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Some caveats on the evolution of the N/O abundance and the star formation history

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Abstract. We carefully analyse how the abundance ratio of nitrogen to oxygen in stellar yields depends on metallicity when the primary component of N is from AGB stars. We show the results obtained with a chemical evolution model grid, calculated with variable star formation efficiencies which produce different star formation histories. Finally we see how the N/O abundance is related to the evolutionary history.

Key words. Galaxy: abundances – Galaxies: abundances – Galaxies: Star formation

1. Introduction

Nitrogen abundances compared with the oxygen, N/O, may, in principle, inform us about the time at which low- and intermediate-mass (LIM) stars formed and, consequently, when the longest episode of star formation took place. This idea is based on the stellar mean-lifetimes for LIM stars, the main producers of N. These are longer than those of massive stars, which eject O to the interstellar medium (ISM).

The data, however, must be carefully interpreted so as not to reach misleading conclusions based on this simple scheme. If a mass of gas forms the bulk of stars simultaneously, in a single stellar populations (SSP), it is true that N appears after O in the ISM with a certain time delay. However, when data from different galaxies or different regions within a galaxy are compared, this scenario is no longer valid because a) most of data refers to spiral and irregular galaxies, where the star formation is a continuous process and, due to that, there are a mix of SSPs and b) the observations correspond to the final stage of an evolutionary path and galaxies follow different tracks.

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2. The closed box model

2.1. The basic scenario

N may be primary, NP, created directly from the original H by the corresponding nuclear reactions, or secondary, NS, if there exists a seed of C or O in the gas from which the star formed. Then the production is proportional to the original oxygen abundance. N is mainly produced as secondary in both massive and LIM stars. But in LIM stars a fraction of N is created as primary during third dredge-up and hot bottom burning (Renzini & Voli 1981). In massive stars stellar rotation provokes an in-

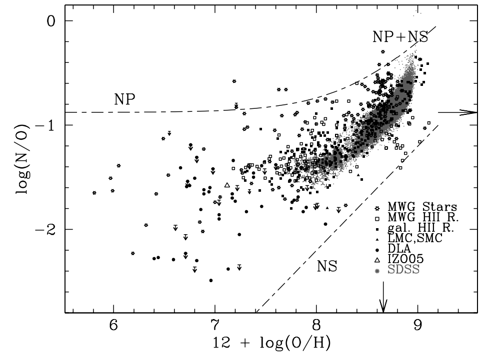

Fig. 1. The nitrogen to oxygen ratio, as $\log_{10}$ (N/O), as a function of the oxygen abundance, as 12 + $\log_{10}$ (O/H), for a wide sample of data from MWG stars and HII regions, other galaxies HII regions (low metallicity objects shown separately), damped lyman alpha clouds and SDSS estimates from Liang et al. (2006).

crease of NP, especially at the lowest metallicities (Ekström et al. 2008).

In the well known closed box model (CBM Tinsley 1980), the abundance of metals, Z, in a region may be expressed by the equation $Z = p \ln \mu^{-1}$, where $\mu = M_{\rm gas}/M_{\rm tot}$ is the gas fraction in that region and p is the integrated stellar yield of elements newly created by a stellar generation (where we assume that all stars that produced metals have already died). By applying this equation for N and O, and assuming that both are primary we find

$$\frac{Z_{\rm N}}{Z_{\rm O}} = \frac{p_{\rm N}}{p_{\rm O}} = \text{constant}, \quad (1)$$

where $Z_{\rm O}$ and $Z_{\rm N}$ are the oxygen and nitrogen abundances and $p_{\rm O}$ and $p_{\rm N}$ are the corresponding integrated stellar yields. If N is secondary, then

$$\frac{Z_{\rm N}}{Z_{\rm O}} = \frac{p_{\rm N}(O)}{p_{\rm O}} \propto O \quad (2)$$

We plot these theoretical lines in the diagram N/O against O/H, Fig. 1. The first case appears as a horizontal line while the second is a straight line with a certain slope[1]. When both contributions exist the horizontal line begins to increase from a certain oxygen abundance. We also plot the observations in Fig. 1 (see references in Mollá et al. 2006). It is evident from this diagram that both components of N are necessary.

