

# Light and heavy elements in the galactic bulge

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Received 10 September 1998 / Accepted 20 October 1998

**Abstract.** In the context of an inside-out model for the formation of our Galaxy we present results for the chemical evolution of the Galactic bulge by assuming that this central region evolved even faster than the Galactic halo. This assumption is required in order to reproduce the observed metallicity distribution of bulge stars as obtained by McWilliam & Rich (1994).

The model is similar to that adopted by Matteucci and Brocato (1990) with the exception that we have adopted the most recent nucleosynthesis prescriptions for either low-intermediate mass stars or massive stars and extended our predictions to most of the  $\alpha$ -elements, Fe, C, N and light elements (D,  $^7\text{Li}$ ). We have tested the effect of changing the slope of the IMF on the predicted stellar metallicity distribution for bulge stars and have compared our results with the distribution obtained from the most recent data. An initial mass function (IMF) favoring the formation of massive stars with respect to the solar vicinity improves the agreement with observations. Then, using our best model, we have made some predictions about temporal evolution of light and heavy species in the Galactic bulge. In particular, we predict that  $\alpha$ -elements should be enhanced relative to Fe for most of the metallicity range, although different  $\alpha$ -elements should show a different degree of enhancement due to the particular nucleosynthetic history of each element. The enhancements are larger than predicted for the halo and thick-disk stars because of the flatter IMF assumed for the bulge. We predict that deuterium, due to the intense star formation occurred in bulge, should be completely depleted whereas  $^7\text{Li}$  should show a trend similar to that found for the solar neighbourhood. We also compared the Li abundance recently measured in one bulge star (Minniti et al., 1998) and concluded that it is very likely that the Li in the star must have been depleted and therefore it does not reflect the Li abundance of the gas out of which the star formed. In the opposite case, one should completely suppress one of the main stellar sources of Li in order to reconcile the model with the observed value.

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

## 1. Introduction

In recent years, several studies dealing with a detailed spectroscopic analysis of K giants in Baade’s window have appeared in literature (Rich, 1983, 1986, 1988; McWilliam & Rich, 1994) and have presented a stellar metallicity distribution of bulge K giants with a shape different from that of the G-dwarf distribution for the solar neighbourhood. In particular, McWilliam & Rich (1994) found that the metallicity peak of the distribution of bulge stars appears at a metallicity higher than for the solar neighbourhood, at around  $[\text{Fe}/\text{H}] \sim +0.0$  dex. New data on the G-dwarf distribution for the solar vicinity (Rocha-Pinto & Maciel, 1996) show, in fact, a well-defined peak in metallicity between  $[\text{Fe}/\text{H}] = -0.3$  and  $+0.0$ .

The stellar metallicity distribution is an important constraint for chemical evolution models, because it is representative of the chemical enrichment of the specific Galactic component it is referring to. In fact, the stars used to give such a distribution have lifetimes greater than or equal to the age of the Galaxy, hence providing a complete picture of the chemical enrichment history for the considered Galactic component. This is because different stellar distributions versus metallicity are likely to be due to different time scales of collapse and different star formation histories.

Matteucci & Brocato (1990) predicted that the ratio of some  $\alpha$ -elements (Si, Mg and O) to Fe in the bulge stars should be larger than solar over most of the metallicity range and similar to what is observed in halo stars. This was due to the assumption of a fast evolution for the bulge leading the gas to be fastly enriched in Fe by essentially supernovae of type II. Later McWilliam & Rich (1994) showed that indeed Mg and Ti are enhanced by  $\sim 0.3$  dex relative to Fe over the whole  $[\text{Fe}/\text{H}]$  range, in very good agreement with Matteucci & Brocato (1990). However, they also found that elements such as Ca and Si closely follow the trend of disk stars, namely they reach solar ratios at  $[\text{Fe}/\text{H}] > -0.2$  dex, at variance with the predictions. More recently, Sadler et al. (1996) found Mg enhancements ( $\sim 0.2$  dex) only for bulge stars with  $[\text{Fe}/\text{H}] < 0.0$ , whereas for stars with larger metallicities they found  $[\text{Mg}/\text{Fe}] = 0.0$ . These discrepancies suggest that more detailed abundances are necessary to assess this point and draw firm conclusions on the bulge formation mechanism. In particular, we would like to assess if the bulge formed very fast

reaching a high metallicity in a short timescale (Rich, 1988; Renzini, 1993, 1994) or if instead it formed by merging of bulgeless spirals on a Hubble time (Schweizer & Seitzer, 1988). In favor of the first hypothesis there are the old ages of stars in the bulge as derived by Terndrup (1988) as well as the old ages of bulge globular clusters (Ortolani et al., 1995), all suggesting that the bulge formed contemporarily or perhaps even before the halo (but see Holtzman et al., 1993). Abundance ratios represent an independent constraint for the mechanism of bulge formation since they can be very different according to rapid or slow star formation. The aim of this paper is to study the behaviour of a large number of abundances and abundance ratios in the bulge under the assumption of a fast bulge formation process.

In particular, we have used a model for the chemical evolution of the bulge which allows us to follow the temporal evolution of twenty chemical and isotopic species (H,  $^2\text{H}$ ,  $^3\text{He}$ ,  $^4\text{He}$ ,  $^7\text{Li}$ ,  $^{12}\text{C}$ ,  $^{13}\text{C}$ ,  $^{14}\text{N}$ ,  $^{16}\text{O}$ , neutron rich species,  $^{20}\text{Ne}$ ,  $^{24}\text{Mg}$ ,  $^{28}\text{Si}$ ,  $^{32}\text{S}$ ,  $^{40}\text{Ca}$ ,  $^{56}\text{Fe}$ , Ni, Cu, Zn, Kr). The model is an extension to the bulge of the model of Chiappini et al. (1997). In this model the halo-thick disk and the thin disk form out of two distinct infall episodes. In particular, the halo forms during the first infall episode on a time scale of roughly 1 Gyr whereas the thin disk forms out of extragalactic gas on long timescales increasing with galactocentric distance (inside-out formation). Here we assume that the bulge formed out of the same gas forming the halo (Wyse and Gilmore, 1992) but it evolved faster than the halo itself being the more condensed central part of the Galactic spheroid. The bulge is represented by a region with a 2 Kpc radius and a total mass of about  $10^{10} M_{\odot}$ . Possible exchange of matter between the bulge and the Galactic disk is not taken into account.

We have also followed in detail the evolution of the  $^7\text{Li}$  abundance in the bulge by assuming several  $^7\text{Li}$  stellar sources in agreement with the results of Matteucci et al. (1995). These predictions are also important since very recently the advent of microlensing has given us the opportunity of observing the faintest objects in our Galaxy and in particular in the bulge. Minniti et al. (1998) have measured the lithium abundance in the atmosphere of a bulge star located near the main sequence turn-off called 97 BLG 45 and claimed that the derived Li abundance reflects the primordial one. This fact, if true, is extremely interesting since all the halo stars show the same Li abundance (Li-plateau, see Bonifacio & Molaro, 1997) which is generally interpreted as being the primordial one.

In paragraph 2 we present the chemical evolution model, in paragraph 3 we show the main results we have obtained (compared, if possible, with the observations) and finally, in paragraph 4, we draw some conclusions.

## 2. The chemical evolution model

The basic assumptions of the bulge model are:

- 1) Instantaneous mixing of gas.
- 2) No instantaneous recycling approximation.

