

Manganese evolution in Omega Centauri: a clue to the cluster formation mechanisms?

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ABSTRACT

We model the evolution of manganese relative to iron in the progenitor system of the globular cluster Omega Centauri by means of a self-consistent chemical evolution model. We use stellar yields that already reproduce the measurements of [Mn/Fe] versus [Fe/H] in Galactic field disc and halo stars, in Galactic bulge stars and in the Sagittarius dwarf spheroidal galaxy. We compare our model predictions to the Mn abundances measured in a sample of 10 red giant members and six subgiant members of ω Cen. The low values of [Mn/Fe] observed in a few, metal-rich stars of the sample cannot be explained in the framework of our standard, homogeneous chemical evolution model. Introducing cooling flows that selectively bring to the cluster core only the ejecta from specific categories of stars does not help to heal the disagreement with the observations. The capture of field stars does not offer a viable explanation either. The observed spread in the data and the lowest [Mn/Fe] values could, in principle, be understood if the system experienced inhomogeneous chemical evolution. Such an eventuality is qualitatively discussed in this paper. However, more measurements of Mn in ω Cen stars are needed to settle the issue of Mn evolution in this cluster.

Key words: nuclear reactions, nucleosynthesis, abundances – globular clusters: individual: ω Centauri – galaxies: evolution.

1 INTRODUCTION

The abundance ratios of chemical elements that are produced on different time-scales by stars of different masses are essential probes of the history of chemical enrichment in different types of stellar populations. They tell which stars – and in which proportions – have contributed to the chemical evolution of a given system at any time. After Tinsley (1979), it has become customary to explain the trend of oxygen relative to iron as due to the different roles played by Type Ia supernovae (SNeIa) and Type II supernovae (SNeII) in the chemical enrichment of galaxies (see also Greggio & Renzini 1983; Matteucci & Greggio 1986). This interpretation is known as the ‘time-delay model’. Oxygen is produced mostly by core-collapse SNe on very short time-scales, of the order of a few Myr to tenths of Myr. The bulk of iron, instead, comes later from SNIa explosions, on time-scales ranging from 30 Myr to a Hubble time. Hence, the [O/Fe] ratio in a given system is high as long as SNeII dominate the interstellar medium (ISM) pollution, then decreases to solar and subsolar values when SNeIa become the major contributors to the

production of Fe. The maximum SNIa rate depends on the adopted progenitor model, as well as on the assumed star formation history (Matteucci & Recchi 2001); thus, the measurements of [O/Fe] are a powerful diagnostics of the star formation history in galaxies.

Of particular interest are those elements whose yields depend on the metallicity of the parent stars; manganese (Mn) is one of them. McWilliam, Rich & Smecker-Hane (2003) confronted the [Mn/Fe] versus [Fe/H] relation in the Galactic bulge, in the solar neighbourhood and in the Sagittarius dwarf spheroidal galaxy (Sgr dSph). They suggested that the Mn yields from both SNeIa and SNeII are metallicity-dependent. Their proposals were in agreement with extant nucleosynthesis calculations for massive stars (e.g. Arnett 1971; Woosley & Weaver 1995), but there was no modelling of explosive nucleosynthesis in SNeIa supporting their findings.

Shetrone et al. (2003) measured the Mn abundances of a dozen individual red giant stars in the Sculptor, Fornax, Carina and Leo I dSphs. They also conclude that SNIa contributions to the synthesis of Mn must be metallicity-dependent, with very little Mn produced until [Fe/H] = -1 .

Later on, Ohkubo et al. (2006) showed that, indeed, [Mn/Fe] – and [Ni/Fe] – in the ejecta of SNeIa depend on metallicity of SNIa progenitors. Furthermore, Cescutti et al. (2008) demonstrated, by

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means of self-consistent chemical evolution models, that the run of $[\text{Mn}/\text{Fe}]$ with $[\text{Fe}/\text{H}]$ in the three independent stellar systems – the Galactic bulge, the solar neighbourhood and the Sgr dSph – can be understood *only in terms of a metallicity-dependent yield of Mn* from SNeIa. The time-delay model alone is insufficient to explain the behaviour of $[\text{Mn}/\text{Fe}]$ versus $[\text{Fe}/\text{H}]$ in the three systems. Cescutti et al. (2008) propose that the yield of Mn in SNeIa increases with the metallicity of the progenitors, $Y_{\text{Mn}}(Z) \propto Z^{0.65}$. This is in agreement with the tight correlation between the Mn-to-Cr mass ratio in the ejecta of SNeIa and the metallicity of the progenitor found by Badenes, Bravo & Hughes (2008), $M_{\text{Mn}}/M_{\text{Cr}} = 5.3 \times Z^{0.65}$.

