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# The chemical evolution of Manganese in different stellar systems

G. Cescutti[1] ⋆, F. Matteucci[1,2], G.Lanfranchi[3], and A.McWilliam[4]

Address(es) of author(s) should be given

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**ABSTRACT**

*Aims.* To model the chemical evolution of manganese relative to iron in three different stellar systems: the solar neighborhood, the Galactic bulge and the Sagittarius dwarf spheroidal galaxy, then we compare our results with the most recent and homogeneous observational data.

*Methods.* We adopt three chemical evolution models able to well reproduce the main properties of the solar vicinity, the galactic Bulge and the Sagittarius dwarf spheroidal; Then, we compare different stellar yields in order to check the best set to match the observational data in these systems.

*Results.* We compute the evolution of manganese in the three systems and we find that, in order to reproduce simultaneously the [Mn/Fe] versus [Fe/H] in the Galactic bulge, the solar neighbourhood and Sagittarius, the SNIa Mn yield should be metallicity dependent.

*Conclusions.* We conclude that the different histories of star formation in the three systems are not enough to reproduce the different behaviour of the [Mn/Fe] ratio, as it occurs for the [$\alpha$/Fe] ratios, but we need to invoke Type Ia SN Mn yields depending on metallicity, as originally suggested by McWilliam, Rich & Smecker-Hane.

**Key words.** nuclear reactions, nucleosynthesis, abundances – Galaxy: abundances – Galaxy: evolution

## 1. Introduction

Mc William et al. (2003) considered the abundance trend of Mn in three contrasting stellar populations: a sample of Galactic bulge K giants, stars in the solar neighbourhood and stars in the dwarf spheroidal galaxy Sagittarius (Sgr dSph). They found that the trend of [Mn/Fe] in the Galactic bulge follows more or less the relation of the solar vicinity, but most stars of Sgr dSph show [Mn/Fe] deficient by $\sim 0.2$ dex. They concluded that to explain this result one has to assume that the yields of Mn both from Type II and Type Ia SNe should depend on the initial stellar metallicity. This conclusion was at variance with a suggestion by Gratton (1989) that Mn is overproduced in Type Ia SNe relative to Type II SNe. Gratton (1989) observed that [Mn/Fe] vs. [Fe/H]

⋆ email to: cescutti@ts.astro.it

in solar vicinity stars show the opposite behaviour of the [$\alpha$/Fe] ratios: in fact, [Mn/Fe] ~-0.4 dex and constant for stars with [Fe/H]< $-1.0$ dex and increases up to the solar value for stars with [Fe/H]> -1.0 dex. As it is well known, first Tinsley (1979) and then Greggio & Renzini (1983) and Matteucci & Greggio (1986) explained the trend of the $\alpha$-elements relative to Fe as due to the different roles played by SNe II and Ia in galactic chemical enrichment. In particular, the higher than solar [$\alpha$/Fe] ratio in Halo stars is interpreted as due to the pollution of SNeII, which explode on very short timescales (of the order of Myr or tenths of Myr) and produce roughly constant [$\alpha$/Fe] ratios. Then the [$\alpha$/Fe] ratio decreases to the solar value in disk stars because of the bulk of Fe produced by Type Ia SNe exploding on timescales going from 30-40 Myr to 10 Gyr. This interpretation is known as "time-delay model" and represents the best interpretation of abundance ratios in galaxies so far. Type II SNe are originating from the core-collapse of massive stars ($M > 10M_{\odot}$), whereas Type Ia SNe are believed to originate from C-O white dwarfs in binary systems, exploding when their mass reaches the Chandrasekhar limit. Two main scenarios can lead to this situation: i) the single degenerate, where a white dwarf explodes after accreting material from a red giant or a main sequence companion; ii) the double degenerate, where two C-O white dwarfs merge and explode after losing angular momentum due to gravitational wave emission. There is not yet consensus on which scenario is better or if both are at work in galaxies. Anyway, in both scenarios Type Ia SNe start exploding after 30-40 Myr and continue to do so for a Hubble time. The maximum SNIa rate depends on the assumed progenitor model but also on the assumed star formation history, being short in systems with a strong burts of star formation (e.g. 0.5 Gyr in the galactic bulge), 1.0-1.5 Gyr in the solar vicinity and several Gyrs in slow star forming systems, such as irregular galaxies (Matteucci & Recchi, 2001). Therefore, the bulk of Fe is aways produced with a delay relative to the $\alpha$-elements produced by Type II SNe. Manganese is an iron-peak element produced both in Type II and Ia SNe: the yields of Mn in massive stars have been computed by Arnett (1971) and Woosley & Weaver (1995) among others, and depend on the neutron excess which means on the metallicity. On the other hand, usually the Type Ia SN yields are considered constant with metallicity: however, Ohkubo et al. (2006) showed that both the yields of Ni and Mn in Type Ia SNe increase with metallicity: the extent of such a growth depends on details of the adopted hydrodynamical models.