- 3) A star formation rate (SFR) expressed as:

$$\psi(r, t) = \nu \left( \frac{\sigma(r, t)}{\bar{\sigma}(\tilde{r}, t)} \right)^{2(k-1)} \cdot \left( \frac{\sigma(r, t_{gal})}{\sigma(r, t)} \right)^{k-1} G^k(r, t);$$

where  $\bar{\sigma}(\tilde{r}, t)$  is the total surface mass density at a radius  $\tilde{r} = 10 \text{ Kpc}$ ,  $k = 1.5$  is suggested as the best value for the solar neighbourhood by Chiappini et al. (1997),  $\nu = 20 \text{ Gyr}^{-1}$  is the star formation efficiency in the bulge. This value is similar to what is usually assumed for an elliptical galaxy of the same mass (Matteucci and Tornambé, 1987) since bulges of spirals are very similar to ellipticals for what concerns their stellar content and fall in the same region of the fundamental plane (Jablonka et al., 1996).

For the solar vicinity  $\nu$  is set equal to  $2 \text{ Gyr}^{-1}$  in the halo and thick disk components and  $1 \text{ Gyr}^{-1}$  in the thin disk component. This choice is made for the models to be in agreement with the observational constraints and follows the prescriptions of the Chiappini et al. (1997) model.

$G(r, t) = \sigma_g(r, t)/\sigma(r, t_{gal})$  is the normalized surface gas density,  $t_{gal} = 15 \text{ Gyr}$  is the Galactic lifetime and  $\sigma$  is the total surface mass density.

- 4) An IMF expressed as a power law, with index  $x_{IMF}$ :

$$\varphi(m) \propto m^{-(1+x_{IMF})}.$$

We have explored four cases: (a)  $x_{IMF} = 1.35$  (Salpeter, 1955), (b)  $x_{IMF} = 1.1$  (Matteucci & Brocato, 1990), (c)  $x_{IMF} = 0.95$  (Matteucci & Tornambé, 1987) for the whole mass range ( $0.1 - 100 M_{\odot}$ ) and (d)  $x_{IMF} = 1.35$  for  $0.1 - 2 M_{\odot}$  and  $x_{IMF} = 1.7$  for  $M > 2 M_{\odot}$  (Scalo, 1986).

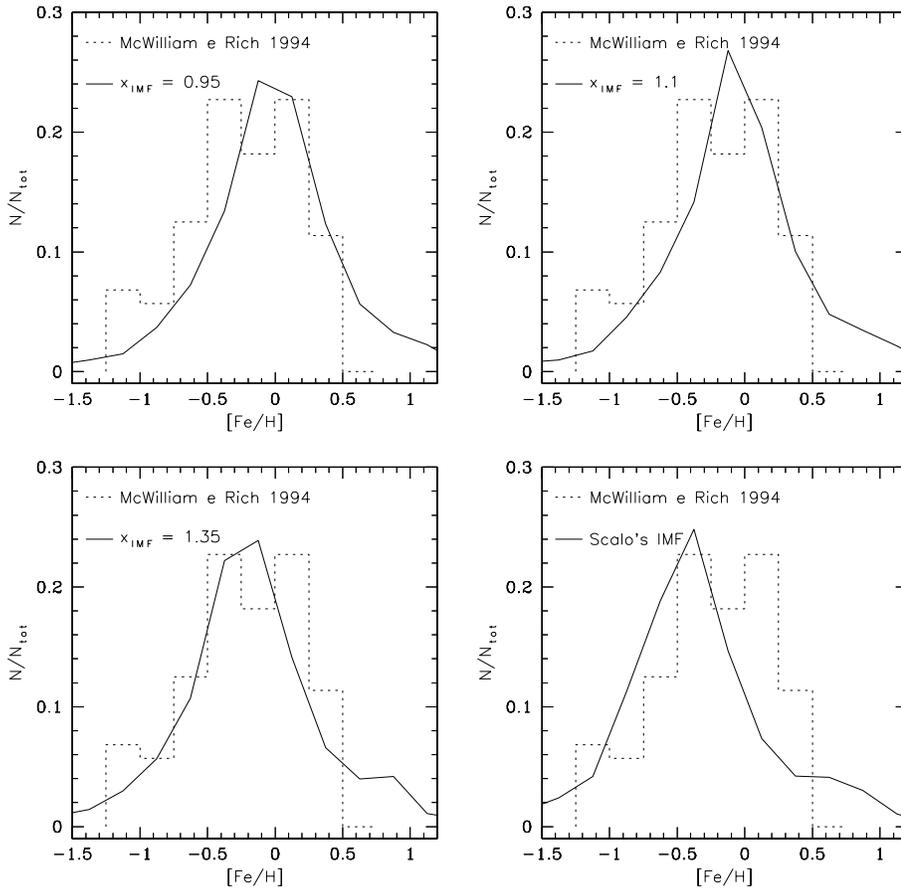
- 5) A gas collapse rate expressed as:

$$\frac{dG(r, t)_{infall}}{dt} = \frac{A(r)}{\sigma(r, t_{gal})} e^{-t/\tau},$$

where  $\tau = 0.1 \text{ Gyr}$  for the bulge,  $\tau = 8 \text{ Gyr}$  for the solar vicinity and  $\tau = 1 \text{ Gyr}$  for the halo.  $A(r)$  is derived from the condition of reproducing the current total surface mass density distribution in the bulge.

- 6) We adopted detailed nucleosynthesis prescriptions for the  $\alpha$ -elements and Fe from type I SNe and type II SNe as in Chiappini et al. (1997). The nucleosynthesis of He, C and N from low and intermediate mass stars ( $0.8 - 8 M_{\odot}$ ) is taken from van den Hoek and Groenewegen (1997) (their standard model). We remind that  $^{13}\text{C}$  and  $^{14}\text{N}$  are partly *secondary* and partly *primary* in low and intermediate mass stars whereas they are only secondary in massive stars. The D is assumed to be completely destroyed and the prescriptions for the production of  $^3\text{He}$  are the same as in Chiappini et al. (1997). The nucleosynthesis prescriptions for Lithium are described in detail in paragraph 3.3.2. Finally, the nucleosynthesis of Cu, Zn, Ni and Kr is the same as in Matteucci et al. (1993).

- 7) The possibility of Galactic winds is not taken into account since they seem not to be appropriate for our Galaxy (Tosi et al., 1998).



**Fig. 1.** Predicted stellar metallicity distributions normalized to the total number of stars  $N_{tot}$  (continuous lines) compared to the recent data sample of McWilliam & Rich (1994) (dashed lines).

**Table 1.** Model inputs.

Model	C-stars	M-AGB	SNeII	$x_{IMF}$
1	$\log N_{Li} = 3.85$	$\log N_{Li} = 4.15$	WW95	1.35
2	$\log N_{Li} = 3.85$	$\log N_{Li} = 4.15$	no	1.35
3	$\log N_{Li} = 3.85$	$\log N_{Li} = 3.5$	no	1.35
4	$\log N_{Li} = 3.85$	$\log N_{Li} = 3.5$	no	1.1

### 3. Model results

#### 3.1. Stellar metallicity distribution

We have studied four cases:  $x_{IMF} = 1.35$ ,  $x_{IMF} = 1.1$ ,  $x_{IMF} = 0.95$  for the whole mass range as well as an IMF like that suggested by Scalo (1986). As shown in Fig. 1, a decrease in the power law index of the IMF moves the peak of the predicted stellar distribution towards higher metallicity values. The observed distribution (McWilliam & Rich, 1994) is shown for comparison. The metallicity distribution of bulge K giants is well reproduced by an IMF with a power index in the range 1.1 – 1.35. This claim is in agreement with Matteucci & Brocato (1990), who suggested a value of  $x_{IMF}$  in the range 1.1 – 1.26 (that is a lower power index than the Salpeter one).

