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Abundance evolution of intermediate mass elements (C to Zn) in the Milky Way halo and disk

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Abstract. We present a comprehensive study of the evolution of the abundances of intermediate mass elements, from C to Zn, in the Milky Way halo and in the local disk. We use a consistent model to describe the evolution of those two galactic subsystems. The halo and the disk are assumed to evolve independently, both starting with gas of primordial composition, and in different ways: strong outflow is assumed to take place during the ∼1 Gyr of the halo formation, while the disk is built by slowly infalling gas. This description of the halo+disk evolution can correctly account for the main observational constraints (at least in the framework of simple models of galactic chemical evolution). We utilise then metallicity dependent yields to study the evolution of all elements from C and Zn. Comparing our results to an extensive body of observational data (including very recent ones), we are able to make a critical analysis of the successes and shortcomings of current yields of massive stars. Finally, we discuss qualitatively some possible ways to interpret the recent data on oxygen vs iron, which suggest that oxygen behaves differently from the other alpha-elements.

Key words: nuclear reactions, nucleosynthesis, abundances – stars: abundances – Galaxy: abundances – Galaxy: evolution – Galaxy: general – Galaxy: halo

1. Introduction

In the past ten years or so, progress in our understanding of the chemical evolution of the Milky Way came mainly from observations concerning the composition of stars in the halo and the local disk. The seminal works of Edvardsson et al. (1993) for the disk, and Ryan et al. (1996) and McWilliam et al. (1995a, 1995b) for the halo (along with many others) provided detailed abundance patterns that reveal, in principle, the chemical history of our Galaxy.

The interpretation of these data is not straightforward, however, since it has to be made in the framework of some appropriate model of galactic chemical evolution (GCE). Only one of the three main ingredients of GCE models can be calculated from first principles at present: the stellar yields. For the other two ingredients, i.e. the stellar initial mass function (IMF) and the star formation rate (SFR), one has to rely on empirical prescriptions.

Considerable progress in GCE studies was made possible after the publication of the yields from massive stars of Woosley & Weaver (1995, hereafter WW1995). This work made available, for the first time, yields for an extensive set of isotopes (from H to Zn), stellar masses (from 11 to 40 $M_{\odot}$) and metallicities (from Z=0 to Z=$Z_{\odot}$), making thus possible a detailed comparison of theory to observations. Only two works until now explored fully the potential of the WW1995 yields. Timmes et al. (1995) adopted a simple GCE model with infall, appropriate for the Milky Way disk but certainly not for the halo (see Sect. 3.3); in the framework of that model they made a case-by-case assessment of the strengths and weaknesses of the WW1995 yields, identifying the large yields of Fe as the main weak point. On the other hand, Samland (1998) utilised a chemo-dynamical model for the Milky Way evolution (describing, presumably, correctly the halo and the disk), but introduced several approximations on the stellar lifetimes and the metallicity dependent yields of WW1995; he evaluated then the deviation of the published yields from the "true" galactic ones, the latter being derived by a comparison of his model results with observations of the halo and disk abundance patterns.

Those two works are the only ones that utilised metallicity dependent yields and studied the full range of intermediate mass chemical elements. Several other works focused on specific elements and utilised only metallicity independent yields (e.g. Pagel & Tautvaisiene 1995; Chiappini et al. 1997, 1999; Thomas et al. 1998 etc.)

In this work we reassess the chemical evolution of the elements from C to Zn in the Milky Way, using the WW1995 yields. Our work differs in several aspects from the one of Timmes et al. (1995) and, in fact, from any other work on that topic, performed in the framework of simple GCE models: the main novelty is that we use appropriate models for *both* the halo and the disk, correctly reproducing the main observational constraints for those two galactic subsystems (see Sect. 4). Moreover, we adopt the Kroupa et al. (1993) IMF, which presumably describes the distribution of stellar masses better than the Salpeter IMF (adopted in Timmes et al. 1995, Samland 1998, and most other studies of that kind). Also, w.r.t. the work of Timmes et al. (1995), our comparison to observations benefits from the wealth of abundance data made available after the surveys of Ryan et al. (1996), McWilliam et al. (1995a, 1995b), Chen et al. (2000) and many

Table 1. Reference list of the observational data for the halo and the disk stars

C	N	O	Na	Mg	Al	Si	S	K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ref
x															x					1
				x	x										x					2
			x	x	x	x			x	x	x	x	x	x	x	x	x	x		3
x	x						x								x					4
						x					x				x		x			5
x	x			x	x				x		x				x		x			6
x	x														x					7
x		x	x	x	x	x			x		x				x		x			8
			x	x	x	x			x	x					x					9
			x	x	x	x									x					10
			x	x											x					11
x	x	x								x					x					12
				x			x								x					13
x	x														x					14
						x		x	x		x				x		x			15
			x	x	x	x			x						x					16
							x								x					17
									x	x	x	x	x	x	x	x	x			18
			x	x	x	x			x	x	x		x		x		x			19
				x	x				x	x	x		x	x	x		x			20
															x		x		x	21
														x	x					22
				x	x				x	x	x		x		x					23
				x	x	x			x		x				x		x			24
			x	x					x		x				x					25
			x						x	x	x		x		x		x			26
		x													x					27
						x			x	x	x	x	x	x	x	x	x			28
				x	x	x			x	x	x		x	x	x	x	x			29
															x		x		x	30

References: 1. Sneden et al. (1979); 2. Carney & Peterson (1981); 3. Peterson (1981); 4. Clegg et al. (1981); 5. Leep & Wallerstein (1981); 6. Barbuy et al. (1985); 7. Laird (1985); 8. Magain (1985); 9. Tomkin et al. (1985); 10. Francois (1986a); 11. Francois (1986b); 12. Gratton & Ortolani (1986); 13. Francois (1987a); 14. Carbon et al. (1987); 15. Gratton & Sneden (1987); 16. Magain (1987); 17. Francois (1987b); 18. Gilroy et al. (1988); 19. Gratton & Sneden (1988); 20. Hartmann & Gehren (1988); 21. Sneden & Crocker (1988); 22. Gratton (1989); 23. Magain (1989); 24. Molaro & Castelli (1990); 25. Molaro & Bonifacio (1990); 26. Zhao & Magain (1990); 27. Bessel et al. (1991); 28. Gratton & Sneden (1991); 29. Ryan et al. (1991); 30. Sneden et al. (1991)

others (listed in Table 1). These data allow to put even stronger constraints on the stellar yields as a function of metallicity. We notice that we do not include yields from intermediate mass stars in our study, since we want to see to what extent those stars (or other sources) are required to account for the observations.

The plan of the paper is as follows: In Sect. 2 we discuss briefly the uncertainties currently affecting the yields of massive stars and present the yields of WW1995. We also present those of a recent work (Limongi et al. 2000), which compare fairly well to those of WW1995 but show interesting differences for several elements. Moreover, we present the recent yields of Iwamoto et al. (1999) for supernovae Ia, calculated for white dwarfs resulting from stars of solar and zero initial metallicities, respectively; they are slightly different from the "classical" W7 model for SNIa (Thielemann et al. 1986), and we adopt them in our study. In Sect. 3 we present our chemical evolution model, stressing the importance of adopting appropriate ingredients for the halo and the disk. In Sect. 4 we "validate" our model by comparing successfully its results to the main observational constraints. We also show that current massive star yields have difficulties in explaining the solar composition of Sc, Ti and V. In Sect. 5 we present the main result of this work, i.e. a detailed comparison of the model to observations of abundance patterns in halo and disk stars. This comparison allows to identify clearly the successes and inadequacies of the WW1995 yields; some of those inadequacies may be due to physical ingredients not as yet incorporated in "standard" stellar models (i.e. mass loss or rotationally induced mixing), but the origins of others are more difficult to identify. Since the evolution of Fe (usually adopted as "cosmic clock") is subject to various theoretical uncertainties - Fe yields of massive stars, rate of Fe producing supernovae Ia etc - we also plot our results as a function of Ca; comparison to available observations (never performed before) gives then a fresh and instructive view of the metallicity dependence of the massive star yields. In Sect. 6, we discuss qualitatively some possible ways to interpret the recent data of

Table 1. (continued)

C	N	O	Na	Mg	Al	Si	S	K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ref
		x													x					31
		x													x					32
		x							x						x					33
x															x					34
		x	x	x	x	x			x		x				x		x			35
				x	x				x	x	x		x	x	x		x			36
x															x					37
x	x	x	x	x	x	x			x	x	x	x	x	x	x	x	x		x	38
x	x	x				x									x					39
		x													x					40
		x		x					x		x		x		x					41
			x	x	x	x			x		x				x					42
x			x	x	x	x			x	x	x		x	x	x	x				43
				x											x					44
		x													x					45
x			x	x	x	x			x	x	x	x	x	x	x	x	x			46
x															x					47
x		x													x					48
				x	x	x			x	x	x		x	x	x	x	x			49
		x	x	x		x			x		x		x		x		x			50
x		x	x	x					x	x	x		x		x					51
					x										x					52
		x													x					53
		x	x	x	x	x			x	x	x	x	x	x	x	x	x			54
				x					x		x	x	x		x		x			55
		x													x					56
										x				x	x					57
		x	x	x	x	x		x	x		x	x	x		x		x			58
			x	x		x			x		x		x		x		x			59
x	x	x	x	x											x					60

References: 31. Spite & Spite (1991); 32. Spiesman & Wallerstein (1991); 33. Nissen & Edvardsson (1992); 34. Tomkin et al. (1992); 35. Edvardsson et al. (1993); 36. Norris et al. (1993); 37. Andersson & Edvardsson (1994); 38. Beveridge & Sneden (1994); 39. Cunha & Lambert (1994); 40. King (1994); 41. Nissen et al. (1994); 42. Primas et al. (1994); 43. Sneden et al. (1994); 44. Fuhrmann et al. (1995); 45. King & Boesgaard (1995); 46. McWilliam et al. (1995a, 1995b); 47. Tomkin et al. (1995); 48. Balachandran & Carney (1996); 49. Ryan et al. (1996); 50. Nissen & Schuster (1997); 51. Baumüller & Gehren (1997); 52. Laimons et al. (1998); 53. Israelian et al. (1998); 54. Feltzing & Gustafsson (1998); 55. Jehin et al. (1999); 56. Boesgaard et al. (1999); 57. Nissen et al. (1999); 58. Chen et al. (2000); 59. Stephens (1999); 60. Carretta et al. (2000)

Israelian et al. (1998) and Boesgaard et al. (1999) on oxygen vs iron; these data suggest that oxygen behaves differently from the other alpha-elements and, if confirmed, will require some important revision of current ideas on stellar nucleosynthesis. Finally, in Sect. 7 we compare the model evolution of the Mg isotopic ratios to recent observations of disk and halo stars; we find that the WW1995 yields underestimate the production of the neutron-rich Mg isotopes at low metallicities.

2. Yields of massive stars and supernova Ia

Massive stars are the main producers of most of the heavy isotopes in the Universe (i.e. those with mass number $A>11$). Elements up to Ca are mostly produced in such stars by hydrostatic burning, whereas Fe peak elements are produced by the final supernova explosion (SNII), as well as by white dwarfs exploding in binary systems as SNIa. Most of He, C, N and minor CO isotopes, as well as s-nuclei comes from intermediate mass stars (2-8 $M_\odot$). A detailed discussion of the yields of massive stars and their role in galactic chemical evolution studies has been presented in a recent review (Prantzos 2000); here we summarize the most important points.

Extensive calculations performed in the 90ies by a few groups with 1-D stellar codes (Woosley & Weaver 1995; Arnett 1996; Thielemann et al. 1996; Chieffi et al. 1998; Maeder 1992; Woosley et al. 1993; Aubert et al. 1996; Limongi et al. 2000) have revealed several interesting features of nucleosynthesis in massive stars. In particular, the structure and composition of the pre-supernova star reflects the combined effect of (i) the various mixing mechanisms (convection, semi-convection, rotational mixing etc.), determining the extent of the various "onion-skin" layers, (ii) the amount of mass-loss (affecting mostly the yields of the He and CNO nuclei, present in the outer layers) and (iii) the rates of the relevant nuclear ractions (determining the abundances of the various species in each layer).

On the other hand, the calculation of the Fe-core collapse supernova explosion is still one of the major challenges in stellar astrophysics. Multi-dimensional hydrodynamical simulations in the 90ies revealed the crucial role played by neutrino transport in the outcome of the explosion (e.g. Janka 1998 and references therein). In the absence of a well-defined explosion scheme, modelers of supernovae nucleosynthesis have to initiate the explosion somehow (by introducing either an "internal energy bomb", or a "piston", e.g. Aufderheide et al. 1991) and adjust the shock energy as to have a pre-determined final kinetic energy, usually the "classical" value of 10^{51} ergs (after accounting for the binding energy of the ejected matter). This procedure introduces one more degree of uncertainty in the final yields. Moreover, the ejected amount of Fe-peak nuclei depends largely on the position of the *mass-cut*, the surface separating the material falling back onto the neutronized core from the ejected envelope. The position of this surface depends on the details of the explosion (i.e. the delay between the bounce and the neutrino-assisted explosion, during which the proto-neutron star accretes material) and cannot be evaluated currently with precision (e.g. Thielemann et al. 1999 and references therein).

In the light of the aforementioned results, intermediate mass elements produced in massive stars may be divided into three major groups:

(i) C, N, O, Ne, and Mg are mainly produced in hydrostatic burning phases. They are mostly found in layers which are not heavily processed by explosive nucleosynthesis. The yields of these elements depend on the pre-supernova model (convection criterion, mixing processes, mass loss and nuclear reaction rates).

(ii) Al, Si, S, Ar and Ca are also produced by hydrostatic burning, but their abundances are subsequently affected by the passage of the shock wave. Their yields depend on both the pre-supernova model and the shock wave energy.

(iii) Fe-peak elements as well as some isotopes of lighter elements like Ca, S and Ti are produced by the final SN explosion (SN II). Their yields depend crucially upon the explosion mechanism and the position of the "mass-cut".

The outcome of nucleosynthesis depends also on the initial metallicity of the star. During H-burning the initial CNO transforms into ^{14}N, which transforms mostly into ^{22}Ne during He-burning, through α-captures and a β decay. The surplus of neutrons in ^{22}Ne (10 protons and 12 neutrons) affects the products of subsequent burning stages, in particular those of explosive burning. This neutron surplus increases with initial metallicity and favours the production of odd nuclei (^{23}Na, ^{27}Al, ^{31}P etc.), giving rise to the so-called "odd-even" effect.

In the past few years, several groups have reported results of pre and post-explosive nucleosynthesis calculations in massive stars with detailed networks. Thielemann et al. (1996) used bare He cores of initial metallicity $Z_\odot$, while Arnett (1996) simulated the evolution of He cores (with polytropic-like trajectories) and studied different initial metallicities. Full stellar models (neglecting however, rotation and mass loss) were studied by Woosley & Weaver (1995, for masses 12, 13, 15, 18, 20, 22, 25, 30, and 40 $M_\odot$ and metallicities Z=0, 10^{-4}, 10^{-2}, 10^{-1}, and 1 $Z_\odot$) and Limongi et al. (2000, for masses 13, 15, 20, 25 $M_\odot$ and metallicities Z=0, 5 10^{-2} and 1 $Z_\odot$). Comparison of the various yields on a star by star basis shows that there are large discrepancies between the different authors (due to differences in the adopted physics) although for some elements, like oxygen, there is a rather good agreement. Moreover, the yields do not show a monotonic behaviour with stellar mass.

Notice that the overall yield used in chemical evolution studies depends on both the individual stellar yields and the stellar IMF. Despite a vast amount of theoretical and observational work, the exact shape of the IMF is not well known yet (Gilmore et al. 1998 and references therein). It is however clear that the IMF flattens in the low mass range and cannot be represented by a power law of a single slope (e.g. Kroupa et al. 1993). The shape of the IMF introduces a further uncertainty of a factor $\sim$ 2 as to the absolute yield value of each isotope (Wang & Silk 1993).

