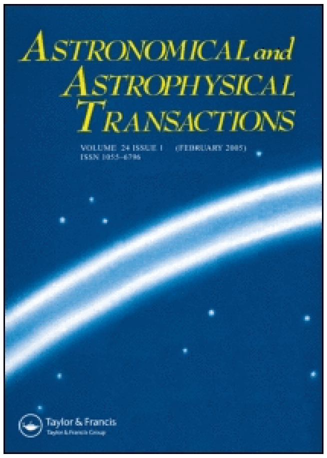

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Oxygen as a tracer of the galactic chemical evolution

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OXYGEN AS A TRACER OF THE GALACTIC CHEMICAL EVOLUTION

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The role played by supernovae of type Ia and II in the chemical evolution of the Galaxy is discussed. Their relative contribution to the chemical yields is estimated. The analyses of the oxygen abundance of young objects suggest that the present value is smaller than that at the epoch of the solar birth. The O abundance in the LMC is also reviewed.

KEY WORDS Chemical evolution of the Galaxy, supernova yields, oxygen abundances.

1. INTRODUCTION

It is now generally recognized that massive stars, which end their lives as type II supernovae (SN II), played an important role in the early chemical evolution of the Galaxy. The bulk of the observed amount of oxygen and elements in the mass number range 18–31 are synthesized by those massive stars, whereas most of the iron in the Galaxy was produced by intermediate mass stars in binary systems, which are probably the precursors of type Ia supernovae (SN Ia). Thus, in principle, we expect that the O/Fe ratio, as a function of the metallicity, can trace the relative contribution of both supernova types as sources for the chemical enrichment of the Galaxy. Moreover, SN Ia make their appearance later than SN II, on a time scale at the order of 10^8–10^9 years (van den Bergh, 1991). As a consequence, the variation of the O/Fe ratio with metallicity contains implicitly a similar time scale.

In the next section we analyze the available data for halo and disk objects in the light of the above picture. A comparison with the Large Magellanic Cloud (LMC) evolution is also made.

2. THE HALO EVOLUTION

Stars with metallicities $[Fe/H] < -1.0$ (and with high velocities) have essentially a constant oxygen-to-iron ratio. The analysis by Barbuy (1988) of a sample of halo stars led to an average value $[O/Fe] = 0.35$. This result was recently confirmed by Kraft *et al.* (1992), who obtained a similar average value for field halo stars in their sample. Such a high oxygen-to-iron ratio is expected from theoretical calculations of SN II yields (Nomoto *et al.*, 1990) and was corroborated by the abundance analysis of the SN 1987A ejecta (Freitas Pacheco, 1989, 1990).

Table 1 Abundances in halo stars

Abundance ratio	*Field stars*	*SN II models*	*SN 1987A*
$\left[\frac{O}{Fe}\right]$	0.35	0.46	0.32
$\left[\frac{\alpha}{Fe}\right]$	0.40	0.40	0.28
$\left[\frac{Na}{Fe}\right]$	−0.39	−0.20	—

Table 1 compares the relative abundances of oxygen, alpha-elements and sodium with respect to iron in field halo stars, SN 1987A and theoretical predictions. We notice a nice agreement between those numbers, fitting quite well with the proposed scenario.

However, the situation is not so clear when we analyze the data for stars in globular clusters (GC's). Chemical abundances of stars in M3 and M13 were derived by Kraft *et al.* (1992). Both clusters have similar metallicities ($[Fe/H] = -1.47$ and -1.51 respectively) and there is no compelling evidence for self-enrichment. Although the stars in each cluster have similar iron content, the data indicate variations in the O/Fe ratio anticorrelated with the Na/Fe ratio. This behaviour is difficult to be understood in the framework of "mixing" or self-enrichment scenarios. In favor of the former possibility, it is worth mentioning that calculations by Denisenkov and Denisenkova (1990) suggest that Na might be produced by the reaction $^{22}Ne(p, \gamma)^{23}Na$ and, in the same location, N is formed through the ON cycle in the interior of a globular giant. In this case, dredge-up episodes would enrich the surface not only in nitrogen and helium but also in sodium. In the case of ω Centauri, there is some metallicity spread, suggesting some self-enrichment also supported by the variation of the relative $(C + N + O)/Fe$ ratio (Milone *et al.*, 1992). Clearly more theoretical work is needed in this field.

