Carnegie Observatories Astrophysics Series, Vol. 4:
Origin and Evolution of the Elements, 2004
ed. A. McWilliam and M. Rauch (Cambridge: Cambridge Univ. Press)

Chemical Composition of the Magellanic Clouds, from Young to Old Stars

VANESSA HILL
GEPI, Observatoire de Paris-Meudon

Abstract

I review the current state of our knowledge of the detailed chemical composition of the Magellanic Clouds, concentrating on the best probes of detailed elemental abundances, namely individual stars observed by means of high-resolution spectroscopy, probing stellar population of all ages from the oldest (>10 Gyr) stellar generations, intermediate-age populations (1–10 Gyr), and young massive stars, complemented by H II region abundances.

1.1 Introduction

As two of our closest neighbor galaxies, the Large and the Small Magellanic Clouds (LMC and SMC) provide a close-by but distinct environment to be compared to our Galactic disk, bulge, or halo. Their young and metal-poor population has no counterpart in the solar neighborhood, making them a unique test-bench for (massive) star evolution, while their distinctive star formation histories, in comparison to that of our Galactic disk, bulge, or halo, provide a perfect opportunity to understand the mechanisms of chemical enrichment in irregular galaxies. In this review I will concentrate on this second aspect, briefly going over the constraints that may be derived from *detailed chemical composition* of Magellanic objects, from the young populations that give a picture of the end-point chemical evolution of each of these galaxies (H II regions and massive stars), to the intermediate and old population that help understand how the chemical enrichment, and particularly, the relative importance of the different nucleosynthetic sources such as Type II supernovae (SNe II), Type Ia supernovae (SNe I), and asymptotic giant branch (AGB) stars have proceeded with time.

Open questions that one would like to answer include: At which epochs did the main episodes of star formation happen? How important have been the bursts (if any) and their relation to the Milky Way-LMC-SMC interactions? What is the relative contribution to the chemical enrichment of SNe Ia and SNe II? Have winds played any significant role in removing metals from these relatively small galaxies? Can the effects of the bursts be seen in the chemical evolution? Are the most ancient stellar populations in the Magellanic Clouds similar to our Milky Way halo stars (could they be drawn from the same population, as would be expected if the halo is made of disrupted satellites of Magellanic-like systems)?

Table 1.1. *Abundances in H II regions of the Magellanic Clouds (after Garnett 1999) compared to Orion (Esteban et al. 1998).*

	C	N	O	Ne	S	Ar
$\log(X/H)_{Orion}$[1]	8.49	7.78	8.72	7.89	7.17	6.8
$\log(X/H)_{LMC}-\log(X/H)_{Orion}$	–0.59	–0.88	–0.32	–0.29	–0.47	–0.60
$\log(X/H)_{SMC}-\log(X/H)_{Orion}$	–1.09	–1.28	–0.72	–0.69	–0.87	–0.90

[1]log (X/H) on a scale where log N(H) = +12.

1.2 Present-day Composition

The *present-day* chemical enrichment state reached by the Magellanic Clouds can be probed using two main indicators: H II regions offer insight on the gas still present (and forming stars) in these galaxies, while young massive stars, which are very numerous in both systems, provide accurate measurement of abundances of stars formed in the last tens of million years. Both indicators are rather bright, and have been widely used for abundance measurement since the 1970s and the 1980s, respectively. I do not intend to review here extensively all the numerous and remarkable observational and analytical efforts that were conducted by many different teams over the world, but rather to summarize the most striking findings of these studies.

1.2.1 Nebular Abundances

Although the abundances of O, N, Ne, S, and Ar derived from optical spectra of Magellanic H II regions are virtually unchanged since the review by Dufour (1990), it is worth noting that the abundances of carbon have taken a new turn with the advent of UV spectroscopy from space—*IUE* as a first step (Dufour, Shields, & Talbot 1982), and then *HST* (Garnett et al. 1995; Kurt et al. 1999; Garnett, Galarza, & Chu 2000). From UV spectra, transitions of C^{+2}, N^{+2}, and O^{+2} and C^{+}, N^{+}, and O^{+} can be observed, allowing one to reduce systematic uncertainties on N/O and C/O (by comparing lines of similar excitation energies and ionization stages). Table 1.1 summarizes the abundances in H II regions in both Clouds, following the review of Garnett (1999), and using the Orion nebula (Esteban et al. 1998) as the Galactic reference.

Inspection of the tabulated O, Ne, S, and Ar abundances reveals, at first glance, the well-known metal deficiency of the LMC by a factor of $\sim$3 (–0.4 dex) relative to the solar neighborhood, and of the SMC by a factor of 6 (–0.8 dex) is obvious for O, Ne, S, and Ar. On the other hand, carbon in the SMC, and nitrogen in both Clouds, seem to be overdeficient by significant factors.

In fact, these low N/O ratios [log (N/O) = –1.5], taken at face value, place the LMC and the SMC among the galaxies with the lowest N/O ratios known (e.g., Pilyugin, Thuan, & Vílchez 2003; their Fig. 4), with a level of nitrogen close to the *plateau*-like behavior defined by the lowest metallicity irregular galaxies, which is commonly interpreted as a primary nitrogen signature. It is quite unexpected that a galaxy that has been actively forming stars over an extended period of time (the LMC contains significant stellar populations ranging from pre-main sequence stars to ages of 15 Gyr, with a possible enhanced star formation period 2–5 Gyr ago) has still managed to enrich itself so little in nitrogen (relative to oxygen);

even adopting intermediate-mass stars as the production site for nitrogen (as proposed by Henry, Edmunds, & Köppen 2000), nitrogen is released into the gas after a moderate time delay (∼250 Myr), so that the intermediate-mass stars formed a few billion years ago in the LMC and the SMC should have contributed fully to the nitrogen enrichment of their host galaxy. Only if the oxygen seen in the Magellanic Clouds had been massively produced in the last 250 Myr (by a burst of star formation) could this low N/O be observed. But in that case, the O/Fe ratio should also reflect this sudden increase of oxygen production, contrary to what is observed (see §1.4.1).

A word of caution should, however, be said concerning nebular abundance uncertainties: different indicators do not always provide the same answer. As an illustration, recent work by Tsamis et al. (2003) on Galactic and Magellanic H II regions have shown that the collisionally excited recombination lines traditionally used to deduce oxygen abundances are lower than those deduced from the supposedly more robust optical recombination lines by factors of ∼2 to 3. In the same work, the authors also show that oxygen abundances deduced from infrared fine structure lines, which are temperature insensitive, are compatible with those deduced from the collisionally excited recombination lines, thus ruling out the suspected temperature fluctuations as a source of the discrepancies between collisionally excited and optical recombination lines. Thus, it is safe to keep in mind that systematic effects can play an important role in nebular abundance determinations (especially CNO). In the particular case of the LMC N/O ratio, using the infrared collisionally excited recombination lines (from the dominating ions N^{2+} and O^{2+}), would bring the galaxy up and away from the primary nitrogen plateau value by ∼0.2 dex (Tsamis et al. 2003).