In Fig. 1 we present the metallicity dependent yields of Woosley & Weaver 1995 (hereafter WW1995) and Limongi et al. 2000 (hereafter LSC2000), folded with a Kroupa et al. (1993) IMF. They are presented as *overproduction factors*, i.e. the yields (ejected mass of a given element) are divided by the mass of that element initially present in the part of the star that is finally ejected, i.e.

$$\langle F \rangle \ = \ \frac{\int_{M1}^{M2} Y_i(M)\ \Phi(M)\ dM}{\int_{M1}^{M2} X_{\odot,i}(M - M_R)\ \Phi(M)\ dM} \qquad (1)$$

where: $\Phi(M)$ is the IMF, $M1$ and $M2$ the lower and upper mass limits of the stellar models (12 $M_\odot$ and 40 $M_\odot$ for WW1995, 13 $M_\odot$ and 25 $M_\odot$ for LSC2000, respectively), $Y_i(M)$ are the individual stellar yields and M_R the mass of the stellar remnant. Adopting $X_{\odot,i}$ in Eq. (1) creates a slight inconsistency with the definition of the overpoduction factor given above, but it allows to visualize the effects of metallicity in the yields of secondary and odd elements.

From Fig. 1 it can be seen that i) most of the intermediate mass elements are nicely co-produced (within a factor of 2) in both calculations of solar metallicity stars; ii) some important discrepancies (e.g. Li, B, F) can be readily understood in terms of neutrino-induced nucleosynthesis, included in the WW1995 but not in the LSC2000 calculation; iii) the odd-even effect is clearly present in both calculations, but seems to be more important in LSC2000. For solar metallicity stars most of the even Z elements are produced with similar yields in both calculations, while odd Z elements in LSC2000 are produced with systematically lower yields than in WW1995. A common feature of both calculations is the relative underproduction of C, N, Sc, V and Ti w.r.t. O. C and N clearly require another source (intermediate mass stars and/or Wolf-Rayet stars, see Prantzos et al. 1994 and Sect. 4.2). The situation is less clear for the other elements, Sc, V and Ti.

In this work we adopt the metallicity dependent yields of WW1995, keeping in mind that the use of LSC2000 yields may

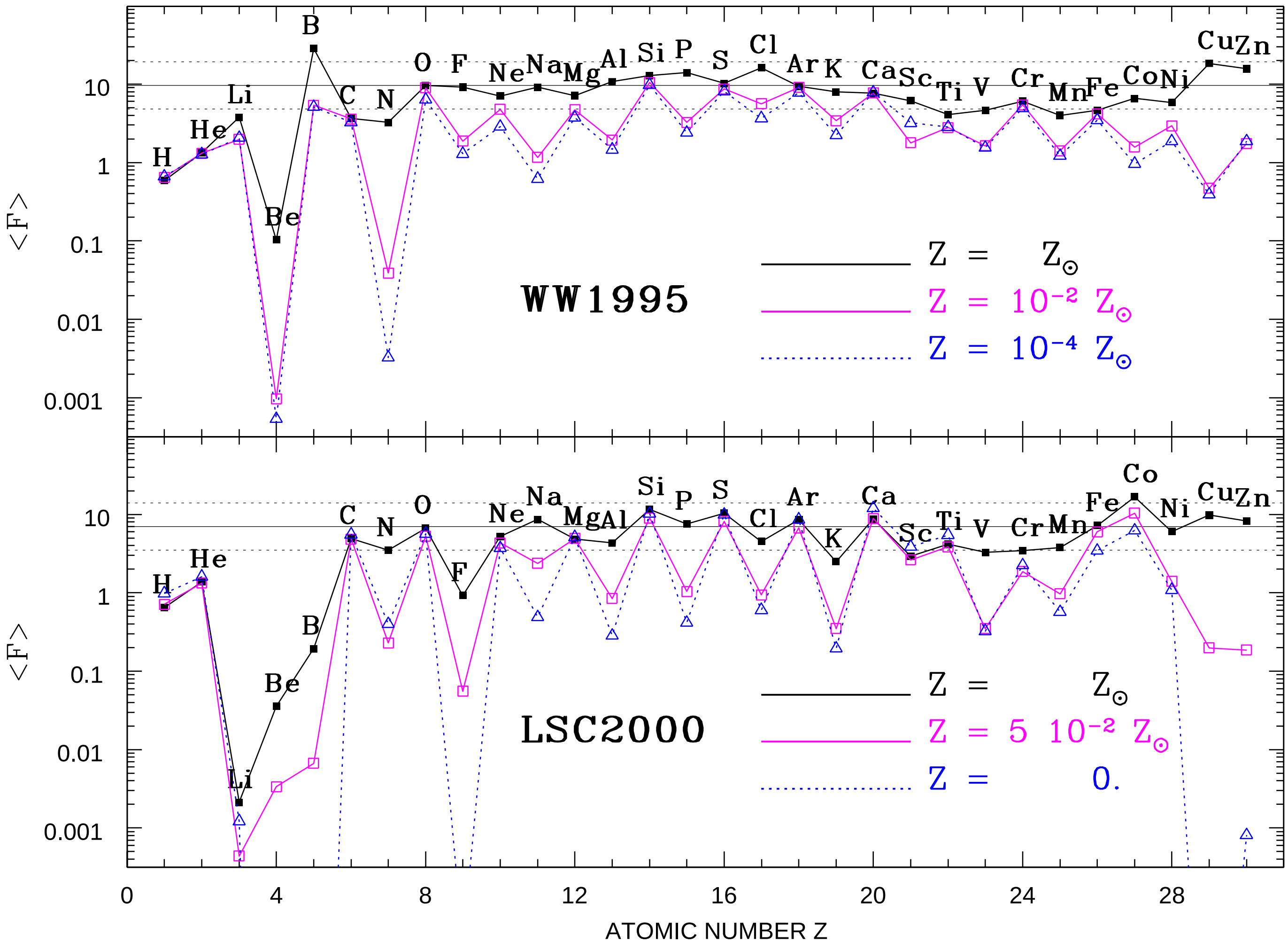

Fig. 1. Average overproduction factors (over a Kroupa et al. (1993) IMF, see Eq. 1) of the yields of Woosley & Weaver 1995 (WW1995, *upper panel*) and Limongi et al. 2000 (LSC2000, *lower panel*) for 3 different initial stellar metallicities. In both cases, the *solid horizontal lines* are placed at F_{oxygen} and the two *dotted horizontal lines* at half and twice that value, respectively. The "odd-even effect" is clearly seen in both the data sets. N behaves as a pure "secondary". The elements He, C, N, Li and Be in both cases (as well as B and F in LSC2000) require another production site

lead to different results for some odd elements. For illustration purposes we shall also use the WW1995 yields at constant (=solar) metallicity. There are interesting differences between the two cases (i.e. constant vs. variable metallicity yields) and this instructive comparison has never been done before. We notice that in the case of the most massive stars (M>30 $M_\odot$) WW1995 performed 3 calculations, making different assumptions about the kinetic energy of the supernova ejecta. We adopt here their set of models A, in which, following the explosion, most of the heavy elements in the inner core fall back to form a black hole of a few solar masses; because of the form of the IMF, these very massive stars play a negligible role in shaping the elemental abundance ratios. As stressed in the Introduction, we consider no yields from intermediate mass stars in this work; our explicit purpose is to check to what extent massive stars can account for observations of intermediate mass elements and for which elements the contribution of intermediate mass stars is mandatory.

There is a strong observational argument, suggesting that massive stars are not the sole producers of Fe peak nuclei in the solar neighbourhood: the observed decline in the [O/Fe] ratio (Fig. 3, lower panel) from its ∼3 times the solar value in the halo stars ([O/Fe] ∼0.5 for [Fe/H]<-1) down to solar in disk stars. This decline is usually interpreted as due to injection of Fe and Fe group elements by SN Ia. Assuming that massive stars are the only source of O and Fe in the halo phase and they produce a ratio of Fe/O∼1/3 solar, the remaining ∼2/3 of Fe in the late disk should be produced by a late source, presumably SNIa.

The WW1995 yields lead to approximately solar abundance ratios of O/Fe (or α-element/Fe). This lead Timmes et al. (1995) to suggest that the Fe yields of WW1995 are probably overestimated. Following their suggestion, we adopt here half the nominal values for the WW1995 yields of Fe-peak elements (from Cr to Zn). Taking into account the uncertainties currently affecting those yields, such a reduction is not unreasonable. Our

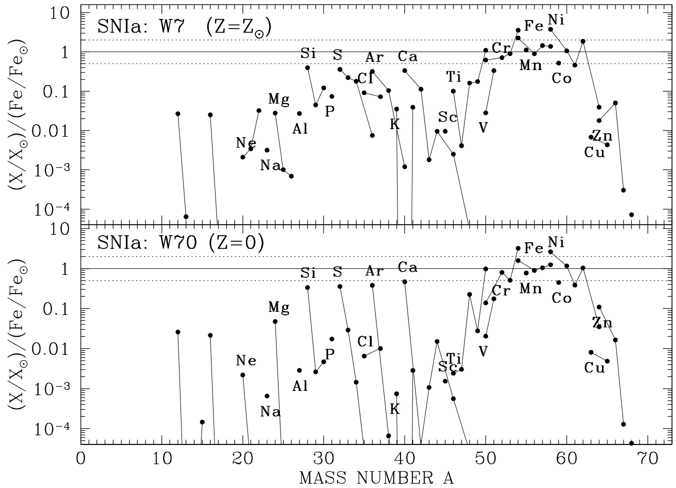

Fig. 2. Isotopic yields of SNIa resulting from Chandrasekhar mass white dwarfs, according to Iwamoto et al. (1999). *Top panel:* model W7 (the white dwarf results from a star of initial metallicity Z=Z$_\odot$). *Bottom panel:* model W70 (the white dwarf results from a star of initial metallicity Z=0). Both models are calculated with updated nuclear reaction rates (with respect to the "old" W7 model of Thielemann et al. 1986). In both cases, the overproduction factor of ^{56}Fe is taken as 1, while variations by a factor of 2 are indicated by *dotted* lines. ^{54}Cr and ^{58}Ni are clearly overproduced in those models

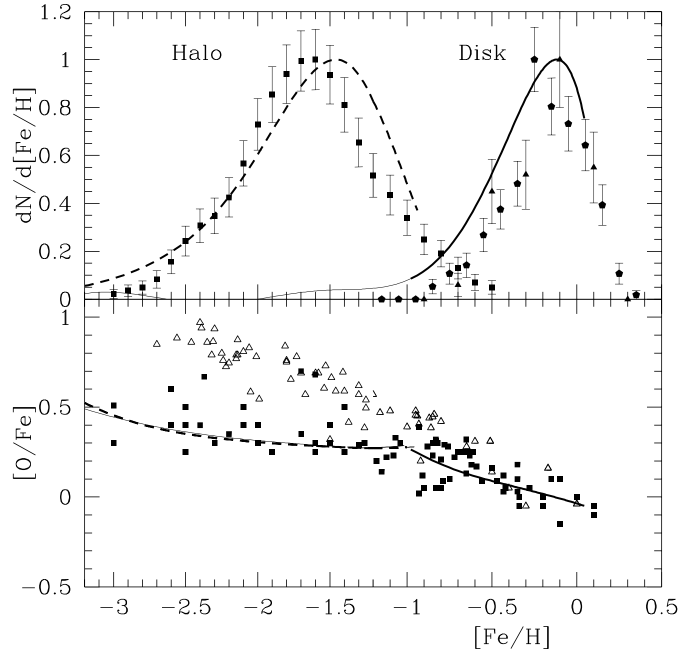

Fig. 3. *Upper panel*: Model metallicity distributions (MD) of the galactic halo (*dashed curve*) and the local disc (*solid curve*) obtained with appropriate models and the metallicity dependent yields of WW1995; The "traditional" disk population, at [Fe/H]>-1, is indicated by a *thick* curve (see Sect. 4.1). Observations for halo MD are from Norris & Ryan (1991, *filled squares*) and for the disk from Wyse & Gilmore (1995, *filled pentagons*) and Rocha-Pinto & Maciel (1996, *filled triangles*). *Lower panel*: [O/Fe] vs. [Fe/H] in the halo (*dashed curve*) and the disk (*solid curve*, *thick* for [Fe/H]>-1 and *thin* for [Fe/H]<-1), according to our model. Observed abundances are from sources listed in Table 1 (*filled squares*), except for those of Israelian et al. (1998) and Boesgaard et al. (1999) (*open triangles*). All MDs are normalised to f_{max}=1

procedure allows to reproduce the observed O/Fe, but does not alter the abundance ratios *between* Fe-peak elements.

To account for the additional source of Fe-peak elements we utilise the recent yields of SNIa from the exploding white dwarf models of Iwamoto et al. (1999). These are updated versions of the original W7 model of Thielemann et al. (1986). In this model, the deflagration is starting in the centre of an accreting Chandrashekhar-mass CO white dwarf, burns $\sim$ half of the stellar material in Nuclear Statistical Equilibrium and produces $\sim$ 0.7 $M_\odot$ of ^{56}Fe (in the form of ^{56}Ni). It also produces all other Fe-peak isotopes and in particular ^{58}Ni and ^{54}Cr. This can be seen in Fig. 2, where the overproduction factors (normalised to the one of ^{56}Fe) of the SNIa yields are plotted for two models: one calculated for a white dwarf resulting from a star with solar initial metallicity (W7) and another for a white dwarf resulting from a star of zero initial metallicity (W70). The main difference between the two model results lies in the large underproduction of odd-isotopes in the latter case. In our calculation, we use the yields of those two models, linearly interpolated as a function of metallicity.

The problem with SNIa is that, although the current rate of SNIa/SNII is constrained by observations in external spiral galaxies (Tammann et al. 1994), the past history of that rate (depending on the nature of progenitor systems) is virtually unknown. Thus, at present, it is rather a mystery why the timescale for the onset of SNIa activity (presumably producing the observed decline of O/Fe in the disk) coincides with the timescale for halo formation. An original suggestion was recently made in Kobayashi et al. (1998), whereby SNIa appear at a rate which is metallicity dependent; the interest of this scenario lies in the fact that SNIa enter the cosmic scene at just the right moment. For the purpose of this work, we shall adopt the formalism of Matteucci & Greggio (1986), adjusting it as to have SNIa appearing mostly after the first Gyr, i.e. at a time when [Fe/H]$\sim$-1.

At this point we would like to point out that two recent observations (Israelian et al. 1998 and Boesgaard et al. 1999) challenged the "traditional" view of O vs Fe evolution, by finding a trend of O/Fe *constantly increasing* with decreasing metallicity (open triangles in Fig. 3). This intriguing trend is not confirmed by subsequent studies (Fullbright & Kraft 1999), but the question remains largely open today. If the new findings are confirmed, some of our ideas on stellar nucleosynthesis should be revised. Some possibilities of such a revision are explored in Sect. 6.

3. The model of galactic chemical evolution

Models of chemical evolution for the halo and the disk of the Milky Way are constructed adopting the standard formalism (Tinsley 1980, Pagel 1997). The classical set of the equations of galactic chemical evolution is solved numerically for each zone, without the Instantaneous Recycling Approximation (IRA). At the star's death its ejecta is assumed to be thoroughly mixed in the local interstellar medium (instantaneous mixing approximation), which is then characterized by a unique composition at a given time. Abundance scatter cannot be treated in that framework, and this constitutes an important drawback of this type of "classical" models, since observations suggest a scatter of element to element ratios which increases with decreasing metallicity (Ryan et al. 1996). The basic ingredients of the model are described below.