More recently, Mn abundances have been studied for the first time on a significant metallicity range in the peculiar globular cluster ω Centauri (Cunha et al. 2010; Pancino et al. 2011). In the metal-poor regime, Cunha et al. (2010) find that the local thermodynamic equilibrium (LTE) values of $[\text{Mn}/\text{Fe}]$ in ω Cen stars overlap those of their solar neighbourhood analogues. However, at variance with the solar neighbourhood trend, $[\text{Mn}/\text{Fe}]$ declines in more metal-rich stars (see also Pancino et al. 2011). Non-LTE calculations confirm the conclusion of a well-distinct pattern of $[\text{Mn}/\text{Fe}]$ versus $[\text{Fe}/\text{H}]$ in ω Cen (Cunha et al. 2010). It is worth noting that, in the metallicity range $-2.7 < [\text{Fe}/\text{H}] < -0.7$, all other Galactic globulars have Mn abundances equivalent to those of halo field stars (Sobeck et al. 2006).

Although historically classified as a globular cluster, ω Cen is possibly the naked nucleus of a small galactic satellite captured by the Milky Way many Gyr ago (e.g. Freeman 1993; Bekki & Freeman 2003). As such, it likely suffered a complex chemical enrichment history, marked by the occurrence of strong differential galactic winds (Romano et al. 2007, 2010a). The challenging bet is: can the low values of $[\text{Mn}/\text{Fe}]$ observed in the more metal-rich stars of ω Cen be explained in the context of its peculiar evolutive history?

In this paper, we contrast the evolution of Mn in the Milky Way with that in ω Cen. The goal of this work is twofold. First, we want to add the analysis of another distinct stellar population to previous theoretical study of the evolution of Mn in different environments by Cescutti et al. (2008). Secondly, we want to get better insight into the mechanisms of formation and evolution of ω Cen. The predictions of our models for the Milky Way and for ω Cen are compared to both LTE and non-LTE Mn abundances in the two systems. The paper is organized as follows. In Section 2, we briefly review the relevant observational data. In Section 3, we describe the adopted chemical evolution models. In Section 4, we discuss the model results. In Section 5, we draw our conclusions.

2 OBSERVATIONAL DATA

For the purpose of comparison with the results of our models, we use LTE Mn I abundances of Galactic stars by Cayrel et al. (2004), Gratton et al. (2003), Reddy et al. (2003), Reddy, Lambert & Allende Prieto (2006) and Feltzing, Fohlman & Bensby (2007). These studies are selected to cover the whole metallicity range of solar neighbourhood stars. Other recent measurements of Mn in Galactic disc and halo stars can be found in Nissen et al. (2000), Prochaska & McWilliam (2000), Norris, Ryan & Beers (2001), Carretta et al. (2002), Bai et al. (2004) and Lai et al. (2008). For ω Cen, we use LTE data from Cunha et al. (2010, 10 stars) and Pancino et al. (2011, six stars). While Cunha et al. (2010) analysed Mn lines around 6000 Å, Pancino et al. (2011) analysed Mn lines around 4000 Å. This could explain the marginal disagreement between the two data sets and lead to an artificial increase of the scatter in the data when the two data sets are plotted together (Fig. 1, right-hand panel). Cohen (1981) and Gratton (1982) also published Mn abundances of ω Cen stars. However, their determinations do not take hyperfine splitting of spectral lines into account and are, thus, not considered here.

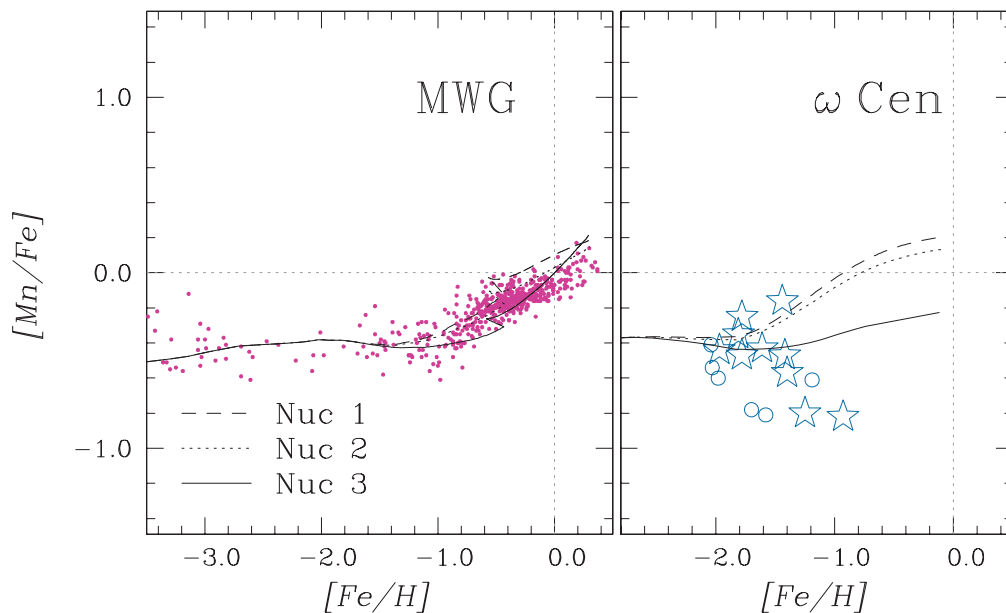


Figure 1. $[\text{Mn}/\text{Fe}]$ versus $[\text{Fe}/\text{H}]$ relation in the solar neighbourhood (left-hand panel) and in ω Cen (right-hand panel). The dashed curves in both panels are the theoretical trends obtained with the metallicity-dependent yields of Woosley & Weaver (1995) for SNeII and the yields of Iwamoto et al. (1999) for solar-metallicity SNeIa at all metallicities. The dotted and solid curves show the effect of taking into account in two different ways (see text) the metallicity dependence of the Mn yield from SNeIa. Left-hand panel: filled circles are LTE data from several sources (see Section 2 for references). Right-hand panel: LTE data are taken from Cunha et al. (2010, stars) and Pancino et al. (2011, open circles).