1.2.2 Abundances from Young Stars

The brightest stars of both Magellanic Clouds (supergiants of all spectral types from B to K) have been studied in detail by means of high-resolution spectroscopy since the mid-1980s and mainly in the 1990s, allowing to derive abundances for many more elements than are available from H II regions. A summary of the most recent of these supergiants studies is given in §1.2.2.2. More recently still, with the advent of high-throughput spectrographs and 8–10 m-class telescopes, B-type stars still on the main sequence ($V \approx 15$ mag in the LMC) could also be studied, leading to very interesting new insights, in particular on the abundance of C and N, which are affected by internal mixing in evolved stars and therefore very difficult to interpret in giants and supergiants. The following section gives an account of these new studies.

1.2.2.1 Carbon, Nitrogen, and Oxygen from Hot Stars

It is of particular interest to compare the C, N, and O abundances as probed by the nebular and stellar abundances. Only in unevolved stars can this comparison be meaningful, assuring that none of the CN-cycled material from the central part of the star has yet been dredged-up to the stellar atmosphere. In recent years, B giants (B IV) (Rolleston et al. 1996; Korn et al. 2000; Rolleston, Trundle, & Dufton 2002) and B main sequence stars (LMC: Korn et al. 2002; SMC: Rolleston et al. 2003) have been observed in both Clouds. References to earlier works on B supergiants in both Clouds can be found in these papers. These two groups have taken two types of approaches to deal with the systematic uncertainties (including significant NLTE effects) that can hamper abundance determinations in these hot stars: Rolleston et al. have used a strictly differential approach between Magellanic and Galactic stars of similar temperatures, while Korn et al. chose to take a direct NLTE approach.

The resulting oxygen abundances derived both for giants and dwarfs are in very good agreement with the nebular abundances, yielding [O/H] = –0.4 and –0.7 dex, respectively, for the LMC and SMC. The carbon abundances, however, even in the dwarfs, seem to be *higher* than the nebular abundances by $\sim$0.4 dex in the SMC (the carbon abundance of the SMC dwarfs, relative to its Galactic counterpart, is –0.65, to be compared to −1.09 for the SMC H II regions, relative to Orion), and by a hardly detectable amount in the LMC. However, uncertainties still present in both stellar and nebular carbon abundance determination could explain a large part of the effect (Korn et al. 2002). The nitrogen abundance, on the other hand, is in very good agreement between the dwarfs and H II regions, consistently pointing toward a very low N/O ratio for both Magellanic Clouds, as discussed in §1.2.1. In giants (and even more in supergiants), the nitrogen abundance increases very rapidly from this initial value, as expected from mixing processes in the star, bringing freshly CN-cycled material toward the surface.

1.2.2.2 Other Elements

A wealth of different elements (over 15 different elements) can be probed in supergiant stars of spectral types A to K, and there are many papers on the abundances measured from such stars in the Magellanic Clouds: samples ranging from three to 10 F supergiants and Cepheid variables were observed in each field of each Cloud by several groups (Russell & Bessell 1989; Spite, Spite, & Barbuy 1989; McWilliam & Williams 1991; Luck & Lambert 1992; Hill, Andrievsky, & Spite 1995; Luck et al. 1998; Andrievsky et al. 2001), six K supergiants in the SMC (Hill, Barbuy, & Spite 1997), and a sample of 10 A-type supergiants in the SMC (Venn 1999). F–G and K supergiants in young populous clusters (rather dense and rich clusters of a few 10^7 yr) in the LMC (Richtler, Spite, & Spite 1989; Hill & Spite 1999) and in the SMC (Spite et al. 1986; Spite, Spite, & Richtler 1991; Hill 1999) have also been studied. No significant differences are found between the abundance ratios measured in the clusters and the field, although some clusters (NGC 330 in the SMC and NGC 1818 in the LMC) seem to be slightly more metal poor than their surrounding field counterparts.

The abundance ratios of representative samples of A to K supergiants in the field of the LMC and SMC are plotted in Figure 1.1 as a function of atomic number. The abundances are plotted *relative* to their solar neighborhood counterparts, to reduce systematic errors linked to the analysis of these luminous objects. The most striking results of Figure 1.1 are, on the one hand, the very good agreement of abundance ratios in the LMC and SMC with the solar abundance ratios (marked as the y = 0 line in the plots, together with two dashed lines showing typical uncertainties) for most elements from oxygen to zinc ($Z \leq 30$), *including the α-elements*, and, on the other hand, the overabundance of the heavy neutron capture elements from Ba to Eu ($Z \geq 56$), by factors of $\sim$2 and 3, respectively, in the LMC and SMC. This overabundance of the heaviest elements was noted since the very first studies of SMC and LMC cool supergiants (e.g., Spite et al. 1986), and came as a surprise: among the elements showing this enhancement is the *r*-process-dominated element Eu, which suggests that the *r*-process has been particularly active in the Magellanic Clouds (Luck & Lambert 1992; Russell & Dopita 1992; Hill et al. 1997). On the other hand, the *r*-process is thought to be produced by massive stars (SNe, binary neutron star coalescence, etc.), and therefore expected to be accompanied by α-element enhancements, which are not observed in the