3.1. Stellar lifetimes and remnant masses

The stellar lifetimes τ_M as a function of stellar mass M are taken from the work of the Geneva group (Schaller et al. 1992, Charbonnel et al. 1996), where the effects of mass loss on the duration of H and He burning phases are taken into account.

Stars with mass M<$9M_\odot$ are considered to become white dwarfs with mass $M_R(M/M_\odot)$ =0.1$(M/M_\odot)$+0.45 (Iben & Tutukov 1984). Stars with mass M $>9M_\odot$ explode as core collapse supernovae leaving behind a neutron star of mass $M_R = 1.4M_\odot$ (as suggested by the observations of neutron stars in binary systems, e.g. Thorsett & Chakrabarty 1999). The heaviest of those stars may form a black hole, but the mass limit for the formation of stellar black holes is not known at present and cannot be inferred from theoretical or observational arguments (e.g. Prantzos 1994), despite occasional claims to the contrary. Due to the steeply decreasing stellar Initial Mass Function in the range of massive stars (see Sect. 3.2), as far as the mass limit for stellar black hole formation is $M_{BH} > 40M_\odot$ the results of chemical evolution are not expected to be significantly affected by the exact value of M_{BH}.

We stress that in our calculations we do take into account the amount of mass returned in the interstellar medium (ISM) by stars with M<11 $M_\odot$ and M>40 $M_\odot$ in the form of H, He, but also of all heavier elements, up to Zn. Since no yields are available for 9-11 $M_\odot$ and >40 $M_\odot$ stars (and since we deliberately neglect yields for intermediate mass stars), we simply assume that those stars return at their death in the ISM their initial amount of each element, i.e. that their *net yield* is zero for all elements (except for deuterium, which is destroyed). In that way we do not introduce any artificial modification of the adopted yields. This procedure is crucial for a correct evaluation of the metal/H ratio at a given time, especially at late times.

3.2. Star formation rate and initial mass function

Observations of average SFR vs. gas surface density in spirals and starbursts (Kennicutt 1998) are compatible with a Schmidt type law

$$\Psi(t) \;=\; \nu \, \sigma_{gas}^{k}(t) \tag{2}$$

with k=1-2. However, this concerns only the *disk averaged* SFR and Kennicutt (1998) points out that the local SFR may have a different behaviour. Indeed, theoretical ideas of SFR in galactic disks suggest a radial dependence of the SFR (Wyse & Silk 1989) and such a dependence is indeed required in order to explain the observed abundance, colour and gas profiles in spirals (Boissier & Prantzos 1999; Prantzos & Boissier 2000). For the purposes of this work we adopt a Schmidt law with k=1.5; when combined with the adopted infall prescription (see next section) this leads to a slowly varying star formation history in the galactic disk, compatible with various observables (see Sect. 4). For consistency, we keep the same form of the SFR in the halo model, although there is no observational hint for the SFR behaviour during this early stage.

We adopt the IMF from the work of Kroupa et al. (1993, hereafter KTG93), where the complex interdependence of several factors (like stellar binarity, ages and metallicities, as well as mass-luminosity and colour-magnitude relationships) is explicitly taken into account. It is a three-slope power-law IMF $\Phi(M) \propto M^{-(1+x)}$; in the high mass regime it has a relatively steep slope of X=1.7 (based on Scalo 1986), while it flattens in the low-mass range (X=1.2 for 0.5<M/$M_\odot$<1. and X=0.3 for M<0.5 $M_\odot$). We adopt this IMF between 0.1 and 100 $M_\odot$, although we are aware that there is some debate as to the exact form of the low-mass part. Again, for consistency, we adopt the same IMF in the halo and in the disk model.

3.3. Gaseous flows: infall and outflow

In most models of chemical evolution of the solar neighbourhood, it is implicitly assumed that the old (halo) and young (disk) stars are parts of the same physical system, differing only by age; the same model is used to describe the whole evolution, from the very low metallicity regime to the current (supersolar) one (e.g. Timmes et al. 1995).

This assumption is, of course, false. The halo and the disk are different entities; different processes dominated their evolution, as revealed by the corresponding metallicity distributions (MD). In the case of the disk, observations show that the number of metal-poor stars is much smaller than what is predicted by the simple "closed-box" model of chemical evolution (the "G-dwarf problem"); the simplest explanation of that is that the disk evolved not as a closed box, but by slowly accreting infalling gas (e.g. Pagel 1997). In the case of the halo, the observed MD suggests that metal production was inefficient in those early times; the currently accepted explanation is that a strong outflow, at a rate ∼9 times the star formation rate, has occured during the halo evolution (as initially suggested by Hartwick 1976).

It is clear, then, that a unique model is inadequate to cover the whole evolution of the solar neighborhood. Still, this is done in most cases. Only in a handful of works has this point been taken into account, by adopting different prescriptions for the halo and the disk (Prantzos et al. 1993; Ferrini et al. 1994; Pardi et al. 1995; Chiappini et al. 1997; Travaglio et al. 1999), although not always the appropriate ones. The importance of that point is twofold: First, the corresponding MDs (the strongest constraints to the models) are only reproduced when appropriate models are used. Secondly, infall and outflow modify the timescales required for the gas to reach a given metallicity. This is important when one is interested in elements produced by e.g. intermediate mass stars, which enter late the galactic scene.

Another important point, related to the first one, is that the halo and the disk are, most probably, not related by any temporal sequence. Indeed, the gas leaving the halo ended, quite probably, in the bulge of the Galaxy, not in the disk, as argued e.g. by Wyse (2000 and references therein) on the basis of angular momentum conservation arguments. The disk may well have started with primordial metallicity, but a very small amount of gas. The corresponding small number of low metallicity stars that were formed by that gas explains readily the G-dwarf problem.

In the light of these arguments, we treat then the halo and the disk as separate systems, not linked by any temporal sequence. The local disk is assumed to be built up by slow accretion of gas with primordial composition. An exponentially decreasing infall rate $f(t) \propto e^{-t/\tau}$ with $\tau > 7$ Gyr is adopted. Such a long timescale has been shown (Chiappini et al. 1997; Prantzos & Silk 1998) to provide a satisfactory fit to the data of Wyse & Gilmore (1995) and Rocha-Pinto & Maciel (1996). We have normalized the infall rate $f(t, R)$, as to obtain the local disk surface density $\Sigma_T(R)$=55 $M_\odot$ pc^{-2} at an age T=13.5 Gyr. Notice that chemodynamical models also support the idea of long time scales for the disk formation (Samland et al. 1997).

For the halo model, there are less constraints: neither the duration of the halo phase, nor the final gas fraction or amount of stars are known. We assume then a duration of 1 Gyr and an outflow rate R_{out} = 9 $\Psi(t)$, in order to reproduce the observed halo MD. For consistency, we use the same SFR law and the same IMF as in the disk.

4. Evolution of the halo and the disk

We run two chemical evolution models, one for the halo (with outflow, for 1 Gyr) and one for the disk (with infall, for 13.5 Gyr), starting in both cases with gas of primordial composition. The only observational constraints common for the halo and the disk are: i) the metallicity distributions of low mass long-lived stars, and ii) the element/element ratio vs. metallicity (in particular, the O vs. Fe evolution). In the case of the disk there are several more constraints (see Sect. 4.2) but we turn first to (i) and (ii).

4.1. Metallicity distribution and O vs. Fe in the halo and the disk

In Fig. 3 we present our results and compare them to observations. The metallicity distributions (f=dN/d[Fe/H]) are normalised to f_{max}=1 and presented in the upper panel of Fig. 3. The adopted prescriptions (strong outflow for the halo and slow infall for the disk) lead to a satisfactory agreement between theory and observations, as expected on the basis of the discussion in Sect. 3.3. Notice that in the case of the disk, the theoretical curve shows a low metallicity tail below [Fe/H]=-1. However, the number of stars in the tail is extremely small, less than 10^{-2} of the total. Although there is no "physical" discontinuity in the disk population at [Fe/H]=-1, we systematically show below all our results for the disk corresponding to [Fe/H]>-1 with *thick* solid curves, in order to stress that they correspond to what is traditionally thought as the "disk phase" of the Milky Way. Results for [Fe/H]<-1 are shown with *thin* solid curves, indicating that such stars do, in principle, exist, but in very small numbers.

Because a large part of Fe in the disk comes from SNIa (at least in our models) it is not clear whether the final G-dwarf metallicity distribution is mostly shaped by infall or by the rate of SNIa. In other terms, how can one be certain that the observed "G-dwarf problem" requires indeed large infall timescales (such as those discussed in Sect. 3.1 and adopted here)? We notice that the G-dwarf problem concerns mainly the low metallicity regime i.e. around [Fe/H]=-1 to -0.6; it is in this metallicity range that the closed box model predicts an excess of low-mass stars w.r.t the observations. But at those early times, corresponding to the first ∼2-4 Gyr of the disk's history, the ratio of SNIa/SNII is still small (with the adopted prescription for the SNIa rate) and most of the Fe comes from SNII. Thus, the success of the model in reproducing the G-dwarf metallicity distribution does rely on the infall prescription, and not on the SNIa rate prescription. SNIa start becoming major sources of Fe somewhat later (around [Fe/H]=-0.5).

In the lower panel of Fig. 3 we show the corresponding evolution of O vs. Fe. It is virtually identical in the two models, up to [Fe/H]∼-1, since both elements are primaries and produced in the same site (massive, short-lived, stars); their abundance ratio is then independent of infall or outflow prescriptions. As discussed in Sect. 2, the observed decline of O/Fe in the disk is reproduced by the delayed appearance of SNIa, producing ∼2/3 of the solar Fe.

Fig. 4 presents the evolution of the halo and the disk in a more "physical" way than in Fig. 3, i.e. various quantities are plotted as a function of time; time is plotted on a logarithmic scale (on the left, so that the halo evolution can be followed) and on a linear scale (on the right). The differences between the two models can be clearly seen. In particular, at a given time, the metallicity [Fe/H] (middle panel) is larger in the halo than in the disk (by 0.3 dex, i.e. a factor of 2); metallicity increases more slowly in our disk model than in the halo one. It takes ∼2 Gyr to the disk to reach [Fe/H]∼-1, compared to ∼1 Gyr in the case of the halo. However, as noticed already, this early disk evolution concerns only very few stars.

4.2. Evolution of the local disk

There are many more observational constraints for the local disk than for the halo; an extensive presentation of those constraints can be found in Boissier & Prantzos (1999, their Table 1 and references therein). Here we present only briefly those constraints. Besides the MD and the O vs. Fe evolution, a satisfactory disk model should also reproduce:

(a) The current surface densities of gas (Σ_G), stars (Σ_*), the total amount of matter (Σ_T) and the current star formation rate (Ψ_0);
(b) The age-metallicity relationship, traced by the Fe abundance of long-lived, F-type stars;

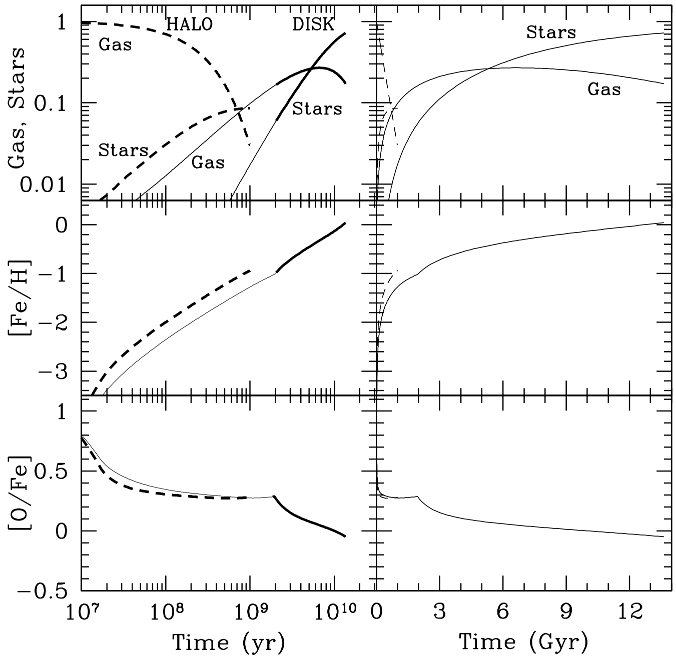

Fig. 4. Evolution of stars, gas and metals in our models for the halo and the disk, plotted as a function of time. A logarithmic time scale is used on the *left*, in order to show better the halo evolution, whereas the *right* panels are more appropriate for the disk evolution. In all panels, results for the halo are shown in *dashed curves* and for the disk in *solid curves* (*thick* for [Fe/H]>-1 and *thin* for [Fe/H]<-1)

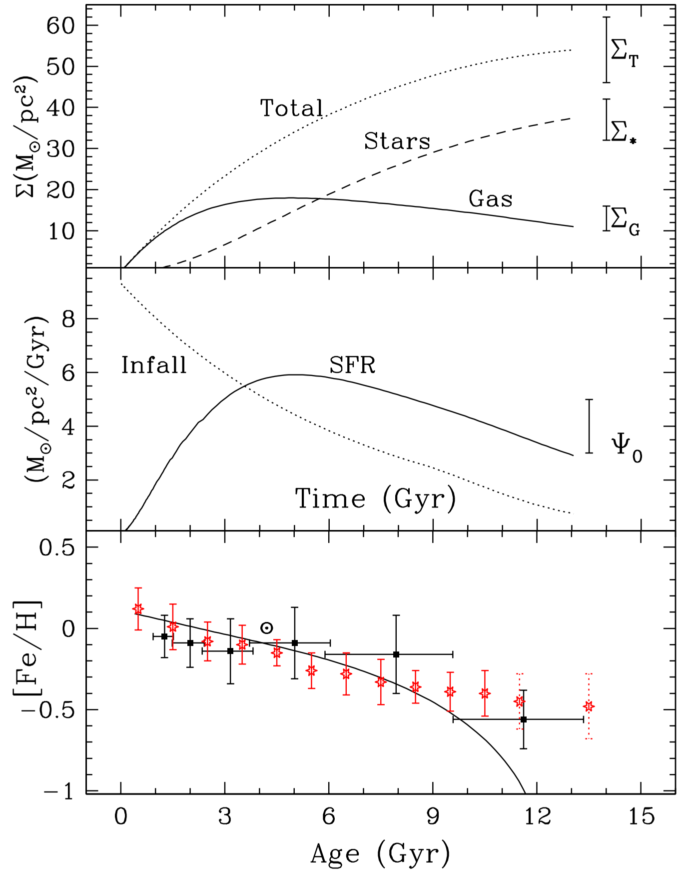

Fig. 5. Comparison of the main observables of the solar neighbourhood to our model predictions. The *upper panel* shows the surface densities of stars, gas and total amount of matter as a function of time. The vertical error bars represent present day values. The *middle panel* shows the star formation rate and infall rate; the current SFR (Ψ_0) is indicated by the error bar. Data for those tow panels are from the compilation of Boissier & Prantzos (1999). In the *lower panel* the solid curve shows the derived age-metallicity relation; data are from Edvardsson et al. (1993, *filled symbols*) and Rocha-Pinto et al. (2000, *open symbols*, with the last two being rather upper limits), while the position of the Sun is shown by the symbol $\odot$

(c) The abundances of various elements and isotopes at solar birth $(X_i, \odot)$ and today $(X_i, 0)$;
(d) The present day mass function (PDMF), resulting from the stellar IMF and the SFR history, which gives an important consistency check for the adopted SFR and IMF.

In Fig. 5 we present our results and compare them to constraints (a) and (b). It can be seen that the adopted SFR and infall rate lead to a current gas surface density of $\Sigma_G \sim 10\ M_\odot$ pc^{-2} and a final stellar surface density of Σ_* ~36 M$_\odot$ pc^{-2}, both in good agreement with observations. A current SFR ~3.5 M$_\odot$ pc^{-2} Gyr^{-1} is obtained at T=13.5 Gyr, also in agreement with observations. The evolution of the SFR is quite smooth, its current value being about half the maximum one in the past.