Despite the adoption of different methods and assumptions to determine the Mn abundances, all the studies mentioned above conclude that Mn is deficient compared to iron ($[\text{Mn}/\text{Fe}] \simeq -0.5$) in metal-poor stars and that $[\text{Mn}/\text{Fe}]$ increases with increasing $[\text{Fe}/\text{H}]$ from the halo to the thin-disc populations. The stars in ω Cen present a trend at odds with that of their solar neighbourhood counterparts, i.e. a $[\text{Mn}/\text{Fe}]$ ratio declining with increasing $[\text{Fe}/\text{H}]$ (Cunha et al. 2010). Note, however, that this statement rests with the determination of Mn in only two stars.

In the LTE approximation, the abundances based on Mn I lines could be underestimated by as much as 0.4 dex at low metallicities, with non-LTE effects being less pronounced in high-metallicity stars (Bergemann & Gehren 2008). Up to now, non-LTE Mn abundances have been computed only for a few stars in the Milky Way (Bergemann & Gehren 2008) and in ω Cen (Cunha et al. 2010). When the non-LTE corrections are applied to solar neighbourhood stars, a shallower rise is found from slightly subsolar values in the halo ($[\text{Mn}/\text{Fe}] \simeq -0.1$) to solar ratios in the thin disc. The non-LTE abundance analysis of ω Cen stars fully confirms the odd behaviour of decreasing Mn with increasing $[\text{Fe}/\text{H}]$ depicted by LTE studies (see discussion in Cunha et al. 2010), but once again the result bases on the analysis of only a handful of stars. We discuss further the non-LTE Mn abundances in comparison to our model results in Section 4.

3 THE CHEMICAL EVOLUTION MODELS

The chemical evolution model for the solar neighbourhood is basically the ‘two-infall model’ of Chiappini, Matteucci & Gratton (1997), except for the adopted stellar lifetimes, nucleosynthesis and initial mass function (IMF; see Romano et al. 2005, 2010b). In particular, the Kroupa, Tout & Gilmore (1993) IMF is assumed instead of the Scalo (1986) one. This makes the predicted present-day SNIa-to-SNII rate ratio to agree with the observations (Romano et al. 2005, their table 4) and allows us to better explain the evolution of deuterium in the Galaxy (Romano 2010).

The adopted model for ω Cen assumes that this cluster was once located at the centre of a more massive system, which evolved in isolation before being accreted and almost totally disrupted by the interaction with the Milky Way. Because of the shallow potential well, the chemical evolution of the original system – and of the embedded protocluster – turns out to be significantly affected by galactic outflows triggered by multiple SN explosions (Romano et al. 2007). These outflows deprive the original system of a large fraction of its metals, thus allowing the observed Na–O anticorrelation and the extreme level of He enhancement to set up in a (minor) fraction of the hosted stars (Romano et al. 2010a).

For details about the basic assumptions and equations of the models, we refer the reader to the papers quoted above. As for the adopted nucleosynthesis prescriptions, they can be found below.

3.1 Nucleosynthesis prescriptions

As already mentioned, Fe and Mn are produced by both SNeII and SNeIa, though in different proportions. In our computations, we explore the consequences of adopting six different prescriptions about the synthesis of Fe and Mn in stars.

(i) *Nuc 1*: we use the metal-dependent yields of Woosley & Weaver (1995) for SNeII and the yields of Iwamoto et al. (1999) for solar-metallicity SNeIa (their model W7) at all metallicities.

(ii) *Nuc 2*: as above, but we interpolate between zero-metallicity and solar-metallicity SNIa yields (models W70 and W7 in Iwamoto et al. 1999).

(iii) *Nuc 3*: as above, but we modify the Mn yield from SNeIa following Cescutti et al. (2008):

$$Y_{\text{Mn}}(Z) = Y_{\text{Mn}}^{\text{W7}} \left(\frac{Z}{Z_{\odot}} \right)^{0.65}, \quad (1)$$

where Z and Z_{\odot} are the metallicities of the SNIa progenitor and of the Sun at birth, respectively.

(iv) *Nuc 4*: we use the metal-dependent yields of Woosley & Weaver (1995) with *Fe yields halved* for SNeII and the yields of Iwamoto et al. (1999) for solar-metallicity SNeIa (their model W7) at all metallicities.

(v) *Nuc 5*: as above, but we interpolate between zero-metallicity and solar-metallicity SNIa yields (models W70 and W7 in Iwamoto et al. 1999).