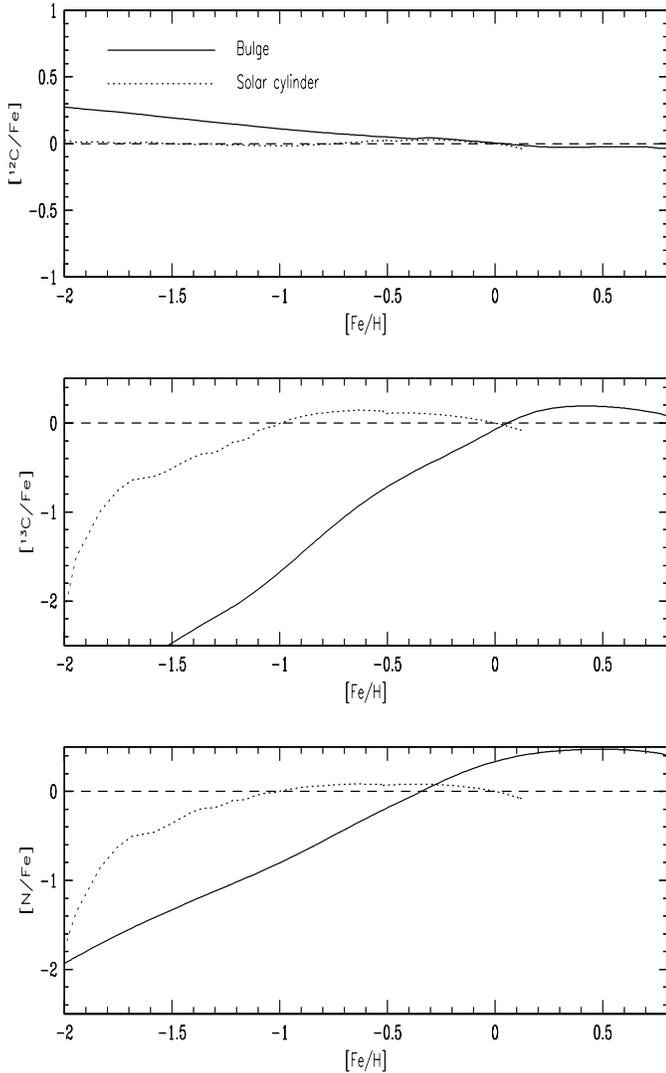
At this point it is worth emphasizing that while Matteucci & Brocato used as a constraint the observed metallicity distribution of bulge K giants of Rich (1988), here we adopt the more

recent one of McWilliam & Rich (1994), which differs from the previous one in the position of the metallicity peak which moves from +0.35 dex to +0.0 dex.

Concerning the solar neighbourhood, in their paper Chiappini et al. (1997) have stressed that the metallicity distribution of G dwarfs can be well reproduced by a long ( $\sim 8$  Gyr) time scale of formation and a moderate SFR. Moreover they have adopted a Scalo IMF; this produces results consistent with both G dwarf distribution and abundance ratios constraints.

#### 3.2. The $[el/Fe]$ versus $[Fe/H]$ relations

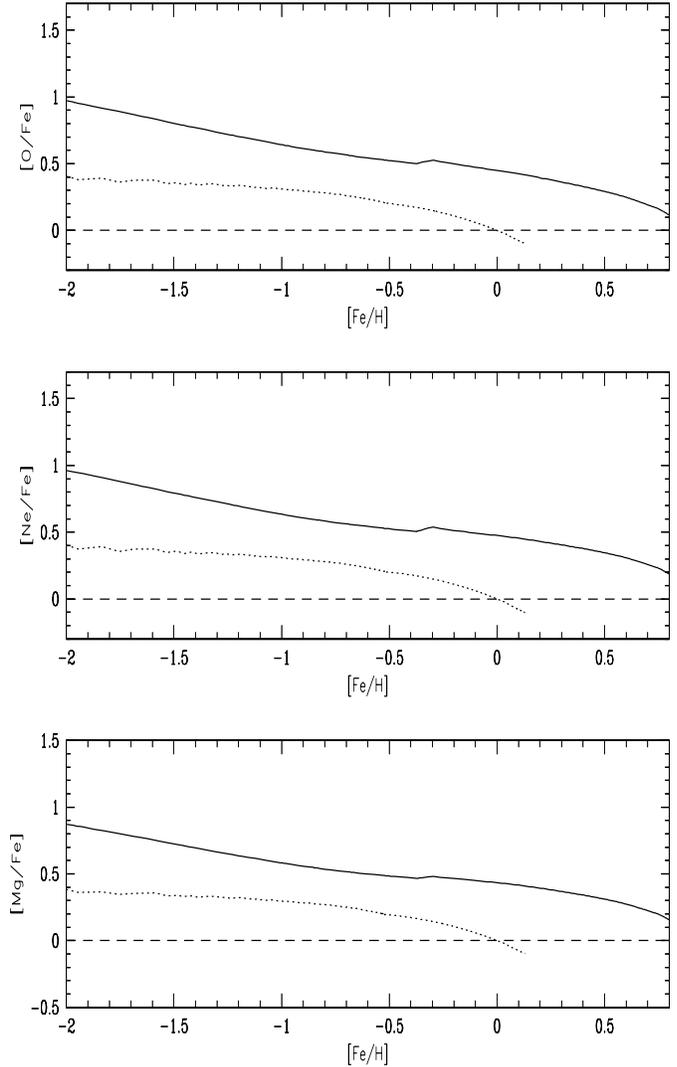
Here we have computed the temporal evolution of the abundances of twenty elements (H,  $^2\text{H}$ ,  $^3\text{He}$ ,  $^4\text{He}$ ,  $^7\text{Li}$ ,  $^{12}\text{C}$ ,  $^{13}\text{C}$ ,  $^{14}\text{N}$ ,  $^{16}\text{O}$ , neutron rich,  $^{20}\text{Ne}$ ,  $^{24}\text{Mg}$ ,  $^{28}\text{Si}$ ,  $^{32}\text{S}$ ,  $^{40}\text{Ca}$ ,  $^{56}\text{Fe}$ , Ni, Cu, Zn, Kr) but we will not discuss them all in detail. Predictions on abundance ratios which should be expected in bulge stars are shown in Figs. 2–5 (where a comparison is made with the same theoretical ratios in halo and disk stars belonging to the solar vicinity). All ratios are normalized to the solar ones given by our model. Note that the Mg yields from massive stars adopted here (Woosley & Weaver, 1995) are probably too low: in fact, the theoretical curve  $[\text{Mg}/\text{Fe}]$  does not fit the observational points in the solar neighbourhood if this ratio is normalized using the solar abundances measured by Anders & Grevesse and not those



**Fig. 2.** The predicted  $[el/Fe]$  vs  $[Fe/H]$  relations for  $^{12}\text{C}$ ,  $^{13}\text{C}$  and  $^{14}\text{N}$  in the Galactic bulge (continuous lines) and in the solar neighbourhood (dashed lines). The predictions for the solar neighbourhood are obtained by means of the model of Chiappini et al. (1997). The assumed solar abundances are those of the model. The differences can be explained as a consequence of the different age-metallicity relations characterizing the bulge and the solar vicinity region, due to faster evolution of the central region. Moreover, a non negligible effect on the abundance ratios is given by the presence of a larger number of massive stars in the bulge (here  $x_{IMF}$  is set equal to 1.1 for the bulge whereas for the solar neighbourhood we adopt a Scalo IMF).

