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METALLICITY DISTRIBUTION AND ABUNDANCE RATIOS IN THE STARS OF THE GALACTIC BULGE

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ABSTRACT

Chemical evolution models for the Galactic bulge are computed assuming that evolution in the bulge was much faster than in the solar neighborhood.

Detailed nucleosynthesis from Type II and I supernovae (SNs) is taken into account in order to compute the temporal evolution of the abundances of several elements (Fe, Si, Mg, and O).

The influence of the various model parameters such as the time scale of bulge formation, the star-formation rate (SFR), and the initial mass function (IMF) on the metallicity ([Fe/H]) distribution, as well as on the abundance ratios of bulge stars is discussed. It is shown that, by assuming a more efficient star-formation rate and a much shorter time scale of collapse than in the solar neighborhood, it is possible to reproduce the metallicity distribution of bulge stars. Variations of the IMF, in the sense of having more massive stars formed in the bulge than in the region of the solar vicinity improve the agreement with observations for what concerns the position of the metallicity peak. However, given the uncertainties still present both in theory and observation relative to the IMF, no firm conclusions are allowed on this point.

Finally, we demonstrate that, due only to the faster evolution of the bulge with respect to the solar neighborhood and irrespective of the chosen IMF, the [O, Mg, Si, Fe] versus [Fe/H] relations in the bulge must be different from those found for stars in the solar vicinity, in the sense that the α-elements should be over abundant ($\simeq +0.5$ dex) with respect to iron in stars with an average metallicity twice the solar value. This result applies also to elliptical galaxies and its importance resides in the fact that the pattern of abundance ratios observed in halo and disk stars in the solar vicinity is not universal.

Subject headings: galaxies: The Galaxy — nucleosynthesis — stars: abundances — stars: evolution — stars: supernovae

I. INTRODUCTION

In recent years, the first detailed spectroscopic study of K giants in Baade's window has been carried out by Whitford and Rich (1983) and Rich (1986, 1988). Rich has found [Fe/H] values between -1 and $+1$, with a mean at around [Fe/H] $= +0.3$ (i.e., twice the solar value), and a shape different from that of the G-dwarf distribution in the solar neighborhood, in the sense that in the bulge there is not a "G-dwarf problem" (the deficiency of metal-poor stars with respect to the predictions of the simple closed-box model). Rich (1986, 1990) and Pagel (1987) have shown that this distribution can be well fitted by a simple closed-box model with an "effective" yield higher than in the solar neighborhood. A similar conclusion has been reached also by Köppen and Arimoto (1990). The effective yield is the only parameter of the simple model, but unfortunately it does not tell us anything about the different physical processes which may have caused the different evolution of the bulge with respect to the solar neighborhood.

For this reason, the physical causes of these differences are explored here in more detail, by means of a chemical evolution model of the Galaxy (Matteucci and François 1989; Matteucci 1990) which takes into account the SFR, the time scale of formation of the system, the IMF, the stellar lifetimes and detailed nucleosynthesis. On one hand, this implies a more complex dependence of the results on the input parameters with a consequent increase of degrees of freedom of the problem. On the other hand, a detailed choice of model parameters allows a deeper investigation of the physical requirements necessary to fit the observational constraints. In particular, we investigate the effect of different input parameters (SFR, IMF, collapse time) using a sensitivity analysis, namely we map the theoretical results by changing one single parameter at the time, leaving all the others unchanged.

Once a suitable choice of parameters is found, the evolution of the abundances of several single elements (O, Mg, Si, and Fe) is predicted. This is especially important for iron which is the measure of stellar metallicity. Simple models usually predict the global metal content, which is a measure of oxygen, and therefore cannot be directly compared with the observed iron. In fact, iron and oxygen evolve in a quite different way, as shown by abundance measurements in solar neighborhood stars. The model we adopt assumes that the bulge formed faster than the solar vicinity region so that the gas was quickly turned into stars and star formation stopped several billion years ago. This is in agreement with the fact that most if not all bulge stars have an age close to those of the halo.

The predicted metallicity distributions of stars in the bulge and in the solar vicinity are compared with observational data and discussed.

Predictions on abundance ratios that should be expected in bulge stars are given and compared with the same ratios in halo stars.