Recent determination of GC ages, taking into account alpha-enhanced chemical compositions in the calculation of the evolutionary tracks (Chaboyer *et al.*, 1992), indicate that halo GC's (galactocentric distances higher than 8 kpc) have an age dispersion of about 1.4 Gyr (excluding Rup 106). This is compatible with the time scales inferred from the first appearance of SN Ia. The observed metallicity dispersion at a given age may probably be explained as a consequence of the huge halo volume, invalidating instantaneous mixing considerations. In spite of problems in star-to-star abundance variations, as discussed above, the data suggest that globulars and halo field stars may have similar ages and chemical evolution.

3. THE DISC EVOLUTION

The galactic disc was probably formed by "mass-loss" from the halo (collapse or infall) and the time scale for the mass transfer halo-to-disc was probably shorter than the time scale for the gas convertion into stars (see, for instance, Hartwick, 1976). Thus, a "non-zero" initial metallicity for the disc is expected in such a scenario.

The O/Fe ratio of disc stars for metallicities higher than $[Fe/H] \approx -1.0$ decreases steadily, as the relative contribution for the iron content in the interstellar medium (ISM) due to SN Ia increases.

An important fact about the chemical evolution of the galactic disc is the following: from the data by Barbuy and Erdelyi-Mendes (1989), the oxygen-to-iron ratio variation can be represented by

$$[O/Fe] \approx -0.26[Fe/H] \quad (\text{for } [Fe/H] > -1.0). \tag{1}$$

If the present iron abundance in the ISM is about $[Fe/H] \approx 0.15$ (the Hyades value), from the above relation we predict an oxygen abundance $\varepsilon(O) = 9.03$ in the usual log scale. As we shall see, there are many indications that the actual oxygen abundance in the ISM may be lower than that value.

The analysis of HII regions by Shaver *et al.* (1983) leads to an average oxygen abundance $\varepsilon(O) = 8.76$, a value about 0.15 dex lower than the solar abundance. A similar result is obtained for diffuse interstellar clouds from OI absorption lines (York *et al.* 1983; de Boer, 1981). Such a deficiency is also observed in young stars. Oxygen in intermediate mass supergiants, having main sequence B stars as progenitors, is deficient by 0.2 dex with respect to the Sun (Luck and Lambert, 1985). The study of B stars in young clusters and B-associations indicates an oxygen deficiency of 0.17 dex (Fitzsimmons *et al.*, 1990). This result is confirmed by the studies of Gies and Lambert (1992) on unevolved B stars and Cunha and Lambert (1992), who showed that the oxygen abundance in Orion stars is similar to that of the nebula. Moreover, these conclusions are strengthened by planetary nebula data, since type I objects having ages less than 2 Gyr are also oxygen deficient by 0.2 dex (Freitas Pacheco, 1993). Table 2 summarizes the results of these different studies. These data suggest a paucity of oxygen in the ISM after the birth of the Sun.

The relative contribution of both supernova types to the observed oxygen-to-iron ratio is given by (Freitas Pacheco *et al.*, 1992)

$$\left(\frac{O}{Fe}\right) = \frac{[(1-r)Y_I + rAY_{II}]}{[(1-r) + rA]} \tag{2}$$

where r is the relative number of type II events with respect to the total number of both supernova types which occurred in the Galaxy; Y_I, Y_{II} are respectively the O/Fe ratio yields from SN Ia and SN II; A is the relative iron yield between both SN II and SN Ia. Using the results by Nomoto *et al.* (1984) on the carbon

