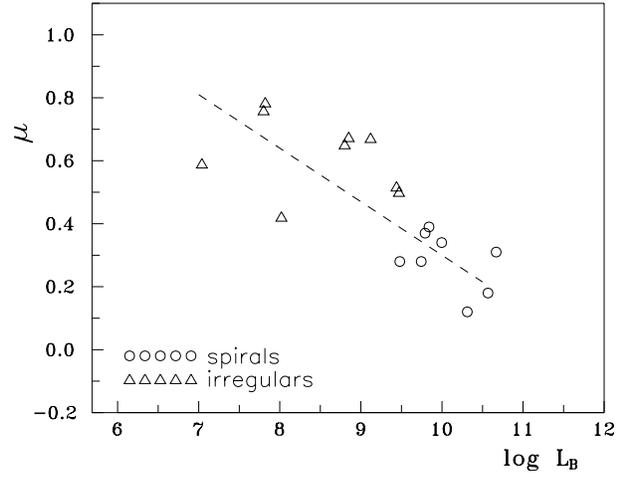
Fig. 2. L_B versus μ for late-type galaxies. The circles are late-type spirals from Pilyugin & Ferrini (1998). The triangles are irregulars from Pilyugin & Ferrini (2000). The line is the adopted relationship between gas mass fraction and luminosity.
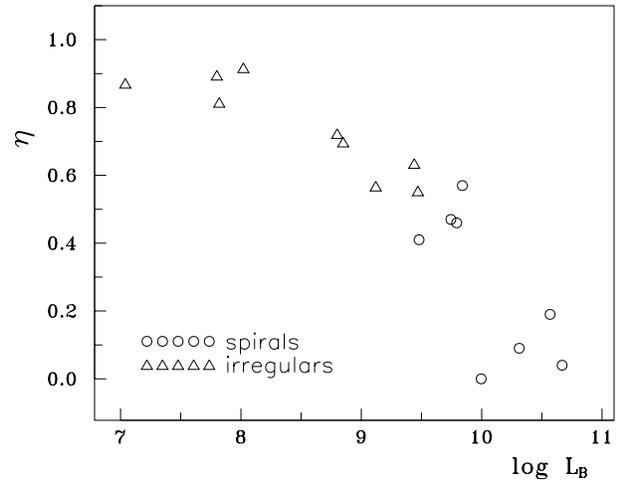
Fig. 3. L_B versus η for late-type galaxies. The circles are late-type spirals from Pilyugin & Ferrini (1998). The triangles are irregulars from Pilyugin & Ferrini (2000).

2000) are shown by the solid curve in Fig. 4. Within the interval $\mu = 0.2$ to $\mu = 0.8$ the dependence can be well represented by the linear expression

$$12 + \log O/H_{CB} = 9.35 - 1.4 \times \mu, \tag{3}$$

shown with dashed line in Fig. 4. The variation in oxygen abundance caused by the increase of astration level with luminosity can be derived from Eqs. (2) and (3),

$$12 + log O/H_{CB} = 6.55 + 0.24 \times log L_B, \tag{4}$$

and it is shown in Fig. 1 by a dashed line. This relation can explain the difference in oxygen abundances between a galaxy of luminosity $log L_B = 8$ and a galaxy of luminosity $log L_B = 10.5$ around 0.6 dex, while as it results from Fig. 1 the observed difference is around 1.2 dex. Thus the increase in astration level causes about half of the effect, in agreement with the fact that
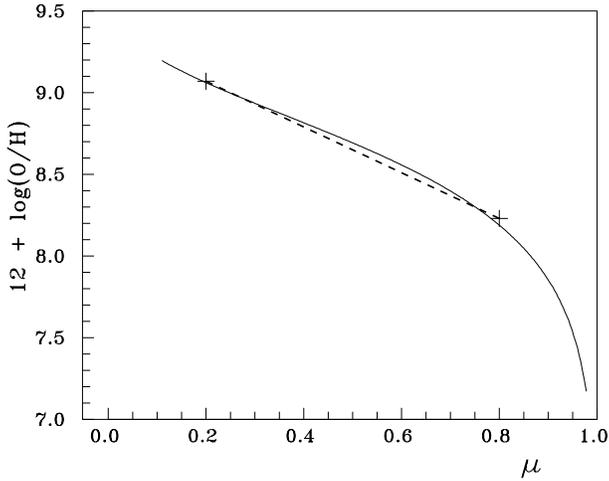
Fig. 4. μ versus O/H diagram. The positions of one-zone closed-box models with different present-day gas mass fraction (the standard curve) is presented by the solid line. The dashed line is the linear approximation on the gas mass fraction interval from $\mu = 0.2$ to $\mu = 0.8$.

elliptical galaxies have oxygen abundances exceeding those of comparably luminous dwarf irregulars (Richer & McCall 1995), but not all of it.