In § II the model will be presented, in § III the main results will be shown and compared with observations. Finally, in § IV some conclusions will be drawn.

II. THE CHEMICAL EVOLUTION MODEL

The model is essentially that of Matteucci and François (1989, hereafter MF) extended to the bulge.

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The adopted current present surface mass density distribution gives a value of $\simeq 45\ M_\odot\ \text{pc}^{-2}$ for the solar neighborhood, in agreement with Kujiken and Gilmore (1989). The bulge is assumed to extend up to 2 kpc from the Galactic center. The total masses obtained for the bulge and the disk are $\simeq 10^{10}\ M_\odot$ and $6.7 \times 10^{10}\ M_\odot$, respectively. Possible exchange of matter between the bulge and the disk is not taken into account and each region of this system (the disk is divided in rings 2 kpc wide while the bulge is represented by a shell with a 2 kpc radius) evolves independently from the others.

The main assumptions can be summarized as follows:

1. Instantaneous mixing of gas.
2. No instantaneous recycling approximation.
3. A Schmidt-type law for the SFR expressed as:

$$\psi(t) = \nu(M_{\text{gas}}/M_{\text{tot}})^k .$$

4. The IMF is expressed as a power law with index x and four cases have been explored: (*a*) $x = 1.35$ for the whole mass range (0.1–80 $M_\odot$), (*b*) $x = 0.95$ for the whole mass range, (*c*) $x = 1.35$ for 0.1–2 $M_\odot$ and $x = 1.7$ for $M > 2\ M_\odot$, and (*d*) $x = 1.1$ for the whole range.

5. The mass is assumed to accumulate, in each ring or shell, at the following rate:

$$dM/dt = A(r)e^{-t/\tau(r)} ,$$

where $\tau = 0.01$ Gyr for the bulge and is assumed to increase with the galactocentric radius, being 3 Gyr in the solar neighborhood taken at 10 kpc. This assumption is discussed in more detail in MF and can be justified by the results of Larson's (1976) dynamical models.

6. Detailed nucleosynthesis as in MF is assumed for Type I SNs (C-deflagrating white dwarfs) and for Type II SNs (core bounce in massive stars).

7. The possibility of galactic winds is not taken into account but a comparison with models by Matteucci and Tornambè (1987) for elliptical galaxies taking into account SN-driven winds, is made.

III. MODEL RESULTS

In Table 1 the main parameters used to calculate the evolution of the bulge and the solar neighborhood are listed, together with the resulting metallicity of the peak in the predicted stellar distribution. In the case of bulge K giants, the observed metallicity is given by [(Fe + Mg)/H], whereas for the solar neighborhood is just [Fe/H]. Since we compute the evolution of both Fe and Mg, we calculate [(Fe + Mg)/H] for the bulge metallicity distribution, and [Fe/H] for the solar vicinity, as indicated in the table. In any case, the predicted distribution as a function of iron plus magnesium does not differ significantly from the distribution as a function of iron alone.

TABLE 1

MODEL PARAMETERS AND RESULTS

Bulge Model	k	ν (Gyr^{-1})	τ (Gyr)	IMF	$[(\text{Fe + Mg})/\text{H}]_{\text{peak}}$
1	1	10	0.01	a	−0.05
2	1	10	0.01	b	+0.55
3	1	10	0.01	c	−0.45
4	1	1	0.01	a	−0.45
5	1	10	2	a	−0.05
BM	1	10	0.01	d	+0.35
Solar Neighborhood Model	k	ν	τ	IMF	$[\text{Fe/H}]_{\text{peak}}$
6	1	1	3	c	−0.65
7	0.5	1	3	a	−0.45
8	1	1	3	a	−0.25
9	2	1	3	a	−0.15
10	1	10	3	a	−0.05
11	1	10	3	c	−0.45
12	1	1	3	b	+0.25

The models are identified by numbers except for the best model for the bulge which is labeled BM. This model predicts the metallicity peak to be at +0.35 dex.