In this paper, we adopt three detailed chemical evolution models for the Galactic bulge, solar vicinity and Sgr dSph. In all the models we will adopt the same yields but different star formation histories tuned to reproduce the majority of the observational constraints on the three systems. We will show that to explain the [Mn/Fe] simultaneously in the three systems, the time-delay model alone is not enough, but we have to assume that the yields of Mn from Type Ia SNe are metallicity dependent. The paper is organized as follows: in section 2 we briefly describe the observational data, in section 3 we describe the chemical evolution models. In section 4 the nucleosynthesis prescriptions are given. In section 5 we discuss our results and in section 6 we draw our conclusions.

## 2. Observational data

The observational data used in this paper for the Bulge and for the Sgr dSph are the ones presented in McWilliam et al (2003). For Sgr dSph a part of the data come from the work of Bonifacio et al. (2000). Concerning the Bulge we added the mean values from three bulge globular clusters measured by Alves-Brito et al. (2005), Alves-Brito et al. (2006) and Ramirez & Cohen (2002). However, it should be noted that to compare the chemical abundances of globular clusters to the results of the chemical evolution model of the Bulge is not entirely safe; in fact, they might have had a different evolution when compared to the evolution of the Bulge or the Halo; moreover, there are still uncertainties in defining if these globular clusters are really belonging to the Bulge system.

The data for the solar neighborhood shown in this paper come from Reddy et al. (2003) and Reddy et al. (2006); they are not the only data available but we selected them in order to have a very homogeneous sample.

## 3. The chemical evolution models

For studying the chemical evolution of the solar neighbourhood we adopted the model of François et al. (2004) which is an implemented version of the original model by Chiappini et al. (1997). This model assumes that the Galaxy formed by means of two main accretion episodes, one giving rise to the halo and thick disk and the other forming the thin disk. The infalling gas is always assumed to be primordial. Detailed nucleosynthesis from low and intermediate mass stars, Type II SNe and Type Ia SNe is taken into account. The IMF is taken from Scalo (1986). For details of this model see François et al. (2004).

For modelling the Bulge we adopted the model of Ballero et al. (2007), where it is assumed that the Bulge formed very rapidly on a timescale of 0.3-0.5 Gyr out of the gas accumulating during the Halo collapse. The efficiency of star formation (star formation per unit mass of gas) is 20 times higher (i.e. $20 Gyr^{-1}$) than in the solar vicinity ($1 Gyr^{-1}$). The IMF is flatter than in the solar vicinity , as required by the observed Bulge stellar metallicity distribution. See Ballero et al. (2007) for details of this model.

To study Sgr dSph we have adopted the model developed for this galaxy by Lanfranchi et al. (2004; 2006). This model assumes that Sgr dSph formed stars for several Gyrs, as suggested by its color-magnitude diagram, and that a strong galactic wind triggered by supernovae was responsible for the gas loss. The star formation efficiency is similar to the one in the solar vicinity but the occurrence of the wind subtracting gas to the galaxy acts like if the star formation efficiency were much lower. Here also the IMF is flatter than in the solar vicinity.

According to the time delay model, the predicted [$\alpha$/Fe] ratios behave differently in the three systems because of the different star formation histories (see Matteucci 2003), in the sense that we expect a long plateau with oversolar [$\alpha$/Fe] ratios in the Bulge because of its fast star formation. In fact, in this case a lot of Fe is produced by Type II SNe before the bulk of it is restored by

SNe Ia. The opposite occurs for slow star formation systems, such as dwarf spheroidals. In this case the oversolar [$\alpha$/Fe] plateau is much shorter than in the solar vicinity since when the Type Ia SNe restore the bulk of Fe, the Fe in the interstellar medium is still quite low. This produces a situation where we expect low [$\alpha$/Fe] ratios at low metallicities as opposed to the high [$\alpha$/Fe] ratios at high metallicities expected for the Bulge. The observed behaviour of the [$\alpha$/Fe] ratio in these three systems is in very good agreement with these predictions.