Because LIM stars produce N by both processes (see Gavilán et al. 2006, hereinafter GAV06, and references therein) we first try to explain the data by using the corresponding yields of LIM and massive stars. In this work we show how N/O evolves when a contribution of NP proceeding from LIM stars exists.

Some people think that low metallicity objects must be young, linking wrongly oxygen abundance with time and therefore assume that they have insufficient time to eject N from LIM stars. Because of that they search for another way to obtain NP.

However, this idea, that links low oxygen abundance to short evolutionary time, is a mistake: the oxygen abundance is not a time scale. It is possible to reach a high oxygen abundance in a very short time or a very low one even in an object which has existed for a long time if it evolves very slowly (Legrand 2000).

2.2. Account the stellar mean-live-timescales

It is possible for us to solve the equation of the CMB for both components by assuming that there are two classes of stars, the massive ones with $m \geq 8M_{\odot}$ which create O and secondary N and the intermediate ones with $4 \leq m \leq 8M_{\odot}$ which eject primary N too. The resulting abundance is given by Henry et al. (2000) as

$$Z_{\rm N} = \frac{p_{\rm NS} p_{\rm C}}{2p_{\rm O}^2} Z_{\rm O}^2 + \frac{p_{\rm NS} p_{\rm C}}{6p_{\rm O}^2} Z_{\rm O}^3 + \frac{p_{\rm NP}}{p_{\rm O}} (Z_{\rm O} - Z_\tau) e^{\frac{Z_\tau}{p_{\rm O}}}, \quad (3)$$

where Z_i is the abundance of each element, C, N or O, p_i is the corresponding yield and the subscripts NP and NS refer to the the primary and secondary components.

Because N begins as secondary, when massive stars die, N/O evolves along a straight

[1] Both lines are drawn with arbitrary yields

line with a certain slope. After a delay time τ, in which the oxygen abundance Z_O reaches a value Z_τ, the NP ejected by LIM stars appears in the ISM. Just at that moment Z_N increases exponentially, owing to the last term of the equation, until it arrives at the primary N level. The behaviour simulates a phase change which occurs exactly when the first stars eject NP, at a time determined by the most massive LIM stars' mean lifetimes.

For stars of 2, 4 or 8 $M_\odot$, mean lifetimes are about 220, 100 and 40 Myr, respectively, as obtained from the functions (Fig. 2) given by the usual Padova and Geneva stellar tracks or by Bazan & Mathews (1990). The evolution described by Eq. 3 is represented in Fig. 3, panel a).

The N/O abundance ratio increases abruptly when the oxygen abundance is Z_τ, which takes a different value for 2, 4, or 8 $M_\odot$: the smaller the stellar mass, the higher the O abundance Z_τ at which the exponential function appears and the N/O increases, as we show in Fig. 3a). From this plot, we could say that, in a single stellar population in which NP is ejected by only by a small range of stellar masses, if, for a given O abundance, N/O is close to the secondary line, stars are, on average, younger than those with a higher N/O nearer to the primary line.

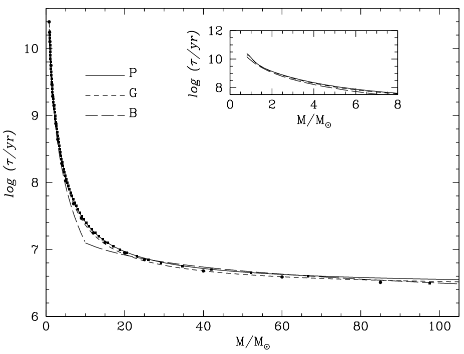

Fig. 2. The stellar life times τ as a function of the stellar mass, as obtained from the Padova group (P), (Bressan et al. 1993), the Geneva group (G) (Meynet & Maeder 2002) or as given by Bazan & Mathews (1990) (B).