The effect of the various parameters appears clear from Table 1: in particular, an increase in the SFR efficiency (ν) leads to a higher metallicity for the peak of the distribution. However, our numerical experiments have shown that one cannot increase arbitrarily the star formation efficiency to increase the metallicity of the peak, because above a certain value of ν (depending on the assumed IMF) the peak metallicity starts decreasing. This is due to the fact that if the star formation efficiency is too high the gas is also consumed too fast and further chemical enrichment is inhibited.

The star-formation efficiency in the bulge should have been much higher than in the solar neighborhood region, since no young stars are observed in the bulge and the old ones have high metallicity. From numerical experiments we find that only values of ν not smaller than $9 \div 10\ \text{Gyr}^{-1}$ are possible if one wants to achieve such conditions.

The same effect of varying ν occurs by changing the exponent k in the SFR, as indicated by models 7, 8, and 9 in Table 1. These models are referring to the solar neighborhood (for the bulge the effect is the same) and show that by increasing k the peak in the distribution moves toward higher metallicities. Since no clear indications exist on the value of k we have assumed $k = 1$ everywhere, although a slightly higher value ($k = 1.1$) was chosen by MF as the best value for the Galactic disk.

A decrease in the power-law index of the IMF, when the SFR is kept constant, also leads the peak in metallicity toward higher values, as shown in Figures 1 and 2 where observed distributions are indicated for comparison, but the effect is greater than that due to variations of the SFR at constant IMF.

Finally, there is a moderate effect due to the assumed time scale of formation of the system (τ). In particular, the peak of the distribution does not change when τ increases, (which is essentially equivalent to go from a closed-box to an open model), but the whole distribution is skewed toward higher metallicities so that it resembles in shape more that in the solar neighborhood. It is well known, in fact, that the G-dwarf problem can be solved by adopting a model where the disk in the solar vicinity is assumed to have formed slowly. This is also what was done in MF and here where the time scale of disk formation at the solar ring (taken at 10 kpc from the Galactic center) is assumed to be 3 Gyr.

In particular we find that, in order to have a good fit for the metallicity distribution, the time scale of collapse for the bulge should not exceed several times 10^7 yrs.

In summary, from these results it appears that the metallicity distribution in the bulge can be explained by models where the star-formation rate has been more efficient than in the solar vicinity by a factor of $\simeq 10$ and the time scale of formation of the system has been much shorter ($\simeq 10^7$ yr). An IMF with a