The lower panel of Fig. 5 shows the disk age-metallicity relation. The existence of an age-metallicity relation (AMR) in the disk is one of the important issues in studies of chemical evolution of the solar neighborhood. Several studies in the past showed a trend of decreasing metallicity with increasing stellar ages (Twarog 1980; Meusinger et al. 1991, and Jonch-Sorensen 1995). Edvardsson et al. (1993) found an AMR consistent with these results but with a considerable scatter about the mean trend. However, this scatter (difficult to interpret in the framework of conventional models), may be due to contamination of the Edvardsson et al. (1993) sample by stars from different galactic regions (Garnett & Kobulnicky 2000). Indeed, the recent survey of Rocha-Pinto et al. (2000, also on Fig. 5), suggests a scatter almost half of that in Edvardsson et al. (1993). In view of the current uncertainty, we consider that the mean trend of the disk AMR obtained with our model is in satisfactory agreement with observations.

In Fig. 6 we compare our results to constrain (c), i.e to the elemental (upper panel) and isotopic (lower panel) composition of the Sun. It is assumed that the Sun's (and solar system's) composition is representative of the one of the local interstellar medium (ISM) 4.5 Gyr ago, but this assumption is far from been definitely established. Indeed, CNO abundances in young stars and gas in the nearby Orion nebula show that the metallicity of this young region is lower than solar (Cunha & Lambert 1994; Cardelli & Federmann 1997); this cannot be readily interpreted in conventional models of chemical evolution. On the other hand, the Fe abundance of young stars determined by Edvardsson et al. (1993) seems to be compatible with the conventional picture, while the data of Rocha-Pinto et al. (2000)

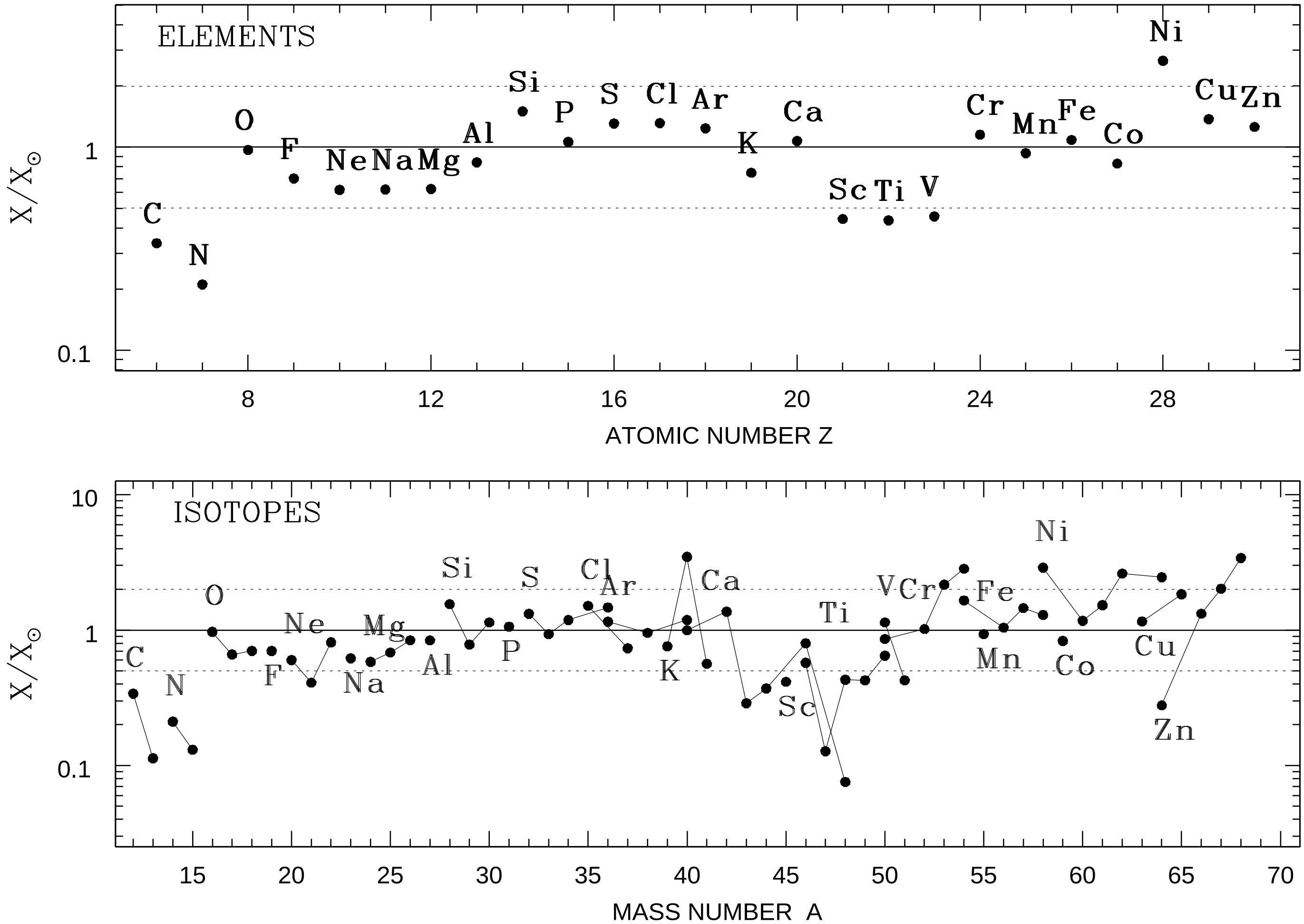

Fig. 6. Ratio of the calculated and observed solar abundances of elements C to Zn (*upper panel*) and their stable isotopes (*lower panel*). Results of our model are shown at a disk age of 8.5 Gyr (Sun's formation), and yields from massive stars (metallicity dependent, from WW1995) and SNIa (from the W7 and W70 models of Iwamoto et al. 1999) are taken into account. The *dotted lines* mark deviations by a factor of 2 from the solar composition. All currently available sets of massive star yields show an underproduction of Sc, Ti and V. C and N also require additional production sources. The overproduction of Ni (in the form of the main isotope ^{58}Ni) results from the W7 model of Iwamoto et al. (1999) for SNIa

suggest that the Sun is indeed Fe-rich w.r.t. other stars of similar age (Fig. 5). One should keep in mind this question (of the Sun being "typical" or not) when making detailed comparison of its composition to model predictions.

An inspection of Fig. 6 shows that there is good overall agreement between theory and observations, i.e. about 80% of the elements and isotopes are co-produced within a factor of two of their solar values. One should notice the following:

- The carbon isotopes require another source. ^{12}C may be produced either by intermediate mass stars, as usually assumed, or by Wolf-Rayet stars with metallicity dependent yields (Maeder 1992; Prantzos et al. 1994). ^{13}C is made probably in intermediate mass stars. The evolution of ^{12}C/^{13}C in the disk and its implications for the synthesis of those isotopes is studied in Prantzos et al. (1998).
- The nitrogen isotopes also require another source. ^{14}N has the same candidate sites as ^{12}C. Novae seem to be a viable source for ^{15}N, but current uncertainties of nova models do not allow definite conclusions.
- Fluorine is produced by neutrino-induced nucleosynthesis in WW1995, and this is also the case for a few other rare isotopes, not shown in Fig. 6 (^{7}Li, ^{11}B). This is an interesting "new" nucleosynthesis mechanism, but because of the many involved uncertainties (see Woosley et al. 1990) it cannot be considered as established yet. One should keep an "open eye" for other, more conventional, sites of fluorine (as well as lithium and boron) nucleosynthesis, like e.g. Wolf-Rayet stars (Meynet & Arnould 2000).
- The obtained overabundance of ^{40}K may reflect the large uncertainty in the abundance of this isotope at solar system formation (see Anders & Grevesse 1989), as already pointed out in Timmes et al. (1995).
- Sc, V and Ti isotopes are underproduced, indicating that all currently available models of massive stars have some problems with the synthesis of these species.

- There is a small overproduction of Ni, due to the isotope ^{58}Ni, which is abundantly produced in the W7 and W70 models of SNIa. This is also true for ^{54}Cr, a minor isotope of Cr. The amount of those nuclides depends mostly on the central density of the exploding white dwarf and the overproduction problem may be fixed by varying this parameter. Alternatives to the W7 model have recently been calculated by Iwamoto et al. (1999). On the other hand, Brachwitz et al. (2000) have explored the effect of electron capture rates on the yields of Chandrasekhar mass models for SNIa; they showed that the problem with ^{54}Cr may disappear (depending on the ignition density) while the one with ^{58}Ni is slightly alleviated. It can be reasonably expected that in future, improved, SNIa models, the overproduction problem of those nuclei will be completely solved.

Notice that in our calculation, the Fe-peak isotopic yields of WW1995 have been reduced by a factor of two, in order to reproduce the observed O/Fe ratio in halo stars ($\sim$3 times solar, see Fig. 3 and Sect. 5); otherwise, the WW1995 massive stars alone can make almost the full solar abundance of Fe-peak nuclei (as shown in Timmes et al. 1995), leaving no room for SNIa. Taking into account the uncertainties in the yields, especially those of Fe-peak nuclei (see Sect. 2) our reduction imposed on the WW1995 Fe yields is not unrealistic.

The nice agreement between theory and observations in Fig. 6 comes as a pleasant surprise, in view of the many uncertainties discussed in the previous section. It certainly does not guarantee that each individual yield is correctly evaluated. It rather suggests that the various factors of uncertainty cancel out (indeed, it is improbable that they all "push" towards the same direction!) so that a good overall agreement with observations results. As stressed in Timmes et al. (1995), the abundances of the intermediate mass isotopes span a range of 8 orders of magnitude; reproducing them within a factor of two suggests that models of massive stars nucleosynthesis are, globally, satisfactory. At least to first order, currently available yields of massive stars + SNIa can indeed account for the solar composition between O and Zn (with the exceptions of Sc, Ti and V, and possibly F).

5. Abundance ratios in the halo and the local disk

We calculated the abundance evolution of all the isotopes between H and Zn in the framework of our halo and local disk models, by using two different sets of massive star yields: i) the yields of WW1995 at constant (=solar) metallicity (Case A in the following), and ii) the metallicity dependent yields of WW1995, by interpolating between the values given for metallicities $Z/Z_\odot$=0, 10^{-4}, 10^{-2}, 10^{-1} and 1 (Case B in the following). Because of our neglect of the C and N yields of intermediate mass stars, total metallicity is not consistently calculated in our models; we use oxygen as metallicity indicator, in order to inerpolate in the WW1995 tables (in the WW1995 models, the initial abundances of all elements are scaled to metallicity). Obviously, Case B (also studied by Timmes et al. 1995) is the "reference" case, whereas Case A is only studied for illustration purposes. In both cases, the yields of the W7 and W70 models of Iwamoto et al. (1999) for SNIa are used (interpolated as a function of metallicity), whereas no yields from intermediate mass stars are considered; our explicit purpose is to check to what extent massive stars can account for observations of intermediate mass elements and for which elements the contribution of intermediate mass stars is mandatory. We stress again that we *do take into account the contribution of intermediate and low mass stars to the H and He "budget"*, since this is crucial for a correct evaluation of the metal/H ratio, especially at late times (Sect. 3.1).

Since most of the available data on the composition of stars concerns elemental abundances, we computed the corresponding evolution by summing over the calculated isotopic abundances. We present our results in Fig. 7 and compare them to a large body of observational data; most of the data come from the surveys of Ryan et al. (1996) and Mc William (1997) for the halo and Edvardsson et al. (1993) and Chen et al. (2000) for the disk, but we included a large number of other works, concerning specific elements (the corresponding references are listed in Table 1). We do not attempt here any discussion on the quality of these data (this would be beyond the scope of this work), and we refer the reader to the recent review of Ryan (2000) for that. It is obvious that systematic differences between various studies introduce a scatter larger than the real one (and, perhaps, unrealistic trends in some cases). Our reference Case B is shown in *thick curves* (*dashed* for the halo and *solid* for the disk), while Case A is in *thin curves*.

Before presenting our results we notice that in our models metallicity reaches [Fe/H]$\sim$-4 at a time t$\sim 10^7$ yr and [Fe/H]$\sim$-3 at a time t$\sim 2\ 10^7$ yr; these timescales correspond to the lifetimes of stars of mass M$\sim$20 $M_\odot$ and M$\sim$10 $M_\odot$, respectively. Any variations in the abundance ratios in the metallicity range -4 $<$ [Fe/H] $<$ -3 results then from the fact that stars of different masses (starting from 100 $M_\odot$ and going to 10 $M_\odot$) enter progressively the galactic scene. The discussion of Sect. 2 shows that the yields of individual stars are very uncertain, much more than those integrated over the IMF (the latter reproduce, at least, the solar composition!). Besides, there is absolutely no guarantee that the model reproduces correctly the relation between age and metallicity at those early times. For instance, in a recent work Argast et al. (2000) find that the halo became chemically homogeneous and reached [Fe/H]=-3 after $\sim$160 Myr, a duration six times longer than in our calculations. For those reasons we consider that any abundance trends of our models at [Fe/H]$<$-3 *are not significant*, but we show them for completeness. Integration over the whole IMF of massive stars is only made for [Fe/H]$>$-3 and we consider that our results are significant only after that point. Finally, we notice that we have reduced the WW1995 yields of Fe-peak isotopes by a factor of two, in order to reproduce the observed α/Fe ratio in the halo.

5.1. Carbon and Nitrogen

Observations indicate a flat [C/Fe]$\sim$0 in the halo and the disk, with a large dispersion at all metallicities. Both our cases A and