Table 2 Oxygen abundance in young objects

Object	$\varepsilon(O)$	*Author*
HII Regions	8.76	Shaver *et al.* (1983)
F-K supergiants	8.70	Luck and Lambert (1985)
B-associations	8.75	Fitzsimmons *et al.* (1990)
B-stars	8.68	Gies and Lambert (1992)
B-stars (Orion)	8.64	Cunha and Lambert (1992)
Type I PN	8.72	Freitas Pacheco (1993)

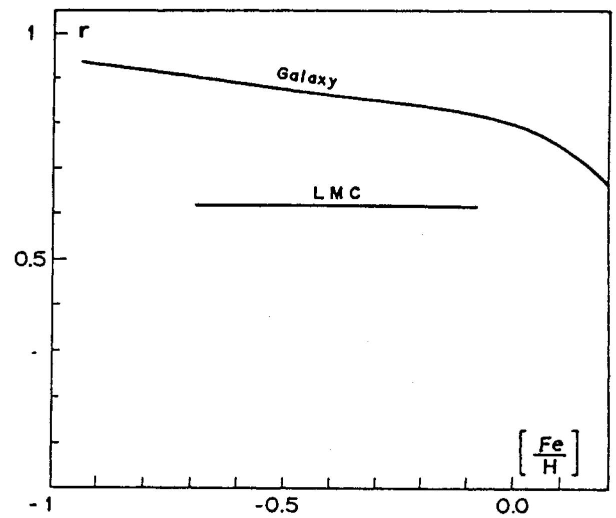

Figure 1 Relative contribution of type II supernovae to the chemical enrichment of the Galaxy and the LMC.

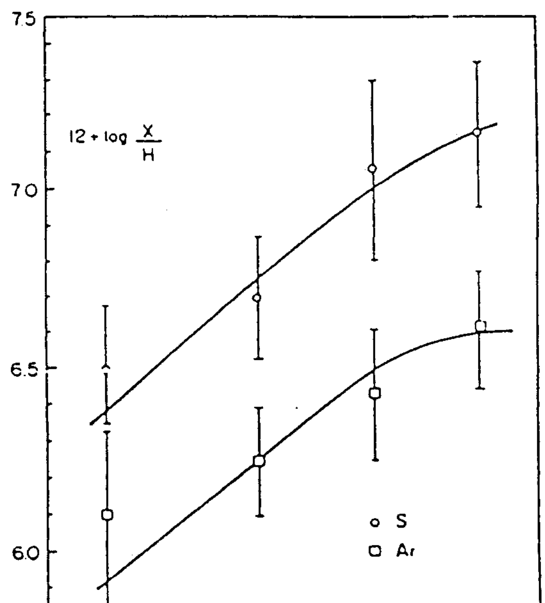

Figure 2 Variation of the sulphur and argon abundances in the galactic disk as a function of metallicity. Data points are from abundance determinations in planetary nebulae. Solid lines are model computations.

deflagration model as representative of the yield of SN Ia and those by Hashimoto *et al.* (1989) for SN II, from Eqs. (1) and (2) the variation of r with metallicity can be calculated. This is shown in Figure 1, where we notice that the relative contribution of SN Ia increased faster after the solar systems formation. In order to check this result, we calculated the variation of the sulphur and argon abundances as a function of the metallicity (Figure 2), comparing with planetary nebula data. The agreement is quite good, supporting the picture derived from the O/Fe data. These results imply that SN Ia produced about 79% of all iron observed in our Galaxy. A possible explanation for the increase in the type Ia frequency would be a flattening of the initial mass function with time.

4. THE LMC EVOLUTION

Abundances in the LMC can be derived from HII regions, planetary nebulae and supergiant stars. A summary of the results obtained prior to 1989 for HII regions and PN's was given by Dennefeld (1989). The comparison of those results reveals a considerable spread in the abundances. Freitas Pacheco *et al.* (1992a) carried out a new study on the abundances of type I planetaries and found them to be consistent with those of HII regions. Table 3 summarizes these data on the oxygen abundance, including some other recent results. The "grand-average" of all these results indicates $\varepsilon(\mathrm{O}) = 8.37$ for the present value of the oxygen abundance in the LMC.