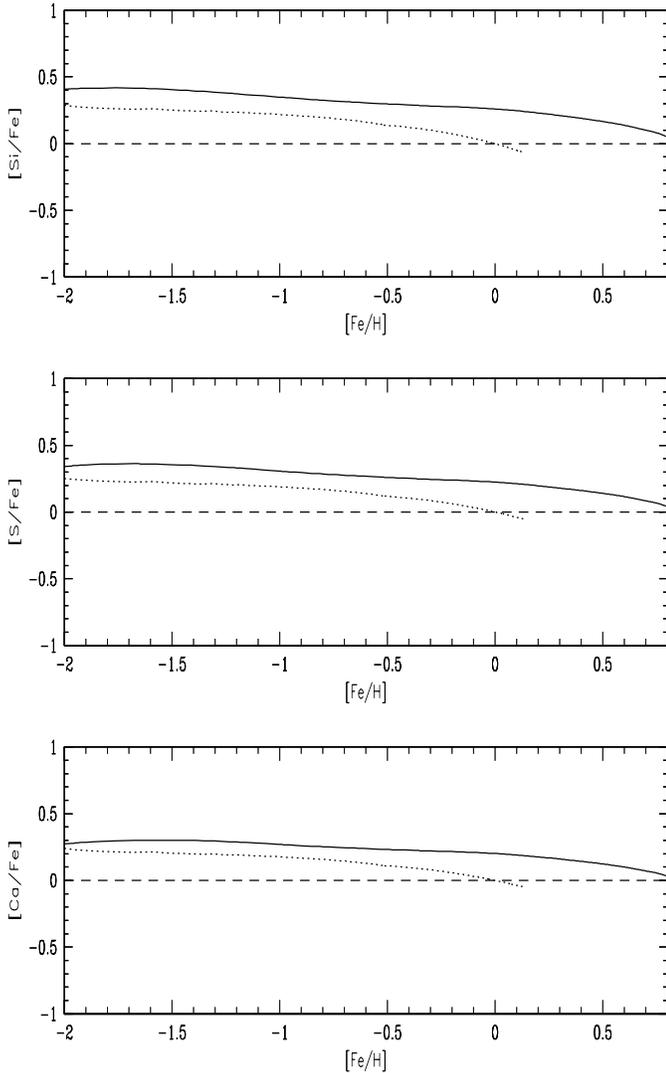
predicted by the model itself (see also Chiappini et al., 1997 and references therein).

At present, observational constraints for the bulge stars are available only for few elements in the range  $-1 \leq [Fe/H] \leq +0.45$  dex (McWilliam & Rich, 1994). In particular, the observed  $[Mg/Fe]$  is overabundant by  $+0.3 \pm 0.17$  dex relative to solar over almost the full  $[Fe/H]$  range; in contrast, Ca and Si closely follow the normal trends for disk giants. However, in order to draw firm conclusions, more accurate data are needed.



**Fig. 3.** The predicted  $[el/Fe]$  vs  $[Fe/H]$  relations for  $^{16}\text{O}$ ,  $^{20}\text{Ne}$  and  $^{24}\text{Mg}$  in the Galactic bulge (continuous lines) and in the solar neighbourhood (dashed lines).

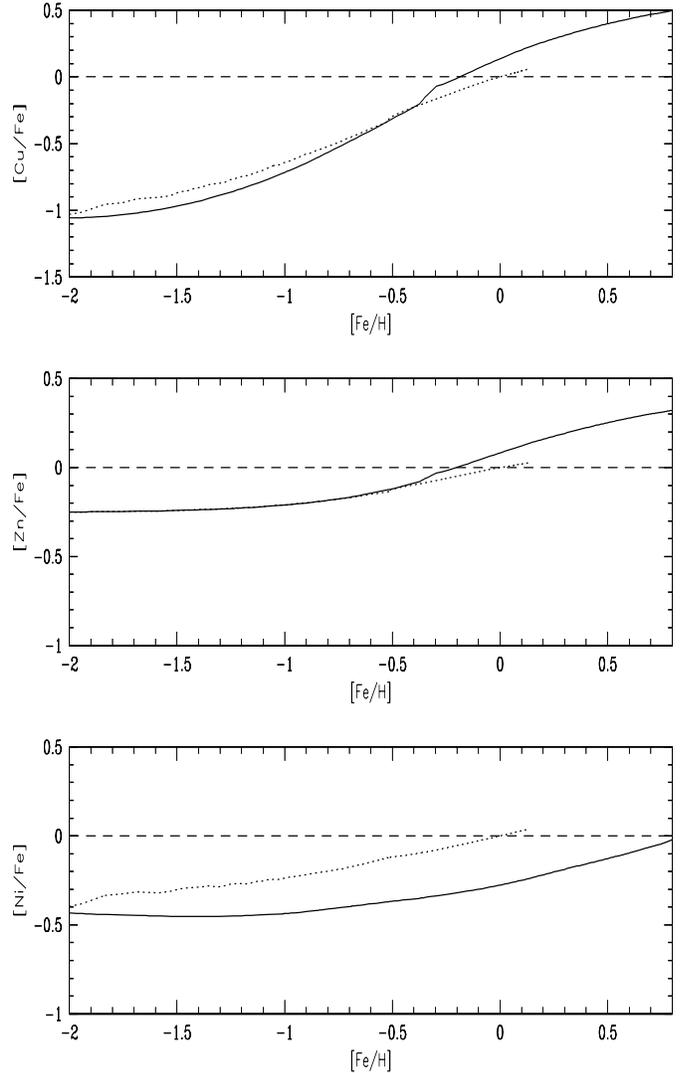
Note that good models for the bulge in Matteucci & Brocato (1990) give  $[\alpha/Fe]$  ratios of the order of  $+0.5 - +0.4$  dex ( $\alpha$  indicates O, Mg, Si); here we distinguish  $\alpha$ -elements in two groups showing different trends: (a) O, Ne, Mg and (b) Si, S, Ca. The elements in group (a) show a larger overabundance relative to Fe relative to those of group (b) and their ratios relative to iron continuously decrease over the  $[Fe/H]$  range whereas the ratios relative to iron of the elements of group (b) show more constant values. These differences could be explained in terms of different time scales of element production: O, Ne, Mg are produced mostly in massive stars on timescales of the order of several million years whereas Si, S, Ca are produced by both massive stars and binary systems ending their life as SNeIa on timescales varying from 30 million years to several billion years thus behaving more similarly to Fe which originates primarily in SNIa events but is also produced by type II SNe. Therefore, O, Ne, Mg are overabundant with respect to Fe until SNeIa



**Fig. 4.** The predicted  $[el/Fe]$  vs  $[Fe/H]$  relations for  $^{28}\text{Si}$ ,  $^{32}\text{S}$  and  $^{40}\text{Ca}$  in the Galactic bulge (continuous lines) and in the solar neighbourhood (dashed lines).

begin to restore the bulk of iron whereas the ratios of Si, S, Ca relative to Fe have a more flat trend over all the metallicity range because in explosive nucleosynthesis from type Ia SNe there is a non-negligible production of Si, S, Ca (Nomoto et al., 1984).