(vi) *Nuc 6*: as above, but with a metal-dependent yield of Mn from SNeIa as in equation (1).

Models without Mn production from SNeIa were computed as well (models labelled Nuc 0) and are discussed in Section 4.2.

The first and third choices are in common with Cescutti et al. (2008), who conclude that the Mn yield from SNeIa must be metallicity-dependent. Their result derives from the simultaneous analysis of the behaviour of $[\text{Mn}/\text{Fe}]$ versus $[\text{Fe}/\text{H}]$ in the Galactic bulge, in the solar neighbourhood and in the Sgr dSph. Here, we add the study of Mn evolution in ω Cen to their survey.

Note that Cescutti et al. (2008) adopted model W7 of Iwamoto et al. (1999) at all metallicities. This was done because the physics – and nucleosynthesis output especially for those elements produced in the inner part of the white dwarf (WD) – of metal-free SNeIa are likely to be not significantly different from those at $Z \neq 0$. Also, only a tiny fraction of all SNeIa that explode in a galaxy forms from truly $Z = 0$ matter. In fact, a few SNII explosions suffice to rise the metal content of the ISM from zero to non-zero. On the other hand, the adoption of an empirical law of the form suggested by Cescutti et al. (2008) for Mn was justified by the fact that it could reproduce the Mn evolution in different objects and that Mn is one of those elements produced in the external layers of the WD and therefore more dependent on the initial metallicity of the progenitor of the C–O WD (Thielemann, private communication).

At this point, it is worth mentioning once again that Badenes et al. (2008) also find that the Mn yield from SNeIa declines with decreasing metallicity. The metallicity dependence they suggest is the same as in equation (1). Their result, which springs from detailed SNIa modelling, is stable against variations in the initial conditions and explosion mechanisms (either delayed detonation or deflagration) of the models explored.

4 MODEL RESULTS AND DISCUSSION

4.1 The classical picture

The dashed curves in Fig. 1 show the behaviour of $[\text{Mn}/\text{Fe}]$ versus $[\text{Fe}/\text{H}]$ predicted for the solar neighbourhood (left-hand panel) and for ω Cen (right-hand panel) with our models using the metallicity-dependent yields of Woosley & Weaver (1995) for SNeII and model W7 of Iwamoto et al. (1999) for SNeIa at all metallicities. The theoretical predictions, in this and all the following figures, are normalized by the solar values of Grevesse & Sauval (1998). Here, the results of the models are compared to LTE data.

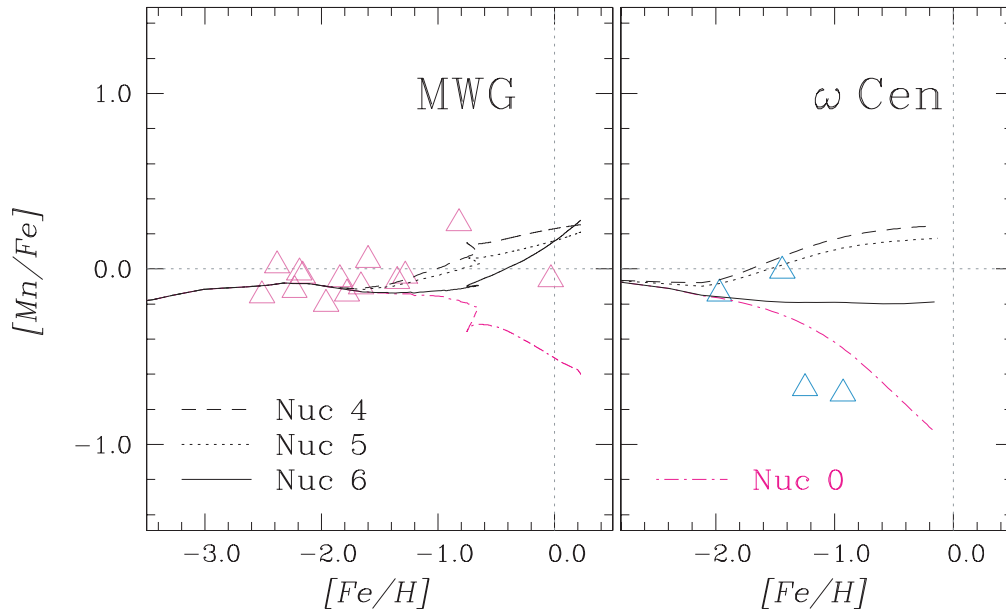


Figure 2. $[\text{Mn}/\text{Fe}]$ versus $[\text{Fe}/\text{H}]$ relation in the solar neighbourhood (left-hand panel) and in ω Cen (right-hand panel). The dashed curves in both panels refer to the predictions of models adopting the metallicity-dependent yields of Woosley & Weaver (1995) with Fe yields halved for SNeII and the yields of Iwamoto et al. (1999) for solar-metallicity SNeIa at all metallicities. The dotted and solid curves show the effect of taking into account the metallicity dependence of the Mn yield from SNeIa. The dot-dashed curves show the predictions of models computed with zero Mn production from SNeIa. Open triangles are non-LTE data (references are given in Section 2).