Using the S/O and the Ar/O ratios derived from their study of type I PN, Freitas Pacheco *et al.* (1992a) estimated that $r = 0.62$ (see previous section), in agreement with the findings by Nomoto and Tsujimoto (1992). Moreover, a constant r value ($r = 0.62$) can explain the variation of the sulphur abundance as a function of the oxygen abundance (Figure 3). These data are derived from the analysis of non-type I planetaries (Freitas Pacheco, 1992b), a group having progenitors with a larger age spread than type I. The O/Fe ratio obtained from the study of supergiant stars varies with metallicity consistently with the same value of r (Freitas Pacheco *et al.*, 1992b), as it can be seen in Figure 4.

5. CONCLUSIONS

The present data on halo field stars indicate that SN II has a major role in the early chemical enrichment of the Galaxy. The abundances derived for SN 1987A reinforce this picture. The evolution of O, S and Ar for metallicities higher than

Table 3 Oxygen abundance in the LMC

Object	$\varepsilon(O)$	*Author*
HII regions	8.38	Dufour (1984)
"Young objects"	8.35	Russel and Dopita (1992)
Type I PN	8.41	Barlow (1991)
Type I PN	8.33	Freitas Pacheco *et al.* (1992a)

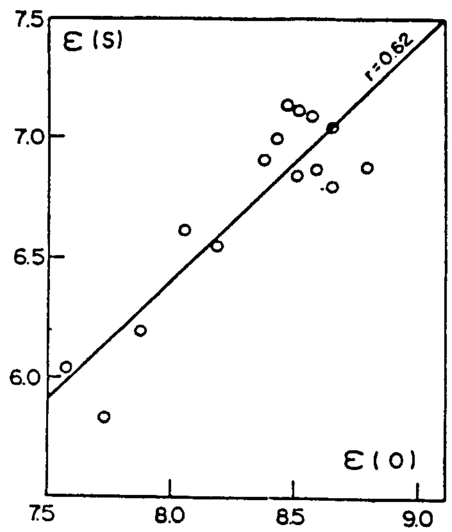

Figure 3 Sulphur variation as a function of the oxygen abundance in the LMC. Data points are from planetary nebulae. Solid line is expected variation for $r = 0.62$.

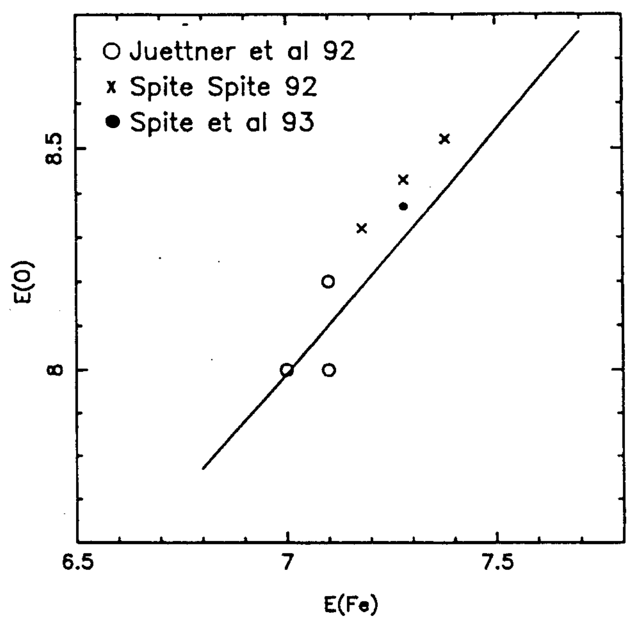

Figure 4 Oxygen as a function of the iron content for LMC supergiants. Solid line is the expected variation for $r = 0.62$.

[Fe/H] > −1.0 is consistent with an increasing relative contribution of SN Ia, varying from about 6% to 28% in the interval $-1.0 < [Fe/H] < +0.15$. A faster increase is observed for $[Fe/H] > 0.0$.

A different behaviour is observed in the LMC, where the relative contribution of SN Ia remained approximately constant (about 38%) in the metallicity interval $-0.7 < [Fe/H] < -0.1$.

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