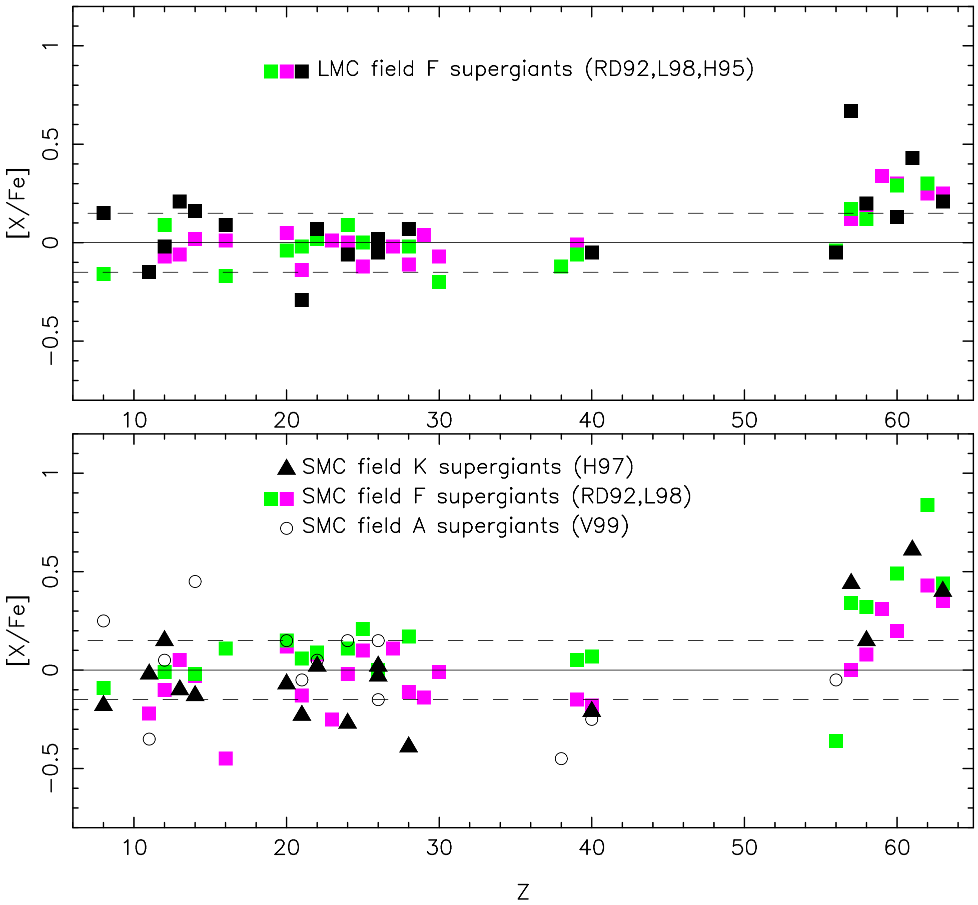

Fig. 1.1. Abundance ratios of young warm and cool supergiants in the LMC (*upper panel*) and SMC (*lower panel*), *normalized to their solar neighborhood counterparts*. Symbols are explained on the figure, with references as follows: RD92, Russell & Dopita (1992); L98, Luck et al. (1998); H95, Hill et al. (1995); H97, Hill et al. (1997); V99, Venn (1999).

Magellanic Clouds. In §1.4.2, a different explanation for the heavy neutron capture elements enhancements is put forward.

To summarize briefly this section, one could say that, despite the likely very different evolutionary paths taken by each of the three systems (SMC, LMC, and solar neighborhood) to reach their present-day chemical composition, and despite the different overall metallicities reached (1/5, 1/3, and 1 times solar metallicity), the three systems have very similar abundance ratios in a wide range of elements. There are two notable exceptions. N and, to a lesser extent, C are underabundant (the N/O ratio is down by a factor of 4), while the heavy neutron capture elements are overabundant by factors of 2 to 3, respectively, in the LMC and the SMC.

1.2.3 Chemical Evolution Models

At this point, it is worth mentioning the attempts to compute chemical evolution models of the Magellanic Clouds, to reproduce the *present-day* abundance ratios and predict abundance ratios to be expected as a function of time (or metallicity) in each of the two Clouds. Two families of models can be considered, depending on which present-day oxygen over iron ratio they aimed to reproduce: (1) the *underabundance* of O/Fe found in Magellanic supergiants when directly compared to what the solar O/Fe ratio was thought to be at the time*, or (2) the *solar* O/Fe ratio, which is found when comparing the same supergiants to their solar neighborhood counterparts. Category (1) includes: Gilmore & Wyse (1991), who showed that a bursty star formation could either enhance or lower O/Fe ratios depending on which epoch from the burst the galaxy is observed (see §1.4.1); Tsujimoto et al. (1995), who used a steeper initial mass function (IMF) slope to lower the massive SN II contribution and therefore lower the O/Fe ratio (they also designed a bursty model, using the same steep IMF); Pilyugin (1996) and de Freitas Pacheco (1998), who advocate α-enriched winds to achieve the low O/Fe ratio. On the other hand, the semi-analytical models of Pagel & Tautvaišienė (1998) fall into category (2), reproducing solar O/Fe ratio at the evolution end-point, and predicting abundance ratios for two distinct cases of star formation histories, continuous or including two separated bursts of star formation. Examples of these predictions are displayed in Figures 1.2 and 1.3.

1.3 Star Formation History and Age-metallicity Relations

It is clear that, to understand correctly through which chemical enrichment path the Magellanic Clouds proceeded to reach the end-point evolution probed by the youngest stellar generations and the interstellar medium, one needs to understand how and when star formation and its associated nucleosynthesis took place. Star formation history reconstruction from deep and detailed color-magnitude diagrams (CMDs) has proven to be extremely powerful in nearby galaxies where stars can be resolved down to the main sequence, as it is the case for the LMC and the SMC. Unfortunately, in systems like the Magellanic Clouds where the star formation has been quite extended in time, the age-metallicity degeneracy in CMDs is not easy to overcome unless some information on the metallicity distribution at each epoch is injected independently (the so-called age-metallicity relation). Here is not the right place to review all the attempts that have been made in this direction, but a couple of key points can be reminded:

(1) Star formation histories deduced from deep *HST* images in different regions of the LMC all detected a significant increase of star formation (burst) at relatively recent times (few Gyr ago), with various detailed characteristics (exact epoch and intensity). A nice overview of these results can be gathered from Holtzman et al. (1997), Geha et al. (1998), and Smecker-Hane et al. (2002). For the SMC, no such detailed studies have been performed to date.

(2) Age-metallicity relations in the LMC and SMC were for a long time probed only from clusters that provide relatively easy age (from deep CMDs in the best cases, and integrated colors otherwise) and metallicity determinations, using either narrow-band (Strömgren or Washington systems) photometry or low-resolution calcium triplet spectroscopy of individual stars (for the LMC, see Geisler et al. 1997; Olzsewski et al. 1991, and references therein; for the

* The solar log (O/H) $\approx$ 8.9 advocated until recently was higher than the O abundance derived from B stars and supergiants in the solar neighborhood. Instead, the current log (O/H) $\approx$ 8.69 derived by Allende Prieto, Lambert, & Asplund (2001) is in agreement with the local B stars and K–F supergiants.