Matteucci & Brocato (1990) have already stressed that different evolutionary histories lead to different age-metallicity relations. We confirm their prediction: the point at which the slope of  $[O, \text{Ne}, \text{Mg}/\text{Fe}]$  vs  $[Fe/H]$  starts changing drastically is attained, in the solar vicinity, at  $[Fe/H] \sim -1.0$ , corresponding at  $t \sim 1$  Gyr. In the bulge, due to faster evolution and larger number of massive stars belonging to a single stellar generation, the same point is achieved when  $[Fe/H] \sim +0.1$ , which corresponds roughly to  $\sim 0.4$  Gyr. In fact, the central region is likely to have undergone a formation process so fast that type Ia SNe did not have time to restore the bulk of iron until a metallicity of  $\sim +0.1$  was reached. In addition, the larger number of massive



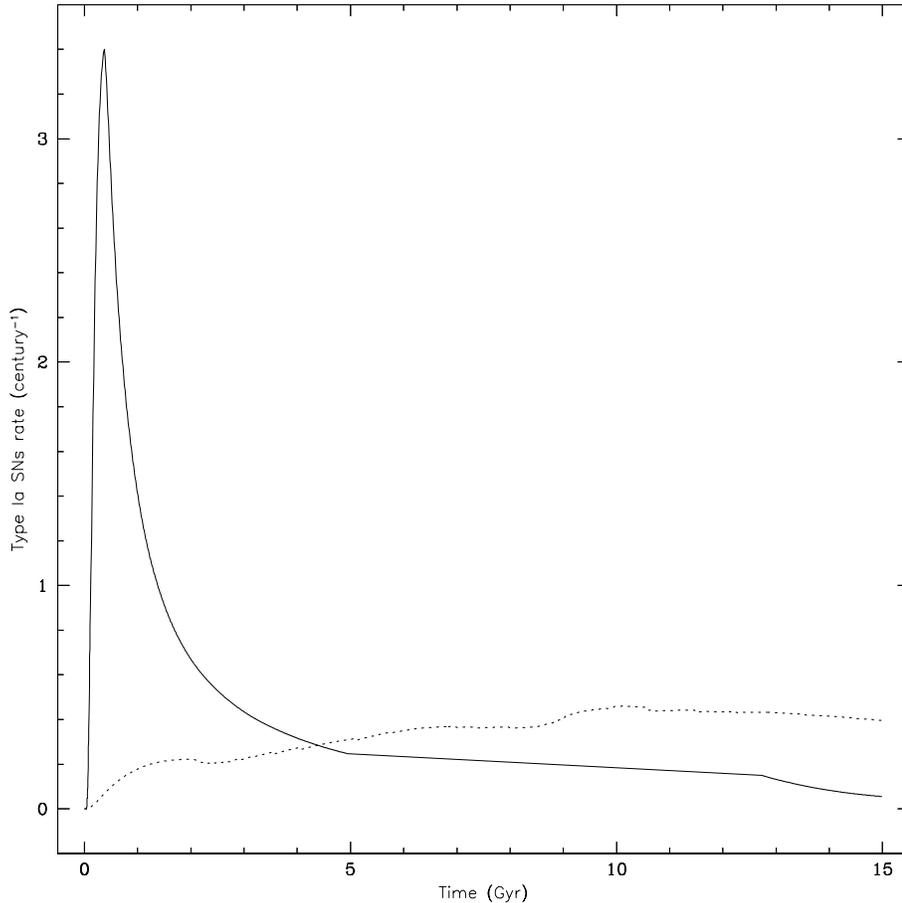
**Fig. 5.** The predicted  $[el/Fe]$  vs  $[Fe/H]$  relations for Cu, Zn, Ni in the Galactic bulge (continuous lines) and in the solar neighbourhood (dashed lines).

stars in the bulge relative to the solar neighbourhood leads to larger  $[\alpha/Fe]$  ratios, as it is evident from Fig. 3.

In Fig. 6 we show the rate at which type Ia SNe explode in the Galactic bulge compared with that in the solar neighbourhood as predicted by our models. We can immediately see that in the bulge a peak appears at 400 million years, while in the solar vicinity the type Ia SNe rate becomes different from zero after  $\sim 1$  Gyr and then increases only slightly until the present time.

So the time at which type Ia SNe restore the bulk of iron is greatly dependent on SFR and IMF parameterization: to assume this time scale to be equal to 1 Gyr is a proper choice only if we are referring to the solar neighbourhood evolution. Otherwise, a different value has to be used, according to the assumed SFR and IMF prescriptions (Matteucci, 1996).

The abundance ratios versus  $[Fe/H]$  for the other heavy isotopic species treated here are also shown in Figs. 2–5. The differences produced with respect to the trends predicted for the



**Fig. 6.** The predicted type Ia SN rates ( $\text{century}^{-1}$ ) in the Galactic bulge (continuous line) and in the solar vicinity (dashed line). It is worth emphasizing that the peak occurring in the bulge at  $t \sim 0.4$  Gyr is mostly due to the shorter time scale of collapse and more efficient SFR.

solar cylinder could likely be explained just in terms of different evolutionary histories and greater IMF richness in massive stars in the bulge. We do not discuss the trends for Cu, Zn and Ni because they have been studied already in Matteucci et al. (1993). We only remind here that all these elements are assumed to be mostly produced by SNeIa, although Cu and Zn are partly produced as s-process elements.

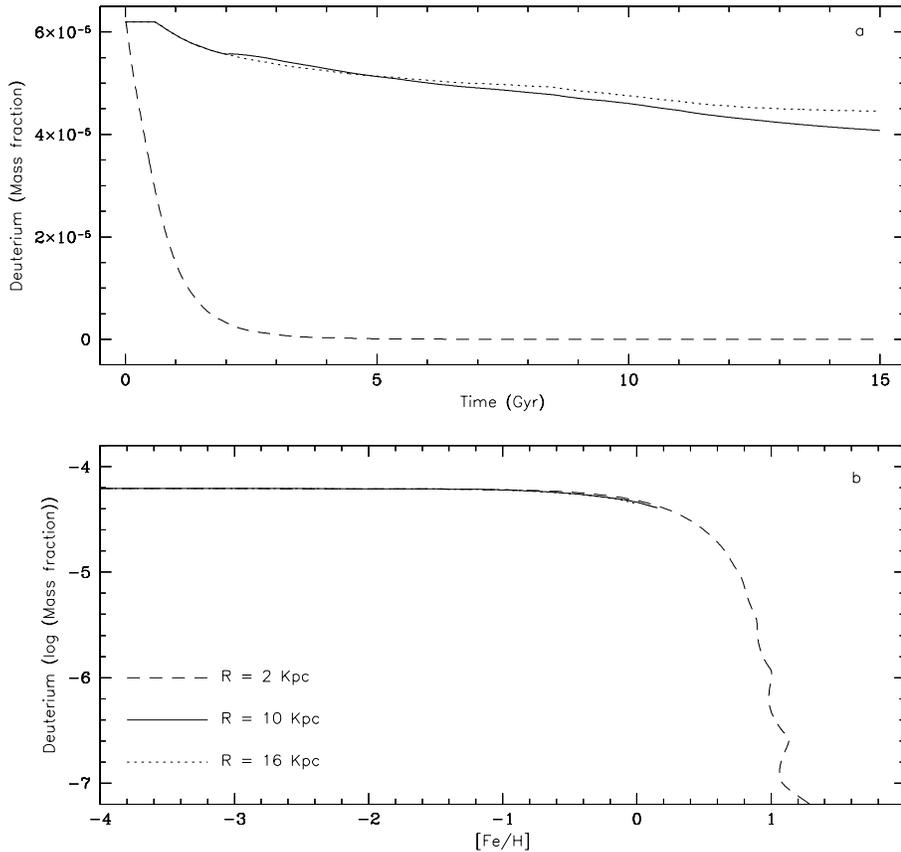
### 3.3. Light elements in the bulge

#### 3.3.1. Deuterium

In the scenario of a shorter accretion process and stronger star formation rate assumed here for the Galactic bulge it is interesting to have a look at the temporal trend exhibited by the deuterium abundance and compare it with the same quantity as predicted for the solar neighbourhood under appropriate assumptions on SFR and IMF.