It can be immediately seen that, as soon as SNeIa start to sensibly contribute to the chemical enrichment of the ISM,¹ the theoretical curves begin to diverge from the observed $[\text{Mn}/\text{Fe}]$ versus $[\text{Fe}/\text{H}]$ relation. This can be interpreted as an indication that the Mn yields from SNeIa are overestimated (see also Cescutti et al. 2008). Indeed, by introducing a metallicity dependence in the Mn yield from SNeIa (either by interpolating between models W70 and W7 of Iwamoto et al. 1999 or by adopting a Mn yield decreasing with decreasing metallicity as in Cescutti et al. 2008 – see equation 1), we get a better fit to the solar neighbourhood data (left-hand panel, dotted and solid lines, respectively). However, the low $[\text{Mn}/\text{Fe}]$ ratios observed in the most metal-rich stars of ω Cen cannot be recovered by the model, which always predicts a $[\text{Mn}/\text{Fe}]$ ratio increasing with time (metallicity) in ω Cen (right-hand panel, dotted and solid lines).

4.2 Turning to non-LTE abundances

The analysis of the evolution of several element-to-iron abundance ratios in the Milky Way led Timmes, Woosley & Weaver (1995) to favour the use of *half the nominal values* of the Fe yields given by Woosley & Weaver (1995) in chemical evolution models. Therefore, we have recomputed our set of chemical evolution models by reducing the Woosley & Weaver (1995) original Fe yields by a factor of 2. The results are shown in Fig. 2, for either metal-independent (dashed curves) or metal-dependent (dotted and solid curves) Mn yields from SNeIa. The theoretical predictions are compared to non-LTE abundance data. The non-LTE-corrected Mn abundances of metal-poor stars are higher than the corresponding LTE values. Therefore, a

very good agreement is obtained between the observed and predicted $[\text{Mn}/\text{Fe}]$ versus $[\text{Fe}/\text{H}]$ trends for the Galactic halo when assuming half the nominal values of the Fe yields by Woosley & Weaver (1995) and the non-LTE-corrected Mn abundances for halo stars. For $[\text{Fe}/\text{H}] > -1.0$, a rise to solar ratios shallower than predicted should be probably preferred, though more data are needed to characterize the run of $[\text{Mn}/\text{Fe}]$ with $[\text{Fe}/\text{H}]$ at disc metallicities. The adoption of a metallicity-dependent yield of Mn from SNeIa produces a constant rather than increasing $[\text{Mn}/\text{Fe}]$ ratio in ω Cen only when the empirical law by Cescutti et al. (2008) is adopted (solid line). Interpolating linearly between models W70 and W7 of Iwamoto et al. (1999), instead, still results in a $[\text{Mn}/\text{Fe}]$ ratio increasing with $[\text{Fe}/\text{H}]$ (dotted line). Even a constant $[\text{Mn}/\text{Fe}]$ ratio, however, does not suffice to explain the observations. Current measurements, in fact, seem to point to an abrupt fall of $[\text{Mn}/\text{Fe}]$ at $[\text{Fe}/\text{H}] \sim -1.2$ in this cluster (Fig. 2, right-hand panel), though one must be aware that this trend is dictated by just two stars. A decreasing $[\text{Mn}/\text{Fe}]$ ratio in ω Cen may be obtained by assuming that SNeIa do not produce any Mn; however, in that case it is impossible to reproduce the Milky Way data (cf. models labelled Nuc 0, dot-dashed lines in Fig. 2). This could imply that SNeIa in the Milky Way and in ω Cen have different progenitors, but the paucity of Mn data for ω Cen prevents us from drawing any firm conclusion.

4.3 Invoking cooling flows and/or field star capture

The extremely low Mn abundance measured for a few stars in ω Cen is not the only chemical peculiarity of this cluster. Some of its stars are, in fact, enormously enriched in helium and *s*-process elements, while characteristic anticorrelations exist among the abundances of particular elements, similarly to what is found in other globular clusters, but at variance with the Milky Way field at the same metallicities.

In order to explain the peculiar patterns observed in the chemical abundances of a significant fraction of Galactic globular

¹ According to the time-delay model, this happens at different times (metallicities) in the two systems, namely 0.5 Gyr from the beginning of the star formation ($[\text{Fe}/\text{H}] \sim -1$) in the solar neighbourhood and 0.1 Gyr from the beginning of the star formation ($[\text{Fe}/\text{H}] \sim -2$) in ω Cen.

cluster stars, D’Ercole et al. (2008) have suggested that the ejecta of first-generation asymptotic giant branch (AGB) stars collect in a cooling flow into the cluster core, where they form a subsystem of chemically anomalous second-generation stars. Though attractive, such a scenario cannot provide a justification for the low Mn abundances ($[\text{Mn}/\text{Fe}] \sim -0.8$) observed in metal-rich stars of ω Cen by Cunha et al. (2010). Indeed, first-generation AGB stars in ω Cen would display a value of $[\text{Mn}/\text{Fe}]$ close to -0.4 (or -0.2 , depending on whether the SNI Fe yields are taken at face value or reduced by a factor of 2) in their ejecta, dictated by SNI nucleosynthesis at low metallicities. This value is well above that suggested by the observations of relatively metal-rich stars in ω Cen. The same considerations apply to the competitive scenario proposed by Decressin et al. (2007), where the chemical peculiarities of second-generation stars are driven by the slow winds of rotating massive stars.