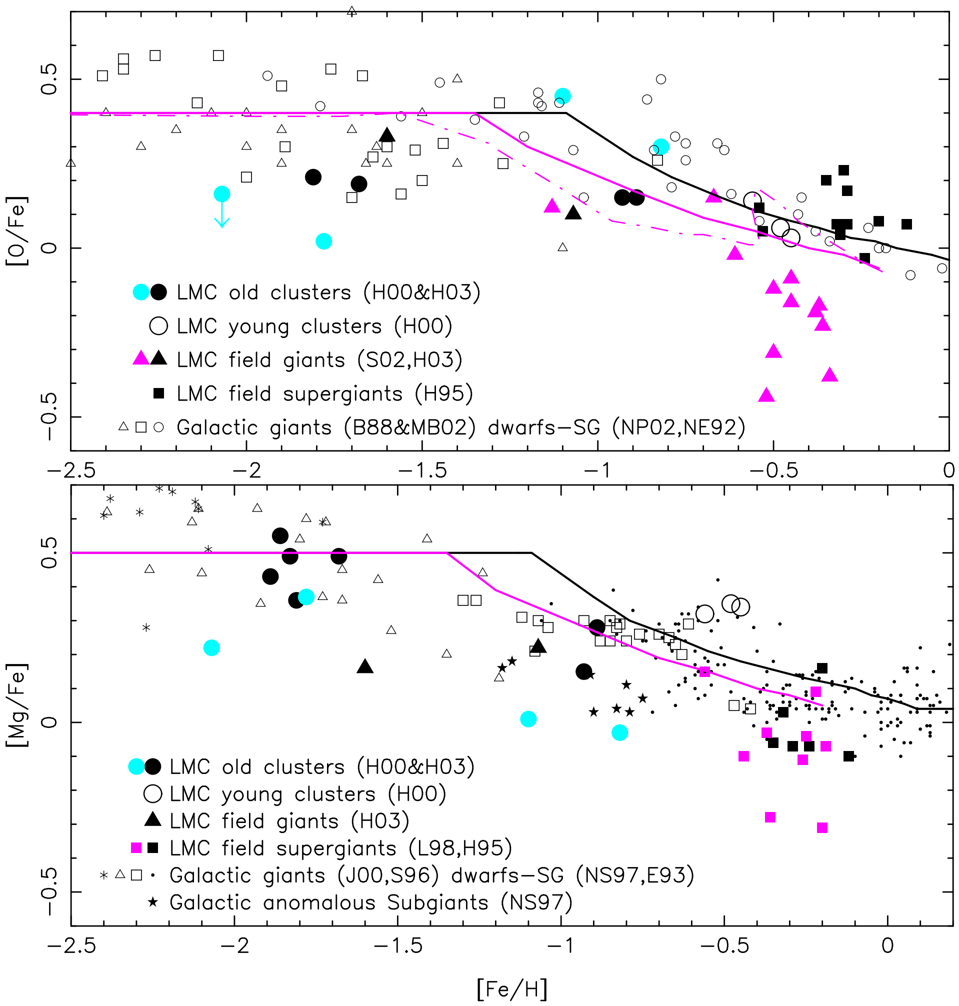

Fig. 1.2. Abundance of the α-elements O and Mg and for LMC stars, compared with Milky Way halo and disk stars. The symbols are explained on each plot, and use the following notation for LMC objects (big or filled symbols): H00, Hill et al. (2000); H03, Hill et al. (2004); S02, Smith et al. (2002); L98, Luck et al. (1998); H95, Hill et al. (1995). Overplotted as black and gray lines are chemical evolution models by Pagel & Tautvaišienė (1995, 1998) for the Galaxy and the LMC, respectively (see text for explanation). The references for Galactic comparison stars are: NE92, Nissen & Edvardsson (1992); B88, Barbuy et al. (1988); MB02, Melendez & Barbuy (2002); NP02, Nissen et al. (2002); E93, Edvardsson et al. (1993); NS97, Nissen & Schuster (1997); J00, Johnson (2002); S96, Shetrone (1996); G91, Gratton & Senden (1991); G94, Gratton & Senden (1994).

SMC, see Da Costa & Hatzidimitriou 1998, and references therein). The two cluster age-metallicity relations are quite distinct: the SMC shows a smooth distribution of cluster ages with slowly rising metallicities, whereas the LMC shows a prominent gap in age between the old ($>$10 Gyr) globular clusters and the young ones ($<$4–5 Gyr), in which no (or very few)

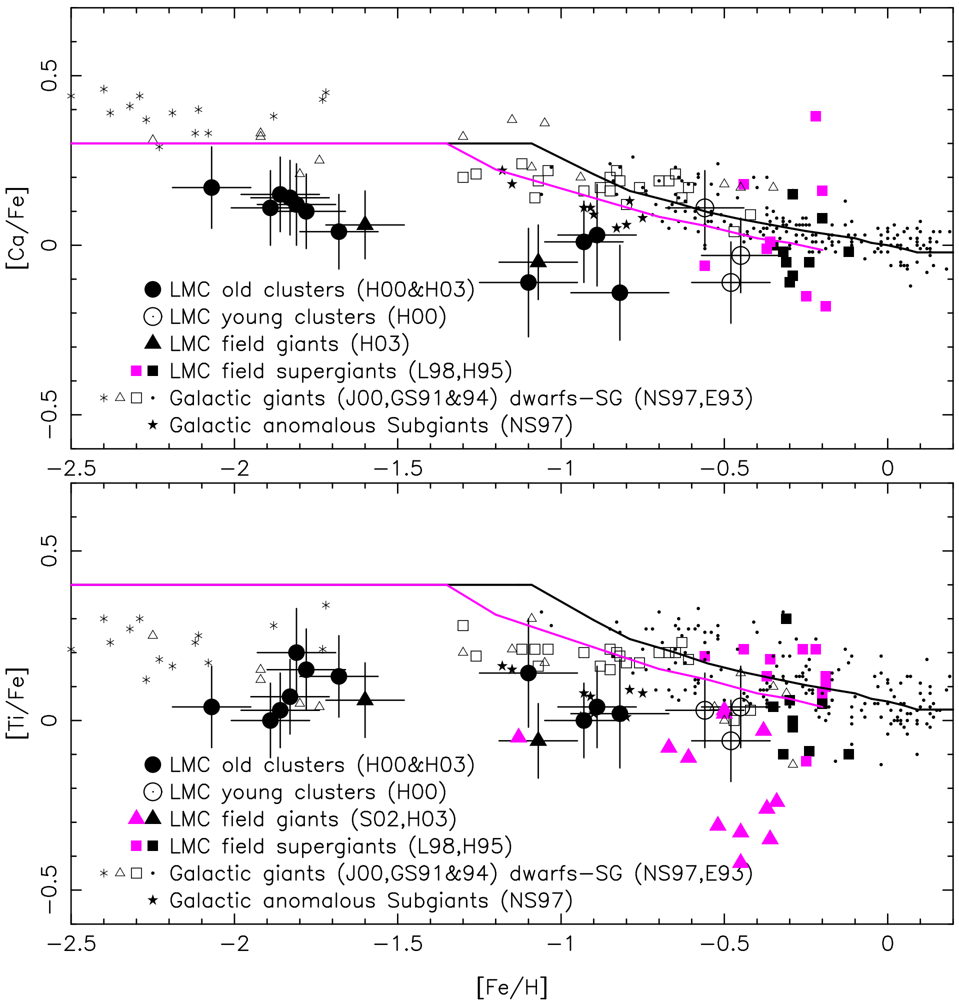

Fig. 1.3. Abundance of the α-elements Ca and Ti and for LMC stars, compared with Milky Way halo and disk stars. Symbols and references as in Fig. 1.2