Deuterium is only destroyed in stellar interiors and its abundance in the central regions of the Galaxy is expected to fall quicker due to the faster stellar consumption with respect to the solar neighbourhood. In Fig. 7a the deuterium evolution at three different galactocentric distances is shown; the deuterium abundance at the distance representative of the bulge falls by almost three orders of magnitude in a time scale as short as  $\sim 4$  Gyr. Here we adopt a primordial deuterium abundance by mass

of  $6 \times 10^{-5}$  corresponding to the deuterium value of Burles and Tytler (1997) although the primordial deuterium abundance, as deduced from chemically unevolved high redshift clouds, is rather controversial, differing by one order of magnitude according to different sources. The revised abundance of Burles and Tytler (1997) is  $(D/H) = 3.3 \times 10^{-5}$  but in the system studied by Webb et al. (1997) it is of  $2 \times 10^{-4}$ . Recently, Tosi et al. (1998) showed that realistic models of Galactic chemical evolution favor the value of Burles and Tytler (1997). The deuterium astration versus metallicity is shown in Fig. 7b. It is remarkable that there is no significant difference among the curves at 2, 10 and 16 Kpc implying a very similar behaviour for the deuterium evolution between the bulge and the solar cylinder. What differs is the time scale of the whole process which is very short in the bulge as compared to that of the Galactic disk for producing the same amount of astration. The present time deuterium abundance in the bulge should be about three orders of magnitudes smaller than that in the disk. However, this prediction would hardly be verified since direct deuterium observations in the bulge cannot avoid the local disk contamination along the line of sight. The interesting aspect of the analysis presented here for the bulge is that it shows that the large difference in the deuterium abundances measured in high redshift clouds can hardly be ascribed to different phases of bulge-like evolution for these clouds. In fact, the deuterium astration is firmly bounded by the increase in the metallicity. The high redshift clouds used for the



**Fig. 7a and b.** The shorter evolution of the bulge ( $R = 2$  Kpc) with respect to that of the solar neighbourhood ( $R = 10$  Kpc) results in an accelerated consumption of deuterium, whose abundance quickly falls to zero. Moreover, the model predicts minor deuterium depletion in the outer regions of our galaxy ( $R = 16$  Kpc is the case sketched here), due to longer time scale of collapse and consequently low efficiency of star formation.

deuterium determination have always a rather low metallicity around  $[Fe/H] < -2$  and therefore, according to the deuterium chemical evolution discussed here, they should have suffered a similar amount of astration.

### 3.3.2. Lithium

We have calculated in detail the temporal evolution of lithium ( ${}^7\text{Li}$ ) in the bulge. Minniti et al. (1998) have recently measured for the first time the  ${}^7\text{Li}$  abundance in the atmosphere of a bulge star, which is the source star of the MACHO microlensing event 97 BLG 45. The star is a dwarf and Minniti et al. have obtained  $\log N_{Li}^1 = 2.25 \pm 0.25$ . The authors suggested that this value is consistent with the most recent determination of the primordial lithium abundance from the halo dwarf population (Bonifacio & Molaro, 1997). However we argue below that this is probably a coincidence and that the Li abundance in this star could not be indicative of the Li primordial value.

We want first to remind to the reader the essential of the lithium evolution in the solar neighbourhood as discussed in Matteucci et al. (1995). These authors presented Galactic chemical evolution models which took into account recent developments about  ${}^7\text{Li}$  stellar production and concluded that the rise off from the plateau in the diagram  $\log N_{Li} - [Fe/H]$  is best re-

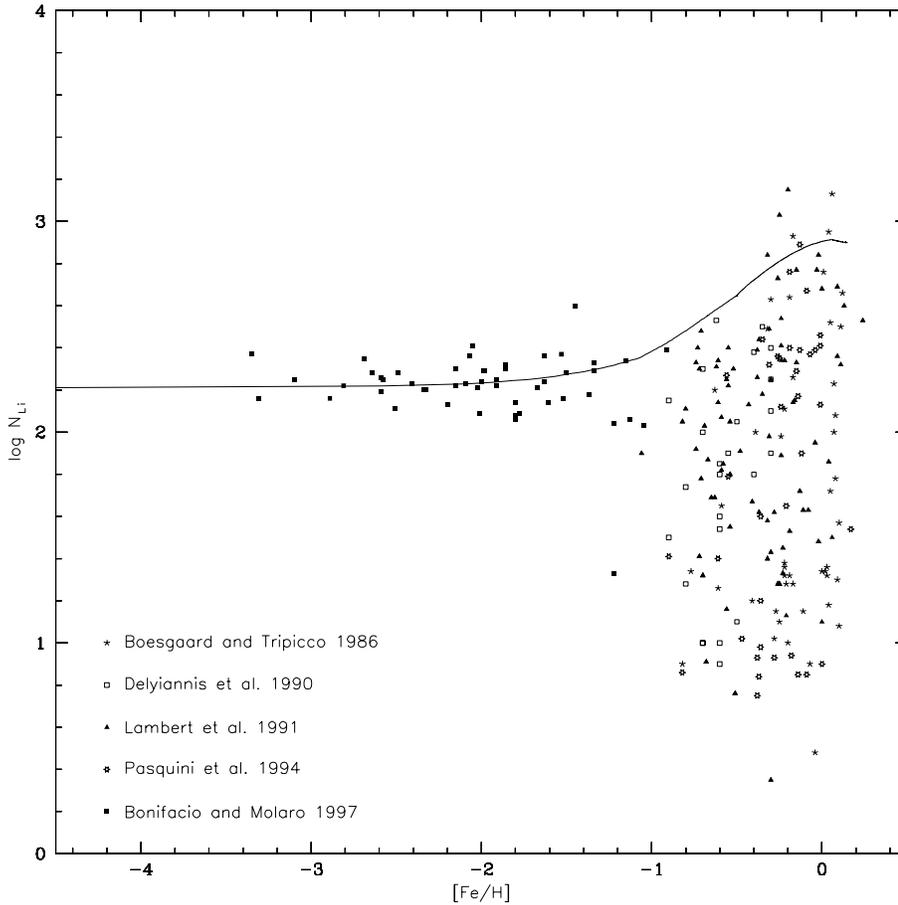
produced with a mix of  ${}^7\text{Li}$  production by  $\nu$ -supernovae, carbon stars and massive asymptotic giant branch (AGB) stars.

We have computed here four models (see Table 1) for the lithium abundance evolution of the bulge, changing the prescriptions about  ${}^7\text{Li}$  stellar production. In all the models here we assume an AGB production of lithium dependent on the initial metallicity of the progenitor. This effect is parameterized through the value of  $M_{up}$  - the maximum mass of a star which develops a degenerate CO core after the exhaustion of He in its center - following Matteucci et al. (1995), who in turn based their choice on the calculations of Tornambé & Chieffi (1986). The overall effect of such a parameterization is that low metallicity AGB stars do not contribute any lithium.