In the next sections we will test if this same scenario works for the [Mn/Fe] ratio, namely if it is enough to change the star formation history in the three systems to reproduce the observed data, which was the original suggestion by Gratton (1989).

## 4. Nucleosynthesis Prescriptions

As already mentioned, Fe and Mn are produced by SNII and SNIa. For the SNII, we start adopting the yields suggested by François et al. (2004). They compared theoretical predictions about the [el/Fe] vs. [Fe/H] trends in the solar neighborhood for the above mentioned elements and they selected the best sets of yields required to best fit the data. For the yields of SNe II they found that the Woosley & Weaver (1995) ones provide the best fit. In fact, no modifications are required for the yields of Fe as computed for the solar chemical composition.

Then, we chose to use for the SNII contribution the Woosley & Weaver (1995) (herafter WW95) yields but as a function of the metallicity, both for Mn and Fe. We adopt the theoretical yields by Iwamoto et al. (1999) for the yields from Type SNeIa and they are not metallicity dependent. Then, we change the SNIa yields of Mn by Iwamoto et al., by introducing a metallicity dependence:

$$Y_{Mn}(z) = Y_{Mn}^{Iwamoto} \left( \frac{z}{z_{\odot}} \right)^{0.65} \tag{1}$$

where $Z$ is the global metal content of the Type Ia SN systems at birth. This dependence is obtained just by requiring the models to fit the data, but very recently we found in Badenes, Bravo & Hughes (2008) found that the Mn/Cr ratio in the ejecta of Type Ia SNe depends on Z, and they modeled a dependence very similar to that in eq. (1),thus supporting our choice. Moreover, nucleosynthesis calculations by Ohkubo et al. (2006) suggested a dependence on metallicity of the yields of Ni and Mn in Type Ia SNe.

## 5. Results with François et al. yields

In Fig. 1 we show the results obtained with the yields of François et al. (2004), and as expected, the data relative to the stars of the solar vicinity are well reproduced. Here and in the following figures, the results of all the models are normalized to the predicted solar abundances, namely the abundances predicted for the interstellar medium in the solar vicinity 4.5 Gyr ago. However, it should be noted that our predicted solar values for most of the considered abundances and, in

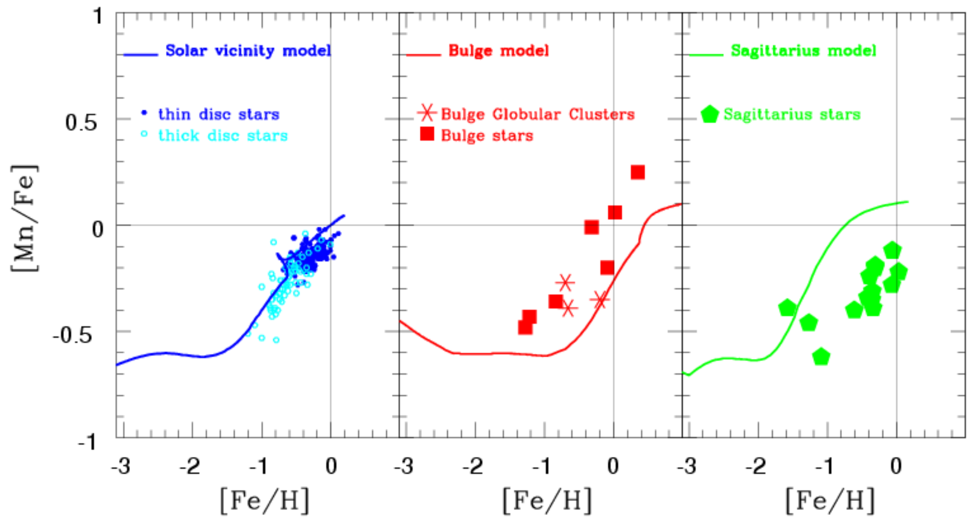


**Fig. 1.** The results with François et al (2004) set of yields. In Fig. the [Mn/Fe] vs [Fe/H] ratios in three different stellar systems; from left to right: Solar neighborhood, Bulge and Sagittarius Dwarf Spheroidal. For the data see Sect. 2

particular for those studied in this paper, differ from the Asplund et al (2005) solar values at most by ~ 0.05 dex.