clusters are to be found (see Sarajedini 1998). Lately (in the LMC only), age-metallicity relations for field stars have appeared, from planetary nebulae (Dopita et al. 1997) or from red giant branch (RGB) stars (Bica et al. 1998; Cole, Smecker-Hane, & Gallagher 2000; Dirsch et al. 2000), showing that (not surprisingly) no such age gap exists in the LMC field.

1.4 Detailed Composition of the Older Populations

A new path can be taken to unravel the history of the Magellanic Clouds, by measuring abundance ratios in stars of various ages, thus probing the chemical content of the galaxies *at different epochs along their evolution*. This can readily be done using high-resolution spectrographs on the 8–10 m-class telescopes to observe red giants (which span a large age and metallicity range) in both Magellanic Clouds. So far, the only published

Table 1.2. *Summary of characteristics of the clusters observed.*

	Age (1)	$[Fe/H]_{CaT}$ (2)	$[Fe/H]_{HRspec}$ (3)	R (4)	
NGC 1841	14	−2.11	-2.07 ± 0.10	14°	S
NGC 2257	14.3	−1.80	-1.86 ± 0.07	8°	NE
NGC 2210	14	−1.97	-1.75 ± 0.07	4.5°	E
ESO 121-SCO3	9.2	–0.93	-0.91 ± 0.11	10°	N
NGC 1978	2	−0.42	-0.91 ± 0.15	3.5°	N
NGC 1866	0.2	...	-0.51 ± 0.08	4°	N

(1): Age in Gyr. (2): Metallicity estimate from the calcium triplet infrared lines at low resolution, from Olszewski et al. (1991). (3): Iron abundance derived from high-resolution spectra (Hill et al. 2000, 2004). (4): Distance to the LMC Bar.

high-resolution analysis of red giants in the Magellanic Clouds concerns the LMC. The only work dealing with field red giants is that of Smith et al. (2002), who analyzed from near-infrared spectra (Phoenix spectrograph on Gemini South), a sample of 12 LMC giants in the metallicity range $-0.3 < [Fe/H] < -1.1$, for which they derive abundances of C, N, O, Na, Sc, Ti, and Fe*. Because it is difficult to select old and metal-poor field stars from CMDs (other than statistically), a very appealing way to select an old and metal-poor component of the Magellanic Clouds is by using globular clusters. This is the path that has been followed so far by our group, using the UVES high-resolution echelle spectrograph mounted on VLT, to measure the abundances of up to 20 different elements in individual RBG stars in LMC clusters. We have selected globular clusters in a wide age-range, from the young NGC 1866 to the oldest and most metal-poor clusters (see Table 1.2) for which we have analyzed 2–4 RGB stars (Hill et al. 2000, 2004). Two LMC field RGB stars ($[Fe/H] = -1.1$ and -1.6) have also been observed for comparison purposes. Johnson (2004) also observed RBG stars in four old clusters, three in the LMC (NGC 1898 and NGC 2019, close to the LMC Bar, and Hodge 11) and NGC 121 in the SMC, but her results are not reported here.

It is not obvious that globular clusters in a galaxy should reflect faithfully the behavior of the whole galaxy. Counting them to trace star formation along an age axis has proved to be quite biased (see §1.3). The star formation episodes that gave rise to the bulk of the intermediate-age stellar population of the LMC does not seem to have left any globular cluster relics behind: most probably, no clusters massive enough to survive longer than a few billion years where formed during that period. On the other hand, abundance ratios in Galactic globular cluster stars trace very well those of the halo field stars (except for a few of the lighter elements; see §1.4.1), and we will therefore use the Magellanic Cloud clusters as representatives of the chemical composition of the LMC gas at the time when they were formed.

From the combined data set (clusters and field stars), it now becomes possible to examine the trends of abundance ratios with time, or metallicity, in the LMC (hopefully, such data will soon also become available in the SMC). The following sections attempt to do so, con-

* And now also fluorine: Cunha et al. (2003).

centrating on two particularly appealing groups of elements: the α-elements and the neutron capture elements.

1.4.1 Oxygen and other α-Elements

The so-called α-elements are produced in massive stars during the hydrostatic burning phase for the lighter elements (O, S, Mg, and Si), but also during the explosive phase of the SNe II (Si, Ca, and Ti). They are obvious chemical evolution tracers as they are released very promptly after a star formation episode, thanks to the short lifetime of their progenitors. The α-elements are also very useful to compare to iron, since as soon as a few SNe Ia start contributing to the chemical enrichment ($\sim$1 Gyr after the star formation episode), most of the iron is produced by SNe Ia. Hence, the ratio [α/Fe] probes star formation time scales and SN II/SN Ia rates.

Figures 1.2 and 1.3 display the LMC abundance ratios for old and intermediate stars (Hill et al. 2000, 2004; Smith et al. 2002), together with comparison samples in the Galactic disk and halo (see figure caption for references) and a selection of young LMC supergiants, normalized to their solar neighborhood counterparts (B stars were excluded from the plot on the basis of their rather uncertain iron abundance measurements). Also plotted on the figures are chemical evolution models for the Galaxy and the LMC assuming a continuous star formation rate over the last 14 Gyr (Pagel & Tautvaišienė 1995, 1998). To illustrate the expected response of α/Fe ratios to a burst of star formation, we also plotted (Fig. 1.2, upper panel) their LMC chemical evolution model assuming two bursts of star formation separated by 9 Gyr of very low activity (dot-dashed gray line): the sudden bump around [Fe/H] = –0.5 is due to the prompt α-elements output from SNe II of the second burst of star formation, some 2 Gyr ago.