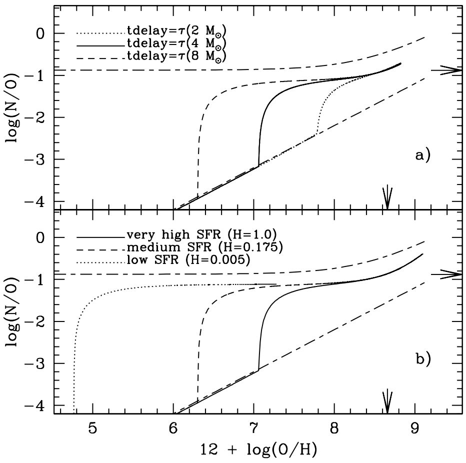

Fig. 3. The evolution of N/O, as $\log_{10}$(N/O) against O/H, as 12 + log_{10}(O/H) according to Eq. 3 a) for stars with different masses, as labelled, ejecting NP and b) for stars of 4 $M_\odot$ ejecting NP but where the star formation occurs with different efficiencies.

2.3. The star formation efficiencies

However, this is not the complete history. In order to obtain the abundance Z_τ, from Eq. 1, it is necessary to know the gas fraction, a quantity that may change with time. Let us assume that the Galaxy starts with $\mu = 1$, so that the mass is completely in the gas phase and that it decreases when stars form[2]. If we assume that the gas mass g depends on time by $\frac{dg}{dt} = -Hg$ then $g = g_0 e^{-tH}$. The mass in stars is $s_* = g_0(1 - e^{-tH})$ and $\Psi = \frac{ds}{dt} = Hg$, where H is the efficiency to form stars. In that case the star formation law results in an exponentially decreasing function of the time, $\Psi(t) = \Psi_0 e^{(-t/t_0)}$, where the time-scale $t_0 = 1/H$. If H is high, the gas is consumed very quickly and, therefore, the gas fraction $\mu = g/(g+s)$ takes a small value after a very short time. Obviously if H is small, the gas fraction remains near to 1.

We show the evolution of $\mu(t)$ in in Fig. 4a) for some values of H as labelled. The oxygen abundance evolves accordingly, as shown in Fig. 4b).

[2] Note that other evolutionary scenarios are possible.

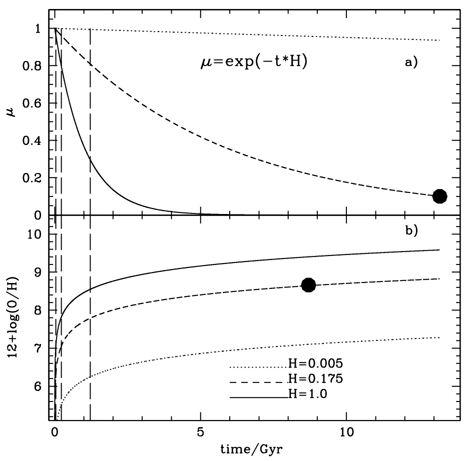

Fig. 4. The evolution of a) the gas fraction μ and b) the oxygen abundance $12 + \log_{10}(O/H)$ for different star formation efficiencies, as labelled. The solar region value is marked as a (yellow) solid large dot. The solar value of the oxygen abundance at 8.7 Gyy assumes the Sun born 4.5 Gyr ago.

Over-plotted on both graphs there are three lines corresponding to times, in increasing order, equal to the mean-lifetimes of stars of 8, 4 and 2 $M_{\odot}$. We obtain three different values for the oxygen abundance Z_{τ} for each evolutionary line. Equivalently, different oxygen abundances Z_{τ} for each stellar mass are obtained, dependent on H. If we assume that stars of 8 $M_{\odot}$ produce NP, $Z_{\tau} \approx 8$, 7.2, 6.8 or even less than 6 for $H = 1$, 0.5, 0.172 or 0.0005 after a time of 40 Myr. That is, the NP appears in the ISM at an abundance that may be as lower as $12 + \log(O/H) = 6$ if the efficiency to form stars is very low, or as higher as 8, if the efficiency is high, but always in a time scale as short as 40 Myr.