The deviation of a galaxy's position from the dashed line in (Fig. 1) indicates the contribution of heavy elements loss to the luminosity-metallicity correlation. The oxygen abundance z_O in the interstellar medium of an irregular galaxy evolving with both non selective heavy elements loss via ordinary galactic winds and selective heavy elements loss via enriched galactic winds is given by

$$z_O = \frac{p_O\,(1 - \lambda_E\,f_O)}{1 + \lambda/\alpha}\,ln\big[\frac{1 + \lambda/\alpha}{\mu} - \frac{\lambda}{\alpha}\big], \qquad (5)$$

(Pilyugin 1994), where α is the proportion of mass in each generation of stars that remains locked up in long-lived stars or remnants, p_O is the yield of oxygen (the mass of new oxygen produced by generation of stars per unit mass locked up in long-lived stars or remnants), λ_O is the efficiency of ordinary galactic wind (the ratio of the mass of the ambient interstellar medium which leaves the galaxy via galactic wind to the mass of star generation which is indirect cause for this wind), λ_E is the efficiency of enriched galactic wind (the fraction of the mass of type II supernovae ejecta leaving the galaxy), f_O is the contribution of type II supernovae to the oxygen production, λ is the total efficiency of mass loss via ordinary and enriched galactic winds

$$\lambda = \lambda_O + \lambda_E\,f_m\,(1 - \alpha), \qquad (6)$$

where f_m is the contribution of type II supernovae to the cumulative mass of matter ejected by a stellar generation into the interstellar medium over the Hubble time.

In case S of nucleosynthesis (Pilyugin & Ferrini 1998) we have; $p_O = 0.00866$, $\alpha = 0.206$, $f_m = 0.315$, and $f_O \approx 1$. In order to establish the contributions of enriched and ordinary

galactic winds to the total mass loss, the abundances of two elements with different values of f_j should be considered. Since only the oxygen abundance is considered here, two cases of evolution of a system (evolution with only an ordinary galactic wind, and evolution with only an enriched galactic wind) will be considered. A "typical" galaxy of luminosity $L_B = 10^8 L_{B,\odot}$ has a gas mass fraction $\mu = 0.65$ (Eq. 2) and oxygen abundance 12+logO/H = 7.85 (Eq. 1). If this galaxy evolves with enriched galactic wind only ($\lambda_O = 0$) then the efficiency of enriched galactic wind would be as large as $\lambda_E \approx 3/4$ (Eq. 5). In other words, a galaxy of luminosity $L_B = 10^8 L_{B,\odot}$ keeps only $\sim 1/4$ of the oxygen produced in course of its evolution. This value is not in contradiction with predictions of hydrodynamic models (de Young & Gallagher 1990; de Young & Heckman 1994; McLow & Ferrara 1999). It should be noted that the derived efficiency of the enriched galactic wind is an upper limit since the ordinary galactic wind was not taken into account. If this galaxy evolves with ordinary galactic wind only ($\lambda_E = 0$) then the efficiency of ordinary galactic wind would be as large as $\lambda_O \approx 6.2$. (Again, the derived value of λ_O is an upper limit since the enriched galactic wind was not taken into account). In other words, a galaxy of luminosity $L_B = 10^8 L_{B,\odot}$ keeps only ~ 0.1 of its initial mass. It should be noted for comparison that a dwarf elliptical galaxy can lose of the order of 99 per cent of its initial mass (Vigroux et al. 1981).

Richer & McCall (1995) have revealed a prominent feature of their metallicity - luminosity relation for irregular galaxies: they have found more scatter at low luminosities, though they found less at high luminosities. The onset of this scatter seems to occur at $M_B \sim -15$ or $log L_B \sim 8.2$. Moreover, Hidalgo-Gamez & Olofsson (1998) have found that there is no relationship between the oxygen abundance and the absolute magnitude in the blue band for dwarf irregular galaxies ($M_B > -17$ or $log L_B < 9$). The following explanation of the disappearance (or increased scatter) of the luminosity-metallicity correlation at low luminosities can be suggested, bearing in mind that the oxygen abundance deficiency becomes constant at low luminosities (Fig. 3). This plateau in the η - L_B relation could be caused by a lack of dependence of galactic winds on luminosity at the low-luminosity end, which in turn could result in the absence of a relationship between luminosity and oxygen abundance. However, the dwarf galaxies with a well determined oxygen abundance deficiency are few in number, so that the edge and even the existence of the plateau are not beyond question.

Thus, both the increase in astration level and the decreasing efficiency of heavy element loss, with increasing luminosity, make comparable contributions to the luminosity-metallicity correlation.