On the other hand, the results for the Bulge are not satisfactory. In fact, there is an offset between the data and the results of the Bulge model, which predicts lower values of the [Mn/Fe] ratio for all the metallicities.

Moreover, with this set of yields the results of Sgr dSph model are also not matching the data. The theoretical curve passes through the observed [Mn/Fe] values only at [Fe/H]$\sim -1.5$ dex, but for higher metallicities the predicted trend is too high compared to the data.

### *5.1. Results with Woosley& Weaver yields*

To improve the match between our models and the data, in particular for the Bulge and Sgr dSph, we then use the yields by WW95 dependent to the metallicity and the results are shown in Fig.2.

The results of the solar neighbourhood model still follow nicely the observational data, although they predict a too low [Mn/Fe] ratios in very metal poor halo stars ([Fe/H]< -1.0 dex). In fact, as shown in François et al. (2004) the data of Cayrel et al. (2004) extending down to [Fe/H]=-4.0 dex show a constant plateau of [Mn/Fe], as it can be extrapolated from our Fig.1. In our best model case (Fig. 3) the [Mn/Fe] seems to be lower at [Fe/H]=-4.0 dex. However, we are not worried here of this effect, since it could be solved just by increasing the Mn yields at very low metallicities and it does not affect the Bulge and Sgr dSph since there are no data for these systems at such low metallicities. Moreover, more recent data from Lai et al. (2008) seem to indicate lower [Mn/Fe] ratios for very metal poor halo stars than in Cayrel et al. (2004). The model results for the Bulge are also more promising; in fact, up to solar [Fe/H] the predictions

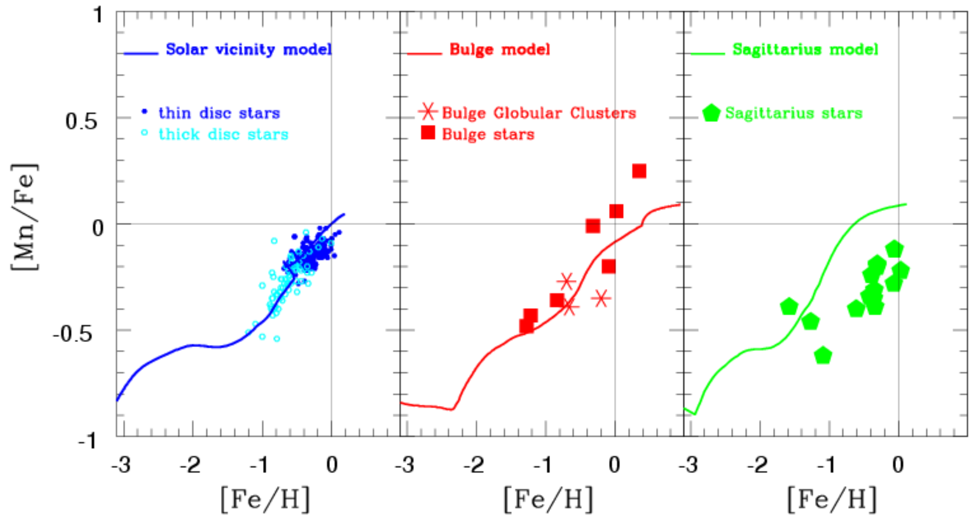


**Fig. 2.** The results Woosley&Weaver (1995) set of metallicity dependent yields. In Fig. the [Mn/Fe] vs [Fe/H] ratios in three different stellar systems; from left to right: Solar neighborhood, Bulge and Sagittarius Dwarf Spheroidal galaxy. For the data see Sect. 2

well trace the observational data. However, for supersolar metallicities the results of the model tend to slightly underestimate the value on [Mn/Fe] in the Bulge stars.

The results for Sgr dSph are still in poor agreement with the data. The model shows a strong increase of the [Mn/Fe] ratio at [Fe/H]$\sim -1.5$ dex, at variance with the data. This enhancement is due to the low metallicity SNeIa, which produce the same amount of Mn as the high metallicity ones.