We want to recall that lithium enrichment by AGB stars occurs both through stellar winds and planetary nebula ejection (see Matteucci et al., 1995, and references therein). The  ${}^7\text{Li}$  production in type II SNe occurs by means of the  ${}^4\text{He}(\nu, \nu n){}^3\text{He}(\alpha, \gamma){}^7\text{Be}(e^-, \nu_e){}^7\text{Li}$  reaction, as discussed in Woosley et al. (1990). Note that the yields we have adopted here for these objects (Woosley & Weaver, 1995) are metallicity dependent.

The models inputs are listed in Table 1 and the data sets relative to the solar neighbourhood are from Boesgaard & Tripicco (1986), Lambert et al. (1991), Pasquini et al. (1994) and from the compilation of Delyiannis et al. (1990) for stars with  $[Fe/H] > -1.5$  and  $T_{eff} > 5500$  K and from Bonifacio & Molaro (1997) for the halo stars. The primordial Li value is assumed 2.2 close to the recent determination of Bonifacio & Molaro (1997).

<sup>1</sup>  $\log N_{Li} = \log_{10}(X_{Li}/7 X_H) + 12$ , where  $X_{el}$  is the mass fraction in form of the generic element  $el$ .



**Fig. 8.**  $\log N_{Li} - [Fe/H]$  diagram showing the observations of several authors relative to the solar neighbourhood. The curve shows the best fitting chemical evolution model (prescriptions on stellar lithium production like in model 1).

In Fig. 8 we show the predicted  $\log N(^7Li)$  versus  $[Fe/H]$  when the Matteucci et al. (1995) Li best model prescriptions are included in the Chiappini et al. model for the solar vicinity. The figure shows that the agreement with the observations is quite good since we want to reproduce the upper envelope of the data distribution. The main difference between the chemical evolution model adopted by Matteucci et al. (1995) and Chiappini et al. (1997) adopted here is in the fact that the latter considers the evolution of halo-thick disk separated from that of the thin disk, but this clearly does not affect the predicted behaviour of Li versus Fe.

In Fig. 9 are highlighted the contributions of the different galactic sources to Li enrichment. Fig. 9a shows the Li astration in absence of Li production, while Fig. 9b and Fig. 9c show the contribution for the AGB stars and  $\nu$ -supernovae. The difference between the two AGB curves reflects the faster iron enrichment in the bulge in relation to the time scale of the AGB Li production. If AGB stars would be the only Li sources then the Li evolutionary curves for the bulge and for the disk would be different with the plateau extending towards higher metallicities in the bulge. In Fig. 9d all the sources are considered giving a prediction for the present Li abundance in the bulge of  $\approx 3.5$ , which is considerably higher than that of the disk.

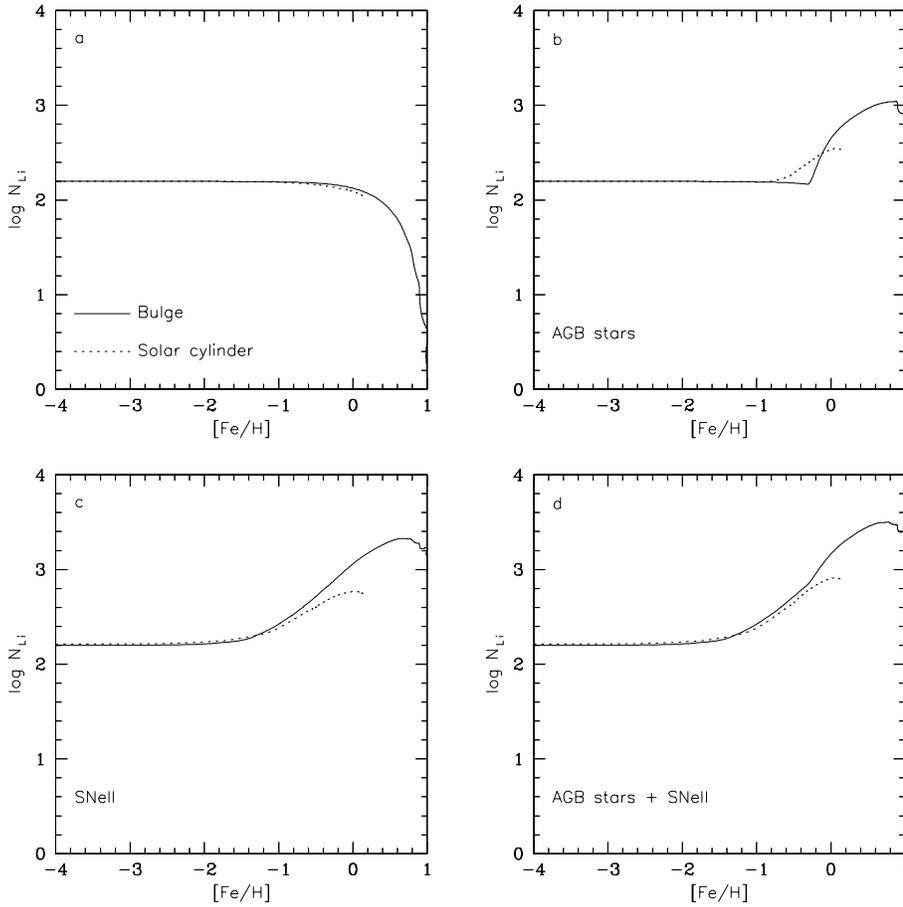
Minniti et al. did not provide the iron abundance for their star. However by using their equivalent width of FeI 6705.1 line we estimated a metallicity of around  $[Fe/H] \approx +0.4$  dex. This

abundance is obtained with a model of  $T_{eff} = 6000$  K, i.e. the temperature adopted by Minniti et al.,  $\log g = 4$ , microturbulence of  $1.7 \text{ km s}^{-1}$  and solar opacity distribution functions (ODF). With this entry the Li evolutionary curve which well reproduces the observed trend in the solar neighbourhood fails to reproduce the Minniti star in the bulge (curve 1 in Fig. 10).

By changing the  $^7Li$  production in stars is possible to extend the plateau further towards higher metallicities, but hardly long enough to approach the experimental point of Minniti et al.

For instance, a possible solution may be to reduce the  $^7Li$  contribution by AGB stars; alternatively one can suppress a particular category of  $^7Li$  factories. Curves 2 and 3 result from the hypothesis that  $\nu$ -supernovae do not contribute any lithium to the interstellar medium pollution; model 3 adopts also a lower  $^7Li$  abundance in the atmosphere of the Li-rich AGB stars. A further improvement can be achieved by lowering the IMF slope. Curve 4 shows the results of model 4 with a slope for the IMF of 1.1.