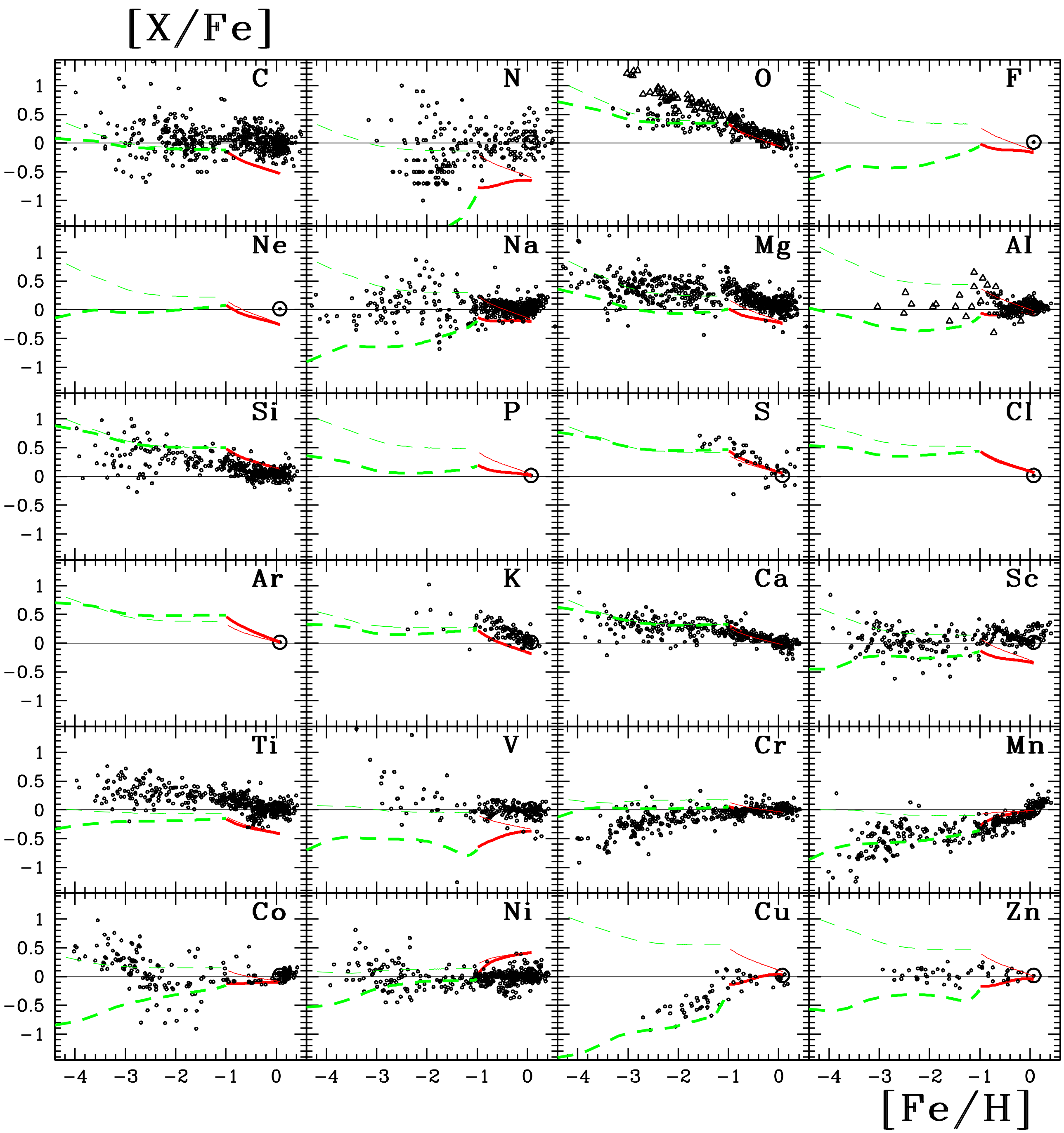

Fig. 7. Abundance ratios [X/Fe] of stars in the halo and the local disk, as a function of [Fe/H]. Theoretical results are obtained with models that treat properly the halo (*dashed curve* assuming *outflow*) and the disk (*solid curve* assuming *slow infall*). Two sets of massive star yields are used, both from WW1995: at constant (=solar) metallicity (*thin curves*, Case A, only for illustration purposes) and at variable metallicity (*thick curves*, the reference Case B). Yields of the W7 and W70 models of Iwamoto et al. (1999) for SNIa are used in both cases (properly interpolated as a function of metallicity); intermediate mass stars are not considered. It should be noted that WW1995 yields of Fe have been divided by 2, in order to obtain the observed α/Fe ratio in halo stars. Model trends below [Fe/H]=-3 are due to the finite lifetime of stars ([Fe/H]=-4 is attained at 10 Myr, corresponding to the lifetime of stars with mass $> 20 M_{\odot}$, while [Fe/H]=-3 is attained at 20 Myr, corresponding to the lifetime of $\sim 10 M_{\odot}$ stars). In view of the yield uncertainties of individual stars (Sect. 2) and of the uncertainties in the timescales at those early times of the halo evolution, those trends *should not be considered as significant*. The observed data points in the figure are taken from sources listed in Table 1. Observed abundance ratios of [O/Fe] from Israelian et al. (1998) and Boesgaard et al. (1999) are shown by *open triangles*; they suggest a trend quite different from all other alpha-elements. The *open triangles* in the [Al/Fe] panel correspond to observed data with NLTE corrections (from Baumüller & Gehren 1997)

B show indeed [C/Fe]∼0 in the halo (since both C and Fe are primaries), and a slow decline of C/Fe in the disk due to Fe production by SNIa. As discussed in Sect. 2, a complementary source of C is required in the disk. This may be either intermediate mass stars (IMS) or Wolf-Rayet (WR) stars. However, as discussed in Prantzos et al. (1994), IMS have masses M>3 $M_\odot$ and lifetimes τ <5 10^8 yr. Such stars can certainly evolve during the halo phase (*if* the duration of that phase is indeed ∼1 Gyr, as assumed here) and enrich the halo with C, thus rising the C/Fe ratio at [Fe/H]<-1. Such a behaviour is not observed, however, suggesting either that low mass stars (M<2 $M_\odot$) or WR stars are the main carbon sources in the disk. The latter possibility is favoured in Prantzos et al. (1994) and Gustafsson et al. (1999)

Nitrogen behaves in a similar way as carbon, i.e. the observed [N/Fe]∼0 in the halo and the disk, with a large scatter at low metallicities. Our Case A (metallicity independent yields) shows also a flat [N/Fe]∼0 evolution in the halo and a decline in the disk, exactly as for carbon. However, in the realistic Case B, N behaves as secondary: [N/Fe] increases steadily up to [Fe/H]∼-1. Its value remains ∼constant in the disk phase, because Fe production by SNIa compensates for the larger N yields of more metal rich stars. However, the final N/Fe is only ∼1/3 its solar value.

Obviously, current massive star yields fail, qualitatively and quantitatively, to reproduce the observed evolution of N/Fe. What are the alternatives? In our view, there are two:

a) Intermediate mass stars, producing primary N through hot-bottom burning in the AGB phase, are the most often quoted candidate. Large uncertainties still affect that complex phase of stellar evolution, but recent studies (e.g. Lattanzio 1998 and references therein) find that hot-bottom burning does indeed take place in such stars. If N is indeed produced as a primary in IMS, and their N yields are metallicity independent, then the N/Fe in the disk should decline (because of SNIa). Metallicity dependent N yields from WR stars (Maeder 1992) could compensate for that, keeping the N/Fe ratio ∼constant in the disk. On the other hand, if N from massive stars is indeed secondary, at some very low metallicity level (let's say [Fe/H]<-3) the N/Fe ratio should also decline; this would be an important test of IMS being the main N source in the halo. If such a decline is not observed, we are led to the second alternative, namely
b) Massive stars, producing primary N by an as yet unidentified mechanism, obviously requiring proton mixing in He-burning zones. Such mixing does not occur in standard stellar models, but "new generation" models including rotation offer just such a possibility (Heger et al. 1999; Maeder & Meynet 2000). In that case, N is produced not by the original carbon entering the star, but by the carbon produced in He-burning; as a consequence, it is produced as a primary. In that case, massive stars could be the main source of N and C in the halo.

The discussion of this section suggests then an intriguing possibility: massive stars could well be the main source of C and N in both the halo and the disk (in the latter case, through the WR winds), leaving only a minor role to intermediate mass stars!

5.2. α - elements O, Mg, Si, S, Ca, Ti

The alpha elements (O, Mg, Si, S, Ca, Ti) present a well known behaviour. The α/Fe ratio is ∼constant in the halo, at [α/Fe]∼0.3-0.5 dex, and declines gradually in the disk. The latter feature is interpreted as due to (and constitutes the main evidence for) the contribution of SNIa to the disk composition.

This behaviour is indeed apparent in Fig. 7; despite the large scatter, all the alpha elements show the aforementioned trend. We stress here again that the recent data of Israelian et al. (1998) and Boesgard et al. (1999), also plotted in Fig. 7 (with different symbols), challenge this picture in the case of oxygen. If true, these new data should impose some revision of our ideas on massive star nucleosynthesis, probably along the lines suggested in Sect. 6.

Until the situation is clarified, we stick to the "old paradigm". In the framework of this "paradigm", Pagel & Tautvaisiene (1995) have shown that the α/Fe evolution can be readily explained by a very simple model (with IRA), the metallicity independent yields of Thielemann et al. (1996) and SNIa during the disk phase. On the other hand, Timmes et al. (1995), using the metallicity dependent yields of WW1995 (but an inappropriate model for the halo, see Sect. 3.3), found good agreement with observations, provided that the Fe yields of WW1995 are reduced by a factor of ∼2.

Our results in Fig. 7 point to the following:

– For O, Si, S and Ca, both Cases A and B give virtually identical results. These elements behave as true primaries, without any metallicity dependence of their yields. Moreover, after the WW1995 Fe yields are reduced by a factor of 2, a fairly good agreement with observations is obtained.
– The situation is far less satisfactory for Mg and Ti. For both of them, the WW1995 yields at solar metallicity are larger than at lower metallicities (see Fig. 1). This is puzzling since Mg and Ti are also supposed to be primaries (in fact, more puzzling in the case of Mg, since Ti is produced close to the "mass-cut" and subject to more important uncertainties). As a result, our Case A is marginally compatible with observations of Mg/Fe; the reference Case B does not match at all the observations, despite the reduction of the Fe yields by a factor of 2. In the case of Ti, both Cases A and B fail to match the observations.

These features were also noticed in Timmes et al. (1995) and the problem with the WW1995 yields of Mg and Ti pointed out; however, no satisfactory alternative was suggested. Since the Mg yields of WW1995 are steeply increasing function of stellar mass, our use of the Kroupa et al. (1993) IMF (steeper than the Salpeter IMF used by Timmes et al. 1995) leads to a low Mg/Fe ratio, even after reduction of the Fe yields. Our Fig. 1 (lower panel) suggests that the yields of LSC2000 could match better the halo data, since the Mg/Fe and Ti/Fe ratios obtained for Z=0 are larger than solar. On the other hand, Fig. 1 shows that in both

WW1995 and LSC2000, Mg and Ti have lower overproduction factors than all the other alpha elements, at all metallicities; this means that, even if the halo Mg/Fe and Ti/Fe ratios are better reproduced with the LSC2000 yields, the corresponding α/Mg and α/Ti ratios will certainly not match the observational data. Thus, at present, none of the two available sets of metallicity dependent yields offers a solution to the problem of Mg and Ti.

The fact that Pagel & Tautvaisiene (1995) find good agreement with observations by using the Thielemann et al. (1996) yields may suggest that this set of yields indeed solves the problem. This is also the case in Chiappini et al. (1999), who use a somewhat different prescription for SNIa rate than here, and metallicity independent yields from Thielemann et al. (1996) and WW19995. Notice, however, that metallicity independent yields (those of Thielemann et al. 1996 are for solar metallicity only) should not be used for studies of the halo, even if the problem is less severe in the case of primary elements. The equivalent set of WW1995 yields also reproduces the Mg/Fe evolution in the halo (our Case A), but it is not appropriate. We need to understand how massive stars make a $\sim$constant Mg/Fe and Ti/Fe ratio at all metallicities, by using stellar models with the appropriate initial metallicity.

5.3. Sodium and Aluminium

Na and Al are two monoisotopic, odd elements. Their theoretical yields are, in principle, affected by the "odd-even" effect (see Sect. 2). This effect seems to be stronger in the case of LSC2000 than in WW1995 (Fig. 1), at least for the adopted IMF.

The observational situation for those elements is not quite clear. Recent observations (Stephens 1999) suggest that Na/Fe decreases as one goes from [Fe/H]=-1 to [Fe/H]=-2, as expected theoretically. However, most other observations do not support this picture, showing instead a flat [Na/Fe]$\sim$0 ratio with a large scatter. Our Case A evolution of Na/Fe is similar to the α/Fe evolution and, obviously, incorrect. In Case B, Na/Fe increases steadily after [Fe/H]$\sim$-2.5 and reaches a plateau after [Fe/H]$\sim$-1. Neither case matches the observations well. As we shall see in Sect. 5.7, the situation improves considerably when only the halo data of Stephens (1999) and the disk data of Edvardsson et al. (1993) and Feltzing & Gustafsson (1998) are used; then Na vs. Ca shows the behaviour of an odd element, as it should.

Ryan et al. (1996) find a steep decline of Al/Fe at low metallicities, down to "plateau" value of [Al/Fe]$\sim$-0.8, but they stress that their analysis neglects NLTE effects and underestimates the real Al/Fe ratio; for that reason we do not plot their data in Fig. 7 (Ryan et al. 1996 suggest that a NLTE correction to their data would move the "plateau" value to [Al/Fe]$\sim$-0.3, i.e. consistent with what expected for an odd-Z element). On the other hand, the NLTE analysis of the data of Baumüller & Gehren (1997, *open triangles* in Fig. 7) suggests a practically flat Al/Fe ratio in the halo, a rather unexpected behaviour for an "odd" element. In our model Case A, Al behaves like an α element. In Case B, the "odd-even" behaviour is manifest: a small increase of Al/Fe is obtained as metallicity increases from [Fe/H]$\sim$-2.5 to [Fe/H]$\sim$-1 (the model trend below [Fe/H]=-3, due to stellar mass and lifetime effects, is not significant, as stressed in the begining of Sect. 5). Once again, theory does not match observations and observations do not show the expected behaviour.

It should be noted at that point that intermediate mass stars of low metallicity could, perhaps, produce some Na and Al through the operation of the Ne-Na and Mg-Al cycles in their H-burning shells and eject them in the interstellar medium through their winds. There are indeed, indications, that in low mass, low metallicity stars of globular clusters such nucleosynthesis does take place (Kraft et al. 1998). If this turns out to be true also for intermediate mass stars of low metallicity, it might considerably modify our ideas of Na and Al nucleosynthesis in the halo.

5.4. Potassium, Scandium, Vanadium

K, Sc and V are three odd-Z elements produced mainly by oxygen burning. However, the first one is produced in hydrostatic burning and the other two in explosive burning, i.e. their nucleosynthesis is more uncertain. Their yields are affected in similar ways by the initial metallicity of the star, as can be seen in Fig. 1.

Currently available observations show a rather different behaviour for those elements: Sc/Fe remains $\sim$solar in the whole metallicity range -3<[Fe/H]<0. V/Fe is also $\sim$solar in the disk and the late halo, but appears to be supersolar in the range -3 <[Fe/H]<-2 (although the data is rather scarce for a definite conclusion). Finally, K/Fe declines in the disk, while the rare halo data point to supersolar ratio [K/Fe]$\sim$0.5, i.e. its overall behaviour is similar to that of an α-element!

From the theoretical point of view, the situation is also unsatisfactory. Cases A and B produce distinctively different results for Sc and V, but not so for K. In Case B, the Sc/Fe and V/Fe ratios are subsolar in the halo, while K/Fe is supersolar. Also, in that case, K/Fe declines in the disk, Sc/Fe remains $\sim$constant and V/Fe increases.

This "strange" theoretical behaviour results from the interplay of several factors, which do not affect all those elements in the same way: odd-even effect, Fe yield reduction and contribution of SNIa. Thus, the metallicity dependence of the yields between Z=0.1 $Z_\odot$ and Z=$Z_\odot$ is stronger for V than for the other two. In fact, the V yield at metallicity Z=0.1 $Z_\odot$ is lower than at Z=0.01 $Z_\odot$ in WW1995, which is counterintuitive (making V/Fe to decrease between [Fe/H]=-2 and [Fe/H]=-1). Also, SNIa contribute more to the production of V than to the one of Sc or K (at least according to the W7 model). For those reasons, Sc/Fe is $\sim$ constant in the disk, while K/Fe declines and V/Fe increases.

Although our Case B seems to match well the available data for K, we think that this is rather fortuitous: we obtain a supersolar K/Fe in the halo because of the reduction of the Fe yields by a factor of two and of the adopted IMF (Timmes et al. 1995 obtain a solar K/Fe in the halo for the same reduced Fe yields, probably because they use the Salpeter IMF).

In our view, the evolution of those three elements is far from being well understood, either observationaly or theoretically. They do not show any sign of the expected odd-even effect (rather the opposite behaviour is observed for K!). However, if theoretical "prejudices" are put aside, the situation may not be as bad for Sc and V: indeed, they are part of the "low iron group" elements and their abundances may well follow the one of Fe, as suggested by current observations. In that case, the "odd-even" effect is overestimated in the theoretical yields adopted here or those of LSC2000 (Fig. 1). We also noticed that their solar abundances are underproduced by current nucleosynthesis models (Sect. 4.2 and Fig. 6).

5.5. Fe-peak elements: Cr, Mn, Co, Ni, Cu and Zn

The various isotopes of the Fe peak are produced by a variety of processes (see WW1995): isotopes with mass number A<57 are produced mainly in explosive O and Si burning and in nuclear statistical equilibrium (NSE). Isotopes with A>56 are produced in NSE (mostly in "alpha-rich freeze-out"), but also by neutron captures during hydrostatic He- or C-burning. Because of the many uncertainties involved in the calculations (sensitivity to the neutron excess, the mass-cut, the explosion energy etc.) the resulting yields are more uncertain than for the other intermediate mass nuclei.