3. Discussion and conclusions

By tradition, the late-type galaxies are divided into two classes (irregulars and spirals), and these classes of galaxies are investigated individually. In particular, the existing models of chemical evolution of spiral galaxies are quite different from the ones applied to irregular galaxies. In order to reproduce the obser-

vational data (mainly for our Galaxy which is a giant spiral) various versions of the infall model, in which an infall of gas onto the disk takes place for a long time, have been suggested for spiral galaxies (Ferrini et al. 1992; Pilyugin & Edmunds 1996, among others). The hypothesis of an infall of gas onto the disks of spiral galaxies is confirmed by the observational data. Wakker et al. (1998) found direct observational evidence for the infall of low-metallicity gas on the Milky Way, required in models of galactic chemical evolution. The Magellanic Stream is another excellent example of the present-day capture of the matter by our Galaxy from satellite galaxies. On the other hand, various versions of models in which an ejection of gas from the galaxy takes place, have been suggested for irregular galaxies (Matteucci & Chiosi 1983; Matteucci & Tosi 1985; Pilyugin 1993, 1996; Marconi et al. 1994; Bradamante et al. 1998, among others). The hypothesis of gas outflows from dwarf galaxies is also confirmed by observational data. Outflows of gas have been observed in a number of galaxies (Marlowe et al. 1995; Heckman 1997). However, from Sc to Im the Hubble sequence is really a luminosity sequence (Binggeli 1994). The morphological properties of galaxies change in a gradual way along a sequence of decreasing luminosity (the bulge-to-disk ratio decreases along a sequence of decreasing luminosity in a gradual manner, and the bulge is lost in faint galaxies; the spiral structure gets more chaotic in fainter galaxies and is also lost) and do not show a sharp line of demarcation between irregulars and spirals (an "irregular versus spiral dichotomy").

It has been demonstrated (Zaritsky et al. 1994; Garnett et al. 1997) that the luminosity-metallicity relationship of spiral galaxies maps almost directly on to that of irregulars. This can be considered as evidence that there is no sharp line of demarcation between irregulars and spirals. However, spirals have radial oxygen abundance gradients with slopes in the interval -0.3 $\div$ -0.1 dex per disk scale length (the slope of the radial oxygen abundance gradient in normal spirals expressed in terms of dex/kpc increases, on average, with decreasing luminosity) (Garnett et al. 1997) while irregular galaxies have no radial oxygen abundance gradients. The transition from the galaxies with radial oxygen abundance gradients to galaxies without them (or the transition from the galaxies with largest radial oxygen abundance gradients in dex/kpc to galaxies without radial oxygen abundance gradients) takes place at the late end of the Hubble sequence in going from spiral to irregular galaxies. Thus, the behaviour of oxygen abundance along a sequence of decreasing luminosity is twofold. On one hand, the luminosity-metallicity relationship seems to be unique both for spirals and for irregulars. On the other hand, a jump-like change of slope of radial oxygen abundance gradient takes place in going from spiral to irregular galaxies.

The unique luminosity-metallicity relationship for late-type spiral and irregular galaxies is not indisputable since this relationship for spiral galaxies depends on the choice of representative oxygen abundance. In investigations of the relationship between the oxygen abundance and the luminosity of spiral galaxies, the concept of the characteristic oxygen abundance has been introduced: it is defined as the oxygen abundance at a pre-determined galactocentric distance r^*. Owing to the presence of radial abundance gradients, the choice of the "representative" abundance for spirals is not a trivial matter. Choices of r^* have included zero (giving the extrapolated central intersect abundance), $r^* = 0.4\rho_0$ (where ρ_0 is the isophotal radius with surface brightness 25 mag arcsec^{-2}) and the disk scale length (Vila-Costas & Edmunds 1992; Zaritsky et al. 1994; Garnett et al. 1997). With any choice of r^*, the value of $O/H(r^*)$ is local parameter, i.e. it represents the oxygen abundance in the region at a given galactocentric distance but not the oxygen abundance of the whole galaxy.

The L_B versus μ diagram (Fig. 2) and the L_B versus η diagram (Fig. 3) provides an additional test of whether the properties of late-type galaxies change in a gradual way along a sequence of decreasing luminosity. Inspection of Figs. 2 and 3 shows that there are no jump-like variations in astration level and oxygen abundance deficiency in going from spiral to irregular galaxies. Thus, the variations of astration level and oxygen abundance deficiency among late-type spiral and irregular galaxies provide additional evidence that the properties of late-type galaxies change in a gradual way along a sequence of decreasing luminosity.

The jump-like change of the value of the slope of the radial oxygen abundance gradient in going from spiral to irregular galaxies may be attributed to the following effect. It is known that the barred spiral galaxies have no or have a smaller values of the radial oxygen abundance gradients as compared to the non-barred spirals (Martin & Roy 1994; Friedli 1999). Almost all Sm galaxies are barred galaxies (Odewahn 1996; Friedli 1999), and therefore they have no radial oxygen abundance gradients. Thus, the jump-like change in the average gradient in going from spirals to irregulars seems to be caused by a variation in the fraction of barred galaxies.

There is a number of still open questions. Is there a sharp line of demarcation between the galaxies evolving with gas infall to galaxies evolving with mass ejection? Or do these kinds of mass exchange between the galaxy and its environment take place simultaneously in some galaxies? What kind of the chemical evolution model should be applied to low-luminous spirals of type Sd?

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