Before commenting further on oxygen and magnesium, it is necessary to recall that in Galactic globular clusters abundance anomalies of O, Na, Mg, and Al are often observed on the RGB (and also now at the turn-off; e.g., Gratton et al. 2001), in the form of chemical inhomogeneity among the stars of a given cluster, which define O-Na and Mg-Al anticorrelations. In the LMC oldest globular cluster, this seems to be also the case (Hill et al. 2000), and the two metal-poor stars that appear as faint gray filled circles in Figure 1.2 are stars that are probably oxygen (and Mg?) poor due to these anomalies, and should likely not be considered representative of the LMC chemical evolution. (The other two more metal-rich cluster stars that appear as faint gray circles are members of NGC 1978 that displayed strong TiO bands, introducing extra uncertainties in the analysis.)

Setting aside these more uncertain data points, several comments can be made from Figures 1.2 and 1.3:

(1) The oldest, most metal-poor population in the LMC (represented by the clusters, as black circles), defines O/Fe and Mg/Fe ratios that are compatible with those of the Galactic halo, although slightly on the lower side in the case of oxygen. Calcium and titanium, on the other hand, are clearly below the halo counterparts. If these low values for some α-elements are confirmed with larger samples, it would set interesting constraints on the formation mechanisms of halos: in canonical views, lower α/Fe ratios in objects as old as $\sim$14 Gyr cannot be due to contributions from SNe Ia but have to be linked to the relative numbers of very massive SNe II to less massive SNe II (producing relatively fewer α-elements than the more massive ones), which contributed to the early chemical enrichment. This relative number (an *effective IMF*) could be altered either by changing the IMF itself, or by selective winds

blowing preferentially α-enriched material out of the galaxy, or by *statistically truncating* the high-mass end of the IMF (see Shetrone 2004). Most of these explanations, however, do not seem very plausible for the LMC: the IMF measured in Magellanic Clouds clusters and associations is compatible with a Salpeter IMF (Massey, Johnson, & DeGoia-Eastwood 1995; Hunter et al. 1997), winds would have to be very strong to escape the potential of the LMC, and the statistical truncation of the IMF, while a valid idea when the mass involved in star formation episodes is very small, does not seem very appealing in a system of the size and mass of the LMC, where present star-forming regions are huge.

(2) For metallicities above [Fe/H] $= -1$, the O and Ti behavior becomes very confused: while the cluster stars (and two field stars) from our own work seem to define very constant [O/Fe] and [Ti/Fe] ratios (around +0.15 dex and 0.0 dex, respectively) merging into the solar O/Fe and Ti/Fe ratios defined by the young supergiants* of Hill et al. (1995) and Luck et al. (1998), the field RGB stars of Smith et al. (2002, gray triangles) define a very strong decrease of the O/Fe and Ti/Fe ratio with increasing metallicity. This difference could be due to several effects, among them the use of two distinct oxygen indicators (Smith et al. 2002 use infrared OH lines, whereas we have used the [O I] forbidden line), but the most probable cause for the disagreement lies in the temperature calibration of the stars. For their sample, Smith et al. (2002) estimate that the uncertainty that they have on temperature is of the order of 100 K (order-of-magnitude estimate of the possible systematic offset between various $(J-K)$ color-temperature relations), which, in turn, translates into an uncertainty of +0.32 dex on their derived [O/Fe] ratios and +0.26 dex on their [Ti/Fe] ratios, while [Fe/H] only decreases by –0.10 dex. Assuming a temperature scale hotter by 100 K would therefore bring their whole sample back into agreement with the rest of the data, both for oxygen and titanium (the published data do not contain Mg or Ca abundances for this sample).

(3) On this hypothesis, one would conclude that the [O/Fe], [Ca/Fe], and [Ti/Fe] ratios are rather flat at all metallicities, defining a slope shallower than predicted by the Pagel & Tautvaišienė (1998) models. It is only in the Mg diagram that a significant evolution of the [Mg/Fe] ratio with metallicity is detected.

(4) An alternative view is developed in Smith et al. (2002; their Fig. 10), who take their [O/Fe] at face value and conclude that the run of [O/Fe] with increasing metallicity defines a sequence *always below* the one defined by the Galactic disk, which they successfully reproduce with a simple closed-box analytical model by lowering the SN II rate by a factor of 3, and the SN Ia rate by a factor of 2, compared to the rates needed to reproduce the Galactic disk O/Fe (in effect, increasing the SN Ia/SN II ratio).

Finally, no detection of the effects of bursts in the chemical evolution diagrams has occurred so far, but no conclusion can be drawn at this stage, owing to small statistics.

1.4.2 Neutron Capture Heavy Elements

Elements heavier than the iron peak are synthesized by neutron capture, which, depending on the neutron capture rate (and therefore the neutron density), is either called slow (*s*-process) or rapid (*r*-process). The *s*-process channel can happen in or in between thermal pulses of AGB stars, whereas the *r*-process requires much more extreme neutron exposures and are thought to take place either in SN II explosions (classical or in ν-driven winds) or in binary neutron stars, all hypotheses requiring massive progenitor stars (see Cowan & Sneden 2004 for a review on the *r*-process). Therefore, the time scale on which

* Normalized to their solar neighborhood counterparts.