Observations show that the abundance ratio to Fe of Cr, Co, Ni and Zn is ∼solar down to [Fe/H]∼-2.5 to -3. This fact, known already in the late 80ies, suggests that those elements behave similarly to Fe (at least in this metallicity range) and, therefore, are produced in a quite similar way. However, observations in the mid-90ies (Ryan et al. 1996; McWilliam 1997) show that, as one goes to even lower metallicities, a different picture is obtained (see Fig. 7): Cr/Fe is subsolar and decreasing, while Co/Fe is supersolar and increasing; the situation is less clear for Ni/Fe, but in all cases the scatter is larger at very low metallicities than at higher ones.

For the reasons mentioned in the beginning of Sect. 5, we do not consider the trends of our models in the range [Fe/H]<-3 to be significant. We do not then attempt here to interpret those recent intriguing findings, which point, perhaps, to some interesting physics affecting the evolution of the first stellar generations. We simply notice that such an attempt is made in Nakamura et al. (1999), who study the sensitivity of the corresponding yields to various parameters (neutron excess, mass-cut, explosion energy). Their conclusion is that the observed Co/Fe excess cannot be explained by any modification of those parameters.

The yields of WW1995 show a mild metallicity dependence in the case of Cr and Ni and a more important one in the cases of Mn, Co, Cu and Zn. For that reason, we obtain different results for those elements between our Cases A and B (Fig. 7). The situation for each of those elements is as follows:

- The Cr/Fe evolution is reproduced satisfactorily for [Fe/H]>-2.5; in the disk, Cr and Fe are produced in similar amounts by SNIa and the Cr/Fe ratio remains ∼constant.
- Co/Fe decreases steadily as one goes to low metallicities (in Case B). This trend is not observed in the data and suggests that the "odd-even" effect for that nucleus is overestimated in WW1995; we notice that LSC2000 find a much smaller effect (Fig. 1).
- The WW1995 yields adequately describe the Ni/Fe evolution, except at the lowest metallicities ([Fe/H]<-3). The LSC2000 yields would face the same problem, as can be seen in Fig. 1. The excess of Ni/Fe obtained in the disk model is due to the overproduction of ^{58}Ni by the W7 model of SNIa (see Sect. 4.2).
- The WW1995 yields suggest a ∼constant (solar) Zn/Fe in the halo, albeit at a value lower than actually observed. On the other hand, they suggest that Zn/Fe should increase in the disk, while observations show no such increase. An inspection of the LSC2000 yields in Fig. 1 suggests that they would face the same problems.
- Finally, the WW1995 yields offer an excellent description of the observed evolution of Mn/Fe and Cu/Fe. If the observations are correct, we have an exquisite realisation of the "odd-even" effect for Fe-peak nuclei (especially in the case of Mn), almost a "text-book" case. An inspection of the LSC2000 yields shows that they would do equally well.

5.6. Fluorine, Neon, Phosphorous, Chlorine, Argon

We present in Fig. 7 the evolution of those elements according to our models, although no observational data exist for them in stars; fluorine is an exception, its abundance being measured in giants and barium stars (Jorissen et al. 1992).

We recall that F is produced in WW1995 mainly by neutrino-induced nucleosynthesis (spallation of ^{20}Ne) and the corresponding yields are very uncertain. As seen in Fig. 1, the F yield of WW1995 are metallicity dependent, and this is also reflected in the evolution of the F/Fe ratio (Case A vs Case B). We notice again that F may also be produced in other sites, like in the He-burning shells of AGB stars (as suggested by the calculations of Forestini & Charbonnel 1997) or in WR stars. The recent calculations of Meynet & Arnould (2000) show that the F yields of the latter site are also metallicity dependent, but they are important only for metallicities [Fe/H]>-1; at lower metallicities, very few massive stars turn into WR. Obviously, if AGB and WR stars are the main producers of F, the evolution of F/Fe ratio may be quite different from the one shown in Fig. 7.

The main Ne isotope is ^{20}Ne, i.e. Ne should evolve as an α-element. The evolution of Ne/Fe in Fig. 7 is similar to the one of C/Fe. The yields of WW1995 show a small metallicity dependence (reflected in Case A vs. Case B) not exhibited by the yields of LSC2000.

Like Ne, Ar is also an even-Z element. There is no metallicity dependence in the Ar yields of WW1995 (which explains the similarity between cases A and B), neither in those of LSC2000. Ar is expected to behave like Si or Ca.

P and Cl are odd-Z elements. When the WW1995 Fe yields are divided by 2, a ∼solar P/Fe and a supersolar Cl/Fe ratio is obtained for halo stars. In the disk, enhanced P production by massive stars (due to the "odd-even" effect) and by SNIa compensate for the Fe production by SNIa; as a consequence, the P/Fe ratio decreases only very slightly. On the contrary, this compensation does not occur for Cl and the Cl/Fe ratio decreases in the disk.

In the absence of observational data, the nucleosynthesis of these elements cannot be put on a firm basis. Their solar abundances are relatively well reproduced with the WW1995 yields (Fig. 6), and this is quite encouraging. On the other hand, we notice that the LSC2000 yields show a more pronounced "odd-even" effect for P and Cl than WW1995.

5.7. Chemical evolution with respect to Ca

Traditionally, the results of galactic chemical evolution studies are presented as a function of Fe/H, i.e. Fe is assumed to play the role of "cosmic clock". However, in view of the uncertainties on Fe production and evolution (due to mass cut and explosion energy in SNII, or to the uncertain evolution of the rate of SNIa), it has been suggested that Fe should be replaced by a "robust" α element, like e.g. O or Ca.

In view of the uncertainties currently affecting the observational status of oxygen, we choose here Ca as the reference element. Among the data listed in Table 1 (and plotted in Fig. 7) we selected those including observations of Ca abundances and we plot the element/Ca ratios in Fig. 8 as a function of Ca/H. We also plot on the same figure the corresponding model results obtained with the metallicity dependent yields of WW1995 and the W7 model for SNIa (i.e. our Case B).

Several interesting features can be noticed:

- For O, Al, K and V, existing data concern only the disk phase and are consistent with X/Ca$\sim$solar. Model results show that O/Ca and K/Ca ratios are solar over the whole metallicity range; they also show clearly the "odd-even" effect for Al/Ca, V/Fe and Cu/Fe.
- Among the α-elements, the observed Mg/Ca and Si/Ca ratios are solar down to very low metallicities. In our models, we also find constant Mg/Ca and Si/Ca ratios, slightly below the observed values in the former case, and in fair agreement with the observations in the latter.
- The observed Na/Ca evolution shows clearly the "odd-even" effect, especially with the recent data of Stephens (1999) for the metallicity range -1.5<[Ca/H]<-0.5 and those of Feltzing & Gustafsson (1998) for [Ca/H]>0. This behaviour is fairly well reproduced by the model.
- The observed Sc/Ca and Ti/Ca ratios are slightly below their solar values in the halo, with some hint for a decrease of the latter ratio at very low metallicities. Model results are broadly compatible with those observations.
- Cr/Ca, Fe/Ca and Mn/Ca ratios are all lower than solar in the whole metallicity range, exactly as observed. The agreement between the model results and the data is excellent for all three cases, down to the lowest metallicities; notice that the evolution of Cr w.r.t. Fe was not so well reproduced by the model at the lowest metallicities (Fig. 7).
- Finally, the observed Co/Ca and Ni/Ca ratios decrease with decreasing Ca/H down to [Ca/H]$\sim$-2 and increase at lower metallicities. The former trend is rather well reproduced by the model, but not the latter. The problematic behaviours of Co and Ni at low metallicities do not disappear when Ca is adopted as "cosmic clock".

6. Alternatives for Oxygen vs. Iron

In the previous sections we treated oxygen exactly as the other α-elements, i.e. by assuming that[O/Fe]$\sim$0.4$\sim$constant in the halo. However, the recent intriguing findings of Israelian et al. (1998) and Boesgaard et al. (1999) suggest that O/Fe continues to rise as one goes from the disk to halo stars of low metallicities (we shall call these data "new data" in this section). Although the observational status of O/Fe is not settled yet, the "new data" certainly call for alternatives to the "standard" scenario to be explored.

An obvious alternative is to assume that Fe producing SNIa enter the galactic scene as early as [Fe/H]$\sim$-3, instead of [Fe/H]$\sim$-1 in the "standard" scenario. Indeed, the first white dwarfs, resulting from the evolution of $\sim$8 $M_\odot$ stars, are produced quite early on in the galactic history; if their companions are almost equally massive, their red giant winds would push rapidly the white dwarf beyond the Chandrasekhar mass, and induce a SNIa explosion. The subsequent evolution of the SNIa rate (not well known today), should then be such as to ensure a continuous, smooth decline of O/Fe with [Fe/H], as the "new data" suggest. Such a behaviour is indeed obtained in the calculations of Chiappini et al. (1999), which have not been adjusted as to fit the new data: it is a direct consequence of their adopted formalism for the SNIa rate.

The problem with this "alternative" is that it also affects the evolution of the other α/Fe abundance ratios in the halo. Observationaly, none of the α-elements shows a behaviour comparable to the one suggested by the "new data" for oxygen (see Fig. 7 for Mg, Si and Ca). The "new data" can simply not be explained in terms of SNIa only, because this would spoil the current nice agreement with the other α-elements (see Fig. 9a). [*Notice*: C/Fe would also decrease with metallicity quite early in that case, but this is not a serious problem, since C from intermediate mass stars could keep the C/Fe ratio close to solar, as observed (and indicated in Fig. 9)].

A second possibility is that the O yields from massive stars are, for some reason, metallicity dependent. It is already known that this happens for the C and N yields of massive stars, for metallicities Z>0.1 $Z_\odot$: because of intense stellar winds, the most massive stars lose their envelope already during He-burning. This envelope is rich in H-burning products (like He and N) and later in early He-burning products (essentially C). Thus, less mass is left in the He-core to be processed into oxygen (Maeder 1992). As discussed in Sect. 5.1, this metallicity dependence of C yields from massive (WR) stars, can indeed explain the observed C/O evolution in the disk. However, Prantzos et al. (1994) have shown that the effect is clearly negligible for the evolution of oxygen in the disk, at least with Maeder's (1992) yields. And at lower metallicities, the effect is virtually inexistent: even the most massive stars present negligible mass losses. Thus, current models suggest that metallicity dependent Oxygen yields cannot help explaining the new data.

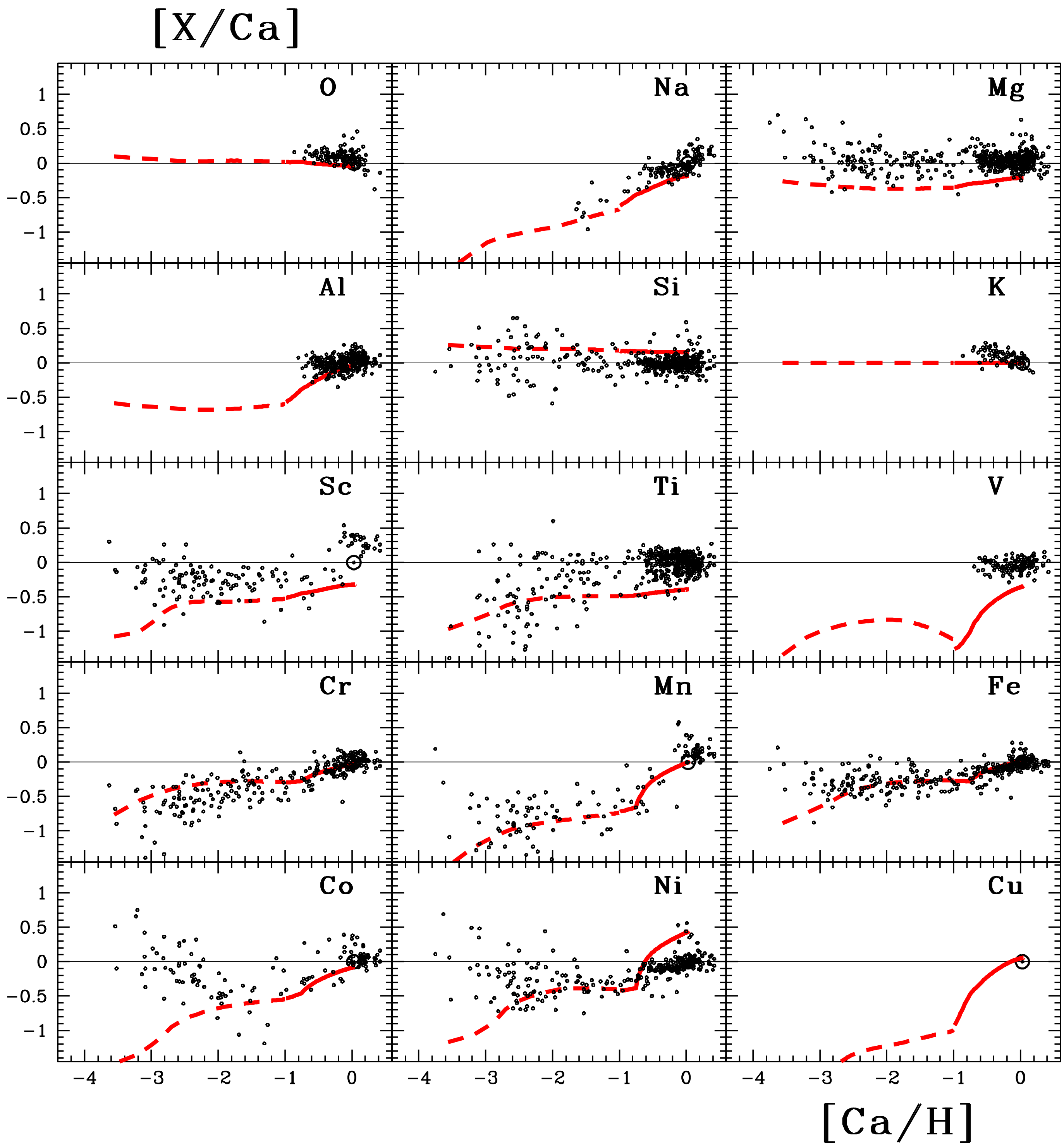

Fig. 8. Evolution of element/Ca abundance ratios as a function of Ca/H. Observations are from references listed in Table 1. Theoretical results (*dashed curves* for the halo and *solid curves* for the local disk) are obtained with the metallicity dependent yields of WW1995 for massive stars and the W7 and W70 models for SNIa (Iwamoto et al. 1999). By adopting Ca as a reference element, some of the uncertainties related to Fe are removed

However, the effect may have been underestimated. After all, stellar mass loss is yet poorly understood. Suppose then that, starting at [Fe/H]∼-3, massive stars produce less and less oxygen as their metallicity increases, because an ever larger part of their envelope is removed. Their inner layers, producing the other α-elements and Fe, are not affected by mass loss; the resulting α/Fe abundance ratio is constant with metallicity, while the corresponding O/Fe is decreasing with metallicity. The