Therefore to consider the lithium abundance measured in the atmosphere of 97 BLG 45 as representative of the primordial value requires a substantial revision of the Li evolutionary behaviour which, on the other hand, is found to match satisfactorily the Li observed trend in the solar vicinity. Otherwise - and this is our claim - the  $^7Li$  abundance of 97 BLG 45 has suffered some  $^7Li$  depletion by one of those Li depletion mechanisms which are known to act during the pre or main sequence in stars



**Fig. 9a–d.**  $\log N_{Li} - [Fe/H]$  theoretical relations in the Galactic bulge (continuous lines) and in the solar neighbourhood (dotted lines) as predicted by our models in four cases: **a** only astration is acting in stellar interiors; **b**, **c** and **d** stellar production by different categories of objects is considered (prescriptions on stellar Li synthesis like in model 1, Table 1).

of relatively high metallicities. Several different mechanisms have been proposed such as diffusion (Michaud, 1986), turbulent mixing (Charbonnel & Vauclair, 1992), mixing driven by rotation (Pinsonneault et al., 1998), pre-main sequence depletion (Ventura et al., 1998). Metal rich stars have deeper convection zones compared to the metal weak ones making relatively easier the mixing of the atmosphere with the more internal and hot layers where Li is burned ( $T > 2 \times 10^6$  K). Considering the field stars with solar or moderate metal deficiency shown in Fig. 8 one sees that a considerable fraction of these stars shows a Li abundance close to the primordial value. For some of these stars with available Be abundance observations it is possible to have indirect evidence that Li has been depleted (Molaro et al., 1997) implying that their original Li content was much higher than the primordial value. Since in the bulge the metal rich stars are older than the solar neighbourhood ones with similar metallicity, the probability of Li depletion should be higher in the bulge stars than in the disk stars.

The predicted Li evolution curve with respect to the metallicity for the bulge is mimicking that for the solar neighbourhood (Fig. 9d). However it will be very difficult to test this observationally. In fact, observations in the bulge will select preferentially metal rich stars and it will be particularly difficult to pick-up a metal poor star belonging to the bulge as it is for instance for the galactic thick disk. Only observations of metal poor dwarfs in the bulge will be informative of the initial Li

content before the significant and quick Li production in the bulge.

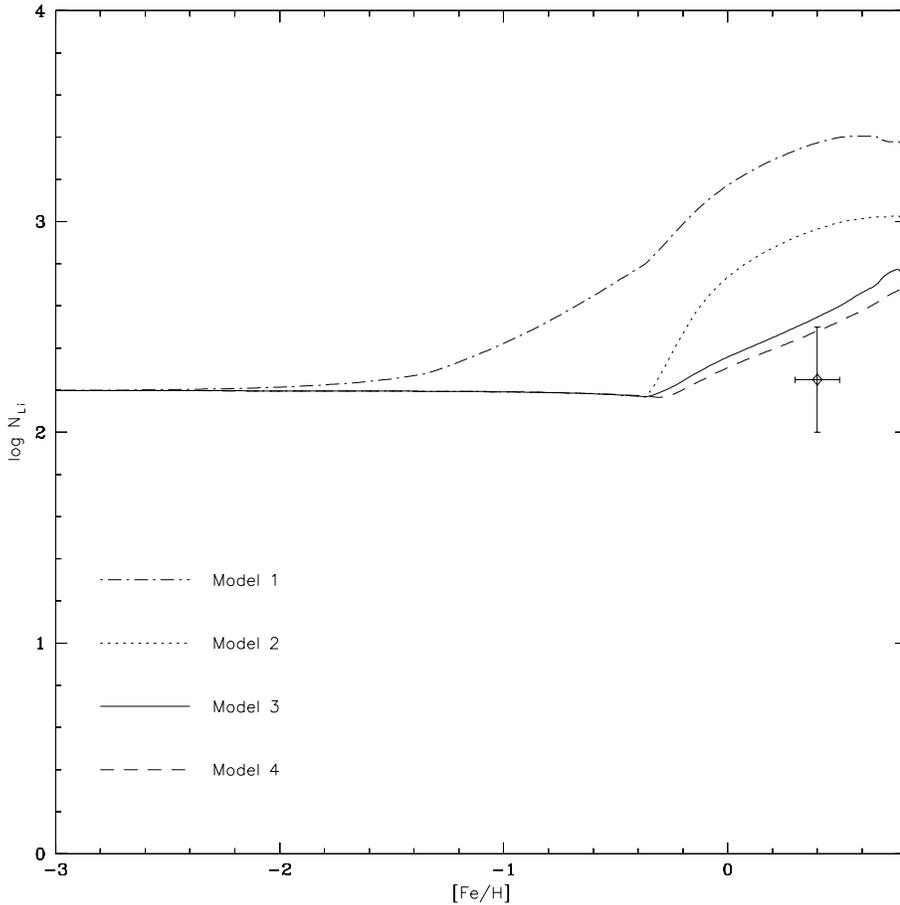
#### 4. Conclusions

In this paper we have computed chemical evolution models for the Galactic bulge. We have shown that a scenario characterized by an evolutionary process much faster than that in the solar neighbourhood and even faster than that in the halo (see also Renzini, 1993) allows us to reproduce very well the observed metallicity distribution of bulge K giants.

We have stressed that to fit the most recent observed distribution (McWilliam & Rich, 1994) one needs to choose an IMF with a power index in the range 1.1 – 1.35, that is to say that in the bulge the formation of massive stars relatively to the solar vicinity region should be favored.

Notwithstanding the uncertainties still present in the remaining model parameterization (SFR efficiency, time scale of collapse, nucleosynthesis prescriptions) we think that our previous considerations should be considered as a probe of the necessity of a variation in the IMF slope between the bulge and the solar neighbourhood.

This requirement stands out also in the work of Matteucci & Brocato (1990). They used values of  $\nu$  and  $\tau$  slightly different from those adopted here ( $\nu = 10 \text{ Gyr}^{-1}$ ,  $\tau = 0.01 \text{ Gyr}$ ) but reached the same conclusions: the position of the metallicity



**Fig. 10.**  $\log N_{Li}$  vs  $[Fe/H]$  relation as predicted by our models for the Galactic bulge. The diamond is the bulge star 97 BLG 45.

peak can be reproduced only by allowing that more massive stars have been formed in the bulge than in the solar vicinity. Our results also show that there is no need for a pre-enriched gas from the halo to form the bulge.

We have then explored the effect of the faster bulge formation and flatter IMF on the temporal evolution of several chemical and isotopic species. We have made theoretical predictions which need to be confirmed or disproved by future observations. In particular, we predicted that the  $\alpha$ -elements should show an overabundance relative to iron for most of the  $[Fe/H]$  range, at variance with what happens in the solar neighbourhood. This overabundance is not constant for all the  $\alpha$ -elements but it depends, for a specific element, on the relative production of this element by supernovae of different types. In particular,  $[Si/Fe]$ ,  $[S/Fe]$  and  $[Ca/Fe]$  should be less overabundant and more constant than  $[O/Fe]$ ,  $[Mg/Fe]$  and  $[Ne/Fe]$ . The  $[^{12}C/Fe]$  ratio is predicted to be solar for the whole range of metallicity as in the solar vicinity, whereas  $[^{13}C/Fe]$  and  $[N/Fe]$  are predicted to be higher than in the solar neighbourhood at low metallicities as due to the faster star formation rate adopted for the bulge. On the other hand, due to the larger number of massive stars relative to the low and intermediate mass stars assumed for the bulge, these two ratios are lower at solar metallicities.

We also predicted that deuterium should be completely exhausted in the bulge, due to the intense star formation, and the  $^7Li$  abundance versus  $[Fe/H]$  trend should be similar to what

is found in the solar vicinity (Fig. 9d). In order to reproduce the low Li abundance recently claimed by Minniti et al. (1998) for a main sequence bulge star, under the assumption that it reflects the original Li abundance in the gas, one has to suppress one or more sources of stellar lithium. On the other hand, it is likely that a star of such a high metallicity ( $[Fe/H] \sim +0.4$  dex) would have depleted most of its Li content already during the pre-main sequence phase (Ventura et al., 1998) although more measurements of Li abundance in bulge stars are necessary before drawing firm conclusions.

*Acknowledgements.* We would like to thank C. Chiappini for useful suggestions and P. Ventura for calculating a stellar evolution model.

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