Alternatively, one might argue that chemically peculiar stars did not originate in the cluster itself, but were accreted from the surroundings (see Fellhauer, Kroupa & Evans 2006, for a possible scenario of field stars trapping by the newborn ω Cen). In this case, they would be no longer representative of the self-enrichment history of the cluster. However, Mn abundances as low as $[\text{Mn}/\text{Fe}] \simeq -0.8$, as measured in ω Cen, have never been detected elsewhere, which makes the field star capture hypothesis highly unreliable. In Fig. 3, we compare the $[\text{Mn}/\text{Fe}]$ versus $[\text{Fe}/\text{H}]$ trends observed in different stellar systems – the solar neighbourhood, several Galactic globular clusters and a few dSphs – to the $[\text{Mn}/\text{Fe}]$ versus $[\text{Fe}/\text{H}]$ relation of ω Cen stars (note that part of the large scatter in the ω Cen data has been artificially introduced by plotting together measurements based on different Mn lines; see discussion in Section 2 and Pancino et al. 2011). It is clearly seen that, below $[\text{Fe}/\text{H}] = -0.8$, all stars, independently of the system they belong to, share a common value of $[\text{Mn}/\text{Fe}]$ of roughly -0.4 . This is not true only for a few stars in ω Cen with $[\text{Mn}/\text{Fe}] \sim -0.8$.

4.4 Inhomogeneous chemical evolution?

At this point, it remains to be assessed whether we can explain the observations by relaxing some of the simplifying hypotheses of our model.

The solid curve in Fig. 4, left-hand panel, tracks down the predicted behaviour of $[\text{Mn}/\text{Fe}]$ as a function of $[\text{Fe}/\text{H}]$ in the ISM of ω Cen, according to our fiducial model for this cluster. In the framework of homogeneous chemical evolution, the chemical composition of the newborn stars is exactly that predicted for the ISM at the time of their formation. Any spread in the data is, therefore, left unexplained.

For $[\text{Fe}/\text{H}] < -1.4$, the majority of the data points is consistent with the predictions of our homogeneous chemical evolution model, within the quoted uncertainties. For $[\text{Fe}/\text{H}] > -1.4$, there are only three stars with Mn determinations in ω Cen, and all of them lie below the theoretical curve. While this may be a hint for a decrease of $[\text{Mn}/\text{Fe}]$ with $[\text{Fe}/\text{H}]$ in ω Cen, it was pointed out to us that one should also consider the possibility that the stars form from a medium that is not well mixed and thus bears the signature of chemical enrichment from a few SNe only.

In Fig. 4, right-hand panel, we show the composition of pure SNI ejecta as a function of the initial stellar mass, for a grid of stellar models from 12 to $40 M_{\odot}$ (filled circles and triangles). We take the yields from Woosley & Weaver (1995) for two values of the metallicity typical of ω Cen stars. If the star formation in ω Cen’s progenitor is initiated by SNe and the stars form from a mixture of ‘snowploughed’ ISM and individual supernova ejecta, in a scenario resembling that suggested for the Galactic halo by Ishimaru & Wanajo (1999; see also Tsujimoto, Shige-yama & Yoshii 1999; Argast et al. 2000; Cescutti 2008, for inhomogeneous chemical evolution modelling of the halo), then a broad distribution of $[\text{Mn}/\text{Fe}]$ in the newborn stars is expected, because of the broad distribution of $[\text{Mn}/\text{Fe}]$ ratios in the ejecta of individual core-collapse SNe. However, the lowest $[\text{Mn}/\text{Fe}]$ ratios observed in ω Cen are left