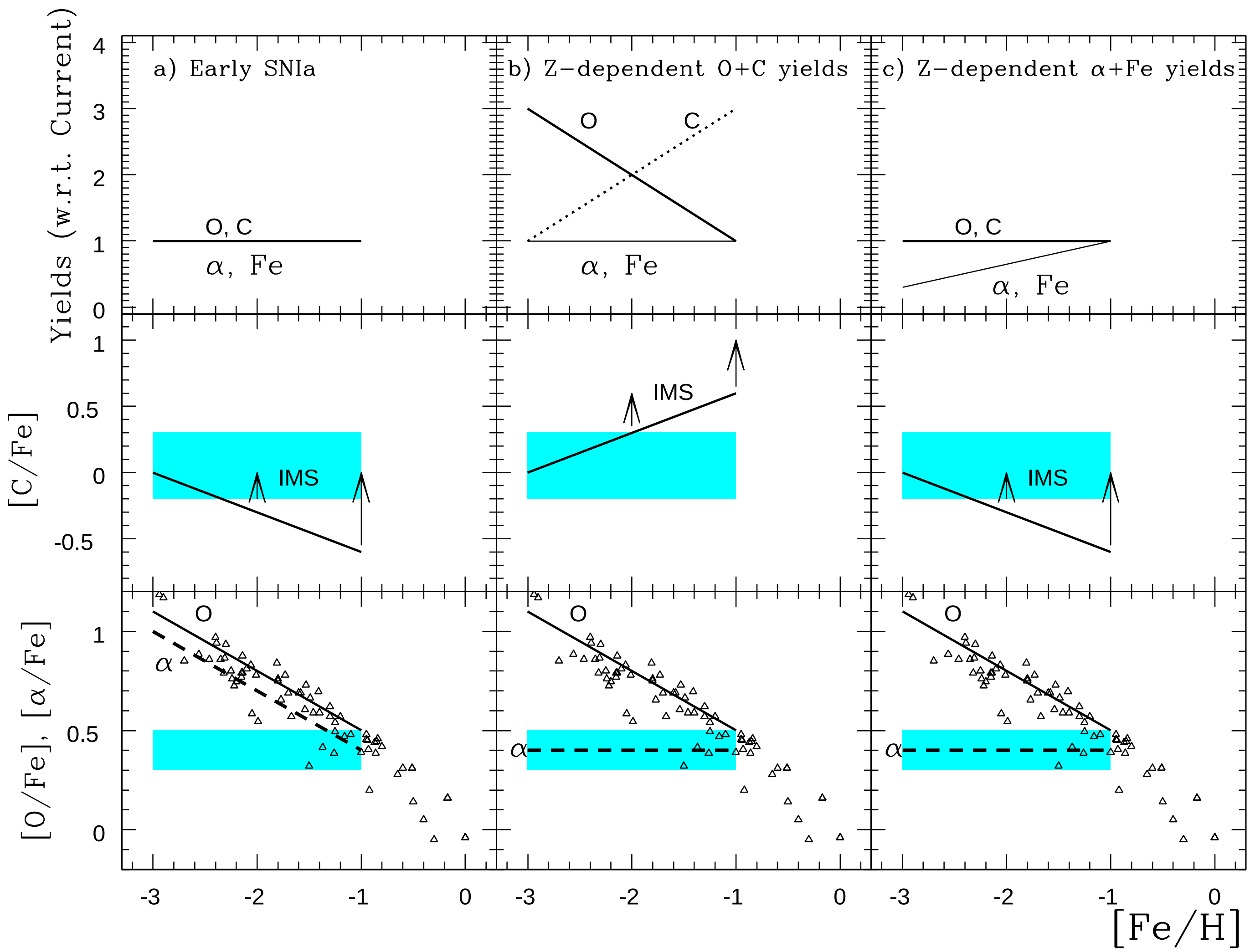

Fig. 9. Attempts to interpret the "new data" of Israelian et al. (1998) and Boesgaard et al. (1999) on O vs. Fe (appearing in the *bottom* panels). For each scenario discussed in Sect. 6 (presented from left to right), we show the required modifications in the yields of massive stars (w.r.t. their current values, *upper panels*), the impact on the evolution of C/Fe vs. Fe/H (*middle* panels) and the impact on the evolution of O/Fe and α/Fe vs Fe/H (*bottom* panels). In the *middle* panels, *thick solid* lines show the modified C/Fe evolution, while the *shaded area* shows the range of observed values; *arrows* show qualitatively the effect of including carbon production from intermediate mass (IMS), definitely excluding Case (b). In the *bottom* panels, the *thick solid* line shows the modified O/Fe evolution, the *thick dashed* line the modified α/Fe evolution, and the *shaded area* represents schematically current observations of α/Fe in the halo. Scenario (c), on the right, seems to be the only able to explain the "new" data of Israelian et al. (1998) and Boesgaard et al. (1999) without violating other obervational constrains. For details see Sect. 6

problem encountered by the first alternative seems to be solved. However, in the expelled mass of those stars, the abundances of He, N and C should be particularly enhanced. The resulting N/Fe and C/Fe ratios should be steadily increasing with metallicity in the halo (see Fig. 9), which is not observed; and introducing N and C from IMS would only make things worse. Thus, several arguments suggest that metallicity dependent oxygen (and, by necessity carbon) yields of massive stars cannot explain the "new data".

A third alternative concerns the possibility of having metallicity dependent yields of Fe and all elements heavier than oxygen (while keeping the O,N,C yields independent of metallicity below [Fe/H]$\sim$-1). In that case, the yields of α-elements and Fe would decrease with decreasing metallicity at the same rate, producing a quasi-constant α/Fe abundance ratio in the halo, as observed. The O/Fe and C/Fe ratios would both decrease with increasing metallicity (Fig. 9); however, in the latter case, this decrease would be compensated by C production from IMS, so that the C/Fe ratio would remain $\sim$constant in the halo, as observed. Thus, from the three studied alternatives, we think that only the last one cannot be at present rejected on observational grounds.

What could be the physics behind such a metallicity dependence of the yields of α-elements and Fe in massive stars? First, we notice that the required effect is very small: a factor of $\sim$3 increase is required in the yields for a 100-fold increase in metallicity (between [Fe/H]=-3 and [Fe/H]=-1, see Fig. 9), i.e. of the same order as the "odd-even" effect in Fig. 1. Our scenario requires that the supernova layers inside the C-exhausted core (i.e. the layers containing all the elements heavier than oxygen) be well mixed during the explosion. Various instabilities could contribute to that, either in the pre-supernova stage (in the O-burning shell, Bazan & Arnett 1998) or during the explosion itself (as in SN1987A, Arnett et al. 1989). This is required in order to ensure that the α/Fe ratio will be $\sim$ constant in the ejecta. But the main ingredient is that the structure of the star depends on metallicity, in the sense that lower metallicity cores are more compact than higher metallicity ones. Then, at the lowest metallicities (say [Fe/H]$\sim$-3), after the passage of the shock wave, a relatively large proportion of the well mixed C-exhausted core will fall back to the black hole, feeling a strong gravitational potential. At higher metallicities, the core is less compact and a larger proportion of the C-exhausted core escapes. At all metallicities, oxygen (and lighter elements as well) are located in the losely bound He-layers and manage always to escape with the same (metallicity independent) yields.

If the "new data" of Israelian et al. (1998) and Boesgaard et al. (1999) on O vs Fe are confirmed, some radical revision of our ideas on stellar nucleosynthesis will be required. At present, we think that our third alternative (schematically illustrated in the right panels of Fig. 9) is both plausible and compatible with all currently available data.

7. Evolution of Mg isotopic ratios

There are very few cases where observations allow to check models of isotopic abundance evolution in the Galaxy, especially concerning the early (i.e. halo) phase of that evolution. One of these rare cases concerns the Mg isotopes ^{25}Mg and ^{26}Mg.

All magnesium isotopes are mainly produced by hydrostatic burning in the carbon and neon shells of massive stars. The production of the neutron-rich isotopes ^{25}Mg and ^{26}Mg is affected by the neutron-excess (i.e. their yields increase with initial stellar metallicity) while ^{24}Mg is produced as a primary (in principle). Thus, the isotopic ratios ^{25}Mg/^{24}Mg and ^{26}Mg/^{24}Mg are expected to increase with metallicity.

Observational evidence of a decline of the abundances of ^{25}Mg and ^{26}Mg relative to ^{24}Mg in low metallicity stars was reported as early as 1980 (Tomkin & Lambert 1980). In a recent work Gay & Lambert (2000) derived Mg isotopic abundance ratios for 19 dwarf stars in the metallicity range -1.8<[Fe/H]<0, using high resolution spectra of the MgH A-X 0-0 band at 5140 Å. They compared their observations with the theoretical predictions of Timmes et al. (1995) in the solar neighbourhood and found an overall good agreement.

The evolution of Mg isotopic abundance ratios of our models is plotted as a function of [Fe/H] in Fig. 10. The upper panel represents the evolution of ^{25}Mg/^{24}Mg and the lower panel the one of ^{26}Mg/^{24}Mg. Both ratios increase slowly with [Fe/H]. ^{25}Mg/^{24}Mg becomes slightly larger than the corresponding solar ratio at [Fe/H]$\sim$0, while ^{26}Mg/^{24}Mg is 60% higher than solar at that metallicity. This is consistent with the results of Fig. 6 (lower panel), showing that ^{26}Mg is produced with its solar value at Sun's formation, while ^{25}Mg and ^{24}Mg are slightly underproduced. We notice that Timmes et al. (1995) find also supersolar Mg isotopic ratios at [Fe/H]=0, but the ^{26}Mg excess is not as large as ours. We think that this difference is due to our use of the Kroupa et al. (1993) stellar IMF, favouring the ^{26}Mg yields w.r.t those of ^{24}Mg; Timmes et al. use the Salpeter IMF.

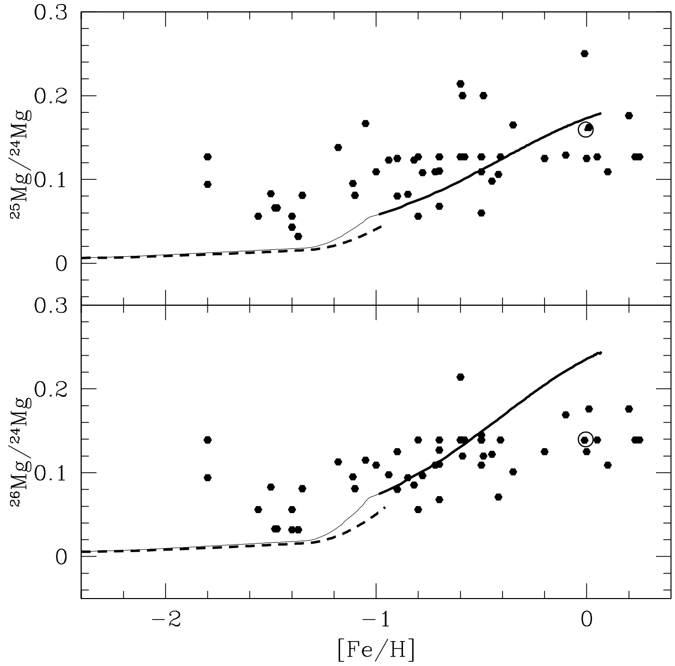

Fig. 10. Evolution of the isotopic abundance ratios of Mg as a function of metallicity [Fe/H]. The *upper panel* shows the evolution of ^{25}Mg/^{24}Mg and the *lower panel* the evolution of ^{26}Mg/^{24}Mg with respect to [Fe/H]. In both panels the *solid curve* corresponds to the disk model and the *dashed curve* to the halo model. The observed isotopic ratios are from Gay & Lambert (2000), McWilliam & Lambert (1988), Burbuy et al. (1985), Barbuy (1985, 1987), Lambert & McWilliam (1986) and Tomkin & Lambert (1980). Corresponding solar ratios in both panels are shown with $\odot$

In Fig. 10 we compare our results with observations from various sources, including the recent data of Gay & Lambert (2000). The observational trends are, globally, reproduced by our model for disk stars, although the ^{26}Mg/^{24}Mg ratio is higher than observed for stars of near solar metallicity. More interesting is the fact that the model isotopic ratios are systematically lower than observations for halo stars (below [Fe/H]$\sim$-1). This was also noticed in Timmes et al. (1995). It may well be that the WW1995 yields underestimate the importance of the neutron-excess in the production of the Mg isotopes at those metallicities. Another possibility is that there is some other source of the neutron-rich Mg isotopes in the late halo, like e.g. AGB stars with He-shells hot enough to activate the ^{22}Ne(α,n)^{25}Mg neutron source. This reaction, would not only provide neutrons for the s-process in those stars, but it would also produce large amounts of ^{25}Mg and ^{26}Mg. At present, the operation of that source in AGB stars of disk-like metallicities seems improbable, but there is no evidence as to what may happen at lower metallicities.

8. Summary

In this work we present a comprehensive study of the evolution of the abundances of intermediate mass elements (C to Zn) in the Milky Way halo and in the local disk. We use a consistent model in order to describe the evolution of those two galactic subsystems. The model assumes strong outflow in the halo phase and slow infall in the disk, which allow to correctly reproduce the corresponding metallicity distributions; these observables constitute the strongest constraints for chemical evolution models of those regions. Also, we consider the halo and the disk to evolve independently, since there is no hint at present for a physical connection between the two (see Sect. 3.3). We note that this type of modelisation has very rarely been done before.

The second important ingredient of this study is the consistent use of metallicity dependent yields for all isotopes. We adopt the yields of WW1995 and we note that there is a remarkably good agreement between them and the more recent ones of LSC2000 (but also some important differences). Only one study of similar scope has been done before with the metallicity dependent WW1995 yields (Timmes et al. 1995), but it utilised an inconsistent model for the halo. The study of Samland (1998) used appropriate models for the halo and the disk, but made several approximations concerning the stellar lifetimes and the metallicity dependence of the yields. We note that we have divided the (uncertain, anyway) Fe-peak isotopic yields of WW1995 by a factor of 2, in order to obtain abundance ratios w.r.t Fe consistent with observations; indeed, Timmes et al. (1995) recognised the problem with the WW1995 Fe yields and presented also results for twice and half the nominal values. We also performed calculations with metallicity independent yields (at solar metallicity only) in order to illustrate the differences with the metallicity dependent ones. In all cases we used the recent yields of Iwamoto et al. (1999) for SNIa, which are also metallicity dependent (this dependence affects very little the results). We only used yields from massive stars and SNIa, in order to find out for which elements and to what extent is the contribution of other sources mandatory.

We compared our results to a large body of observational data. In Sect. 4 we "validated" our model, by showing that it reproduces in a satisfactory way all the main observational constraints for the halo and the local disk. We found that the resulting elemental and isotopic compositions at a galactic age of 9 Gyr compare fairly well to the solar one; among the few exceptions, the most important ones concern:

a) The C and N isotopes, which are underproduced. For the major ones (^{12}C and ^{14}N), both WR and IMS are candidate sources; for ^{13}C and ^{15}N, IMS and novae are, respectively, the main candidates.
b) The isotopes of Sc, Ti and V, for which there is no other candidate source. The fact that the corresponding LSC2000 yields are even lower than those of WW1995 may point to some generic problem of current nucleosynthesis models for those elements.

We consider our results for the halo evolution to be significant only above [Fe/H]>-3. The reason is that at lower metallicities massive stars have lifetimes comparable to the age of the halo at that point; since the yields of individual stars are very uncertain, we consider that the corresponding results have little meaning. Only when the age of the halo becomes significantly larger than the lifetime of the "lightest" massive star (and ejecta are averaged over the IMF for all massive stars) we consider our results to become significant. For that reason, we are not able to draw any conclusion on the puzzling behaviour of the Fe-peak elements (Cr, Co, Ni) observed recently below [Fe/H]$\sim$-3.