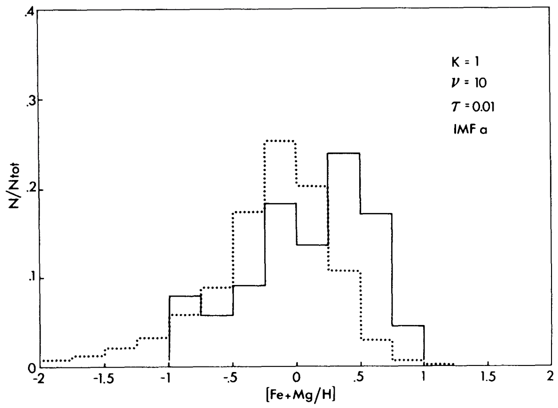

FIG. 1*a*

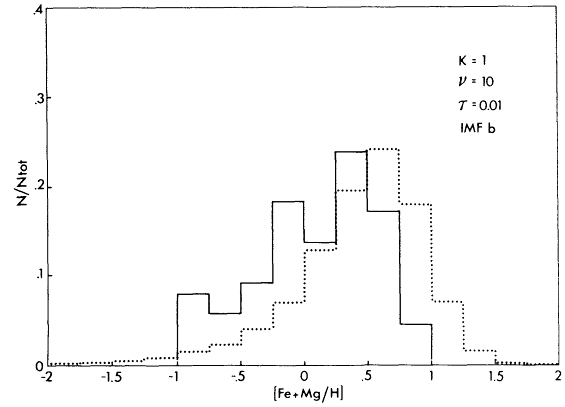

FIG. 1*b*

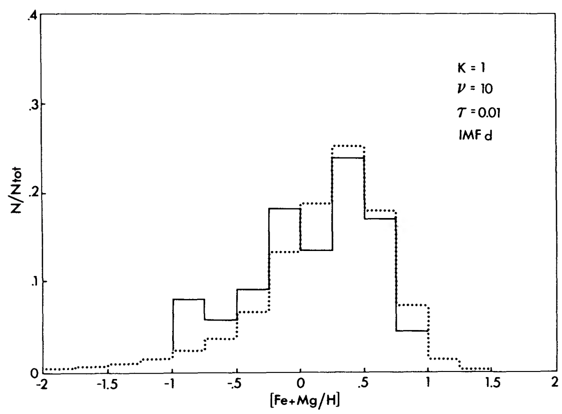

FIG. 1*c*

FIG. 1.—Predicted metallicity distributions (*dashed lines*) normalized to the total number of stars N, and compared to the data of Rich (1988) for bulge K giants (his Solution 1), indicated by the continuous line. (*a*) Predicted distribution from Model 1. (*b*) Predicted distribution from Model 2. (*c*) Predicted distribution from the best model (BM).

slope x between 1.1 and 1.26 should be preferred for the bulge, since it predicts the peak in the metallicity distribution to occur between [Fe + Mg/H] = +0.35 and +0.1, as shown in Figure 3.

Concerning the solar vicinity the best model requires a long time scale of formation and a moderate SFR. Both the G-dwarf distribution (see Fig. 2) and abundance constraints (MF; Tosi 1988) suggest that the IMF in the solar neighborhood should have a slope (in the range of massive stars) lower or at maximum equal to our Case a. From an observational point of view Scalo (1986) suggested that the IMF in the solar neighborhood should be similar to our Case c. However, given the uncertainties still present in nucleosynthesis calculations as well as in the determination of the IMF, we do not think that this necessarily requires a variation in the IMF between the bulge and the solar neighborhood.

Good models for the bulge (for example BM) predict [α/Fe] ratios, where α indicates O, Mg, and Si, of the order of +0.5 to +0.4 dex, independently of the assumed IMF. These ratios are very similar to those observed in very metal poor stars in the solar neighborhood (see Wheeler, Sneden, and Troran 1989). The reason for this resides in the fact that systems like bulges and elliptical galaxies are likely to have undergone a much faster evolution than the solar neighborhood (e.g., faster collapse and star-formation rates), so that they are likely to have attained a metallicity larger than solar in too short a time scale to allow the Type I SNs to restore the bulk of iron, which is the cause for the decrease of [α/Fe] ratios in the solar neighborhood. Models of chemical evolution reproducing the majority of observational constraints (MF, Matteucci 1990) predict, in fact, that [Fe/H] = −1.0 (the point at which the slope of [α/Fe] vs. [Fe/H] starts changing drastically) in the solar vicinity is attained in roughly 0.5–1 Gyr.

This means that we should not consider the [α/Fe] versus [Fe/H] relation observed in the solar vicinity as a universal one, since different galaxies or even different regions of the same galaxy are likely to have evolved at different rates, leading to different age-metallicity ([Fe/H]) relations.

IV. CONCLUSIONS

In this paper we have shown that one can reproduce very well the metallicity distribution of bulge K giants under relative simple assumptions: a fast evolution characterized by a fast collapse (not longer than 10^7 yr) and by a very efficient star-formation rate relatively to the solar vicinity region, (a factor of 10 larger) and by an IMF with a slightly lower power index than the Salpeter (1955) one (x should be in the range 1.1–1.26), is all that is required.

Our numerical experiments have shown that the range of variation for the star-formation efficiency and of the time scale of formation of the system, in order to reproduce the main characteristics of bulge stars, is quite narrow. Therefore, the major uncertainty resides in the IMF, depending on the peak of the metallicity distribution of bulge stars which is uncertain by at least 0.2 dex.

In this framework, we have predicted the abundance ratios of α elements with respect to iron which should be expected to be found in bulge stars, and that are independent of the adopted IMF. These ratios appear to be overabundant by the same amount as observed in metal-poor halo stars in the solar neighborhood, which have the same age but a much lower metallicity than bulge stars. This can be explained as due to the competition of two factors: different age-metallicity relations and the same nucleosynthesis and time scales of restitution of iron from Type I SNs.