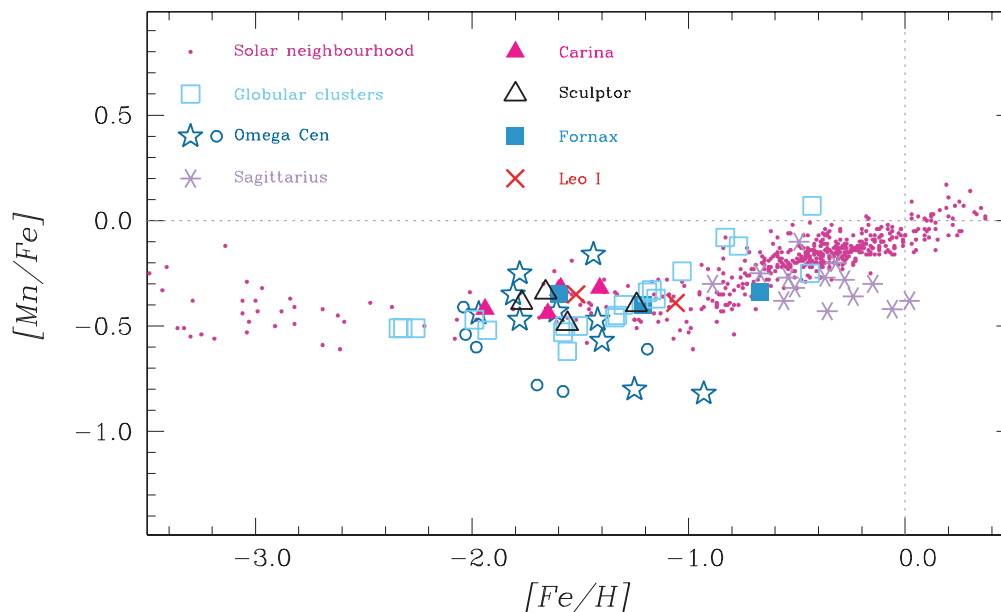


Figure 3. Observational $[\text{Mn}/\text{Fe}]$ versus $[\text{Fe}/\text{H}]$ relationships for field stars in the solar neighbourhood (filled circles; Gratton et al. 2003; Reddy et al. 2003, 2006; Cayrel et al. 2004; Feltzing et al. 2007), 20 Galactic globular clusters (open squares; Gratton et al. 2006; Carretta et al. 2007; Carretta 2010, private communication), ω Cen (stars: Cunha et al. 2010; open circles: Pancino et al. 2011), Sgr (main body and Terzan 7, asterisks; Sbordone et al. 2007) and four dSphs of the Local Group (filled triangles: Carina; open triangles: Sculptor; filled squares: Fornax; crosses: Leo I; Shetrone et al. 2003).

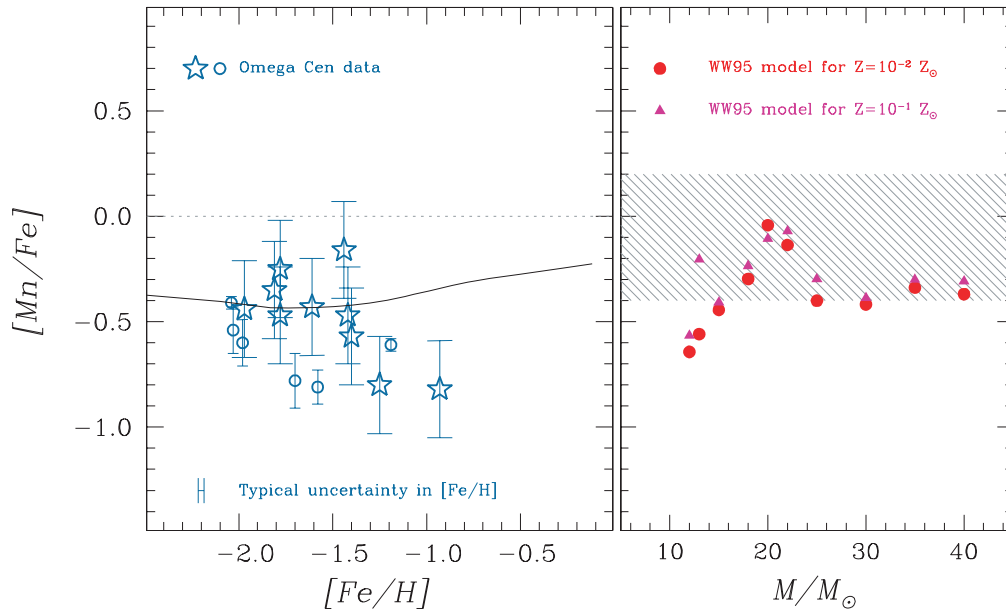


Figure 4. Left-hand panel: $[\text{Mn}/\text{Fe}]$ versus $[\text{Fe}/\text{H}]$ in ω Cen as measured in giants (stars; Cunha et al. 2010) and subgiants (empty circles; Pancino et al. 2011) and predicted by our fiducial chemical evolution model (solid line). Right-hand panel: chemical composition of pure SNIa ejecta from individual massive stars from Woosley & Weaver (1995), for metallicities typical of the cluster’s stars (filled circles: $Z/Z_{\odot} = 10^{-2}$; filled triangles: $Z/Z_{\odot} = 10^{-1}$); shaded area: $[\text{Mn}/\text{Fe}]$ ratio in the ejecta of SNIa for metallicities typical of the cluster, according to Cescutti et al. (2008) recipe. The masses of the binary systems leading to SNIa explosions go from 3 to $16 M_{\odot}$.

unexplained. Also shown in Fig. 4 are the $[\text{Mn}/\text{Fe}]$ ratios in the ejecta of SNIa that explode in ω Cen’s progenitor (shaded area; the Mn yield from SNIa is computed according to the recipe of Cescutti et al. 2008). Once again, it is seen that the stars with the lowest $[\text{Mn}/\text{Fe}]$ ratios in ω Cen cannot be explained as forming from pure SN ejecta.