We have compiled a large number of observational data on the composition of halo stars. The main conclusions of the comparison of our results to those data (Sect. 5 and Figs. 7 and 8) are the following:

– C and N require other sources than those studied here. For C, it could be WR or low mass stars, contributing to C production in the disk. For N, the source of primary N required in the halo could be either IMS with hot-bottom burning or rotationally induced mixing in massive stars.
– The evolution of the α-elements O, Si, S and Ca is well understood (baring the discrepant "new data" for O, see below) with the assumption that SNIa contribute most of Fe in the disk; however, the WW1995 yields underproduce Mg and Ti, and inspection of the LSC2000 yields shows that they would not be of help.
– Similarly, the odd-Z elements Sc and V are underproduced at all metallicities by both WW1995 and LSC2000 yields; this discrepancy points to some important revision required in current models of nucleosynthesis in massive stars, at least for those elements. It is significant that observationally, neither Sc nor V show the theoretically expected behaviour of odd-Z elements, suggesting that the "odd-even" effect may be overestimated in current nucleosynthesis models.
– Observed abundances of Na and Al also do not show the theoretically expected behaviour of odd-Z elements, when they are plotted w.r.t Fe (Fig. 7). However, other sources may be involved in the nucleosynthesis of those two elements (e.g. H-shell burning in intermediate mass stars in the red giant stage), which prevents from drawing definite conclusions. It is remarkable that, when the observed Na evolution is plotted vs. Ca (Fig. 8), Na shows indeed the expected behaviour of odd-Z element. Observations of Na vs Fe at low metallicities are necessary to establish the behaviour of this element. In the case of Al, NLTE effects play an important role in estimating its abundance at low metallicities and render difficult a meaningful comparison of observations to theory.
– Among the Fe-peak elements, several important discrepancies between theory and observations are found when results are plotted w.r.t. Fe (Fig. 7). The theoretical trends of Cr, Co, Ni and Zn deviate from the observed ones to various extents; in the case of Ni, the adopted W7 model for SNIa largely overproduces the main isotope ^{58}Ni in the disk, as well as ^{54}Cr, a minor Cr isotope. We notice that, when results are

plotted w.r.t. Ca (Fig. 8), the observed behaviour of Cr is well reproduced by the model; this might imply that it is the Fe yields that are problematic at low metallicities. We notice that Cr is produced at layers lying at larger distance from the core than Fe, and are thus less subject to the uncertainties of the mass-cut.
– There is a remarkably good agreement between the theoretical and the observed behaviour of the odd-Z Fe-peak elements Mn and Cu, when their evolution is plotted w.r.t. Fe (or w.r.t. Ca, in the case of Mn).

The recent data of Israelian et al. (1998) and Boesgaard et al. (1999) suggest that oxygen behaves differently from the other α-elements. Although this new picture of O vs Fe is not confirmed yet, we explored in this work a few alternatives to the "standard" scenario presented here. We thus showed in Sect. 6 (and Fig. 9), albeit qualitatively only, that the only "reasonable" way to accomodate the new data is by assuming that the yields of both Fe and all α-elements (except O, C and He) decrease with decreasing metallicity for [Fe/H]$<$-1; we also proposed a qualitative explanation for such a behaviour.

Finally, we compared the model evolution of the Mg isotopic ratios to current observations (Sect. 7 and Fig. 10). We found that, although the WW1995 yields of Mg describe relatively well the observations in the disk, they systematically underproduce the halo data. This suggests that the "odd-even" effect for those isotopes has been underestimated at low metallicities in WW1995.

In summary, we have revisited the chemical evolution of the halo and the local disk with consistent models and metallicity dependent yields of massive stars and SNIa. We showed that current yields are remarkably successful in reproducing a large number of observations, but need revision in several important cases. For some of those cases, the inclusion of non-classical ingredients in stellar models (i.e. mass-loss for C, rotationally induced mixing for primary N) could clearly help, but for most of the others (Sc, V and Ti at all metallicities, Fe-peak elements at very low metallicities) the situation remains unclear. Finally, we explored a few alternatives that could help to explain the new O vs Fe data and concluded that viable solutions exist, but would require some important modifications of our current understanding of massive star nucleosynthesis.

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References

Anders E., Grevesse N., 1989, GeoCosmActa 53, 197
Andersson A., Edvardsson B. 1994, A&A, 290, 590
Argast D., Samland M., Gerhard O.E., Thielemann, F.-K., 2000, (astro-ph/9911178)
Arnett D., 1996, *Supernovae and Nucleosynthesis,* Chicago University Press
Arnett D., Bahcall J., Kirshner R., Woosley S., 1989, ARAA, 27, 629
Aubert O., Prantzos N., Baraffe, I., 1996, A&A, 312, 845
Aufderheide M., Baron E., Thielemann F.-K., 1991, ApJ, 370, 630
Balachandran S.C., Carney B.W., 1996, AJ, 111, 946
Barbuy B., 1985, A&A 151, 189
Barbuy B. 1987, A&A 172, 251
Barbuy B., Spite F., Spite M., 1985, A&A 144, 343
Baumüller D., Gehren T., 1997, A&A 325, 1088
Bazan G., Arnett D., 1998, ApJ 496, 316
Bessel M.S., Sutherland R.S., Ruan K., 1991, ApJ 383, 71
Beveridge R.C., Sneden C., 1994, AJ 108, 285
Boesgaard A.M., King J.R., Deliyannis C.P., Vogt S.S., 1999, AJ 117, 492
Boissier S., Prantzos N., 1999, MNRAS 307, 857
Brachwitz F., Dean D., Hix W.R., et al. (2000), ApJ submitted (astro-ph 0001464)
Carbon D.F., Barbuy B., Kraft R.P., Friel E.D., Suntzeff N.B., 1987, PASP 99, 335
Cardelli J., Federman S., 1997, In: Görres J., Mathews G., Shore S., Wiescher M. (eds.) Nuclei in the Cosmos IV, Elsevier, Amsterdam, p. 31
Carney B.W., Peterson R.C., 1981, ApJ 245, 238
Carretta E., Gratton R., Sneden C., 2000, A&A, in press (astro-ph/0002407)
Clegg R.E.S., Tomkin J., Lambert D.L., 1981, ApJ 250, 262
Charbonnel C., Meynet G., Maeder A., Schaerer D., 1996, A&AS 115, 339
Chen Y.Q., Nissen P.E., Zhao G., Zhang H.W., Benoni T., 2000, A&AS in press (astro-ph/9912342)
Chiappini C., Matteucci F., Beers T., Nomoto K., 1999, ApJ 515, 226
Chiappini C., Matteucci F., Gratton G., 1997, ApJ 477, 765
Chieffi, A., Limongi, M. & Straniero, O. 1998, ApJ 502, 737
Cunha K., Lambert D.L., 1992, ApJ 399, 586
Cunha K., Lambert D.L., 1994, ApJ 426, 170
Edvardsson B., Anderson J., Gustafsson B., Lambert D.L., Nissen P.E., Tomkin J., 1993, A&A 275, 101
Feltzing S., Gustafsson B., 1998, A&AS 129, 237
Ferrini F., Molla A., Pardi M., Diaz A., 1994, ApJ 427, 745
Forestini M., Charbonnel C., 1997, A&AS 123, 241
Francois P., 1986a, A&A 160, 264
Francois P., 1986b, A&A 165, 183
Francois P., 1987a, A&A 176, 294
Francois P., 1987b, A&A 195, 226
Fuhrmann K., Axer M., Gehren T., 1995, A&A 301, 492
Fullbright J., Kraft R., 1999, AJ 118, 527
Garnett D., Kobulnicky H., 2000, ApJ, in press (astro-ph/9912031)
Gay P.L., Lambert D.L., 2000, ApJ, in press (astro-ph/9911217)
Gilmore G., Parry I., Ryan S. (eds.), 1998, *The Stellar Initial Mass Function,* Astron. Soc. Pac., San Francisco
Gilroy K.K., Sneden C., Pilachowski C.A., Cowan J.J., 1988, ApJ, 327, 298
Gratton R.G., 1989, A&A 208, 171
Gratton R.G., Ortolani S., 1986, A&A 169, 201
Gratton R.G., Sneden C., 1987, A&A 178, 179
Gratton R.G., Sneden C., 1988, A&A 204, 193
Gratton R.G., Sneden, C. 1991, A&A 241, 501
Gustafsson B., Karlsson T., Olsson E., Edvardsson B., Ryde N., 1999, A&A 342, 426
Hartmann K., Gehren T., 1988, A&A 199, 269
Hartwick F., 1976, ApJ 209, 418
Heger A., Langer N., Woosley S.E. 1999, ApJ, in press, (astro-ph/9904132)

Iben I., Tutukov A., 1984, ApJ 284, 719
Israelian G., Garcia-Lopez R., Rebolo R., 1998, ApJ 507, 805
Iwamoto K., Brachwitz F., Nomoto K., Kishimoto N., Hix R., Thielemann K.-F., 1999, ApJS 125, 439
Janka T., 1998, In: Prantzos N., Harissopoulos S. (eds.) *Nuclei in the Cosmos V.* Frontieres, Paris, p. 241
Jehin E., Magain P., Neuforge C., Neuforge C., Noels A., Parmentier G., Thoul A.A., 1999, A&A 341, 241
Jonch-Sorensen H., 1995, A&A 298, 799
Jorissen A., Smith V.V., Lambert D.L., 1992, A&A 261, 164
Kennicutt R., 1998, ApJ 498, 541
King J.R., 1994, ApJ 436, 331
King J.R., Boesgaard A.M., 1995, AJ 109, 383
Kobayashi C., Tsujimoto T., Nomoto K., Hachisu I., Kato M., 1998, ApJ 503, L155
Kraft R., Sneden C., Smith G.H., Shetrone M.D., Fullbright J., 1998, AJ 115, 1500
Kroupa P., Tout C., Gilmore G., 1993, MNRAS, 262, 545
Laird J.B., 1985, ApJ 289, 556
Laimons Z., Nissen P.E., Schuster W.J., 1998, A&A 337, 216
Lattanzio J.C., 1998, In: Prantzos N., Harissopoulos S. (eds.) *Nuclei in the Cosmos V.* Frontieres, Paris, p. 163
Lambert D.L., McWilliam A., 1986, ApJ 304, 436
Leep E.M., Wallerstein G., 1981, MNRAS 196, 543
Limongi M., Straniero O., Chieffi A., 2000 (astro-ph 0003401)
Maeder A., 1992, A&A 264, 105
Maeder A., Meynet G., 2000, ARAA, in press
Magain P., 1985, A&A 146, 95
Magain P., 1987, A&A 179, 176
Magain P., 1989, A&A 209, 211
Matteucci F., Greggio L., 1986, A&A 154, 279
Meusinger H., Reimann H.G., Stecklum B., 1991, A&A 245, 57
McWilliam A., Lambert D.L., 1988, MNRAS 230, 573
McWilliam A., 1997, Annu. Rev. Astron. Astrophys. 35, 503
McWilliam A, Preston G.W., Sneden C., Searle L., 1995a, AJ 109, 2757
McWilliam A, Preston G.W., Sneden C., Shectman S., 1995b, AJ 109, 2736
Meynet G., Arnould M., 2000, A&A, in press (astro-ph/0001170)
Molaro P., Bonifacio P., 1990, A&A 236, L5
Molaro P., Castelli F., 1990, A&A 228, 426
Nakamura T., Umeda H., Nomoto K., Thielemann F., Burrows A., 1999, ApJ, 517, 193
Nissen P.E., Edvardsson B., 1992, A&A 261, 255
Nissen P.E., Gustafsson B., Edvardsson B., Gilmore G., 1994, A&A 285, 440
Nissen P.E., Chen Y.Q., Schuster W.J., Zhao G., 1999, astro-ph/9912269 (to be published in A&A)
Nissen P.E., Schuster W.J., 1997, A&A 326, 751
Norris J.E., Peterson R.C., Beers T.C., 1993, ApJ 415, 797
Norris J.E., Ryan S.G., 1991, ApJ 380, 403
Pagel B., 1997, Nucleosynthesis and Galactic Chemical Evolution, Cambridge University Press
Pagel B.E.J., Tautvaisiene G., 1995, MNRAS 276, 505
Pardi M.C., Ferrini F., Matteucci F., 1995, ApJ 444, 207
Peterson R.C., 1981, ApJ 244, 989
Prantzos N., 1994, A&A 284, 477
Prantzos N., 2000, In: Schaerer D., Delgado R.G. (eds.) The Interplay between Massive Stars and the ISM. New Astronomy Reviews, in press (astro-ph/9912203)
Prantzos N., Boissier S., 2000, MNRAS 313, 338
Prantzos N., Silk J., 1998, ApJ 507, 229
Prantzos N., Casse M., Vangioni-Flam E., 1993, ApJ 403, 630
Prantzos N., Vangioni-Flam E., Chauveau S., 1994, A&A, 285, 132
Prantzos N., Aubert O., Audoure J., 1996, A&A 309, 760
Primas F., Molaro P., Castelli F., 1994, A&A 290, 885
Rocha-Pinto H., Maciel W., 1996, MNRAS 279, 447
Rocha-Pinto H., Maciel W., Scalo J., Flynn C., 2000, A&A, submitted (asro-ph/0001382)
Ryan S.G., 2000, In: Noels A., Magain P., Caro D., et al. (eds.) The Galactic Halo: From Globular Clusters to Field Stars, in press (astro-ph/0001235)
Ryan S.G., Norris J.E., Beers T.C., 1996, ApJ 471, 254
Ryan S.G., Norris J.E., Bessell M.S., 1991, AJ 102, 303
Samland M., 1998, ApJ 496, 155
Samland M., Hensler G., Theis Ch., 1997, ApJ 476, 544
Scalo J., 1986, FundCosmPhys 11, 1
Schaller G., Schaerer D., Maeder A., Meynet G., 1992, A&AS 96, 269
Sneden C., Crocker D.A., 1988, ApJ 335, 406
Sneden C., Gratton R.G., Crocker D.A., 1991, A&A 246, 354
Sneden C., Lambert D.L., Whitaker R.W., 1979, ApJ, 234, 964
Sneden C., Preston G.W., McWilliam A., Searle L., 1994, ApJ 431, L27
Spiesman W.J., Wallerstein G., 1991, AJ 102, 1790
Spite M., Spite F., 1991, A&A 252, 689
Stephens A., 1999, AJ 117, 1771
Tammann G., Loefler W., Schroder A., 1994, ApJS 92, 487
Thielemann F.K., Nomoto K., Hashimoto M., 1996, ApJ 460, 408
Thielemann F., Nomoto K., Yokoi K., 1986, A&A, 158, 17
Thielemann F.-K., Brachwitz F., Iwamoto K., et al., 1999, In: Walsh J., Rosa M. (eds.) *Chemical Evolution from Zero to High Redshift*(ESO Astrophysics Symp), p. 10
Thomas D., Greggio L., Bender R., 1998, MNRAS 296, 119
Thorsett S.E., Chakrabarty D., 1999, ApJ 512, 288
Timmes F.X., Woosley S.E., Weaver T.A. 1995, ApJS 98, 617
Tinsley B.M., 1980, Fund. Cosmic Phys. 5, 287
Tomkin J., Lambert D.L., 1980, ApJ 235, 925
Tomkin J., Lambert D.L., Balachandran S., 1985, ApJ 290, 289
Tomkin J., Lemke M., Lambert D.L., Sneden C., 1992, AJ 104, 1568
Tomkin J., Woolf V.C., Lambert D.L., Lemke M., 1995, AJ 109, 2204
Travaglio C., Galli D., Gallino R., Busso M., Ferrini F., Straniero O., 1999, ApJ, 521, 691
Twarog B.A., 1980, ApJ 242, 242
Wang B., Silk J., 1993, ApJ 406, 580
Woosley S.E., Hartmann D.H., Hoffman R.D., Haxton W.C. 1990, ApJ 356, 272
Woosley S.E., Weaver T.A., 1995, ApJS 101, 181
Woosley S., Langer N., Weaver T., 1993, ApJ 411, 823
Wyse R., Gilmore G., 1995, AJ 110, 2771
Wyse R., Silk J., 1989, ApJ 339, 700
Wyse R., 2000, In: Noels A., Magain P., Caro D., et al. (eds.) The Galactic Halo: from Globular Clusters to Field Stars, in press, (astro-ph/9911358)
Zhao G., Magain P., 1990, A&A 238, 242