We show in panel b) of Fig. 3 the evolution of the relative abundance $\log_{10}(N/O)$ with the oxygen abundance $12 + \log_{10}(O/H)$ for three values of star formation efficiencies assuming that NP is ejected by stars of 4 $M_{\odot}$. We see a similar behaviour to that shown in panel a).

3. The metallicity dependent stellar yields

The previous section's results were obtained with constant effective yields p_{NP}, p_{NS} and p_{O}. Actually, the stellar yields depend on the metallicity Z with which the stars form. And therefore the effective yield for a single stellar population also depends on Z. In the case of LIM stars, this question is even more important because the proportion NP/N must change with Z. If the star has a very low Z, the abundance of O, the seed for the NS, is also low, so most N is created as NP.

This is clearly seen in fig. 2 of GAV06 where the ratio NP/N is represented as a function of the stellar mass for some sets of stellar yields found in the literature. In panel a) the solar abundance yields of Gavilán et al. (2005), van den Hoek & Groenewegen (1997) and Marigo (2001) (hereinafter BU, VG and MA) are represented. In panels b), c) and d) the same is shown for two values of Z for each one of these sets separately, as labelled. In all cases NP/N is higher for the low Z set than for the solar abundance one.

The dependence on Z of the integrated yields for a simple stellar population is shown in fig.3 of GAV06. In panel a) the integrated yield of N tends to be larger for higher Z. In panel b) the ratio p_{NP}/p_{N} decreases with Z, as it must do. The different sets, however, have different behaviour. BU has smaller total yields of N than VG and more similar to values of MA but the dependence on Z is smoother than this one shown by VG and MA.

By using dependent yields on the CBM equation of the previous section we obtain the results shown in Fig 5. Results for different efficiencies, H low, solar and high, appear in panels a), b) and c) as dotted lines. The main effect of changing yields with Z is that the evolutionary tracks elongate when the star formation rate is high, as it is in c). Therefore the efficiency to form stars, which defines the shape of the star formation history and the level of the starburst in which the stars form, is essential to obtain an elongated or flat evolutionary track in the plane NO–OH.

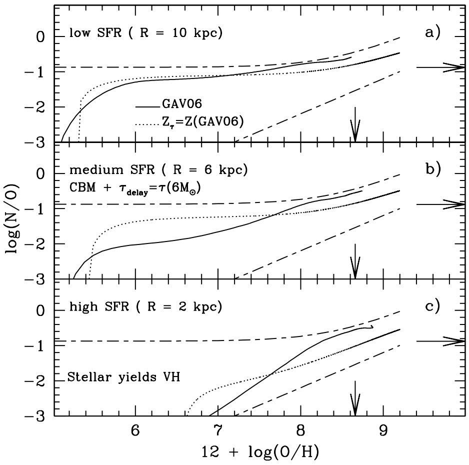

Fig. 5. The evolution of $\log_{10}$(N/O) as a function of $12 + \log_{10}$(O/H) for different star formation rates, a) low, b) intermediate and c) high efficiency, respectively. Dotted lines are the CBM results while the solid lines are the results obtained by GAV06 for different regions of the MWG disc.

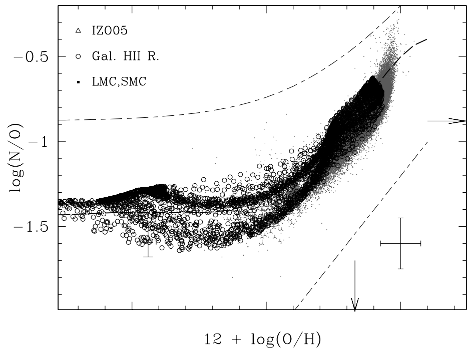

Fig. 6. Multiphase chemical evolution model results for the present time for a grid of 440 galaxies as open dots. Small dots in the background are the SDSS data and the other symbols are extragalactic and Galactic HII regions data as labelled (see a colour version in arXiv.org).