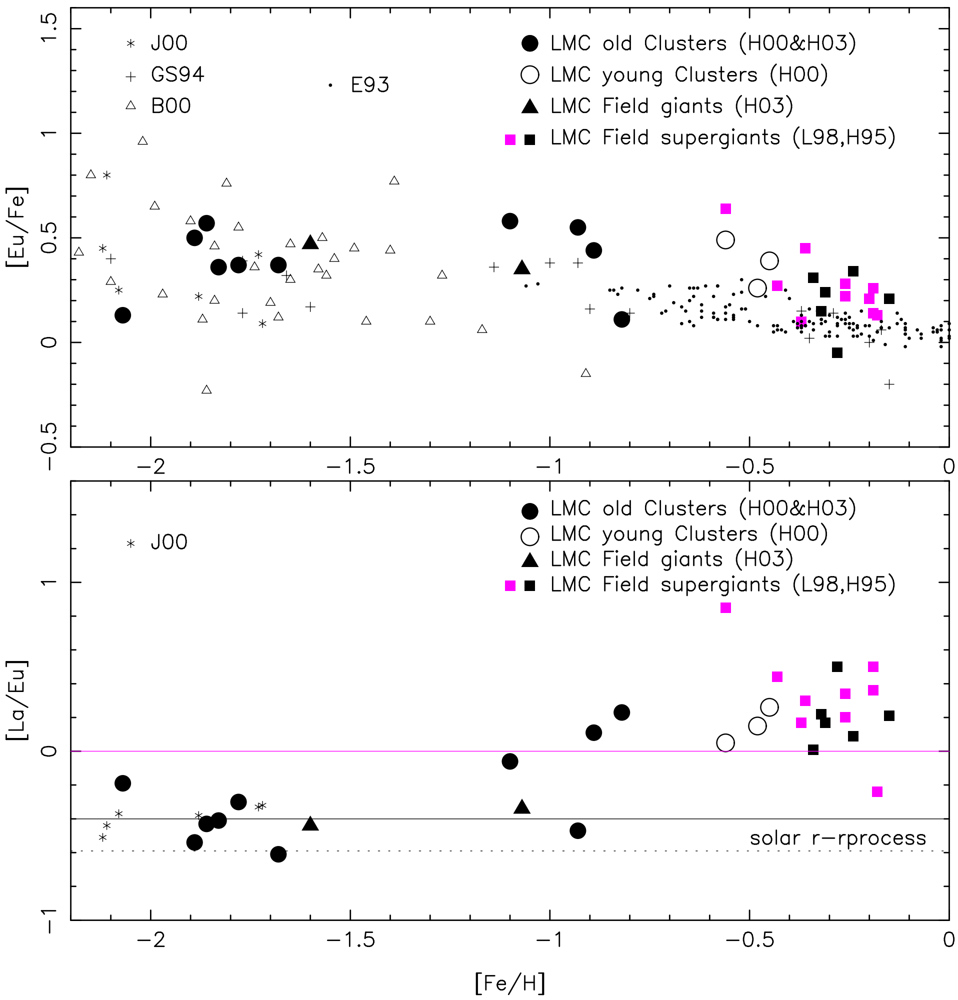

Fig. 1.4. Abundance of the *r*-process element [Eu/Fe] and the *r*-/*s*-process ratio indicator [La/Eu] for LMC stars, compared with Milky Way halo and disk stars. Symbols and references as in Fig. 1.2, except for the addition of B00 (Burris et al. 2000).

the *r*-process starts contributing to the chemical enrichment of a system is expected to be much shorter than for the *s*-process, as it is indeed observed in Galactic halo stars that are still dominated by the *r*-process up to metallicities of at least −2, or even −1 (Burris et al. 2000; Johnson 2002).

We have seen in §1.2.2.2 that the *present-day* neutron capture element abundances in the LMC (and even more strikingly in the SMC) are enhanced compared to what is observed in our Galaxy, and the cause of this enhancement is not well understood. The epoch (or metallicity) to which this enhancement can be traced back yields precious information to understand the process responsible for it.

The upper panel of Figure 1.4 shows the abundance ratio of europium (an element produced almost entirely by the *r*-process) to iron, as a function of [Fe/H] for the LMC sample (mainly globular clusters this time, since Smith et al. 2002 did not have access to any heavy element transitions in their infrared spectra), while the lower panel displays the abundance ratio of lanthanum to europium, a diagnostic of the *s*-/*r*-process ratio (as soon as the *s*-process starts contributing, La is dominated by *s*-process). A few remarks arise from the inspection of these plots:

(1) At the lowest metallicities (oldest globular clusters), both the overall [Eu/Fe] and the *s*-/*r*-process ratio are indistinguishable from that of the Galactic halo. This shows that, at early times, the *r*-process is the process dominating the neutron capture element synthesis (the pure *r*-process [La/Eu] ratio is displayed in the figure as black full and dashed lines, following the solar *r*-process decompositions of Burris et al. 2000 and Arlandini et al. 1999), and that the efficiency of the *r*-process in the LMC and Galactic halos were the same (giving rise to a same [Eu/Fe] ratio).

(2) The clear positive slope of the [La/Eu] ratio versus metallicity is the signature of an increasing *s*-process contribution with increasing metallicity, reaching a solar *s*-/*r*-process ratio (gray line) at metallicities around and above -1. It is interesting to note that this increase is already visible in the cluster ESO 121-SC03 (two points at [Fe/H] ≈ -0.8), which is a 9 Gyr cluster.

(3) The [La/Eu] ratio at the highest metallicities and youngest ages, reaches values that are above the solar ratio, suggesting that the *s*-process becomes even more efficient in the LMC than in our own Galaxy. In this case, the *s*-process would be responsible for the strong neutron capture enhancement in the present-day matter of the LMC, originating from AGBs rather than the massive stars needed to produce the *r*-process.

1.5 Conclusions

We have reviewed the current state of our knowledge of the chemical composition of the Magellanic Clouds, concentrating on the best probes of detailed elemental abundances.

We have seen that despite the likely very different evolutionary paths taken by the SMC and the LMC (compared to our own Galaxy) to reach their present-day chemical composition, and despite the different overall metallicities reached (1/5 and 1/3 solar, respectively), both Magellanic Clouds have reached very similar abundance ratios in a wide range of elements, apart from two notable exceptions: nitrogen and, to a lesser extent, carbon are underabundant (the N/O ratio is down by a factor of 4), while the heavy neutron capture elements are overabundant by factors of 3 and 2, respectively, in the SMC and the LMC.

At the other end of evolution, the oldest population in the LMC also seems to be very like the Milky Way halo stars, except for the notable exception of calcium and titanium (and maybe oxygen to a lesser extent). The situation in between these two extremes so far suffers from a lack of statistics, with only one study of 12 field RGB stars (Smith et al. 2002), and two intermediate-age clusters (Hill et al. 2000) in the LMC. Two alternative views are emerging from the two samples, favoring an evolution more strongly dominated by SNe Ia (compared to the Galactic disk) that leads to lower α/Fe ratios in all intermediate and young populations in one case, and in the other case, a remarkably flat variation of these α/Fe ratios along the whole evolution.

References

Allende Prieto, C., Lambert, D. L., & Asplund, M. 2001, ApJ, 556, L63

Andrievsky, S. M., Kovtyukh, V. V., Korotin, S. A., Spite, M., & Spite, F. 2001, A&A, 367, 605

Arlandini, C., Käppeler, F., Wisshak, K., Gallino, R., Lugaro, M., Busso, M., & Straniero, O. 1999, ApJ, 525, 886

Barbuy, B. 1988, A&A, 191, 121

Bica, E., Geisler, D., Dottori, H., Clariá, J. J., Piatti, A. E., & Santos., J. F. C. 1998, AJ, 116, 723

Burris, D. L., Pilachowski, C. A., Armandroff, T. E., Sneden, C., Cowan, J. J., & Roe, H. 2000, ApJ, 544, 302

Cole, A. A., Smecker-Hane, T. A., & Gallagher, J. S. 2000, AJ, 120, 1808

Cowan, J. J., & Sneden, C. 2004, in Carnegie Observatories Astrophysics Series, Vol. 4: Origin and Evolution of the Elements, ed. A. McWilliam & M. Rauch (Cambridge: Cambridge Univ. Press), in press