### *5.2. Results with Woosley & Weaver yields and metallicity dependent Mn yields from SNeIa*

In this last set both the SNII and SNIa yields of Mn are dependent on the metallicity. In particular, the Mn yields from SNe Ia follow eq. (1). This set of yields does not change the agreement between model and solar vicinity observational data. At the same time, the supersolar data in the Bulge are nicely fitted. So, the use of this new set of yields had improved the predictions of the Bulge model. Finally, the most interesting results is the excellent agreement of the Sgr dSph model with the data. This is due to the lower contributions to the Mn enrichment of the SNIa of low metallicity. So a very important conclusion is that the yield of Mn produced by SNIa is should be metallicity dependent in order to fit the data in Sgr dSph. Moreover, we get excellent agreement also for the Bulge and solar vicinity stars. It is worth noting that it was not possible to obtain this result without the simultaneous comparison of the three independent stellar systems. This hypothesis, that the SNIa Mn yield had to be dependent to the metallicity, was for the first time introduced by McWilliam et al. (2003).

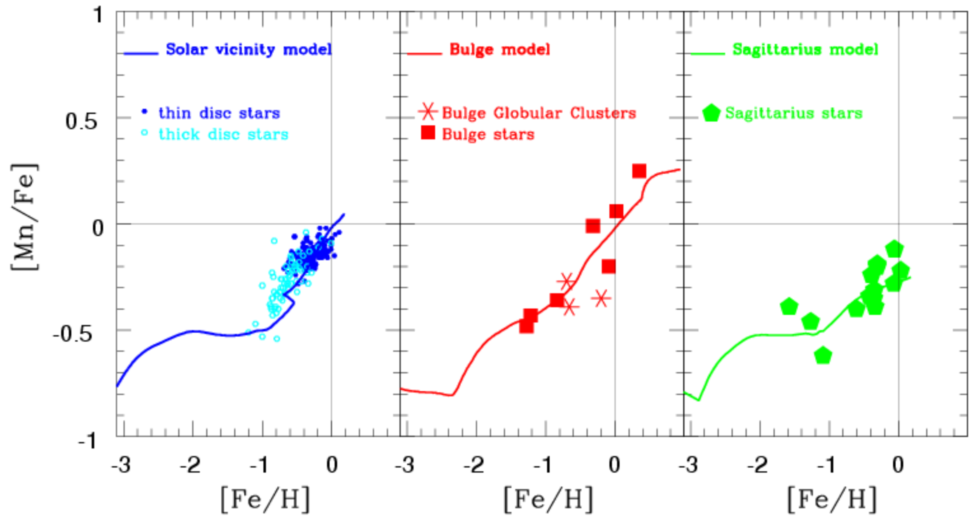


**Fig. 3.** The results with a metallicity dependence in the SNIa yield for Mn. In Fig. the [Mn/Fe] vs [Fe/H] ratios in three different stellar systems; from left to right: Solar neighborhood, Bulge and Sagittarius Dwarf Spheroidal. For the data see Sect. 2

## 6. Conclusions

For the first time, we have proven, by means of galactic chemical evolution models, that the SNIa Mn yields must be metallicity dependent. We have shown that by fitting simultaneously the [Mn/Fe] trend in three independent stellar systems: the Galactic bulge, the solar vicinity and the Sgr dSph. To do that we have adopted detailed chemical evolution models well reproducing the main features of the three stellar systems and adopting the same yields but different star formation histories. We have shown clearly that the "time-delay model" alone cannot explain the different behaviour of the [Mn/Fe] in Bulge, solar vicinity and Sgr dSph, as it does for [$\alpha$/Fe] ratios. In fact, in the case of the [$\alpha$/Fe] ratios, the same models can well reproduce the observed [$\alpha$/Fe] vs. [Fe/H] trends in the three stellar systems without invoking metallicity dependent yields. This is because the production of $\alpha$ and Fe elements is mildly dependent on the initial stellar metallicity. We have suggested a possible metallicity dependence of the Mn yields in Type Ia SNe ($\propto Z^{0.65}$) which should be tested by nucleosynthesis calculations. Our result is supported by the results of Ohkubo et al. (2006) suggesting that the yields of Mn from Tye Ia SNe has a strong dependence on metallicity and by a recent finding by Badenes et al. (2008), who showed that the Mn to Cr ratio in the ejecta of Type Ia SNe should depend on the metallicity Z of the progenitor star in a very similar way to what we have suggested. Finally, we have shown that metal poor Type Ia SNe producing less Mn than high metallicity ones, are necessary to reproduce the data and this imposes constraints on possible metallicity effects in Type Ia SNe, such as the suggestion of Kobayashi et al. (1998) about having no TypeI SNe for metallicities [Fe/H]$< -1.0$ dex.

## 7. Acknowledgments

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