4. The chemical evolution model grid

4.1. The local universe

Until now only CBM results have been analysed. However modern chemical evolution models are usually numerical codes that include more information and take into account the mean lifetimes of stars, the IMF, the stellar yields, a large number of elements etc. We have over-plotted in Fig. 5, with solid lines, the results from GAV06, obtained with the multiphase chemical evolution model (Ferrini et al. 1994; Mollá & Díaz 2005) with the VG stellar yields for different regions of the Milky Way Galaxy (MWG), located at 10, 6 and 2 kpc from the centre of the Galaxy. They are similar to those for the CBM.

Following the same scenario as GAV06, we have compute models for 44 sizes or masses of galaxies and 10 values of efficiencies in the range [0,1] for each one of them (see Mollá & Díaz 2005; Mollá et al. 2006, for details). The results for the present time are shown in Fig. 6 with open circles while the small (grey) dots represent the SDSS data and other HII region data found in the literature. Our results even reproduce the high dispersion observed in the NO–OH plane. There are two regions where the dispersion is higher, one located around (7.8, -1.45) and a second one around (8.7,-1), just where the low-mass and the bright massive galaxies fall. These models demonstrate clearly that the efficiency to form stars has an important role in the evolution of tracks in the NO-OH plane and are essential to reproduce the data.

4.2. The role of the star formation history

Mallery et al. (2007) have shown that the location of a galaxy in the NO-OH plane is related to the specific star formation rate, the star formation rate per unit mass in stars, sSFR. They found that the highest values of N/O correspond to the smallest values of the sSFR.

Because we also reproduce this trend (see a colour version of Fig. 6, where this is evident, in arXiv.org) we may explain the underlying reasons for this correlation. In our models the smallest sSFRs occur in galaxies where the star formation was high in the past, at the earliest times of evolution. The gas was rapidly consumed and therefore the star formation rate

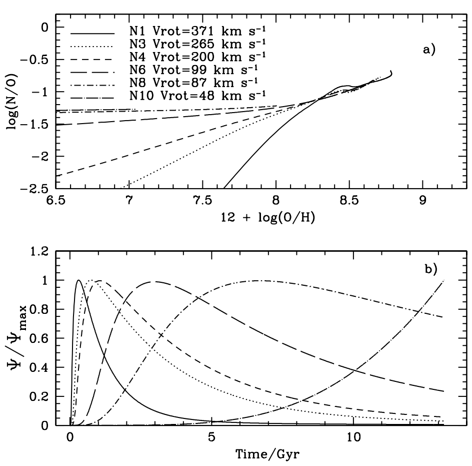

Fig. 7. a) Evolutionary tracks for six different theoretical galaxies in the NO-OH plane and b) star formation histories for the same six models

decreased since then, and is now very small. On the opposite side, when the efficiency to form stars is very low, the star formation history increases with time and, because of that, the present star formation rate is high. The evolutionary track of an object and its final point in the NO-OH plane depends on the star formation history suffered by the galaxy. In order to demonstrate this, we show in Fig. 7a) six different evolutionary tracks in the NO-OH plane and the corresponding star formation rate in panel b) of the same figure.

The low-mass galaxies with low efficiencies have not had a high star formation rate in the past and they may be considered young from the point of view of the average age of most of their stars, created mainly in recent times. But they also have old stars able to eject nitrogen, that was processed as primary, because at that time Z was very low.

5. Conclusions

The present day data as well as the high-redshift trends in the O/H-N/O plane may be reproduced by chemical evolution models with stellar yields in which LIM stars create a certain quantity of NP. Differences in the star formation histories of galaxies are essential to reproduce the data and the observed dispersion. The present position of a galaxy in the diagram showing N/O against O/H is determined by this evolutionary history. It is possible to have NP ejected by LIM stars even at a low O abundance because O abundance is not a time scale.

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