Da Costa, G. S., & Hatzidimitriou, D. 1998, AJ, 115, 1934

de Freitas Pacheco, J. A. 1998, AJ, 116, 1701

Dirsch, B., Richtler, T., Gieren, W. P., & Hilker, M. 2000, A&A, 360, 133

Dopita, M. A., et al. 1997, ApJ, 474, 188

Dufour, R. J. 1990, in Evolution in Astrophysics: IUE Astronomy in the Era of New Space Missions, 117

Dufour, R. J., Shields, G. A., & Talbot, R. J. 1982, ApJ, 252, 461

Edvardsson, B., Andersen, J., Gustafsson, B., Lambert, D. L., Nissen, P. E., & Tomkin, J. 1993, A&A, 275, 101

Esteban, C., Peimbert, M., Torres-Peimbert, S., & Escalante, V. 1998, MNRAS, 295, 401

Garnett, D. R. 1999, in IAU Symp. 190, New Views of the Magellanic Clouds, ed. Y.-H. Chu et al. (Dordrecht: Kluwer), 266

Garnett, D. R., Galarza, V. C., & Chu, Y. 2000, ApJ, 545, 251

Garnett, D. R., Skillman, E. D., Dufour, R. J., Peimbert, M., Torres-Peimbert, S., Terlevich, R., Terlevich, E., & Shields, G. A. 1995, ApJ, 443, 64

Geha, M. C., et al. 1998, AJ, 115, 1045

Geisler, D., Bica, E., Dottori, H., Claria, J. J., Piatti, A. E., & Santos, J. F. C. 1997, AJ, 114, 1920

Gilmore, G., & Wyse, R. F. G. 1991, ApJ, 367, L55

Gratton, R. G., et al. 2001, A&A, 369, 87

Gratton, R. G., & Sneden, C. 1991, A&A, 241, 501

——. 1994, A&A, 287, 927

Henry, R. B. C., Edmunds, M. G., & Köppen, J. 2000, ApJ, 541, 660

Hill, V. 1999, A&A, 345, 430

Hill, V., et al. 2004, in preparation

Hill, V., Andrievsky, S., & Spite, M. 1995, A&A, 293, 347

Hill, V., Barbuy, B., & Spite, M. 1997, A&A, 323, 461

Hill, V., François, P., Spite, M., Primas, F., & Spite, F. 2000, A&A, 364, L19

Hill, V., & Spite, M. 1999, Ap&SS, 265, 469

Holtzman, J. A., et al. 1997, AJ, 113, 656

Hunter, D. A., Light, R. M., Holtzman, J. A., Lynds, R., O'Neil, E. J., & Grillmair, C. J. 1997, ApJ, 478, 124

Johnson, J. A. 2002, ApJS, 139, 219

——. 2004, in Carnegie Observatories Astrophysics Series, Vol. 4: Origin and Evolution of the Elements, ed. A. McWilliam & M. Rauch (Pasadena: Carnegie Observatories, http://www.ociw.edu/ociw/symposia/series/symposium1/proceedings.html)

Korn, A. J., Becker, S. R., Gummersbach, C. A., & Wolf, B. 2000, A&A, 353, 655

Korn, A. J., Keller, S. C., Kaufer, A., Langer, N., Przybilla, N., Stahl, O., & Wolf, B. 2002, A&A, 385, 143

Kurt, C. M., Dufour, R. J., Garnett, D. R., Skillman, E. D., Mathis, J. S., Peimbert, M., Torres-Peimbert, S., & Ruiz, M.-T. 1999, ApJ, 518, 246

Luck, R. E., & Lambert, D. L. 1992, ApJS, 79, 303

Luck, R. E., Moffett, T. J., Barnes, T. G., & Gieren, W. P. 1998, AJ, 115, 605

Massey, P., Johnson, K. E., & DeGoia-Eastwood, K. 1995, ApJ, 454, 151

McWilliam, A., & Williams, R. E. 1991, in IAU Symp. 148, The Magellanic Clouds, ed. R. Haynes & D. Milne (Dordrecht: Kluwer), 391

Meléndez, J., & Barbuy, B. 2002, ApJ, 575, 474

Nissen, P. E., & Edvardsson, B. 1992, A&A, 261, 255

Nissen, P. E., Primas, F., Asplund, M., & Lambert, D. L. 2002, A&A, 390, 235

Nissen, P. E., & Schuster, W. J. 1997, A&A, 326, 751

Olszewski, E. W., Schommer, R. A., Suntzeff, N. B., & Harris, H. C. 1991, AJ, 101, 515

Pagel, B. E. J., & Tautvaišienė, G. 1995, MNRAS, 276, 505

——. 1998, MNRAS, 299, 535
Pilyugin, L. S. 1996, A&A, 310, 751
Pilyugin, L. S., Thuan, T. X., & Vílchez, J. M. 2003, A&A, 397, 487
Richtler, T., Spite, M., & Spite, F. 1989, A&A, 225, 351
Rolleston, W. R. J., Brown, P. J. F., Dufton, P. L., & Howarth, I. D. 1996, A&A, 315, 95
Rolleston, W. R. J., Trundle, C., & Dufton, P. L. 2002, A&A, 396, 53
Rolleston, W. R. J., Venn, K., Tolstoy, E., & Dufton, P. L. 2003, A&A, 400, 21
Russell, S. C., & Bessell, M. S. 1989, ApJS, 70, 865
Russell, S. C., & Dopita, M. A. 1992, ApJ, 384, 508
Sarajedini, A. 1998, AJ, 116, 738
Shetrone, M. D. 1996, AJ, y112, 1517
——. 2004, in Carnegie Observatories Astrophysics Series, Vol. 4: Origin and Evolution of the Elements, ed. A. McWilliam & M. Rauch (Cambridge: Cambridge Univ. Press), in press
Smecker-Hane, T. A., Cole, A. A., Gallagher, J. S., & Stetson, P. B. 2002, ApJ, 566, 239
Smith, V. V., et al. 2002, AJ, 124, 3241
Spite, F., Spite, M., & Richtler, T. 1991, A&A, 252, 557
Spite, M., François, P., Spite, F., Cayrel, R., & Richtler, T. 1986, A&A, 168, 197
Spite, M., Spite, F., & Barbuy, B. 1989, A&A, 222, 35
Tsamis, Y. G., Barlow, M. J., Liu, X.-W., Danziger, I. J., & Storey, P. J. 2003, MNRAS, 338, 687
Tsujimoto, T., Nomoto, K., Yoshii, Y., Hashimoto, M., Yanagida, S., & Thielemann, F.-K. 1995, MNRAS, 277, 945
Venn, K. A. 1999, ApJ, 518, 405