This prediction is valid also for elliptical galaxies, which are likely to have evolved in a similar way as bulges. Chemical evolution models computed for ellipitcal galaxies with SN-driven winds (Arimoto and Yoshii 1987; Matteucci and Tornambè 1987) can, in fact, also reproduce the observed distribution of stars in the bulge but only when an initial mass of 10^{12} $M_\odot$ is assumed. In this case the final mass is only

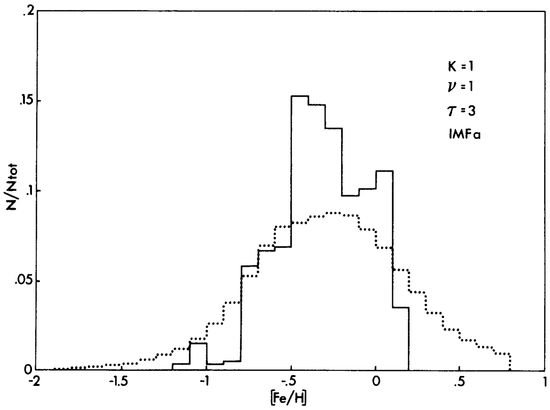

FIG. 2*a*

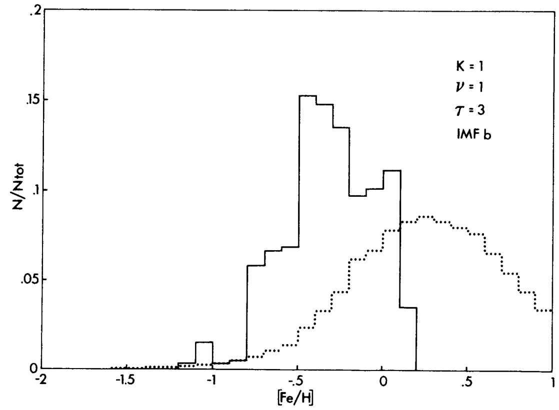

FIG. 2*b*

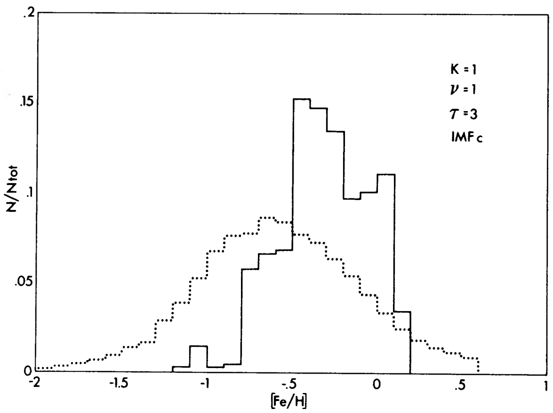

FIG. 2*c*

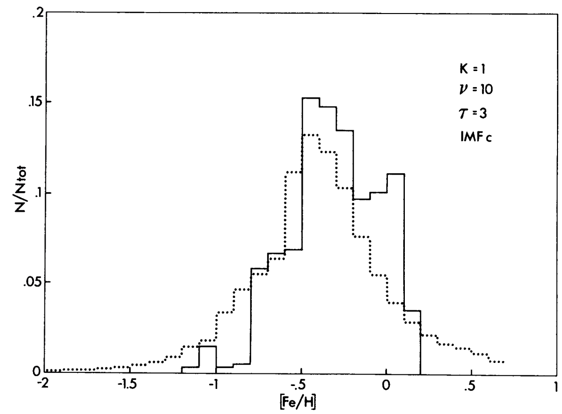

FIG. 2*d*

FIG. 2.—Predicted and observed G-dwarf distributions for the solar neighborhood region. The data, from Pagel (1989), are indicated by a continuous line. (*a*) Predictions from Model 8, (*b*) Predictions from Model 12, (*c*) Predictions from Model 6, (*d*) Predictions from Model 11: this model fits very well the observed distribution but unfortunately, given the high efficiency of star formation assumed ($\nu = 10$), it does not reproduce other features of the solar neighborhood (current abundances, gas fraction, SFR, etc.) so well as Model 6. We show Model 11 to point out how useful it is to adopt models of Galactic evolution which allow us to distinguish among different parameters.

slightly lower than the initial one because the galactic wind occurs when most of gas has already been consumed by star formation, and this mass is far too large to be appropriate for the bulge of our Galaxy. On the other hand, models for lower mass ellipticals fail in reproducing the bulge stellar distribution, since they lose most of their enriched gas at early epochs. Calculations of stellar tracks with α-elements overabundant with respect to iron and high global metallicity are in progress to test the effect of this abundance pattern on the integrated colors of bulges and elliptical galaxies.