Though relaxing the hypothesis of homogeneous chemical evolution seems a promising way to obtain for some stars theoretical Mn abundances lower than predicted for the gas, the model predictions can hardly be brought into agreement with the observations of the most metal-rich stars. We also want to emphasize the following. Inhomogeneous chemical evolution models for the Galactic halo always predict that the spread in the data is reduced in the course of the evolution of the system (see the references above), eventually leading to convergence with the predictions from homogeneous models. However, in ω Cen, we would see exactly the opposite, i.e. an increase in the dispersion with time, *unless the data for the most metal-rich stars are tracing a genuine decrease* of the $[\text{Mn}/\text{Fe}]$ ratio in the cluster. This is an intriguing aspect that should be further investigated in more populous samples of high-metallicity ω Cen stars.

5 CONCLUSIONS

In this paper, we present the theoretical $[\text{Mn}/\text{Fe}]$ versus $[\text{Fe}/\text{H}]$ relationships predicted with our self-consistent chemical evolution model for ω Cen by using different prescriptions on Mn and Fe synthesis in stars. In particular, as for Mn production from SNIa, we adopt either a metal-independent yield, by assuming the W7 model of Iwamoto et al. (1999) at all metallicities, or a metal-dependent one, by interpolating between models W70 and W7 of Iwamoto et al. (1999) or by adopting the empirical law of Cescutti et al. (2008). We also run models without Mn production from

SNIa. The theoretical relations are then compared to LTE and non-LTE data on Mn abundances in ω Cen giants.

The adopted chemical evolution model reproduces all the major chemical properties of ω Cen – its metallicity distribution function, age–metallicity relation, average trends of several α -element-to-iron abundance ratios as functions of $[\text{Fe}/\text{H}]$ (Romano et al. 2007). It also accounts for the presence of extreme He-rich stars (in the right percentage) and for the existence of a Na–O anticorrelation in the cluster (Romano et al. 2010a). However, the trend of decreasing $[\text{Mn}/\text{Fe}]$ with increasing $[\text{Fe}/\text{H}]$, displayed by both LTE and non-LTE data, is not reproduced by the model, which predicts instead a $[\text{Mn}/\text{Fe}]$ ratio either increasing or constant in time, depending on the choice of stellar yields. The adoption of a metallicity-dependent, rather than metal-independent, Mn yield from SNIa leads to an almost flat $[\text{Mn}/\text{Fe}]$ versus $[\text{Fe}/\text{H}]$ trend in ω Cen only if the empirical law of Cescutti et al. (2008) is adopted. By interpolating between models W70 and W7 of Iwamoto et al. (1999), i.e. between models computed for metal-free and solar-metallicity SNIa, respectively, we still produce a $[\text{Mn}/\text{Fe}]$ ratio increasing with $[\text{Fe}/\text{H}]$ in ω Cen. On the basis of the discussion in Section 4 and on previous results by Cescutti et al. (2008), we conclude that a flat trend has to be preferred over an increasing one.

In our chemical evolution model for ω Cen, the chemical properties of the cluster are mainly driven by the action of strong differential galactic winds, which deeply affect the evolution of its dSph precursor (see Romano et al. 2007, and references therein, for details on the adopted scenario). Allowing for cooling flows or field star capture would not help to explain the presence of low-Mn stars in the cluster. Relaxing the hypothesis of homogeneous chemical evolution, i.e. allowing the stars to form from a mixture of ISM and individual SN ejecta, could eventually lead (for some stars) to the prediction of Mn abundances lower than predicted for the gas. However, this would hardly accommodate the Mn abundances of the two most metal-rich stars in the Cunha et al. (2010) sample

in a scenario of flat – rather than decreasing – Mn evolution with time.

We suggest that more measurements of Mn in ω Cen stars at high metallicity are needed to finally set the issue of Mn evolution in ω Cen. Interestingly, [Mn/Fe] in Sgr stays almost flat (Sbordone et al. 2007; see Fig. 3), and Sgr is likely to be the local counterpart of the accretion episode which led to the formation of ω Cen some 10 Gyr ago (Bellazzini et al. 2008; Georgiev et al. 2009; Carretta et al. 2010). Hence, it would be not surprising if future measurements of Mn in a much bigger sample of ω Cen stars should reveal a constant run of Mn with [Fe/H], rather than the decreasing trend suggested by Cunha et al. (2010) on the basis of extant data. On the other hand, would future measurements confirm a fall of the [Mn/Fe] ratio towards higher metallicities, a revision of current scenarios of the formation of the cluster may be needed, since none of them is able to explain a decreasing trend of Mn in ω Cen. We have shown that, if Mn production from SNeIa is totally suppressed in ω Cen, a [Mn/Fe] ratio decreasing with time (metallicity) can be found in the cluster. While it is pointless to speculate on this theoretical result until more Mn data for ω Cen stars become available, we note that Johnson & Pilachowski (2010) observe consistently elevated $[\alpha/\text{Fe}]$ ratios for nearly all stars in the cluster (their sample totals 855 giants) and interpret this as evidence against a significant contribution to ω Cen’s chemical enrichment from SNeIa.

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