If our interpretation is correct, one can also extrapolate these considerations to less evolved systems such as Magellanic Irregulars or the external regions of the disk of the Galaxy. In this case, we should expect that a slower evolution has led the abundance ratios to drop at lower metallicities than in the solar vicinity. In other words, although at the moment we do not have detailed calculations, we can predict that ratios such as [O/Fe] in the Magellanic Clouds should appear less overabundant with respect to the solar neighborhood of our Galaxy at the same [Fe/H]. Indications for a similar behavior come from observations of Russel, Bessel, and Dopita (1988), who instead interpreted this effect as due to preferential loss of ejecta from high-mass stars in low-mass galaxies. In Figure 4 the predicted different evolution of [O/Fe] vs. [Fe/H] in different systems, as due to their different age-metallicity relations is sketched.

Before concluding, we should mention that there is evidence

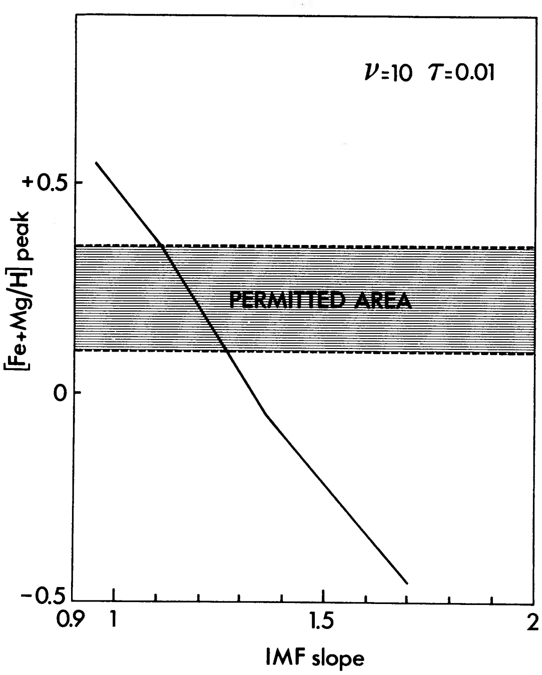

FIG. 3.—The predicted values of the metallicity peak in the distribution of bulge stars is plotted as a function of the slope of the IMF, in order to identify the range of permitted IMFs. The shaded area indicates the range where the metallicity peak should be found.

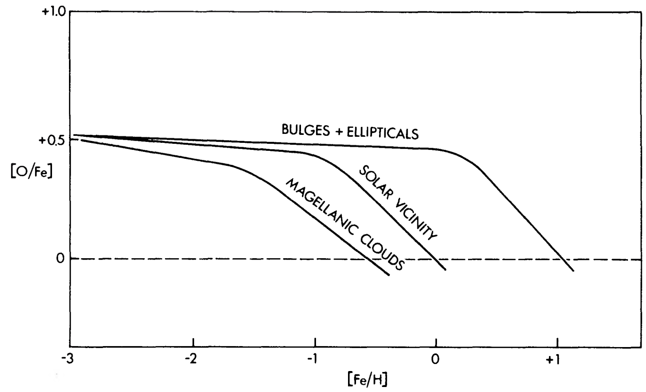

FIG. 4.—A sketch of the predicted [O/Fe] vs. [Fe/H] relations in different systems as a consequence of their different [Fe/H]-*t* relations.

for a strong metallicity gradient in the bulge (Frogel 1988), and this requires that rates of collapse and star formation be inversely proportional to radial distance. This is exactly what is assumed in our model, and although at the moment we have studied the bulge as a single zone, we could easily compute the bulge evolution as a two- or three-zone model with different time scales of collapse in each zone. This will probably produce a metallicity gradient, as already shown by MF for the Galactic disk.

Finally, observational efforts in measuring abundance ratios in bulge K giants would be extremely welcome and useful to test what we have really understood about its chemical evolutionary history.

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